Editorial Summary:
Bam Earthquake of 05:26:26 of 26 December 2003, Ms6.5

1. Introduction

The Magnitude *Ms* = 6.5 earthquake of 26th December 2003 occurred at early morning (05:26:26 local time) along Bam fault with no recorded of any major earthquake, at least, approximately in past 2500 years; and while many residents of the Bam historical city were still sleeping. The traditional mud-brick and clay homes put up little resistance to the violent shaking, and as walls and roofs crumbled and collapsed; more than 100,000 of victims were trapped beneath the rubble and from them around 26,500 lost their lives. Close to 11,000 of the city's students perished, along with one to five of Bam's 5,400 teachers. Tens of thousands were left homeless and up to 6,000 children were orphaned. Arg-e-Bam (Bam Citadel), the largest mud-brick complex in the world and other historical buildings were almost totally destroyed. Bam earthquake not only shook the heart and mind of the Iranian, but the world and created on the biggest human solidarity. This earthquake have created a new initiative in Iran's risk reduction program and consequently provides a unique window of opportunity to raise international awareness of the importance of the effective implementation of a comprehensive earthquake risk reduction program in hazard-prone countries.

2. The Seismotectonic, Seismicity and Strong Ground Motion of Bam

The Bam region in south east of Iran is located in an active seismic zone, however the Bam city itself had no reported major historical earthquake before the event of 26/12/2003. The earthquake was associated with two fresh surface rupture 5*km* apart trending north-south and 2*km* wide zone of hairline fractures developed between the two main ruptures in the north of Bam. The Bam fault with a near north-south direction passes from the vicinity of the city of Bam (less that 1*km* distance to the east of Bam, and between the cities of Bam and Baravat. The other segment 5*km* to the west of the Bam fault passes through the city. The whole system of fresh ruptures associated with the main event is not direct manifestation of the earthquake faults but are secondary structures. No direct surface faulting were associated with the earthquake; however, the surface fissures created after the Bam earthquake are observed around the Bam fault between the cities on Bam and Baravat. Considering that the Bam earthquake was multiple event; the focal depth of the main event is estimated to be 8*km*, while the second event was 10*km*. *Mw*6.5 was calculated for this event based on the seismic moment of the main shock. Using the data from a dense network in the Bam, the focal depth distribution of the aftershocks show a nearly vertical alignment of aftershocks located between 6 to 20*km* depth. The focal mechanism of the main events and aftershocks indicate right lateral strike slip faulting on *N-S* trending faults which is compatible with the fault traces that were observed by the *IIEES* tectonic group.

The strong motion record obtained by *BHRC* in the Bam station shows the Horizontal *PGA* of 0.8*g* and 0.7*g*, and 1.02*g* for the vertical component. The effective duration of the earthquake were estimated between 7 to 10 seconds. Two strong phases of the energy have been seen in the accelerograms; the first is interpreted to represent a starting sub-event with right-lateral strike slip mechanism and located south of Bam. The preliminary observations on the strong motion record obtained in the Bam station, as well as the observed damages in the region shows a vertical directivity effects which caused the amplification of the low frequency motions in the fault-normal direction as well as the greater amplitude of the motion in the vertical direction. The demolished walls and building of Bam are representative for such effects in the up-down (vertical) and east-west directions (fault-normal). The attenuation of strong motion was rapid which was even faster in the fault-normal direction. This fact has been observed from the damage distribution as well. The dominant period of this earthquake (1*sec.* for the vertical component) is around the period of the adobe buildings, which can be one the main cause of their failure.

3. The Macroseismic Intensity and the Isoseismal Map

The macroseismic intensity of the earthquake is estimated to be I_0=*IX* (in the *EMS*98 scale), where the strong motions and damaging effects seems to be attenuated very fast especially in the fault-normal direction. The intensity levels are estimated to be *VIII* in Baravat, *VII* in New-Arg (Arg-e Jadid) and the airport area. The intensity level was estimated to be around *IV*-*V* in Kerman and Mahan.

4. Geotechnical Aspects

There were not any major geotechnical failures observed in the Bam; However, many land subsidence due to collapse of Qanats (underground irrigation tunnels), local toppling and block slides along riverbanks or man-made channels were observed. For the purpose of geotechnical microzonation of Bam, seismic hazard analysis, geological studies accompanied by geophysical surveys and aftershock and microtremor measurements were carried out to provide preliminary site classification and *PGA* distribution maps for two return periods of 475 and 2475 years. Reasonable agreements exist between the site classification and 2475 years *PGA* distribution maps of the city and the damage distribution map of the recent earthquake. Almost all damages of the low rise buildings occurred in sites with stiff shallow and medium depth soils, which possess a considerable amplification potential in the high frequency range. The maximum value of the peak ground acceleration was evaluated in the south-east part of the city, where the highest value of damage percent (80-100) was experienced. The minimum value of the peak ground acceleration was evaluated in the north-west part of the city, where the least value of damage percent (20-50) was experienced. In addition, the 475 years *PGA* microzonation map could be used as a preliminary useful hint in reconstruction and urban planning of the city.

5. Structural Engineering Aspects

Existed buildings in Bam composed of Adobe and Masonry housing units (90%); Steel (8%) and Reinforced Concrete (2%). Based on the statistical evaluation of 550 buildings (74% :1-story, 22% :2-story and 4% :3 story or more) of the partially damaged, it was concluded that 62% could not be used for occupation, 34.8% could be retrofitted and 3.2% were safe.

The main reason for the failure of the adobe and masonry buildings were the heavy roofs and walls as well as the lack of structural integrity, specially in the newly build ones. The good performance of the arch roof of the old adobe buildings was good example of the importance of structural integrity. Most of the steel building were damaged due to lack of code implementation, poor workmanship, poor connections (specially Khorjinie or satchel connection), weld rupture, buckling (overall, out of plane and lateral-torsional) of the weak columns specially in the batten columns, rupture and plastic shear of the battens, local buckling and rupture of *X* bracing and lack of frame in one direction of the buildings. The buildings that had followed the minimum code requirements were not damaged. Performance of the concrete buildings were poor for the residential cases and good for the essential ones.

Up to 95% of the buildings and walls within the 2500-years-old-ancient-Arg-e-Bam (Bam Citadel), the largest adobe construction in the world, were collapsed. The failure were mainly due to improper and lack of seismic safety consideration in the restoration program.

6. Lifeline and Special Structures

The Lifeline systems of Bam were shut down due to various type of equipment failure; However most of the lifeline systems were restored within the first week after the earthquake. The performance of the bridges, roads, railways were good and slight damages did not cause interruption of their services. The failure of the Bam airport tower caused delay in using the airport facilities. However its rapid restoration of the airport played very important role in the rescue and relief operation. Without the airport the human casualty were become much more. Water distribution systems for both drinking water and agricultural water which were done through the traditional irrigation system (Qanats) were seriously damage. Water tower and underground water storage tank

and deep well sustained some damage and in general had acceptable performance. Nonstructural damage in the *PTT* buildings caused the communication interruption. The cell phones started to work within a few hours. There were little damage to high voltage transmission lines and towers and moderate damage to electrical equipment in the Bam substation. Most factories and other industrial facilities were either not damaged or stayed intact. However, they remain dysfunctional due to loss of workers.

7. Conclusion

The Bam earthquake disaster, despite its high casualties and losses, provides a unique window of opportunity to raise international awareness of the importance of the effective implementation of a comprehensive earthquake risk reduction program in Iran as well as in hazard-prone developing countries. It gives a challenge to the governments to make the highest use of the existing know-how on earthquakes and its integration into development programs. It also compels the scientific and engineering community to provide more socio-economic-cultural compatible solutions to national needs. Moreover, the public at large should become more concerned about the hazard and increase its own preparedness level. The *UN* Strategy document, Bam Declaration and Recommendation for Bam citadel, Bam reconstruction paper and formation of the *UNESCO-UNDP-UN/ISDR-IIEES* Alliance for earthquake risk reduction in developing countries are sample of the initiatives for the better future.

Acknowledgment

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Surface Expression of the Bam Fault Zone in Southeastern Iran: Causative Fault of the 26 December 2003 Bam Earthquake

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ABSTRACT: *The Bam fault zone is a major active fault zone in southeastern Iran. Geomorphic evidence indicates that it has been responsible for repeated faulting events since late Pleistocene. The December 26, 2003 Bam earthquake was associated with two fresh surface ruptures 5 km apart trending north-south and a 2 km wide zone of hairline fractures developed between the two main ruptures in north Bam. The amount of slip along the surface ruptures ranges between 0.5-5.5 cm across the zone. The whole system of fresh ruptures associated with the Bam earthquake is not direct manifestations of the earthquake fault but are secondary structures such as synthetic shears (Reidel shears), mole tracks and oblique grabens which are strongly indicative of right-lateral motion along principal displacement zone in the earthquake source. This is compatible with the focal mechanism solutions of the Bam earthquake and fault displacements during the late Pleistocene.*

Keywords: Bam; Active fault; Strike-slip fault; Geomorphology; Bam Fault

1. Introduction

On the early morning of Friday, December 26, 2003 the southeastern part of Iran was shaken by one of the worst earthquakes in Iranian history. The earthquake which was located south of Bam caused catastrophic damage in the Bam city. Preliminary estimates placed the death toll at 26,500 and 85 percent of buildings damaged or destroyed in the Bam area. International Institute of Earthquake Engineering and Seismology (*IIEES*) placed the epicenter at 29.02°*N*, 58.30°*E* with a focal depth of 8 kilometers, and assigned a surface wave magnitude (*Ms*) of 6.5 to the earthquake.

The fault segment responsible for the December 26 earthquake is difficult to locate as there is no direct surface faulting associated with this earthquake. The only fault which can be related to the earthquake, the Bam fault zone, is not clearly expressed at the surface along its large extent as a result of rapid sedimentation. However, aerial photographs and field observations along some of its sections show geomorphic evidence for repeated surface faulting events. The objective of this paper is to describe the main geomorphic features of the Bam fault zone and fresh ground fractures associated with the earthquake. Based on surface ruptures and fault displacements during the late Pleistocene, the fault zone responsible for the Bam earthquake is recognized.

2. Geological Setting

The Bam earthquake of December 26, 2003 occurred in the low plateau region of southeastern Iran, (see inset in Figure (1)). This region of Lut block constitutes a continental basin environment and is

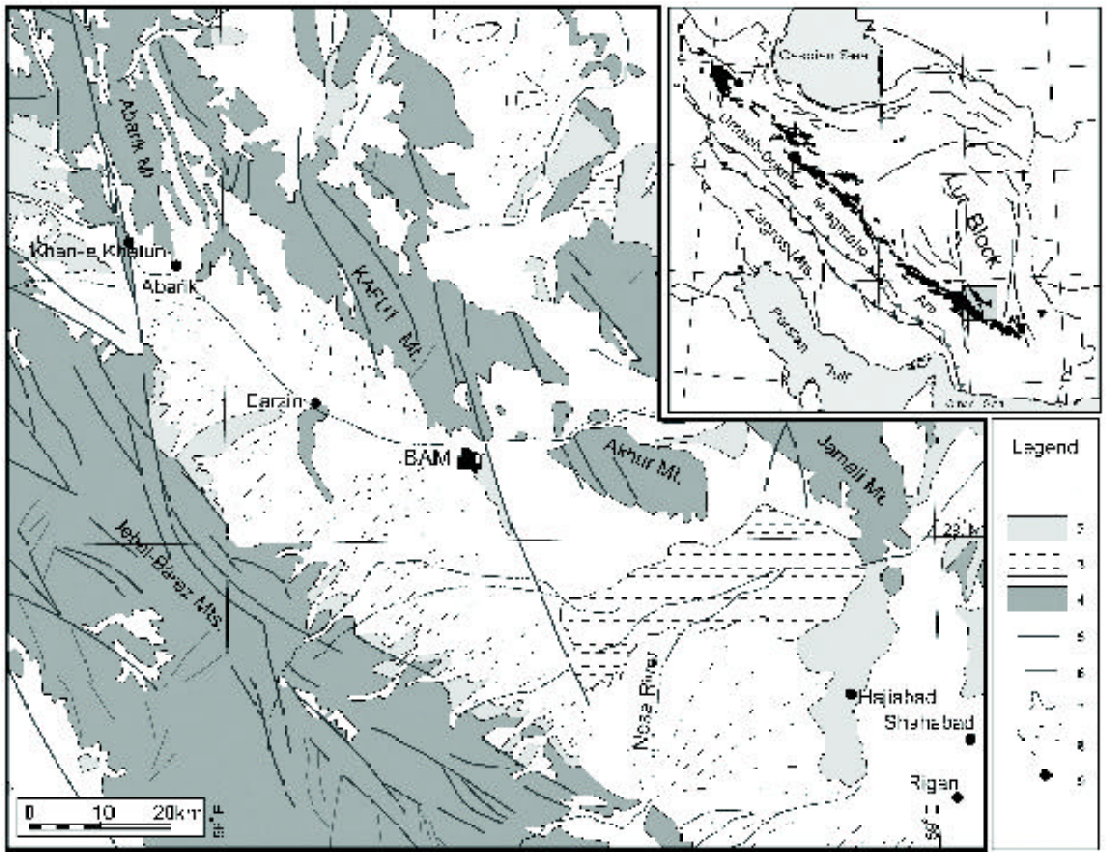


Figure 1. Simplified map of geology-geomorphology of the Bam area, modified after National Iranian Oil Company (1977). The upper right inset shows location of the map, Urmieh-Dokhtarmagmatic arc (in black) and the Lut block. 1. Recent fluvial and alluvial deposits, 2. Low terraces and the edge of Dasht, 3. Lake deposits, 4. Volcanic rocks, 5. Major fault, 6. Minor fault, 7. River, 8. Alluvial fan, 9. Town.

tectonically very active compared to the central parts of the block. Cretaceous to Recent continental deposits are found throughout this region.

The Bam area is about 1067 m above sea level and located between two NW-trending mountain ranges (Figure (1)). To the north, the Kafut mountain with an elevation of 2424 *m* represents the highest summit among the many mountains in the north of Bam. Jebal-Barez mountains to the south is the southeastern continuation of the Urmieh-Dokhtar magmatic arc, (see inset in Figure (1)). This arc represents a thin elongated zone of great tectonic movement and manifests itself as an area of intense eruptive and volcanic extrusives of Eocene age. The rivers drain northwestern flank of the Jebal-Barez mountain range and, to less extent, the southwestern flank of the Kafut mountain feed into the main NW-trending drainage system occupying the broad valley between the two ranges. This process is resulted in about 150 meters alluvial deposits overlying the volcanic rocks exposed a few *km* north of Bam.

The Quaternary deposits in the Bam area can be seen as three stratigraphic units. Lake deposits exposed at some 25 *km* to the south, as well as 40 *km* north of Bam, are lower Quaternary in age. The upper Quaternary is represented by low terraces and the edge of Dasht and mainly composed of silt, marl, sand and fine gravels. This unit is overlain by coarse gravels of fluvial and alluvial origin (Figure (1)).

3. Active Tectonics

The active faults of Iran result from active crustal deformation due to the on-going continental convergence between Arabia and Eurasia. Earthquake focal mechanisms suggest that this convergence has been accommodated mainly through *NNW*-trending right-lateral strike-slip faults in eastern Iran (Figure (2)). These strike-slip faults consist of several discontinuous fault segments which are arranged in an en-echelon pattern. Some of these segments ruptured during several earthquakes: the along Kuh-Banan fault zone in 1933 and 1977 [1], and along the Gowk fault zone in 1981, 1989 and 1998 [3]. The Bam fault zone, however, has been seismically inactive during the last two millennia [1].

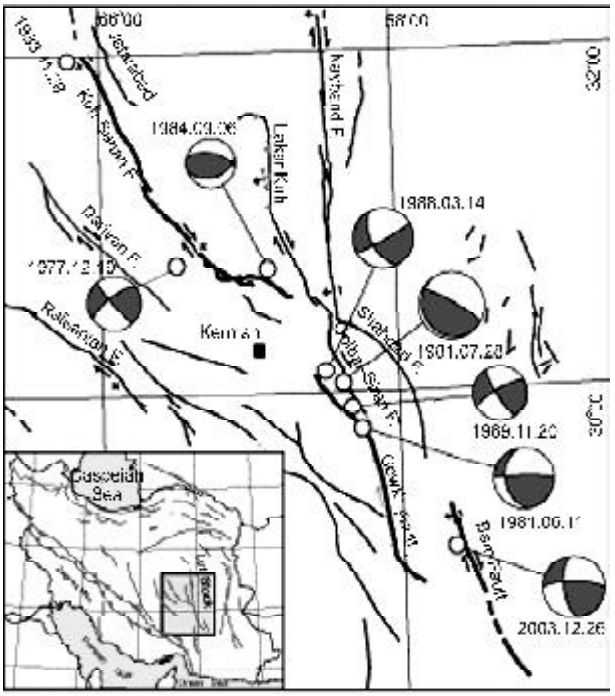


Figure 2. Major faults with CMT solutions of some of the large earthquakes in Eastern Iran. Seismicity occurs along the NNW-trending right-lateral transpressional faults shown by thicker lines.

4. The Bam Fault Zone

The Bam fault zone is considered as one of the active zones in southeastern Iran, (Figure (3)). Offset streams and scarps in alluvium outline this previously mapped fault and indicate that it has been active in Recent times [2, 7]. It has an average strike of *N-NW* over a length of about 50 *km* and dipping west (Figure (3)). Three major fault segments can be recognized along the Bam fault zone namely southern, eastern and northern segments. The geomorphic evidence indicating the late Pleistocene displacements along the Bam fault zone is well preserved along the eastern and northern segments compared to the southern segment. This is because rate of sedimentation along the Bam fault zone generally decreases from south to north as the distance between the Jebal-Barez mountains and the Bam fault zone increases northward.

4.1. The Southern Segment

The southern segment is some 33 *km* long and strikes *N* 18°*W* (Figure (3)). This segment of the Bam fault zone is not directly expressed at the surface along its great extent as a result of rapid sedimentation. Although, the fault zone along this segment is buried by the alluvial and fluvial deposits, it can be mapped on aerial photographs. The lower Pleistocene lake deposits to the east are juxtaposed across this fault segment against the upper Pleistocene deposits of fluvial origin (Figures (1) and (3)). Young alluvial fans and stream beds drain north-western flank of the Jebal-Barez mountains are truncated by this section of the Bam fault zone. A topographic profile across the southern segment is shown in Figure (4a). This profile as well as field observation (Figure (5)) indicates that this segment of the Bam fault forms an uplifted area elongated *NNW* which may represent an incipient fault-propagation fold incised by recent channels. The recent channels are locally displaced right-laterally along the crest of this uplifted area but it is not clearly evident everywhere.

4.2. The Eastern Segment

Some 5 *km* south of the town of Baravat, the southern segment steps left and continues generally northward in the direction of Baravat (Figure (3)). This segment of the Bam fault is about 10 *km* long, trends almost *N-S* and is clearly visible in the geomorphology.

The eastern segment forms a prominent fault scarp whose east side is downthrown relative to the west side. The vertical displacement varies from place to place between 15 and 25 meters. This scarp is a fault-propagation fold verging east as a result of slip along a buried thrust dipping west (Figure (6a)). However, the thrust has reached to the surface across one of its sections in north Baravat (Figure (6b)).

A topographic profile across the eastern Bam fault segment is shown in Figure (4b). As it can be seen a shorter scarp is formed 200 m to the west of the thrust front on the main uplifted surface. Along this shorter scarp channels are systematically displaced right-laterally (Figures (7a) and (7b)). The most spectacular feature among them is two lines of Qanats (underground water tunnels, marked by lines of access shafts) displaced right-laterally for about 11 ± 1 *m* (Figure (7b)). Offsets of several stream beds elsewhere along this section of the fault contain evidence for cumulative displacements by several individual offset events, however, these offsets are difficult to interpret. The vertical component of displacement along this shorter scarp varies between 2 and 3 meters, but in any case, the dip-slip component is subsidiary to the main right-lateral strike-slip movement. The existence of parallel

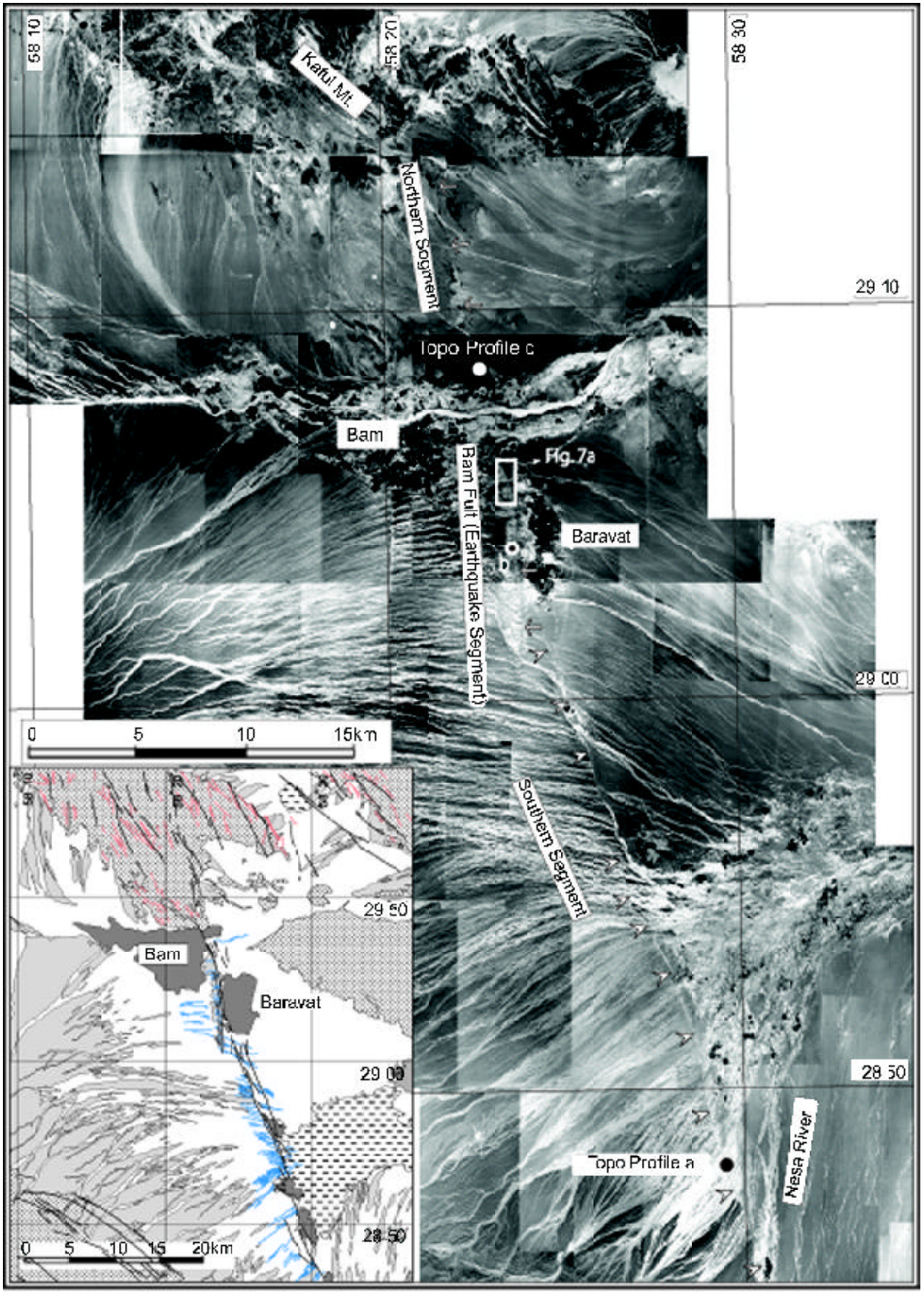


Figure 3. Aerial photomosaic of the Bam region. Bam lies between the Kafut mountains to the north and Jebal-Barez mountains to the south (see the lower left inset). The southern, eastern and northern segments of the Bam fault zone are discussed in the text. Filled circles show the location of topographic profiles in Figure (4). The rectangle encloses Figure (7a).

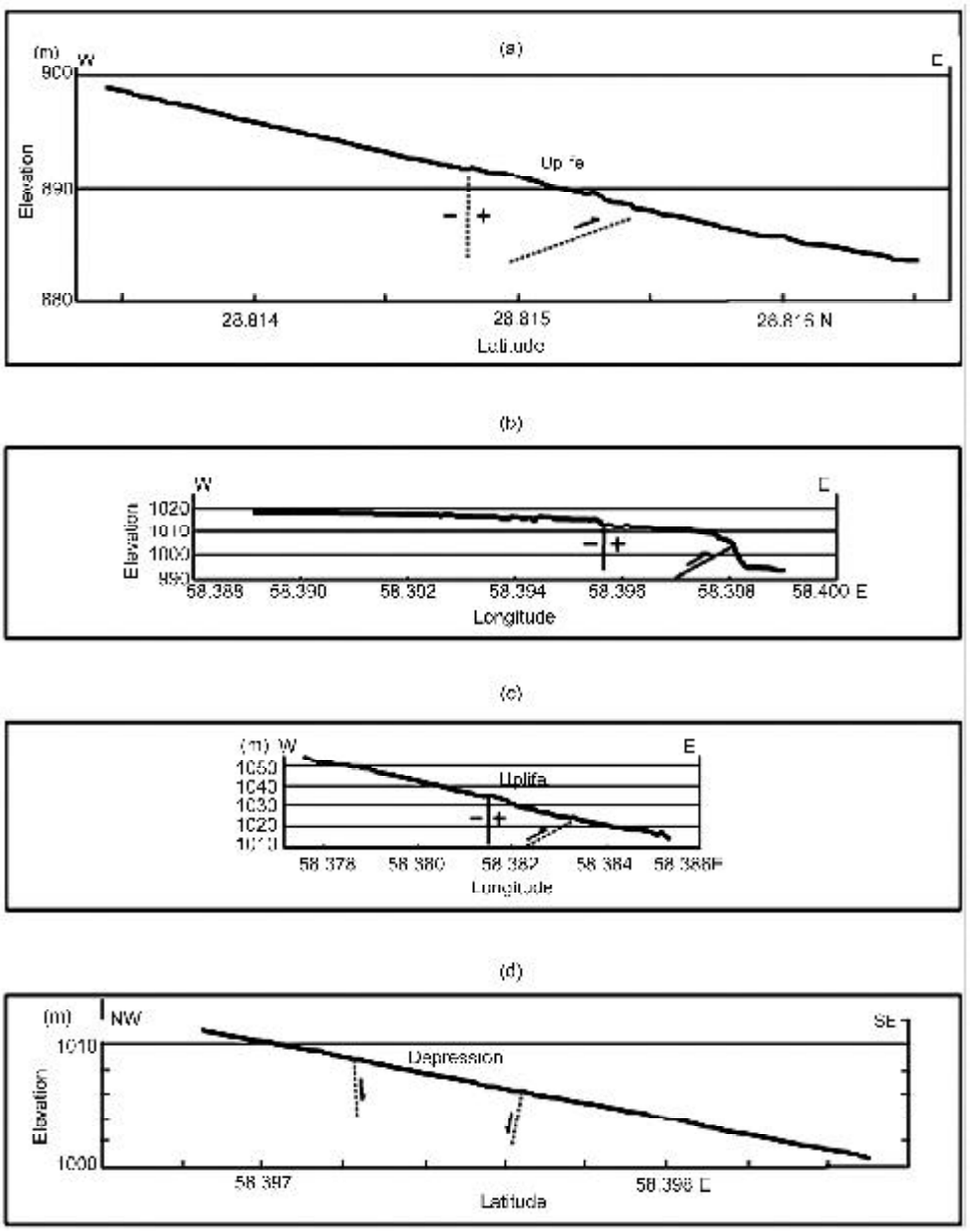


Figure 4. Topographic profiles across the Bam fault zone at several locations surveyed by two System 500 Leica receivers, see Figure (3) for location of the profiles. a, b and c indicate total vertical displacement across the fault scarps. Solid line with sense of motion indicates that the fault is exposed at the surface. Dashed line shows inferred fault. d, topographic profile across co-seismic graben structure formed following the Bam earthquake.

Figure 5. Eroded surface and incised channels across the southern segment of the Bam fault zone forming an elongated uplift. Looking southeast.

active thrust and strike-slip faults along this segment of the Bam fault zone may indicate strain partitioning in this region.

The only direct estimate of the horizontal slip rate along this section of the Bam fault is based on the offset Qanats (Figure (7b)). The maximum age of the Qanat line is 3000 years [5, 6, 8, 11]; because it is horizontally offset for 11±1 *m*, it implies a minimum horizontal slip rate of 3-4 *mm/yr*. These rates are two times larger than the rates of 1-2 *mm/yr* suggested by Walker and Jackson [13] for the northern continuation of the Bam fault (i.e. along the Nayband-Gowk-Sabzevaran fault system).

Figure 6. a. Fault-propagation fold verging east, looking north-east. b. Thrust fault exposed at the front of the Bam scarp, looking southeast.

Age of the uplifted surface is not known, however, by making some assumptions on the age of the uplifted surface, we can estimate long-term slip rates of this fault segment. The upper most layers of the upper Pleistocene sediments, incised by drainages that show a 25 *m* vertical displacement could be attributed to the last important post-glacial deposition following the last glacial peak (18 to 10 *ka*). If this assumption is correct, the minimum vertical slip rate is 1.4-2.5 *mm/yr*.

4.3. The Northern Segment

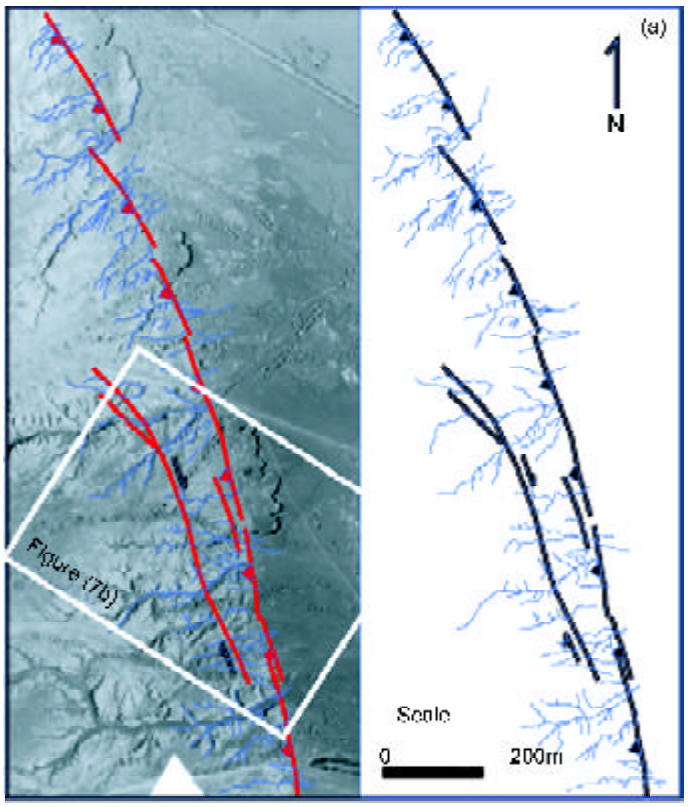
The northern segment trends *N* 10° *W*. Here stream beds and gullies are systematically offset along the fault trace (Figure (8)). Right-lateral offsets of some stream beds along this section of the fault contain evidence for cumulative displacements by several individual offset events. Channels incised within the upper Pleistocene (maximum 125 *ka*) sediments are right-laterally offset for about 320 meters, indicating a minimum slip rate of about 2.6 *mm/yr*. This value is close to the slip rate along the eastern segment.

5. Co-Seismic Ground Ruptures

The geological effect of the Bam earthquake consists of two fresh surface ruptures that trend *N-S* and are 5 *km* apart, south and east of Bam (Figure (8b)).

The fresh surface rupture to the east of Bam developed along the eastern and northern segments of the Bam fault zone and extended discontinuously from south (south of Baravat) to the north for about 11 *km* (Figure (8)). On the eastern segment, the deformation zone consists of numerous tension cracks and fractures along which very small right-lateral motion (0.5-1 *cm*) can be seen (Figure (9)). This indicates that much of the right-lateral motion of the ground surface is distributed over a wide area in east Bam. The most spectacular feature along this segment is two normal faults 12 m apart forming an oblique graben on the crest of the fold on the main road connecting Baravat to Bam (Figures (4d) and (10)). The *N*100° trending normal faults at this locality suggest right-lateral movement along the principal displacement zone. On the northern segment, however, deformation is distributed over a 2 *km* wide zone in the northern Bam vicinity where numerous hairline ruptures trending *N* 20°*W* were evident (Figure (8)). The amount of displacement on individual fractures is as small as 0.5-1 *cm* right-lateral motion. The eastern side of this rupture zone follows exactly the previously mapped fault trace (i.e. the northern segment). The most characteristic deformational structure along the northern segment is mole tracks (Figure (11)). The size of mole tracks varies from 4 to 8 *cm* high, 10 to 50 *cm* wide and 1 to 1.5 *m* long. Mole tracks are typical push-up structures along the strike-slip rupture zones [4].

Following the Bam earthquake, an en-echelon rupture pattern stepping left developed in alluvium deposits in south of Bam, where no fault trace is visible in the geomorphology (Figure (8)). Each of individual ruptures trend *N*30°*E* and represent synthetic shear fractures (Reidel shears) which have developed along a *N-S* trending principal right-lateral fault zone in the basement. The maximum amount of right-lateral displacement observed along the fresh synthetic shears was about 5.5 *cm* (Figure (12)). This rupture zone which has been also revealed by *InSAR*, is considered as the main strike-slip fault responsible for the Bam earthquake [12]. However, on the northern and eastern segments of the Bam fault the same amount of co-seismic displacement or more is distributed over a wide fracture zone but, it is not delineated by *InSAR*. This is because, using



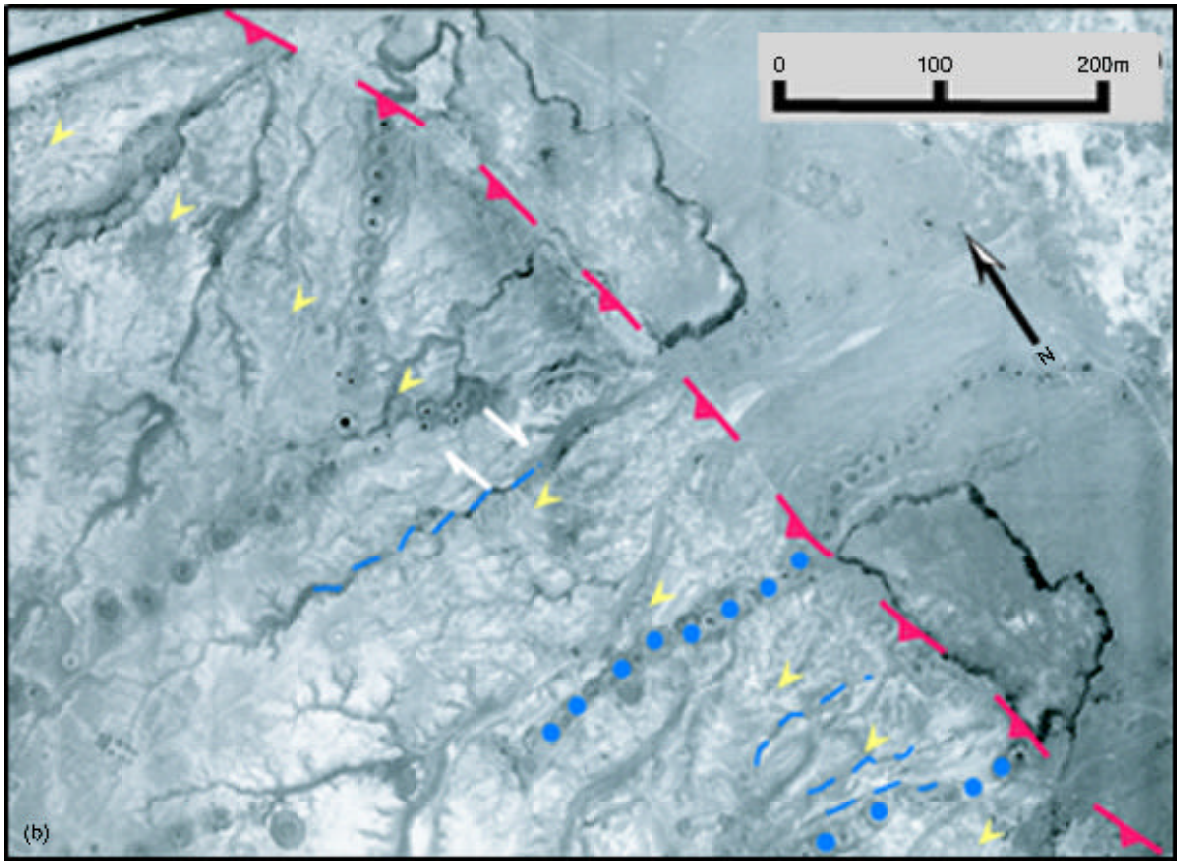


Figure 7. Aerial photographs of the eastern segment of the Bam fault zone. a. shows parallel active thrust and strike-slip faults forming this segment of the Bam fault zone. The rectangle encloses Figure (7b). b. stream beds and lines of Qanats are systematically offset along the fault trace. Red dashed line shows the Bam thrust forming the Bam scarp east of Bam, yellow arrowheads mark the strike-slip fault trace, blue circles mark the Qanat's shafts displaced right-laterally.

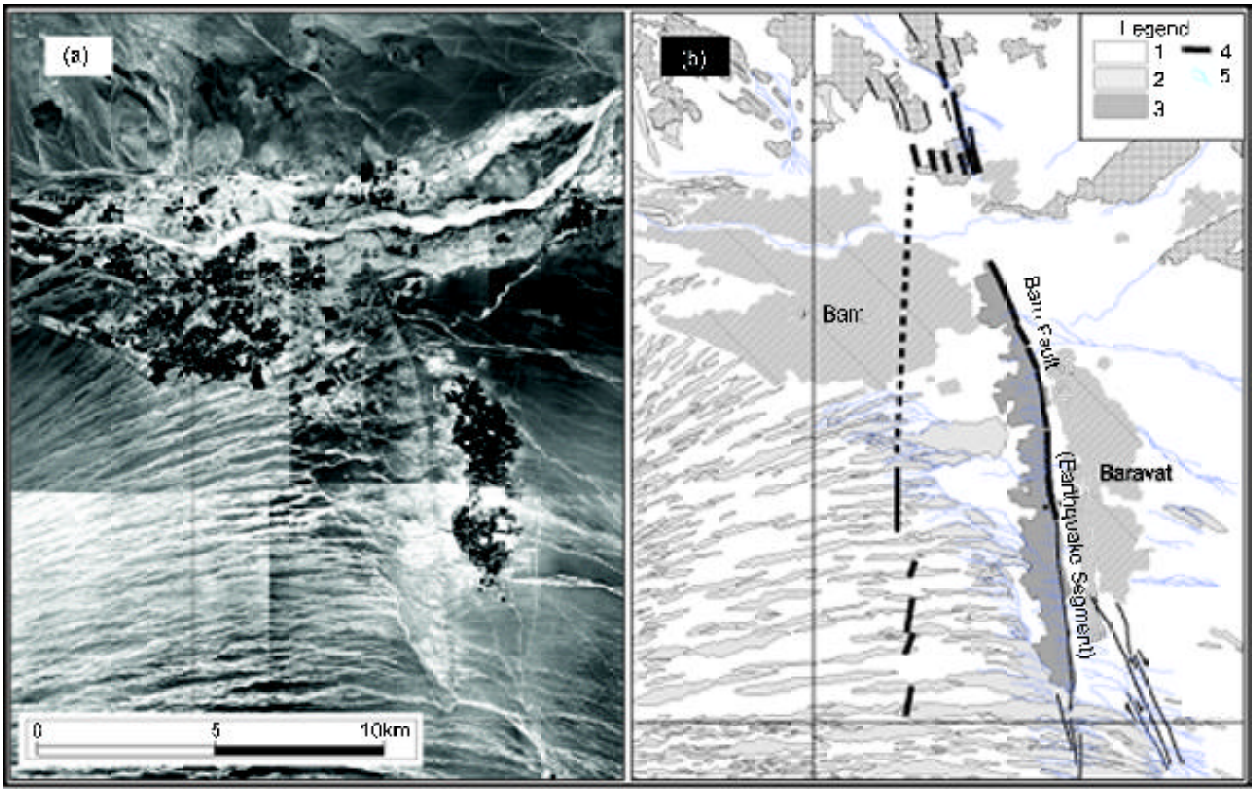


Figure 8. a. Aerial photomosaic of the Bam area. b. Line drawing showing surface ruptures associated with the Bam earthquake. Note 2km wide co-seismic hairline ruptures in the northern Bam vicinity. 1. Alluvial deposits 2. Fluvial deposits 3. Low terraces 4. Co-seismic rupture 5. Draiage channels.

interferometery, it is not easy to define displacements of 0.5-1 *cm* or less [9].

Finally, fresh ground displacements along co-seismic surface ruptures are not representative of total amount of slip along the principal earthquake fault which was not exposed at the surface. However, direction and sense of motion along co-seismic ruptures (synthetic shears, mole tracks and grabens) in the Bam area indicates right-lateral motion on a

Figure 9. Tension cracks with 0.5 cm lateral displacement west of Baravat.

Figure 10. Two different views of the oblique graben structure on the crest of the fold on the main road connecting Bam to Baravat.

Figure 11. Two different views of mole tracks north of Bam. Upper photograph looking south, the lower one looking north.

wide strike-slip fault zone whose eastern side is marked by the right-lateral Bam fault. In other words, the co-seismic ruptures in east, northeast and south Bam were related structures in a right-lateral zone 5 *km* wide. This is compatible with the *CMT* solution which corresponds to right-lateral strike-slip motion on a fault striking $N172^{o}E$ (Figure (2)).

Figure 12. Maximum 5.5 cm lateral displacement measured south of Bam.

6. Conclusions

The Bam fault zone is composed of sub-parallel strike-slip and thrust faults which have clear expression in the geomorphology. The December 26, 2003 Bam earthquake was an example for a good correlation between long-term cumulative deformation along an active fault zone and source parameters of an earthquake. The fault responsible for the Bam earthquake was not exposed directly at the ground surface. However, surface ruptures associated with the earthquake at Bam imply that the earthquake occurred along right-lateral segments of the Bam fault zone. This is compatible with the focal mechanism solution of the earthquake and fault displacements during the late Pleistocene.

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References

1. Ambraseys, N.N. and Melville, C.P. (1982). "A History of Persian Earthquakes", Cambridge University Press, Cambridge.

2. Berberian, M. (1976). "Contribution to the Seismotectonics of Iran", Rep. II. Publs. Geol. Surv., Iran, **39**, p.516.

3. Berberian, M., Jackson, J.A., Fielding, E., Parsons, B.E., Priestley, K., Qorashi, M., Talebian, M., Walker, R., Wright, T.J., and Baker, C. (2001). "The 1998 March 14 Fandoqa Earthquake (Mw 6.6) in Kerman Province, Southeast Iran: Re-Rupture of the 1981 Sirch Earthquake Fault, Triggering of Slip on Adjacent Thrusts and the Active Tectonics of the Gowk Fault Zone", *Geophys. J. Int.*, **146**, 371-198.

4. Deng, Q., Wu, D., Zhang, P., and Chen, S. (1986). "Structure and Deformational Character of Strike-Slip Fault Zone", *Pure and Applied Geophysics*, **124**, 203-223.

5. Forbes, R.J. (1964). "Studies in Ancient Technology", **1**, Leiden, Brill.

6. Goblot, H. (1979). "Les Qanats: Une Technique D'acquisition de L'eau, Paris, Mouton.

7. Hessami, K., Alyasin, S., and Jamali, F. (1997).

"An Investigation of Some Historical Earthquakes and Paleoseismic Sources in Iran, Historical and Prehistorical Earthquakes in the Caucasus", In: D. Giardini and S. Balasanian (eds.), NATO Asi Series, 2. Environment, Vol. 28, Kluwer Academic Publishers, The Netherlands, 189-199.

8. Kamiar, M. (1983). "The Qanat System in Iran", Ekistics, **50**, 467-472.

9. Massonnet, D., Feigl, K., Rossi, M., and Adragna, F. (1994). "Radar Interferometric Mapping of Deformation in the Year After the Landers Earthquake", Nature, **369**, 227-230.

10. National Iranian Oil Company (1977). Geological Map of Iran, Sheet No. 6, South-east Iran, Scale 1: 1000,000, Natl. Iran. Oil. Co., Explor. and Prod., Tehran, Iran.

11. Potts, D.T. (1990). "The Arabian Gulf in Antiquity", **1**, from Prehistory to the Fall of the Achaemenid Empire, Oxford, Clarendon Press.

12. Talebian, M., Fielding, E.J., Funning, G.J., Ghorashi, M., Jackson, J., Nazari, H., Parsons, B., Priestley, K., Rosen, P.A., Walker, R., and Wright, T.J. (2004). "The 2003 Bam (Iran) Earthquake: Rupture of a Blind Strike-Slip Fault", Geophysical Research Letter, **31**(11), L11611, 10.1029.

13. Walker, R. and Jackson, J.A. (2002). "Offset and Evolution of the Gowk Fault, SE Iran: A Major Intra-Continental Strike-Slip System", *Journal of structural Geology*, **24**, 1677-1698.

Seismological Aspect of 26 December 2003 Bam Earthquake

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ABSTRACT: *A waveform inversion algorithm, based on least square method, has been applied to the P and S waves of the 26 December 2003 Bam earthquake. The aftershocks of this event distributed along a narrow zone (approximately 20km) in N-S direction. In this research, estimates of centroid depth, seismic moment, and source mechanism have been obtained. The source mechanism derived from the inversion of long period body waves revealed that two events occurred on N-S trending strike-slip fault with a thrust component. According to the source model estimated in this study, the Bam earthquake was a multiple event. The rupture following the first event started at a depth of about 8km. However depth of the second event is about 10km. The total seismic moment estimated from inversion processes is 8.34×10^{18}Nm. The seismic moment of the second event is less than the first one (the seismic moment of second event is calculated as 2.34×10^{17}Nm). The pulse duration of main shock and the second event was determined from source time function and it is 1.7s and 0.8s respectively. Corner frequency and source radius have been calculated for main shock and the second event by using pulse duration. The range of corner frequency and source radius are from 0.187Hz -0.397Hz and 5.47km-2.57km for main shock and second event, respectively.*

Keywords: Bam; Seismicity; Error ellipse; Waveform modeling; Mainshock

1. Introduction

The 26 December 2003 Bam earthquake, *Mw* = 6.5, occurred at 01:56:56 *GMT*, in southeast of Iran, see Figure (1) near the city of Bam which had a population of about 100,000. The earthquake killed around 26500 people, destroyed and damaged more than 70 percent of buildings completely, and damaged the surrounding area. The strong motion record of the main shock indicates a peak horizontal and vertical acceleration of about 0.79*g* and 1.01*g* respectively [1] where the maximum intensity was assigned as *IX* (*EMS* 98 scale). This is generally accepted that the first aftershocks which occurring during the first 24 or 48 hours after the main shock defines the relevant rupture surface [2]. Based on this fact, from the first hours after the main shock, International Institute of Earthquake Engineering and Seismology (*IIEES*) started to locate the aftershocks using local and regional permanent seismic stations. The largest aftershock was located by *IIEES* during the first 2 days after the main shock had a magnitude of *Ms* = 5.1.

Using first motion analysis of P-wave or S-wave polarization provides a powerful tool in order to determine the most consistent orientation of a double couple mechanism which fits a number of observations. However such studies rarely constrain the focal mechanism tightly, since in many cases there are insufficient readings in many azimuths around the epicenter. Furthermore, the first arrivals describe only the early part of the source mechanism, which is not necessarily representative of the whole earthquake source process, and they give no information on the scalar moment. In the recent years, technical improvement for calculating synthetic seismograms and modeling the observed waveforms has become an important tool in the study of source mechanisms. The

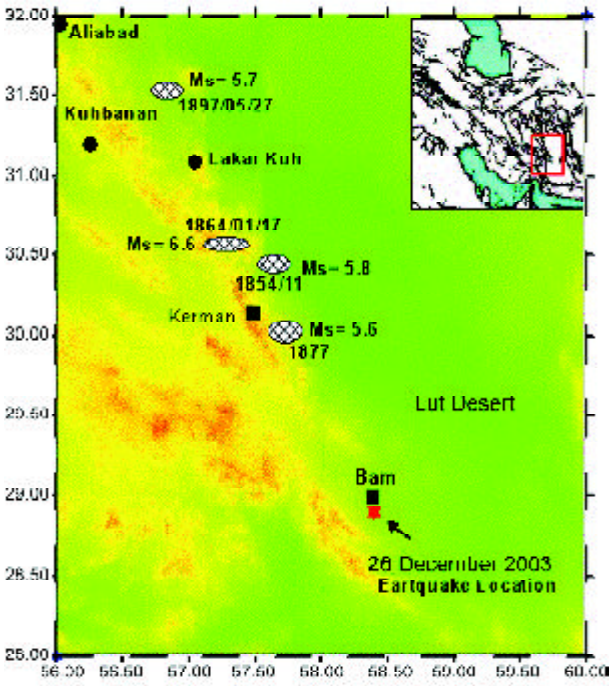

Figure 1. Map showing the location of 26 December 2003 main shock (star), Bam and Kerman city (black square), villages (black circle), and Historical event ( ).

methods of earthquake quantification have been developed for different phases and frequency bands way compare observed and theoretically predicted wave shapes and amplitudes. Although this information is of fundamental interest, it is desirable to know more about the spatial and temporal distribution of moment release. The teleseismic source time function gives information about fault ruptures or source complexity [3]. The principal purpose of this study is to determine the source characteristics, evaluate fault rupture or source complexity, and prepare information about time history of displacement on the Bam fault based on analysis of the three component waveform data from the far-field *GDSN* stations in the epicentral range 30°- 90°.

2. Historical and Instrumental Earthquakes

A study of historical earthquake records [4] shows that some of damaging earthquakes had occurred in Kerman province (the capital of Kerman province is Kerman city) while the Bam city itself experienced no great historical events during the past 2000 years. Figure (1) shows the location of some of historical events near the Bam city. The most significant events are:

The 27 May 1897 earthquake with magnitude M =5.7 which affected a larger area, caused damage in the Kerman. In 17 January 1864, the Chatrood earthquake (M = 6.0) occurred in the region. In April 1854, the Horjand earthquake (M = 5.8, I_o=*VIII*) occurred in northeast of Kerman. This catalogue shows that the earthquake had a same trend as Lakarkuh fault. In 1877 Sirch-Hasan-abad earthquake (M = 5.6) destroyed some of villages (Ab-e-garm, Sirch, Hasanabad, Deh-Gholi and Hashtadan villages). Figure (2) shows the location of the four major earthquakes with magnitudes of greater than 5.6 that have struck the cities and villages in the northwest of Bam during the period of 1981 to 1998. These events are listed bellow:

1. The Golbaf earthquake of 11 June 1981, *Ms*6.7,
2. The Sirch earthquake of 28 July 1981, *Ms*7.1,
3. The South Golbaf earthquake of 20 November 1989, *mb*5.6,
4. The North Golbaf (Fandogha) earthquake of 14 March 1998, *Mw*6.6.

Sirch earthquake is the largest event recorded instrumentally in the Kerman province. The large earthquakes in 1981 were associated with a total 64*km* of fresh movements along northern end of Golbaf (Gowk) fault and 10*km* at the southern segment of Lakarkuh fault. A maximum vertical displacement of 10*cm* were observed east of Golbaf, whereas after the second shock displacement of 14*cm* vertical and 20*cm* horizontal (Dextral) were measured near Chahar-Farsang and Poshteh along the Lakarkuh fault system [5].

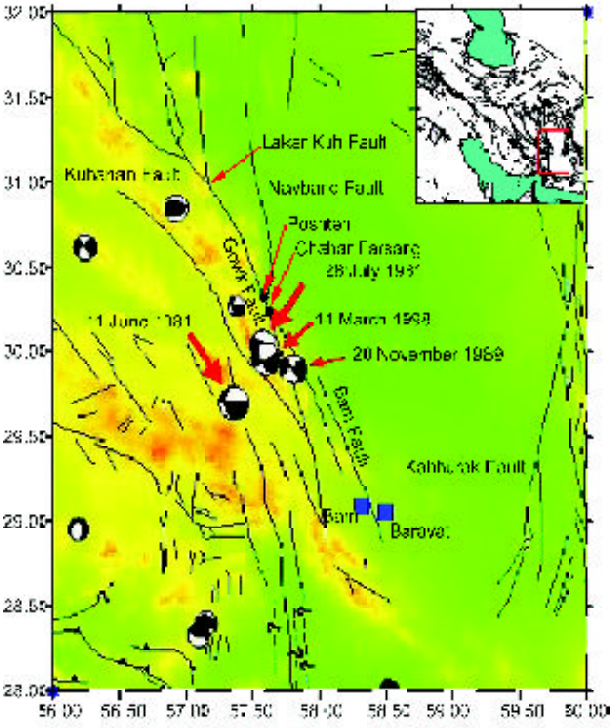

Figure 2. Moment tensor solutions (reported by CMT), fault Map of the Bam and surrounding area [6].

3. Aftershock Sequence

Following the Bam earthquake, *IIEES* recorded 158 aftershocks with magnitude between 2.0< *ML*<5.1 during the first month. For detailed study of the aftershocks nearly two days after the main event, *IIEES* deployed local temporary seismic stations in the epicentral area. This network consisted of nineteen medium-band and short period stations with an operating period of more than one month, starting December 28, 2003. Figure (3) shows the distribution of these events by the end of January 2004.

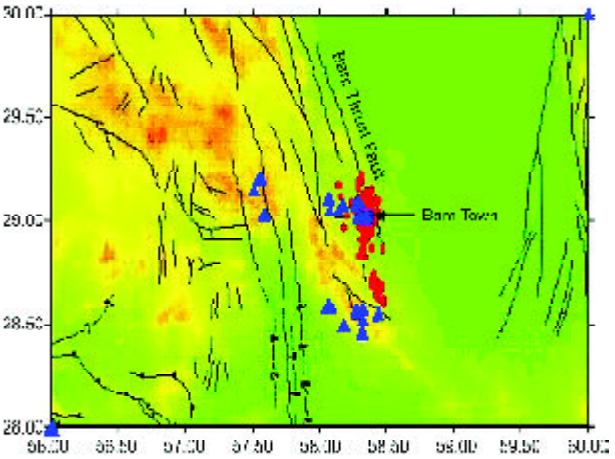

Figure 3. Map show distribution of temporary local stations (▲), aftershocks (●), and Bam city (■).

For locating the aftershocks we used *P* wave velocity model with a horizontal layered structure and with lateral variation of thickness of the upper-most layers was employed, which has been previously used by Zohoorian et al [5]. The parameters of horizontal layered structure are listed in Table (1). *S* wave velocities were calculated on the assumption that the V_p/V_s ratio is 1.73. More than three hundred Aftershocks having four or more *P* times were located and plotted as shown in Figure (3). In this view most part of the aftershocks for a length of about 20*km* closely follows the west of the Bam thrust fault. To get the local magnitude of each event, instrument correction and simulation of standardized instruments have been done using maximum peak-to-peak amplitudes [7]. The most part (75 percent) of these aftershock have magnitude range 1.0<*ML*<3.0. The ranges of depth of these aftershocks are changed between 6-20*km*.

Table 1. Initial model for the southern parts of the Kerman province (north of Bam) based on Zohoorian et al [5].

Layer	V_s (km/s)	D (km)
1	5.00	0.0
2	5.50	6.0
3	6.50	16.0
4	8.00	41.0

4. Evaluate of Errors in Location Coordinate and Error Ellipsoid of the Larger Aftershocks

Evaluate of discrepancies in location parameter and error area for common events (aftershocks) reported by the International Data Center (*IDC*), and *IIEES* are show in Figures (4) and (5).

The Minimum and Maximum *IDC* Error ellipse area are changed 105Km^2 to 530Km^2 (in *REB* bulletin).The minimum and maximum misslocation between the far-field (*IDC*) and near field (*IIEES*) data are 79*km* and 92*km*, respectively shown in Figure (5).

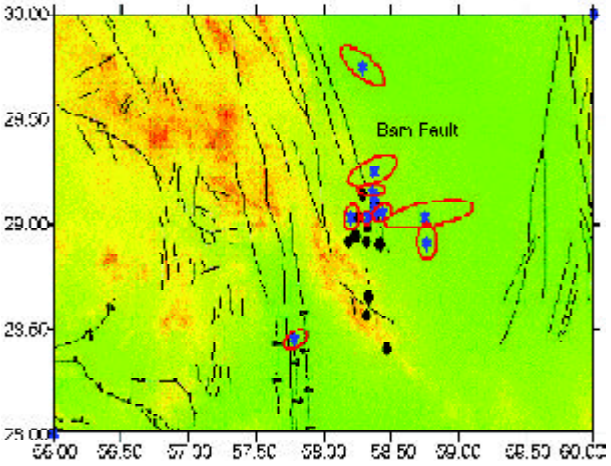

Figure 4. The Map shows epicenter error area (-.-.-) reported by International Data Center (IDC), and the location of epicenter reported IIEES.

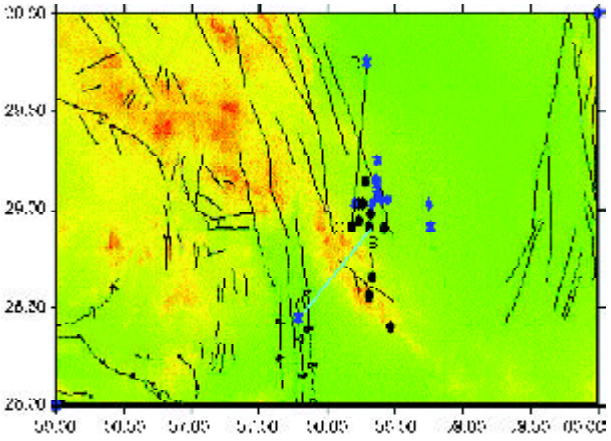

Figure 5. The map shows maximum and minimum Miss location of the epicenter reported by IIEES (●) and IDC (✱), location difference, 79km A——B and location difference, 92km C——D .

5. Waveform Inversion of Body Waves and Source Parameters

Body wave modeling has become one of the most important tools available to seismologist for refining earth structure models and understanding fault-rupturing process. Both *P*- and *SH*- were used to constrain earthquake source parameters. We compared the shapes and amplitudes of long-period *P*- and *SH*- wave recorded by *GDSN* stations. *IASPEI SYN*4 algorithm [8], which is a recent version of Nabelek's [9] inversion procedure based on a weighted least squares method, was used for waveform inversion. The source time function (described by a series of overlapping isosceles triangles) [8], centroid depth, and the fault orientation parameters (strike, dip, and the rake) are used in order to compute synthetic seismograms and the seismic moment.

The inversion procedure adjusts the relative amplitudes of the source time function element, the centroid depth, the seismic moment and source orientation. This solution has been referred as the minimum misfit solution. The Green's function for *P* and *SH* waves can be express in the form [10]:

$$g(t)=CR(t)*M(t)*g^{S}(t) \quad (1)$$

Where $g^{S}(t)$ is the displacement of the *P* or *SH* waves emerging at the base of the crust in the source region in response to a impulse, $M(t)$ and $CR(t)$ are the responses to these waves by the mantle and crust at the receiver respectively.

Amplitudes which are corrected for geometrical spreading and attenuation is introduced with a $t^*=1s$ for *P* wave and $t^*= 4s$ for *SH* wave [9]. As explained by Fredrich [12], uncertainties in t^* effect the source duration and seismic moment, rather than the source orientation or centroid depth.

The seismic moment clearly depends on the duration of the source time function, and to some extends on centroid depth and velocity structure [12]. As the main interest was on source orientation and depth, we did not concern much with uncertainties in seismic moment, which in most cases are probably about 30 per cent. The lengths of a time function was estimated by increasing the number of isosceles triangles until the amplitudes of the later ones became insignificant.

6. Uncertainties in Source Parameters

Having found a set of acceptable source parameters, the procedure described by MaCaffrey and Nabelek [11], Fredrick et al [12], and Taymaz [10] was followed, in which the inversion routine is used to carry out experiments to test how well individual source parameters are resolved. One parameter at a time was investigated by fixing it at a series of values either side of its value yielded by the minimum misfit solution, and allowing the other parameters to be found by the inversion routine. The quality of fit between observed and synthetic seismograms was then visually examined to see whether it had deteriorated from the minimum misfit solution. In this way we were able to estimate the uncertainty in strike, dip, rake and depth for each event. In common with the authors cited above, we believe this procedure gives a more realistic quantification of likely errors than the formal errors derived from the covariance matrix of the solution (strike test is show in Figure (6)).

Uncertainties in seismic moment and centroid depth arise from errors in the source velocity model. The crustal structure at the source and receiver is modeled as a single layer over a half space. The material constants assumed for region are $V_P = 6.5 km\ s^{-1}$, $V_s = 3.7 km\ s^{-1}$ and $\rho = 2.9 gr.cm^{-3}$.

A number of automatic preliminary *CMT* solutions for Bam earthquake have been reported by *USGS-PDE* and the others. Among them the best double-couple fault plane solutions determined by Harvard. While all solutions show dominant strike slip faulting. Long-Period body wave seismograms were inverted to obtain a detailed fault mechanism solution and source parameters of the 26 December 2003 Bam earthquake. In the distance range of about 30°-90° $M(t)$ includes only the effects of an-elastic attenuation, geometrical spreading and travel time. Body waves propagate steeply (15°-35° from the downward vertical) through the crust and uppermost mantle and are therefore influenced mostly by the vertical structure below the source and receiver [10].

In this reason good quality *GDSN* long period P-waves and S-waves recorded in the distance range of 30°-90° were selected. All waveforms were low-pass filtered (Butterworth) at a cut of frequency of $0.2 Hz$ in order to remove the high frequency component which may cause instability during the inversion. When the *P* waveforms were examined prior to the inversion procedure, it was recognized that the occurrence of a second source with a considerable delay time is quite probable. The source parameters of inversion process are given in Table (2). The minimum misfit solution for the main shock is shown in Figure (7). According to direction of local

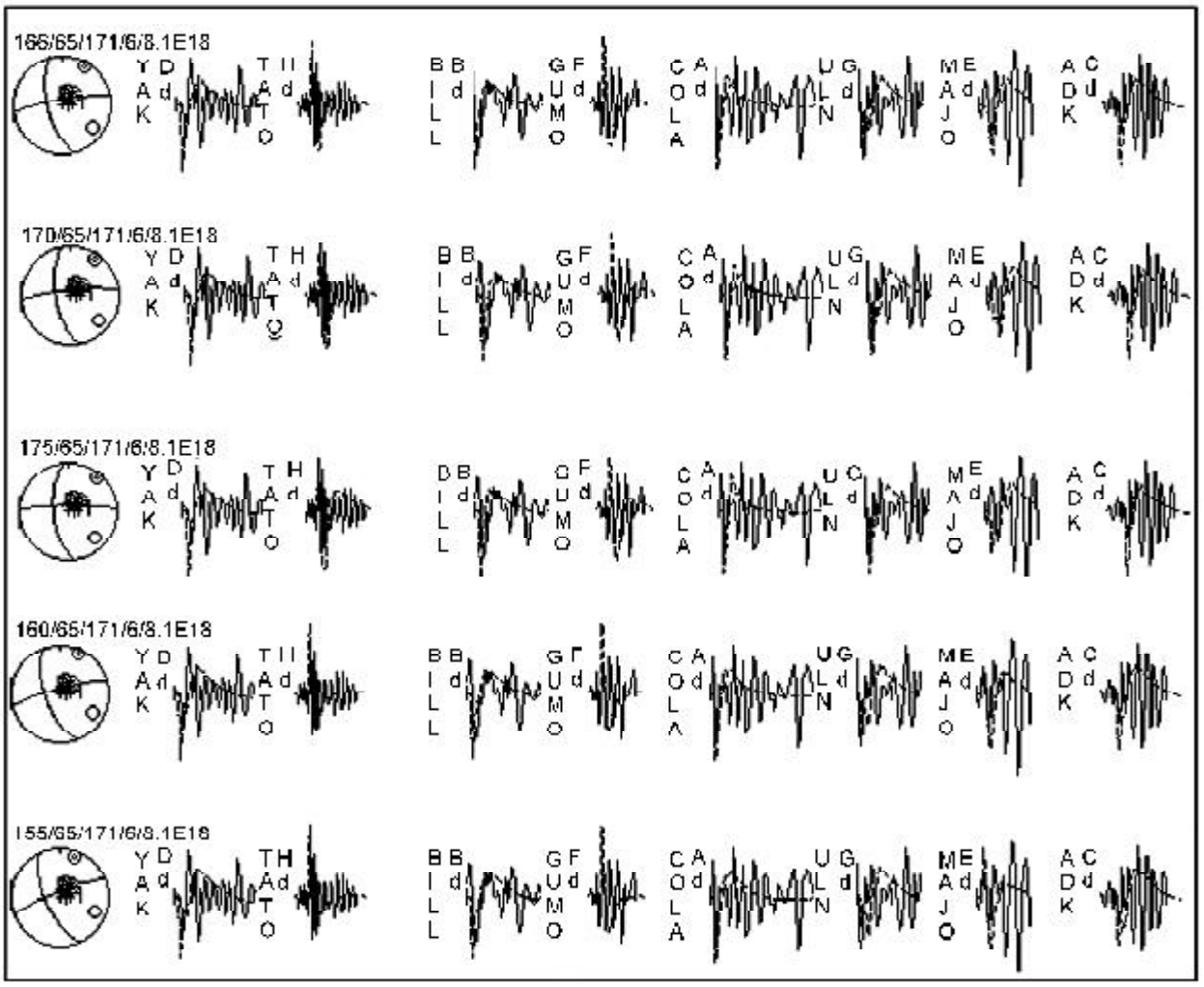

Figure 6. In this each row shows a selection of waveforms from a run of the inversion program. At the start of each row is the P focal sphere for the focal parameters represented by the five numbers (strike, dip, rake, depth and moment. The station code is identified to the left of each waveform. Observed waveform (solid lines) and synthetic data (dotted lines) shown in this figure.

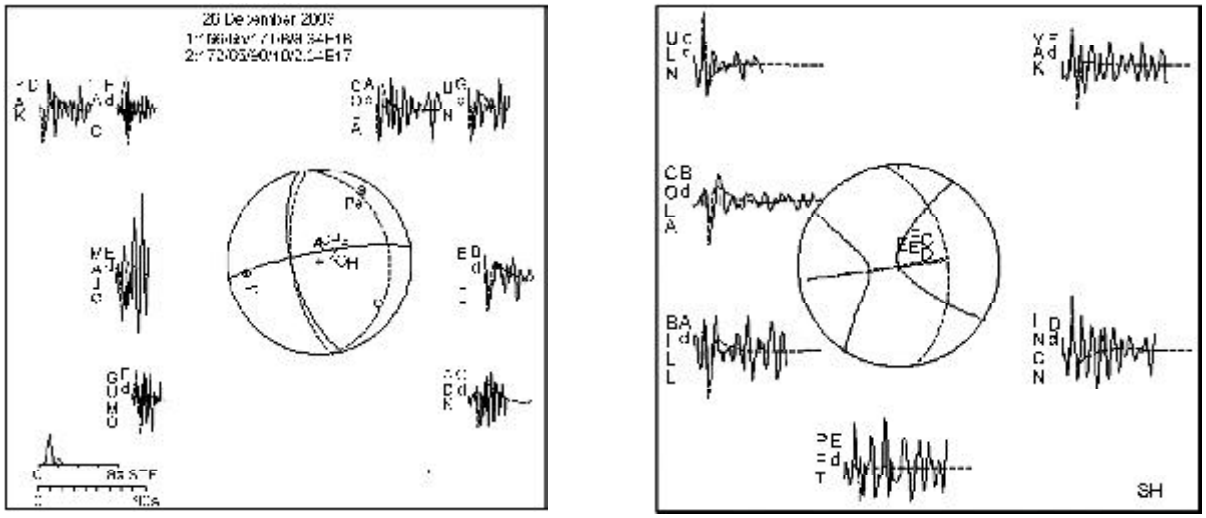

Figure 7. The P and SH radiation patterns of minimum misfit solutions for the earthquake of26.12. 2003 main shock are shown in this figure. Observed waveform (solid lines) and synthetic data (dotted lines), source time function shown in this figure. The compression (Ps, Pt points for strike slip and thrust component fault respectively) and dilatation axes are marked by solid and open circle respectively. The station code is identified to the left of each waveforms, and lower case letter that indicates the type of instrument (d= GDSN long period).

Table 2. Source parameters of the 26 December 2003 Bam earthquake.

Nodal plane 1				Nodal Plane 2			
Source No	Strike (o)	Dip (o)	Rake (o)	Strike (o)	Dip (o)	Centroid Depth (km)	M_o (Nm)
1	166±10	36±8	17±5	260±7	81±10	7.9±4	8.34e+18
2	172±9	65±12	90±-	352±6	25±12	10±6	2.34e+17

faults in area, see Figure (2) [18], displacement observations in the field [19] and aftershocks distribution, we think the nodal plane one is the main strike slip fault.

7. Source Time Function

The teleseismic source time function gives information about fault ruptures or source complexity. The physical features of teleseismic source time functions appraise the source complexity of the earthquakes. These features include the overall duration, multiple or single event character, individual source pulse widths, and roughness of the time function. The measures of source size and complexity can then be compared with the plate convergence rate, and other physical parameters in collision zone [3]. The earthquakes larger than about M_s6.9 can rarely be represented by a single point source, even at the wavelengths recorded by the *WWSSN* 15-100 long period instruments (with a peak response at a bout 15*s* period). These earthquakes usually consist of several discrete ruptures, separated by several seconds in time and several km in space, often occurring on faults with different orientations [13]. From the source time function it appears that the rupture broke two asperities in the total rupture time 3*s*, see Figure (8). The seismic moment of the second event was less than the first one. We estimated the corner frequency is very approximately given by $f_0 = 1/\pi\tau_p$ where τ_p is the largest pulse duration [14, 15]. The essential purpose of calculating the corner frequency is evaluating the source dimension. Then we have calculated source radius using [16] relation for a circular fault, see Table (2). We used 2.75*km*/*sec* for rupture velocity [17].

$$R = 2.34v/2\pi f_0 \qquad (2)$$

The seismic moment, M_o, is given by $M_o = \mu.A.\hat{u}$, where μ is the rigidity ($\sim 3\times10^{10}Nm$), A is the fault area, and $\hat{u}$ is the average displacement in source, see Table (3). Average displacement in source was calculated by using source time function.

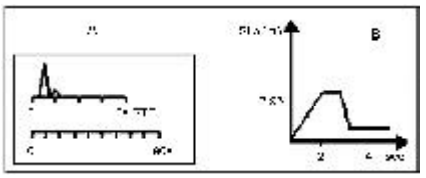

Figure 8. The source time function (A) and average displacement (B) in the source.

Table 3. Source parameters that are obtained from source time function.

Source No.	Pulse Duration τ_p (sec)	Corner Frequency f_0 (Hz)	Source Radius r_0 (km)	Source Area (km^2)	Displacement in Source (m)
1	1.7	0.187	5.47	93.99	2.95
2	0.8	0.397	2.57	20.74	0.35

8. Discussion and Conclusion

The mechanism of the 26 December 2003 earthquake derived from the inversion of long period body waves and field observations comprises a strike-slip solution. In addition we have derived thrust component for this earthquake but we have not found any clear geologic surface data in the field. The geological observations suggest that the essential fracturing is occurred in broad zone with diameter 9*km* and width 4*km* in south to north of Bam. According to focal mechanism, no surface faulting observation [19] aftershocks distribution, it is assumed that this fault has *N-S* trend in south of Bam and it has blind characteristic. Varying the seismic moment along total duration of *STF* is direct the related to the variation the source velocity structure did have an effect on centroid depth and seismic moment. In addition uncertainties in attenuation factor, *t**, mainly affect estimates of source duration and seismic moment. The centroid depth of main shock is less than second event. We can see clearly in the source time function this earthquake has larger moment release in the first part of the process with respect to the second event. In addition the source dimension of second event is less than main shock, see Table (3). The nature of this function shows that the faulting consists of several fractures separated by strong barriers. In conjunction with the spatial and temporal behavior of this event the complexity of rupture suggests that strain accumulated gradually on a system of fault in different geological structure. The effect of a critical rupture (the first event of the main shock) was to cause a rapid release of stress (dominant event of the main shock) as well as a more gradual release of stress (the second event) on adjacent conjugate fault.

Acknowledgment

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References

1. Zare, M. and Hamzeloo, H. (2004). "Study of Strong Ground Motion Data for the 2003 Bam Earthquake", SE Iran, Published in This Issue.
2. Kisslinger, C. (1997). "Aftershocks and Fault Zone properties", *Advances in Geophysics*, **38**, 1-35.
3. Hartzell, S. and Heaton, T. (1985). "Teleseismic Time Functions for Large, Shallow Subduction Zone Earthquakes", *Bull. Seism. Soc. Am.*, **75**(4), 965-1004.
4. Berberian, M. (1994). "Natural Hazards and First Earthquake Catalogue of Iran, V.1. Historical Hazards in Iran Prior to 1900", International *Institute of Earthquake Engineering and Seismology (IIEES)*, P.603
5. Zohoorian, A.A., Mohajer-Ashjai, A., Kabiri, A., and Hosseinian-Ghamsari, M. (1984). "Damage Distribution and Aftershock Sequence of Two Destructive Earthquakes in 1981 in Eastern Kerman", *J. Earth and space phys.*, **10**(1, 2).
6. Cornel University, Building Digital Earth Project, Institute for the Study of Continent (INSTOC) Cornell University.
7. Hutton, L.K. and D. Boore (1987). "The ML Scale in Southern California", *Bull. Seism. Soc. Am.*, **77**, 2074-2094.
8. McCaffery, R., Abers, G., and Zwick P. (1991). "Inversion of Teleseismic Body Waves", In: Digital Seismogram Analysis and Waveform Inversion (ed. By W. H. K. Lee), IASPEI software Library, **3**, 81-166.
9. Nabelek, J.L. (1984). "Determination of a Earthquake Source Parameters from Inversion of Body Waves", Ph.D. Thesis, MIT, Cambridge Massachusetts.
10. Taymaz, T. (1990). "Earthquake Source Parameters in the Eastern Mediterranean Region", Ph.D. Thesis., Drawing college Cambridge.
11. McCaffrey, R. and Nabelek, J. (1987). "Earthquakes Gravity, and the Origin of the Bali Basin: an Example of a Nascent Continental Fold-and-Thrust Belt, *J.Geophys. Res.*, **92**, 441-460.
12. Fredrick, J., McCaffrey, R., and Denham, D. (1988). "Source Parameters of Seven Large Australian Earthquakes Determined by Body Waveform Inversion", *Geophys. J.*, **95**, 1-13.
13. Butler, R., Stewart, G.S., and Kanamori, H. (1979). "The July 27 1976 Tangshan China Earthquake -a Complex Sequence of Intraplate Events, *Bull. Seism. Soc. Am.*, **69**, 207-220.
14. Helmberger, D.V. and Malone, S.D. (1975). "Modeling Local Earthquakes as Shear Dislocations in a Layered Half-Space, *J. Geophys. Res.*, **80**, 4881-4888.
15. Husebye, E.S. and Mykkeltveit, S. (1980). "Identification of Seismic Sources Earthquake or Underground Explosion. Proceeding of the NATO Advanced Study Institute Held at Voksenasen", Oslo, Norway, 72-97.
16. Brune, J.N. (1970). "Tectonic Stress and the Spectra of Seismic Shear Waves from Earthquakes, *J. Geophys. Res.*, **75**, 4997-5009.
17. Hartzel, S., Langer, C., and Mendoza, C. (1994). "Rupture Histories of Eastern North American Earthquakes", *Bull. Seism. Soc. Am.*, **84**(6), 1703-1772.
18. Berberian, M., Jackson, J.A., Fielding, E., Parsons, B, E., Priestley, K., Qorashi, M., Talebian, M., Walker, R., Wright, T.J., and Baker, C. (2001). "The 1998 March 14 Fandooqa Earthquake (Mw6.6) in Kerman Province, Southeast Iran: Re-Rupture of the 1981 Sirch Earthquake Fault, Triggering of Slip on Adjacent Thrust and Active Tectonics of the Gowk Fault Zone, *Geophys. J. Int.*, **146**, 371-398.
19. Hessami, K., Tabassi, H., Okumura, K., Azuma, T., Echigo, T., Kondo, H., and Abbassi, M.R. (2004). "Surface Expression of Bam Fault Zone in Southeastern Iran: Causative Fault of the December 26, 2003 Earthquake", Press in this Volume.

Aftershocks Study of the 26 December 2003 Bam Earthquake

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ABSTRACT: *From 29 December to 30 January, a dense seismological network of 20 stations surrounding the epicentral area of the 26 December 2003 Bam earthquake was installed to study the seismic activity that took place after the main shock. The aftershock distribution is consistent with a 30 km north-south striking fault. The focal depths distribution shows a nearly vertical alignment of aftershocks located between 6 to 20 km depth. The focal mechanism solutions indicate right lateral strike slip faulting on N-S trending fault, parallel to the Bam fault trace. However, there is a small offset of about 5km westward between the Bam fault trace and the aftershocks distribution.*

Keywords: Bam; Aftershocks; Strike slip fault; Focal mechanism; Local seismological network

1. Introduction

The active deformation of Iran is the result of Arabia-Eurasia convergence [1, 2], which is mainly accommodated by distributed deformation in the Zagros [13, 14], distributed faulting in the Alborz and Kopeh-Dagh mountain belts [18], and *N-S* right lateral shear between central Iran and Afghanistan. The major N-S right lateral fault systems east of Iran are the result of this shearing [17]. The overall convergence of the two Arabian and Eurasian plates is estimated to be about 30*mm/yr* at 50°*E* and 40*mm/yr* at 60°*E* [7, 9].

The present-day deformation of Iran deduced from *GPS* measurements [15] shows that about ~10*mm/yr* is accommodated in the Zagros. The rest is accommodated partly in the Alborz and Kopeh-Dagh (8+/-2*mm/yr*) and east of Iran on the Nayband-Gowk-Sabzevaran and Neh-Zahedan fault systems (8*mm/yr*). The eastern deformation of Iran has been the cause of the several recent large earthquakes up to magnitude of 7.0 that occurred during the last years [3]. The recent earthquake of December 26, 2003 (*Ms* = 6.5) near the small city of Bam, with around 26,500 human causalities, is one of the most destructive events that stroke this part of Iran. The seismogenic fault of this earthquake is a small fault between the two major strike slip fault systems of Nayband-Gowk-Sabzevaran and Neh-Zahedan on the west and east sides of the Dasht-e-Lut, see Figure (1).

The Bam earthquake occurred in a region where seismic activity is very low based on instrumental and historical catalogues for the last 2000 years, see Figure (2). As the figure shows, most of the historical and instrumental earthquakes located northwestern of Bam are related to activity on the Nayband, Gowk and Shahdad faults, and southwest of this city to the Jiroft active region. The 1854 Khorjand earthquake with an estimated intensity of *VIII*, the 1864 Chatrood historical event with a magnitude of *Ms*~6, and the 1897 Kerman-Chatrood earthquake with *Ms*~5.5 are the most important historical events that are located *NW* of Bam. As the largest instrumental earthquakes, which have occurred *NW* of the epicentral area of the Bam earthquake we can refer to the 11 June 1981 Golbaf earthquake (*Mw* = 6.6) and 28 July 1981 Sirch earthquake (*Mw* = 7.1). These events are associated with the activity of the Gowk fault. The most recent earthquake on this fault is the 14 March 1998 Fandoqa earthquake of magnitude *Mw* = 6.6 [3, 5, 6].

With the exception of the destructive earthquake of 26 December 2003, there is not any historical and

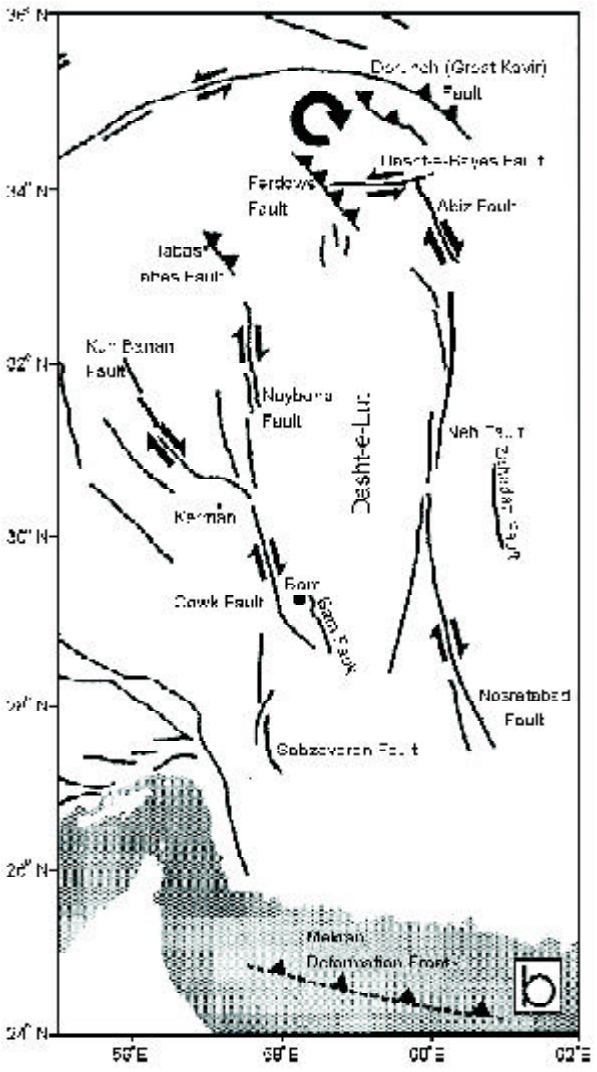

Figure 1. Major N-S trending, right lateral strike slip fault systems in eastern Iran [17].

instrumental earthquake recorded in the region surrounding Bam at least for distances closer than 120*km*.

In order to study aftershocks seismicity of the Bam earthquake, an array of 20 portable, 3-components stations was deployed around the epicentral area of the main shock on December 28, 2003, in an attempt to better understand the location, geometry and kinematics of the causative fault in the region. The experiment started 3 days after the main shock and lasted for a month. In this study, the results of the first week recording of aftershocks, from 29 December 2003 to 4 January 2004 are presented.

2. Recording and Analysis of Aftershocks

The 20-station temporary seismological network consisted of 10 short-period *CMG*-6*TD* seismometers connected to *CMG-DM*24 Guralp digitizers, and ten *CMG*-40*T* broadband seismometers, connected to MiniTitan recorders. The seismic instruments belonged to the Laboratoire de Géophysique Interne et Tectonophysique, University of Joseph Fourier, (France), and to the International Institute of Earthquake Engineering and Seismology (Iran). All stations were programmed to record in continuous mode. The signals from the short-period *CMG*-6*TD* were sampled at 100*Hz*, whereas a sampling rate of 62.5*Hz* was used for *CMG*-40*T* broadband seismometers. The stations were located around the epicenter of the main shock reported by *NEIC*, a few hours after the Bam earthquake, see Figure (2). More than 4000 events were recorded during the one-month duration of the experiment. The primary results of analyzing more than 500 aftershocks, recorded during the first week after the main shock, will be addressed in this paper.

More than 450 events recorded by at least 4 stations were selected. First, using *HYPO*71 [11], all the aftershocks (of magnitude ranging from 0.5 to 4.0) were located. Only 250 earthquakes were kept for which at least two *S* arrival times could be read. With a subset of 187 events, having a root mean square travel times residual (*RMS*) smaller than 0.2*s*, horizontal (*ERH*) and vertical (*ERZ*) uncertainties smaller than 2*km*, and an azimuthal gap smaller than 180°, a mean *Vp/Vs* ratio of 1.75+/-0.01 averaging *Ts-Tp/Tp-T*0 was computed. Then, the velocity structure of the crust assuming layers of variable thickness and of variable velocity was investigated. A one-dimensional velocity model obtained, see Figure (3) by inversion of the arrival times using the program *VELEST* [10] that relocates the earthquakes and simultaneously inverts for the velocity structure. The convergence of the inversion for 50 different starting models that are randomly distributed was checked, see Figure (3).

The simplest velocity structure obtained for the Bam region that fits our data consists of an upper layer 9*km* thick with a velocity of 5.7 *km/sec* overlying an half space of 6.4*km/sec*. The convergence of the obtained results in using several random starting models were tested. The resulting velocity model and station residuals were used in the Hypo71 locating program to relocate selected aftershock.

Lower-hemisphere fault plane solutions of single events were determined from first-motion data. The aftershocks with a minimum of 12 *P*-wave polarities were selected for the focal mechanism determination. The quality of the polarity reading, the type of wave

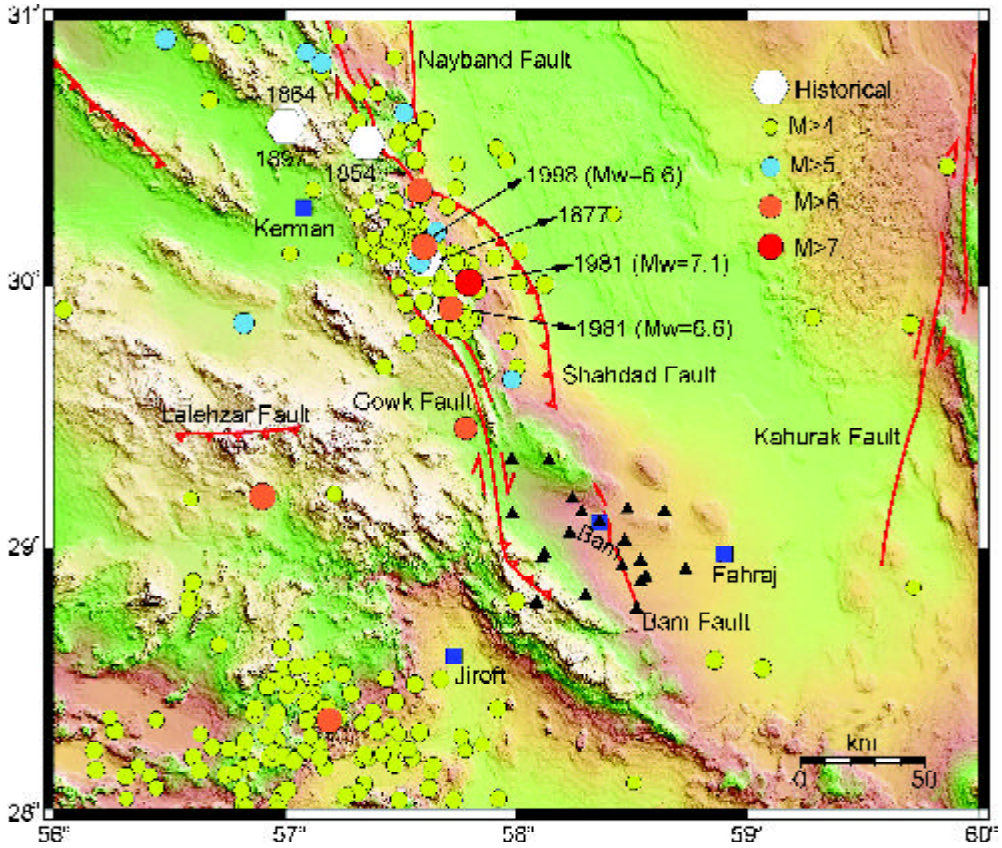

Figure 2. Seismicity map of historical and instrumental earthquakes in the regions surrounding the epicentral area of the Bam earthquake. Triangles indicate the location of temporary seismic stations.

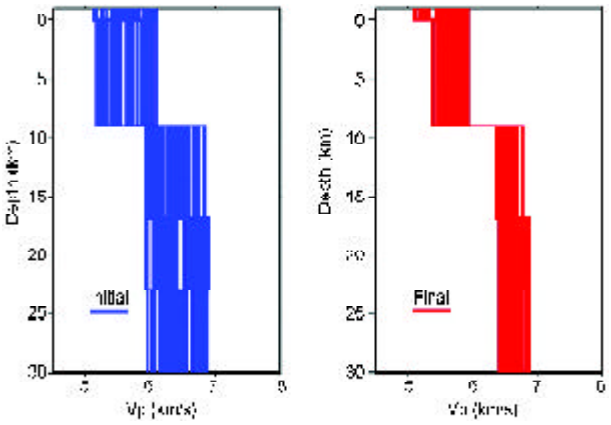

Figure 3. Velocity structure obtained for the shallow crust by inversion of the travel times of selected aftershocks recorded on the temporary seismological network. 50 random initial models (left) have been converged to a simple model consist of two layers (right).

(direct or refracted), and the azimuthal coverage on the focal sphere were taken into consideration in order to distribute the solutions into three categories depending on their reliability. In category A the mechanisms were used whose 3 quadrants are sampled and for which the two planes are constrained within 20°. In category *B*, only one plane was well constrained, but the orientation of the *P* and *T* axes were determined within 20°. In category *C*, none of the planes were constrained within 20°, and these solutions were used only to give an indication of the type of faulting.

Local magnitude (*Ml*) was computed for more than 400 events, which indicate the aftershocks magnitude range between 0.5 and 4.0. Maximum pick-to-pick amplitudes was measured [8], after doing instrument correction and simulation of standardized instrument.

2. Aftershocks Distribution and Focal Mechanism

Among the 250-recorded aftershocks until January 4, 187 reliably located events (*ERH* and *ERZ*<2*km*, *RMS* < 0.2*sec*, *N* >12 stations) were selected that show a narrow *NS* trending aftershock zone, see Figure (4). This aftershock zone is centered on 29.10°*N* latitude and 58.37°*E* longitude. It is located right beneath the Bam city, which can explain the high level of destruction. The aftershock distribution defines a *N-S* trending zone extending from south to about 30*km* north of Bam roughly 7*km* wide.

The density of seismological stations ensures a

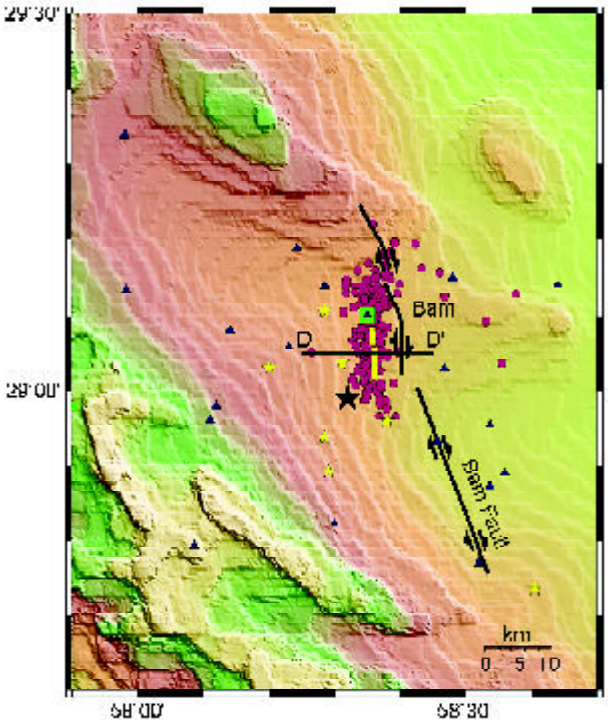

Figure 4. Seismicity map of the selected aftershocks recorded at more than 12 stations, with rms errors in time < 0.2s and in location < 2 km. The triangles are the seismological stations. The black star is the main shock and the yellow stars are the EHB teleseismically relocated main aftershocks (Engdahl, personal communication). The Bam fault is plotted in black and the seismic cracks in yellow.

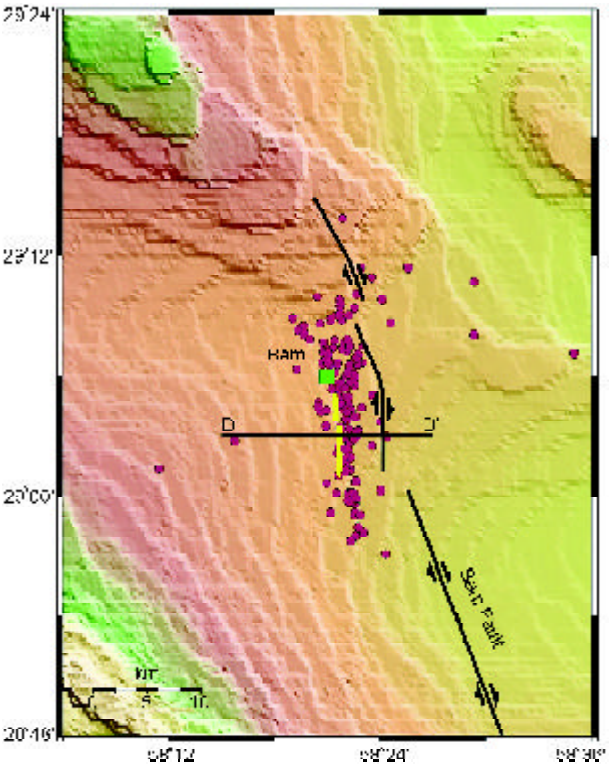

Figure 5. Seismicity map of the relocated aftershocks using the double difference method [15]. The distribution of relocated events shows a slightly more accurate picture of the seismogenic fault than the initial distribution.

much more accurate location than teleseismically located earthquakes. There is a systematic shift of ~10*km* to the *NE* relative to the *EHB* teleseismically relocated events, see Figure (4) by Engdahl (personal communication).

In order to refine the interpretation, the 180 earthquakes previously located with an uncertainty better than 2*km* both in epicenter and depth for events pairs with a minimum of 12 links were located, using the double difference method [16], see Figure (5). If the hypocentral location between events is small compared to the distance to the stations, the errors in the ray path are minimized. This method is particularly useful to map clusters of earthquakes and infer possible active faults. As Figure (5) shows, the seismicity is slightly better defined after relocating by the HypoDD technique. It confirms that the active fault was trending *NS* and dipping vertically.

The *E-W* cross section striking perpendicular to the distribution of aftershocks, see Figure (6) reveals that most of the seismicity is located between 6 and 20*km* of depth and therefore is likely to be located in the upper part of the crust. The distribution of focal depths based on the located (Hypo71) and relocated (HypoDD) selected aftershocks shows a fault plane dipping vertically.

A dense seismological network above the earthquakes provides a more complete coverage of the focal sphere than the teleseismic recording. Fault plane solutions for 40 aftershocks were computed, see Table (1). Most of the focal mechanisms within the aftershocks correspond to *NS* trending, right lateral strike slip faulting, in agreement with the seismicity and the mechanism of the main shock computed by *NEIC* and *HRDV*, see Figure (7) and Appendix (I). The trend of the *NS* trending fault planes is slightly (15°) rotated counterclockwise, which is consistent only with the rotation of northern termination of the Bam fault.

4. Discussion and Conclusion

A strong earthquake of magnitude (*Mw* = 6.5) devastated the city of Bam in the southeast of Iran. This earthquake occurred due to the rupturing of a fault, which is located within two major north-south, strike slip fault systems.

The distribution of aftershocks on map as well as

Table 1. Parameters of determined focal mechanisms.

Nb	Date	Time	Lat	Lon	Depth	Mag	Az1	Pl1	de1	Az2	Pl2	de2	Azp	dep	Azt	det	Im	Q
98	123103	11:33	29.07	58.35	13.53	1.4	55	80	-5.7	146	84.3	-170	10.8	11.1	280	3	-1	C
99	123103	11:44	29.06	58.35	10.00	2.4	95	80	-26.7	190	63.7	-169	49.6	25.9	145	11	-1	B
100	123103	11:50	29.05	58.34	16.23	1.7	95	80	-26.7	190	63.7	-169	49.6	25.9	145	11	-1	B
111	123103	14:57	29.07	58.35	14.97	1.6	55	80	-26.7	150	63.7	-169	9.6	25.9	105	11	-1	B
114	123103	15:36	29.00	58.37	10.00	2.5	80	80	-26.7	175	63.7	-169	34.6	25.9	130	11	-1	B
115	123103	15:43	29.07	58.35	13.75	1.3	60	70	-27.2	160	64.5	-158	18.6	23.1	111	3.6	-1	A
116	123103	15:52	29.03	58.35	12.80	1.7	130	80	-153	35	63.7	-11.2	355	25.9	260	11	-1	B
121	123103	18:45	29.02	58.36	11.05	2.1	65	80	26.7	160	63.7	169	19.6	25.9	115	11	1	A
122	123103	18:48	29.06	58.36	11.54	3	60	70	-14.3	155	76.5	-159	18.6	24	287	4.4	-1	A
128	123103	21:16	29.08	58.36	14.74	1.6	60	70	-14.2	155	76.5	-159	18.6	24	287	4.4	-1	B
130	123103	22:06	29.07	58.36	10.00	1.5	110	80	26.7	15	63.7	169	240	11	335	25.9	1	C
139	10104	2:39	29.01	58.36	11.51	1.4	140	80	26.7	45	63.7	169	270	11	54	25.9	1	B
143	10104	4:05	29.10	58.31	16.53	1.7	70	80	-26.7	165	63.7	-169	24.6	25.9	120	11	-1	B
157	10104	10:06	29.09	58.37	16.38	1.6	240	80	-5.7	331	84.3	-170	196	11.1	105	3	-1	B
158	10104	10:08	29.02	58.37	14.43	1.3	70	80	-153	335	63.7	-11.2	295	25.9	200	11	-1	B
160	10104	10:17	29.12	58.38	14.39	1.4	280	80	-26.7	15	63.7	-169	235	25.9	330	11	-1	B
162	10104	10:44	29.04	58.36	12.31	3.2	90	80	-26.7	185	63.7	-169	44.6	25.9	140	11	-1	C
164	10104	11:10	29.15	58.36	12.27	1.8	250	70	-14.3	345	76.5	-159	209	24	117	4.4	-1	C
171	10104	13:43	29.04	58.37	13.23	3.4	100	80	-26.7	195	63.7	-169	54.6	25.9	150	11	-1	A
177	10104	16:09	29.07	58.34	16.50	1.9	240	80	-26.7	335	63.7	-169	195	25.9	290	11	-1	B
178	10104	16:52	29.05	58.37	14.50	1.5	65	80	5.7	324	84.3	170	19.8	3	289	11.1	1	A
181	10104	17:46	29.09	58.36	12.29	1.7	220	80	-26.7	315	63.7	-169	175	25.9	270	11	-1	B
190	10104	22:25	29.05	58.36	12.11	1.8	315	50	153	50	63.7	11.2	5	11	270	25.9	1	B
197	10204	2:52	29.13	58.37	17.30	1.6	155	50	90	335	40	90	245	5	65	85	1	A
201	10204	3:21	29.10	58.36	14.15	1.9	160	80	-153	65	63.7	-11.2	25.4	25.9	290	11	-1	A
202	10204	3:22	29.12	58.36	13.75	1.4	75	80	-21.9	169	68.4	-169	30.2	22.5	124	7.9	-1	A
204	10204	4:24	29.02	58.36	10.88	1.7	90	80	26.7	355	63.7	169	220	11	315	25.9	1	C
217	10204	10:20	29.03	58.36	16.76	1.6	70	80	-26.7	165	63.7	-169	24.6	25.9	120	11	-1	A
219	10204	10:34	29.02	58.36	13.75	1.4	85	80	-26.7	180	63.7	-169	39.6	25.9	135	11	-1	B
222	10204	11:44	29.05	58.37	12.40	1.8	85	80	-26.7	180	63.7	-169	39.6	25.9	135	11	-1	B
223	10204	12:28	29.09	58.35	15.91	1.5	150	80	-174	59	84.3	-10	14.2	11.1	105	3	-1	A
229	10204	16:19	29.12	58.37	14.85	1.9	265	80	-26.7	360	63.7	-169	220	25.9	315	11	-1	B
230	10204	16:56	29.04	58.36	10.72	1.4	60	80	-26.7	155	63.7	-169	14.6	25.9	110	11	-1	C
234	10204	17:55	29.10	58.35	11.58	1.6	235	80	5.7	144	84.3	170	190	3	99.2	11.1	1	B
236	10204	18:21	29.05	58.37	14.76	3.3	60	80	-26.7	155	63.7	-169	14.6	25.9	110	11	-1	A
238	10204	20:11	29.07	58.35	10.00	1.6	50	80	26.7	315	63.7	169	180	11	275	25.9	1	B
239	10204	20:28	29.08	58.34	16.39	1.4	55	75	-3.9	146	86.3	-165	11.4	13.2	280	7.9	-1	A
241	10204	20:38	29.04	58.36	11.92	1.5	80	80	-26.7	175	63.7	-169	34.6	25.9	130	11	-1	C

Lat, Lon, Depth are the coordinates of the aftershocks, Mag is the local magnitude, Az1, Pl1, de1, AZ2, Pl2, de2 are Azimuth, dip and slip of plane 1 and 2 respectively. Azp, dep, Azt, det are azimuth and dip of P- and T-axis respectively. Im is 1 for reverse and -1 for normal faulting respectively. A, B and C are a factor of quality of the fault plane solutions.

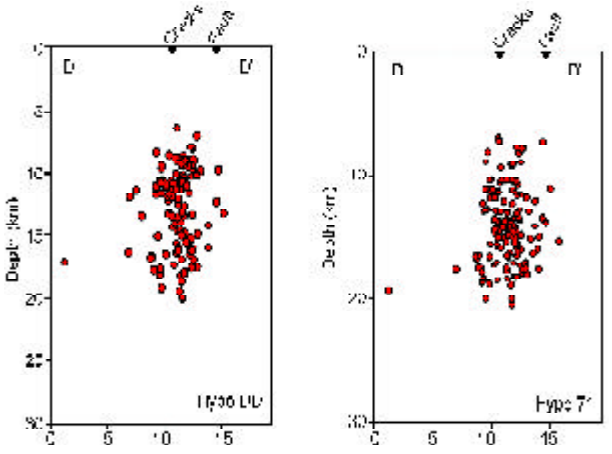

Figure 6. Cross-sections, trending EW of the selected aftershocks (Right) showing a fault plane dipping vertically. Focal depth of relocated events using double difference method (Left) defines the fault plane better than the initial hypocenters.

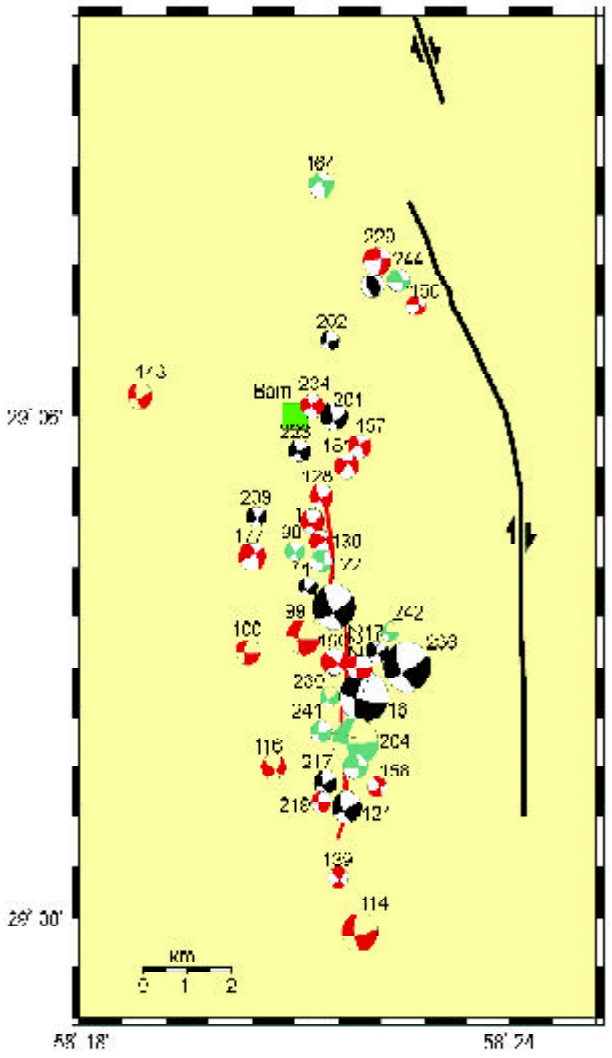

Figure 7. Map of the focal mechanisms for aftershock located better than 2km (horizontally and vertically), with a minimum of 12 polarities. The calculated focal mechanisms are divided to three groups based on their quality: A (Black), B (red) and C (green).

on cross-section indicates a *NS* striking seismogenic fault dipping vertically located precisely beneath the city of Bam. The focal depth distribution of relocated aftershocks does not support a westward dipping fault plane. The depth of the aftershocks are between 6 and 20*km*, and therefore deeper than the centroid depth of the main shocks computed by teleseismic body wave modeling [12].

The good consistency in direction for most of the *P*-axes, see Figure (8), specially in the southern part of the seismogenic fault, in addition of the *NS* trending, right lateral strike slip mechanisms, obtained for most of the aftershocks, south of Bam, does not support the existence of a secondary thrust fault as proposed by Talebian et al [12].

The counterclockwise rotation of *NS* trending nodal plane of some aftershocks, which is supported by clockwise rotation of *P*-axes north of the Bam, indicates a slight shortening component due to Arabia-Eurasia convergence north of Bam. The

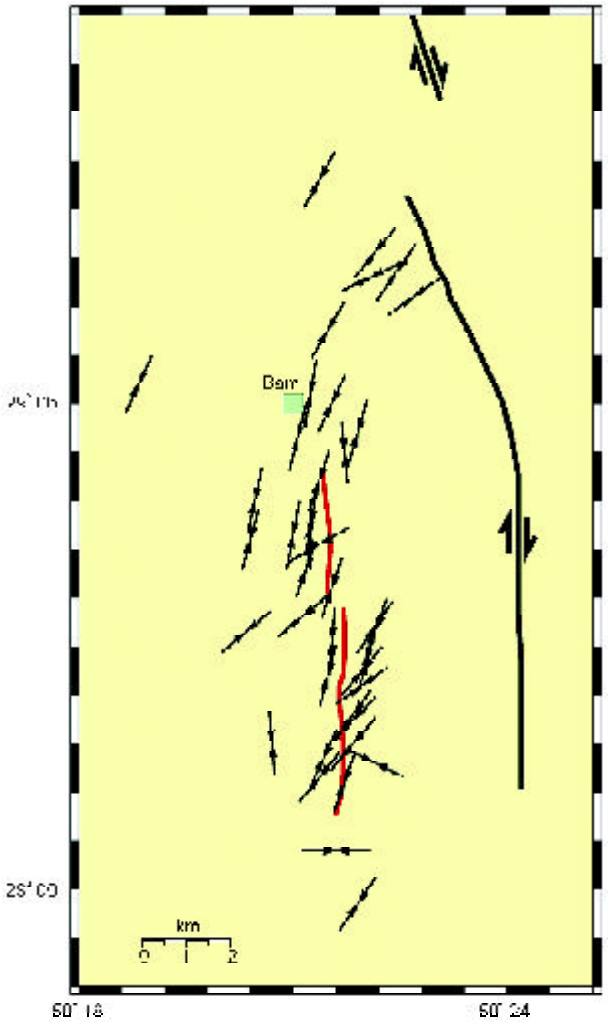

Figure 8. Horizontal projection of the P-axes associated with the focal mechanisms.

compressional component of a few fault plane solutions and the presence of at least one well constraint reverse focal mechanism, are another evidences on shortening effects of the northern part of the Bam seismogenic fault. However, it is not unusual to have reverse faulting at the termination of strike-slip faults.

One of the main questions raised after the Bam earthquake was related to the spatial extent of the rupture, since no surface rupture could be observed in the area. The spatial distribution and mechanism of the aftershocks reveal a seismogenic zone 30*km* long and ~7*km* wide, trending N-S, located right beneath Bam. A histogram of relocated aftershocks shows that the majority of earthquakes are located between ~6-20*km* of depth with a maximum number of events at 10-11 *km*, see Figure (9). No earthquakes located reliably at a depth greater than 20*km*, indicating that the seismicity is likely to be located in the upper part of the crystalline basement.

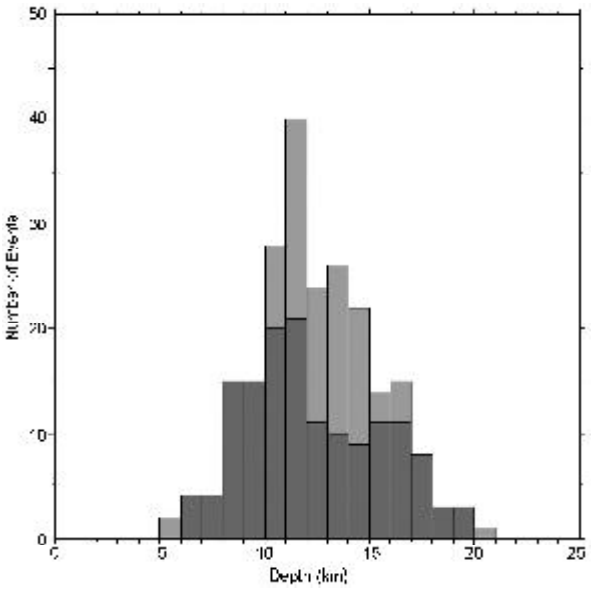

Figure 9. Depth distribution of aftershocks. Light purples for selected events. Dark is HypoDD relocated after-shocks. There is no seismic activity shallower than 5km.

Acknowledgment

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References

1. Berberian, M. (1981). "Active Faulting and Tectonics of Iran, in Zagros-Hindu-Kush-Himalaya Geodynamic Evolution", Gupta, H.K., and Delany, F.M. (edts), *Am. Geophys. Union*, Geodyn. Ser., **3**, 33-69.

2. Berberian, M., King, G.C.P. (1981). "Towards a Paleogeography and Tectonic Evolution of Iran", *Can. J. Earth Sci.*, **18**, 210-265.

3. Berberian M. and Qorashi, M. (1994). "Coseismic Fault-Related Folding During the South Golbaf Earthquake of November 20, 1989, in Southeast Iran", *Geology 22*, 531-534.

4. Berberian M. and Yeats, R.S. (1999). "Pattern of Historical Earthquake Rupture in the Iranian Plateau", *Bull. Seism. Soc. Am.*, **89**, 120-139.

5. Berberian, M., Jackson, J.A., Ghorashi, M., and Kadjar, M.H. (1984). "Field and Teleseismic Observation of the 1981 Golbaf-Sirch Earthquakes in SE Iran", *Geophys. J. R. Astr. Soc.*, **77**, 809-838.

6. Berberian, M., Baker, C., Fielding, E., Jackson, J.A., Parsons, B.E., Priestley, K., Qorashi, M., Talebian, M., Walker, R., and Wright, T.J. (2001). "The March 14 1998 Fandoqa Earthquake (Mw = 6.5) in Kerman Province, SE Iran: Re-Rupture of the 1981 Sirch Earthquak e Fault, Triggering of Slip on Adjacent Thrusts, and the Active Tectonics of the Gowk Fault Zone", *Geophys. J. Int.*, **146**, 371-398.

7. De Mets, C., Gordon, R.G., Argus, D.F., and Stein, S. (1994). "Effects of Recent Revisions to the Geomagnetic Reversal Time Scale on Estimates of Current Plate Motions", *Geophys. Res. Lett.*, **21**, 2191-2194.

8. Hutton, L.K. and Boore, D. (1987). "The ML Sacle Southern California", *Bull. Seis. Soc. Am.*, **77**, 2074-2094.

9. Jackson, J.A. (1992). "Partitioning of Strike-Slip and Convergent Motion between Eurasia and Arabia in Eastern Turkey and the Caucuses", *Journal Geophys. Research*, **97**, 12471-12479.

10. Kissling, E. (1988). "Geotomography with Local Earthquake Data", *Rev. of Geophys.*, **26**, 659-698.

11. Lee, W.H.K. and Lahr, J.C. (1972). HYPO71 (Revised), A Computer Program for Determining Hypocenters, Magnitude and First Motion Pattern of Local Earthquakes, *U.S. Geol. Surv. Open File Rep.*, 75-311.

12. Talebian, M., Fielding, E.J., Funning, G., Jackson, J., Nazari, H., Parson, B., Priestley, K., Qorashi, M., Rosen, P.A., Walker, R., and Wright, T.J. (2004). "The 2003 Bam (Iran) Earthquake-Rupture of "Truly Blind" Fault", *Submitted to Geophys. Res. Lett.*

13. Tatar, M., Hatzfeld, D., Martinod, J., Walpersdorf, A., Ghafori-Ashtiany, M., and Chéry, J. (2002). "The Present Day Deformation of the Central Zagros (Iran)", *Geophys. Res. Lett.*, **29**, 33-1 to 33-4, doi:10.1029/2002GL015159.

14. Tatar, M., Hatzfeld, D., and Ghafory-Ashtiany, M., (2004). "Tectonics of the Central Zagros (Iran) Deduced from Microearthqauke Seismicity", *Geophys. J. Int.*, **156**, 255-266.

15. Vernant, Ph., Nilfroushan, F., Hatzfeld, D., Abbassi, M., Vigney, C., Masson, F., Nankali, H., Martinod, J., Ashtinay, M., Bayer, R., Tavakoli, F., Chery, J. (2004). "Contemporary Crustal Deformation and Plate Kinematics in Middle East Constrained by GPS Measurements in Iran and North Oman", *Submitted to Geophys. J. Int.*

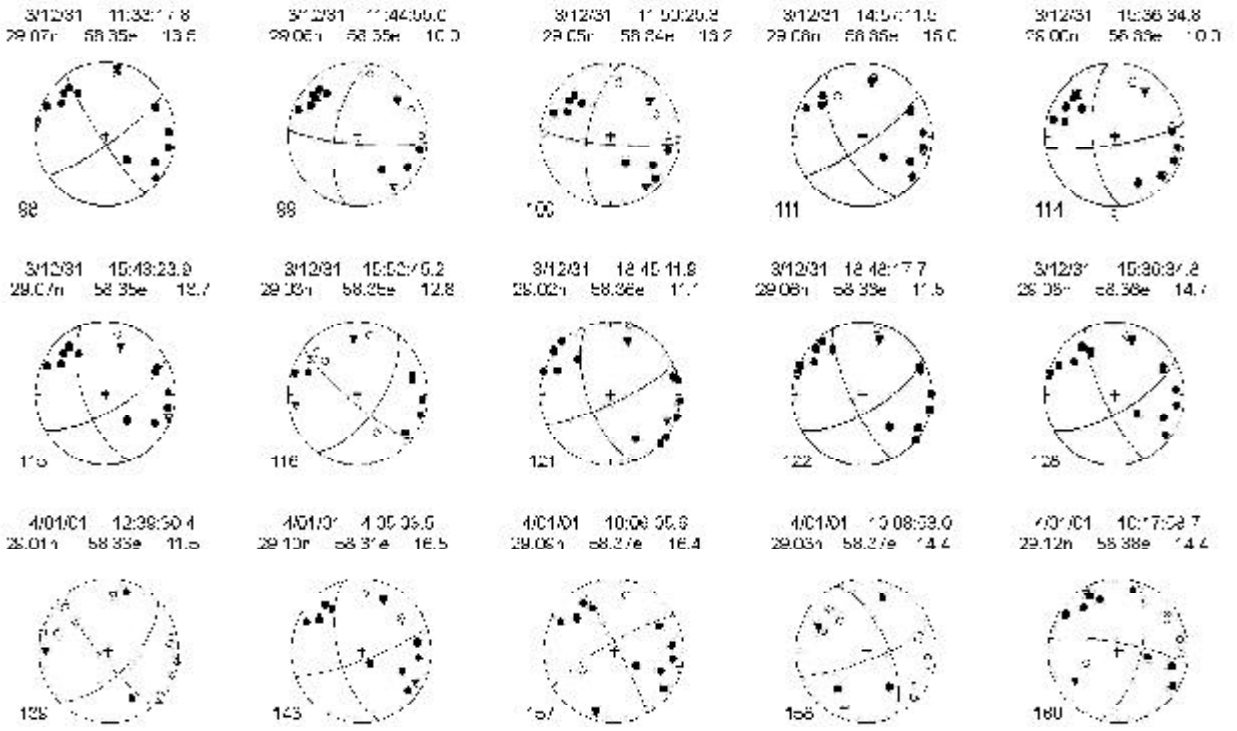
16. Waldhauser, F. and Ellsworth, W.L. (2000). "A Double Difference Earthquake Location Algorithm: Method and Application to the Northern Hayward Fault, California, *Bull. Seism. Soc. Am.*, **90**, 1353-1368.

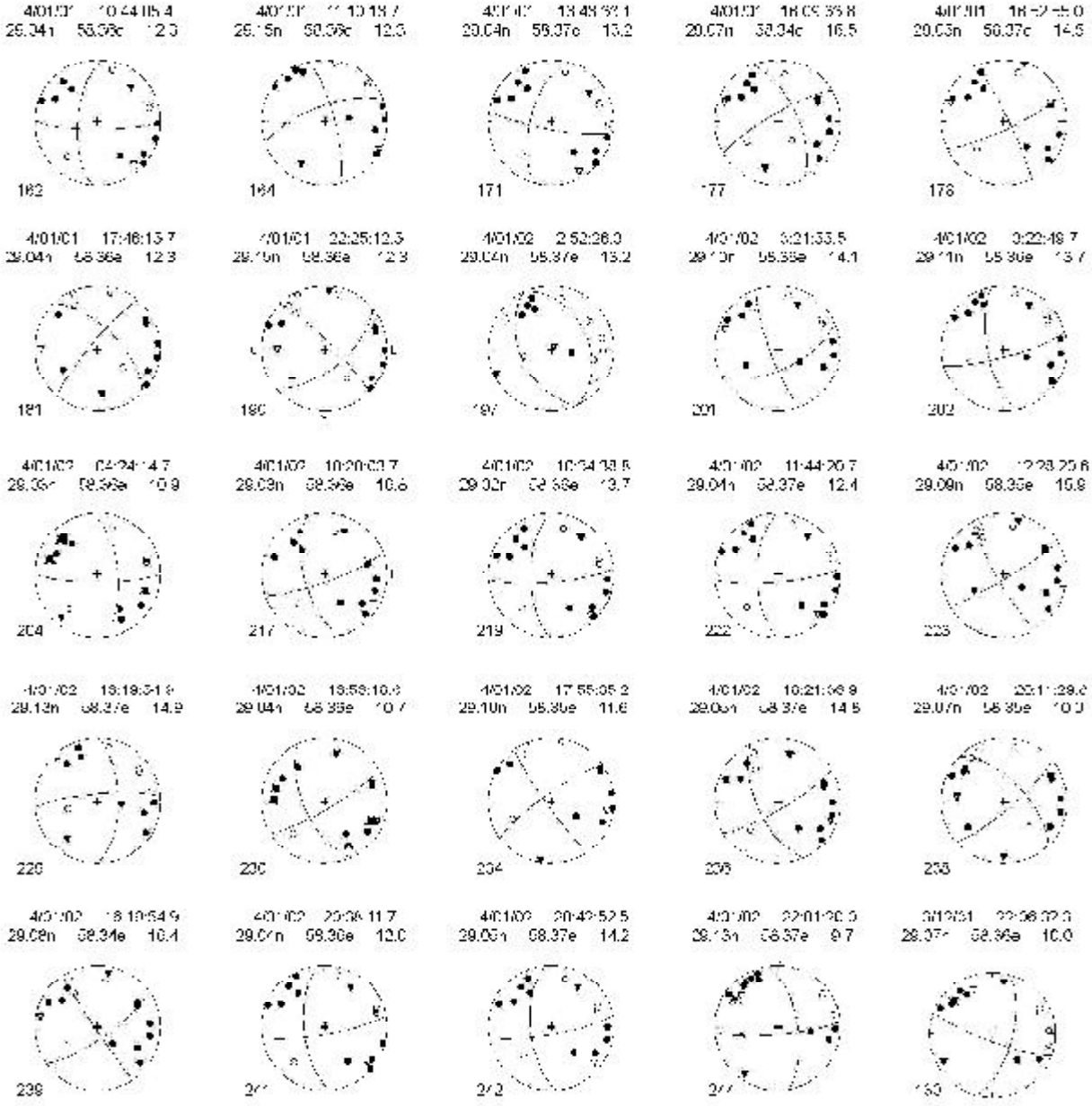
17. Walker, R. and Jackson, J. (2002). "Offset and Evolution of the Gowk Fault, S.E. Iran: a Major Intra-Continental Strike Slip System", *J. Structural Geology*, **24**, 1677-1698.

18. Walker, R., Jackson, J.A., and Baker, C. (2003). "Surface Expression of Thrust Faulting in Eastern Iran: Source Parameters and Surface Deformation of the 1978 Tabas and 1968 Ferdows Earthquake Sequences, *Geophys., J. Int.*, **152**, 749-765.

19. Wessel, P. and Smith, W.H.F. (2000). "The Generic Mapping Tools (GMT)", University of Hawai'i.

Appendix I: Lower-hemisphere equal-area fault plane solutions for selected aftershocks. Compressional first motions are shown as solid circles, dilatation first motion as open circles. P-axes are shown as solid triangles and T-axes as open triangles.





A Study of the Strong Ground Motions of 26 December 2003 Bam Earthquake: Mw6.5

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ABSTRACT: *The Bam earthquake of 26 December 2003 (Mw6.5) occurred at 01:56:56 (GMT, 05:26:56 local time) around the city of Bam in the southeast of Iran. The Bam earthquake of 26/12/2003 (Mw6.5) has demolished the city of Bam, having a population of about 100000 at the time of the earthquake. The Bam fault-which was mapped before the event on the geological maps-has been reactivated during the 26/12/2003 earthquake. It seems that a length of about 10km (at the surface) of this fault has been reactivated, where it passed exactly from the east of the city of Bam. The fault has a slope towards the west and the focus of the event was located close to the residential area (almost beneath the city of Bam). This caused a great damage in the macroseismic epicentral zone; however the strong motions have been attenuated very rapidly, specially towards the east-and west (fault normal) direction. The vertical directivity effects caused the amplification of the low frequency motions in the fault-normal direction as well as the greater amplitude of the motion on the vertical direction. Two strong phases of energy are seen on the accelerograms. The first comprises of a starting sub-event with right-lateral strike slip mechanism which is located south of Bam. The mechanism of the second sub-event is reverse mechanism. The comparison of observed and simulated ground motion indicates that rupture started at a depth of 8km, south of Bam and propagated toward north.*

Keywords: Bam; Strong Motions; Data processing; Source parameters; Simulation; Stress drop; Velocity; Displacement; SH waves; Sub-events

1. Introduction

The Bam earthquake of December 26, 2003 (*Mw*6.5) demolished the city of Bam in the southeast of Iran, see Figure (1). The earthquake happened at 5:26*am* local time when most of the inhabitants were asleep, that was one of the causes of the great life losses. The number of victims was declared officially to be about than 26500 at the time of the preparation of this article (19/01/2004). More that 50000 people were injured and about 100000 people remain homeless.

The damage was limited to the city of Bam and to a smaller city, Baravat, which is located east of Bam. The inhabitants of the villages located near Bam have left their houses after the earthquake, due to the fear of greater earthquakes (aftershocks) and because of extensive to moderate damage to their buildings.

The city of Bam is well-known for the historical citadel of Arg-e-Bam, which is about 2000 years old. It was almost destroyed in the 2003 Bam earthquake, see Figure (1) [1]. Arg-e Bam is the biggest known mud-brick complex in the world. This historical monument is located on an igneous hill, on the verge of the Silk Road. It has an area of some 240,000 square meters. There is no information about the exact date of its construction but according to Persian history it goes back to 2000 years. It has been repaired several times, and was inhabited until 150 years ago.

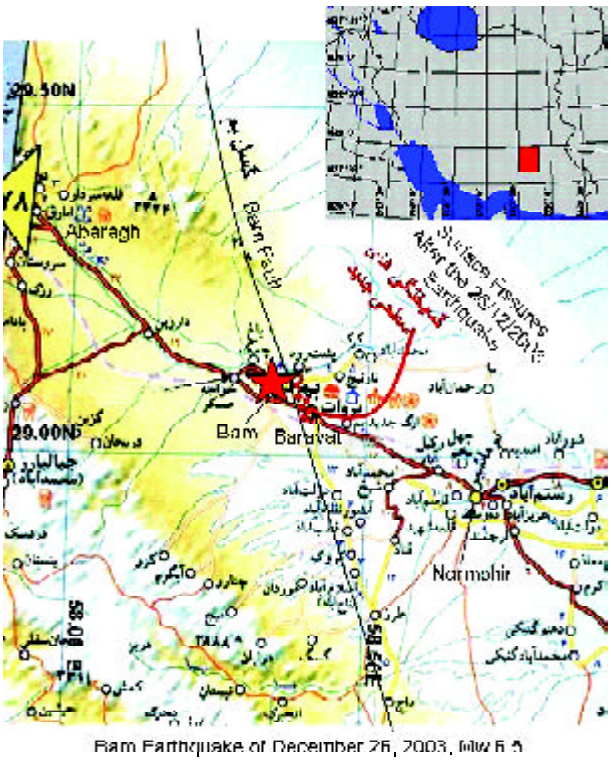


Figure 1. The location map of the Bam earthquake epicentral region in SE of Iran.

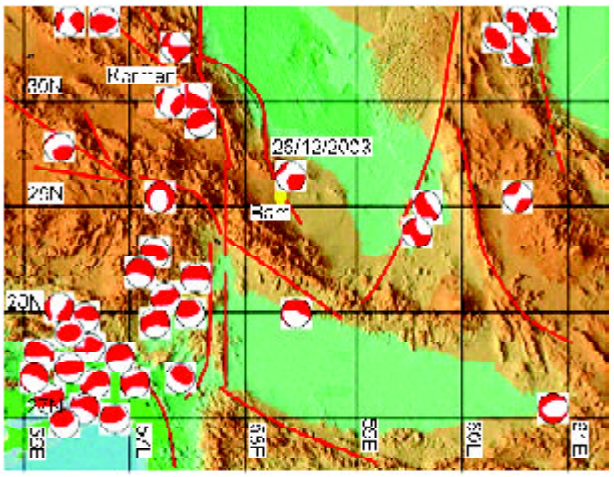


Figure 2. The seismotectonic map of the Bam Region (The base topographic map from USGS Global Digital Data Series [4], focal mechanism from: CMT solutions, Harvard University website [5]).

Since there is no report of the earthquake occurrence near the city of Bam, in the Iranian historical earthquake catalogue, it seems that it was the first time during the last 2000 years that a disastrous earthquake has taken place due to the reactivation of the Bam fault. The date(s) of the previous earth-quake(s) should be determined through paleoseismological studies on the Bam fault.

This paper is prepared to summarize the latest studies of strong ground motions. The strong motions recorded in this event are introduced and most of the paper is focused on the source parameters and on the frequency content of the accelerogram recorded in Bam station, which was located at the Bam city center.

2. Seismotectonics of the Studies Area

The southeast Iran is an active seismic zone, see Figure (2). The Bam city itself had no reported great historical earthquake before the 2003 event [2]. Northwest of Bam, 4 major earthquakes with magnitudes greater than 5.6 have shaken the cities and villages between 1981 and 1998 [3]. The trend of the main faults (including the Bam fault) in this region is North-South, and *NW-SE*, see Figure (1) [1]. These two systems intersect in western Lut area. The NW-SE faults (Kuhbanan and Ravar faults) and the north-south faults (Nayband, Chahar-Farsakh, Anduhjerd, Gowk, Sarvestan and Bam faults) have determined the border of the north-south structures in the Lut area with the *NW-SE* structures. These intersection zones are the main sources for the disastrous earthquakes. The Gowk fault system is representative for its surface ruptures during 1981, 1989 and 1998 earthquakes as well as a hot spring system nearby Sirch. In the west of Golbaf-Sirch valley, there is the Lut depression, where a vertical topographic offset of more than 4000 meters is evident. Four great earthquakes have shaken the region during the recent years: Golbaf earthquake of 11 June 1981, *Ms*6.6, Sirch earthquake of 28 July 1981, *Ms*7.0, South Golbaf earthquake of 20 November 1989, *mb*5.6 and the North Golbaf (Fandogha) earthquake of 14 March 1998, *Mw*6.6. The Golbaf earthquake of June 11, 1981 has struck the region of Golbaf in the southern parts of the Golbaf valley (with the strike of *N*5-15*E*). This earthquake which was associated with a fault rupture along the Gowk fault resulted in a life loss of 1071 persons. The event caused great damage in Golbaf region. The Sirch earthquake of July 28, 1981 occurred 49 days after the Golbaf earthquake and caused 877 deaths. It seems that it started as secondary faulting along the Gowk fault (*N-S* trend), or was triggered by activation of the Gowk fault in the hidden continuation of the Kuhbanan fault (*NW-SE* trend), in their intersection zone. Such conditions may have lead to the great earthquakes around Sirch in 1877 and 1981 (both with magnitudes greater than 7.0). South Golbaf earthquake of November 20,1989 killed 4 people

injured 45 and caused some damage in Golbaf. Some surface faulting and folding have been reported to be related to this event. During the North Golbaf earthquake of March 14,1998 5 people were killed and 50 injured. The event was associated with surface faulting (about 20km length) in northern Golbaf. The focal mechanism of these earthquakes show the compressional and strike slip mechanisms along the Gowk and Kuhbanan fault systems, see Figure (2).

2.1. Focal Mechanism

The focal mechanism of December 26, 2003 Bam earthquake was reported as strike slip fault (*CMT* solution, Harvard university, web site [5]), see Figure (2), which coincides well with the surface evidence of right-lateral strike slip movement of the Bam fault. The reactivated fault plane had a near north-south direction and sloped towards the west. The focal mechanism reported by Harvard University shows a small reverse component for the fault plane as well. The focal mechanisms reported for the earthquakes which occurred in the region around Bam, see Figure (2), show that most of the earthquakes, which occurred between 1975 and 2003 had strike-slip to compressional mechanisms.

2.2. Bam Fault Scarp

The Bam fault has created a major topographic dislocation in the eastern Bam plain towards Baravat, see Figure (3). This fault scarp shows the vertical displacement of about 10 to 20 meters in different places. It consists of 3 major segments. The total length of such segmented fault system is about 100*km*. The fault escarpment was visited several times after the earthquake but no major earthquake related displacement could be found in its vicinity. The surface fissures, however, are found along this fault zone.

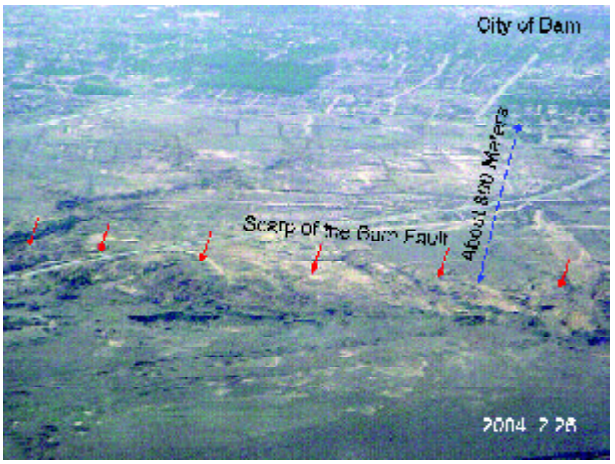


Figure 3. The Bam fault scarp from air (photo by M. Zare, February 2004).

The earthquake induced surface fissures were found in a region between Bam and Baravat and in the vicinity of the Citadel of Arg-e Bam, as well as in the eastern parts of the city of Bam. There was no appearance of the surface displacement on the surface, possibly due to the depth of the earthquake (8*km*) and because of the small dimensions of the source of an earthquake of such magnitude (*Mw*6.5).

2.3. Source Parameters

Based on a preliminary estimation of the seismic moment, a *Mw*=6.5 is assessed for the Bam earthquake. The focal depth of the 2003 Bam earthquake is estimated to be 8*km* and the hypocentral distance for the record obtained at the Bam station is then 12*km* (Based on a *S-P* estimation on the record obtained from the mainshock). The seismic moment is estimated by the author to be based on the fast Fourier transformations using the Haskell method [6] applied to the accelerogram recorded at the Bam station. The stress drop is estimated to be 480 bars.

Section 2.4. (Seismic Gap Is Eliminated)

2.4. Aftershocks

The aftershocks recorded by 25 stations of a temporary network installed by *IIEES* within 3 months after the earthquake are mostly located towards the west of the Bam fault, which is consistent with the slope of the Bam fault towards the west. Most of the focal mechanisms estimated for these aftershocks (for the events having at least 5 well recorded seismograms) show similar mechanisms the *CMT* solution (Harvard University), see Figure (2), for the mainshock. Therefore, the reactivated Bam fault (with a slop towards west and a strike of *NNW-SSE*) was active for 3 months after the mainshock, and most of the aftershocks were focused in the central and southern parts of the Bam fault (east to south of Bam).

3. Recorded Strong Ground Motions

The strong motions of this event were recorded at 22 stations of the national Iranian strong motion network (according to Building and Housing Research Center, *BHRC* web site) [7], see Figure (4). The strong motion records are studied and processed and the preliminary results are presented mostly based on the

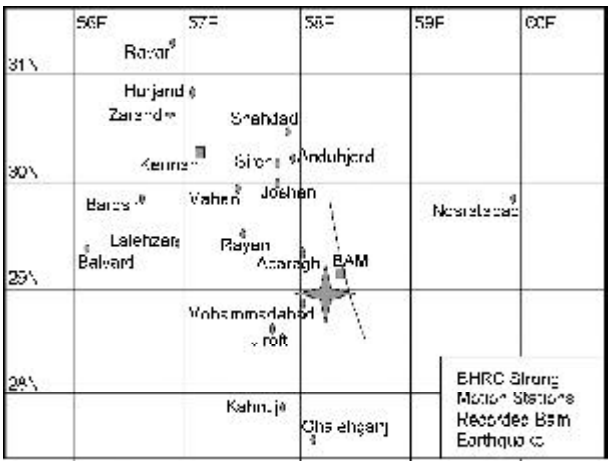


Figure 4. The BHRC strong motion stations that recorded the Bam earthquake.

mainshock and aftershock records obtained at Bam station. All of the strong motion data obtained during the Bam earthquake were recorded by digital Kinemetrics SSA-2 accelerographs. The attenuation of the strong motions was studied based on the records with good signal to noise ratio at 6 stations. The isoseismal map of the region is presented based on the site visits.

3.1. Strong motion Data Processing

The record obtained at Bam station, see Figure (5) -after band-pass filtering between 0.11 and 40*Hz*- shows the *PGA* of 775 and 623cm/sec^2 for the east-west and north-south horizontal components, respectively, and 992cm/sec^2 for the vertical component. This processing is performed based on the estimation of the signal to noise ratio, see Figure (6). The Fast Fourier transformation, see Figure (7) shows more energy at longer periods for the fault normal horizontal component.

A comparison of the *H/V* ratio obtained at Bam station during the mainshock and 13 aftershocks, which occurred in the first 24 hours after the earthquake, see Figure (7) shows very well low frequency amplification between 0.1 and 0.2*Hz* which is evident in the mainshock and it is not evident in the aftershocks. This may be taken as an evidence for

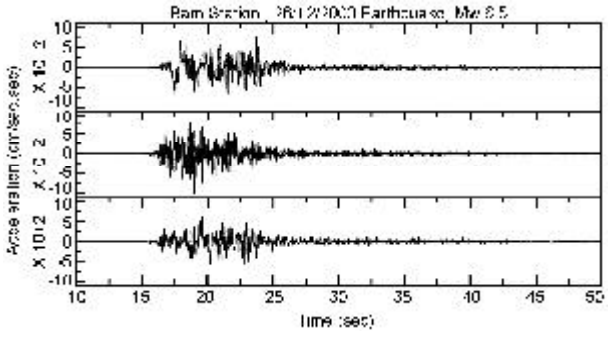


Figure 5. The Bam accelerogram after filtering (between 0.11 and 40Hz).

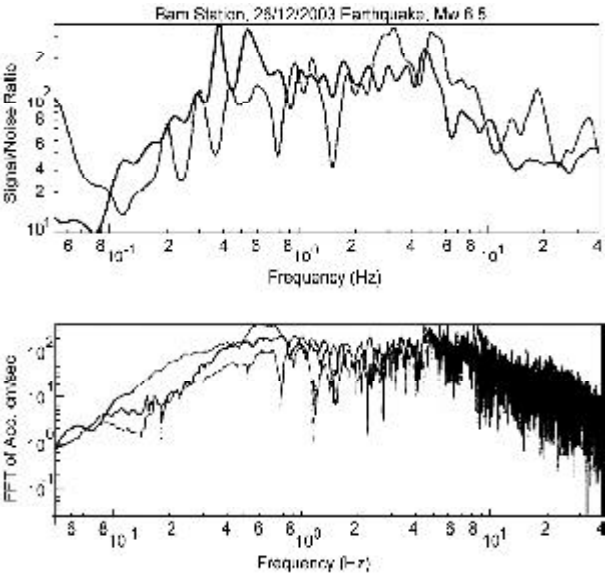


Figure 6. The signal to noise ratio (up) and the FFT of acceleration (down) for the three-components record of Bam.

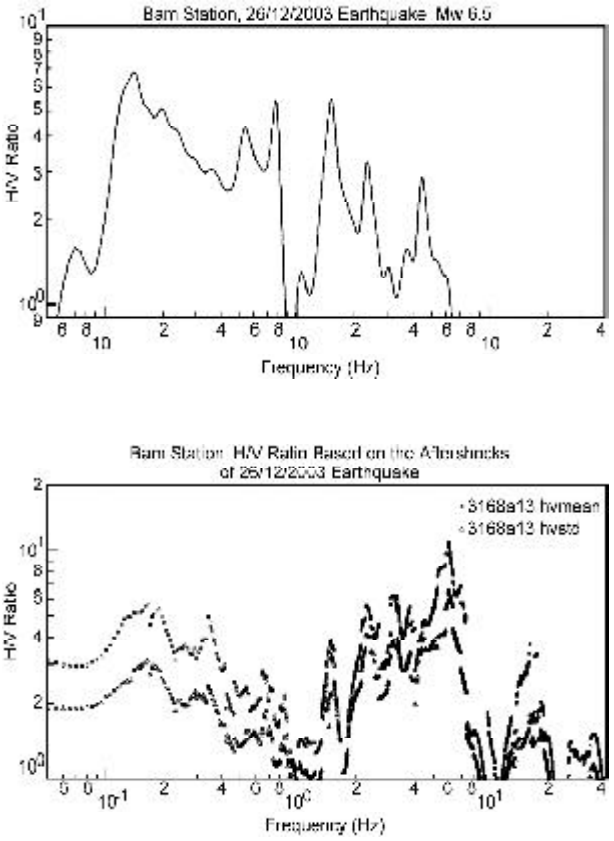


Figure 7. The H/V ratio for a) the mainshock and b) aftershocks recorded in Bam strong motion station.

the vertical directivity effect [18]. The vertical directivity might be explained in the Bam earthquake with the rupture propagation from the depth to the surface with an inclination towards the north. This effect can be assigned to the Bam earthquake fault rupture propagation towards the surface and obliquely towards the north. A strong fault-normal (east-west) motion is created during the mainshock as well. The demolished walls and buildings of Bam are representative for such effects in the up-down (vertical) and east-west directions (fault-normal). The Bam residents that survived the quake explained for the reconnaissance team members that they felt strong up-down displacements during the mainshock. The site class however may be taken for class "3" since the site fundamental frequency was about 2 to 5 *Hz* (equal to a site condition having the average shear wave velocity of about 300 to 500 *m/sec* in the first 30 meters of the deposits, [8]).

The velocity and displacement time-histories of the Bam record obtained based on single and double integration of Bam accelerogram are shown in Figures (8) and (9), respectively. These time-histories show a great pulse specially in the fault-normal component (east-west direction).

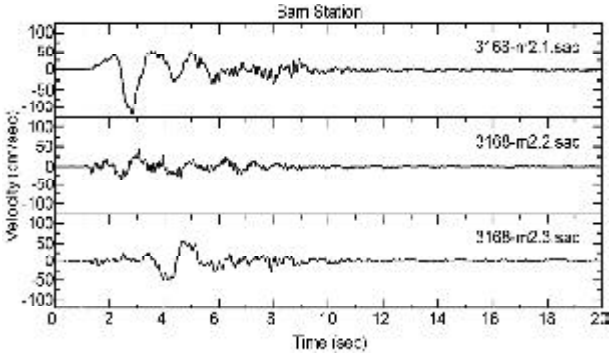


Figure 8 The velocity time-history based on single integration of accelerogram recorded in Bam.

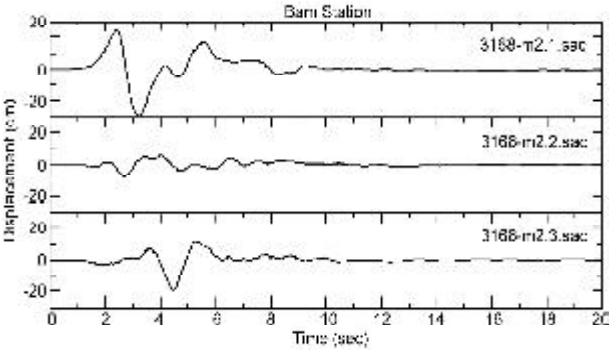
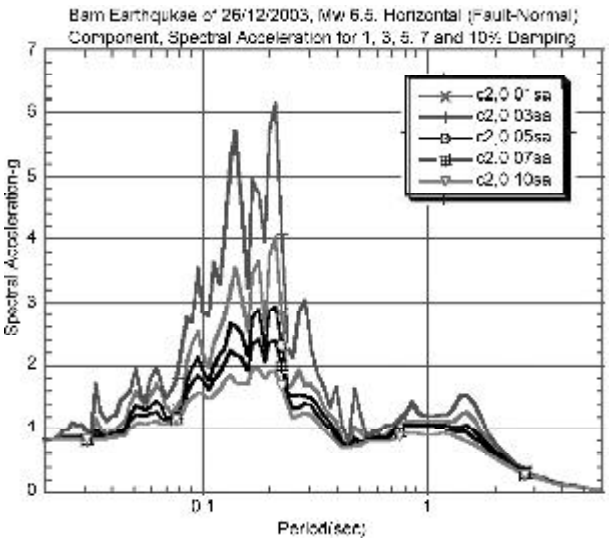


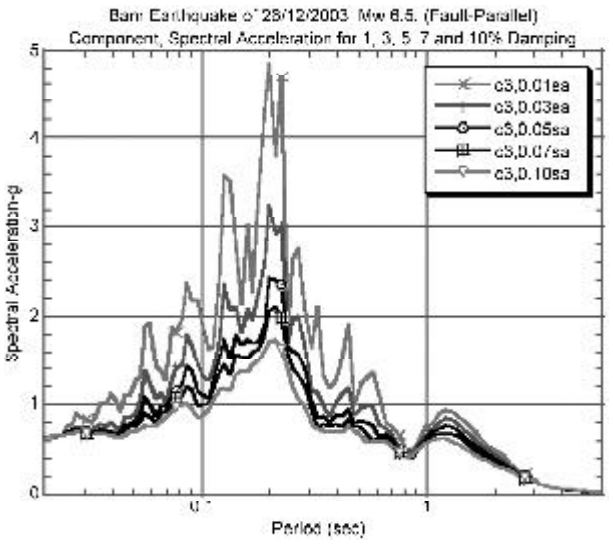
Figure 9. The displacement time-history on double integration of accelerogram recorded in Bam.

The spectral accelerations for 5% damping are shown in Figure (10) for the three-component acceleration recorded at Bam station. The predominant period is the period corresponding to the highest peak in a response spectrum. The response spectra in Figure (10) shows the predominant periods of 0.1 second for vertical and 0.2 second for 2 horizontal components. Figure (10) also shows higher spectral ordinates for the vertical and for the fault-normal components of motion.

The records obtained at the *BHRC* stations around the epicenter, see Figure (4), were processed and the

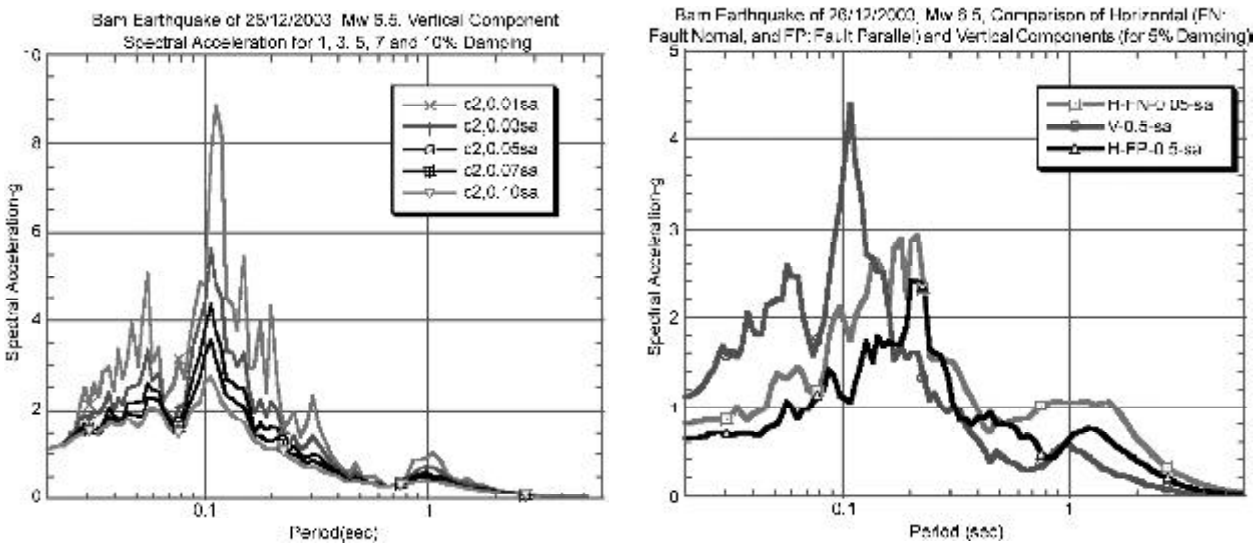


(a)



(b)

Figure 10. The spectral acceleration for 1, 3, 5, 7 and 10% damping, the values for 10a) horizontal-fault normal (FN), 10b) fault parallel (FP) and 10c) vertical components are shown. The response spectra for the damping value of 5% are compared for different components in figure 10d.



(c) **(d)**

Figure 10. Continued ...

acceleration time-histories obtained at Bam, see Figure (5), Abaragh, see Figure (11), Mohammadabad-e Maskun, see Figure (12), Jiroft, see Figure (13), Golbaf, see Figure (14), and Sirch, see Figure (15) were selected for the detained strong motion studies. These records were filtered according to their corresponding signal to noise ratio and the band-pass filters are selected are shown in Table (1). Those strong motion records obtained at the stations Anduhjerd, see Figure (16), Cheshmehsabz, see Figure (17), Balvard, see Figure (18), Mahan, see Figure (19), Bardsir, see Figure (20), Hurjand, see Figure (21), Joshan, see Figure (22), Kahnuj, see Figure (23), Kerman-Maskan, see Figure (24), Kerman-Farmandari, see Figure (25), Lalehzar, see Figure (26), Zarand, see Figure (27), Nosratabad, see

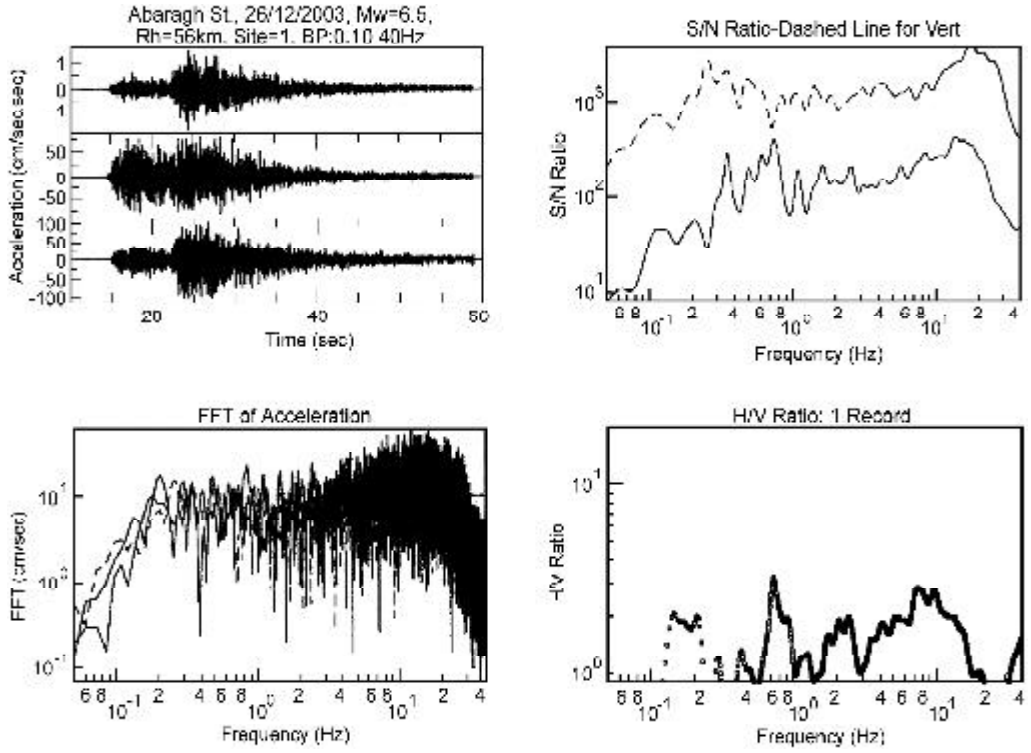


Figure 11. The processing of the record obtained at Abaragh station (56km hypocentral distance): filtered acceleration time-history (above-left); the signal to noise ratio (above-right); the FFT of acceleration before filtering (below-left) and the H/V ratio (below-right).

Figure (28), Ghalehganj, see Figure (29), Shahdad, see Figure (30), Rayen, see Figure (31) and Ravar, see Figure (32) for which the signal to noise ratios are small are presented in the paper but are excluded from the detailed studies of the strong motion parameter.

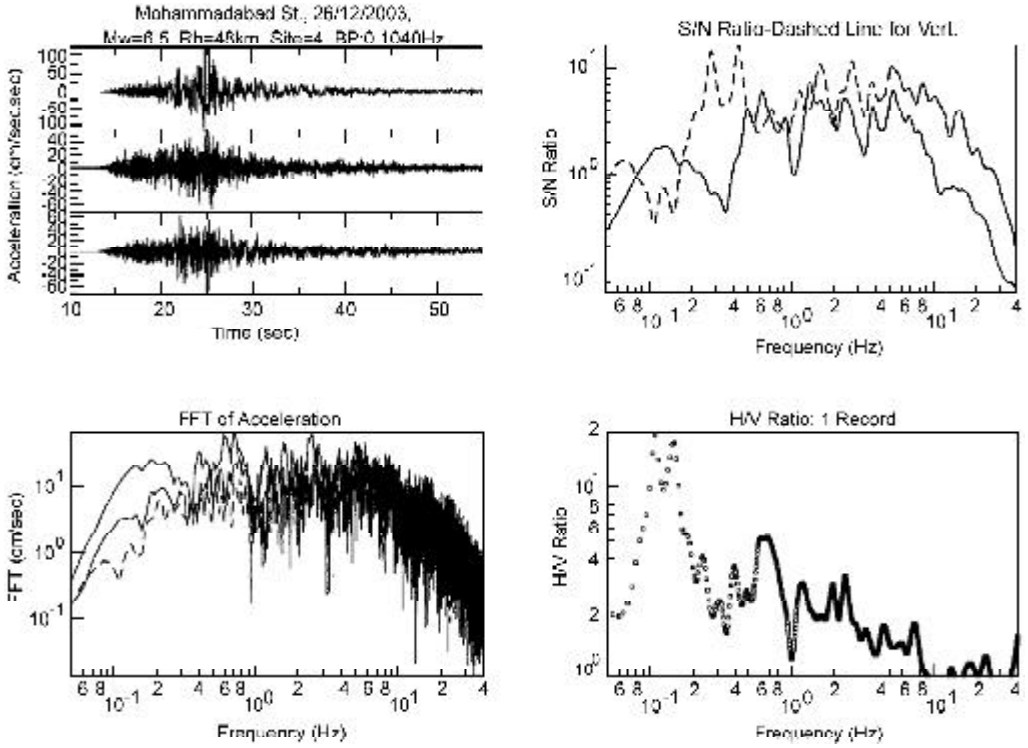


Figure 12. The processing of the record obtained at Mohammadabad-e Maskun station (48km hypocentral distance): filtered acceleration time-history (above-left); the signal to noise ratio (above-right); the FFT of acceleration before filtering (below-left) and the H/V ratio (below-right).

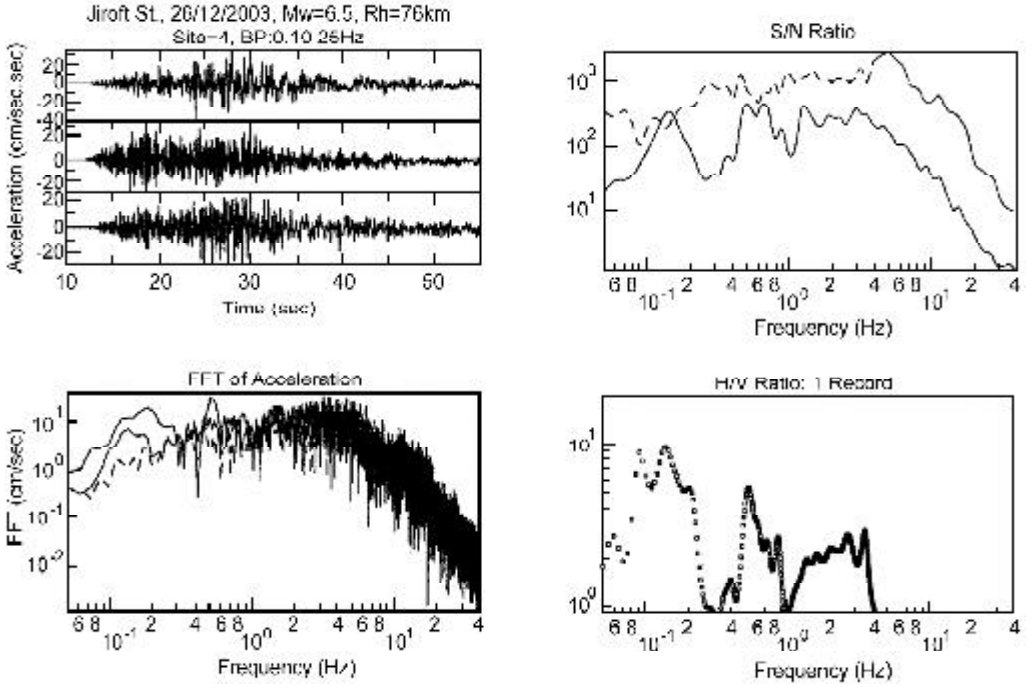


Figure 13. The processing of the record obtained at Jiroft station (76km hypocentral distance): filtered acceleration time-history (above-left); the signal to noise ratio (above-right); the FFT of acceleration before filtering (below-left) and the H/V ratio (below-right).

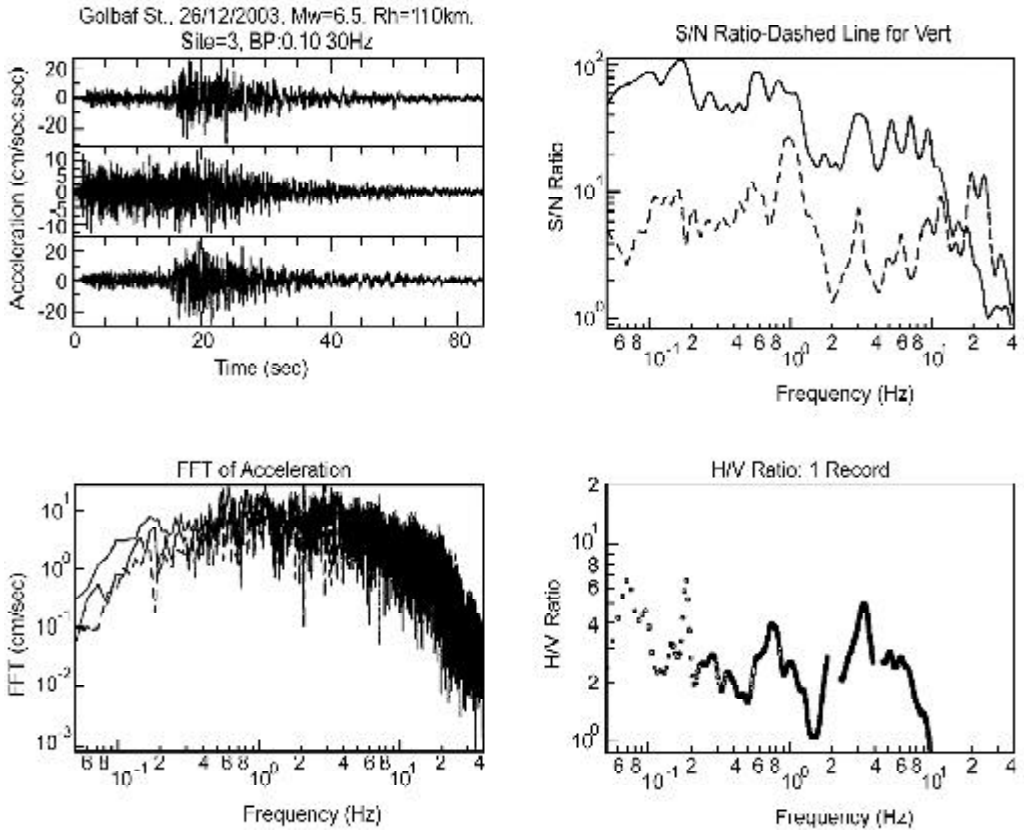


Figure 14. The processing of the record obtained at Golbaf station (110km hypocentral distance): filtered acceleration time-history (above-left); the signal to noise ratio (above-right); the FFT of acceleration before filtering (below-left) and the H/V ratio (below-right).

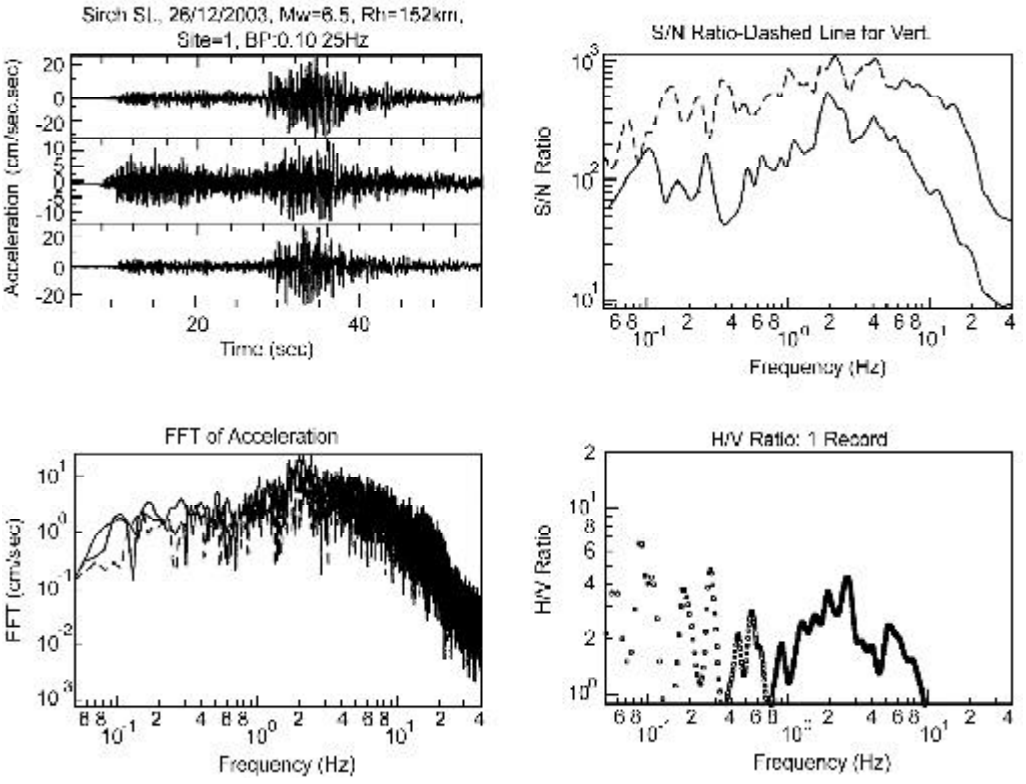


Figure 15. The processing of the record obtained at Abaragh station (152km hypocentral distance): filtered acceleration time-history (above-left); the signal to noise ratio (above-right); the FFT of acceleration before filtering (below-left) and the H/V ratio (below-right).

Table 1. The strong motion parameters estimated for 5 records having better qualities (part-1).

No. of Trace	Record	Station	Lat. N	Long. E	Sites	BP Filter (Hz)	HPGA1 (cm/sec^2)	VPGA (cm/sec^2)	HPGA2 (cm/sec^2)	HPGV1 (cm/sec)	VPGV (cm/sec)	HPGV2 (cm/sec)	HPGD1 (cm)	VPGD (cm)	HPGD2 (cm)	To (Hz)	Emax -H	Emax -V	Hypocentral Distance (km)
1	3161	Bam	30.24N	57.57E	1	0.1-25	80.2	14	29.2	2.4	1	2.5	0.4	0.2	0.3	0.4	8	15	152
2	3162-1	Mohammad-Abad	29.97N	57.88E	4	0.1-40	120.1	69.2	71	10.4	3.1	3.3	2.1	0.6	0.8	0.4	6	8	48
3	3168-2	Bam	29.12N	58.38E	3	0.11-40	775	392	625	92.3	52.5	72.6	26.4	6.3	15.2	0.2	9	18	12
4	3170-2	Jiroft	28.68N	57.76E	1	0.1-25	99.6	30.5	37.9	3.5	1.3	3.1	0.9	0.4	5.1	0.45	9.5	5	76
5	3176-1	Abarqh	29.38N	57.97E	1	0.1-40	162.6	83.2	107.7	8.2	8.1	10.3	2.8	2.6	2.2	0.25	18	25	56

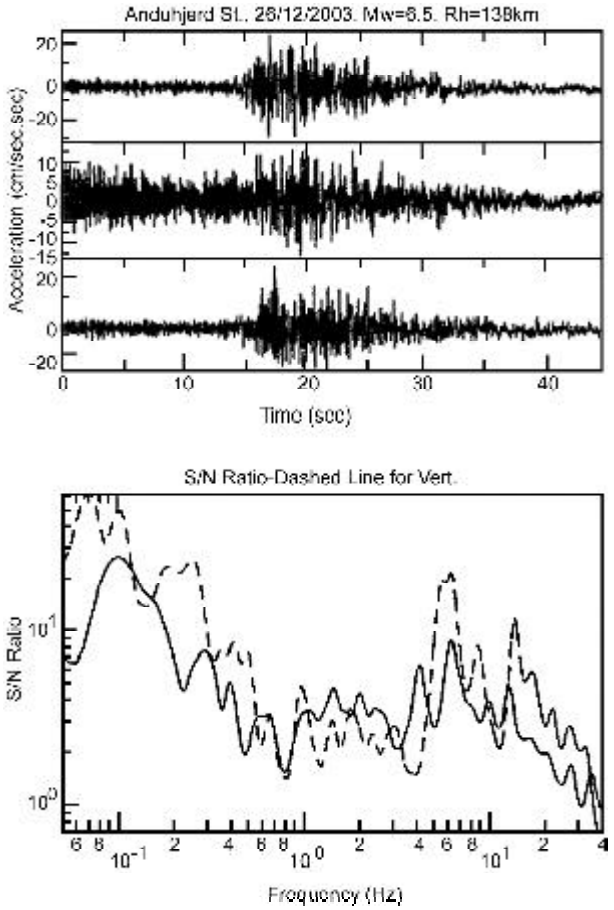


Figure 16. The acceleration time-history (above) and signal to noise ratio for the record obtained at Anduhjerd (138km hypocentral distance).

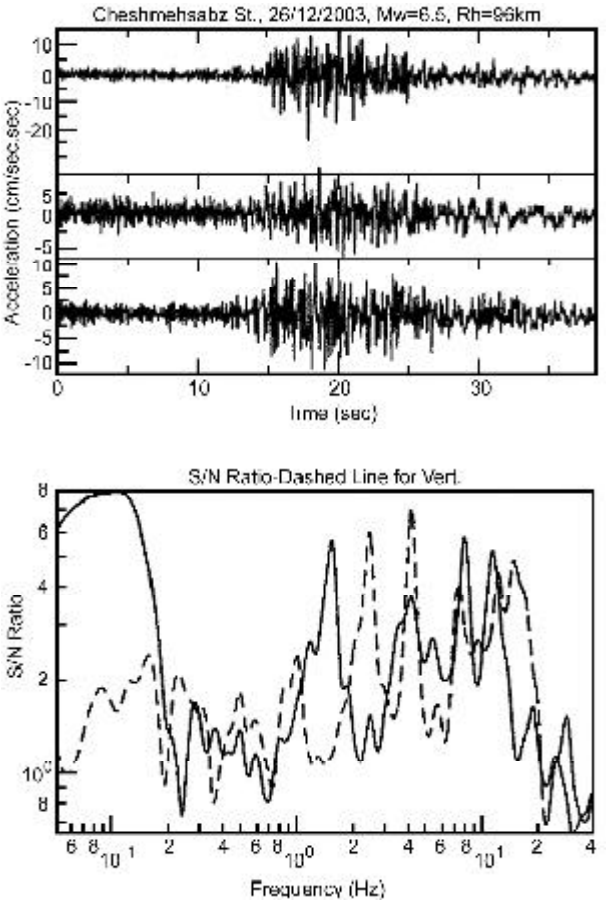


Figure 17. The acceleration time-history (above) and signal to noise ratio for the record obtained at Cheshmehsabz (96km hypocentral distance).

3.2. Strong Motion Parameters

The strong motion parameters estimated for five selected strong motion records are presented in Tables (1) and (2). The estimated parameters for the selected records are explained briefly herein.

3.2.1. Peak Acceleration, Velocity and Displacement

The peak acceleration is the maximum absolute value of acceleration. The peak acceleration provides a useful measure of the strength of the higher frequency components (about 1 to 10*Hz*) of a ground motion. Peak Velocity is the maximum absolute value of velocity. The peak velocity provides a useful measure of the strength of the intermediate frequency components (about 0.5 to 5*Hz*) of a ground motion. Peak Displacement is the maximum absolute value of displacement. The peak displacement provides a useful measure of the strength of the lower frequency components (about 0.1 to 1*Hz*) of a ground motion. These values are presented in the columns 8 to 16 of Table (1).

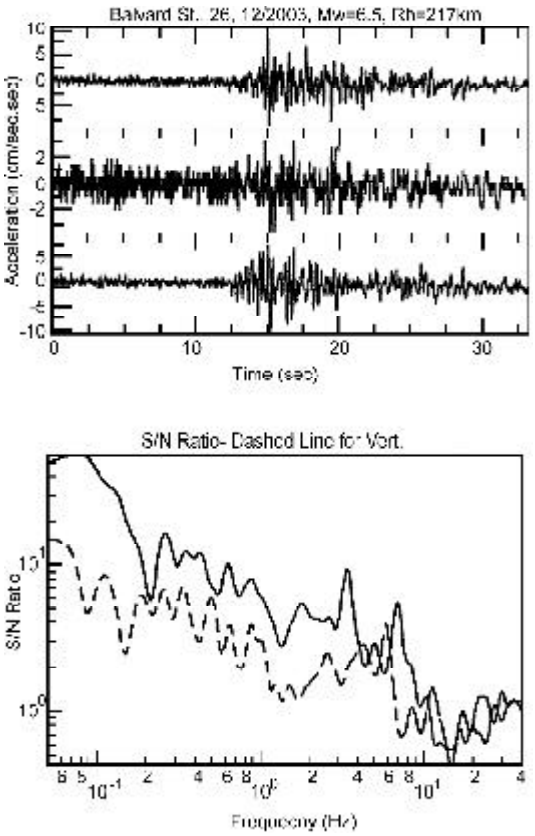


Figure 18. The acceleration time-history (above) and signal to noise ratio for the record obtained at Balvard (217km hypocentral distance).

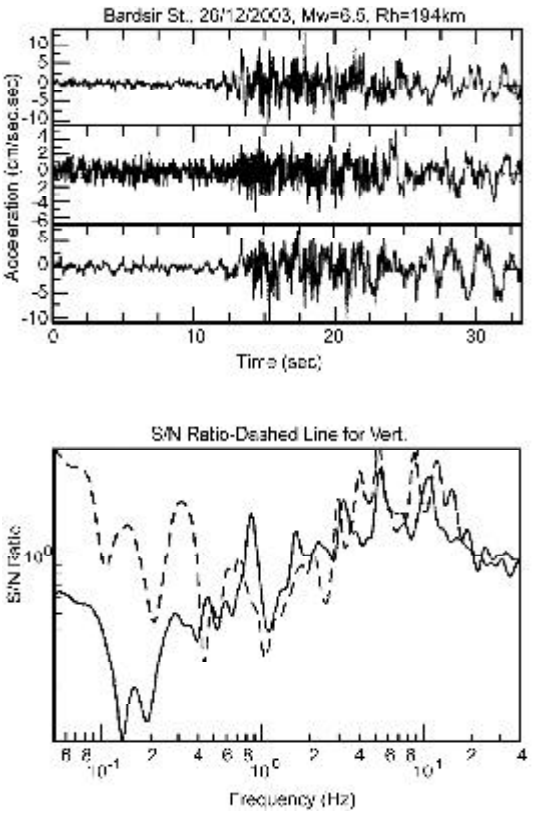


Figure 20. The acceleration time-history (above) and signal to noise ratio for the record obtained at Bardsir (194km hypocentral distance).

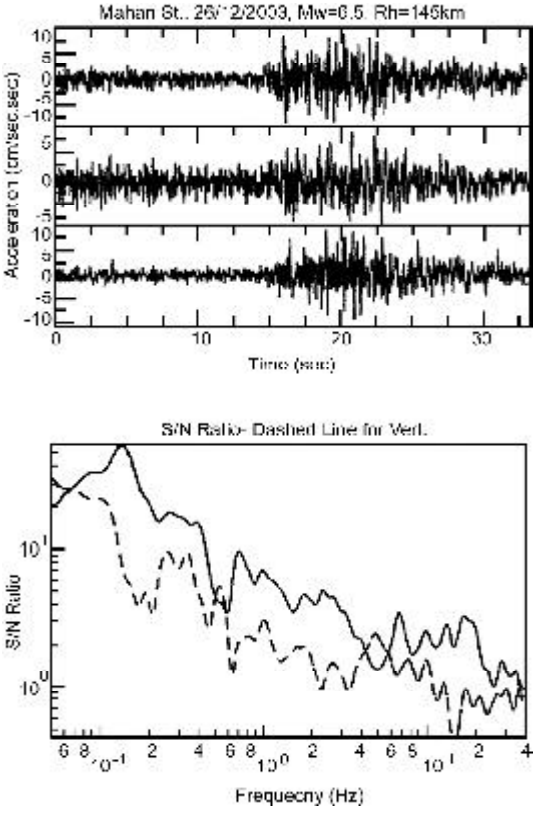


Figure 19. The acceleration time-history (above) and signal to noise ratio for the record obtained at Mahan (145km hypocentral distance).

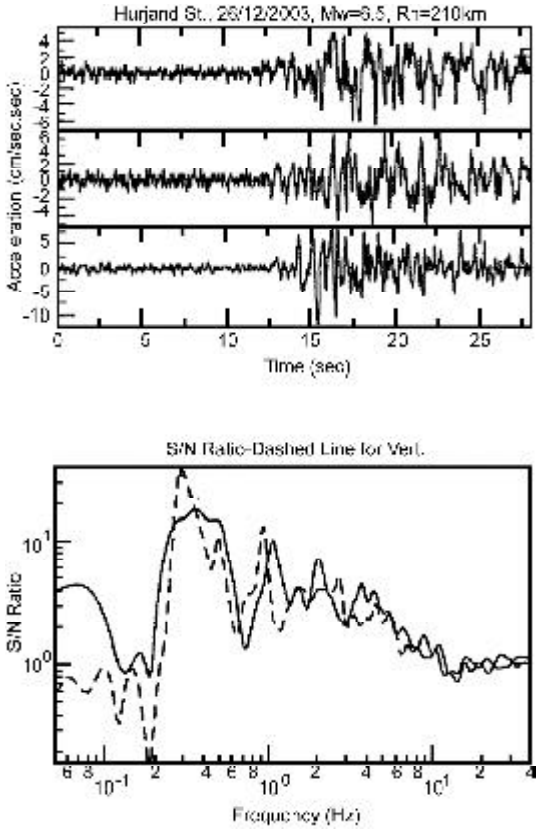


Figure 21. The acceleration time-history (above) and signal to noise ratio for the record obtained at Hurjand (210km hypocentral distance).

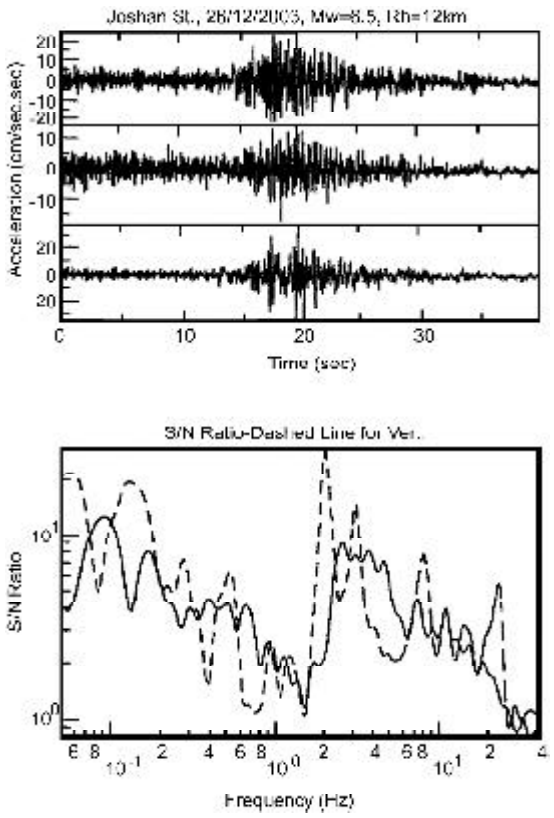


Figure 22. The acceleration time-history (above) and signal to noise ratio for the record obtained at Joshan (129km hypocentral distance).

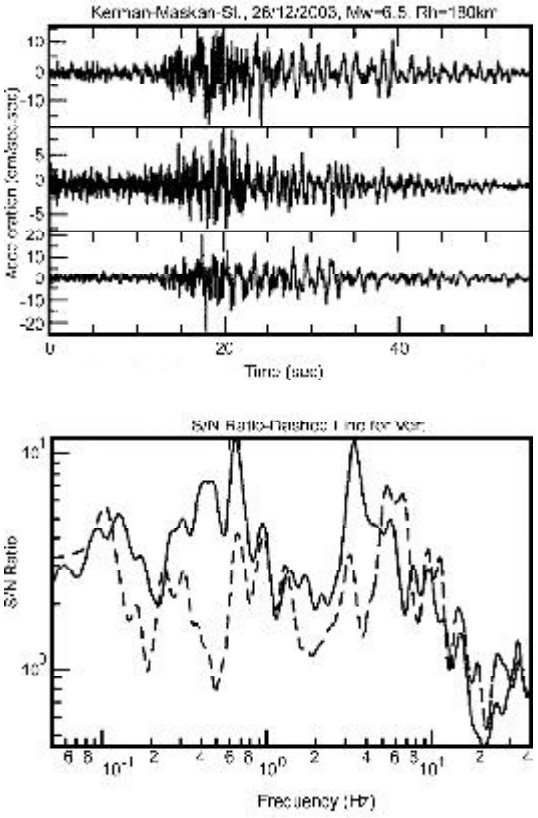


Figure 24. The acceleration time-history (above) and signal to noise ratio for the record obtained at Kerman-Maskan (180km hypocentral distance).

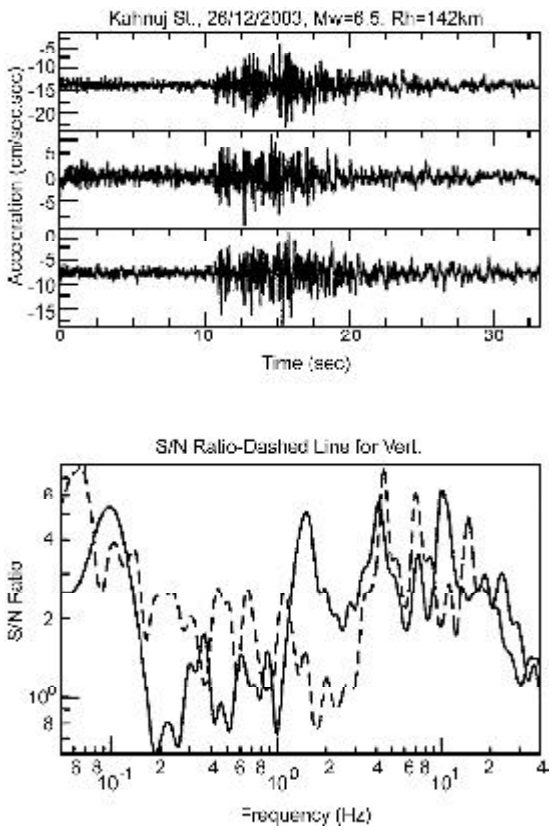


Figure 23. The acceleration time-history (above) and signal to noise ratio for the record obtained at Kahnuj (142km hypocentral distance).

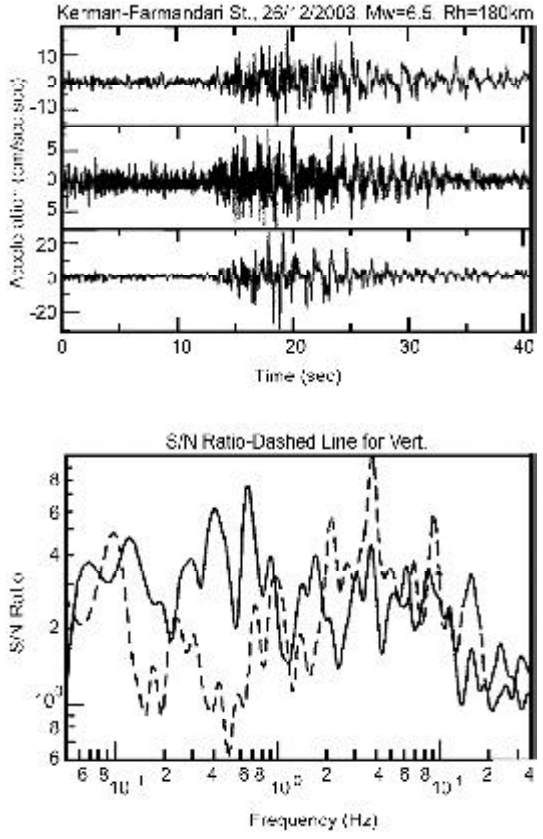


Figure 25. The acceleration time-history (above) and signal to noise ratio for the record obtained at Kerman-Farmandari (180km hypocentral distance).

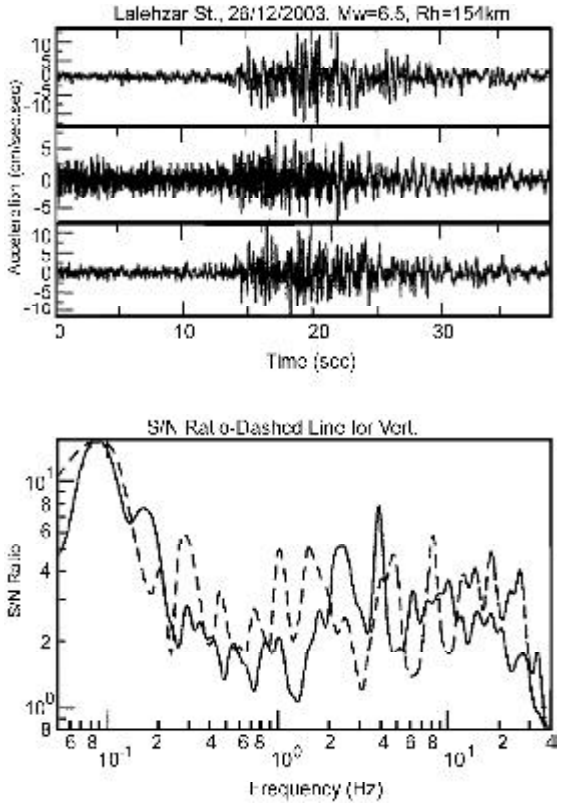


Figure 26. The acceleration time-history (above) and signal to noise ratio for the record obtained at Lalehzar (154km hypocentral distance).

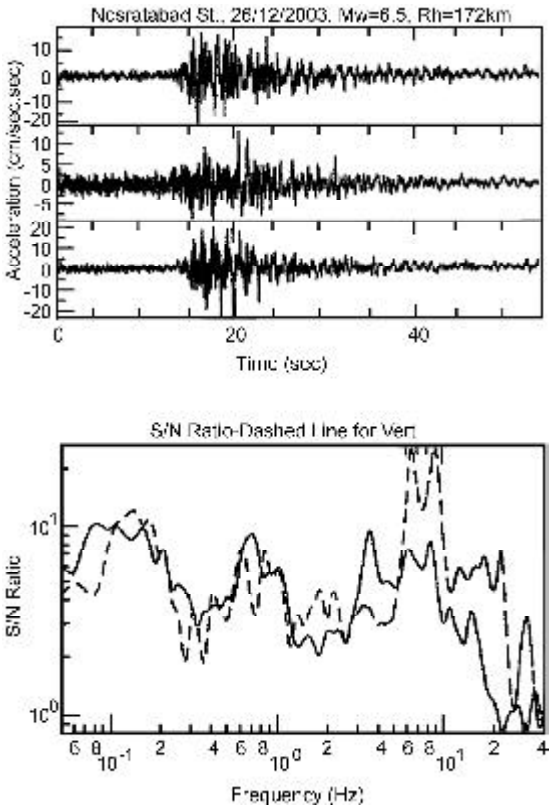


Figure 28. The acceleration time-history (above) and signal to noise ratio for the record obtained at Nosratabad (172km hypocentral distance).

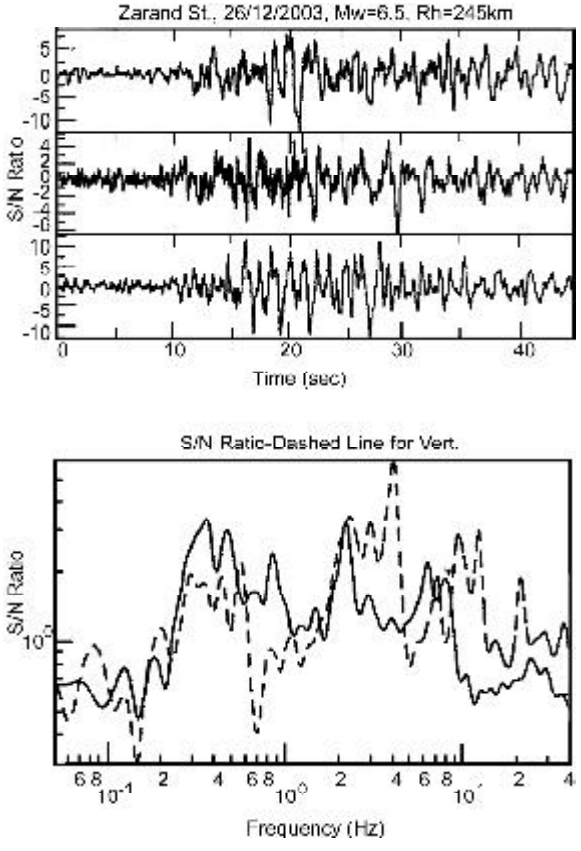


Figure 27. The acceleration time-history (above) and signal to noise ratio for the record obtained at Zarand (245km hypocentral distance).

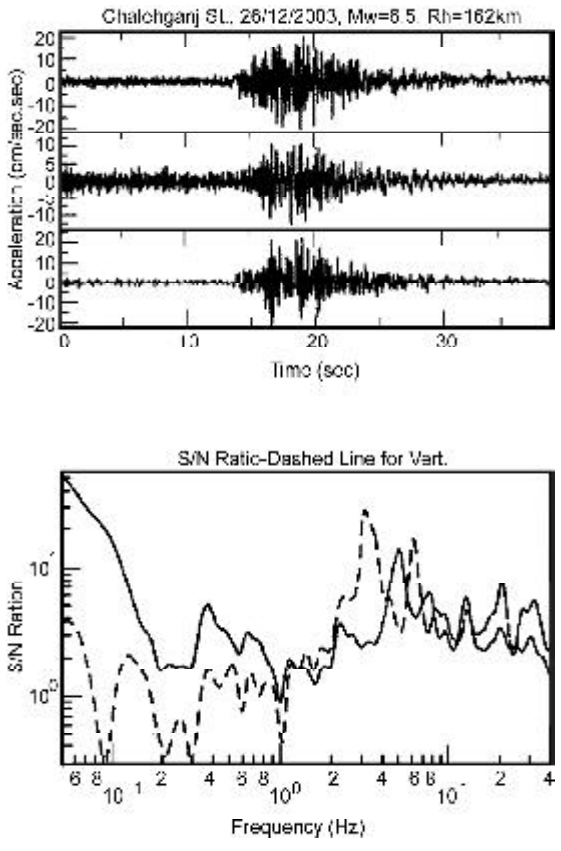


Figure 29. The acceleration time-history (above) and signal to noise ratio for the record obtained at Ghalehganj (162km hypocentral distance).

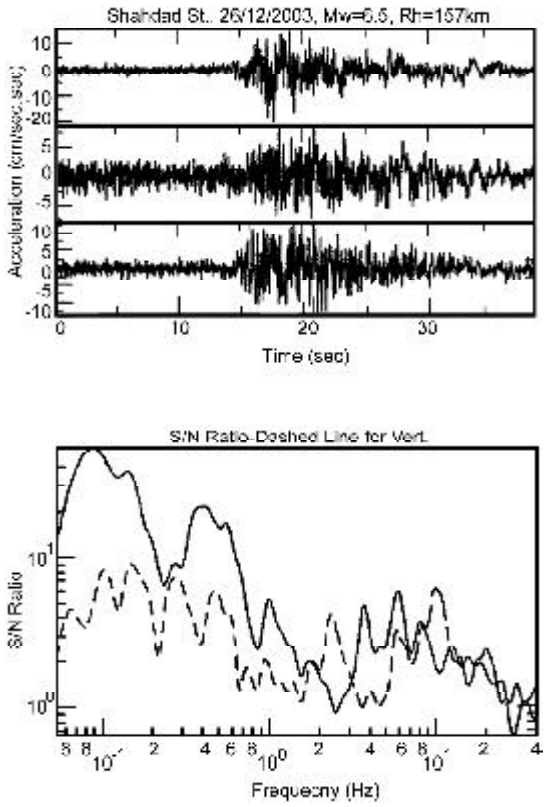


Figure 30. The acceleration time-history (above) and signal to noise ratio for the record obtained at Shahdad (157km hypocentral distance).

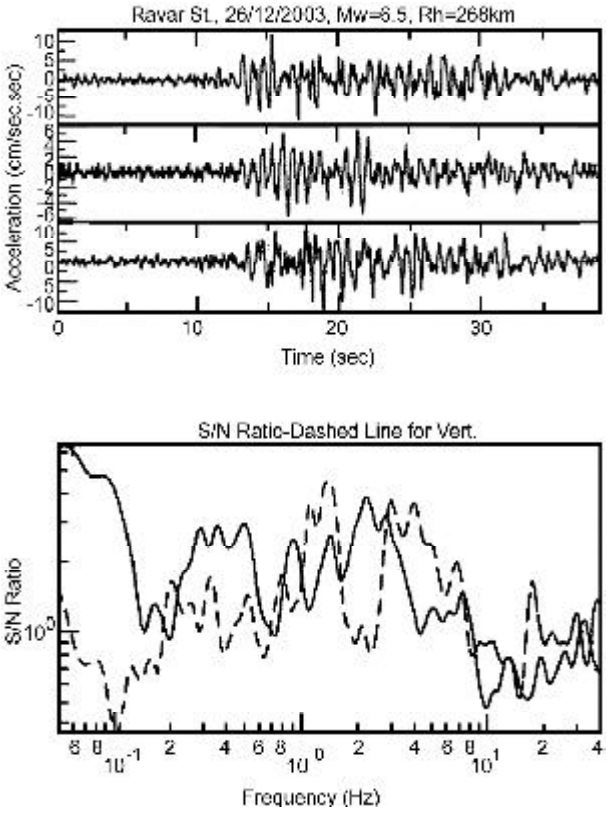


Figure 32. The acceleration time-history (above) and signal to noise ratio for the record obtained at Ravar (268km hypocentral distance).

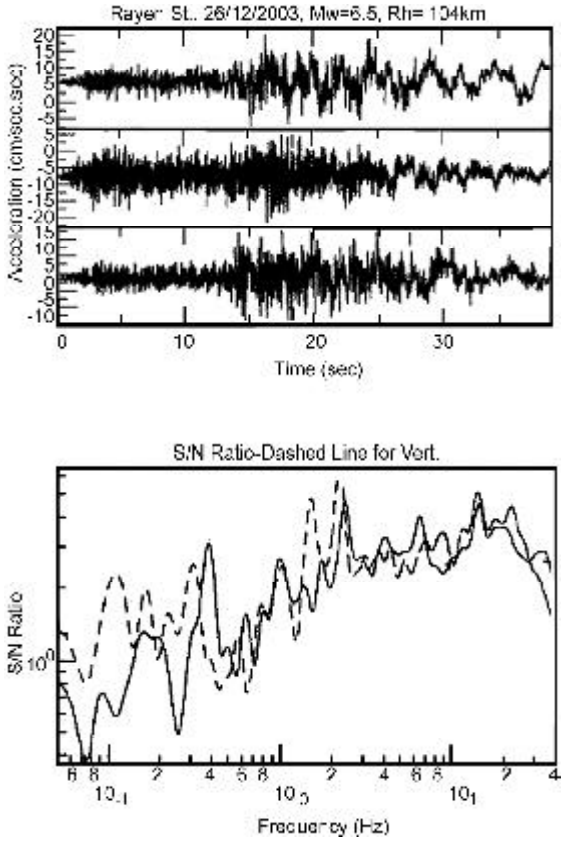


Figure 31. The acceleration time-history (above) and signal to noise ratio for the record obtained at Rayen (104km hypocentral distance).

3.2.2. Root Mean Square (RMS) Acceleration

The *RMS* acceleration is a single parameter that includes the effects of the overall amplitudes of a strong motion record

$$a_{rms} = \sqrt{\frac{1}{Td}\int_{0}^{Td}[a(T)]2dt} \qquad (1)$$

where *Td* is the duration of the motion. Because the integral is not strongly influenced by large, high frequency accelerations (which occur only over a very short period of time) and because it is influenced by the duration of strong motion, the *RMS* acceleration can be a useful parameter for engineering purposes. In the present study we used Trifunac's definition of the duration for computation of the *RMS* acceleration. The estimated values of *RMS* acceleration for the selected records in this study are presented in columns 4 to 6 of Table (2).

3.2.3. Arias Intensity

The Arias Intensity, I_a [9], that is influenced by amplitude, frequency content, and duration, of strong motion. It is defined as

Table 2. The strong motion parameters estimated for 5 records having better qualities (part-2).

No. of Total	Record	Station	Accs-H1 (cm/sec²)	Accs-V (cm/sec²)	Accs-H2 (cm/sec²)	Arias-Int. H1 (cm/sec)	Arias-Int. V (cm/sec)	Arias-Int H2 (cm/sec)	Vel. Spectral Int. H1 (cm/sec)	Vel. Spectral Int. V (cm/sec)	Vel. Spectral Int. H2 (cm/sec)	Duration H1-sec	Duration V-sec	Duration H2-sec
	2161	Sirch	3.8	3	3.2	2.4	0.7	2	8.2	2.2	8.6	17.3	30.9	17.1
2	3 6241	Mohammad-Abad	11.5	7.3	7.1	16.6	7	6.8	44.6	13.4	16.9	13.9	20.7	22.6
3	3 6823	Bam	140.6	135.9	110	99.1	71.8	48.4	3061.4	1580	815.9	7.7	7.5	8.4
4	2170-2	Jirofl	6.1	5.6	5.7	3.2	2.8	2.8	16.5	6.7	11.4	23.6	27.6	26
5	2176-1	Abaragh	19.5	19.3	16.9	36.2	22.1	27	33.2	33.7	35	15	16.4	19.1

$$I_a = \frac{\pi}{2g}\int_0^{\infty}[a(t)]^2 dt \qquad (2)$$

where $a(t)$ is the acceleration time-history. The Arias Intensity has units of velocity and is usually expressed in meters per second. Since it is obtained by integration over the entire duration, rather than over the duration of strong motion, its value is independent of the method used to define the duration of strong motion. The estimated values of Arias intensity for the selected records are given in columns 7 to 10 of Table (2).

3.2.4. Response Spectrum Intensity

The response spectrum intensity $I_a = \frac{\pi}{2g}\int_0^{\infty}[a(t)]^2 dt$ [10] is defined as

$$SI(\xi) = \int_{0.1}^{2.5} PSV(\xi,T)dT \qquad (3)$$

i.e., the area under the pseudo-velocity response spectrum (*PSV*) between periods of 0.1 second and 2.5 seconds. The response spectrum intensity is computed here for a structural damping ratio of 5%. It captures overall spectral amplitudes (in the range of primary importance for structures) in a single parameter. The values of velocity response spectral intensity are given in columns 11 to 13 of Table (2) for the selected records.

3.2.5. Trifunac Duration

The Trifunac duration [11] is defined as the time interval between the points at which 5% and 95% of the energy in a ground motion have been delivered. Numerically, it corresponds to the time between the 5% and 95% points on a Husid plot. A Husid plot [$H_n(t)$] shows how the energy of the ground motion is distributed in time. Mathematically, it is a plot of normalized cumulative squared acceleration, i.e.

$$H_n(t) = \frac{\int_0^t [a(t)]^2 dT}{\int_0^{\infty} [a(t)]^2 dT} \qquad (4)$$

where $a(t)$ is the acceleration time history. The estimated durations of selected records are presented in columns 13 to 15 of Table (2).

4. Attenuation of Strong Motions

The Attenuation of strong motions is studied in terms of the processed records obtained at 6 stations (with the accepted level of signal to noise ratios) at Bam, Abaragh, Mohammadabad-e Maskun, Jirof, Golbaf and Sirch. The attenuation of strong motions was studied by Zaré [12] in Iran based on the strong motions recorded between 1974 to1996. A catalogue of Iranian strong motions is published in Bard et al [13]. The attenuation of strong motions recorded at these 6 stations is compared with the values obtained for previous empirical relationships [12] for the *Mw*6.5 earthquake for horizontal and vertical components. The results are shown in Figures (33) and (34) respectively. These figures show very well the coincidence of the estimated and observed values specially for the far-field records.

5. SH Wave Analysis

The analyses of teleseismic and strong ground motion data have been used by different investigators to infer and identify about the complex rupture process and sub-events [14-15]. It is expected that the energy releases from these sub-events will be identifiable in the near field strong motion data and an attempt can be made to study their properties. For this purpose, a method of Sarkar et al [15] has been used to estimate fault plane parameters using strong ground motion data pertaining to *SH* wave only. This method is based on a point source representation and non-linear least square formulation which estimates the strike, dip and rake of the causative fault and a grid

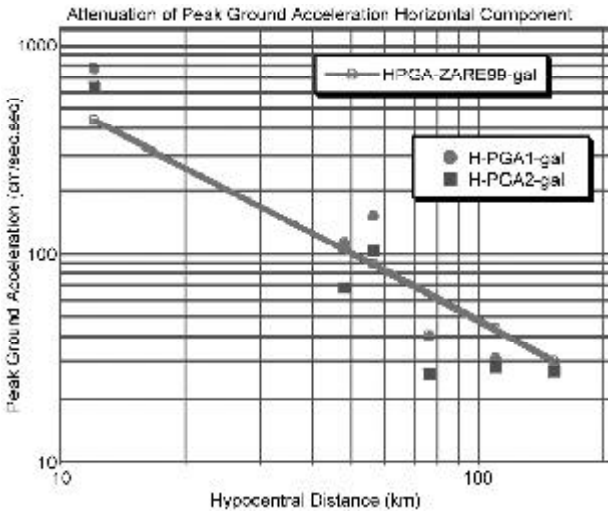


Figure 33. The attenuation of strong motion estimation by Zaré [9] attenuation laws for the horizontal component compared with the observed values in Bam earthquake in 2 horizontal components of 6 selected records.

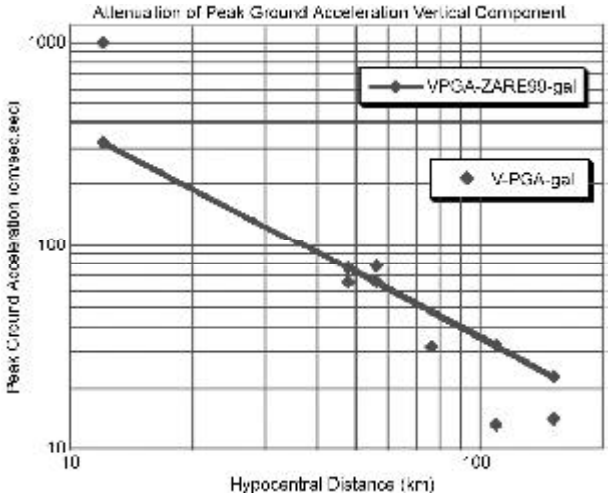


Figure 34. The attenuation of strong motion estimation by Zaré [9] attenuation laws for the vertical component compared with the observed values in Bam earthquake in vertical components of 6 selected records.

search technique that provides separate estimates of the strike, dip and rake. The analysis confines to *SH*-waves because these are minimally affected by crustal heterogeneity [16]. Further, use of *SH*-waves minimizes the need for corrections for the mode conversion at the free surface and other heterogeneities disregarded in the model used here. The spectral amplitudes at various stations are measured at the longest wavelength (lowest frequency) permitted by the data [15]. This is done in order that the point source approximation may be as appropriate as possible.

The observed spectral amplitudes of the acceleration are picked at a common frequency "*f*" on all stations for a particular event, which lies in the flat portions of the spectra and converted into the corresponding values of the spectral displacements. The values are then corrected for geometrical divergence. The corresponding theoretical estimates of *SH*-wave amplitudes of displacement are obtained from the formulae for the radiation pattern of SH-waves in a full space (see for instance) [17-18]. The error function *E* (strike, dip, rake) is written as:

$$E\ (strike,\ dip,\ rake) = \Sigma_i\ (A_{oi} - A_{ti})^2 \qquad (5)$$

Here A_{oi} and A_{ti} denote the observed and theoretical amplitudes of the near field *SH*-wave displacement at the selected frequency at the i^h station. The summation is over all stations that recorded the particular sub-event. The non-linear Newton technique has been used to simultaneously obtain those values of strike, dip, rake which minimize *E* (strike, dip, rake) in the least square sense.

For appropriate selection of *SH*-wave components of the recorded data the radial (*L*) and transverse (*T*) components of recorded acceleration and displacement are suitably rotated so that corresponding estimates along and perpendicular to azimuth direction are obtained. The rotated transverse components provide acceleration and displacement data of SH-waves, recorded at each station. The *SH*-wave accelerogram records for the 2003 Bam earthquake are shown in Figure (35).

5.1. Fault Plane Parameters of Sub-Events

It was observed in Rudbar-Manjil earthquake that strong ground motion data exhibits three strong phases which were interpreted to be related to three asperities [15]. It is expected that the energy releases from these sub-events will be identifiable in the near

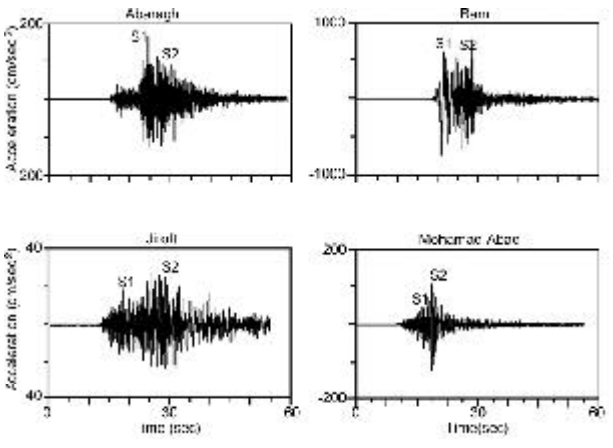


Figure 35. The SH- wave accelerogram records from the four stations of strong motion array.

field strong motion data and an attempt can be made to study their properties. For this purpose, we rotate the observed horizontal component accelerograms appropriately and derive the transverse component accelerograms. These approximately represent the *SH*-wave accelerograms. We next identify the strong phases on these derived accelerograms as signatures of the sub-events. Our assumption here is that a particular phase recorded at a station represents the radiation from the related asperity on the fault. We next consider each strong phase, available from those particular accelerograph stations that recorded it distinctly and the corresponding *SH*-wave spectral amplitude data, in an ensemble. We compensate for geometric divergence, anelastic attenuation, and free surface effect in this data. Then we conduct a non-linear least square inversion on the spectral amplitude in the high fidelity band of the observed spectrum to obtain an average estimate of the strike, dip and rake of the corresponding rupture. In the case of Bam earthquake two strong phases can be seen in recorded strong ground motions, see Figure (35).

In the absence of a common time code, it was not feasible to locate independently the hypocenters of the two sub-events on the basis of the accelerogram data. However, a master event technique was employed to estimate the hypocentral location of the sub-event from where the *S*1 phase of energy was possibly radiated. Generally, a value of two-thirds is usually assumed for the ratio between vertical and horizontal peak accelerations. It has been observed however in recent earthquakes that in near-field there is often a potential for significant vertical component of ground shaking. The Bam station recorded vertical peak acceleration of 992cm/sec^2, which is larger than for two horizontal components. It seems at Bam station a strong up-down motion has occurred. This strong up-down motion was also reported by the observers.

At the time of an earthquake, the damage is maximum in the epicentral region, where the ground experiences intense shaking. Therefore, it is assumed here that the chosen master event viz. the sub-event corresponding to the release of the *S*2 phase was located near 58.35° and 29.09° at depth of 8km (below the Bam strong motion station). Considering this as location of *S*2 phases, acceleration time histories from the four stations viz. Bam, Abaragh, Mohammadbad and Jiroft, see Table (3) have been used to estimate that the S1 phase of energy was released from 29.02°*N*, 58.30°*E*, at a depth of 8km depth, about 8 second before the release of the *S*2 phase of energy.

Table 3. The salient features of recording stations.

Station	Lat.	Long.	Elve.	L/T direction
Abaragh	29.34	57.94	1644	72/162
Bam	29.09	58.35	1094	278/8
Jiroft	28.67	57.74	275	240/330
Mohamad-Abad	28.90	57.89	1961	350/80

The acceleration spectra have been obtained for each of the *S*1 and *S*2 phases using relevant time windows on the appropriately rotated transverse component accelerograms. These spectra were obtained using Fast Fourier Transform (*FFT*) along with a Hamming-Turkey window so as to reduce the effect of data truncation. We performed several variations on the window sizes and placement to confirm the stability of these spectra in terms of their general structure and frequency content. The spectra for *S*1 and *S*2 are shown in Figures (36) and (37), respectively.

The fault plane solution corresponding to the *S*1 sub-event, see Figure (38) estimated using spectra at 4 stations is as follows: strike=174°*N*, dip=85°, rake=

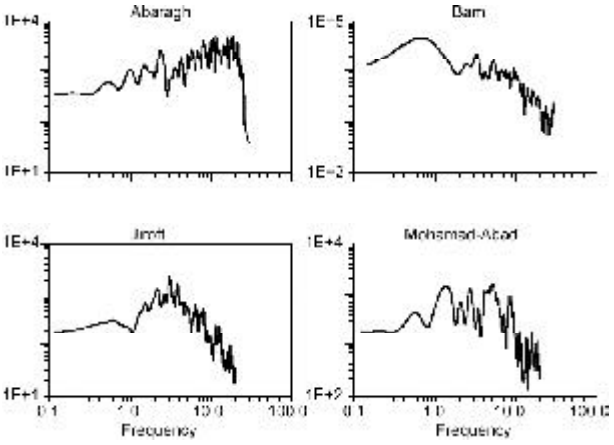


Figure 36. The observed acceleration spectra for S1 sub-event.

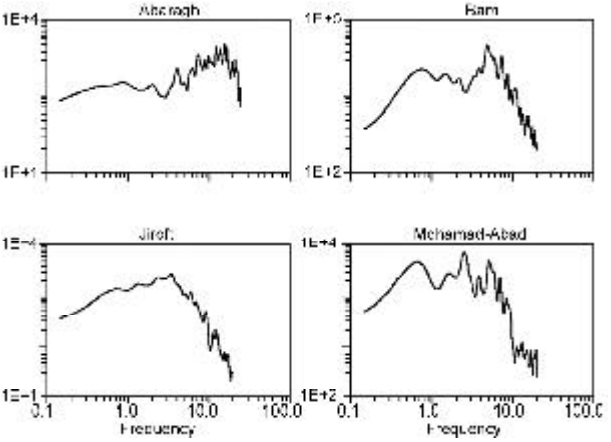


Figure 37. The observed acceleration spectra for S2 sub-event.

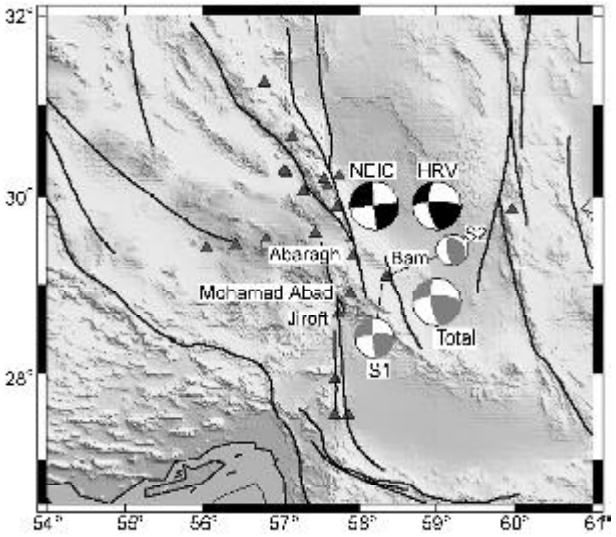


Figure 38. Fault plane solution of two sub-events, total solution from analysis of SH-wave and fault plane solution reported by NEIC and HRV.

170°. The standard error of estimate is 0.50. As mentioned earlier, this event was surmised to have occurred at 29.02°*N*, 58.30°*E*, 8*km*.

For the causative fault of the *S*2 sub-event, see Figure (38), spectral data from four stations have been used to estimate the following parameters: strike= 172°*N*, dip=65°, rake=110°. The standard error of estimate is 0.18. We have earlier estimated that the epicenter of this event is located at 29.09°*N*, 58.34°*E km* and occurred about 8 seconds after the event *S*1.

The total fault plane parameters, see Figure (38) by considering the SH-wave spectra which includes both *S*1 and *S*2 are as follow: strike=172°, dip=72°, rake=156°. The standard error of estimate is 0.32.

6. Simulation Method

Ground motion records from the epicentral region can be of great help in understanding the earthquake process as effects of transmission path are minimal and rupture on the causative fault can be modeled. The strong motion simulation procedures play an important role in complementing traditional approaches to the estimation of strong ground motions. They provide a means of augmenting to the relatively sparse set of strong motion recording close to large earthquake, giving more confidence in the estimation of ground motion characteristics. Simulation procedures also provide a means of estimating the dependence of strong ground motions on variations in specific fault parameters. Simulation procedures provide a means of including specific information about the earthquake source, the wave propagation path between the source and the site and local site response in estimation of ground motion [19].

The strong ground motions have been simulated by considering the fault plane parameters reported by *NEIC*, *HRV* and estimated parameters from *SH*-wave analysis. Strong ground motion has been simulated using a hybrid method, which combine stochastic and Empirical Green's Function (*EGM*) methods. For this purpose small event has been simulated using a stochastic method based on seismological model. This method has been applied to simulate small event because the source size of the small event is small enough to neglect the rupture propagation effect. The Fourier amplitude spectrum of small event, $AS(f,r)$, used in a seismological model [20, 21, 22, 23, 24] can be expressed as a product of a source factor, $S(f)$, a geometrical attenuation factor, $D_{geo}(r)$, a whole path attenuation factor, $D_{An}(f,r)$, upper crust attenuation factor, $P(f)$, and site effects factor, $Z(f)$ as follow:

$$AS(f,r) = S(f).\ D_{geo}(r).\ D_{An}(f,r).P(f).Z(f) \qquad (6)$$

The Fourier amplitude spectrum derived from seismological model defines the frequency content of the earthquake ground motion. Then, the synthetic small event is generated using procedure given by Boore [21] and Safak [25]. Finally strong ground motion from the target earthquake are simulated by applying the *EGF* method of Irikura [26] at selected observation points. The simulated ground motion then is compared with observed ground motion based on the basis of peak ground acceleration, duration and root mean square error (rmse) between observed and simulated response spectra for 5% damping.

A design engineer is always interested in knowing about the maximum force that the structure will experience in the event of an earthquake. For this purpose, the concept of response spectrum is important. In the case of Fourier transform, given a Fourier spectrum, Inverse Fourier Transform (*IFT*) can be performed to determine the accelerogram, which gave rise to that Fourier transform. Although there is a unique response spectra for each time history, the reverse is not true. This implies that inverse mapping of accelerogram from response spectrum is not possible as more than one time histories can be compatible with a response spectrum. In the present study root mean square error is computed using Eq. (7) as measure of goodness for comparison between simulated records from three different models.

$$rmse = \left[\frac{1}{N}\sum_{i=1}^{N}\{(R_{obs} - R_{sim})/R_{obs}\}^2\right]^{1/2} \qquad (7)$$

where R_{obs} and R_{sim} are the observed and simulated response spectra, respectively. For an objective choice from amongst the many models, the following two criteria are used for choosing the preferred model;

1. The model that gives a maximum number of extracted features (*P.G.A* and duration) that have a less than 10% difference between observed and simulated records i.e., the match for each variable is at least 90%.
2. The model that gives maximum number of stations for which *rmse* is minimum between observed and simulated response spectra.

6.1. Simulation Results

Using modeling parameters of rupture plane, see Table (4) and hybrid simulation method strong ground motion have been simulated at four stations. Strong ground motion at four station have been simulated for three models. First model (M_1) is according to *NEIC* solution. Strike, dip and rake for this model are considered as 174°, 88° and 178°, respectively. The second model (M_2) is based on *HRV* solution. The strike, dip and rake are 173°,63°, and 164°, respectively. The strike dip and rake for the third model (M_3) are considered based on analysis of *SH*-wave as 172°, 72° and 156°. The other modeling parameters, see Table (4) are kept constant for these three models. The simulated and observed records at Bam, Abaragh, Mohamadabad and Jiroft stations for these three models are shown in Figures (39) to (41). The

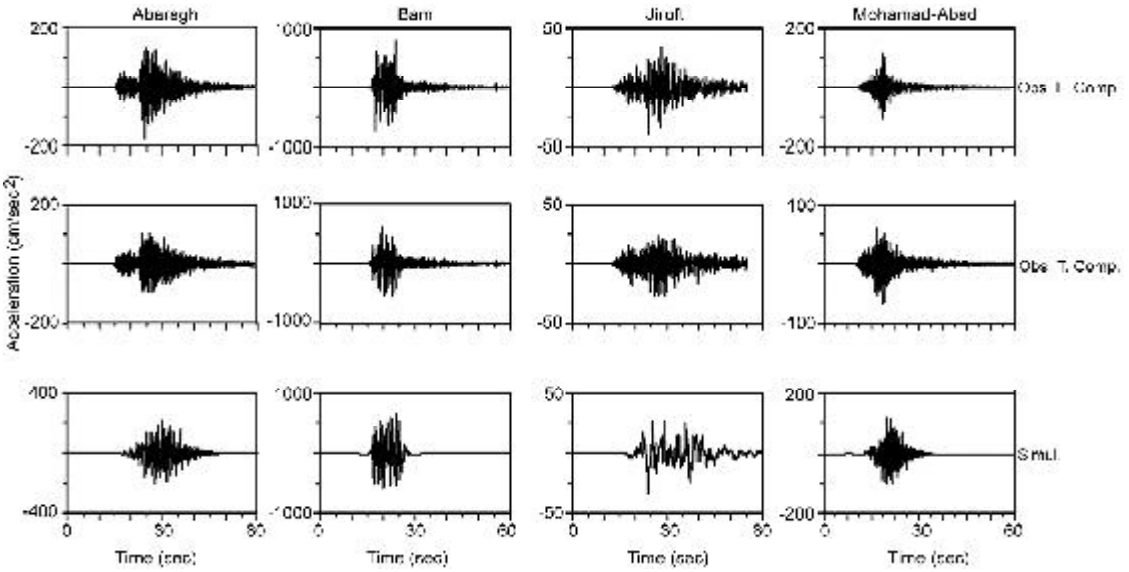


Figure 39. The observed horizontal acceleration and simulated records for model M1 based on NEIC solution.

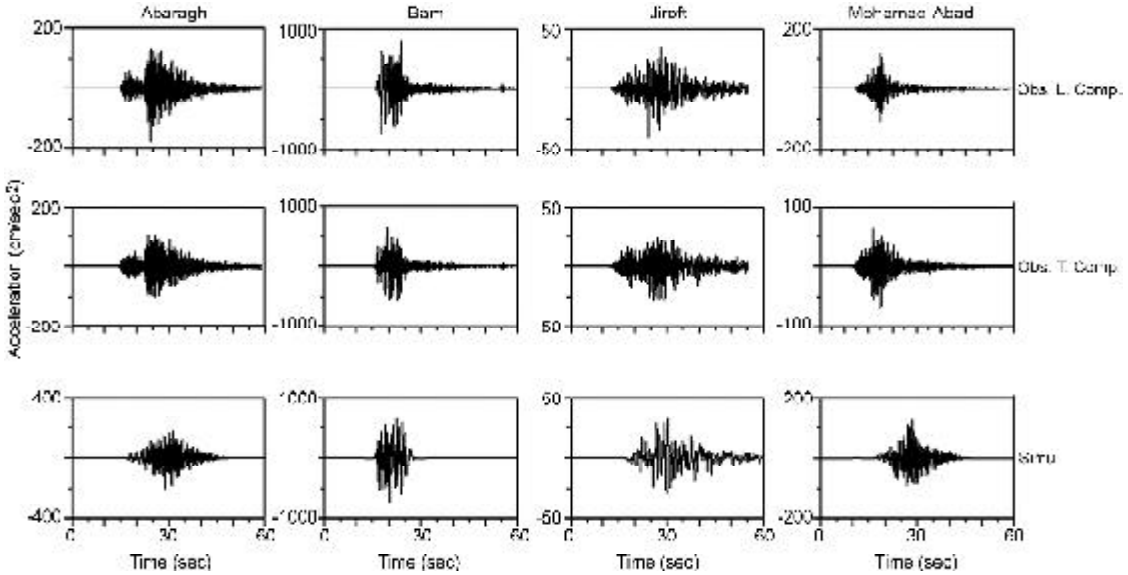


Figure 40. The observed horizontal acceleration and simulated records for model M2 based on HRV solution.

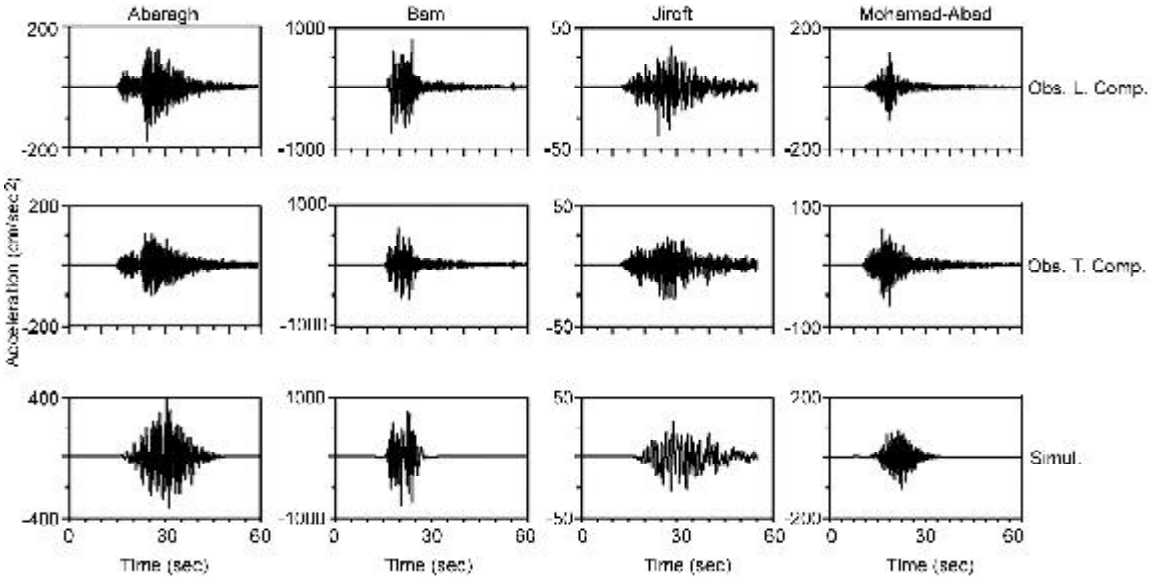


Figure 41. The observed horizontal acceleration and simulated records for model M3 based on analysis of SH-wave strong ground motion.

estimated peak ground acceleration and duration using Trifunac and Brady (1975) [?] for observed and simulated records for these three models at four stations are tabulated in Tables (5) and (6). The root mean square error (rmse) for 1, 2 and 3 sec between observed and simulated response spectra for these for stations are calculated using equation 3 and given in Table (5) for three different models of M_1, M_2 and M_3.

Table 4. Modeling parameters of rupture plane.

Modelling Parameters	
Length (km)	18 km [29]
Weight (km)	10 km [29]
S-wave velocity	3.2 km/sec
Rupture velocity	2.6 km/sec
Element dimension Number of element	3.6×2 25
$Q = 194\ f^{0.77}$	[30]

Table 5. Observed and simulated peak ground acceleration for three models.

Station	Observed P.G.A (cm/sec^2)		Simulated P.G.A (cm/sec^2)		
	L	T	Model 1	Model 2	Model 3
Abaragh	162.6	107.7	217	204	194
Bam	775	623	663	747	804
Mohammad-Abad	120.1	71	118	124	104
Jiroft	39.6	27.3	34	32	29.4

Table 6. Observed and simulated duration for three models.

Station	Observed Duration (sec)		Simulated Duration (sec)		
	L	T	Model 1	Model 2	Mode. 3
Abaragh	15.3	19.2	14.0	14.6	14.6
Bam	8.0	9.7	8.0	8.3	8.3
Mohamad-Abad	13.5	22.4	13.0	12.9	12.9
Jiroft	23.2	25.9	20.6	21.5	21.5

7. Macroseismic Intensity and Isoseismal Maps

The north eastern parts of Bam were demolished more during the earthquake. The damage distribution map, see Figure (42), *SERTIT* European satellite image), shows higher damages in the northern Bam, where it could be related to bad construction material and older building concentrated in these parts of the city. The higher damages in eastern Bam, however, could be related also to the near-fault conditions.

The isoseismal map of the Bam earthquake is prepared based on a field reconnaissance study [27] performed in the area immediately after the event, see Figure (43). Based on this study, the macroseismic intensity of the earthquake is estimated to be *IO=IX* (in *EMS*98 scale), where the strong motions and damaging effects seems to be attenuated very fast specially in the fault-normal direction. The intensity levels are estimated to be *VIII* in Baravat, *VII* in New-Arg (Arg-e Jadid) and airport area. The intensity level was estimated to be around IV-V in Kerman and Mahan.

8. Discussion

The Bam earthquake causes greatest human disaster in 2003 with more than 30000 victims and the demolishing the city of Bam. The 22 strong motion records obtained in this event are studied and six records were selected based on their high signal to noise ratio. The vertical and fault-normal (horizontal)

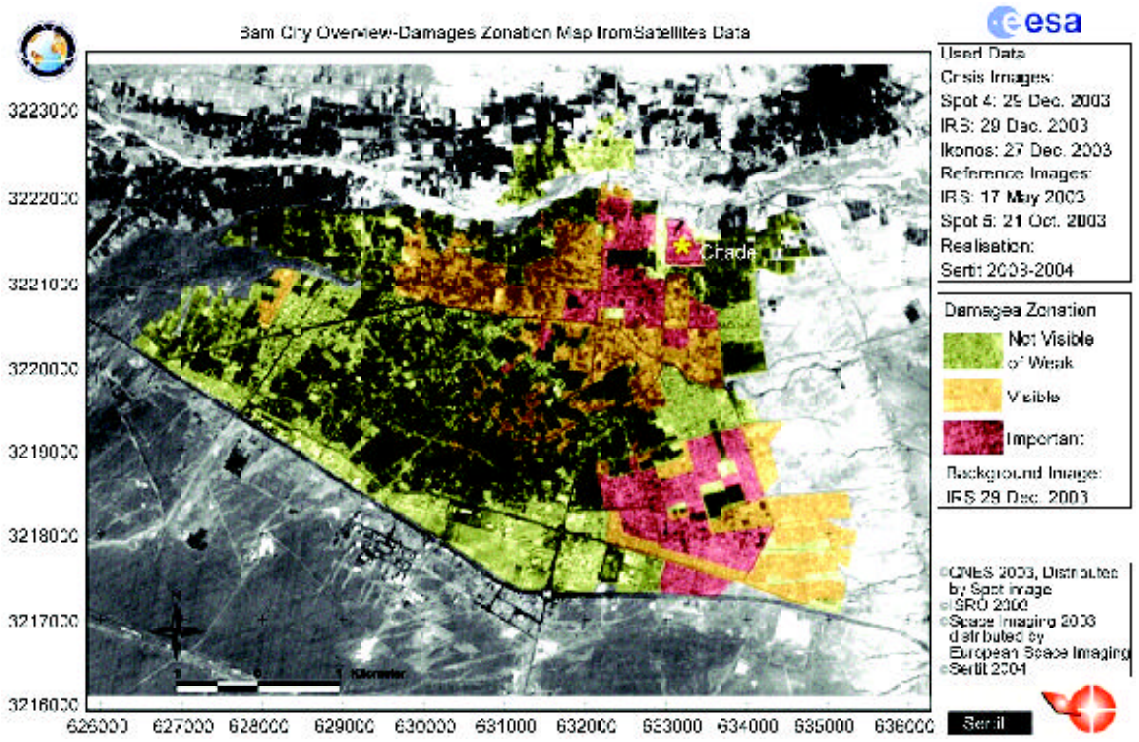


Figure 42. The damage zoning map estimated ESA using the SERTIT European satellite. The trace of the Bam fault scarp is shown by the author on the image. The red-shaded parts of the city are representative for the important damages where the brown and green parts are showing the moderate and lower damages.

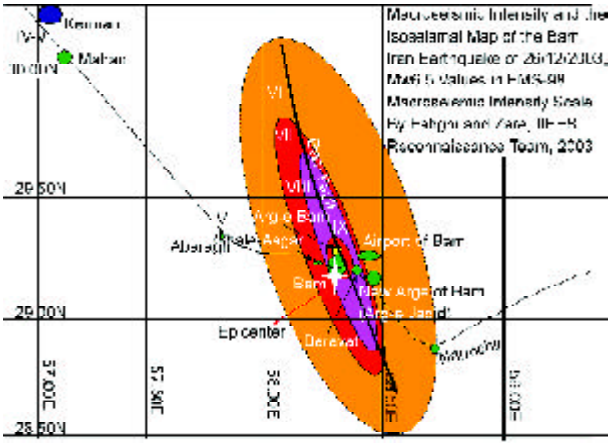


Figure 43. The isoseismal map prepared by the IIEES earthquake reconnaissance team [28]. The intensity values are given in EMS-98 scale.

directivity effects could be observed based on the greater damages along vertical and fault-normal horizontal directions, as well as the long period amplification in 5 to 10 seconds in the mainshock. Such effects are evident in the *H/V* ratios estimated for the Abaragh, Mohammadabad and Jiroft stations, see Figures (11), (12) and (13). These figures shows two major peaks for the *H/V* ratio at 0.1*Hz* and 0.6*Hz*. These two peaks could be related to the source directivity effects. The soil conditions in these stations probably did not lead to an amplification around 0.1*Hz*. The attenuation of strong motions in the fault normal direction was higher than in the fault-parallel direction and the attenuation rate was very high. The higher attenuation rate could be related to the high stress drop estimated for this event and low duration (about 10 seconds).

NEIC and *HRV* have analyzed far field broad band data to provide estimate of the strike, dip and rake for the 2003 Bam earthquake. *NEIC* suggest a strike, dip and rake of 174°, 88°, and 178°, while the *HRV* gives values of 173°, 63°, and 164°, respectively. It is noticed that the value of strike, dip and rake from these two studies are in fair agreement with the estimated strike, dip and rake from analysis of *SH* waves of recorded near field data, see Figure (38). Strong phases related to two sub-events have been identified on the strong ground motion data. It is observed that the causative fault for sub-event *S*1 has right-lateral strike slip mechanism, see Figure (38), while for *S*2 it is reverse mechanism with right-lateral strike-slip mechanism. The estimated location of sub-event *S*1 is at 58.30 and 29.02 at depth of 8*km* and it occurred 8 second before the sub-event *S*2. The sub-event *S*2 is located at 58.34 and 29.08 at depth of 8*km*. The high peak ground acceleration, which was observed at Bam station, can be explained by occurrence of the second sub-event with reverse mecha-

nism. The focal mechanisms of sub-events are determined on the basis of sparsely distributed accelerographs in relation to the overall size of the fault. Local strong ground motion records are generally known to be more sensitive to faulting of those sections of the fault closest to the station, while the more distant stations are unable to contribute suitable constraints for these sections of the fault. Meanwhile, the results obtained based on *SH*-wave analysis of strong ground motion for two sub-events are in fair agreements with the results obtained from waveform inversion of teleseismic data reported by Mostafazzde and Nalbant [28]. They also fond that the first sub-event had right-lateral strike-slip mechanism and second sub-event have reverse mechanism.

In the present study the rupture plane for Bam earthquake has been modeled using different parameters. Three models were considered based on *NEIC*, *HRV* and *SH*-wave analysis and acceleration time histories were simulated at four stations for which observation records were available. Comparison of simulated and observed records based on peak acceleration, duration and rms between observed and simulated response spectra indicate that model three is the preferred rupture model. This selection was done on the basis of two criteria:

(i) Maximum number of extracted features (peak ground acceleration and duration) showing less than 10% difference between observed and simulated observed for model *M*3 and

(ii) the preferred model gives maximum number of stations for which rmse is least between observed and simulated response spectra.

The peak ground acceleration and duration values for both observed and simulated records for the 2003 Bam earthquake are tabulated in Tables (5) and (6). Figure (44) shows distribution of these values with distance for model *M*3. In general, local topography, seismic source, propagation path and local site conditions will influence peak ground acceleration. It is observed that the values of peak ground acceleration at these stations are in fair agreement with observed values for model *M*3 compare to models *M*1 and *M*2. The distribution of simulated peak ground acceleration versus distance shows similar trends to observed peak ground acceleration.

The duration of simulated records are also in fair agreement with observed records. Again model 3 shows more match with observed compare to model *M*1 and model *M*2.

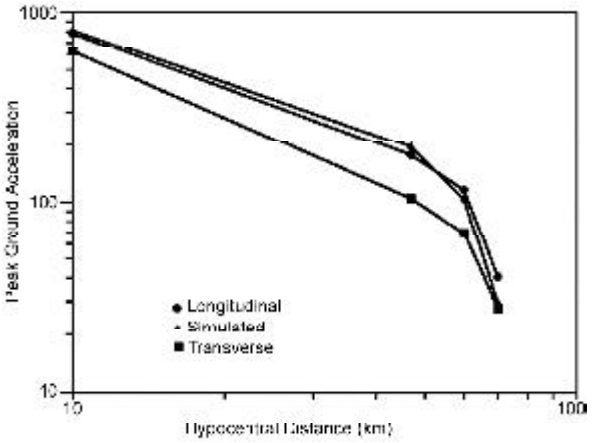


Figure 44. Comparison between observed peak horizontal acceleration and simulated peak acceleration for model M3.

On the other hand the comparisons of root mean square error (*rmse*) at these four stations for three model shows that rmse error between observed an simulated response spectra is less for model *M*3, see Table (7). Figure (45) shows response spectra for 5% damping for both horizontal components and simulated records for model *M*3. Comparison between observed and simulated records indicate that the rupture started at a depth of 8*km* and propagated from south toward Bam and north.

Table 7. Root mean square error between observed and simulated Response spectra for three models.

Model M1						
Station	Componet L			Componet T		
	1sec	2sec	3sec	1sec	2sec	3sec
Abaragh	3.70	4.30	4.20	5.50	6.50	6.50
Bam	0.60	0.62	0.63	0.91	0.92	0.92
Jiroft	0.33	0.39	0.49	1.09	1.01	1.03
Mohamad-Abad	0.59	0.56	1.28	0.58	0.74	2.2
Model M2						
Station	Componet L			Componet T		
Abaragh	2.19	0.50	2.46	3.25	3.49	3.91
Bam	0.82	0.84	0.84	0.84	0.82	0.82
Jiroft	0.48	0.46	0.45	1.52	1.45	1.53
Mohamad-Abad	0.62	0.98	1.03	0.63	1.37	1.57
Model M3						
Station	Componet L			Componet T		
Abaragh	1.90	1.80	1.70	2.90	2.70	2.60
Bam	0.30	0.40	0.41	0.70	0.68	0.65
Jiroft	0.29	0.29	0.39	0.38	0.41	0.62
Mohamad-Abad	0.62	0.61	0.59	0.96	0.88	0.88

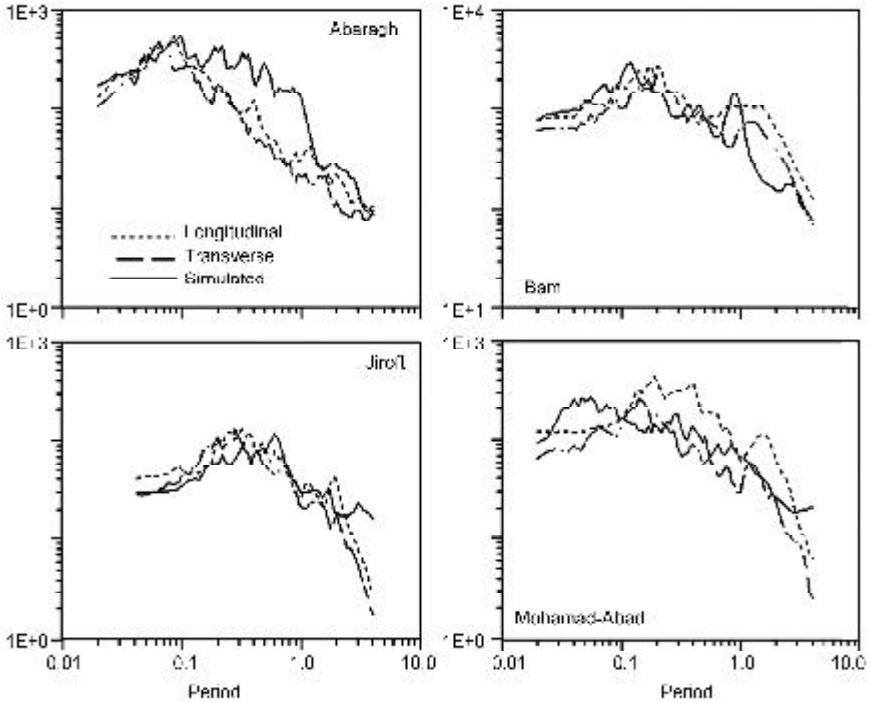


Figure 45. Comparison between observed and simulated response spectra for model M3.

9. Conclusion

The strong motions records and intensities observed in the Bam earthquake records are representative a very strong but short earthquake that had the large vertical and fault-normal near-fault effects. This earthquake had no visible surface fault displacement, but some surface fissures created during the earthquake are observed along the Bam fault scarp. The shallow depth (8*km*) and the location of the epicenter near the city of Bam, along with the old and weak buildings caused the high levels of life and property losses during this event.

The following conclusions have emerged from the analysis of strong ground motion data for Bam earthquake:

- Although the duration of the strong motions in Bam was short (7 to 10 seconds), the long period (about 10 seconds) large amplitudes of the motions caused by the directivity effects in the fault-normal and vertical directions could be imagined as a continuations to the damage caused by this earthquake.
- The attenuation of strong motion was rapid. The rate of attenuation was even faster in the fault-normal direction (relative to the fault parallel direction).
- The Bam earthquake was a complex earthquake. The *SH*-wave accelerograms exhibited distinct phases corresponding to the energy released from two separate asperities.
- Two strong phases of energy are seen on the accelerograms. The first is interpreted to represent a starting sub-event with right-lateral strike slip mechanism and located south of Bam. The asperity corresponding to the second release of energy is interpreted to be released 8*sec* after first sub-event. The mechanism of the second sub-event is reverse mechanism.
- The ground motion indicates that the rupture started at a depth of 8*km* south of Bam and then propagated toward north. The high vertical peak acceleration in Bam station was due to occur rence of the second sub-event, which was located very close to the recording station.

Acknowledgment

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References

1. Zaré, M. (2003). "Seismological Aspects of the Bam, SE Iran Earthquake of 26/12/2003, Mw 6.5", IIEES Web Site, http://www.iiees.ac.ir.

2. Ambraseys, N.N. and Melville, C.P. (1982). "A History of Persian Earthquakes", *Cambridge Earth Sci. Ser.*

3. National Earthquake Information Center (USGS), Web Site (2004). http:/neicr.usgs.gov.

4. United States Geological Survey, USGS, Digital Data Series DDS-62-C, 2001.

5. Harvard University, Seismology Department, Web Site (2004). http://www.seismology.harvard.edu, http://www.seismology.harvard.edu/

6. Haskell, N.A. (1964). "Total Energy and Energy Spectral Density of Elastic Wave Radiation from Propagating Faults", *Bull. Seism. Soc. of America*, **54**, 1811-1841.

7. Building and Housing Research Center (BHRC) (2004). http://www.bhrc.gov.ir/

8. Zaré, M., Bard,P-Y., Ghafory-Ashtiany, M. (1999). "Site Characterizations for the Iranian Strong Motion Network", Journal of Soil Dynamics and Earthquake Engineering, **18**(2), 101-121.

9. Arias, A. (1970). "A Measure of Earthquake Intensity", In Seismic Design of Nuclear Power Plants, R.J. Hansen Editor, M.I.T. press.

10. Housner, G.W. (1959). "Behavior of Structures During Earthquakes", *Journal of the Engineering Mechanics Division, ASCE*, **85**(EM14), 109-129.

11. Trifunac M.D. and Brady, A.G. (1975). "A Study on the Duration of the Strong Earthquake Ground Motions", *Bull. Seismol. Soc. of America*, **65**(3), 581-626.

12. Zaré, M. (1999). "Contribution à L'étude des Movements Forts en Iran: Du Catalogue Aux Lois D'atténuation", Université Joseph Fourier, Thése de Doctorat (Ph.D. Thesis), 237p.

13. Bard, P.-Y., Zare, M. and Ghafory-Ashtiany, M. (1998). "The Iranian Accelerometric Data Bank, A Revision and Data Correction", *Journal of Seismology and Earthquake Engineering*, **1**(1), 1-22.

14. Campos, J., Madariaga, R., Nabelek, J., Bukchin, B.G., Deschamps, A. (1994). "Faulting Process of the 1990 June 20 Iran Earthquake from Broad-Band Records", *Geophys. J. Int.*, **118**, 31-46.

15. Sarkar, I., Hamzehloo, H., and Khattri, K.N. (2003). Estimation of Causative Fault Parameters of the Rudbar Earthquake of June 20, 1990 from Near Field SH-Wave Data", *Tectonophysics*, **364**, 55-70.

16. Haskell, N.A. (1960). "Crustal Reflection of Plane SH Waves", *J. Geophys. Res.*, **65**, 4147-4150.

17. Aki, K. and Richards, P.G. (1980). "Quantitative Seismology", Theory and Methods, **1**, Freemn, San Francisco, 558p.

18. Lay, T. and Wallace, C. (1995). "Modern Global Seismology".

19. Somerville, P.G., Sen, M., and Cohee, B. (1991). "Simulation of Strong Ground Motion Recorded During the 1985 Michoacan, Mexico an Valparaiso, Chile Earthquakes", *Bull. Seismol. Soc. Am.*, **81**, 1-27.

20. Brune, J.N. (1970). "Tectonic Stree and Spectra of Seismic Shear Waves from Earthquakes", *J. Geophys. Res.*, **75**, 4997-5009.

21. Boore, D.M. (1983). "Stochastic Simulation of High-Frequency Ground Motions Based on Seismological Models of the Radiated Spectra, *Bull. Seismol. Soc. Am.*, **73**, 1865-1894.

22. Atkinson, G. and Boore, D.M. (1995). "Ground-Motion Relations for Eastern North America", *Bull. Seism. Soc. Am.*, **85**, 17-30.

23. Atkinson, G. and Boore, D.M. (1998). "Evaluation of Models for Earthquake Source in Eastern North America", *Bull. Seismol. Soc. Am.*, **88**, 917-934.

24. Atkinson, G., Silva, (1997). An Empirical Study of Earthquake Source Spectra for Californian Earthquakes, *Bull. Seismol. Soc. Am.*, **87**, 97-113.

25. Safak, E. (1988). "Analytical Approach to Calulation of Response Spectra from Seismological Models of Ground Motion", *Earthquake Engineering Struct. Dyn.*, **16**, 121-134.

26. Irikura, K. (1986). "Prediction of Strong Ground Acceleration Motions Using Empirical Green's Function", *Proc. 7th Japan Earthquake Engineering Symp.*, 151-157.

27. Eshghi, S., Zare, M., Naser-Asadi, K., Seyed-Razzaghi, M., Noorali-Ahari, M., and Motamedi, M. (2004). Reconnaissance Report on 26 Dec. 2003 Bam Earthquake, International Institute of

Earthquake Engineering and Seismology (IIEES), Report in Persian.

28. Mostafazadeh, M. and Nalbant, S. (2004). "Waveform Inversion of 26 December 2003, Bam Earthquake", *J. Seismol. Earthquake Engineering* (Submitted).

29. Wells, D.L. and Coppersmith, K.J. (1994). "New Empirical Relationships Among Magnitude, Rupture length, Rupture Width, Rupture Area, and Surface Displacement, *Bull. Seismol. Soc. Am.*, **84**, 974-1002.

30. Farahbod, M. and Alahyarkhani, M. (2003). "Attenuation and Propagation Characteristics of Seismic Waves in Iran", *Proc. 4th Int. Conf. Earthq. Engg.*, Tehran, I.R. Iran.

Geotechnical Instabilities Occurred During the Bam Earthquake of 26 December 2003

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ABSTRACT: *This paper describes the geotechnical instabilities such as landslide, liquefaction, and ground subsidence caused by the Bam earthquake. Based on the results of geotechnical investigations, after the Bam earthquake, land subsidence due to collapse of Qanats (underground irrigation tunnels), local toppling, and block slides along riverbanks or man-made channels were the most dominant geotechnical instabilities of the event. These effects will be introduced and discussed in this paper and the distribution of them will be presented based on the study of aerial photos and site investigations. In addition, the geological setting of the area based on field investigations and evaluation of some geophysical data will be discussed.*

Keywords: Bam; Geological settings; Qanats; Landslide; Liquefaction; Sinkhole

1. Introduction

Bam Earthquake, which occurred at 01:56:56 (*GMT*) on 26^{th} December 2003, destroyed the city of Bam, Baravat, and some small villages at the area (southeast of Iran) and caused around 26,500 deaths and thousands of disappeared and injured. The *Ms* of this destructive event was equal to 6.5 (*IIEES*) and focal depth evaluated to be about 8*km*. The corrected *PGA* values of this earthquake recorded at Bam station are equal to 992, 775 and 623cm/sec^2 for vertical, lateral and tangential components [3].

Besides the structural damages, Bam earthquake has been accompanied with some geotechnical instabilities such as landslide, land subsidence and ground fissures, however based on the surface evidences, no effects of liquefaction observed at the area that can be related to the level of ground water and type of the soil and its characteristics.

In the first part of this paper, a summary about the geological and topographical conditions of the Bam area will be presented and in the second part the instabilities and geotechnical aspects of this event will be discussed.

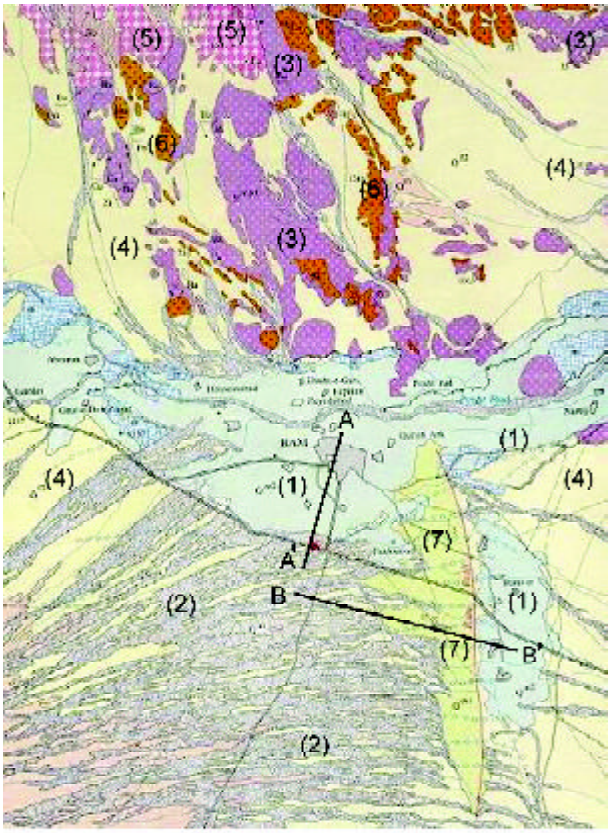
2. Geographical Situation

The city of Bam is located in the southeast of Iran at $175^{th}km$ of the main road of Kerman to Zahedan. The area of the city is about 5400 Hectares having a nearly flat topography and smooth morphology. The altitude of the city is approximately 1050 meters above sea level in average. The main topographical features of the city are the volcanic hills located at the north and south west of Bam.

Climatologically, the area is located at an arid region having dry weather. The total amount of annual rainfall is not considerable especially during the recent years. There is one seasonal river passing through the Bam city called Posht-e-Rood that is nearly dry most of the year but water from some Qanats flow in this river. Due to small amount of rainfall and surface water, the main resource to supply water for drinking and irrigation purposes is the underground water that are extracted mainly by using deep wells and Qanats. In the recent years, due to heavy use of deep wells, the ground water table is lower than 30 meters in most parts of Bam and its vicinity.

3. Geological Setting

Figure (1) shows a schematic view of the 1:100,000 geological map of the area prepared by Geological



1. Light Brown Gravel, Sand and Silt (Q^{m2})
2. Alluvium Fans and Young Terraces (Q^{a1})
3. Ash Flow Tuffs (E^{v3t})
4. Alluvial Fan Deposits (Q^{f2})
5. Dacite, Rhyolite and Andesite Lavas (E^{v2d})
6. Trachyandesitic and Basaltic Lavas (E^{v3a})
7. Yellow to Brown Siltstone and Sandstone (Q^{m1})

Figure 1. Geological setting at Bam and Baravat based on the 1:100,000 geological map.

Survey of Iran. Due to the scale problem, the borders are not exactly mapped and some differences can be observed between aerial photos and the prepared map.

In order to improve the existing data about the geological conditions, a complementary program of site investigation has been arranged in Bam and its vicinity by *IIEES*.

Based on the results of these investigations and the previous available data, five different lithologies have been characterized at the area including: recent and late Quaternary alluvium, Paleogene sedimentary rocks, Eocene volcanic rocks, and intrusive igneous rocks (Granodiorite).

Most parts of the city of Bam have been constructed on Quaternary alluvial. Arg-e-Bam located at the northwest of the city, is the only site where a rock outcrop can be observed. This outcrop is consisted of Andesite and Basalt without considerable effects of weathering. Of course at the vicinity of the fault these layers have been eroded and weathered considerably, see Figure (2).

The alluvial sediments in most parts of Bam and Baravat are related to the Quaternary including the following types: yellow to brown sand and silt (Q^{m1}), brown gravel, sand and silt deposited due to seasonal flooding (Q^{m2}), coarse grain gravel of alluvial fans (Q^{f2}) and coarse grain deposits of the rivers. These types of deposits covered nearly most parts of Bam and Baravat.

Figure 2. Erosion and weathering in Andesite and Basalt at the vicinity of Bam fault.

The deposit (Q^{m1}) can be observed along the Bam fault having about 5 degrees dip toward east. The density of this layer is lower than the other deposits, although it is older. Deep erosions on this layer can be observed frequently at the site. Figures (3) and (4) depict some features of these layers at different parts of Bam and Baravat.

As it is shown in Figure (1), most parts of Bam and Baravat are covered with Q^{m2} deposits including gravel, sand and silt. There are some thin layers of fine grain sediments as lenses inside these deposits. The

Figure 3. Deposits of (Q^{m1}), West of Baravat.

Figure 4. Deep erosion at (Q^{m1}), South of Bam.

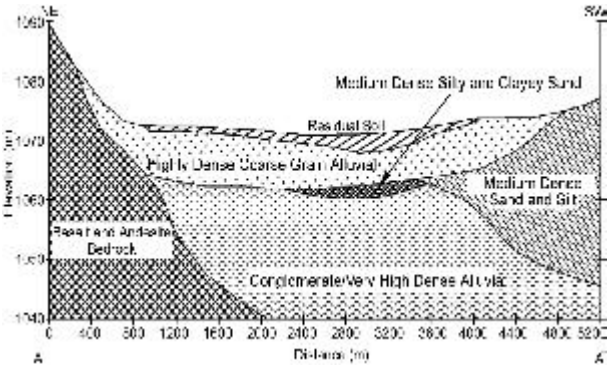


Figure 5. Geological profile of section A -A' shown at Figure (1).

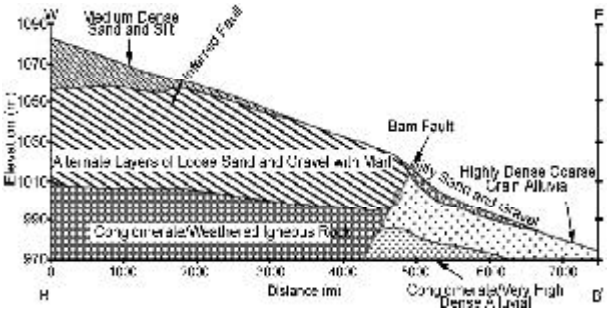


Figure 6. Geological profile of section B -B' shown at Figure (1).

thickness of these dense layers is from a few meters to more than 50 meters, depending on their location. A weak cementation caused by infiltration of surface water, can be observed in some parts of these deposits. Shear wave velocity at this layer is about 600*m/s* at depth of 5 meters, based on geophysical measurements carried out by *IIEES*.

The alluvial fan (Q^{f2}) is another quaternary deposits extended at the eastern part of Bam. It is formed by coarse grain sediments having thickness up to 100 meters.

Finally, the youngest layers of alluvium at Bam area are alluvium fans and terraces (Q^{a1}) extended along the seasonal river. These sediments are quite loose without cohesion and cementation.

In order to have better understanding about deep geological setting, several geophysical explorations have been carried out at the area by geophysical group of *IIEES*. Figures (5) and (6) present two schematic geological sections prepared based on the collected data during site investigation and geophysical explorations. As it can be observed there is a complex geological condition at the area that could affect the site response to earthquake. This subject is now under further study and its results will be presented later on.

4. Ground Subsidence Due to Qanat Collapse

4.1. A Summary About Qanats

Qanats are one of the traditional irrigation systems developed in Iran thousands years ago and it is still one of the best economical methods to transport water in the arid and semiarid regions. A Qanat is a horizontal underground gallery including several shafts that conveys water from an aquifer in pre-mountainous alluvial fans to lower-elevation irrigated fields, see Figure (7).

The first shaft is usually sunk into an alluvial fan to a level below the ground water table. Other shafts normally excavate at intervals about 20-30 meters to supply air for the diggers and also to take out the excavated soil. The soil is dumped around the opening of the shaft to form a small mound to keep surface runoff from entering the shaft bringing silt and other contamination with it.

The Qanat gallery has a gently slope and water can

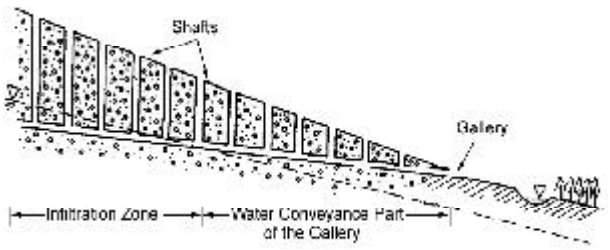


Figure 7. Schematic views of different parts of a Qanat [7].

flow into the gallery only by gravity force. As water passes most of its route underground, the seepage and evaporation of water will be much less than the open channels.

The diameter of vertical shafts and the galleries normally are between 80-150*cm*. If the soil is firm, no lining is required for the tunnels and shafts but in loose soil, reinforcing rings are installed at intervals in the tunnel to prevent cave-ins. These rings are usually made of burnt clay. Figure (8) shows the method of excavation of a Qanat.

4.2. Qanats in Bam

Qanats are one of the main sources of drinking and irrigation water in Bam. Before the earthquake, about 50% of the required water of the area have been supplied by 67 Qanats among the Bam city and 370 Qanats in the Bam region [6]. Most of these Qanats can be observed at the aerial photos, see Figures (9) to (11). In addition there are some galleries and shafts related to the very old Qanats that their locations are unknown. Of course these old Qanats are now dry and partially collapsed, but there are still some cavities remained at their galleries and shafts that could make the risk of collapse and inducing small sinkholes.

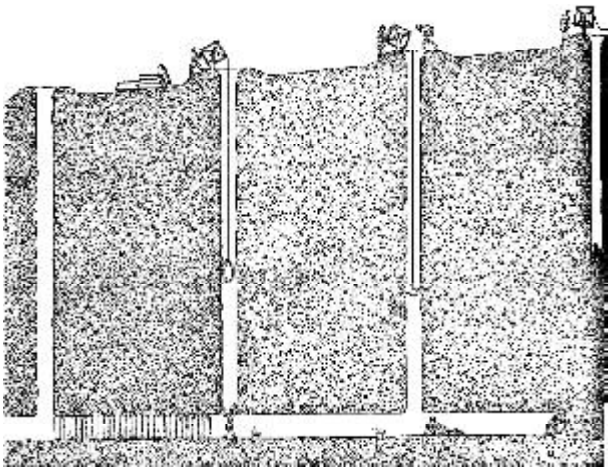


Figure 8. Excavation of a Qanat using reinforcing rings [7].

The depth of Qanat's galleries and shafts in Bam city and its vicinity is different and varies from 3-40 meters depending on length and location of irrigation. Some of these Qanats have been supported by hand made rings called “Kaval” especially those which pass through the soft and collapsible layers, see Figure (12).

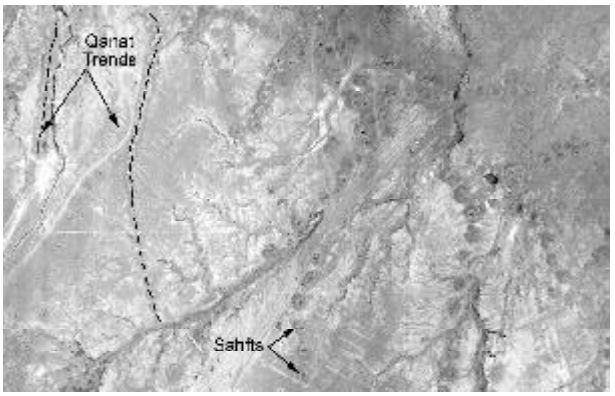


Figure 9. The Location of some Qanats on aerial photo (West of Baravat).

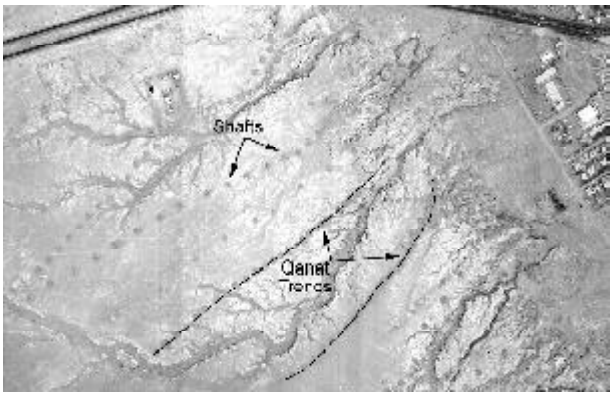


Figure 10. The location of some Qanats on aerial photo (South of Bam).

Figure 11. A Qanat trend near Bam city (The photo has been taken during pilot study by helicopter).

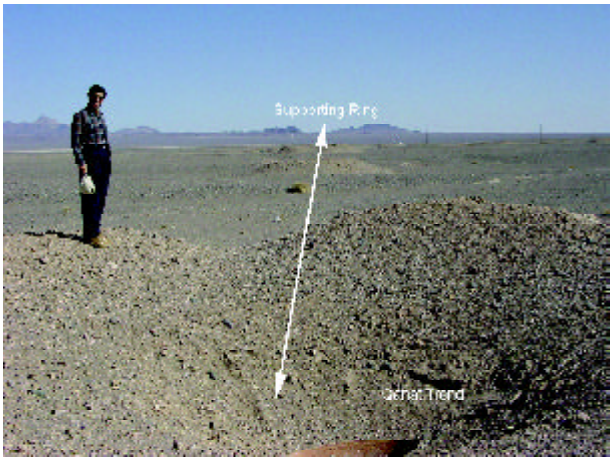


Figure 12. A Qanat trend at the 8th*km* Bam to Kerman road supported by burnt clay rings.

4.3. The Behavior of Qanats During Strong Earthquakes

Although underground openings and tunnels assumed to be more stable against earthquake and seismic waves in comparison with the above ground constructions, there are several evidences of damaging to Qanats or collapse of shafts and galleries during the historical or recent earthquakes occurred in Iran.

In some cases due to partial or complete collapse of the Qanats galleries or shaft, as result of an earthquake, water can not flow any more along the Qanat and this makes a Qanat to be dried. Another main effect of earthquake on Qanats is land subsidence in form of sinkholes that can be observed on the ground surface in different sizes. These features may cause secondary damages on building or lifelines as will be discussed in the next parts. A summary about the damages to Qanats due to historical and recent earthquakes of Iran is presented in Table (1). Most of the strong earthquakes of Iran occurred at arid or semi-arid regions caused damage to the existing Qanats. These damages are more severe when Qanat is close to the epicenter of the event.

4.4. The Behavior of Qanats during Bam Earthquake

Bam Earthquake affected the existing Qanats at the area of Bam city and its vicinity considerably. Based on the preliminary evaluations, about 40 percent of the Qanats at Bam and its vicinity collapsed or have been severely damaged due to the earthquake. In some cases the collapse of the Qanats blocked the water flow inside their galleries completely. As the water of Qanats is the main supply of the irrigation water for palm and citrus gardens at the area, these damages may cause considerable secondary economic losses. At the moment several workers and diggers are working on the Qanats to repair them and open the galleries to provide necessary water for irrigation purposes.

Table 1. The Qanat's behavior during historical and recent earthquakes in Iran [1].

Date	Location	Damage to Qanat
856	Ghomes	Blockage of Water Flow
1780	Tabriz	Blockage of Water Flow
1853	Shiraz	Collapse
1893	Ghochan	Collapse and Long Ground Fissures (5-8m)
1895	Ghochan	Collapse in 5km of Qanat Length
1923	Laleh Zar	Collapse
1929	Kopeh Dagh	Collapse
1930	Ab-Mobarak Abad	Collapse
1933	North Behabad	Crack Along an Old Qanat
1947	Dasht Abad	Collapse and Blockage of Water Flow
1948	Gavak	Blockage of Water Flow
1968	Dashte Bayaz	Collapse
1968	Ferdows	Collapse
1972	Ghir-Kazerun	Collapse of 5km Qanat Tunnel and 180 Access Wells
1979	Karizan-Khavaf	Collapse

Site investigations carried out during the first days after the earthquake showed different levels of damages to Qanats. In addition, at some locations the collapse of the Qanats caused some secondary damages on the buildings and lifelines of the area and increased the losses. These features will be discussed in the following sections.

4.4.1. Land Subsidence Above the Qanats

Based on the site visits and evaluations of aerial photos taken after the Bam Earthquake, the most important effects of the event on Qanat systems are damages to their shafts and tunnels. Several sinkholes induced as a result of the earthquake along the Qanat's galleries due to the collapse of overburden layers. Most of the observed damage were related to the collapse of shallow Qanats, but some sinkholes induced on deep Qanats too. Although most of the Qanats at the area have been supported by hand made rings, these systems could not improve considerably the stability of Qanats against applied dynamic loads due to earthquake. In some locations because of existing close galleries, very large sinkholes induced at the ground surface, due to their collapses.

Near the Bam Fault the damages were more severe and several small and large sinkholes could be observed at the vicinity of the Fault. Far from the fault the effects of earthquake on Qanats are less considerable and only some fissures and cracks can be observed along the galleries and shafts that can be related to the small settlement or partial collapse of some parts of the Qanats. Figures (13) to (18) depict some sinkholes induced by Bam earthquake.

4.4.2. The Effects of Earthquake Induced Sinkholes on Structures and Lifelines

The sinkholes induced during Bam Earthquake caused some damage on the structures and lifelines. These damages were more severe at Baravat and south parts of Bam. At these parts several buildings and main and bypass roads constructed on the old Qanats, have been damaged considerably. Due to the dynamic loadings of the event the stability of these underground openings decreased and collapse occurred in many places. These collapses then made some minor to severe damages to roads and buildings in the area.

Figure (19) shows damage to one of the access

Figure 13. Sinkhole induced due to the collapse of a Qanat gallery; west of Baravat

Figure 14. Sinkhole induced due to collapse of a Qanat gallery; west of Baravat

Figure 15. Large sinkholes at northeast of Bam; (The photo has been taken during pilot study by helicopter).

Figure 16. Large sinkhole; south of Bam.

Figure 17. Large sinkhole observed at west of Baravat.

Figure 18. Collapse of shafts and tension crack along the galleries of old Qanats, west of Baravat.

Figure 19. Sinkhole induced due to collapse of an old Qanat on one of the bypasses at Baravat.

roads to Baravat due to collapse of an old Qanat. Such sinkholes could be observed in this area under the main and bypass roads, and made some difficulties for rescue and relief teams to reach the area after the earthquake. The main road from Kerman to Zahedan passing south of Bam was also damaged severely because of a sinkhole. At the time of the visit, this sinkhole has been filled but the same sinkholes around the road remained without changes, and one sample is shown in Figure (20). Based on the reports, the sinkhole induced under the main road caused a heavy traffic in this part after the event. Considering the importance of first hours after an earthquake for rescue, it is obvious how such sinkholes can affect these activities.

Besides of the effects of sinkholes on roads, there are some damages to the buildings and constructions due to collapse of Qanats specially at Baravat. Figure (21) shows the damage to a building at Baravat due to

Figure 20. Sinkhole observed close to the main road of Bam to Zahedan near Baravat: same sinkholes induced under the road at the time of earthquake that affected the access of rescue and relief teams to the region.

Figure 21. Damage to a building due to collapse of an old hidden Qanat (Baravat).

collapse of an old Qanat during the earthquake. As it can be observed, this sinkhole caused severe damage to this house.

Figure (22) presents damage to a religious arc due to collapse of a hidden Qanat under its column. Along the trend of this hidden Qanat, several sinkholes were observed at the area.

4.5. Distribution of Collapsed Qanats at the Bam Area

In order to get a better idea about the distribution of collapsed Qanats at Bam and Baravat, a *GIS* based map has been prepared based on the data collected during the site investigation and study of aerial photos. Figures (23) and (24) show these maps. As shown in Figure (24), the area of concentration of damage to Qanats is around the Bam fault, in which

Figure 22. Damages to road and a religious arc due to the collapse of a hidden Qanat (Baravat). Photo has been Taken by Dr. M. Zare one day after the event.

several sinkholes can be observed along the existing Qanat trends. This fact may help seismologist to get a better idea about the source of Bam Earthquake, as a sharp surface rupture has not been reported at the area after the earthquake. It should be also considered that the concentration of Qanat in this area is higher than the other parts.

5. Landslides Triggered by Bam Earthquake

The Bam Earthquake induced more than 3000 block falls and landslides over an area $61 km^2$, in which most of them were concentrated in $18 km^2$, especially at the east of Bam and west of Baravat. These block falls and landslides have been documented before based on the site investigation and study of aerial photos [2]. In order to prepare the base map of the landslides triggered by the earthquake, these points were digitized and some computer-generated maps have been prepared and evaluated.

In this section, the distribution of block falls and landslides in the area will be presented and a brief description about the prepared landslide map and factors affecting the landslides distribution will be discussed.

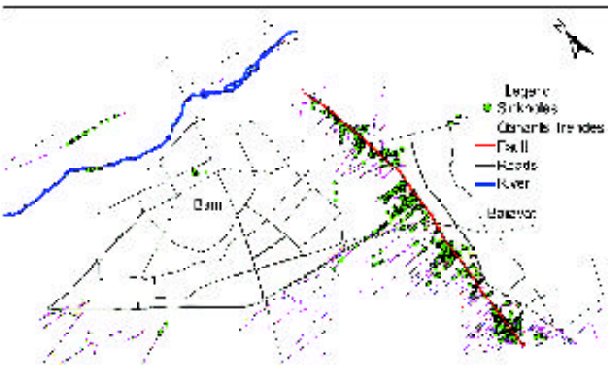


Figure 24. Distribution of sinkholes and trends of Qanats in Bam and Baravat.

5.1. Landslides Map of Bam Area

Field investigations to document earthquake-triggered landslides were initiated 4 days after the earthquake. In that study, based on the distance to the epicenter, concentrations of landslides (included small rock and

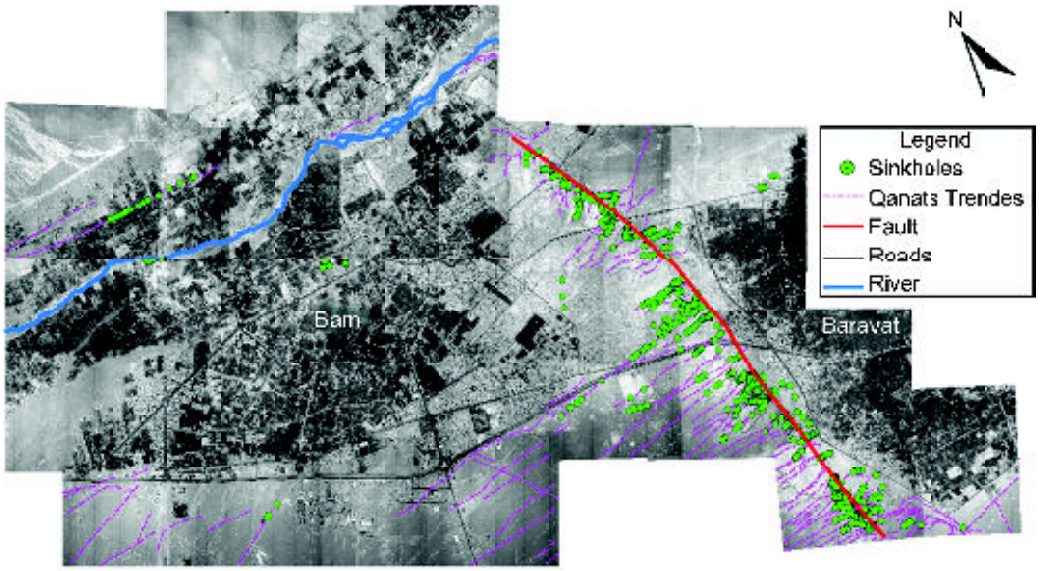


Figure 23. Photo mosaic used to locate the distribution of Qanat in Bam and Baravat.

soil block falls to very large blocks at the river banks and man made channels) have been investigated. In addition high-resolution aerial photos (nominal scale 1:10000) of Bam and Baravet that were taken two days after the event by the National Cartographic Center of Iran were evaluated and used to map new and fresh landslides at the area. These maps has been printed in 1:2000-scale and due to their high qualities and the time of photography were quite useful to locate geological instabilities as well as damage to the buildings. Figure (25) shows one of these photos in which the location of some blocks and landslides have been marked.

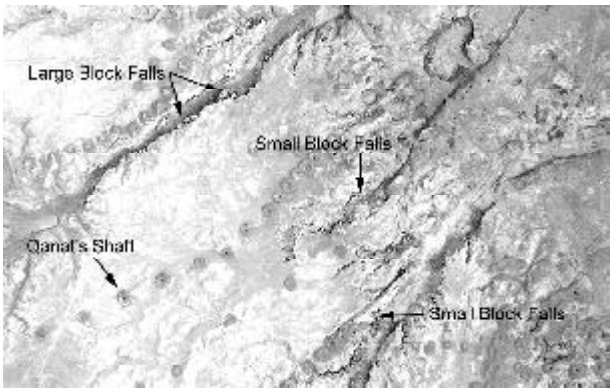


Figure 25. Some small and large block falls and landslides shown at one of the aerial photos; West of Baravat.

Based on these evaluations, more than 2370 individual blocks and landslide have been located on 1:50000 scale map, adopted as the base map, and by using Geographic Information System (*GIS*) all collected data have been entered to its database. Depending on size and distribution of blocks and landslides different methods have been used. The final map contains all data related to the block falls and landslides triggered by earthquake at Bam and Baravat.

5.2. Distribution and Types of Landslides

The most concentrated zones of block falls and landslides are around the Bam fault, see Figure (26). As mentioned before the main geological formation in this area is alluvial sediment having weak cementation (Q^{m1}). This part has been folded and uplifted due to the tectonic deformations resulting by Bam fault activities. These young and weak materials do not have significant tensile strength and so can be weathered and eroded easily. This procedure can make steep-walled narrow valleys. The combination of low strength materials and steep relief makes these slopes

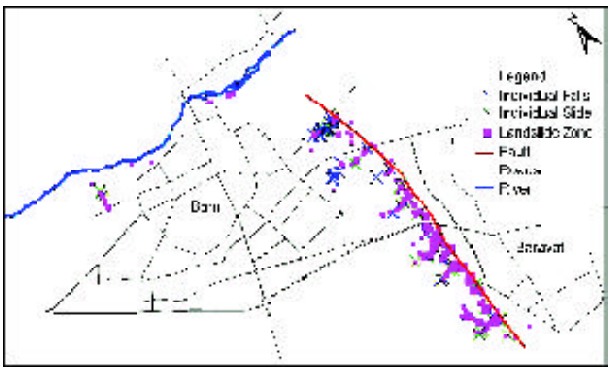


Figure 26. Areas of concentration of landslide triggered by the Bam earthquake

quite susceptible to sliding during shaking.

Along the riverbanks of Posht-e-Rood River in the north of Bam, landslides are more scattered due to the relative long distance from causative fault and the strength of existing layers, that is a bit higher at this place as described before. Few landslides can be observed in the northern and southern mountains, which consist of more competent rocks.

The most common types of landslides triggered by Bam Earthquake can be categorized as: highly disrupted shallow falls, soil block slides and rock block toppling.

- ***Shallow, Disrupted Landslides***

The hills located at the west of Baravat and in the east of Bam are extremely susceptible to failure during seismic shaking. In this area, more than 75 percent of the slopes were affected by the earthquake and several shallow disrupted landslides induced as a result. The main characteristics of landslides at this area are their small sizes, shallow deeps and their dry, highly disaggregated material accumulated at down slopes in a flatter area. The volumes of these slides vary from a fraction of a cubic meter to hundreds of cubic meters, see Figure (27).

At the northwest of the earthquake epicenter, fewer and more scattered rock falls can be observed specially at the Posht-e-Rood Riverbanks, which consist of recent quaternary deposits. However there is an exceptional site along the Posht-e-Rood River bank called Rahmani village where many landslides have been induced by the earthquake.

- ***Deep, Coherent Landslides***

Few deep, coherent landslides have been induced by the earthquake. These slides having volumes of several hundreds to thousands of cubic meters can be

Figure 27. Soil block falls triggered by Bam earthquake at west of Baravat. (The photo has been taken during pilot study by helicopter).

observed mostly in more competent sedimentary units at Bam and Baravat. In addition several deep landslides were triggered at the north of Rahmani village, see Figures (28) and (29).

5.3. Effects of Earthquake-Triggered Landslides on Building and Lifelines

Landslides induced during the Bam earthquakes did not have any considerable direct effects on the life and properties of inhabitants at the area, as no important lifelines or structures were constructed at the landslide prone zones. Of coarse it would be necessary to remove the soil blocks to clear the riverbed for the next seasonal flooding.

The only damage observed due to the landslide was related to the collapse of a house located at the top of an excavation at Esfikan; north of Bam, see Figure (30).

6. Liquefaction

The liquefaction potential of Bam area has been evaluated using geological data, ground water level and soil conditions based on the geological information and field investigation. Although the soil condition in most parts of Bam city and its vicinity shows high percentages of fine grain sediments such as fine sand and silt, but due to low level of ground water, the risk of liquefaction is not considerable in most parts of the city.

In some locations there was some saturated zone

Figure 28. Deep tensional crack and soil blocks fall induced during the earthquake, North of Rahamani village.

Figure 29. Soil blocks falls and slide due to earthquake, west of Baravat.

Figure 30. Damages to a building located at top of an excavation due to landslide, Esfikan village, Northeast of Bam.

due to existence of small ponds, see Figure (31), or flow of Qanat's water through the channels, but no evidences of liquefaction have been observed in these sites, and this can be due to the small thickness of sand layers and its compaction.

Figure 31. Small pond at Esfikan, Northeast of Bam.

7. Conclusion

Based on the observations and evaluations carried out after the Bam earthquake, Qanats instabilities are the most important geotechnical instabilities occurred at the area. In addition several blocks and landslides have been triggered by the event. Both of these effects were more severe at the vicinity of Bam fault. Far from the fault (except in Rahmani Village), the instability of Qanats and slopes are rarely reported. In addition there were no evidences of liquefaction at the area due to the depth of ground water table and the type and compaction of the existing soil layers.

Acknowledgment

The authors would like to acknowledge Dr. Jafari and Dr. Tabasi for their scientific guidance during preparation of this paper and Dr. Shafiee and Mr. Azadi for providing geophysical data used for preparation of geological sections. In addition we would like to appreciate Mr. Ravanfar and Mr. Pass for their assistance during site visits and *GIS* group of *IIEES* (including Mrs. Rakhshandeh, Miss. Kamalpoor, Mrs. Banki and Miss. Mohammadi) for their efforts to prepare the *GIS* maps in time.

References

1. Ambraseys, N.N. and Melville, C.P. (1982). "A History of Persian Earthquakes", *Cambridge University Press*, UK.

2. Amini Hosseini, K., Mahdavifar, M., Keshavarz Bakhshayesh, M., and Rakhshandeh, M. (2004). "Engineering Geology and Geotechnical Aspects of Bam Earthquake", Preliminary Report, Website: http://www.iiees.ac.ir/English/bam_report_english _geo.html.

3. Zare, M. and Hamzehloo, H. (2004). "A Study of the Strong Ground Motion in the Bam Iran Earthquake of 26 December 2003 Mw 6.5", *JSEE*, **6**(1).

4. EERI (2004). "Preliminary Observations on the Bam, Iran, Earthquake of December 26, 2003", EERI Special Earthquake Report.

5. Eshghi, S. and Zare, M. (2003). "Bam (SE Iran) Earthquake of 26 December 2003, Mw6.5: A Preliminary Reconnaissance Report", Website: http://www.iiees.ac.ir/English/bam_report_english_recc.html.

6. PCI, OYO (2004). "The Bam Earthquake Study", Report Prepared for Japan International Cooperation Agency.

7. Wulff, H.E. (1968). "The Qanats of Iran", Scientific American, 94-105, http://users.bart.nl/~leenders/txt/qanats.html.

Preliminary Seismic Microzonation of Bam

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ABSTRACT: *After the devastating earthquake of 26 December 2003 in Bam, a discipline was followed to prepare a preliminary site effect microzonation map for the city. Seismic hazard studies for two return periods, geological studies accompanied by geophysical surveys and aftershock and microtremor measurements were carried out to provide site classification and PGA distribution maps. The results of this study show that reasonable agreements exist between the 2475 years PGA distribution map and the damage distribution map for the recent earthquake. The 475 years PGA microzonation maps could also be used as a preliminary useful hint in reconstruction and urban planning of the totally destroyed city.*

Keywords: Bam; Seismic microzonation; Site effect; Microtremor; Shear wave velocity; Peak ground acceleration; Urban planning

1. Introduction

Nowadays it is well established that ground motions are strongly influenced by source, path and local site effects. The city of Bam in the south-eastern part of Iran was hit by an earthquake of *Ms* 6.5 at a local time of 5:26 *am* on 26 December 2003. Among many research groups of different disciplines, the authors carried out their investigation on evaluation of site effects on ground motion in Bam city. The main aim of this investigation was to prepare preliminary seismic microzonation maps for the Bam city.

It is well known that the capability of local geologic deposits to amplify strong ground shaking depends on the physical properties of the materials as well as their three-dimensional geometrical distribution. Due to the dominant construction of adobe and low rise buildings in Bam, valuable data on geotechnical properties and three-dimensional distribution of materials were not available throughout the city in sufficient detail. Consequently the microzonation maps were developed using the distribution of geologic materials as mapped at the ground surface, geophysical surveying, microtremor and aftershock measurements. The methodology of the site effect assessment throughout the study area adopted in this study, consisted of the following steps:

1. Preparing the seismic hazard maps of the study area for two return periods of 475 and 2475 years;
2. Revising the existent geological map, utilizing field observations and aerial photo studies;
3. Defining the representative geophysical groups, based on the geological map and the geophysical investigations. Non-linear amplification capability of the representative sites were estimated using the latest empirical correlations between the site type and the relative amplification factor;
4. Estimation of the natural frequencies throughout the study area based on the microtremor and aftershocks measurements;
5. Preparing the site classification map, based on the geological map, the representative geophysical groups and the estimated natural frequencies;
6. Preparing the peak ground acceleration (*PGA*) distribution maps of the study area, by

superimposing the peak ground acceleration (*PRA*) distribution maps and the site classification map, for the return periods of 475 and 2475 years.

The above mentioned methodology could be incorporated into the category of Grade-2 zoning methods, according to the Japanese *TC4* zoning Manual [1]. Finally the prepared *PGA* distribution map for the return period of 2475 years and also the site classification map were compared to the damage distribution map of 2003 Bam earthquake [2].

2. Seismic Hazard Map

The basis for earthquake hazard analysis is the analysis of seismicity or the occurrence of the earthquake in space and time. The historic records may contain reports of earthquakes that occurred during the hundreds and, in some cases, thousands of years of recorded human history. The instrumental record yields information about those earthquakes for which actual instrumental evidence exists. The 2003 Bam earthquake occurred in southeast of Iran with epicenter close to Bam. The seismicity in Bam did not show any historical and instrumental strong earthquake at least in the last 2200 years ago. The most important earthquakes which occurred in *NW* of Bam are the 1981 Golbaf earthquake (*Mw* 6.6), the 1981 Sirch earthquake (*Mw* 7.1) and the 1998 Fandoqa earthquake (*Mw* 6.6).

A reliable assessment of seismic risk in a region requires knowledge and understanding of both the seismicity and the attenuation of strong ground motion. On the basis of geological and seismological studies, the hazard maps for 10% and 2% probability of exceedence in 50 years have been developed for Bam region, see Figures (1) and (2). These hazard maps correspond to return periods of 475 and 2475 years, respectively. The effects of all the earthquakes of different sizes, occurring at different locations in different earthquake sources are integrated into hazard map. The hazard map is generated based on spatially smoothed seismicity [3] and hazard from specific fault sources and attenuation relationships given by Boore et al [4] and Zare [5]. Also a uniform source zone encompassing east central Iran has been considered to quantify possibility of having an earthquake (with magnitude 5.0-7.0) in the area that have potential for damaging earthquake and quiescent historically. Such model has been suggested by different investigators (e.g. [3]).

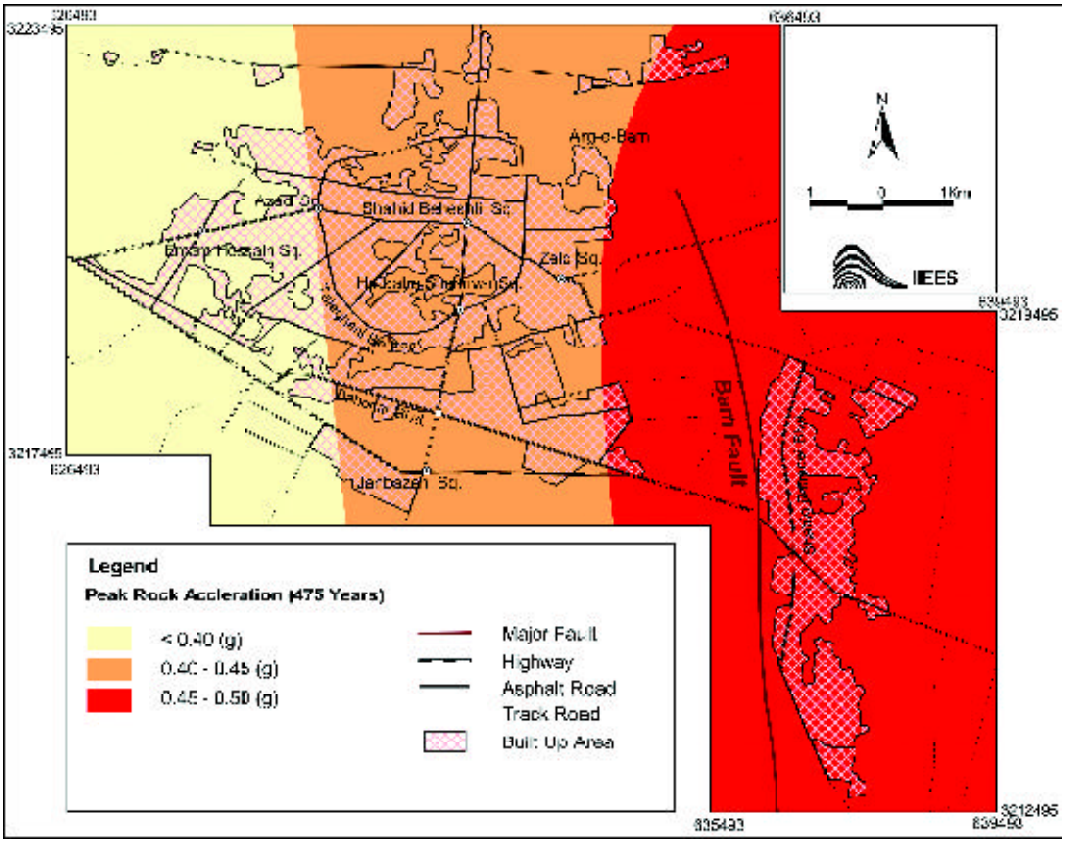

Figure 1. Peak rock acceleration map of Bam (475 years).

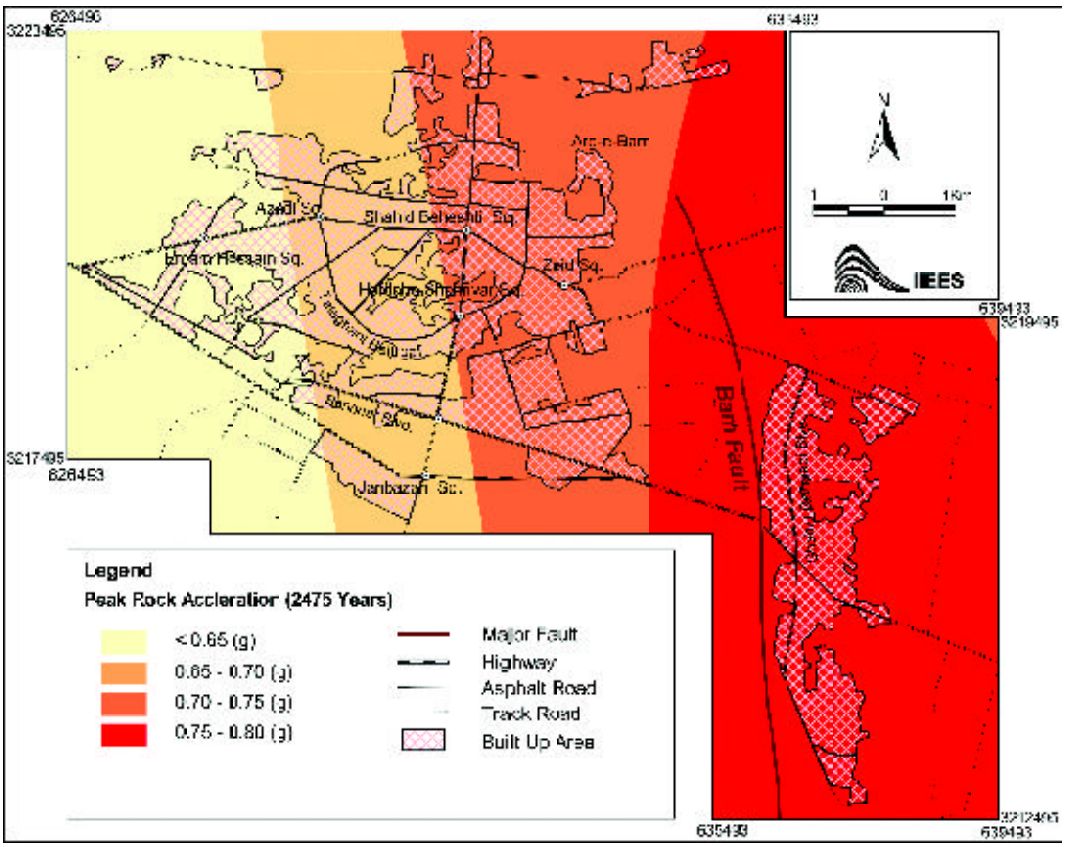

Figure 2. Peak rock acceleration map of Bam (2475 years).

3. Site Classification Map

Underground geological condition plays the main role in seismic microzonation. The site classification map of Bam has been prepared based on the geological map of the study area and also on complementary site investigations conducted by *IIEES*. These site investigations included geophysical surveys, microtremor and aftershock measurements. In this regard 8 Geo-electrical soundages and 10 seismic refraction profiles were surveyed. Data of 8 temporary seismometer stations accompanied by the 30 minute time window ambient vibration at 18 stations were used for Spectral analysis. Figure (3) presents the location of Geo-electrical soundages, seismic refraction profiles and the seismic stations (including aftershocks and microtremors).

3.1. Geological Map

Figure (3) also shows the geological map of the study area prepared by Geological Survey of Iran [6]. This geological map has been slightly modified using field observations and aerial photo studies.

The geological map shows that most parts of Bam (and Baravat) have been constructed on Quaternary alluvial. Arg-e-Bam located at the northwest of the city, is the only site where a rock outcrop can be observed. The quaternary materials can be divided into 4 groups based on general and special characteristics. These groups are the recent alluvium in river base (Q^{al}), late Quaternary alluvium (Q^{t2}), young fan deposits (Q^{f2}), and finally early quaternary materials (Q^{m1} and Q^{m2}). These types of deposits covered nearly most parts of Bam and Baravat. Eocene volcanic rocks are the only outcrops which consist less than 1 percent of surface in the study area.

The Q^{m1} deposits can be observed along the Bam fault having about 5 degrees dip toward east. The density of this layer is lower than the other deposits, although it is older. The geological map also shows that most parts of Bam and Baravat are covered with Q^{m2} deposits including gravel, sand and silt. There are some thin layers of fine grain sediments as lenses inside these deposits. The thickness of these layers varies from a few meters to more than 50 meters, depending on their location. A weak cementation caused by infiltration of the surface water, can be observed in some parts of these deposits. Shear wave velocity of this layer is about 600*m/s* at a depth of 5 meters, based on geophysical

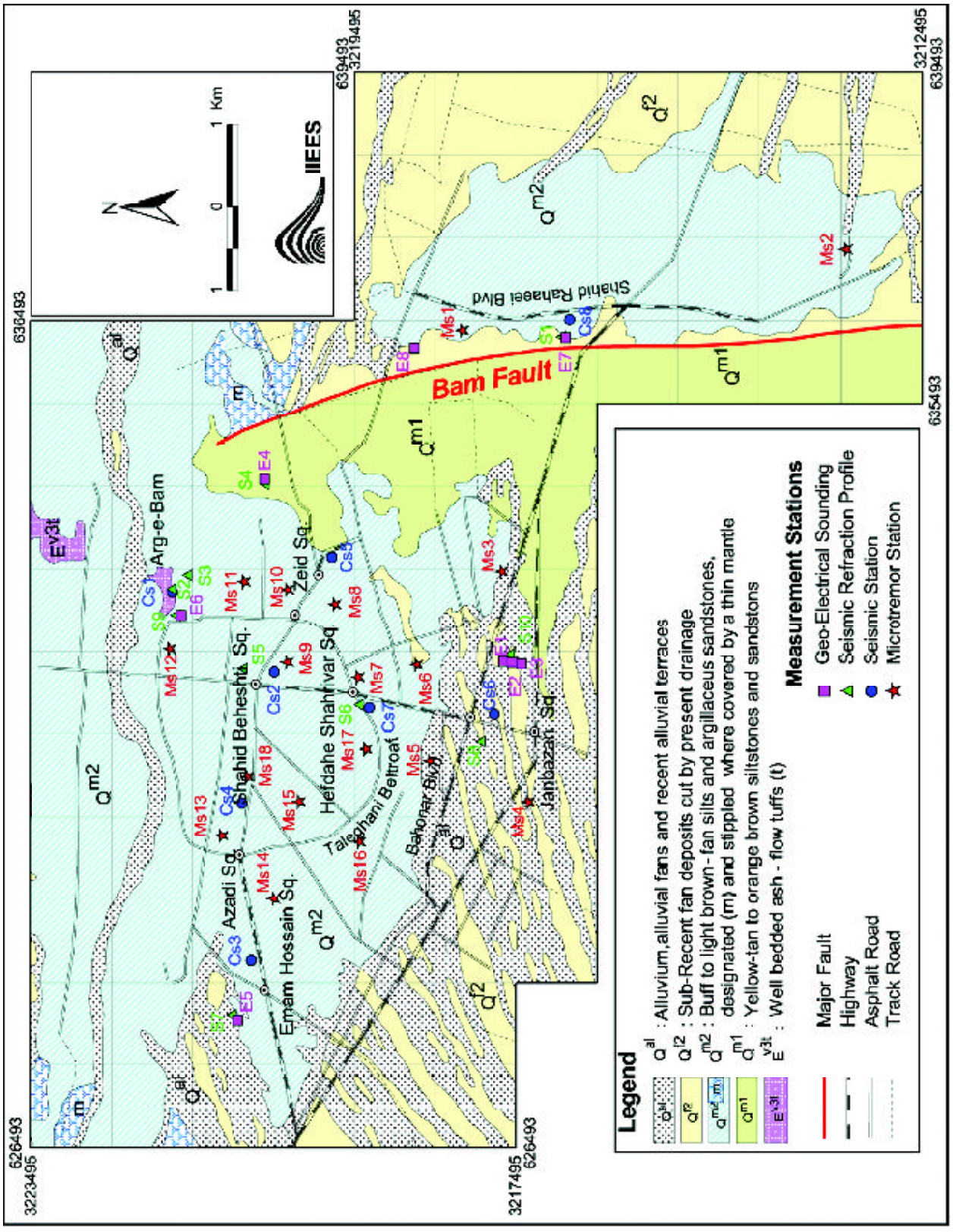

Figure 3. Gelogical map of Bam, stations of geophysical surveying, aftershock and microtremor measurements.

measurements. The alluvial fan (Q^{f2}) is another quaternary deposits extended at the eastern part of Bam. It is formed by coarse grain sediments having thickness up to 100 meters. Finally, the youngest layers of alluvium at Bam area are alluvium fans and terraces (Q^{a1}) extended along the seasonal river. These sediments are quite loose without cohesion and cementation.

Thickness of deposits increases from north to south generally; although some irregularities at bedrock may exist at southern part of Bam city which is due to volcanic rocks inherent nature and fault effects. The thickness of unconsolidated materials ranges from zero in north to 300 meters in south of Bam. Deep Geo-electrical surveying at the site show the similar subsurface condition at higher depths [7]. The maximum depth of quaternary alluvial in study area is evaluated to be about 300m based on geophysical studies.

3.2. Representative Geophysical Groups

Borcherdt [8] proposed a site classification scheme in which the ground conditions were classified into six distinct classes with acceleration dependent short-period and long-period amplification factors. The site classification scheme adopted by the 1994, 1997 and 2000 *NEHRP* provisions [9-11], the 1997 Uniform Building Code (*UBC*) [12] and the 2000 and 2003 International Building Codes (*IBC*) [13, 14] were primarily based on Borcherdt's scheme. Seed et al [15] proposed a somewhat more detailed site classification scheme that consisted of eight main classes and several subclasses with acceleration dependent peak ground surface amplification relative to competent rock sites. All these amplification relationships were based on available empirical data from the 1985 Mexico, 1989 Loma Prieta and 1994 Northridge earthquakes and also on calculations using both equivalent linear and fully nonlinear site response methods.

Figure (4) presents the 10 seismic refraction profiles surveyed in the study area. As can be seen, the resulted shear wave velocity profiles can be categorized into the following four distinct geophysical groups: Group 1 which represents rock like sites with soil thicknesses of less than a few meters; Group 2 which represents stiff shallow sites with a soil thickness of 8 to 15 meters, high shear wave velocity gradients and considerable contrast ratios of 2 to 3 with respect to the seismic bedrock; Group 3 which represents stiff sites with a higher soil

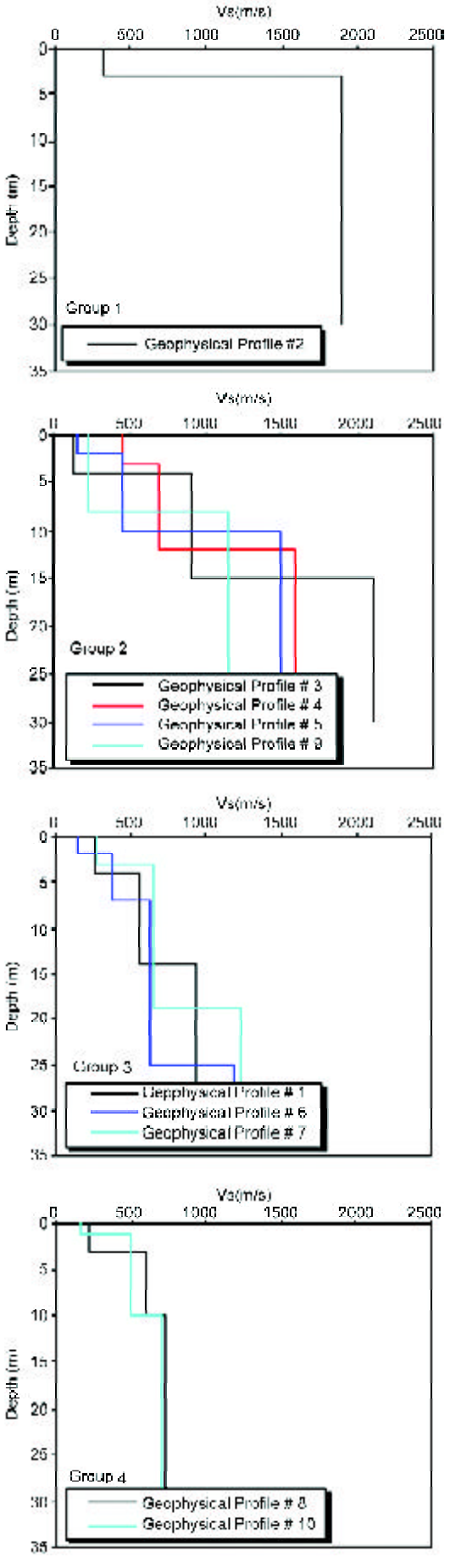

Figure 4. Seismic refraction profiles of Bam.

thickness of 14 to 25 meters, lower shear wave velocity gradients and lower contrast ratios with respect to the seismic bedrock, compared to the second group; Group 4 which represents medium to dense sites with a comparatively high thickness of more than 30 meters, low gradients of shear wave velocity and much lower contrasts with respect to the seismic bedrock. The seismic bedrock is the same as the geological bedrock in geophysical groups 1 and 2, whereas in geophysical groups 3 and 4, the geological bedrock is deeper than the seismic one.

Table (1) indicates that these four geophysical groups can also be categorized according to the above mentioned site classification systems. Figure (5) shows the proposed amplification factors for the geophysical groups 1-4 as functions of peak rock acceleration. Figure (5a) indicates that geophysical group 1, which is the well known competent seismic bedrock introduced by almost all building codes, has an amplification factor of 1.0, irrespective of the *PRA*. Figures (5b) and (5c) indicate that although the amplification factors proposed for geophysical groups 2-4 show some difference with the site classification schemes, but as expected, the amplification factor decreases as the *PRA* increases. Proper curves were fitted to the maximum values of the proposed amplification factors for each of the geophysical groups 2-4. These conservative acceleration dependent correlations provided the required basis for preparing the *PGA* distribution maps of the study area.

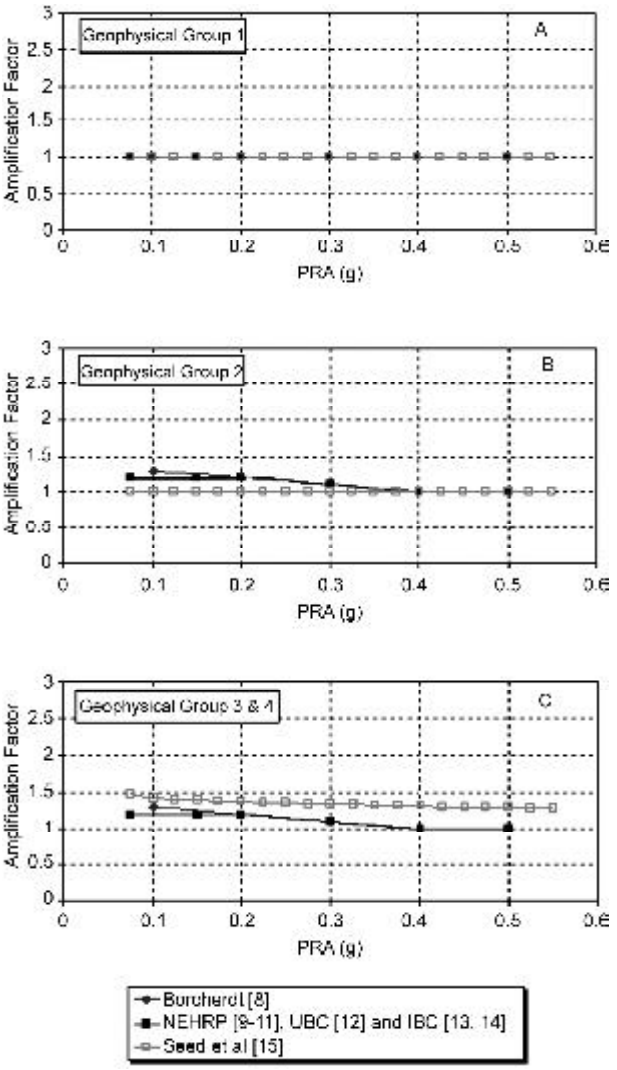

Figure 5. Empirical amplification factors of the representative geoghysical groups.

Table 1. Representative geophysical groups of the study area.

Geophysical Groups	Geophysical Profiles	Site Classification Schemes		
		Borcherdt [8]	NEHRP [9-11] UBC [12] IBC [13, 14]	Seed et al [15]
1	2	I-b	S_B	A
2	3,4,5,9	II	S_C	A
3	1,6,7	II	S_C	AB2
4	8,10	II	S_C	AB2

3.3. Site Natural Frequencies In Bam

3.3.1. Aftershock and Microtremor Measurements

The portable 3-component Guralp (*CMG*-6*TD*) seismometers are used in aftershock and microtremor measurements. The frequency operating range of these Mid-band seismometers is approximately 0.1 to 50*Hz*.

The seismic network including eight 3-components Guralp (*CMG*-6*TD*) seismometers were installed along the main streets in *N-S* and *E-W* directions at Bam City ("*Cs*" named stations in Figure (3)). One station is also installed at Baravat City, located in southeastern of Bam City. Each seismometer was adjusted to record two horizontal components in *NS* and *EW* directions and one in vertical direction. The instruments were delivered with *GPS* units for synchronization. The network was operating for near two months in the period of 12 January to 30 February, 2004. Due to the high capacity of the flash memory of the seismometers, vibrations including aftershocks and microtremors were recorded continuously with a sampling rate of 100 samples per second. The network recorded more than 2000 aftershocks as well as continues recording of microtremors during day and night. The 30 minutes microtremor vibrations measured at the additional 18 stations ("Ms" named stations in Figure (3)) were recorded by the same above mentioned seismometers.

3.3.2. Data Analysis Procedures

The aftershock data of Bam earthquake were used to analyze site amplification characteristics using spectral ratio analysis. In this analysis, the fourier spectrum was calculated for 10*s* time window of seismograms for the whole length of the record started from the beginning of P-wave arrival. The spectra were smoothed using a rectangular moving average window having a bandwidth of 0.4*Hz*. Then, the ratio of two smoothed spectra was calculated. Two times in succession smoothing were applied to the raw spectra. This number was chosen empirically considering its visual effect on the spectral shape. This procedure was repeated for the spectral ratio of both components (*N/V* and *E/V*) and, then the vector average of two ratios was calculated.

The microtremors were also used to identify the site amplification characteristics at the site. In spectral analysis of microtremors, the following steps were processed:

1. Preprocessing: filtering the signal in 0.2-20*Hz* frequency range.
2. Parameters selection: to maximize the accuracy of computed fundamental frequency, selected parameters for the frequency analysis were required to be optimized. The number of spectral averages (n_d) and the spectral resolution (B_e) are important parameters and, for a finite data record, they are directly related to each other. However, they have a conflicting influence on the error in the spectral estimates [16]. These calculations revealed that a 0.048*Hz* frequency resolution and a 2048 block length yield the optimum spectrum.
3. The selected time windows were Fourier transformed using cosine tapering before transformation. The spectra were then smoothed with a triangular moving Hanning window (1 time with 15 points).
4. In order to obtain spectral ratios, the spectra of an *EW* and *NS* channel at a site were divided by the spectra of the vertical channel and the average of each individual ratio was computed.

3.3.3. Data Analysis Results

Based on the amplification functions obtained by spectral analysis (the spectral peak and corresponding amplification factor), the 26 measurement stations can be classified into the following four distinct categories: Category one, which includes station *Cs*1 (Arg-e-Bam), lies on a rock outcrop and has a fundamental frequency in the range of 0.8-1.2*Hz* with an amplification factor of greater than 5; Category two, which includes stations *Cs*2, *Cs*6, *Ms*2, *Ms*3, *Ms*4 and *Ms*12 and shows a clear dominant frequency in the low frequency range (less than 3*Hz*); Category three which includes stations *Cs*3, *Cs*4, *Cs*5, *Ms*1, *Ms*5, *Ms*6, *Ms*16 and *Ms*17 and shows two distinct peaks, one in less than 3*Hz* and the other in more than 5*Hz*; Category four, which includes stations *Cs*7, *Cs*8, *Ms*7, *Ms*8, *Ms*9, *Ms*10, *Ms*11, *Ms*13, *Ms*14, *Ms*15, *Ms*18 and demonstrates a single peak in the high frequency range (more than 5*Hz*). Figure (6) shows the typical amplification functions of the aftershocks and microtremors for the above mentioned 4 categories.

3.4. Site Classification Map

Although the number of seismic refraction profiles were not sufficient to prepare the site classification map, but combining them with the results of the microtremor and aftershock measurements enabled this task. Figure (7) shows the distribution of the representative geophysical groups throughout the study area. It seems that moving from north to south of the study area, although the site thickness increases, but both of the shear wave velocity gradient and the contrast with respect to the bedrock decrease. Moving from west to east of the study area, it does not seem that considerable variations exist. Figure (7) also shows the distribution of the measured natural frequencies throughout the study area. As can be seen, most stations in the city indicate a high amplification potential in the high frequency range. Northern and southern parts of the city indicate the existence of high amplification potentials in the low frequency range as well. Based upon these findings, the ground conditions of the Bam city could be classified primarily into the following five distinct sites:

1. Rock like sites in which the soil thickness is less than a few meters.
2. Stiff shallow sites in which only the low frequency range indicates a considerable amplification potential.
3. Stiff shallow sites in which only the high frequency range indicates a considerable amplification potential.
4. Stiff medium depth sites in which both of the high and low frequency ranges indicate considerable amplification potentials.
5. Stiff to medium stiff deep sites in which only the

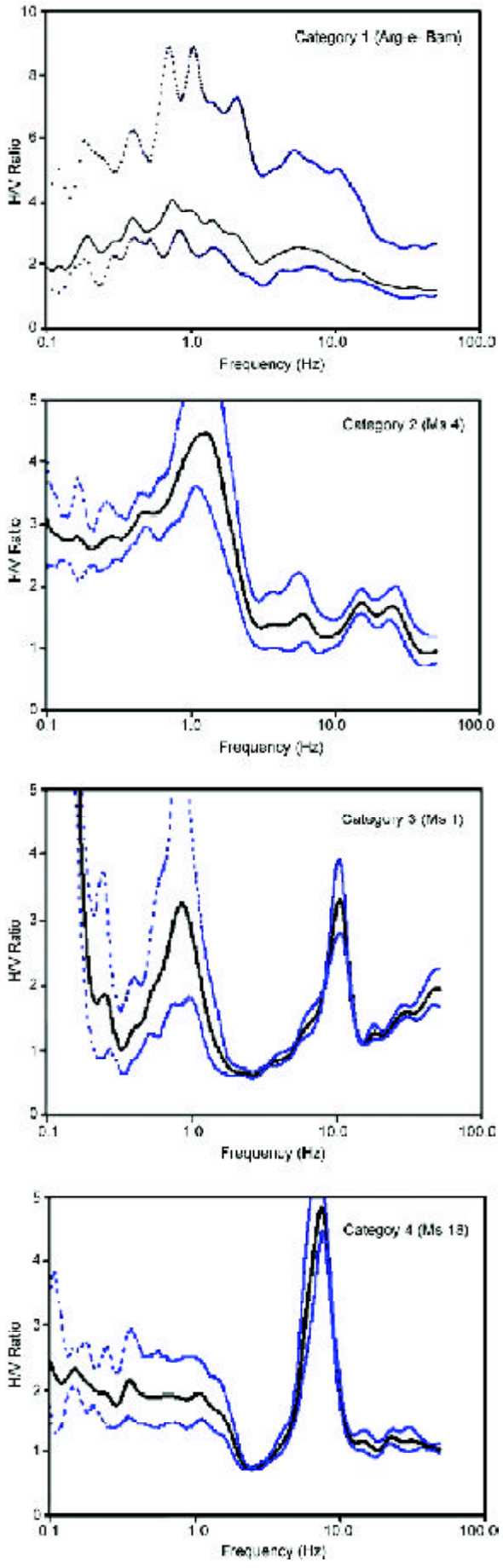

Figure 6. Typical amplification functions of the spectral analysis categories.

low frequency range shows a considerable amplification potential.

Figure (7) shows the preliminary site classification map of the Bam city. As could be seen, the north part of the city is covered with the site classes 1 and 2, the central part is covered with the site classes 3 and 4 and the south part is covered with the site class 5.

4. PGA Distribution Maps

The site-corrected *PGA* distribution maps were constructed as composites of the corresponding *PRA* distribution maps and the site classification map. Figures (8) and (9) present the horizontal *PGA* distribution maps of the study area for return periods of 2475 and 475 years, respectively.

The only accelograph in the city, located at the governor's building at Hefdahe Shahrivar Square ($29.09N$, $58.35E$), recorded during the 2003 Bam earthquake (corrected) peak values of $0.79g$ ($799cm/s^2$) and $1.01g$ ($992cm/s^2$) for horizontal and vertical components, respectively [17]. According to Figure (8), the estimated *PGA* value for the same location lies also in the range of $0.7g$ to $0.8g$ justifying the 2475 years return period selection for comparison with the damage distribution in the affected area.

Figure (8) indicates that in a return period of 2475 years, peak ground accelerations vary from a value of less than $0.7g$ to a value of $0.9g$ to $1.0g$ throughout the study area, depending on distance from the causative faults and type of the underlying geologic deposit. Figure (8) presents also the damage distribution of the 2003 Bam earthquake throughout the study area [2]. As it can be seen, the highest value of the peak ground acceleration occurs in the south-east part of the city, where the highest value of damage percent (80-100) was experienced. The least value of the peak ground acceleration occurs in the north-west part of the city, where the least value of damage percent (20-50) was experienced. Although the north-east part of the city indicates a moderate value of peak ground acceleration, but since the adobe buildings were concentrated in this part of the city, the highest value of damage percent was experienced. Indeed much less shaking intensities would be sufficient to totally destroy these adobe buildings. Of course probable near source effects may be another possible factor explaining the damage concentration in this part of the city, which should be studied in detail later. Although the central part of the city indicates a moderate value of peak ground acceleration too, but since most buildings were

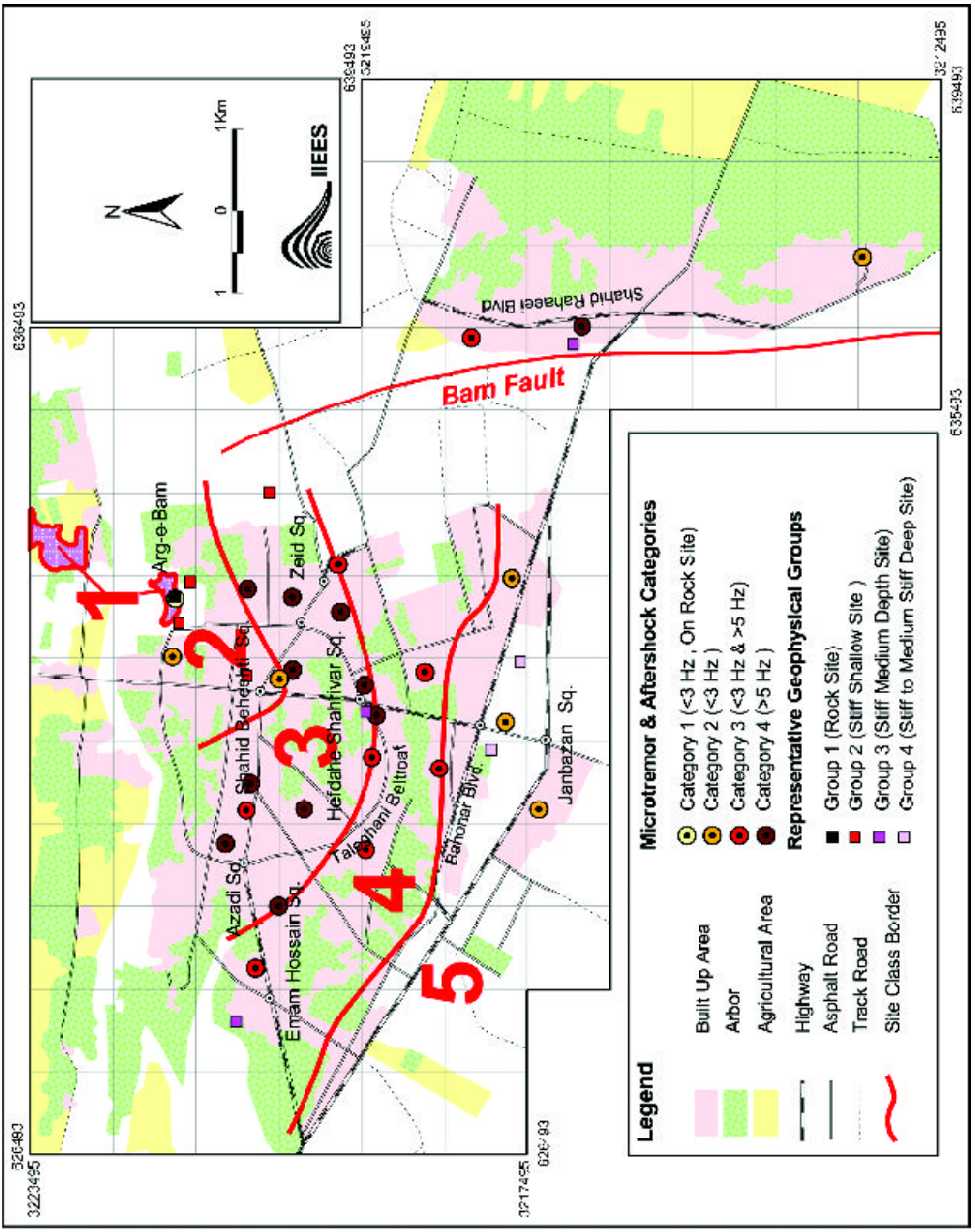

Figure 7. Site classification map of Bam.

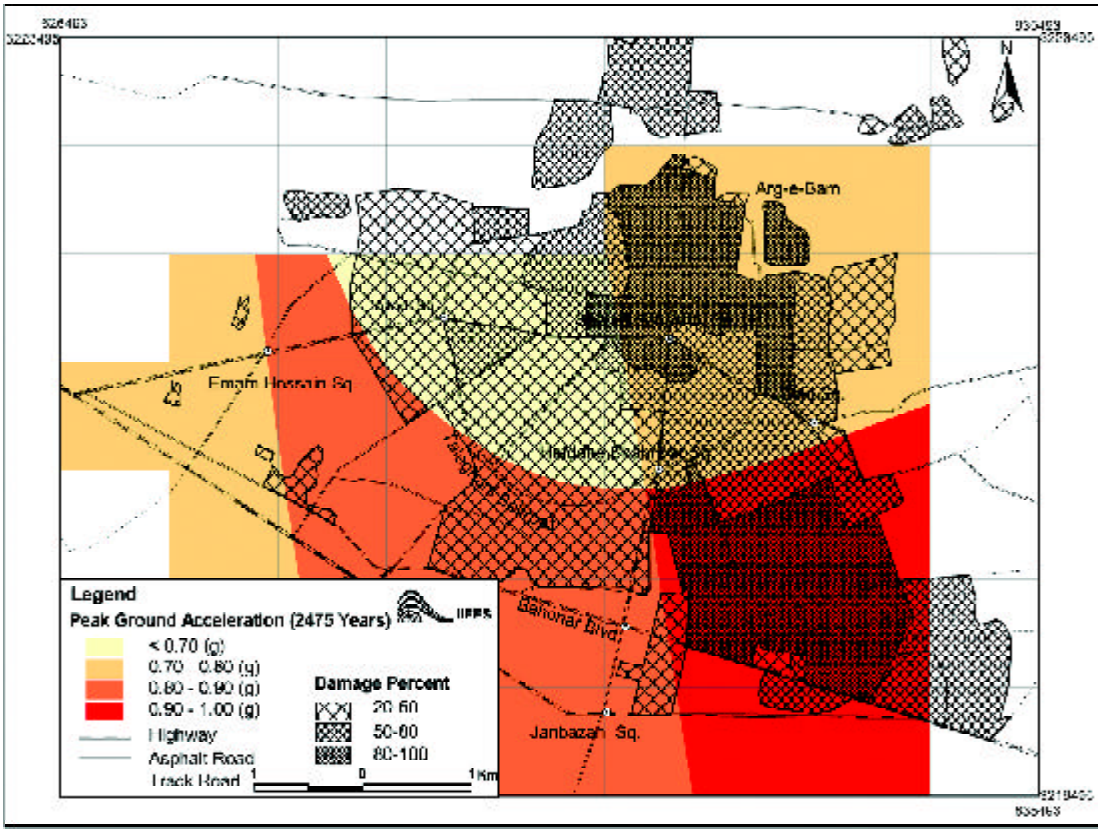

Figure 8. Peak ground acceleration map of Bam (2475 years).

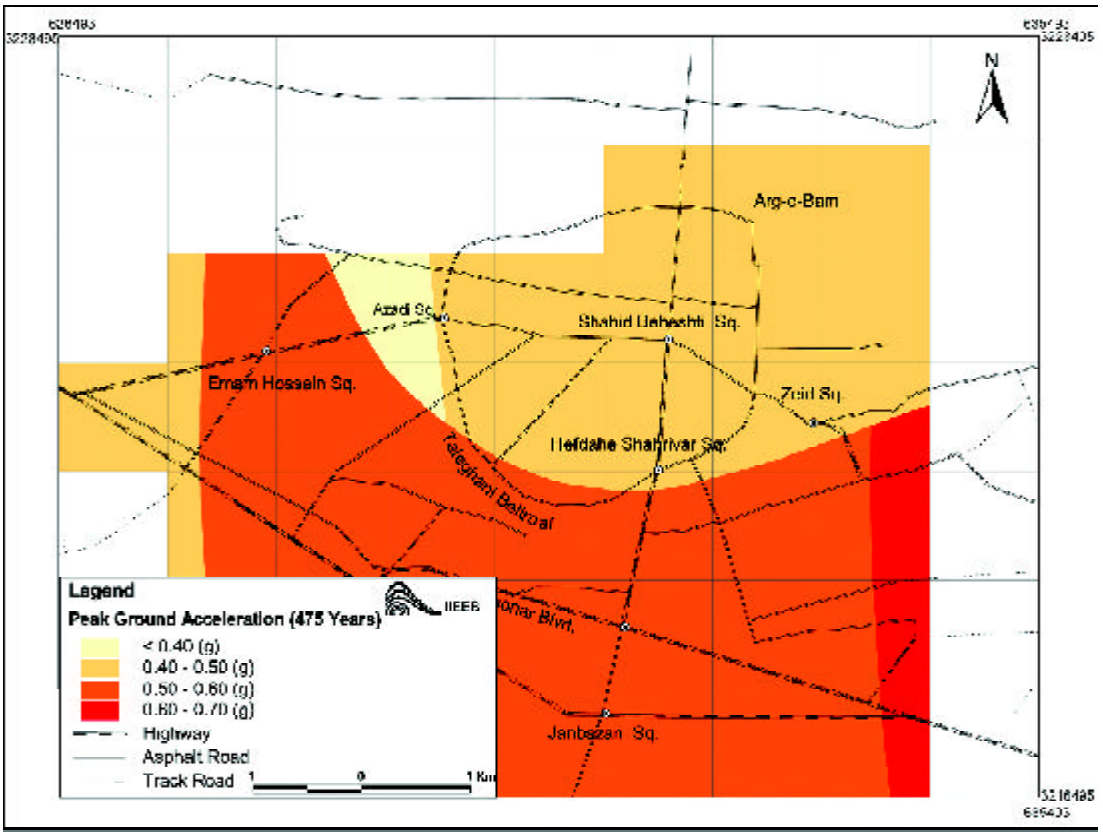

Figure 9. Peak ground acceleration map of Bam (475 years).

designed and constructed on engineering basis, the experienced value of damage percent was the least. The damage distribution of Figure (8) could also be compared with the site classification map of Figure (7). As can be seen, almost all damages of low rise buildings occurred in site classes, which possess a considerable amplification potential in the high frequency range.

Figure (9) indicates that in a return period of 475 years, peak ground accelerations vary from a value of less than 0.4*g* to a value of 0.6*g* to 0.7*g* throughout the study area. Comparison of Figures (8) and (9) shows that irrespective of the return period, the peak ground acceleration increases by moving from north to south and from west to east of the city.

5. Conclusions

After the devastating earthquake disaster in the Bam city of Iran, a discipline was followed to prepare preliminary seismic microzonation maps for this city. This paper presented the preliminary results of seismic microzonation studies of the Bam city. The site effect evaluations were based on geophysical, microtremor and aftershock measurements conducted by *IIEES* in the study area. Good agreements existed between the 2475 years *PGA* distribution map and the damage distribution map of the recent earthquake. Highest values of damage percents concentrated in sites with stiff shallow and medium depth soils, which possessed considerable amplification potentials in high frequency ranges. The obtained microzonation maps could be used as a preliminary useful hint in reconstruction and urban planning of the totally destroyed city. It is obvious that more accurate evaluations of ground motion characteristics require more geotechnical and geophysical data, consideration of multi-dimensional sub-surface topographic effects as well as all possible near source effects.

References

1. The Technical Committee for Earthquake Geotechnical Engineering (TC4) (1993). "Manual for Zonation on seismic Geotechnical hazard", The Japanese Society of Soil Mechanics and Foundation Engineering.
2. National Cartographic Center (2003). "Damage Distribution Map of Bam Earthquake".
3. Frankel, A. (1995). "Mapping Seismic Hazard in the Central and Eastern United States", Seismological Research Letters, **66**(4), 8-21.
4. Boore, D.M., Joyner, W.B., and Fumal, T.E. (1997). "Equations for Estimating Horizontal Response Spectra and Peak Acceleration from Western North American Earthquakes: A summary of Recent Work", Seismological Research Letters, **68**(1), 128-153.
5. Zare, M. (1999). "Contribution a L'etude Des Movements Forts en Iran: Du Catalogue Aux Lois D'attenuation", These De L'universite Joseph Fourier, Grenoble, France.
6. Geological Survey of Iran (1993). Geological Map of Iran, 1:100000 Series, Sheet 7648-Bam.
7. Abkav Consulting Engineers (1973). "Geo-Electrical Studies of Bam and Narmachir Region", Ministry of Water and Electric.
8. Borcherdt, R.D. (1994). "Estimates of Site-Dependent Response Spectra for Design (Methodology and Justification)", Earthquake Spectra, **10**, 617-653.
9. The NEHRP Recommended Provisions for Seismic Regulations for New Buildings (1994) Edition.
10. The NEHRP Recommended Provisions for Seismic Regulations for New Buildings (1997) Edition.
11. The NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures (2000) Edition.
12. Uniform Building Code (UBC) (1997). Chap. 16.
13. International Building Code (IBC) (2000). Chap. 16.
14. International Building Code (IBC) (2003). Chap. 16.
15. Seed, R.B., Cetin, K.O., Moss, R.E.S., Kammerer, A.M., Wu, J., Pestana, J.M., and Riemer, M.F. (2001). "Recent Advances in Soil Liquefaction Engineering and Seismic Site Response Evaluation", *Proceedings Fourth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics and Symposium in Honor of Professor W.D. Liam Finn*, San Diego, California, (SPL-2).

16. Bendat, J.S. and Piersol, A.J. (1993). "Engineering Application of Correlation and Spectral Analysis", *John Willey & Sons Inc.*, Second Edition.

17. Zare, M. and Hamzehloo, H. (2004). "A Study of the Strong Ground Motion in the Bam Iran Earthquake of 26 December 2003 Mw 6.5", *JSEE*, **5**(4) and **6**(1).

Post-Earthquake Quick Inspection of Damaged Buildings in Bam Earthquake of 26 December 2003

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ABSTRACT: *A procedure developed for quick inspection of buildings in earthquake damaged areas of Bam by a group of volunteer engineers is introduced. The procedure is applied to 550 masonry, steel and reinforced concrete buildings. Distribution and statistics of the buildings characteristics such as their use, number of stories, penthouse and stairs damages, type of material and structural systems and type of diaphragms are determined. The information has provided important data about the design, detailing and construction deficiencies of common types of buildings in Bam.*

Keywords: Bam; Post-earthquake inspection; Damaged building

1. Introduction

Following any major damaging earthquake that disrupts and threatens life and normal activities, there is likely to be shock, confusion and chaos in the period following that usually lasts some appreciable time. Although, there might be a scene of apparent disruption and emotion, actions are required to respond to the emergency and to start the process of recovery. An important action is to address the safety of buildings, to establish those that cannot be used, to make those damaged so that they can be used, and to identify those that can continue to be fully used. There will be a mix of extent of damage to buildings within an area and between different areas. Many buildings at first may appear to be undamaged, but on closer inspection these may be found to be perhaps severely damaged. Very often the full extent of damage continues to emerge over time.

With Iran's history of earthquakes and other disasters, one of the most important post-disaster activities is to determine the safety and functionality of buildings and especially the key facilities. These facilities include emergency operation centers, hospitals, sewage plants, water treatment systems, and airports. However, the most challenging task is to address the safety of large stack of private homes.

In some countries, a group of professionals immediately after earthquake begin to evaluate the damaged buildings. The evaluation consists of some phases. At the beginning, the first phase of evaluation that is called “rapid screening” or “quick inspection” is done. The aim of this step is to find out whether a building is safe for occupying or it need some structural and non-structural retrofitting or it is not recommended for occupying. Because inspection is done very quickly, providing retrofitting details in this phase is not possible. Although, there are some countries that have developed postearthquake evaluation procedures, only Japanese and American quick inspection development histories are briefly reviewed here.

When the Southern Italy Earthquake struck in 1980, the then Ministry of Construction of Japan (at present, the Ministry of Land, Infrastructure and Transportation) started the “project for advanced repairing technology for earthquake damaged buildings” in 1981. It created a series of methods; from risk evaluation of damaged buildings to repairing technology of wooden, steel and reinforced concrete structure buildings. When the Mexico Earthquake occurred in 1985, the temporary risk evaluation method for damaged reinforced concrete buildings was applied. After the project of comprehensive technology was undertaken, the Building Disaster Prevention Association of Japan published, “The

standard of damage evaluation and the guidance of repairing technology for the buildings hit by earthquakes". Then a technological standard was established, Shizuoka government established a temporary risk evaluation system of damaged buildings in 1991, followed by the Kanagawa government in 1992. When the Great Hanshin-Awaji Earthquake occurred in 1995, the temporary risk evaluation of damaged buildings was applied for the first time in Japan. Then many other local governments established their own system.

In July 1987 the California Governor's Office of Emergency Services (*OES*), California Office of Statewide Health Planning and Development (*OSHPD*), and Federal Emergency Management Agency (*FEMA*), jointly awarded *ATC* a contract to develop procedures for postearthquake safety evaluation of buildings. This led to the development of the *ATC*-20 [1] report "Procedures for Post earthquake Safety Evaluation of Buildings". *ATC*-20 documents procedures and guidelines for the safety evaluation of damaged buildings. These are written specifically for volunteer structural engineers, and building inspectors and structural engineers from city building departments and other regulatory agencies, who would be required to make on-the-spot evaluations and decisions regarding continued use and occupancy of damaged buildings [2]. To provide the ATC-20 methodology in a concise, easy to use field reference document, a Field Manual was developed as part of the *ATC*-20-1 [3] project. The Field Manual is intended to be taken into damaged areas and used by those trained in the *ATC*-20 methodology.

A three-tier posting classification system is recommended by ATC-20 and is described in the publication series Procedures for Postearthquake Safety Evaluation of Buildings. The modified forms and placards are described in the Addendum to *ATC*-20 (*ATC*-20-2) [4]. The colored placards (tags) are tools posted on inspected structures to easily identify facility damage assessment results from a distance. They are normally posted at all building entrances. The following describes the circumstances by which inspectors should post each type of placard.

- ***Inspected:*** (Green Tags) Buildings can be damaged, yet remain safe. If the safety of a building was not significantly changed by the disaster, it should be posted with a green placard reading *INSPECTED.*
- ***Unsafe:*** (Red Tags) Buildings damaged by a disaster that pose an imminent threat to life or safety under expected loads or other unsafe conditions should be posted with a red placard reading *UNSAFE*. These are not demolition orders.
- ***Restricted Use:*** (Yellow Tags) When there is some risk from damage in all or part of the building that does not warrant red-tagging, a yellow tag should be used. The placard should indicate the specific restriction (i.e., entry, duration of occupancy, use, etc.). When the extent of damage is uncertain or cannot be ascertained within the time and resources available to a Rapid Evaluation team, the building should be posted with a yellow placard reading Restricted Use indicating additional inspection requirements, and any restrictions on use or occupancy should be clearly noted on the placard. Although a building may be placarded Restricted Use, specific areas in and around the building could be further identified as unsafe. This specific area should be identified and posted with a red placard reading Area Unsafe. An Area Unsafe placard helps identify dangerous situations that may exist around or within an otherwise structurally sound building. A building posted Restricted Use may have a specific area that is posted Area Unsafe. In this situation, the Restricted Use placard should indicate the specifics of the restrictions and identify the location of the Area Unsafe [1].

In this paper, a procedure for quick inspection of buildings that has been developed by a group of volunteer engineers is introduced. The procedure then applied to 550 buildings in Bam. For each building, a set of forms has been filled. Then the data is collected in a database. A study on the data provides some statistics about buildings and common construction practices in Bam area.

2. Procedure Used

In order to quickly inspect damaged buildings of Bam city, a form has been prepared that contains some structural and non-structural related items. The items are selected based on the available quick inspection forms, considering special features of common buildings in Iran. In the conclusion part of this form three cases have been mentioned:

1. Building is relatively safe and can be occupied with probably some non-structural retrofitting;

2. Building can be occupied with structural retrofitting;
3. The building is not recommended for occupation. A translation of forms to English is included in Appendix [A].

The questions in the forms are intended to summarize the type and extent of damages in a building. They are also designed to compare the building characteristics with the minimum requirements of "Iranian Code of Practice for Seismic Resistant Design of Buildings" [5].

3. Quick Inspection Form Items

Rapid evaluation form has been shown in Appendix [A]. This form has nine parts. The form items should be completed according to the available data in the location of building. A brief explanation of each part of the form follows.

Part A) Building general information: In this part, the general information of the building, such as address, area, building use and its owner are mentioned.

Part B) Building general characteristics: In this part, general characteristics of the building such as number of stories, height of stories, existence or lack of basement, penthouse and cantilever and their damage level are marked.

Part C) Material: In this part, the material of structural elements (frame, wall, and foundation) and non-structural elements (partitions, finishing and ceiling) are entered.

Part D) Stairs: In this part, the stairs and stairs side wall damages are mentioned.

Part E) Structural system characteristics: This part is one of the most important parts in the quick inspection report and contains structural data of the building such as structural system type in each direction, type of bracing, slab system, foundations system and structural elements such as columns, beams, bracings, connections, base plates and infills.

Part F) Visible plastic deformations: The large story drifts and inappropriate deformations shall be mentioned in this part.

Part G) Non-structural elements damage: In this part the damage level of non-structural elements such as ceilings, pipes, partitions, facets, parapets and electrical and mechanical equipments are mentioned.

Part H) Conclusion: By evaluating the items in each section of the form, the buildings can be classified into three categories:

1. Building is relatively safe and can be occupied with probably some non-structural retrofitting;
2. Building can be occupied with structural retrofitting;
3. The building is not recommended for occupation.

Due to rapid nature of inspection, the conclusion is somehow dependent to the level of skill of inspector. To avoid inconsistent results, some training session was held for the volunteer engineers for familiarizing them to interpretation of form items.

Part I) Recommendations: In order to prevent later damages and dangers and guarantee the safety of the residents, any special point that may have been observed during the evaluation, shall be recommended to the residents. These recommendations are mentioned in the last part of the form. At the end of the form, a schematic drawing of the structure should be drawn.

The forms have been filled for 550 buildings in Bam. The collected data of buildings has been transferred to a database program that has been developed for gathering and processing the data. Figure (1) shows the forms in database format.

4. Damage Statistics

Having compiled all the form items for 550 buildings in the database, one may extract different statistics out of the information. The statistics are about different buildings characteristics such as their use, number of stories, penthouse and stairs damages, type of material and structural systems and type of diaphragms. The information helps identifying many design, detailing and construction deficiencies of common types of buildings in Bam. Some of this information is presented in this section.

Shown on Figure (2) is the percentage of buildings function and use. It is noteworthy that the buildings are mainly private homes that are registered for surveying by their owners in municipality. Therefore, it is not surprising that the number of residential buildings is much more than other types of buildings.

Shown on Figure (3) is the number of stories for the surveyed buildings. Almost 75% of surveyed buildings are single story buildings. It can be concluded that most of these building are short period structures.

The widespread damage to penthouses was a

Figure 1. Building database for quick inspection (Appendix I).

feature of Bam earthquake. In many buildings the penthouse was built without any structural integrity to the main structure and without any structural system. An item in the inspection form was designed to identify whether the penthouses has structural system or not. Another item in the form shows whether the penthouse has been severely damaged. According to Figure 4, the cause of damage in more than 75% of penthouses was lack of structural system.

Figure (5) shows the percentage of each building type in the surveyed buildings. Masonry solid brick wall buildings are by far the dominant type of building in this study. The relative percentage of building as shown in Figure (5) is consistent with the data in most other cities of Iran.

Stairs are important items in any quick inspection approach. A damaged stair causes difficulty for occupants to exit building in an emergency situation. Shown on Figure (6) is the percentage of damaged stairs in the surveyed buildings. According to the figure, in more than 25% of cases, both stairs and its sidewall have been damaged. Also, more than 20% of sidewalls were damaged, while the stair itself was undamaged. On the other hand in less than 10% of cases, the stair has been damaged while its sidewall was undamaged. The high number of damaged stairs

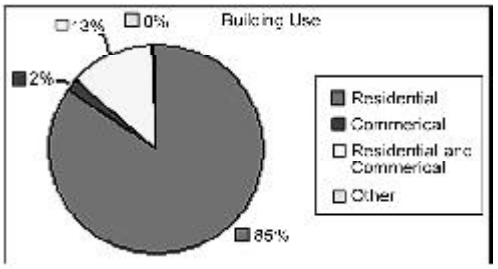

Figure 2. Types of building uses.

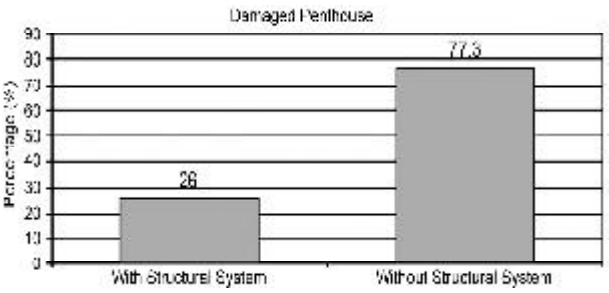

Figure 4. Damage to penthouses.

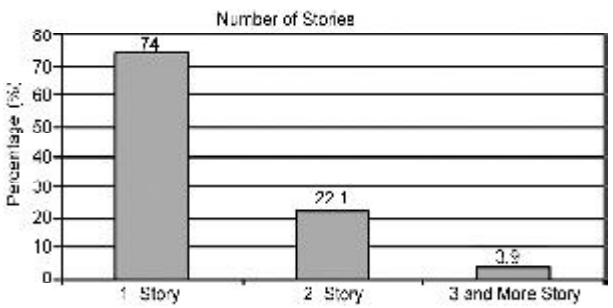

Figure 3. Number of stories for buildings.

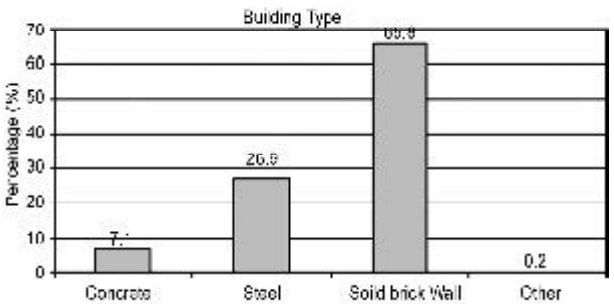

Figure 5. Distribution of building types.

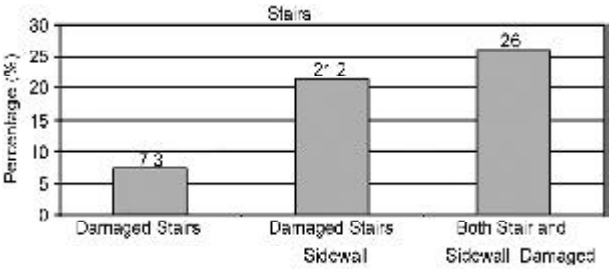

Figure 6. Damage to stairs.

shows some serious flaws in construction practice in Bam.

Shown on Figure (7) is the distribution of structural systems for the buildings surveyed. According to this figure, almost half of the buildings have somehow used unreinforced bearing wall. The use of tie beams as emphasized by the Iranian Building Code [5] is not common. The satchel type of simple framing is the second popular system. According to the Iranian Building Code [5], a satchel frame is a simple frame that can not resist lateral loads and needs bracing. However, in most cases in Bam, no bracing is used.

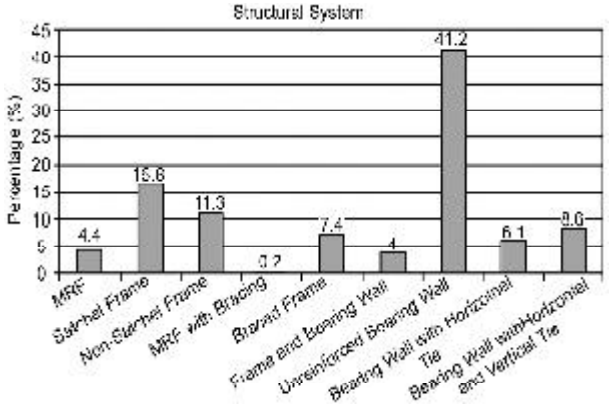

Figure 7. Structural system types.

The percentages of diaphragm systems of buildings are shown in Figure 8. Brick floor (archaic) diaphragms are the most common type in Bam; the same is true for other parts of Iran. According to Figure (8), more than half of all diaphragms are brick floor that does not satisfy code requirements with respect to using rods for their integrity. More reliable diaphragms consist of joist and block is accounted for only 10% of cases.

By completing the set of forms for each building, one may arrive to final conclusion. Due to nature of a rapid inspection, the conclusion is somehow dependent to the level of skill of inspector. To avoid inconsistent results, training sessions were held for

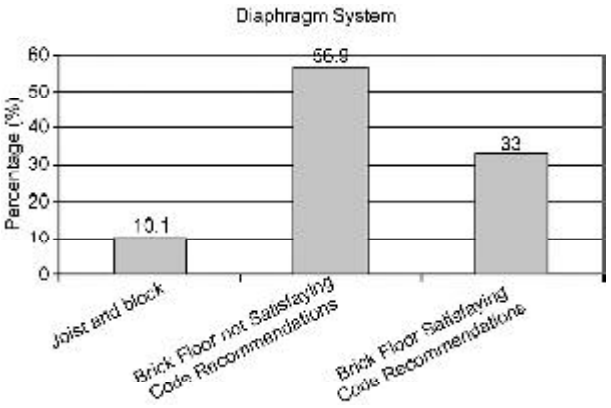

Figure 8. Diaphragm types.

the volunteer engineers for familiarizing them to interpretation of form items. The items in the forms are intended to summarize the building characteristics as well as type and extent of damages in a building. They are also designed to compare the building characteristics with the minimum requirements of "Iranian Code of Practice for Seismic Resistant Design of Buildings" [5]. By careful consideration of all aspects, the inspector arrives at the final conclusion. Figure (9) shows the percentage of each case. Unfortunately most of surveyed buildings did not meet the minimum requirements of codes.

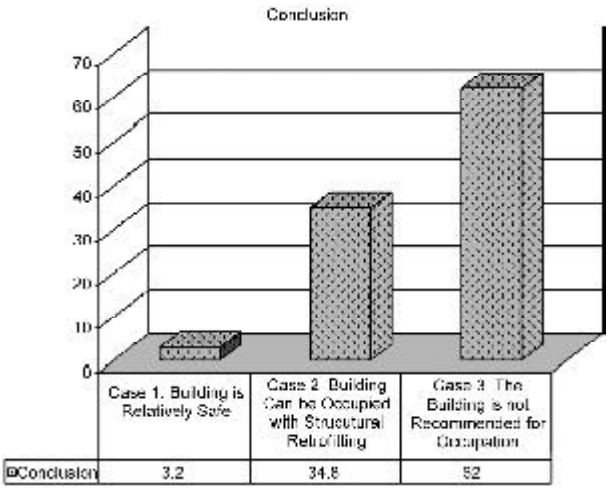

Figure 9. The comparison of results.

5. Some Observations from Application of the Procedure to Damaged Buildings in Bam

Collecting the buildings information in a database greatly facilitates the processing of the information. By carrying out different queries, important data about the common design, detailing and construction deficiencies of buildings in Bam has been provided.

Some of the findings are summarized in following sections for different types of buildings.

5.1. Masonry Buildings

The masonry structures that have been evaluated are categorized in two groups: Bearing wall without vertical and horizontal tie beams, bearing wall with vertical and horizontal tie beams (lintels). In the masonry structures without tie beams, the bearing walls and even partitions had been activated during earthquake and resisted the applied load and had experienced significant damages. Most of the damages are limited to shear cracks (diagonal, 45 degree cracks). In some cases all the wall were damaged and collapsed. According to "Iranian Code of Practice for Seismic Resistant Design of Buildings" [5], these buildings are not acceptable, due to lack of tie beams. If concrete condition and reinforcement detailing in vertical and horizontal tie beams of the masonry structures be proper, then the tie beams act as effective elements and resist earthquake load. Because of their short height and short period, their strength rather than ductility is important. To mobilize their full strength the tie beams should be able to keep the integrity of the walls. In many masonry buildings, because of the inappropriate details and concrete condition, some damages had occurred in tie beams, see Figure (10), and in the connections, see Figure (11). Also the bars had buckled and the concrete cover of tie beams had cracked. Some horizontal tie beams were not at the same level, which is not acceptable according to the code.

5.2. Steel Buildings

Structural system of the most existing steel structures in Bam city is continuous side connection (satchel connection) simple frame in one direction and simple frame in the other direction, see Figure (12). In some cases, there is not any frame in the other direction. In braced steel structures, the bracings and their connections were often suffering from different construction deficiencies. Most of the bracings had experienced buckling and damaged in the connection region, see Figure (13). In some steel structures without bracing, the stairs were performed as bracing

Figure 10. Crack in tie beam due to lack of reinforcement.

Figure 11. Improper connection of vertical and horizontal tie bars.

Figure 12. Simple steel frame without bracing.

Figure 13. Buckling of bracing and connection damage.

system and prevented the building from collapse. In these buildings, the stairs had often experienced sever damages. Penthouses of the most structures being evaluated had no structural system and had experienced significant damages.

5.3. Reinforced Concrete Buildings

The number of reinforced concrete buildings in Bam was far less than number of masonry or steel buildings. Poor quality of concrete, improper forming, and incorrect reinforcement detailing was widespread. In many reinforced concrete buildings, due to existence of many stiff and strong infills, the beam and columns of frames had performed as tie (lintel) beams for the frames. Therefore, in many reinforced concrete frame buildings, the infills suffer significant damages, but the beams and columns with poor quality remain intact, as they had only acted as tie beams. A sample of poor detailing in connections is shown in Figure (14). A common practice of damaging columns for installing staircase is shown in Figure (15).

Figure 14. Poor detailing in connection.

Figure 15. Removing concrete to install stair case.

6. Conclusions

A procedure for quick inspection of buildings in earthquake damaged areas of Bam that was developed by a group of volunteer engineers is introduced in this paper. The quick inspection forms are tailored for common building types of Iran. The procedure is applied to 550 masonry, steel and reinforced concrete buildings. Distribution and statistics of the buildings characteristics such as their use, number of stories, penthouse and stairs damages, type of material and structural systems and type of diaphragms are determined. The information has provided important data about the design, detailing and construction deficiencies of common types of buildings in Bam.

Based on experience in quick inspection of buildings in Bam, some suggestion can be made. The most important is that an effort should be made to organize a systematic approach for quick inspection of buildings in Iran. Following an earthquake or a catastrophic disaster, there is an immediate need for damaged building inspections. People must be kept from using unsafe buildings. It is essential that qualified inspectors quickly identify safe and unsafe structures. To address this need, a building inspection program for catastrophic disaster events such as earthquakes in Iran should be established. Also specialized training should be organized for engineers, architects and building professionals who will volunteer their time to conduct building inspections after disaster events. Any building professional wishing to become a volunteer must attend the Post Earthquake Safety Evaluation of Buildings course. Graduates should receive inspector credentials and become a team member qualified to inspect earthquake damaged buildings. A panel of earthquake and structural experts and building officials should approve all training materials used in this course. During the course, procedures and documents should be presented to promote uniformity in the rating of building damages so that different individuals examining the same building will arrive at the same conclusion about its relative safety.

Acknowledgment

Data gathering from 550 buildings in Bam and development of quick inspection forms (in Farsi) is done by a group of 20 volunteer engineers that the authors of this paper were among them. The authors wish to thank their colleagues for their hard work. Special thanks to Mr. Taheri-Behbahani (also a team

member) and Ms. Beski for their important roles in organizing the effort. Also much appreciation is due to Mr. Rahmankhah for writing the database software. The authors like to thank Mr. Rahmankhah, Ghafarbeigi and Adib-Haji Bagheri for their help in entering the data to the database. The authors wish to thank Memar Magazine and *IIEES* for facilitating their work.

References

1. Applied Technology Council (ATC) (1989). "Procedures for Postearthquake Safety Evaluation of Buildings", Report ATC-20, Applied Technology Council, Redwood City, CA.
2. Gallagher, R.P. (1989). "Postearthquake Safety Evaluation of Buildings", *Proceedings of Structures Congress '89, ASCE*; 100-109.
3. Applied Technology Council (ATC) (1989). "Field Manual: Postearthquake Safety Evaluation of Buildings", Report ATC-20-1, Applied Technology Council, Redwood City, CA.
4. Applied Technology Council (ATC) (1995). "Addendum to the ATC-20 Postearthquake Safety Evaluation Procedures", Report ATC-20-2, Applied Technology Council, Redwood City, CA.
5. Permanent Committee for Revising the Iranian Code of Practice for Seismic Resistant Design of Buildings (1999). "Iranian Code of Practice for Seismic Resistant Design of Buildings", Standard No. 2800, Building and Housing Research Center, Tehran, Iran.

Appendix I. The quick inspection forms.

Name of inspectors: Inspection date: Photo numbers:

A) Building General Information

Owner name: File number: Area:

Address: Tel.: Inspection No.:

Building use: ❍ Residential ❍Commercial ❍Office ❍Other

B) Building General Characteristics

Number of stories (without basement): Approximate height of stories:

Basement: ❍Portion of the plan ❍All the plan ❍Not exist ❍Damaged ……

Penthouse: ❍With struc. System ❍Without struc. system ❍Not exist ❍Damaged ……

Cantilever: ❍Exist ❍Not exist ❍Damaged ……..

C) Material:

C-1) Structural

Frame: ❍Reinforced concrete ❍Steel ❍Damage ……

Bearing wall: ❍Solid brick ❍Concrete block ❍Clay ❍Damage ……

Foundation: ❍Concrete ❍Lime soil ❍Invisible ❍Damage ……

Bearing wall mortar type: ❍Sand and cement ❍Lime ❍Bustard ❍Other

C-2) Non-Structural

Partition: ❍Solid brick ❍Hollow brick ❍Hollow block ❍Concrete block

Finishing : ❍Stone plate ❍Brick ❍Cement plaster

Partition mortar type: ❍Sand and cement ❍Lime ❍Bustard ❍Other

Ceiling:

D) Stairs

❍Exist ❍Not exist ❍Stairs damage ❍Stairs sidewall damage

E) Structural system characteristics

E-1) Load resisting system	Transversal direction	Longitudinal direction	Damaged	Description
Moment frame	❍	❍	❍	.....
Continuous side connection (satchel) simple frame	❍	❍	❍	.....
Non-continuous side connection simple frame	❍	❍	❍	.....
Moment frame with bracing	❍	❍	❍	.....
Simple frame with bracing	❍	❍	❍	.....
Composite system (simple frame and bearing wall)	❍	❍	❍	.....
Unreinforced bearing wall	❍	❍	❍	.....
Bearing wall with horizontal tie beams	❍	❍	❍	.....
Bearing wall with horizontal and vertical tie beams	❍	❍	❍	.....

E-2) Bracing type (if exist)	Transversal direction	Longitudinal direction	Damaged	Description
X	❍	❍	❍	.....
∧	❍	❍	❍	.....
∨	❍	❍	❍	.....
K	❍	❍	❍	.....
Other bracings(shear wall,knee bracing,EBF,…)	❍	❍	❍	.....

E-3)Slab system

❍Joist and block ❍Cast-in-place concrete slab ❍Composite

❍Brick floor without satisfying the code ❍Brick floor with satisfying the code

❍Other ❍Damage …….....

E-4) Structure of the foundation

❍Single ❍Combined ❍Mat ❍Invisible ❍Damage……

❍ With tie beams ❍Without tie beams ❍Damage…….

E-5) Structural Elements

-Columns: ❍Open double profile column flat-bars condition (dimensions,…)

❍Closed double profile ❍Steel box ❍Other (steel)

Welding quality: ❍Good ❍Moderate ❍Poor

❍Concrete rectangles ❍Concrete circle ❍Other (concrete) ❍Damage……

-Beams: ❍Rolled ❍Cast beams ❍Plate girder ❍Composite cross-section

Welding quality: ❍Good ❍Moderate ❍Poor

❍Concrete beam ❍Other ❍Damage ……...

-Longitudinal direction connections: ❍Continuous side connection ❍Pin ❍Rigid

❍Other ❍Damage……

-Transversal direction connections: ❍Continuous side connection ❍Pin ❍Rigid

❍Other ❍Damage……

-Connections welding quality: ❍Good ❍Moderate ❍Poor

-Bracings:

Bracing cross-section: ……..

X bracing middle connections details: …….

X bracing connections details at end joints: ……

Damage and description: ……

-Base plate:

Column to base plate connection method: ❍With angle ❍with plate

❍invisible ❍Damage ……..

-Bolts: ❍Non-deformed bar ❍Deformed bar ❍Welded connection

❍Bolted connection ❍Damage …….

-Infill:

❍Exist ❍Not exist ❍Activated ❍Non-activated ❍Damage ……

F) Plastic Deformations

	❍Story drift	❍Beam	❍Column	❍Bracing	❍Connection elements
estimation	…….	..……	……..	……..	……

G) Non-Structural Elements Damage

❍Ceiling ❍Pipes ❍Interior partitions ❍Faces ❍Parapets

❍Electrical and mechanical equipments

H) Conclusions:

❍Building is relatively safe and may be occupied with probably some non-structural retrofitting

❍Building may be occupied with structural retrofitting

❍Not recommended for occupation

J) Schematic drawing of the structure.

Reconnaissance Report on Building Damage Due to Bam Earthquake of 26 December 2003

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ABSTRACT: *The post earthquake investigations of the 26 December 2003 Bam-Iran earthquake were conducted by the Joint Reconnaissance Team of the Architectural Institute of Japan (AIJ), the Japan Society for Civil Engineers (JSCE), the Japan Association for Earthquake Engineering (JAEE) and the Ministry of Education, Culture, Sports, Science and Technology (MEXT) in collaboration with the International Institute of Earthquake Engineering and Seismology (IIEES). This paper reports the results of the AIJ team on damage evaluation of the buildings around the Bam strong motion station operated by the Building and Housing Research Center (BHRC). The seismic capacity of damaged buildings was approximately estimated. The results show that many residential houses in the investigated area were seismically vulnerable structures such as adobe and simple masonry structures. Poor construction quality was also found in some of the investigated buildings designed according to the current Iranian seismic code. Moreover, good correlation between wall area ratio and damage levels was observed. Therefore, wall area ratio may be applicable for evaluating the seismic capacity and screening retrofit candidates.*

Keywords: Bam; Damage Statistics, Iranian seismic building code; Directional damage; Seismic capacity; Structural system

1. Introduction

This paper describes the outcomes of the reconnaissance team of the Architectural Institute of Japan (*AIJ*) on the damage survey due to the 2003 Bam-Iran earthquake.

The 2003 Bam-Iran earthquake struck Bam city on December 26, 2003, destroyed many buildings and houses and killed more than 25,600 people, almost 25% of the population in Bam city. The *AIJ* established a reconnaissance team chaired by Prof. M. Motosaka, Tohoku University, in order to investigate the stricken area. Damage investigation was carried out by the Joint Reconnaissance Team of the *AIJ*, the Japan Society for Civil Engineers (*JSCE*), the Japan Association for Earthquake Engineering (*JAEE*) and the Ministry of Education, Culture, Sports, Science and Technology (*MEXT*) in collaboration with the International Institute of Earthquake Engineering and Seismology in Iran (*IIEES*).

In this paper, a brief summary of Iranian building seismic code, results of the investigation by the *AIJ* team on building damages around the Bam Seismological Observatory, running by the Building and Housing Research Center (*BHRC*), and approximate evaluation of seismic capacity of the damaged masonry building are presented.

2. Building Seismic Code of Iran

The history of preparing the seismic code in Iran refers back to the 1963 Bouein-zahra earthquake with magnitude of 7.2. On 1967 the Iran ministry of Housing and Development published "the building safety code during earthquake". In this code buildings higher than 11m were restricted to steel-frame or reinforced concrete frame structures. The code had two chapters: 1- masonry buildings 2- analysis of the buildings against the earthquake. The code became legally the instruction basis of construction activities in the country on 1969, published by Iran Planning and Budget Organization. Later the second chapter of the code was added to the Iran National Standard code No. 519 (Minimum loads applied to the buildings). Since then the code became the basis of the seismic resistant design of buildings [1, 2].

In 1987, the National standard code No. 2800 "Iranian Code of Practice for Seismic Resistant Design of Buildings" was replaced instead of chapter 8th of code No. 519. Subsequently, the second revision of the code has been put into practice since 1999 [3]. The code is applicable for the design and construction of reinforced concrete, steel, wood and masonry buildings, in order to determine the minimum criteria and regulations for seismic buildings design. The criteria to design general buildings against the earthquake forces are described in chapter 2 and the seismic base shear coefficient is obtained as follow:

$$C = \frac{ABI}{R} \tag{1}$$

where:

A: Design base acceleration (ratio to gravity acceleration), which differs from 0.35, 0.30, 0.25 or 0.20 according to the regions.

B: Building response factor obtained from design response spectrum as follow:

$$B = 2.5\left(\frac{T_0}{T}\right)^{2/3} < 2.5 \tag{2}$$

T: The building natural period (sec), T_0: a scalar quantity determined according to soil specifications and may be 0.4, 0.5, 0.7 or 1.0.

I: Building importance factor (0.8, 1.0 or 1.2).

R: Building behavior factor (4 to 11).

However, the B/R ratio must in no case be less than 0.09.

Bam city is located in region 2 of seismic microzonation map of Iran with high relative seismic hazard (A=0.3g). Based on the type of the buildings investigated in area and by assuming B = 2.5, I = 1.0 and R = 4, the base shear coefficient in the area may roughly be estimated as C = 0.19.

Chapter 3 of the code describes the criteria for unreinforced masonry (confined masonry with reinforced concrete or steel elements as tie-beams or tie-columns) buildings. These buildings are limited to 2 floors with minimum 6% and 4% of relative wall sectional area in each direction for the first and second floor, respectively.

3. Typical Structural Systems in the Stricken Area

The common structural system in the stricken area, considering the load-bearing system, can roughly describe as below:

1. Adobe: adobe bricks with mud or lime mortar in form of cylindrical dome or wood beam roof.
2. Simple masonry: brick or sometimes stone and concrete block with cement mortar and jack arch roof system.
3. Unreinforced masonry: brick walls with confining elements and jack arch roof.
4. Reinforced concrete moment resisting frame with cast in place or precast slab and masonry infill walls.
5. Steel moment resisting or brace frame with jack arch or cast in place slab and masonry infill walls. (Some steel frames had no lateral resisting components)

The common slab in the buildings was the brick jack arch type, see Figure (1). The system consists of parallel I-shape steel beams at about 90*cm* distance. These beams support the brick arches, which are covered and leveled off by gypsum plaster in the bottom and mortar and tiling at the top.

These slabs are heavy and behave as a flexible diaphragm unless detailing is considered. The slabs constructed in this way are usually not tied together and to the supporting walls or girders. Therefore these kinds of slabs have caused heavy building failures and an unusually high death toll in many recent earthquakes in Iran.

4. Damage Statistics of Buildings Around the Bam Seismological Observatory

4.1. Outline of the Survey

An inventory survey of the buildings around the Bam seismological observatory (Governor's Building) operated by the *BHRC* was carried out in order to investigate the building characteristics and the

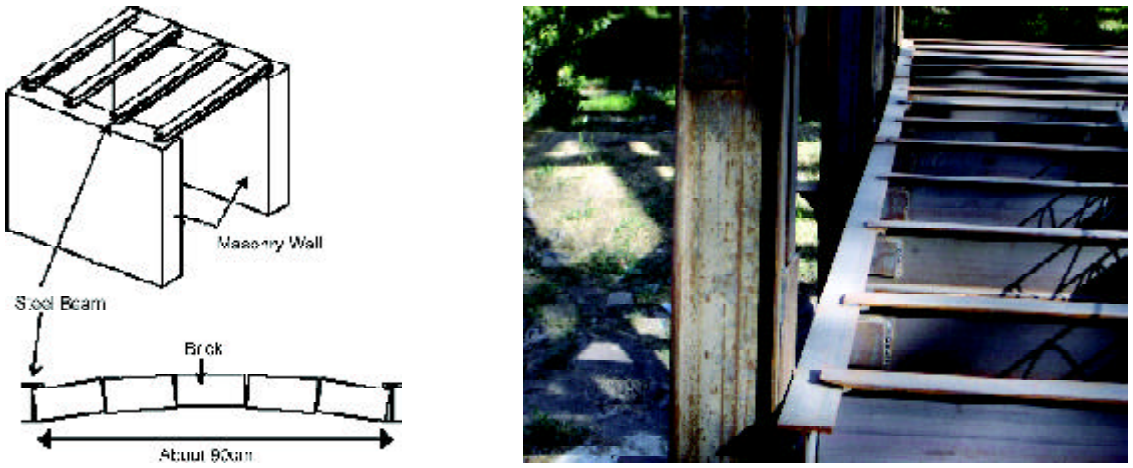


Figure 1. Commonly used jack arch slab (left: wall supporting, right: girder supporting).

damage levels. This investigation was conducted within one block along the main street in *N-S*, *E-W*, and *NW-SE* directions from the center point of Governor's Building, see Figure (2).

Data regarding to *I*: building name, *II*: structural system, *III*: age, *IV*: number of stories, *V*: usage, and *VI*: damage level of 94 buildings in the investigated area were collected. The type of buildings is categorized as follows:

Adobe : adobe masonry.
SM : simple masonry.
S-frame+SM : steel moment resisting frame with simple masonry wall.
S-brace+SM : steel braced frame with simple masonry wall.
RC-tie+SM : simple masonry wall confined with reinforced concrete tie.
RC-frame+SM : reinforced concrete resisting frame with simple masonry wall.
S : steel moment resisting frame.

Figure (3) shows the distribution of the structural systems in the investigated area. The distributions of usages of Adobe, *SM*, *S-frame+SM*, and *S-brace+SM* buildings, which occupy 90% of all 94 buildings in this area, are shown in Figure (4). The ratios of

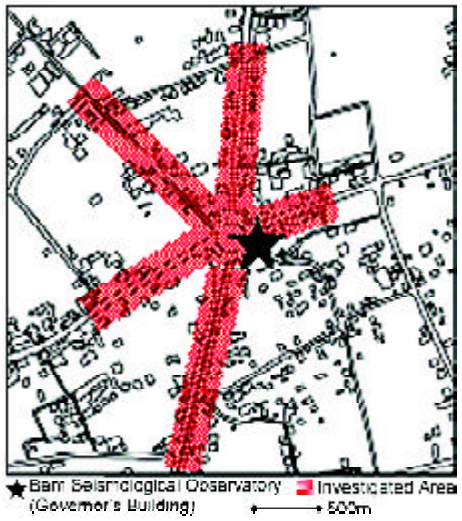


Figure 2. Investigated area.

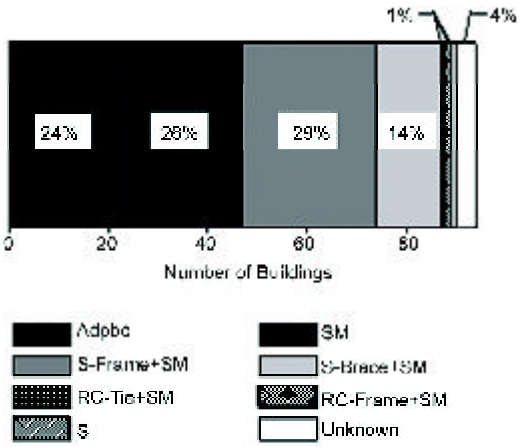


Figure 3. Distribution of structural systems.

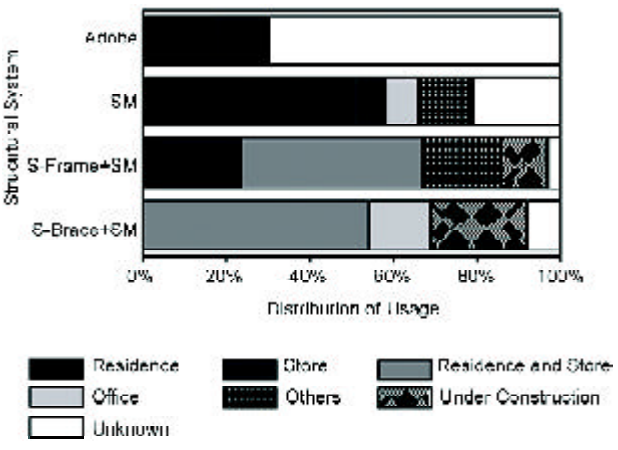


Figure 4. Distributions of usage of major structural systems.

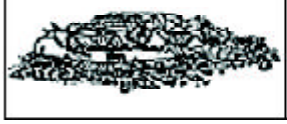
S-frame+SM and *S-brace+SM* buildings, which were mainly used for residence and store buildings, are large as those of Adobe and *SM* buildings, which were mainly used for residential buildings, because the investigated area is located in the center part of the city.

In order to have a framework for evaluating the damage grade of the buildings, the European Macroseismic Scale 98 (*EMS*-98) classification of masonry buildings as shown in Table (1) [4] was selected for the investigation. In this classification, the building damages are categorized into 5 grades.

4.2. Damage Distributions around the Bam Seismological Observatory

Figure (5) shows the damage distribution of each structural system. All Adobe buildings were classified into Grade 4 and Grade 5. The sum of the ratio of Grade 4 and Grade 5 in *SM* buildings exceeded 30%, which was much smaller than the Adobe buildings. The damage ratios of *S-frame+SM* and *S-brace+SM* buildings were considered to be much less than that of the *SM* buildings, however, there were no big differences among them. This was caused by brittle fracture of poor welded connections in a few *S-frame+SM* and *S-brace+SM* buildings. On the other hand, the damages of *RC-tie+SM* and *RC-frame+SM*

Table 1. Damage grade according to EMS-98 [4].

Classification of Damage to Masonry Buildings	
	Grade 1: Negligible to slight Damage (No Structural Damage, Slight Non-Structural Damage) Hair-line Cracks in Very Few Walls Fall of Small Pieces of Plaster Only Fall of Loose Stones from Upper Parts of Buildings in Very Few Cases.
	Grade 2: Moderate Damage (Slight Structural Damage, Moderate Non-Structural Damage) Cracks in Many Walls. Fall of Fairly Large Pieces of Plaster. Partial Collapse of Chimneys
	Grade 3: Substantial to Heavy Damage (Moderate Structural Damage, Heavy Non-Structural Damage) Large and Extensive Cracks in Most Walls Roof Tiles Detach, Chimneys Fracture at the Roof Line; Failure of Individual Non-Structural Elements (Partitions, Gable Walls)
	Grade 4: Very Heavy Damage (Heavy Structural Damage, Very Heavy Non-Structural Damage) Serious Failure of Walls; Partial Structural Failure of Roofs and Floors
	Grade 5: Destruction (Very Heavy Structural Damage) Total or Near Total Collapse.

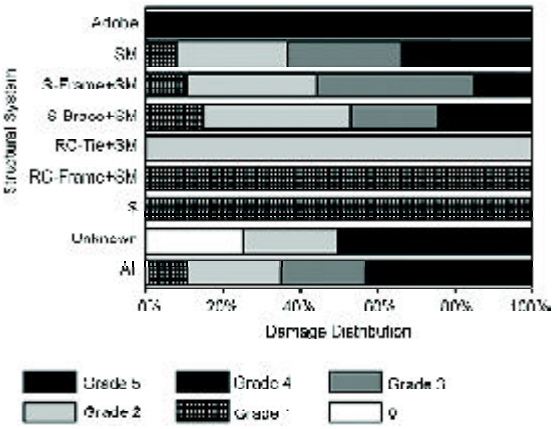


Figure 5. Damage distribution of each structural system.

buildings were quite slight because the connections in these buildings were constructed monolithically with other elements. These results, however, were derived from the only case in each system. The damage level of the only *S* building, which was the gymnasium structure, was Grade 1.

Subsequently, the relationships between the damage level and the number of stories, the construction age, and the location were investigated, however, adobe buildings were excluded from the data in order to prevent affecting the statistics. The effect of number of stories on damage distributions is investigated in Figure (6). The ratios of Grade 5 and Grade 4 were larger in case of higher buildings except the only four-story building case. Figure (7) shows the damage distributions before the establishment of National Standard code No. 2800 in 1987, from 1987 to the revision in 1999, and after 1999. No big differences were observed among these distributions; however, these results were derived from about half buildings except the unknown ones. This was caused by the technical and social backgrounds in Iran. These results revealed that the

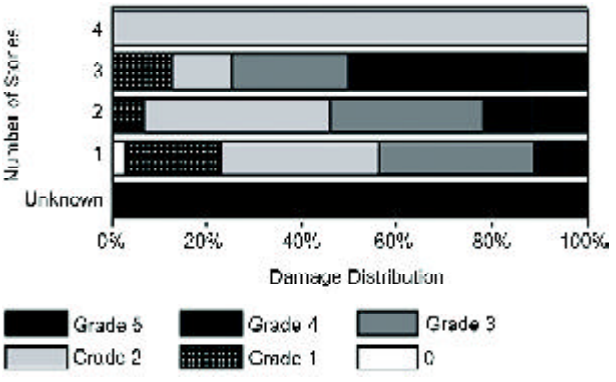


Figure 6. Effect of number of stories on damage distributions.

seismic performances of Iranian buildings were strongly affected by partial weak points, in especial the jack arch slab and poor welded connections, and that the seismic code might be not spread in the local areas. In order to investigate the effects of the input directivity (*EW* components>*NS* components in the records) on the building damages, the damage distributions of the buildings along the *N-S* and *E-W* streets are shown in Figure (8). The building damages along the *E-W* street are estimated to be lager than those along the *N-S* street considering the horizontal irregularity due to arrangements of openings in buildings along the streets, whereas the statistics result does not show significant directivity of the building damages.

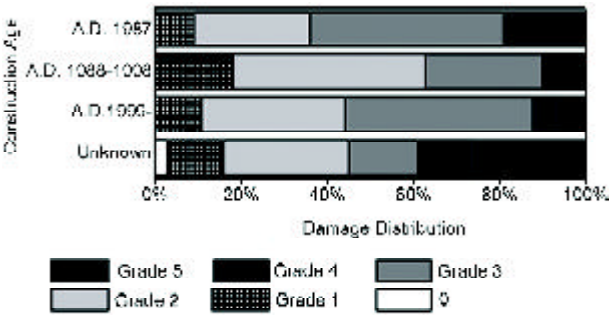


Figure 7. Effect of construction age on damage distributions.

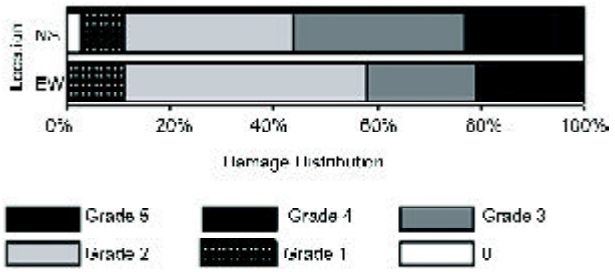


Figure 8. Damage distribution along the N-S and E-W streets.

5. Damages and Seismic Capacity Estimation of Individual Building

Four buildings are investigated in detail in order to clarify the building collapse mechanism, the relations between the damage level and the wall ratio, and the seismic capacity. The selected buildings are Governor's Building, Bam Tourist Inn which is the neighboring building of Governor's Building, 17 Shariwar High-School and an under construction residence and store building which are a few hundreds meters away from Governor's Building.

5.1. Governor's Building

Governor's Building is a two-story *SM* building with reinforced concrete horizontal ties, as shown in Photo (1). This building has an irregular plan. The wall arrangement is illustrated in Figure (9). The damage level, classified by *EMS*-98, was Grade 4 due to the partially collapses of *NW*- and *SW*-sections as shown in Photo (2). The location of the seismograph is also illustrated in Figure (9), which shows that the seismograph was placed far from both collapsed areas. The wall ratios (= the sum of the first floor wall sectional area / the first floor area) were 6.4% to 6.8% in the *NS* direction and 5.8% to 6.7% in the *EW* direction considering the unknown collapsed area.

Moreover, the damage levels and the maximum crack widths of all masonry walls in the first story were measured in Governor's Building according to the criteria shown in Table (2). The damage levels of walls are also shown in Figure (9) and the

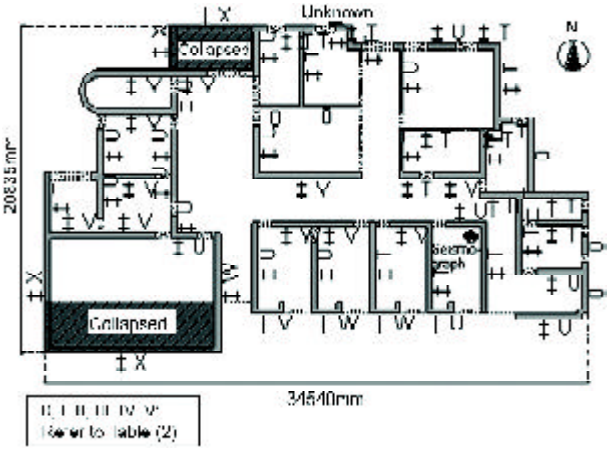


Figure 9. First floor plan and damage levels of masonry walls of Governor's building.

Photo 1. North view of Governor's building.

Photo 2. Collapse at the south west section.

Table 2. Definition of damage level of masonry wall.

Damage Level	Definition
I	Hair Crack in Finishing Materials
II	Hair Crack, Which Does not Cross the Wall Section, in Masonry Walls
III	Moderate Crack, Which Crosses the Wall Section, in Masonry Walls
IV	Partial Collapse and Serious Damage of Masonry Walls
V	Collapse of Masonry Walls

distribution of the wall damage level in each direction was shown in Figure (10). The averaged damage level of all walls in the *EW* direction of 2.3, which is calculated as the mean value of damage levels of walls in Figure (10), is larger than that in the *NS* direction of 1.7, which means the directivity of the input motions, estimated by the wall ratios (*NS*˜*EW*) and damage levels (*NS*<*EW*), corresponds to that of the actually recorded data (*NS*<*EW*).

5.2. Bam Tourist Inn

Bam Tourist Inn, used as hotel and restaurant, is a two-story SM building as shown in Photo (3). The plan of this building is relatively regular, see Figure (11). The damage level, classified by *EMS*-98, was as low as Grade 2 as estimated from Photo (3),

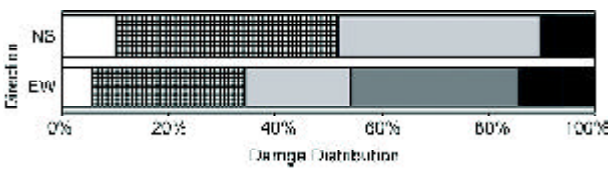


Figure 10. Distribution of the wall damage level in Governor's building.

however, the roof of the penthouse fell down as shown in Photo (4). The wall ratio in the *NS* direction was 9.4%, which was much larger than those of Governor's Building, and that in the *EW* direction was 5.5%. The damage levels of the walls, which were evaluated based on the definition in Table (2), were illustrated in Figure (11). Figure (12) shows the distribution of the wall damage level in each direction. The averaged damage level of walls in the *NS* direction of 1.3 was a little smaller than that in the *EW* direction of 2.3, which roughly corresponds to the damage level of Governor's Building except the collapsed area.

Figure (13) shows the relationships between the wall ratio and the averaged damage level and correlation between the wall ratio and the maximum crack width, respectively. It can be concluded from Figure (13a) that the averaged damage levels were larger in case of smaller wall ratio. The maximum crack widths were also larger in case of smaller wall ratio

Photo 3. South west view of Bam Tourist Inn.

Photo 4. Falling down of the roof of penthouse.

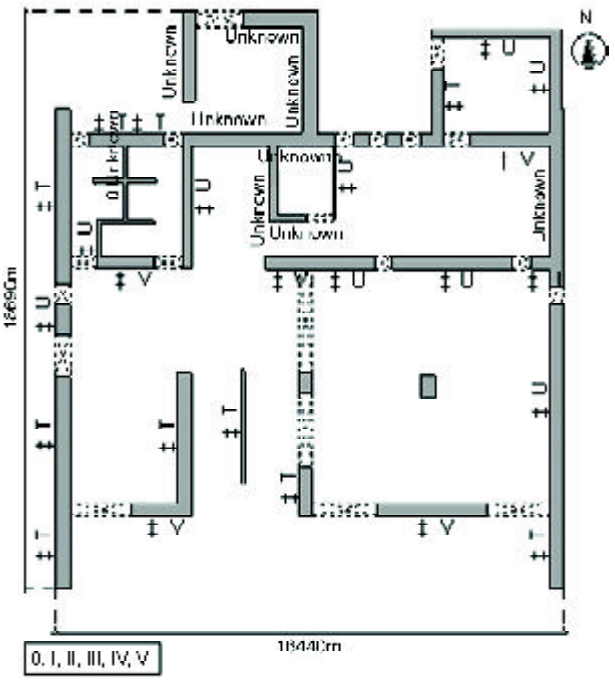


Figure 11. First floor plan and damage levels of masonry walls of Bam Tourist Inn.

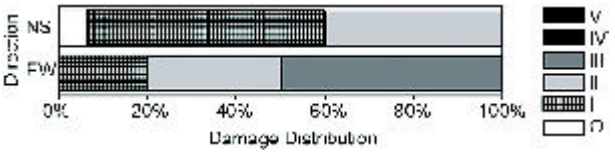


Figure 12. Distributions of the wall damage level in Bam Tourist Inn.

among the *NS* direction of Governor's Building and both directions of Bam Tourist Inn, as shown in Figure (13b). However, the maximum crack width in the EW direction of Governor's Building was much higher than those in the other cases. This may be caused by the torsional responses due to the horizontal irregularity of Governor's Building, because the larger crack widths were observed in the outside walls. The building damages can not be clarified in detail based on only the wall ratio as mentioned here, however, it can be concluded that the wall ratio is considered to be one of the reliable indexes for evaluating the seismic performance of unreinforced masonry buildings.

The base shear coefficient, *C*, of this kind of buildings can be estimated using the wall ratio in the first floor A_w/A_f and the floor weight per area w as follow:

$$C = \frac{\tau A_w}{wNA_f} \qquad (3)$$

where, N: Number of stories (=2).

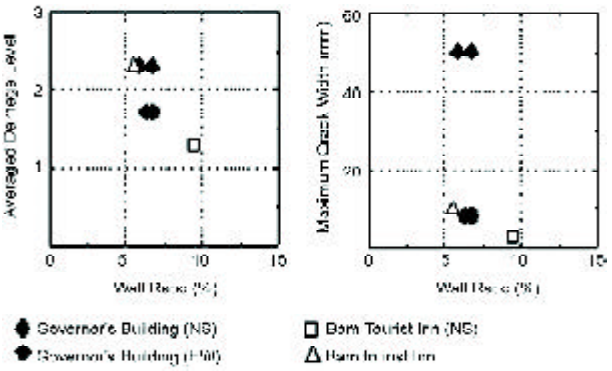


Figure 13. Relationships between the wall ratio and the wall damage level.

In general, simple masonry buildings are designed by assuming the floor weight per area of $800kgf/m^2$, spoken by some Iranian engineers. It is generally difficult to estimate the averaged shear strength per area of masonry walls τ, however, it is assumed to be $1kgf/m^2$=$10000kgf/m^2$ herein. As a result of these assumptions, base shear coefficients, *C*, are obtained as 0.63 in case of A_w/A_f=10% and 0.31 in case of A_w/A_f=5%.

5.3. 17 Shariwar High-School

17 Shariwar High-School is located a few hundreds meter west of Governor's Building and consists of three SM buildings. The two single-story buildings escaped severe damage, as shown in Photo (5), although minor cracks were found on brick walls. On the other hand, the two-story building was partially collapsed, see Photo (6). This building consists of intermediate steel frame and exterior brick walls. The floor slab system is a jack arch type, mentioned earlier. The floor plan of the collapsed part is shown

Photo 5. Single-story school building (slight damage).

Photo 6. Collapsed two-story school building.

Photo 7. Residence and store building under construction.

in Figure (14). The roof and floor slab fell off due to the collapse of an east exterior brick wall.

The wall area ratio in the first story is obtained as 4.1% in *NS* direction and 11.0% in *EW* direction. Note that the value in *NS* was calculated assuming that the area of collapsed east exterior wall is 0, not only because thickness and length of the collapsed wall could not be identified but also very short wall length may be expected due to existence of the windows and doors. The wall area ratio in *NS* direction of 4.1%, in which severer damage occurred, is less than values of the two buildings mentioned before.

5.3. Under Construction Residence and Store Building

The under construction building, see Photo (7) is located a few hundreds meter south of Governor's Building. The structural system of this building is quite typical of the buildings along the main streets in the downtown. The three-story steel structure consists of 4 bays in *NS* direction along the street and one bay in transverse direction (*EW*) as shown in Figure (15). Columns are erected using coupled I-shaped steel column, see Figure (16). Steel braces (I-shape, 70*mm*x14*mm*, 7*mm* in thickness) are installed in both exterior frames in *EW* direction. Brick walls, which are post-installed in the frame without confining by surrounding steel frame, are not expected to contribute for carrying lateral load. I-shaped steel profiles are also used for the girders and beams, see Photo (7).

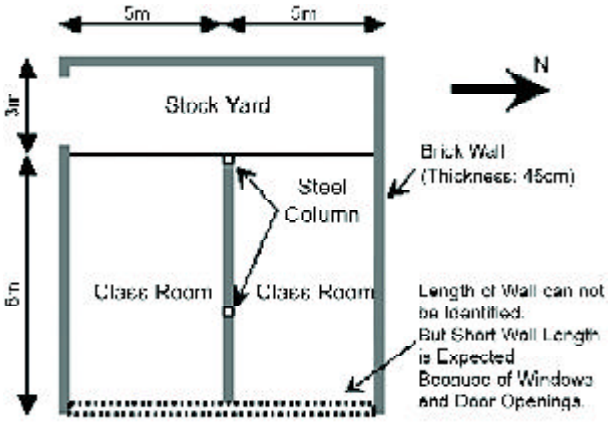


Figure 14. Floor plan of collapsed part of two-story school building.

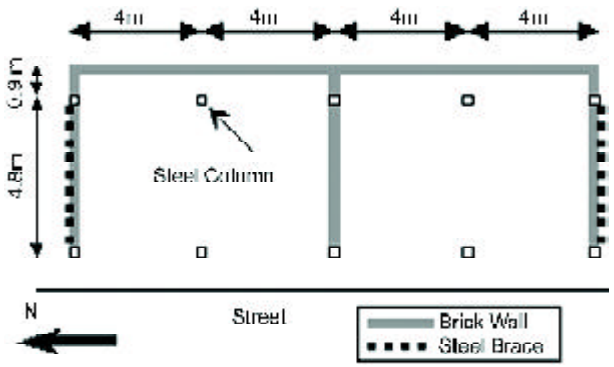


Figure 15. First floor plan.

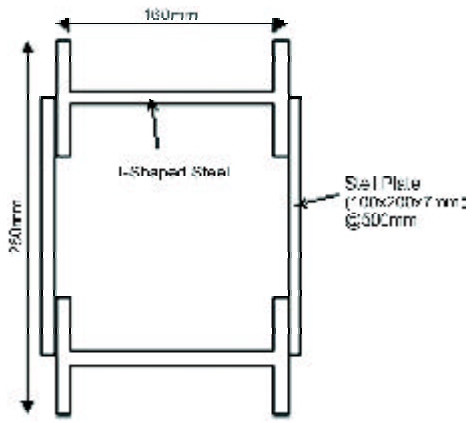


Figure 16. Section of coupled I-shaped steel column.

In the first story, fractures of welding joint and buckling of steel brace were observed, see Photos (8) and (9), and as a result, the brick walls were collapsed. Damage to the brick wall in the second story, see Photo (10) was also observed. No remarkable structural damage to the steel columns in *NS* direction was found, although bricks fell off the facade of the building.

Lateral load carrying capacity for the first story in *EW*, in the direction that the most severe damage occurred, was approximately estimated based on the following assumptions: (1) yielding strength of steel is $2.4 tf/cm^2$, (2) angle of steel brace is 45 degree, (3) unit weight of the building for each floor is $800 kgf/m^2$, and (4) floor area is $5.7m \times 16m = 91.2m^2$. These assumptions give a base shear coefficient, *C*, of 0.33. This base shear coefficient is relatively lower than the approximated values for both Governor's Building and Bam Tourist Inn. This may be one reason why this building suffered severe damage. Other reasons may be poor quality of welding, see Figures (8) and (9), and unconfined brick walls.

Photo 10: Buckling of steel brace and damage to brick wall.

Photo 8. Fracture of welded joint of a steel brace.

Photo 9. Close-up of Figure (8).

6. Concluding Remarks

Presented in this paper are the study results of the *AIJ* reconnaissance team on damage assessment due to the 2003 Bam-Iran earthquake. Many residential houses in the stricken area were seismically vulnerable structures such as adobe and simple masonry structures. Poor construction quality was found in some of the investigated buildings, designed according to the current Iranian seismic code. These might be some of the reasons for such a tragic damage to the buildings and human lives in spite of moderate magnitude (*Mw* = 6.6) earthquake.

Good correlation between wall area ratio and damage levels was observed. Although this result was derived from only two buildings (four cases), wall area ratio might be applicable for evaluating seismic capacity and screening retrofit candidates. Further studies are expected to apply it for practical design of masonry buildings.

The improvement of seismic capacity for adobe and masonry structures is a prior and urgent matter, in order to mitigate further seismic damages in such buildings, since these structural systems are most popular construction system not only in Iran but also in many Asian countries.

Acknowledgment

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References

1. BHRC Website, http://www.bhrc.gov.ir.
2. Institute of Standards and Industrial Research of Iran, "ISIRI No. 519".
3. BHRC (1999). "Iranian Code of Practice for Seismic Resistant Design of Buildings Standard No. 2800 2nd edition".
4. Grünthal, G. (1998). "European Macroseismic Scale 1998", http://www.gfz-potsdam.de/pb5/pb53/projects/en/ems/menue_ems_e.html.

Performance of Batten Columns in Steel Buildings During the Bam Earthquake of 26 December 2003

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ABSTRACT: *In recent decades, the seismic behavior of steel and steel reinforced concrete buildings has been, in many cases, unsatisfactory. In fact, after the 1989 Loma Prieta, 1994 Northridge and the 1995 Kobe earthquakes, several engineered steel structures suffered heavy damage or collapsed due to failures in their structural components or welded parts. In some countries, non-engineered buildings using reinforced concrete or steel columns and beams (particularly shopping centers and schools) were responsible for the majority of casualties because of lack of safety procedures against the effects of horizontal seismic forces. In Bam, many residential, commercial and governmental buildings were steel structures. Use of built up columns with batten plates is very common in different regions of Iran. The design of the batten columns is guided by the INBC, which is limited to the calculation of the axial capacity of these column under gravity loads. In order that the shear deformations do not reduce the axial capacity of the batten columns, some recommendations are also provided by the INBC. Taking to account the INBC recommendations the column is expected to buckle along the axis parallel to batten plates in which the buckling load is not influenced by the shear deformation. In this paper, the behavior and failure modes of steel buildings during the Bam earthquake are briefly presented. The different failure modes of batten columns observed in damaged buildings are discussed and compared with those that are expected to happen when a batten column is designed according to code provisions. An initial evaluation of damage patterns from the Bam earthquake revealed failure modes in columns, such as global buckling about the axis perpendicular to batten plates (hollow axis), local buckling, batten plate failure, and lateral torsional buckling. This demonstrates that the seismic performance of batten columns is unsafe and their use must be avoided in regions characterized by high seismic risk, at least until their behavior under dynamic loads is better understood. Finally, it is necessary to update the INBC, introducing specific seismic requirements taking into account the importance of inelastic structural response to large earthquakes and criteria based on "performance-based design" and "capacity design" principles.*

Keywords: Bam earthquake; Steel building; Batten column; Batten plate; Shear softening; Khorjini connection

1. Introduction

After the 1989 Loma Prieta, 1994 Northridge and the 1995 Kobe earthquakes, several engineered steel structures were subjected to heavy damage or collapse, due to failures in their structural components or in welded parts [1-8]. In other countries, non-engineered buildings using reinforced concrete or steel columns and beams (particularly shopping centers and schools) were responsible for the majority of casualties because of lack of safety procedures against the effects of horizontal seismic forces [9].

The unsatisfactory seismic behavior of steel buildings was also observed during the Bam earthquake in Iran. Many residential, commercial and governmental steel buildings there have been constructed in a fashion similar to those existing in other regions of Iran, using built-up columns with batten plates and khorjini connections. The latter consists of a pair of continuous beams spanning several columns and connected to the column sides by means of angle sections. Different structural systems used in these buildings are: khorjini frames in two braced directions; khorjini frames braced in the direction of the khorjini connection; khorjini frames braced perpendicular to the direction of the khorjini connection; unbraced khorjini frames; simple braced frames in one direction; simple braced frames in two directions; and simple unbraced frames.

The most common type of column in steel buildings in Iran is built-up members connected by means of batten plates. The main reason for the use of this type of column is the absence of wide-flange column sections in Iran. Special provisions for designing batten columns are presented in the Iranian National Building Code (INBC), part 10 [10]. The code provisions are limited to the calculation of the axial capacity of these columns under gravity loads.

There are also provisions for prevention of local failure of column elements and a strong recommendation that the exertion of bending moment about the hollow axis be avoided. By applying these provisions to the design of batten columns under axial load, it is expected that undesirable failure modes will be prevented and the overall buckling of the column about the axis parallel to the batten plates will be the only dominant failure mode of the column. Also, when the column is under both axial load and bending moment about the axis parallel to the batten plates, the axis of buckling and bending coincide. Adversely, when the column axis bending is about the hollow axis, lateral torsional buckling occurs because the column's weak axis is perpendicular to its bending axis.

As a result of the earthquake, many steel structures sustained major damage and different modes of failure were observed in their structural elements. In most of these buildings, batten columns with different structural systems were used. Failure studies of batten columns in Bam show the different local failure modes and also global buckling about hollow axis. These different failure modes reveal uncertainties about the seismic behavior of these columns.

Many studies on the behavior of batten columns have been done by different researchers. Most of these studies focused on the buckling of these columns under gravity loads. Unfortunately, there are no studies on the behavior of batten columns under earthquake excitation [11]. Despite the prevalence of batten columns in low seismicity regions, including European countries such as Germany, there are no seismic provisions for the design of these columns in building codes.

In order to better understanding the behavior of batten columns under dynamic loads, research and testing programs are urgently needed in Iran [12]. The results of such programs can be used to update the *INBC*, and introduce specific seismic requirements that recognize the importance of inelastic structural response to large earthquakes and criteria based on performance-based design and capacity design principles.

Many of buildings in Bam were damaged during the devastating earthquake. In most of steel buildings, batten columns with different structural systems such as simple frames, simple braced frames and frames with "khorjini" connections, were used. Failure studies of batten columns in Bam show the different local failure modes and also the global buckling about hollow axis. These different failure modes show the existence of uncertainties in seismic behavior of these columns.

In this paper, different failure modes of steel buildings and batten columns, observed in Bam after the earthquake, are presented. In constructing steel structures in most regions of Iran the batten columns are used. Therefore, in order to understand the seismic behavior of these types of columns, more researches in seismic design or rehabilitation of existing buildings with these columns, are needed.

2. The Performance of Steel Buildings

Different failure modes in steel buildings, including overall collapse and damage to or failure of structural components such as columns, braces and connections, were observed in Bam after the earthquake. The most common type of column used was the batten column. In some buildings, box columns were used and, with this type of column, failure modes such as rupture in the longitudinal joint, see Figure (1) and local buckling, see Figure (2) were observed.

The concentrically *X* braced system using channels, angles, I sections and bars is the most

Figure 1. Rupture of longitudinal joint in box column.

Figure 2. Local buckling of box column.

common type of bracing in steel braced frames in Bam. The observed failure modes in these braces were out of plane buckling and rupture of connections. The major reasons for these failures were construction defects and incomplete welding of connections. Some examples of bracing failures are shown in Figures (3) and (4).

Beam to column connections in most steel buildings in Bam are khorjini and simple connections with top and bottom angles. Weld fractures, rupture of connection devices and rupture of connection plates from batten columns were failure modes observed in these connections. Some examples of these failures are shown in Figures (5) to (7). Because of the wide range of failures in connections, one can concluded that the collapse of structures was mostly initiated by connection failures. Failure modes in steel structures such as were seen in Bam have been reported in most earthquakes [1-8].

Figure 3. Rupture of connections in concentrically X bracing.

Figure 4. Out of plane buckling of concentrically X bracing.

3. Design Basis of Batten Columns

As previously mentioned, special provisions for the design of batten columns under axial load are presented in part 10 of the *INBC*. The most important difference between batten columns and columns with

a continued web is the influence of shear flexibility on the axial capacity of batten columns when the column buckles about its hollow axis. To consider the effect of shear deformation on the axial capacity of batten columns buckled about its hollow axis, the equilibrium differential equation of buckled column is rewritten by considering the shear curvature in addition to bending curvature. Solving the equation introduces a coefficient to modify the column slenderness ratio for buckling about the hollow axis. This approach is commonly used in building codes, the only difference being the magnitude of the coefficient.

Figure 5. Weld rupture of web and top angle of connection and separation of column plate.

Figure 6. Rupture of seat angle of simple connection.

Figure 7. Separation of connection plate of batten column.

In part 10 of the *INBC*, an equation for the calculation of the modified slenderness ratio of batten columns that buckle about their hollow axis is introduced. Also, special provisions for details of batten plates, including their dimensions and distances from each others are presented. Meeting these provisions allows one to use the presented equation for calculation of a modified slenderness ratio. To ensure that the dominant failure mode of the batten columns is the overall buckling about the axis perpendicular to the hollow axis, it is recommended that the effective slenderness ratio of the column about the hollow axis be less than for the other axis.

Batten plates are the most important parts of batten columns and shear forces between chords induced by bending of the column are transferred by these components. In other words, the perfect operation of batten plates allows the batten column to have a similar performance to columns with unit sections.

If the column axial force is equal to P and the column lateral displacement at any arbitrary section due to the effect of axial force in the initial geometric imperfection is W, the bending moment M and the shear force V at this section will be equal to:

$$M = Pw \tag{1}$$

$$V = \frac{dM}{dx} = P\frac{dw}{dx} \tag{2}$$

With the assumption that the slope of the buckled column shape, dw/dx, is approximately equal to 0.02, the additional shear force due to the axial force becomes 2% of the magnitude of axial force. This shear force is only due to the inevitable initial imperfection of the column. According to the *INBC*, part 10, the shear force that is used in designing batten plates is equal to the first order shear force of the column due to column lateral loading or column end moments, plus 2% of column axial force. It is clear from the above discussion that the proposed

design force of batten plates is mainly obtained when the column is under pure axial force. If the bending moment about the hollow axis applied to the column or the slope of the buckled column (dw/dx) is larger than 0.02, the magnitude of the applied shear force on the batten plates will become larger than that considered in the design code, and this may lead to premature failure of the batten plates. Therefore, it is strongly recommended that the induction of the bending moment about the hollow axis be avoided. Furthermore, the bending moment about the hollow axis can increase the axial force of chords and initiate premature local buckling of these members.

4. Overall Buckling of Batten Columns

The overall buckling of batten columns was observed in some steel buildings in Bam. An example of overall buckling in the columns of a pharmacy is shown in Figure (8). It is significant that the buckling has occurred about the hollow axis. As mentioned earlier, according to the code, this type of buckling

Figure 8. Overall buckling of batten columns about hollow axis In a pharmacy.

is undesirable. The other important point revealed in Figure (8) is the occurrence of buckling in the top story of the building, in which columns have low gravity loads. This may be due to the increased column axial force through the effect of the high vertical component of the earthquake. Reyas-Salazar et al [13] studied the effect of vertical acceleration on the seismic response of steel frames with flexible connections. Another example of overall buckling of the batten column about the hollow is shown in Figure (9).

Figure 9. Overall buckling of batten columns about hollow axis in a store.

5. Local Buckling of Batten Columns

An example of local buckling in one of the chords of a batten column is shown in Figure (10). Because of the relative direction of batten columns and khorjini connections, in spite of code recommendations, a bending moment about the hollow axis could be applied to batten columns. This bending moment, as mentioned before, may lead to the occurrence of local buckling in batten columns, as shown in Figure (10).

Figure 10. Local buckling of one chord of batten column.

6. Lateral-Torsional Buckling of Batten Columns

Lateral-torsional buckling is a probable mode of failure in batten columns. Nevertheless, there is no special provision regarding lateral-torsional buckling of batten columns in the part 10 of the *INBC*. In some cases, lateral-torsional buckling was observed in batten columns in Bam. An example of this mode of failure is shown in Figure (11).

Figure 11. Lateral-torsional buckling of batten column in a store building.

7. Failures of Battens in Batten Columns

As previously mentioned, battens are the most important component of batten columns. In fact, shear transfer between the chords of a column is done through the battens. Therefore, failure of battens leads to separation of chords and a severe decrease in the axial capacity of a batten column.

Upon the failure of a batten plate, the distance between its adjacent battens is increased. The applied bending moment on adjacent battens also increases and could lead to failure of these and their adjacent battens. With an increase of distance between the battens, the magnitude of the modified slenderness ratio of the column about a hollow axis also increases and, hence, the axial capacity of the column may decrease or change the direction of buckling.

Special provisions for the design and detailing of battens in part 10 of the *INBC* is discussed in Section 3. Nevertheless, many cases of batten failure in batten columns were observed in Bam.

7.1. Rupture of Battens

Some examples of rupture in battens are shown in Figures (12) to (14). In Figure (12), the dimension of battens are smaller than those that are common in steel buildings. The rupture of these battens could occur due to incorrect design and construction, or usage of improper materials.

In Figures (13) and (14), battens having proper dimensions are observed. The rupture of these battens may be due to the increase of applied forces on battens relative to design forces in the codes. As mentioned, an increase of applied forces may result in the application of bending moment about the hollow axis or the occurrence of large deformations in columns. Such failures in battens are undesirable and must be prevented. It is evident that further study into the design forces of battens is required.

7.2. Ruptures of Batten's Welds

In many cases, the failure of battens in batten columns occurs in the weld of the battens to chords. Some examples of weld ruptures are shown in Figures (15) to (17). Because of the absence of quality

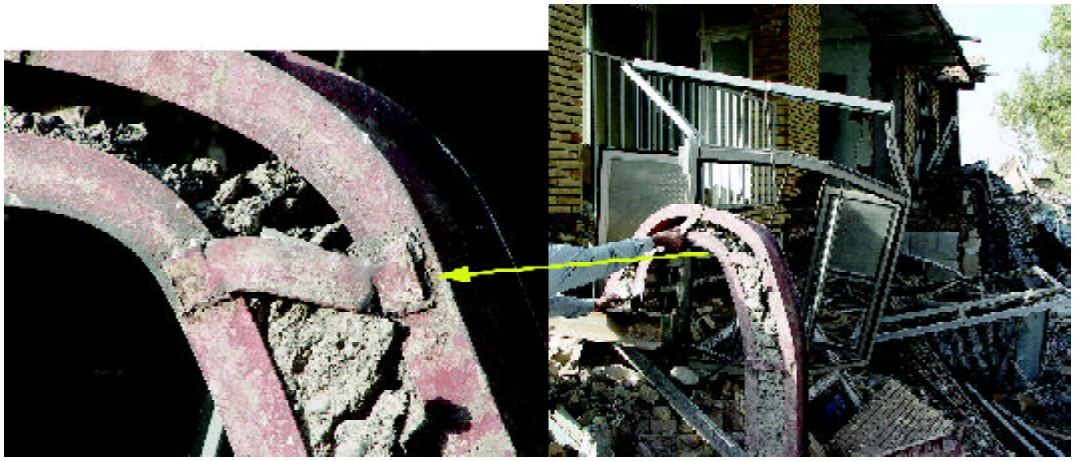

Figure 12. Rupture of battens in a two story residential building.

Figure13. Rupture of battens in a pharmacy.

Figure 14. Rupture of battens in a shopping center.

control for welding in Iran, the occurrence of weld failures in different components of steel buildings during earthquakes is expected. However, batten rupture may also lead to the rupture of batten welds. In the column shown in Figure (16), all of the battens failed at the welds. This failure may have led to separation of the chords and the collapse of the batten column.

Figure15. Weld rupture in battens of batten column in a pharmacy.

Figure 16. Weld rupture in all battens of batten column in a pharmacy

Figure17. Weld rupture in battens of batten column in an insurance building

7.3. Plastic Shear Deformation of Battens

Plastic shear deformation of battens in batten columns increases the influence of shear in the capacity of batten column and also leads to a decrease in the distance between the chords, which may cause a decrease in the axial capacity of the batten column. An example of plastic shear deformation of battens is shown in Figure (18).

8. Splice Failure in Columns

In all types of steel columns, splices are important and their failure eventuate the collapse of columns and the structure. Design and detailing and construction of

splices in columns must be scrupulous. An example of splice failure of a batten column is shown in Figure (19).

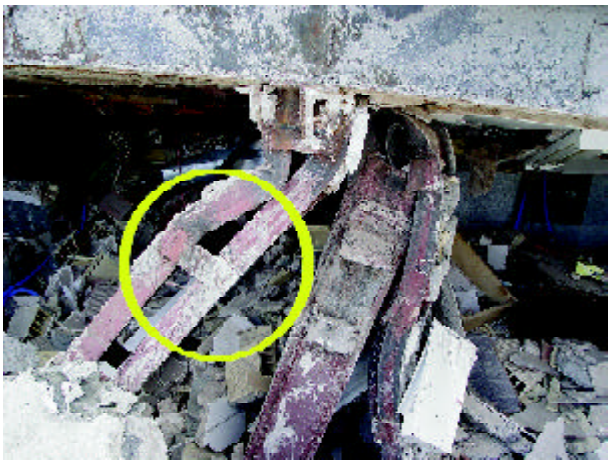

Figure18. Plastic shear deformation of batten of battens.

Figure19. Failure of batten column in splice location in kimia building.

9. Conclusions

A brief review the behavior and modes of failure of batten columns that have been observed after the Bam earthquake was presented. Important modes of failure of batten columns are overall buckling, local buckling of one chord, lateral-torsional buckling and batten failure. Some of these modes of led to a severe decrement in the axial capacity of the batten column and hence, and must be prevented.

More research is required on the seismic behavior of batten columns, which is clearly poorly understood at present. Such research is needed not only for the design of batten columns under earthquake excitation, but also for seismic rehabilitation of existing steel buildings constructed with batten columns and which are common throughout Iran. Because the existing provisions of codes for batten columns are based on static behavior under axial loading, it is proposed that the use of these columns in high seismicity regions be prohibited until codification of special seismic provisions for batten columns can be developed.

References

1. Wang, C.H. and Wen, Y.K. (2000). "Seismic Response of 3-D Steel Buildings with Connection Fractures", Paper 814, *12WCEE*, Auckland, New Zealand.

2. Minami, K., Sakai, J., and Matsui, C. (2000). "Analysis of Damage of Stell Reinforced Concrete Building Frames by 1995 Hyogoken-Nambu Earthquake", Paper 1127, *12WCEE*, Auckland, New Zealand.

3. Hyland, C., Clifton, C., Butterworth, J., and Scholz, W. (2000). "Performance of Rigid Welded Beam to Column Connections Under Severe Seismic Conditions", Paper 2541, *12WCEE*, Auckland, New Zealand.

4. Mahin, S., Malley, J., Hamburger, R., and Mahoney, M. (2000). "Overview of a Program for Reduction of Earthquake Hazards in Steel Frame Structures", Paper 2541, *12WCEE*, Auckland, New Zealand.

5. Hamburger, R., Fouth D., and Cornell, C. (2000). "Performance Basis of Guidelines for Evaluation, Upgrade and Design of Moment-Resisting Steel Frames", Paper 2543, *12WCEE*, Auckland, New Zealand.

6. Malley, J. and Frank, K. (2000). "Materials and Fracture Investigations in the FEMA/SAC Phase 2 Steel Project", Paper 2544, *12WCEE*, Auckland, New Zealand.

7. Krawinkler, H. (2000). "System Performance of Steel Moment Resisting Frame Structures", Paper 2545, *12WCEE*, Auckland, New Zealand.

8. Roeder, C. (2000). "Performance of Moment-Resisting Connections", Paper 2546, *12WCEE*, Auckland, New Zealand.

9. Arya, A.S. (2000). "Non-Engineered Construction in Developing Countries - An Approach Toward

Earthquake Risk Reduction", Paper 2824, *12WCEE*, Auckland, New Zealand.

10. Iranian National Building Code, Part 10: Steel Structures (1373). Ministry of Housing and Urban Development, Tehran.

11. Hosseini Hashemi, B. and et al (2003). "A Study on Seismic Behavior of Batten Columns with Linear Static and Dynamic and Nonlinear Static Analysis", IIEES Research Bulletin, **6**(1).

12. Ghafory-Ashtiani, M., Jafari M.K., and Tehranizadeh, M. (2000). "Earthquake Hazard Mitigation Achievement in Iran", Paper 2380, *12WCEE*, Auckland, New Zealand.

13. Reyes-Salazar, A. and Haldar, A. (2000). "Consideration of Vertical Acceleration and Flexibility of Connections on Seismic Response of Steel Frames", Paper 1171, *12WCEE*, Auckland, New Zealand.

Lessons Learned from Steel Braced Buildings Damaged by the Bam Earthquake of 26 December 2003

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ABSTRACT: *Every earthquake provides new lessons for the earthquake engineering profession. The widespread damage to welded connections in steel structures was one of the major overall lessons of the Bam earthquake of December 26, 2003. The brittle nature of the fractures detected in weakly welded steel bracing connections, essentially invalidated the design approaches and code provisions based on "ductile" structural response. This paper reviews the performance of steel braced buildings during the Bam earthquake and the implications for design practice. The results can be used to develop and verify reliable and cost-effective methods for the inspection, evaluation, repair, and rehabilitation of similar existing steel buildings.*

Keywords: Bam earthquake; Steel buildings; Welded bracing connections; Brittle failure

1. Introduction

The Bam earthquake occured on Friday, December 26, 2003, southwest of the ancient city of Bam in Kerman province of southeast Iran [1, 2]. The earthquake struck in the early morning hours (5:26*am* local time) when most inhabitants were asleep, resulting in great loss of life. Tens of thousands of individuals were crushed by the collapsing walls and roofs of poorly-constructed dwellings made of non-reinforced mud bricks. Over 85% of the buildings and infrastructure in the area were damaged or destroyed.

An additional devastating blow was the destruction of Arg-e-Bam, a citadel on the historic Silk Road which is more than 2,000 years old. Arg-e Bam is the largest mud-brick complex in the world. This historical monument was destroyed in 12 seconds of strong ground motion duration of the Bam earthquake.

The total collapse of traditional mud or mud-brick construction is evidently the result of a lack of ductility and the poor quality of the materials. However, widespread damage to and the failure of welded connections in new steel buildings is of major concern. The brittle nature of the fractures detected in numerous welded steel connections, essentially invalidated design approaches and code provisions based on “ductile” structural response.

Several fundamental questions must be answered to develop effective and economical design procedures and construction standards, and to restore public and professional confidence in current forms of construction. These questions include:

- What caused the observed extensive damage to the steel buildings during the Bam earthquake?
- How can steel buildings that have sustained relatively minor damage be identified?
- How safe are these damaged steel buildings and do they need to be repaired? How can damaged buildings be reliably repaired and/or upgraded?
- How can be new buildings designed and constructed so that they will not sustain such damage?
- Can the vulnerability of existing steel buildings to future earthquakes be reliably determined and mitigated through effective rehabilitation procedures?
- What are the economic, social and political costs

of new design or construction practices?

Answering these questions requires consideration of factors including: metallurgy, welding, fracture mechanics, connection behavior, system performance, and practices related to design, fabrication, erection and inspection. Fortunately current theoretical knowledge and code requirements are adequate, but unfortunately, current technical and professional knowledge is inadequate.

2. Strong Ground Motion

The strong ground motion of Bam earthquake was recorded by digital *SSA*-2 accelerograph in Bam station. The geographic coordination of this record was (58.35E, 29.09N) and the direction of the longitudinal and transverse components to the North direction were 278 and 8 degrees, respectively [3].

The peak ground acceleration (*PGA*), velocity (*PGV*), and displacement (*PGD*) of the Bam earthquake in different directions are summarized in Table (1). The duration of strong ground motion based on *PGA*>0.05g was about 12 seconds. These show that the greatest *PGA* of 0.98g occurred in Vertical direction and the maximum horizontal *PGA* of 0.76g occured in the Longitudinal (East-West) direction. The *PGA* of the vertical component is about 30% greater than the *PGA* of the longitudinal component.

Table 1. Strong Ground Motion parameters of Bam earthquake.

Direction	PGA (g)	PGV (cm/sec)	PGD (cm)	Dominant Period (sec)
Longitudinal	0.76	118.1	30.4	0.20
Transverse	0.60	53.3	18.8	0.20
Vertical	0.98	40.5	7.4	0.10

The spectral accelerations of the earthquake and also the Bam design spectra for 5% damping ratio are shown in Figure (1). The Bam design spectra is determined based on the Iranian code of practice for the seismic resistant design of buildings by considering design base acceleration of 0.3g (high seismicity region) and soil type *II* with T_o= 0.50*sec*. To is the period at which the constant acceleration and constant velocity regions of the design spectrum intersect (corner period).

It is clear from spectral accelerations that the dominant period of ground motion in the horizontal and vertical directions are about 0.2*sec* and 0.1*sec*,

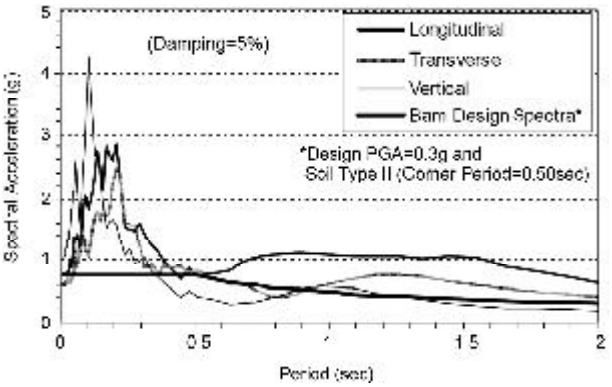

Figure 1. Spectral accelerations of Bam earthquake and Bam design spectra.

respectively. The maximum spectral accelerations at these periods are 2.85g and 4.25g respectively. Also, the acceleration amplification in these periods are about 4.0 for both horizontal and vertical components. This value is 1.6 times greater than the Iranian seismic code design requirements (standard 2800) [4].

Comparison between response spectra of the Bam earthquake and design spectra shows that the recorded event is greater than the design values (see Figure (1)). For example, the spectral acceleration of the horizontal component in dominant period (0.2*sec*) is about four times greater than the design value. This means that lateral seismic loads in the elastic range based on the Iranian seismic code are lower than those implied by Bam earthquake, especially in low rise buildings.

3. Intensity and Damage Distribution

The intensity level of the Bam earthquake is estimated to be I_o=*IX* (*EMS*98 scale), where the strong motions and damaging effects seems to have attenuated very fast especially in the fault-normal direction. The intensity levels were estimated to be *VIII* in Baravat, *VII* in Arg-e Jadid and the airport area. Also, the intensity level was estimated to be about *IV-V* in Kerman and Mahan [2].

A general view of the damaged areas of the Bam region based on the Arial photographs (1:10000 scale) is shown in Figure (2) [5]. The high level of destruction occured in old parts of the city with traditional adobe construction. However, damage distribution along the North-West to South-East direction is similar to the isoseismal map presented by Eshghi and Zare [2].

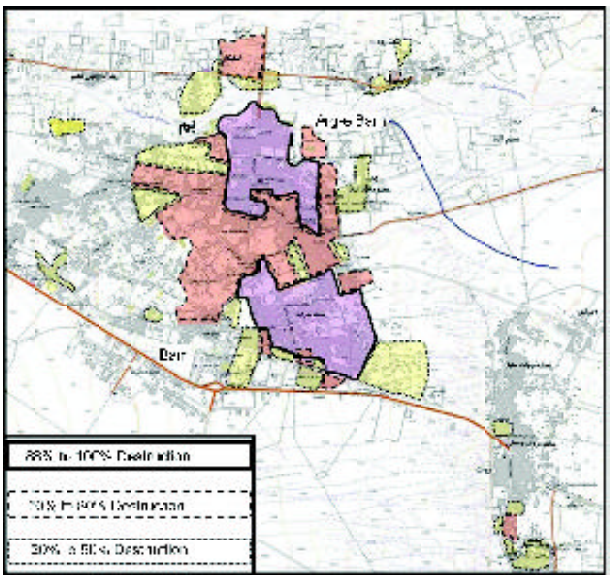

Figure 2. General view of damaged areas of Bam region [5].

Figure 3. Northern view of Kimia building.

Figure 4. Southern view of Kimia building

4. Damage to Structural Steel Construction

The use of structural steel in building construction in Iran is popular. The economy, and supposed earthquake resistance of braced steel framed buildings has led to their common usage. The same type of construction found in Bam has been used extensively throughout Iran. Thus, the effects of the Bam earthquake are an example of earthquake scenarios that have occurred in the past.

The 2003 Bam earthquake focused the attention of the earthquake engineering community in Iran on the probable seismic response of braced frames. Special attention was paid to the performance of new steel construction in the epicentral region to ascertain if the damage patterns observed had been repeated.

Five steel braced buildings have been selected by the author to investigate the effects of the Bam earthquake. These buildings are located near one an other in Bam, thus, the input earthquake motion of the selected buildings is similar. However, the earthquake *PGA* in East-Vest direction was about 27% greater than in the North-South direction, (see Table (1)), making damage in the East-Vest direction dominant. General damage patterns and failure modes of the sample buildings are described in the following sections.

4.1. Kimia Building

Northern and southern views of this five story residential steel braced building is shown in Figures (3) and (4). The lateral load resisting system of this building was diagonal bracing in the East-West direction and a simple frame in the North-South direction. As shown in these Figures, the bracings in the second and third stories fractured and a lateral movement of about 400 cm, occurred in these stories. The remaining fourth and fifth stories collapsed in aftershocks. Failure of the slender rod braces (Ø18) with very weak connections shown in Figures (5) and (6) led to a dramatic reduction in the lateral strength and stiffness of the building in second and third stories.

4.2. Insurance Bbuilding

Eastern and northern views of this four story braced building are shown in Figures (7) and (8). For architectural considerations, cross bracing of this building on the Eastern side (on the street) and also in

Figure 5. Rod bracings in stories.

Figure 7. Eastern view of the insurance building.

Figure 6. Rod bracing connections.

Figure 8. Northern view of the insurance building.

the second story was not considered. This resulted in horizontal and vertical irregularities. Weak cross bracings and very poor welded braced connections caused a sudden change in stiffness and strength of this story. Therefore, excessive lateral-torsional deformations of about 50*cm* occurred in the corner column of the second story. It should be mentioned that the height of this story was greater than for the other stories. This is a common problem occurance in buildings with shops in the ground floor. No damage occurred in the basement, surrounded by brick masonry infill walls.

A typical cross bracing member of this building (*L*80x80x8) spliced with a rod (Ø16) is shown in Figure (9). However, the failure occurred in bracing connection, not in the spliced section. In other words this kind of weak splice was stronger than the bracing connections. The masonry infill brick walls of the first story prevented the total collapse of this building. Because of excessive deformation and damage that occurred in the second story, the owner decided to demolish and reconstruct this building (Figure (10)).

4.3. Residential Building

The Northern view of this four story braced building is shown in Figure (11). Cross bracings in the second and third stories of this building failed during the earthquake. Lateral deformations of about 40*cm* occurred in the second and third stories. Fracture of tension brace member connections and buckling of compression members were the main modes of failure as shown in Figures (12) and (13). Fracture of connection plates between columns and gusset plates was another type of failure (Figure (14)).

4.4. Nursery Building

The Southern view of this three-story governmental building (a housing organization) is shown in Figure (15). This building was under construction during

Figure 9. Brace spliced with a rod.

Figure 10. Demolition of the insurance building.

the earthquake. A combination of cross and diagonal bracings was chosen as the lateral load resisting system.

Failure of cross bracing connections in the first story is shown in Figure (16). Excessive damage of bracing members is caused by the impact of compression bracing after connection failure. A compression buckling of diagonal bracings of the first story is shown in Figure (17). Built up cross sections similar to columns were used as diagonal bracings. Another type of failure in the cross bracing connections to the frame system is shown in Figure (18). This kind of connection was considered in some cross bracings that lacked sufficient length.

Figure 11. North view of the residential building.

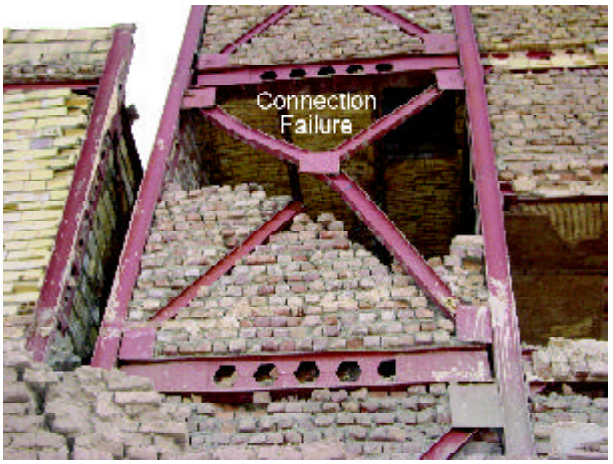

Figure 12. Fracture of bracing connections.

Figure 13. Fracture of bracing connections.

4.5. Bank Tejarat

The Southern view of this two-story braced building is shown in Figure (19). Very poor braced connections and braced member splices caused heavy damage. An example of bracing member fracture in a poor spliced section is shown in Figure (20). The small dimensions of the gusset plate, and poor quality and insufficient welding are clear in Figures (21) and (22).

Figure 14. Fracture of bracing-to-frame connections.

Figure 17. Buckling of diagonal bracings.

Figure 15. Southern view of nursery building.

Figure 18. Failure of bracing connections to frame.

Figure 16. Failure of cross bracing connections.

Figure 19. Southern view of bank Tejarat.

Figure 20. Fracture of spliced bracing members.

Figure 22. Fracture of bracing connections.

Figure 21. Very poor bracing connections.

As shown, extremely bad detailing has been used in the bracing connections of this building. It should be mentioned that all bank buildings were heavily damaged during the earthquake.

5. Seismic Demand and Capacity of Sample Buildings

The example buildings were investigated in accordance with the Iranian code provisions (standard 2800) [4]. Based on these provisions, the equivalent static method can be used for the analyses of the selected buildings. In this method, minimum base shear of a building in each direction can be determined from the following equations:

$$V = CW \quad (1)$$

$$C = ABI/R \quad (2)$$

$$B = 2.5(T_0/T)^{2/3} \leq 2.5 \quad (3)$$

$$T = 0.05H^{3/4} \quad (4)$$

In the above equations:
V = base shear
W = total weight of the building (dead load + 20% live load)
C = Base shear coefficient
A = design base acceleration (= 0.30g for Bam region)
I = importance factor of building (=1 for ordinary buildings)
R = reduction factor (= 6.0 for concentric steel braced buildings)
B = amplification factor
T_o =Corner period of the acceleration response spectra (= 0.5 sec for soil type *II*)
T = fundamental period of the building
H = height of the building from the base (in meters).

In accordance with Eq. (2), code base shear coefficient, C, or design lateral strength, $V = F_{des}$, is determined by dividing the design lateral force required to keep the structure linear-elastic during an earthquake, F_{elas}, by a response modification coefficient, $R = R_{des}$, (Figure (23)). This force reduction is allowed provided that the resulting maximum nonlinear displacement demand, D_{nlin}, can be accommodated. The maximum displacement, Δ_{nlin}, depends on the R coefficient used in design. The R coefficient in current code provisions is based on a point of first "significant yield" in the lateral load resisting system. The term "significant yield" is defined as that level causing complete plastification of at least the most critical region of the structure (e.g., formation of a first plastic hinge in the structure). This procedure is a "force-based" design procedure [6].

Based on the Capacity spectrum procedure, inelastic demand spectra S_{ai} are constructed by

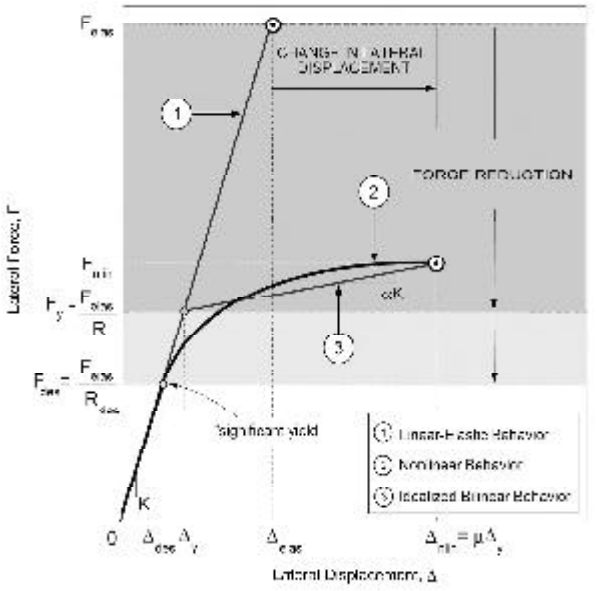

Figure 23. Lateral force-displacement relationships [6].

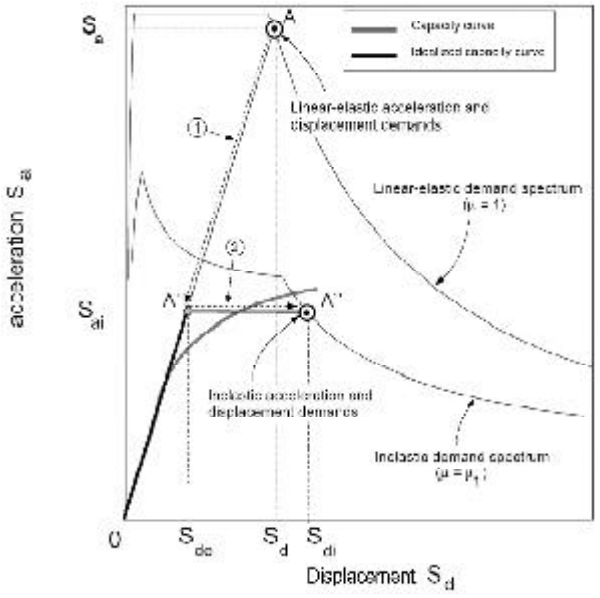

Figure 24. Inelastic demand spectra [6].

dividing the linear-elastic acceleration demand, S_a, with the R coefficient to determine the inelastic acceleration demand as:

$$S_{ai} = S_a / R \tag{5}$$

This equation can be explained in term of base shear coefficient as:

$$C_e = S_a / g \tag{6}$$

Then, the inelastic displacement demand, S_{di}, (Figure (24)) is determined by multiplying the linear-elastic displacement demand, S_{de} corresponding to S_{ai}, with the displacement ductility demand, μ (= Δ_{nlin}/Δ_y) as:

$$S_{di} = \mu S_{de} = \mu (T / 2\pi)^2 S_{ai} \tag{7}$$

Either R or μ can be specified to construct the inelastic demand spectra for use within the framework of a "force-based" or "displacement-based" design procedure. In the displacement based design procedure, a target displacement ductility, $\mu = \mu_t$, is specified and the corresponding R coefficient is calculated using an assumed R-μ-T relationship. The inelastic demand spectrum is constructed using this procedure. Inversely, in the force-based procedure, an R coefficient is specified and the corresponding displacement ductility demand, μ, is calculated [6]. A "force-based" design procedure was investigated in this article.

Parameters C, and C_e in the above equations are the code required and earthquake demand base shear coefficients, respectively. These parameters are determined for sample buildings by assuming R = 6. It should be noted that the assumed value for R parameter is considered for comparison between code and real earthquake demands and is not the real value of the sample buildings.

As noted in the previous sections, the brittle fractures detected in welded steel connections, essentially invalidated design approaches and code provisions based on "ductile" structural response. Therefore, in order to evaluate structural adequacy of sample buildings, base shear strength is compared to the demand base shears. The yield strength of a building, C_y, in terms of base shear coefficient (which can be considered as seismic capacity) is determined as:

$$C_y = V_y / W \tag{8}$$

In the above equations, V_y is the yield base shear force of a building. This parameter was evaluated based on the bracing cross section capacities or welded connection capacities in the example buildings using *AISC* code requirements [7]. All as-built structural details include tension and compression strength of brace members, strength of spliced sections, quality and quantity of welded brace connection considered in the strength evaluation. Torsional effects are ignored and only the responses of example buildings in East-West direction (critical direction) are

determined. Also, the effect of infill walls (generally hollow clay units with poor quality mortar) or other nonstructural elements have been neglected in the determination of lateral capacities.

The main seismic parameters and the results of base shear coefficients (C, C_e, and C_y) determined for the example buildings are summarized in Table (2). In these calculations, an equivalent one mass system is considered by assuming the first mode shape and ignoring the other modes. Also, the weakest story is considered for calculation of C_y as story yield strength.

Table 2. Seismic demand and capacity of sample buildings in East-West direction

Name of building	No. of Stories	W (ton)	T (sec)	R	C	C_e	C_y
Kimia Building	5	570	0.40	6.0	0.125	0.145	0.033
Insurance Building	4	380	0.34	6.0	0.125	0.210	0.011
Residential Building	4	320	0.32	6.0	0.125	0.230	0.05
Nursery Building	3	1320	0.27	6.0	0.125	0.250	0.096
Bank Tejarat	2	220	0.20	6.0	0.125	0.460	0.032

One important conclusion can be obtained by comparing C_e and C, as determined for the sample buildings. In the case of the five-story Kimia Building with a fundamental period of $T = 0.4sec$, the earthquake demand and code requirement base shears are similar ($C_e = C$). But for the two-story Bank Tejarat building with $T = 0.20sec$, C_e is greater than C ($C_e = 3.7C$). Therefore, the seismicdemands of the Bam earthquake were greater than the Iranian code requirements in the case of low rise buildings with low dominant periods.

Another important conclusion can be obtained by comparing C (or C_e) and C_y. It is clear that in all sample buildings, the code required base shear coefficients (earthquake demands) are about 1.4 to 11.4 times greater than the yield capacity. Generally, this lack of lateral load capacity of steel braced buildings is generated from very weak welding in the gusset plate connections or bracing members themselves. Since the fracture of welded connections is brittle, there is no ductility in this kind of construction and a ductility reduction factor of $R_\mu = 1$ should be considered for the example buildings. In fact, the brittle nature of the fractures invalidated design approaches and code provisions based on ductile structural response. Therefore, the failure of this kind of buildings was inevitable. A similar conclusion has been reported by Mahin [8]. However, determination of force reduction factor, R, by considering of structural overstrength factor, and allowable stress design factor in a global system (entire structure) is a difficult problem and needs more investigation.

The effect of infill walls (generally hollow clay units with poor quality mortar) or other nonstructural elements have been ignored in the determination of lateral capacities of the sample buildings. However, in some braced or unbraced steel buildings in Bam, the solid brick masonry infill walls with good quality cement mortar performed well and survived the earthquake forces. An example of this kind of good performance is shown in Figure (25). This figure shows a Southern view of a three-story building (with a basement) without any bracing in the first and second stories. The brick masonry infill is the only lateral load resisting system of this building in East-West direction. It experienced some cracking in the brick walls but the damage is much less than the adjacent braced buildings. However, where hollow clay units or poor quality mortar were used, heavy damage or total failure occurred in masonry infill walls.

It should be noted that for out-of-plain buckling in bracing members, failure of infill walls is inevitable. An example of this type of buckling in built-up braced members and failure of the infill walls is shown in Figure (26). As can be seen, no stitches have been used in the bracing members and out of plane buckling occurred in individual elements.

6. Evaluation of Seismic Code Provisions in Sample Buildings

Based on a detailed investigation of the sample buildings, the main drawbacks of steel braced frames with respect to Iranian seismic code requirements [4] and *AISC* requirements [7] can be summarized as follows:

6.1. Bracing Members

1. Slenderness: Based on Iranian code requirements, bracing members shall have slenderness ratio $Kl/r \leq 6025/\sqrt{F_y}$. Very slender rods and small size angles used as bracing membersin sample buildings do not meet this requirement.
2. Lateral force distribution: In order to prevent the use of non-redundant structural systems it is required that braces in a given line be deployed such that at least 30% of the total lateral force is resisted by tension braces and at least 30% of the total lateral force is resisted by compression

Figure 25. Masonry infill building.

Figure 26. Out of plane buckling of built up bracing.

braces. This requirement had not been observed in the sample buildings. In fact, light rods and very slender braces experienced elastic buckling under very low compressive forces.

3. Built-up members: Based on the Iranian code requirements, the spacing of stitches shall be such that the slenderness ratio (l/r) of individual elements between the stitches does not exceed 0.7 times the governing slenderness ratio of the built-up members. Generally, this requirement was not observed in built-up bracing members. An example of this kind of bulking is shown in Figure (26).

6.2. Bracing Connections

1. Required strength: Based on the Iranian code requirements, the brace connections to beam and column (including beam-to-column connections if part of the bracing system) must be stronger than the braces themselves. Investigation showed that the strength of welded brace connections in sample buildings was about 10% of the bracing members. The extremely low strength of the connections caused brittle failure of the bracing connections. This lack of strength happened both in brace-to gusset plate and gusset plate-to-frame connections.
2. Eccentricity: The axes of bracing members should be aligned with beam and column axes. Highly eccentric brace connections used in residential building tend to fail prematurely due to the large secondary stresses induced by the eccentricities (Figures (11) to (14). These secondary stresses are generated both in bracing connections and in beam and column sections.
3. Tension Strength: Based on *AISC* requirements, the design tensile strength of bracing members and their connections, based on the limit states of tensile rupture on the net section and block shear rupture strength shall be based on expected yield strength of the brace $F_{ye} = R_y F_y$ which typically exceeds its specified minimum yield strength, F_y. In Iranian code it is assumed that $F_{ye} = F_y$. However, this requirement was not met in sample buildings.
4. Flexural strength: *AISC* requirements stipulate that the design flexural strength of the connections shall be equal to or greater than the expected nominal flexural strength $1.1\, R_y\, M_\rho$ of the brace about the critical buckling axes. This requirement is not included in the Iranian code. An sample of connection failure due to bracing buckling has been observed in sample buildings as shown in Figure (17).
5. Gusset plate: Based on *AISC* requirements, the design of gusset plates shall include consideration of buckling. Otherwise, the connection elements will themselves yield in flexure (such as gussets out of their plane). This requirement is also not included in the Iranian code. In the sample buildings, compression strength of bracing members and strength of welded connections were very low. Therefore, no buckling or failure occured in gusset plates. Astane-Asl, et al [9] suggested providing a clear distance of twice the plate thickness between the end of the brace and the assumed line of restraint for the gusset plate to permit plastic rotations and to preclude plate buckling.

7. Concluding Remarks

Hundreds of damaged and collapsed steel buildings in Bam have been identified, including hospitals and health care facilities, government, civic and private offices, cultural and educational facilities, residential structures, and commercial buildings. Damage occurred in new as well as old low rise (generally lower than 5 stories) buildings. While inadequate workmanship was believed to play the major role in the damage observed, very few damaged buildings are believed to have been constructed according to new codes and standards of practice. The effect of these observations has been a loss of confidence in the procedures used in the past to design and construct welded connections in steel braced frames and a concern that existing structures incorporating these connections may not be sufficiently safe. Based on the field investigations and detailed evaluations of sample steel braced buildings presented in this paper the following conclusions can be drawn:

- Current professional judgment is that the old or traditional practices used for the design and construction of bracing connections do not provide adequate reliability and safety and should be revised in the construction of new buildings intended to resist earthquake ground shaking through inelastic behavior.
- Common failure modes of bracing members include buckling of slender members, lack of compression strength, and weak spliced sections. Also, common failure modes of bracing connections include lack of strength in welded connections, brittle failure of nonductile connections, failure of brace-to-beam-column connections, failure of gusset plate connection due to out of plane buckling.
- Lack of strength in slender and weak bracing members and lack of strength in bracing welded connections limited the lateral strength of braced buildings to 0.10 to 0.5 times that of the code requirements and earthquake demands. Since the fracture of welded connections is brittle, there is no ductility in this kind of construction and the a ductility reduction factor $R_{\mu} = 1$ should be considered for these buildings.
- Sudden failure of brittle and weak welded connections of gusset plates introduced additional impact to earthquake forces in steel braced buildings. In accordance with second order effects (P-Δ effects), this caused large drifts in soft and weak stories. Damage was so severe in some buildings that all of bracing connections on one or more stories failed or significant permanent lateral displacement (between 40-400*cm*) occurred. From these observations in Bam, it can be concluded that no bracing is better than poor bracing.
- Damage to solid brick masonry infill walled buildings with good quality cement mortar was much less than to similar braced buildings. For out of plane buckling in brace members, failure occurred in infill walls.

References

1. Eshghi, S., et al (2003). "A Preliminary Reconnaissance Report on 26 December 2003 Bam Earthquake", IIEES Research Bulletin, **6**(3 and 4), Tehran, Iran.
2. Eshghi, S. and Zaré, M. (2003). "Bam (SE Iran) Earthquake of 26 December 2003, Mw6.5: A Preliminary Reconnaissance Report", IIEES, http://www.iiees.ac.ir.
3. BHRC (2003). "The History of Bam Accelerograph Station", http://www.bhrc.ac.ir.
4. BHRC (1999). "Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard 2800)", 2^{nd} ed.
5. Geological Survey of Iran (GSI) (2003), http://www.gsi.org.ir.
6. Farrow, K.T. and Kurama, Y.C. (2001). "Capacity-Demand Index Relationships for Performance-Based Seismic Design", Report # NDSE-01-02, University of Notre Dame, Notre Dame, Indiana.
7. AISC (2002). "Seismic Provisions for Structural Steel Buildings", ANSI/AISC 341-02.
8. Mahin, S.A. (1997). "Lessons from Steel Buildings in Northridge Earthquake", NISEE, University of California, Berkeley.
9. Astaneh-Asl, A., Goel, S.C., and Hanson, R.D. (1986). "Earthquake-Resistant Design of Double Angle Bracing", Engineering Jouranl, 23 (4), (4^{th} Qtr.), AISC, Chicago, IL.

Performance of Roofs and Floor Slabs During Bam, Earthquake of 26 December 2003

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ABSTRACT: *Collapse of non-engineered roofs and floor slabs during the Bam earthquake of December 2003 was the single major contributor to the large fatalities during that earthquake. Different floor systems of buildings in the city of Bam can be categorised into three types namely; the traditional masonry dome or vault, the steel I-beam jack arch system and the concrete beam-hollow block system. In this paper the seismic performance of each type of flooring as observed after the Bam earthquake is discussed and their points of weakness and strength are highlighted. Also the poor seismic performance of the traditional dome and vault roofs and the unanchored jack arch slabs are noted and the seismic merits of the anchored jack arch slabs and concrete beam-hollow block slabs are discussed.*

Keywords: Bam earthquake; Seismic response; Domes and vaults; Jack arch slabs; Concrete beam-block slab

1. Introduction

The Bam earthquake of 2003 caused widespread devastation in the city of Bam. Despite the relatively low magnitude of the earthquake, the shallow depth of the event resulted in very high and localised ground accelerations both in horizontal and vertical directions. The recorded accelerations of 0.8*g* in the horizontal direction and 1.0g in the vertical direction were amongst the highest accelerations ever recorded for an earthquake. As a result of the high global ground accelerations, various modes of failure could be observed in structural systems and elements. The most important of the structural elements, so far as their effect on the level of earthquake fatalities is concerned, are floor and roofs.

Majority of buildings in the city of Bam at the time of the earthquake were unreinforced masonry buildings with load bearing walls or low rise steel-framed buildings. The former buildings were roofed by either the traditional masonry domes or vaults or non-engineered, unanchored, jack arch flooring system, whereas the latter buildings were mainly floored by anchored jack arch slabs. In some of the more recently constructed buildings, the floors consisted of concrete beam-hollow block slabs.

A large number of the buildings in the older quarters of Bam were traditional masonry types having masonry dome or vault roofs. These buildings are generally characterised by weak, brittle materials, weak element connections and excessive weight. The construction materials and techniques used for this type of construction have remained unchanged throughout the history for thousands of years. From around the middle of 20^{th} century a new type of floor construction in the form of steel beam jack arch slab was introduced into Iran from Europe. The new flooring system, considered as a non-engineered construction, became very popular in Iran such that the majority of existing buildings in provincial towns and villages and a vast number of buildings in Tehran are floored with this type of construction. In this flooring method a number of parallel steel I-beams are placed directly on the load bearing walls at between 80*cm* to 1.0*m* spacing and spanning from one wall to the other. The space between the two adjacent I-beams is then filled with a series of shallow brick arches, see Figure (1). The process is repeated until the whole slab area is covered. A layer of lime-clay mortar or concrete is then placed on the brick arches to create a flat surface. The slab is subsequently plastered underneath to create a flat

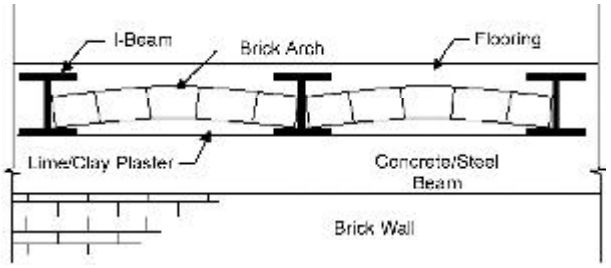

Figure 1. Steel beam, jack arch flooring system.

ceiling. Due to a number of advantages including ease of construction, speed of construction and low cost, the jack arch system is still popular in Iran. In Figure (2) the jack arch construction as a percentage of the total construction in provincial towns and cities is shown for recent years. This figure highlights the importance of studying the seismic performance and dealing with seismic design and retrofitting of this flooring type.

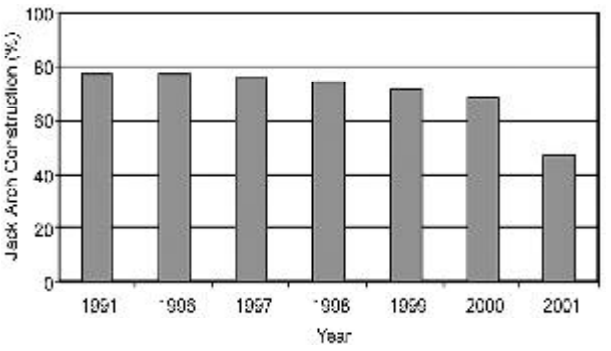

Figure 2. The trend of jack arch construction in recent years in Iran (as a percentage of total floor construction).

The steel I-beam jack arch systems are stable under normal static conditions as the brick arches transfer the gravity loads, mainly in compression. However, reports of slab damage and collapse in recent earthquakes in Eastern Europe and Iran [1-3] reflect the weakness of the unanchored slab under dynamic loading. To overcome this problem, it is suggested that the slab beams be joined together at their ends by either transverse beams or by steel tie bars [4]. This form of anchored jack arch slab has a better seismic response as the relative movements of the slab beams are somewhat prevented.

In recent years, there has been a notable trend away from the jack arch construction in favour of the more robust concrete beam-hollow block floors. This flooring system is similar in principle to the steel beam jack arch system but uses different materials and construction techniques. In this method, the steel *I*-beams are replaced by small section pre-cast reinforced concrete beams. The concrete beams are, however, placed more closely to each other at about 40*cm* intervals. The gaps between the adjacent concrete beams are filled with purpose-cast hollow concrete or earthenware blocks. The beams are inverted *T*-shaped in cross-section so that the hollow blocks can be supported on the bottom flanges as seen in Figure (3). The resulting beam-block slab is then reinforced by the addition of a 5 to 10*cm* thick reinforced concrete slab. In this way a relatively light and insulated reinforced concrete composite flat slab is constructed without using scaffoldings.

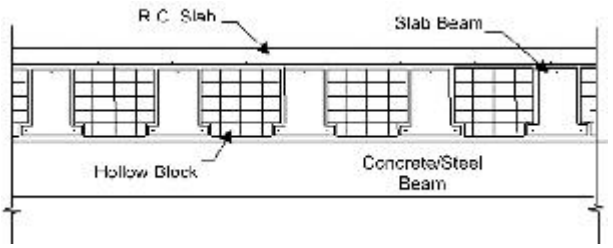

Figure 3. Concrete beam, hollow block flooring system.

2. Masonry Buildings Roofed with Domes and Faults

The poor behaviour of this type of construction under earthquake forces, observed in numerous past Iranian earthquakes, is well documented [3, 5]. Low material strength, poor workmanship, weak mortar, brittleness of sun-dried or traditionally fired bricks, lack of proper connections between perpendicular walls and between walls and the roof and non-homogeneous roofs are but a few parameters contributing to the general weakness of the structures. Added to these weaknesses, the excessive weight of the structure resulting from the thick walls and massive roofs causes an increased seismic load on the structure. The fate of the majority of these buildings in the Bam earthquake was to disintegrate into a heap of mud and brick rubble causing many casualties.

Many of the roofs of these types of buildings were vaults spanning between shared parallel load bearing walls. The typical mode of failure was the partial or total failure and collapse of the weak and heavy load bearing walls followed by the local or global collapse of the roof. These types of non-homogeneous, brittle roofs are not capable of restraining the top of their supporting walls. However, a number of vaulted and domed roofs survived the earthquake. These were in

buildings where the supporting walls had remained in place under earthquake loading, see Figure (4).

Figure 4. Survival of masonry vault roof during the earthquake.

3. Performance of Masonry Jack Arch Slabs

Many of the residential and commercial buildings in Bam were roofed with the masonry jack arch slabs. As was discussed, these slabs may be divided into two groups namely; the unanchored jack arch slabs and the anchored jack arch slabs.

3.1. Unanchored Jack Arch Slabs

Depending on the response of the load bearing walls and the construction details of the slab, in buildings floored with this type of slab, different modes of failure, stemming from certain points of weakness could be observed. A discussion on these will follow.

i) Short bearing length of the slab beams: In many instances it was noted that the bearing length of slab beams over the load bearing walls were minimal, in some cases the ends of the beams were simply resting on the edge of the walls, see Figure (5). This short supported length of beams caused increased concentration of stresses in regions of the walls already highly stressed. At the onset of ground shaking, local support failures under the slab beams resulted in the movement of the beams causing the subsequent collapse of the masonry arches. Also as the unrestrained load bearing walls moved away from the slab under ground shaking, the beams simply separated from their supporting walls and collapsed as seen in Figure (5).

ii) Use of end walls to support end brick arches: To reduce the construction cost, it appeared common practice to omit the slab beam over the end walls and to use the end walls to support the end jack arches. Since there are no proper connections between the perpendicular walls, separation of the end walls from the load bearing walls was a common mode of failure resulting in the collapse of the end masonry arches as seen in Figure (6).

Figure 5. Collapse of jack arch steel beams as a result of small bearing length.

Figure 6. Collapse of masonry arches due to the movement of end support wall.

iii) Inability of the slab to act as a diaphragm: The ill-connected composite form of the unanchored slab does not allow for a diaphragm action as is required for good seismic performance. It was observed that when a part of the load bearing wall or supporting beam failed under earthquake loading, the unsupported section of the slab had also failed. This can be seen in Figure (7) where the collapse of load bearing walls has caused the collapse and disintegration of the composite, non-homogeneous slabs.

Figure 7. Collapse and disintegration of unanchored jack arch slabs.

Figure 9. Failure of masonry arch as a result of out-of-plane bending loads.

iv) Failure of the masonry arches due to the earthquake induced in-plane forces: In the traditional one-way slabs, the in-plane axial and shear loads are transferred mainly by the brick arches. The brick arches are however ill-suited to transfer these forces. An example of the failure of a masonry arch due to in-plane loads in the direction perpendicular to the main beams can be seen in Figure (8).

Figure 8. Failure of masonry arch due to in-plane transverse loading.

v) Failure of the masonry arches caused by the out-of-plane forces: Bam earthquake was associated with very large vertical accelerations. The vertical component of the quake had caused large out-of-plane dynamic loading on the slabs. The geometry of the brick arches makes them far stiffer than the steel beams in vertical vibration. Therefore, the vibration-induced stresses tend to concentrate in the stiff brick arches rather than the more flexible and ductile steel beams, resulting in the failure of the former, see Figure (9).

vi) Weak slab materials: The type of brick and mortar used for construction of arches is of prime importance for good seismic response. The bricks used in construction of the arches were traditionally fired, heavy solid bricks with low strength to weight ratios. Using this type of bricks, not only does not increase the strength of the arch but results in a heavy slab, increasing the gravity and seismic loads.

vii) Poor workmanship: Poor workmanship was another shortcoming of the older unanchored jack arch slabs. The ability of the brick arch to transfer the load in compression depends on the rise of the arch. As it was noted in Bam, the masons tend to reduce the rise of arch as much as possible to almost a flat brick slab so that the amount of plaster required to make a flat surface is reduced to a minimum. This will change the load-carrying behaviour of the brick arch into one of a flat brick infill, susceptible to flexural failure under small loads.

3.2. Anchored Jack Arch Slabs

The above general points of weakness, as was observed repeatedly in the response of buildings in the Bam earthquake, make the unanchored traditional jack arch system unsuitable for earthquake prone areas. Considering the apparent popularity of the jack arch system, Iranian seismic code [6] proposes to anchor the ends of the slab beams to their supporting walls through concrete or steel ring beams and to join the parallel beams together by diagonal steel bars. Although observations made during recent earthquakes including the Bam earthquake of 2003 have shown the inadequacy of the code recommendations,

a better seismic performance for the anchored slabs was noted. In fact some observed performances of the anchored jack arch slabs reinforce previous numerical and experimental findings of the author regarding the seismic capabilities and resilience of the anchored slab. A good example of the resilience of anchored jack arch slab can be seen in Figure (10). This figure shows the collapse of the second floor jack arch slab of a two storey steel-framed building due to the failure of the main beam/column connections on one line of support. The slab beams are joined together by transverse beams acting as girders. The confined brick arches survived both the earthquake shaking and the collapse of the slab. Also it is noted in the same figure that the first floor jack arch slab of the building had also survived the earthquake loads and the massive shock caused by the collapse of the upper floor slab.

Figure 10. Integrity of the anchored jack arch slab under earthquake loading and after collapse.

Another example of the ability of the anchored jack arch slab to act as a diaphragm can be seen in Figure (11). The failure of the supporting columns of this building, caused by the excessive sway has resulted in the collapse of the jack arch floor slab. However, the slab has managed to retain its integrity and act as a diaphragm.

The jack arch slabs have been considered to be non-ductile, brittle composite systems. However, the behaviour of a large number of jack arch slabs during the Bam earthquake showed a different response. It was noted that the masonry arches, when confined, underwent large deformations along with their supporting steel beams and remained intact. An example of this behaviour can be seen in Figure (12) in which the masonry arch shows large deformations compatible with plastic deformations of the supporting steel beams.

Perhaps the best example of the strength and ductility of the anchored jack arch system is the masonry building shown in Figure (13). The roof of this three-bayed, single-storey building consists of continuous steel beams spanning over the supporting masonry walls and resting on purposely placed concrete blocks. The beams are joined together at

Figure 11. Ability of the anchored jack arch slab to act as a diaphragm.

Figure 12. Ability of the anchored jack arch slab to undergo large deformations.

Figure 13. Resilience of anchored jack arch slab in withstanding diverse loading conditions.

their ends by transverse steel beams. Under the earthquake loading the end support wall has completely collapsed leaving the 3.5*m* span of the slab to act as a cantilever, supported by the remaining load bearing wall. The fact that such a large cantilevered slab was capable of supporting its own weight and the subsequent large out-of-plane earthquake loading is witness to the abilities of the anchored jack arch slabs.

A large number of buildings, which survived the earthquake, had anchored jack arch slabs. In many instances the floor slabs were so intact that even minor failures in the form of cracks in plaster could not be seen. The code-designed single-storey masonry building with concrete ring beams shown in Figure (14) is but one example of such behaviour. Some of the anchored jack arch slabs had construction material and details and workmanship similar to the slabs of the building seen in Figure (15). This unfinished building also survived the Bam earthquake. The brick arches of the slab consist of lightweight perforated brick units and lime/clay mortar. The lightweight perforated bricks are far more suitable for jack arch construction as they reduce the weight of the slab as well as provide better bond between the mortar and bricks. The parallel load bearing beams of the slab are also well restrained by transverse beams at their ends.

Figure 14. No damage in this code-designed masonry building having ring-beam supported, jack arch slab.

Figure 15. Good seismic performance of anchored jack arch slabs made with lightweight perforated bricks.

It should be noted that the contemporary jack arch slab construction in Iran is still considered as a non-engineered slab in the Iranian seismic code as there are no particular design procedures for their engineered design. They still suffer from weaknesses in transferring in-plane axial and shear loads as well as the out-of-plane bending loads and the detrimental effects of dynamic interaction between steel beams and brick arches. On the other hand, considering the advantages of this type of flooring system compared to other types of flooring, the author and his colleagues have conducted a number of investigations on the jack arch slabs evaluating their seismic response [7]. Simple methods of increasing the seismic performance of the slab in the form of inter-span transverse beams were then proposed and their effectiveness investigated both experimentally and numerically [8, 9]. Finally, procedures for their engineered design and construction were introduced [10]. Although these design procedures were not applied in the construction of the jack arch slabs in the city of Bam, some existing anchored slabs had details compatible with the proposed engineered version of the slab. An example of the effectiveness of the use of mid-span transverse beams can be seen in Figure (16). It can be seen in this figure that the portion of the slab in which inter-span transverse beams are utilised to join the main beams together, has remained in place, whereas the front section of the slab which lacks similar transverse beams has disintegrated and collapsed.

4. Performance of Concrete Beam-Hollo Block Slabs

In recent years, the concrete beam-hollow block roofing system has become popular in flooring the framed structures. As a result a number of buildings in the city of Bam were floored with this type. The seismic performance of concrete beam-hollow block roofing systems were generally more favourable than the jack arch slabs. The materials and construction details of the floor provide homogeneous slabs capable of diaphragm action. The state of the concrete beam-block floors of the unfinished building in Bam

Figure 16. Effectiveness of inter-span transverse beams in keeping the integrity of the slab.

shown in Figure (17) is indicative of the good seismic performance of this type of flooring. Although the floor is inherently robust with favourable seismic response, poor workmanship could be identified as the main reason behind the failure and collapse of a number of floors of this type during the Bam earthquake. The poor workmanship may result in one or more of the following points of weakness.

i) Pre-construction damage to concrete beams and hollow blocks: In many instances the cause of slab failure could be traced back to the state of the constituent elements of the floor prior to the earthquake. Mishandling of the rather delicate pre-cast concrete beams and hollow blocks during transportation and construction had resulted in cracks and breakages in these elements prior to the earthquake.

Figure 17. Good seismic performance of well-constructed concrete beam-hollow block slabs.

ii) Lack of proper connection between the slab concrete beams and the slab support beams: During construction, the pre-cast concrete beams of the slab are positioned in place with their exposed reinforcements extended into the slab support beams. Some extra bars acting as negative reinforcements are also positioned over the slab beams and the support beams. The support beams are then cast together with the slab so that an integrated slab-support beam is obtained. It is too frequently observed that the slab beam reinforcement extensions are inadequate or non-existent and that the all-important negative reinforcements are altogether omitted. In steel framed buildings, these connection details are even more problematic as the connection arrangement between the slab concrete beams and the steel support beams is difficult to administer. This can be seen in Figure (18) in the form of separation of the slab concrete beams from their supporting steel beam.

iii) Separation of the slab reinforcement and the overlying concrete: During construction of this type of floors care should be taken to provide enough cover space between the hollow blocks and the slab reinforcement. This construction detail howeve r is often ignored a nd the slab reinforcement is slackly placed directly over the hollow blocks. In this way the overlying concrete is reduced to an unreinforced cover, susceptible to brittle failures. This can clearly be seen in the collapsed slab shown in Figure (19) in which the slab reinforcements can be seen between the blocks and the overlying concrete and detached from the latter.

Figure 18. Lack of proper connection between the slab concrete beams and the steel support beam.

Figure 19. Poor workmanship in construction of concrete beam-hollow block slab.

5. Conclusions

The performance of different types of roofs and floor slabs during the Bam earthquake of 2003 as discussed in this paper may be summarised as:

- The poor seismic behaviour of the traditional Iranian domed or vaulted unreinforced masonry buildings as observed repeatedly in past earthquakes was also well apparent in the Bam earthquake. More that 90% of this type of construction collapsed or were damaged beyond repair during the earthquake. As far as the performance of the dome and vault roofs are concerned, although they are incapable of providing sufficient anchorage for the walls, as long as the supporting walls remained in place they also did not collapse.
- The non-engineered unanchored type of jack arch slabs also performed poorly during the earthquake. However, ample examples of the potential of this flooring system as an earthquake resistant slab could be seen when the slab was anchored. It is noted that the seismic performance of existing unanchored and anchored jack arch slabs may be greatly enhanced by the provision of transverse beams at the ends and at the inter-span of the main beams according to the design provisions detailed by the author in other publications.
- The concrete beam-hollow block slabs are well suited for earthquake resistant construction. However, good workmanship is a key factor for realisation of their good seismic response.

References

1. Razani, R. and Lee, K.L. (1973). "The Engineering Aspects of the Qir Earthquake of April 10, 1972 in Southern Iran", *Report, National Academy of Engineering*, Washington DC.

2. Maheri, M.R. (1990). "Engineering Aspects of the Manjil, Iran Earthquake of 20 June 1990", Report Published by EEFIT (Earthquake Engineering Field Investigation Team), Society for Earthquake and Civil Engineering Dynamics, UK.

3. Maheri, M.R. (1998). "Lessons from Golbaf, Kerman Earthquake of 14 March 1998", *Proc. 1st Iran-Japan Workshop on Recent Earthquakes in Iran and Japan*, Tehran, 319-330.

4. Moinfar, A.A. (1968). "Seismic Activities and Conditions of Rural Houses in Countries of the Region", *Proc. CENTO Conf. On Earthq. Hazard Mitigation*, Turkey.

5. Ambraseys, N.N. and Tchalenko, J.S. (1969). "The Dasht-e-Bayaz (Iran) Earthquake of August 31, 1968, a Field Report", *Bul. Seism. Soc. of America*, **59**(5).

6. Iranian Code for Seismic Resistant Design of Buildings, Standard 2800, Building and Housing Research Centre (1988). Publication No. 82, (in Persian)

7. Maheri, M.R. (1992). "Manjil, Iran Earthquake of June 1990, Some Aspects of Structural Response", Structural Engineering Review, **4**(1), 1-16.

8. Maheri, M.R. and Imanipour, A. (1999). "Seismic Evaluation of a Proposed Two-Way Jack Arch Slab", *Proc. 3rd International Conf. Earthquake Engineering and Seismology*, **III**, Tehran, Iran.

9. Maheri, M.R. (2001). "The Gravity and Seismic Design of Jack Arch Slabs", Iranian National Research Report No. NRCI-ZL-479 (in Persian).

10. Maheri, M.R. and Rahmani, H. (2003). "Static and Seismic Design of One-Way and Two-Way Jack Arch Masonry Slabs", *Engineering Structures*, **25**, 1639-1654.

Soil Dynamics and the Earthquake Destruction of the Earthen Architecture of the Arg-e Bam

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ABSTRACT: *The Arg-e Bam is a remarkable example of earthen architecture and construction that was heavily damaged in the Bam, Iran earthquake of 26 December 2003. This paper presents the hypothesis that the collapse of the walls was caused largely by a combination of the effects of (1) the additive changes made to the walls, particularly in recent restorations resulting in variations in the density and response to vibrations of different layers of unfired earth construction in the walls, and (2) extensive damage from termites and loss of the cohesion of the clay from degradation and excessive drying out, all of which interacted with the earthquake vibrations of unusually high frequency in such a way that many walls effectively burst from the subsidence of their clay internal cores. Concern is raised about the possibility of similar risks to other earthen monumental structures from future earthquakes.*

Keywords: Earthen architecture; Earthen construction; Adobe, Khesht; Cob; Chineh; Termites; Soil dynamics; Earthquake vibration frequency; Vertical earthquake accelerations; Bam citadel; Arg-e Bam; Bam earthquake; Iran

1. Introduction

During the four months that followed the December 26, 2003 earthquake that destroyed much of the Iranian desert city of Bam, much has been said in the international press about the damage to the Arg-e Bam, a majestic historic earthen walled citadel in Iran, see Figure (1). Nowhere in this coverage, however, were there any comments about termites. While I was on a visit to the ruins of the Arg during the International Workshop on Bam sponsored by *UNESCO*, *ICOMOS*, and the Iranian Cultural Heritage Organization (*ICHO*) and, I noticed evidence of an insect infestation in the broken remains of the city's walls. The Iranian archeologists working on the site identified the insects as termites, explaining to me that such termites are relatively common in Iran, but few other conservation architects or engineers with whom I spoke were aware of the termites in the Arg [1].

While there is no question but that termites did not cause the destruction of the historic Arg-e Bam, the evidence of extensive infestation in the ancient earthen monument was unmistakable, see Figure (2). This raises the following question: Did this infestation contribute to the extraordinarily large amount of earthquake damage? While it took only 12 seconds for the earthquake to shake this majestic monument down into formless piles of rubble, the seeds of its destruction in this earthquake may have been laid over the many centuries of continuous erosion, decay, and rebuilding that have taken place on the site. When assessing earthquake damage to an earthen site, it is often easy to look no further than the earthquake shaking itself before considering any peculiarities, such as insects, that may have further weakened the earthen walls.

Many engineers and seismologists have pointed to the intensity of the Bam earthquake itself as sufficient to explain much of the damage. The seismograph records show that the vertical component of the vibrations near the site of the Arg was greater than the horizontal component, reaching a level of almost 1*g*. With such intense vertical vibration, the loads on the

Figure 1. The Arg-e Bam upper citadel before and after the earthquake. Before photo by James Conlon, 2003.

Figure 2. Evidence of termite damage in a wall of the Arg-e Bam showing extensive deposits of frass with insect tunnels.

earthen walls were rapidly cycled from losing their overburden weight to having to sustain double that weight. Because buildings are designed to carry well more than their own weight, the vertical earthquake forces are not generally considered to be as dangerous as the lateral forces. However, for earthen construction, when the overburden weight on the walls is reduced or eliminated, the lateral forces can be far more destructive than if there were only lateral motion. In addition, with vertical forces of almost 1*g*, the ancient walls were forced to sustain almost double the weight with each cycle. As will be described below, the degraded state of the inner cores of some of these walls may simply have been unable to sustain this momentary additional weight. Even so, the extent of the collapses in the Arg was greater than one would have expected. There was almost no middle ground. Almost every structure suffered partial or total collapse into formless piles of rubble, while, of those parts that did survive; some had very few cracks.

The destruction of earthen and masonry structures in large earthquakes is often accepted by observers as inevitable. Thus, inquiry into the causes of such destruction often stops with the analysis of the lateral forces measured against the capacity of the unreinforced earthen structures without consideration of other factors such as pre-existing pathologies. Yet one important anomaly in the damage distribution in the Arg-e Bam is worthy of further investigation - those structures that had not been recently maintained or restored survived with significantly less damage than did those that had been restored and even strengthened in recent years, see Figures (3), (11), (18), and (27).

Despite its history as a fortified site, all of the walls and buildings in the Arg were composed of unfired earth, and thus were weak and brittle. Yet even if one recognizes this fact, the extent of the destruction was

Figure 3. Unrestored ancient earthen structures including the Shahrbast Wall in the distance after the earthquake. These structures were only lightly damaged.

nevertheless remarkable. There have been few past earthquakes to prepare one for the extent of the destruction seen both in the Arg and in the modern town adjacent to it. There was hardly a single building type, ancient or modern, that did not suffer total destruction. Even many of the steel frame buildings constructed over the last decade ended up with their steel frames wrapped into shapes like pretzels on top of heaps of crumpled infill masonry walls and floors. In the case of the ancient Arg, little remained that resembled complete buildings. A sea of formless rubble extended out as far as the eye could see (Figure (4) and (13)). Even the Governor's House and Tower astride the hill that formed the central symbolic image for the site disappeared, leaving behind ruins that resembled a natural rock outcropping, untouched by human hands, see Figures (1) and Figure (29) for location of sites.

What occurred to cause all of this? Is it explained by the intensity of the shaking alone? In a comprehensive ten-year research project on the seismic behavior and protection of historic adobe building by the Getty Conservation Institute, the researchers concluded that "It is often assumed that an unreinforced masonry structure (such as adobe or brick) is safe only while it is largely undamaged, that is, if it has not sustained substantial cracking. The usual analysis assumes that once cracks have developed the materials have lost strength and continuity - and therefore the building is unsafe. However, a thick-walled adobe building is not unstable after cracks have fully developed, and the building still retains considerable stability characteristics even in that state" [2].

Figure 4. View of the ruins of the Arg-e Bam.

Since it took only a little over 10 seconds for the earthquake to level much of the Arg-e Bam, the Getty project's important findings on adobe structures clearly cannot be applied to this site. Why did the Arg prove to be so unstable? Shouldn't the structures and ramparts, with their thick earthen walls, have remained standing, even if heavily cracked? Were they simply overwhelmed by the unusually large surface shaking for a 6.5 earthquake, or is this now an unsettling exception to the Getty Seismic Adobe Project's findings? In either case, does this mean that the rest of Iran's most celebrated monuments, many of which are largely constructed of unfired earth, eventually may suffer the same fate?

2. The Citadel and Walled City of Bam

The Arg-e Bam has been recognized as the world's largest earthen complex. Unlike many earthen monuments that are clad with brick or stone, the structures in the Arg were entirely composed of unfired earthen construction. This construction was of two distinct types - unfired "adobe" masonry, known in Farsi as "Khesht", and built up earth or "cob" construction, known as "chineh" [1], see Figure (5).

Even the arches, vaults and domes were constructed of sun-dried bricks using a technique of construction that avoided the need to provide structural centering. Both types of construction could be found in many of the structures, sometimes in layers where the later work, including 20^{th} century restoration work, would be in Khesht, while the original work would be chineh, see Figures (7) and (17).

The news accounts that spread around the world gave the impression that tens of thousands of people died in ancient mud buildings. Instead, almost all of the 30,000 who died in the earthquake were in

Figure 5. Chineh wall inside the Arg-e Bam that was only slightly damaged in the earthquake.

buildings that were less than thirty years old [4]. For five decades prior to the earthquake, the Arg was an archeological museum. At the time of the earthquake, which occurred at 5:27*am*, only three people were sleeping in the Arg complex. The two guards sleeping in the gatehouse were killed, but the chief conservator, who was sleeping in the archeology office in the Arg, was rescued from under the rubble. Had the earthquake happened during the daytime, there undoubtedly would have been more fatalities in the Arg.

As an archeological site, many of the structures in the Arg were already in ruins prior to the time of the earthquake. The walled town was gradually abandoned in the nineteenth century as people migrated out to houses located in the date palm orchards nearby. Gradually, the houses and public buildings in the Arg fell into ruin through a slow process of erosion of the earthen walls and domes. Only the structures on the rock outcropping continued to be used and maintained as a military base until vacated under orders from Reza Shah following the demise of the Qajar Dynasty in 1925, see Figure (6).

Beginning in 1953, the site became recognized as a nationally significant historic site and a gradual process of conservation and restoration began. Most of the restoration work has been carried out over the past 25 years. Some of the ruins in the shadow of the military citadel were restored back into complete buildings. The final step in this restoration process was to plaster the exterior surfaces with a layer of mud plaster reinforced with straw. Most of this modern-day restoration work appears to have been done with square sun-dried bricks, rather than in chineh.

Figure 6. Late Qajar Period (19th Century) view showing soldiers in the inner citadel.

Figure 7. View of collapsed outer walls of a round tower. The Khesht construction of the outer layer has fallen off of the earlier inner layers that are most likely a combination of periods of building in different methods.

3. Damage to the Arg-e Bam

The following observations on the damage to the Arg were made over a brief two-day series of visits to the Arg, during a seven-day period in April 2004 when the *UNESCO-ICOMOS-ICHO* Workshop was held. The following explanations of the causes of the damage are hypotheses based on this rapid survey. Definitive determinations on all of the causes of the damage could not be done during such a short visit, but it is hoped that these observations can help to define areas for further research.

At first view, the damage to the Arg is so extensive as to defy any attempt to classify or interpret it. The structures were pulverized, often leaving only mounds of rubble at the base of a few remaining standing walls and piers. Few of the walls survived to their pre-earthquake height, and many of those structures that had been fully restored back into

buildings were returned to a ruined state with less remaining standing than had existed prior to the last fifty years of restoration work.

After an exploration of the site, some patterns in the damage began to emerge. These included the following: (1) the circular structures, such as the turrets on the ramparts, fared worse than the long straight walls and rectangular structures (Figure (1)); (2) the Governor's House and other structures on the top of the hill were more completely destroyed than were the structures lower down the hill (Figure (1)); (3) almost every structure in the Arg that remained standing showed evidence of the onset of damage through the spreading to their walls from the inside-out as evidenced by the preponderance of vertical cracks, see Figures (7), (8), (16) and (17); (4) most of the earthen masonry domes and vaults in the complex, many of which had been rebuilt in the late 20th century, collapsed. The largest dome in the complex on the icehouse, a structure that was outside of the walled town that had been converted to an auditorium, collapsed as if punched in.

With regard to interesting examples of surviving structures, one could not help but notice the following: (5) a brick reconstruction of a structure with internal vaults over an ancient water cistern in the center of the stables courtyard, see Figures (9) and (10), survived with no evidence of even so much as a crack from the earthquake. In aerial photographs taken in 1974, the cistern was uncovered and the current structure is a recent reconstruction in modern fired brick masonry. (6) The outer ramparts on the south, east and west sides of the walled city suffered a great deal of damage, with the loss of their projecting turrets and complete destruction of the top crenellations and walkway, yet the north facing ramparts survived in better condition, see Figure (18). (7) In the structure known as the "Small Caravansary", the second level of the side that had a series of buttresses along the outside wall collapsed, whereas the opposite side, which had no buttresses, survived almost intact, see Figure (19).

Most intriguing and significant, perhaps, are (8), those structures that had been maintained and

Figure 8. Pier in a partially collapsed section of the Caravansary showing the bursting of the outer layers from internal expansion from the earthquake vibrations.

Figures 9 and 10. Before (November 2003) and After (April 2004) of the same view of the Stables courtyard showing the superstructure over the cistern that was recently reconstructed in fired bricks (Before photo by James Conlon, 2003).

repeatedly modified and expanded over time (such as the structures of the inner citadel) and those structures that had been partially or wholly strengthened and restored during the late 20th century (such as the outer ramparts and buildings of the lower town) fared significantly worse than did those ancient structures - both inside and outside of the Arg - that had not been maintained, modified or restored.

The unmodified and restored structures included most of those in the north-west section of the walled town known as the "Konari" neighborhood, and also those structures just outside of the Arg to the north-east including the tall "Shahrbast Wall", (Figures (3) and (20)) located near the icehouse, and the "Khale Dokhtar", (Figure (28)) located on the opposite riverbank to the north. Some of these surviving unrestored structures are of considerable size and height, and were undoubtedly subjected to shaking of close to the same characteristics as the rest of the Arg, but they remained standing, except for some smaller parts that broke off (Even in these few collapsed sections in the Khale Dokhtar and other structures, termites were also in evidence), see Figures (3), (11), (20) and (27).

Figure 11. Unrestored ruins in the Konari neighborhood of the Arg-e Bam that survived the earthquake with comparatively little damage.

The question that presented itself after these observations was: Is there any single condition that can explain all of these phenomena? During the brief study of the site, two unrelated experiences have contributed to my assessment of what may have caused so much damage, in addition to the high frequency vertical earthquake vibrations. One was the discovery of the termite infestations on my first visit to the Arg, and the second was the chance experience of the largest aftershock to be felt at the site in many weeks. The aftershock, 3.8 on the Richter Scale [5], rolled through the site at 7:10 *am* on the 20th of April. Fortunately that was a day that a small group of us had visited the site shortly after dawn. Standing in the middle of the Arg, the aftershock was felt as a high frequency vertical vibration. It can be described as being like standing on a platform above an engine that was just starting up, but not firing on all cylinders. It lasted only for about four or five seconds. A small amount of dust rose from the complex, but no further damage was sustained.

This vibration was at the opposite end of the spectrum from the kind of earthquake that had, for example, affected Mexico City in 1985 or even San Francisco in 1989. Emanating from directly below the site, rather than from some distance away, the waves caused vertical shaking and vibrated at a high frequency. The earthquake records from the one instrument that was in Bam that was located near the site of the Arg recorded strong vertical vibrations of between 15 and 20*hz* (cycles per second), a higher frequency than the predominant horizontal vibrations that were about 10*hz* [6]. Strong high-frequency vertical shaking alone is capable of causing extensive damage to load-bearing earthen and masonry structures, but there had to be a plausible explanation for the counter-intuitive observation that the unrestored parts of the complex did better than those that had been strengthened and restored. That is where the issue of the termites enters into the picture.

I first noticed the insect damage on the one rampart wall in the center of the complex that survived the earthquake intact, the "second wall of the Governmental Quarter". There was one small area on this wall that had been broken open, exposing the inner core of the wall. Insect tunnels were visible on this newly exposed section, and the entire surface was covered with frass (fecal pellets).

I followed this observation with a crude visual experiment. During the walk out of the Arg, selecting walls at random, I looked to see if similar insect evidence could be found on other broken surfaces. In every instance, insect damage was in evidence on each of the newly exposed inner surfaces that had been broken open by the earthquake. This evidence consisted of both tunnels into the still standing portion of the walls, and large amounts of frass on the interface between the fallen and standing portions. The earth itself in these areas was extremely friable.

There was evidence that the surfaces between many of the fallen and standing portions of walls had been the interface between earlier and later work. This interface had contained many channels left by the insects that gave access to those tunnels that drove deeper into the (usually) older material that was still standing.

Termites live in earth and feed on organic material - that is, the same kind of cellulose that is frequently used to reinforce adobe bricks and the earth stucco used in earthen construction. Thus, the concentration of termite passageways in the interface between newer and older construction appeared to have weakened and separated the different layers of construction.

Figure 12. View of section of earthquake-caused collapse showing timber consumed by termites.

If further research does prove that the termites were concentrated in the interface between zones of construction of different periods, it can explain why the later construction tended to fall off of the older cores of the walls. In addition, once they have perforated the matrix of the earthen wall, the termite tunnels may have contributed to the further drying out of the earth itself, with a commensurate loss of cohesion that comes from an excessive drying out of the earthen structure [7].

4. Collapse from the Inside Out

The termites are only a part of the larger problem of the internal degradation of the walls, but seeing how pervasive the insect tunnels were throughout the ruins did alert me to consider the possibility that the many of the collapses in the Arg may have initiated from failures deep inside the thick walls.

As I explored the ruins of the still impressive earthen complex, it was, of course, difficult to come up with a single theory that could explain the nature and extent of the damage. I had expected to experience the kind of damage described by the Getty Seismic Adobe Project with the classic signatures of structural weaknesses inscribed on them: shear “X” cracks, cracks propagating out from the tops of windows and doors, collapsed corners, overturned walls, etc. However, in the Arg, even the usually common diagonal or "X" cracks were relatively rare. It appeared as if the structures had exploded from the inside and crumbled straight to the ground in a scatter of small pieces. Rubble was everywhere. It formed a mat of broken material that in some places was almost as high as the still-standing remains of the walls. The previously completely restored Grand Mosque, for example, was completely unrecognizable after the earthquake. In the rubble pile, there was even barely enough left intact to discern the outline of what had been its large courtyard, see Figure (13).

Figure 13. Ruins of the Grand Mosque. The north-west section of the main courtyard was on the right side of the view.

It was only after having a chance to take in all of the evidence that could be seen in four short visits to the site over a six-day period that a pattern began to emerge. First it became apparent that walls did not crack into a series of larger sections that could rock back and forth as the Getty project had predicted based on the adobe buildings they had studied.

Instead, the Arg buildings appeared to have responded to the high-frequency vibrations like unconsolidated earth fill. The study of the situation thus seemed to require a change of discipline - from structural engineering to soil dynamics.

The more we examined the site, the more compelling this explanation became. In a number of locations there was evidence of lateral spreading of the kind that one would expect to find around the shore of a lake - but in this case it was located on dry ground where historically the surface had been built up to create the level terraces on which the buildings were constructed on the lower hillside. One section of the terrace that supported a building above the stables collapsed altogether, carrying away the front half of the rooms constructed on it, see Figure (14). The round turrets appeared to have failed at the bottom, instead of splitting apart at the top as one might have expected. Their seemingly strong walls were simply pushed out at the base, with sections of the upper walls having slid down the rubble with the upper ornamentation remaining as the only recognizable pieces left.

Figure 14. Buildings above the Stables courtyard that collapsed from the lateral spreading failure of the retaining wall and fill beneath.

While trying to make sense out of this chaos, I recalled (without remembering the name of the site) a pair of lecture slides seen years before of a truncated stone pyramid in Central America that had an earthen core. The first image was of a seemingly indestructible squat stone pyramid. In the second image, taken after an earthquake, the stone exterior of the structure lay scattered on the ground, leaving only a lower mound of earth where the structure had been. The earthquake had simply blown the heavy stone shell apart with explosive force as the earthen core shook down to a new level [8]. It seemed an implausible kind of damage at the time, but, after seeing the same phenomenon in the Arg, the parallel was unmistakable. If the earthen core in a wall loses its cohesion, then the settling of the core can blow out of the containing exterior surfaces. It is like a child's sand castle on the beach when stepped on by an older brother.

The aftershock at 7:10*am* on the 20th of April provided a palpable sense of what had happened during the main shock. As the records did show, the main earthquake on December 26th was recorded as having a high frequency vibration, particularly in the vertical direction. From the sensation felt during the aftershock, it did feel like the kind of vibration that could cause soil subsidence - much the same way that a vibrator causes freshly-placed wet concrete to flow. The experience then began to explain each of the seemingly disparate and sometimes counter-intuitive phenomena described in the list above.

For example, in the case of (1) the first observation, the particular vulnerability of the circular turrets may be explained by the fact that they had contained large amounts of unconsolidated fill in their bases. One of the few that survived is to the right of the 2nd gate (Figure (15)), and it has a timber floor diaphragm with timbers penetrating the walls located beneath the upper windows, with a room, rather than solid fill, below. The absence of the fill, combined with the effectiveness of the floor diaphragm may have been instrumental in holding it together.

Figure 15. One of the few surviving turrets has a room in its base, as shown by the ground floor window. The floor diaphragm timbers extend through the walls, and are now visible after the stucco fell off. The collapsed masonry and stucco is from what appears to be a modern-day modification of the shape of the tower in the tradition of Viollet-le-Duc. The tower's original surface underneath is intact.

In the case of (2) the collapse of the structures at the top of the hill (Figure (1)), this seemed to be caused in part because the failure of the retaining walls and fill that had been constructed up from the lower hillside to widen the platform at the top of what had originally been a narrow rock outcropping. The failure of (3) the walls of many of the buildings and ramparts was also consistent with the lateral spreading of the material in the cores of their walls, with the exterior adobe bricks being forced out as manifested by the greater frequency of vertical cracks as compared to diagonal cracks, see Figure (16) and (17).

Figure 16. Collapsed round turret on the ramparts that shows evidence of having burst apart from collapse of internal layers.

Figure 17. A massive pier composed of different periods and types of Khesht and chineh construction that have separated from each other during the earthquake.

In the case of (4), the collapse of the domes throughout the complex, many simply may have followed their bursting supporting walls to the ground. Others which collapsed inward, like that of the Icehouse, suffered from the effect of the intense vertical vibrations on the soft adobe brick masonry. The momentary doubling of the weight of the domed structures was probably more than they could handle. In the case of the Icehouse, the 1974 aerial photographs provide evidence that the part of the dome that did collapse had been reconstructed after that date, as it was missing in those photographs [9].

By contrast to the bursting walls (5), the masonry structure over the cistern in the center of the stables courtyard performed much better despite being of unreinforced masonry. Most likely in this case, the walls were of a uniformly solid and bonded masonry construction without a rubble core. The fact that it was constructed of fired brick would have contributed to its strength, but what may even have been more important was the fact that the walls were of a fully cohesive material of uniform density without voids or vertical gaps.

As for the better behavior of the north-facing ramparts compared to the other city walls (6), the subsurface soil conditions along the riverbank where the wall is located may account for some of this difference because the alluvial soils may have served to damp out some of the vibrations, rather than intensify them, as is often the case with earthquakes where the epicenter is farther away. Further research is needed to determine whether this may be one explanation. Also, like the nearby Konari neighborhood, these walls had not been altered and restored along their tops as much as had the other walls around the Arg. It was the newer restored upper level battlements, walkways and crenellations that consistently suffered the most, possibly because of the different densities and vibration response of the new and old material and the additional weight.

Figure 18. North-facing ramparts that were significantly less damaged in the earthquake than the other city walls. Notice that the crenellations are still intact on this one section, the only section where that was observed to be the case.

The second-to-last item (7) is the Caravansary, where the rooms on the second level of the buttressed west side of the complex collapsed, leaving the east side that lacked buttresses largely intact. The buttresses themselves were also damaged, with one collapsing from the crushing of its base.

The story of this complex became even more interesting when I learned from the old photos that the side that collapsed had been almost completely reconstructed only a few years earlier, whereas the still standing side had mostly survived from antiquity. In aerial photographs of the caravansary taken in 1974 [10], the domes on the east side were almost completely intact, whereas on the west side they had collapsed. At that time, the buttresses on the west side only extended up to the level of the first floor. As late as 1996 the condition of both sides was similar to 1974, except that the small holes in the east side domes had been fully repaired [11].

Figure 19. The ruins of the Caravansary show that the domed rooms on the second level behind the buttresses have collapsed, while the ones opposite still remain. There are no buttresses behind the external wall of the opposite side. The base of the 5th buttress is crushed.

At the time of the earthquake, photographs show that the restoration of the west side of the Caravansary had been completed [12]. The domes had been reconstructed and the west wall and buttresses had been extended up to the roof level. Ironically, in the earthquake it was this newly constructed and fully buttressed side that fell. This was simply one more example of the finding that the areas with the greatest amount of strengthening, reconstruction, or even of continued maintenance were the most heavily damaged.

All of this evidence taken together seems to point

Figure 20. The interior of the unrestored "Shahrbast Wall" showing 3-story high walls that survived the earthquake. Notice the older section with later work constructed around it. This is a good example of the onset of damage at the interface of construction of different age and type, as a small area of collapse has revealed this interface. Notice the debris on the ground.

to a phenomenon where those earthen walls that are composed of material of different densities and construction characteristics resulting from their different phases of construction, repair and reconstruction, proved to be more vulnerable to the earthquake vibrations. As long as one perceives of the earthen construction as having a uniform composition, it is difficult to understand why the strengthened and restored walls would fare worse than the unrestored and naturally eroded walls. However, the succeeding phases of construction in the Arg over the centuries had produced walls of a very different composition than that of a newly constructed earthen building.

No longer did many of these walls consist of horizontal layers of earth or sun-dried bricks, and those that did consistently appeared to be less damaged. Instead, through generations of erosion, repair and remodeling, many of the walls had evolved into a series of vertical layers of earth, standing together like books on a shelf without bookends. Each of the different layers was of a different density and cohesion resulting from the different ages, construction characteristics, and degradation. For example, modern Khesht (adobe masonry) frequently encased older chineh (cob) construction (Figure (17)), and the organic material used for reinforcement had rotted or been consumed by insects, leaving cavities and friable earth (Figure (12)).

Further research is needed on this subject, but it was only after I began to interpret what I saw at the site as the behavior of vertically disconnected

unconsolidated earth, rather than as the uniform horizontally bedded earthen construction of the sort analyzed for the Getty project, that a possible explanation for the nature and extent of the earthquake damage began to emerge. Based on the Getty research, the thick walls of the ramparts and main citadel in the Arg of Khesht or chineh construction would normally be expected to be the most resistant, rather than the most vulnerable as they turned out to be. If the hidden interior parts of the walls are composed of a series of vertical segments, and especially if the inner segments had large voids, crevices, and dried-out unconsolidated fill that lacked connections to the outer layers, the high frequency vibrations of this earthquake could cause the inner older and more degraded portions of the walls to settle. This then could exert a horizontal force from the inside-out onto the outer layers at the base of the structures, causing the walls to collapse, not by tipping over, but by crumbling in place.

In addition, variations in the density and cohesion in the earthen layers in a wall, particularly resulting from different periods of erosion and reconstruction and changes from chineh to Khesht quite possibly can cause the earthquake vibrations - particularly vibrations in the high frequency range experienced in Bam - to ricochet off of the layers of different densities, causing the onset of damage from the local intensification of the vibrations. Evidence of such behavior can be seen in (Figure (20)) where the wall began to break out at the interface between two vintages of Khesht construction, both of which appear to be pre-20th century. This is a subject in need of further research specific to earthen construction in order to establish if this phenomenon can be explained in this way, but such research may have a significant bearing on the protection of other earthen monuments that have been altered over the centuries. The North and South American adobe structures that were the primary subjects for the Getty research are less likely to be subject to this phenomenon because they are usually composed of uniform layers of adobe masonry.

This is why the observation of the widespread infestation by termites may turn out to be important. Not only did it appear that the ancient construction in the Arg was perforated by the insects, but that the insects had also succeeded in separating the different vertical segments from each other and reducing the cohesion of the inner core of the walls. In a trip to Isfahan after the mission to Bam, during meetings with the professional restorers of several of the historic monuments in that splendid city (Figure (21)), I learned that termites were also found in the walls during the recent restorations. These professional conservators explained that the damage caused by the termites had to be addressed in the restorations by consolidating the earthen cores of some of the walls.

Figure 21. The Imam Mosque in Isfahan, April, 2004. The inner cores of many of these walls and the walls of other great monuments in Isfahan are constructed of unfired clay.

In contrast to this strengthening work in Isfahan, some of the 20th century restoration work seen in Bam may have aggravated the problem. Clay stucco added before the earthquake was reinforced with copious amounts of straw - a material that appeared in many areas to have been consumed by termites. By contrast, the older reinforcement of shredded date palm tree bark appeared to have been more resistant. Perhaps the termite population inadvertently has been increased in modern times, simply because of this "banquet" of non-resistant straw-reinforced stucco.

5. The Risk to Earthen Mounments

What many people do not realize is that new buildings in any country constructed of modern materials to code are not designed to withstand major earthquakes without damage. For earthen structures, elastic analysis procedures provide little guidance on how such buildings will behave in the post-elastic range. Quoting again from the Getty Seismic Adobe Project report: "The sole use of an elastic approach can be justified only when there is a known relationship between the level at which yielding first occurs and the level at which the structure collapses. In the case of thick-walled adobe construction, there is no clear relationship between these two events. … While a

strength-based analysis can accurately predict when cracks will occur, it cannot provide insight into the post-elastic performance of adobe buildings".

This report makes a very important distinction between what is described as a "strength-based" approach and a "stability-based" approach to seismic upgrading. The report identifies that the current "conventional engineering approach to seismic retrofitting" is a strength-based approach, which is based on increasing the elastic strength of a building's structural system. They go on to explain that for adobe buildings, a "stability-based approach" is more suitable. The objective in stability-based design is to ensure that the structure remains standing long after the elastic range of its structural system has been exceeded. Since the elastic capacity of adobe masonry is low, seismic hazard mitigation of adobe structures depends on maintaining its stability long after it begins to crack.

The Getty Report then goes on to describe the potential that adobe buildings have for "structural ductility" even though they lack "material ductility". The structural ductility can come from the inherent stability that even the cracked adobe walls can have so long as the cracked wall sections remain bearing one on another. This is an important finding that can be used as effective basis for design for many adobe structures that otherwise would be condemned. However, in retrospect, what the Bam earthquake has proved is that, in spite of the thickness of the ancient earthen walls in the Arg, stability was quickly lost after the elastic range was exceeded. The earthquake on 26th December 2003 was recorded to have lasted only 12 seconds, so the collapse of the Arg was almost instantaneous. Structural ductility thus was not to be found in the structures of the Arg.

Who could have ever known there was such a risk? The interiors of the walls with their voids and degraded materials were hidden. An engineer doing a structural analysis would normally have based the analysis on measurements of the thick walls without anticipating the effect of the fractured and weakened conditions of their internal cores. Research is now needed to find ways to be able to evaluate such walls as non-destructively as possible, and then to find ways to address the kinds of problems that may be discovered that would lead to their rapid loss of structural cohesion when subjected to earthquake vibrations.

6. Why did the Arg-e Bam Prove to be so Vulnerable?

If the changes to the walls of the Arg over the centuries, and during recent restorations can be proven to be a major part of the cause of its wide-spread collapse, then there are two remaining questions that need to be asked. The first is:, Since the Arg is located in a known earthquake region, why was its construction not more responsive to the threat? Before answering this question, one must ask whether or not the original construction prior to its alteration and degradation over time was in fact designed to be more resistant. These are both particularly difficult questions because the subject of the inquiry is archaic construction using a limited palate of materials - namely unfired earth with a small number of undressed timber logs - not something that provides much opportunity for modification to resist large earthquake forces.

Earthquake resistance is not an absolute. One must alter one's expectations to reflect what could be achieved in a culture where only unfired earth and a limited amount of timber were available. In the present, expectations of earthquake safety have been shaped by the existence of steel, either as the structural building material itself, or imbedded into concrete, or even when used to reinforce the connections between timbers. The frequent catastrophic failures of modern buildings of steel and concrete, as we have seen in Bam, in the case of steel, and other recent earthquakes in the case of reinforced concrete, notwithstanding, the existence of steel as a building material has raised expectations, making it harder now to recognize pre-modern mitigation efforts.

Traditional construction - particularly in a desert environment - did not have the luxury of an abundance of timber, much less access to modern steel. Much of what could be done was the product of trial and error leading to the evolution of building practices over many centuries. Thus, out of all of the influences on the evolution of construction practices, it is not easy to discern those specifically that are a response to earthquakes. Earthquakes themselves are not always the same. The December 26, 2003 earthquake in Bam was only 6.5, but it was a shallow earthquake with its epicenter located almost directly beneath the Arg-e Bam. The likelihood of being directly above the epicenter of an earthquake is significantly less than being nearby. Thus, it is entirely possible that the Arg had never been subjected to such a high frequency vertical vibration over the prior 2000 years of its history [14].

The earthquake risk most often analyzed by computing the static equivalent forces on structures, but in this case, the frequency of the vibrations may

have been particularly significant. Even a small difference in the location of the epicenter, would have shifted the ground shaking under the Arg away from such high frequency vertical vibrations to a lower frequency vibration with a smaller vertical component. How this may have affected the spectrum of damage in the Arg is difficult to determine, but important to know because it can shed light on the degree to which other monuments are at risk. If high frequency is a large part of the cause of the damage, the odds of a recurrence under other monuments is less than if a broad range of frequencies will cause similar damage.

7. An Approach to Mitigation Based on Historical Precedent

In order to recognize pre-modern seismic mitigation practices, one must accept that people would have responded to earthquakes in the past, just as they do today, with consideration of what could be done to reduce the risks. Whether they were successful or not does not change the fact that in centuries past, people did not always simply acquiesce to the risk. In Italy, Turkey, and some other seismically active areas, where earthquakes have been relatively frequent, such that there is living memory from one generation to the next, there has developed what some scholars have defined as a "seismic culture" [15].

For example, there are many types of stone construction around the world, but some forms, such as rubble stone, have proved to be less resistant than dressed and horizontally bedded ashlar, yet in many places rubble stone is all that is available or affordable. In parts of Turkey, and in Kashmir, both brick and rubble stone construction were often modified by the laying of timbers into the wall much as if one had laid a wooden ladder horizontally onto the partially completed wall beneath and above the windows and at the floor levels as masonry construction proceeded. The timbers were placed in the wall not to provide a frame, but to resist the propagation of cracks and the lateral spreading of the masonry [16]. In Kashmir, the timber-laced masonry was often rubble made up with small stones or bricks set into a thick bed of clay mortar with the timbers holding the walls together. In Srinagar, after an earthquake in 1885, a British visitor observed:

Part of the Palace and some other massive old buildings collapsed ... [but] it was remarkable how few houses fell.... The general construction in the city of Srinagar is suitable for an earthquake country; wood is freely used, and well jointed; clay is employed instead of mortar, and gives a somewhat elastic bonding to the bricks… the whole house, even if three or four stories high, sways together, whereas more heavy rigid buildings would split and fall [17].

There are few people today who would consider using "clay… instead of [lime] mortar". For years, the accepted wisdom is that not even lime mortar is strong enough. It must now be cement. Many national building codes often reflect this. More significantly, this 19^{th} century quote highlights the virtues of flexibility over strength.

Ensuring stability in earthquakes of earthen structures like those in Bam is clearly more difficult without the timber that was available in Turkey, Kashmir and other regions. The more lush sections of Northern Iran are reported to share the timber-laced building tradition found in Turkey, but in dry deserts of southern Iran people do not have the luxury of using extensive amounts of timber, but the date palms logs were sometimes imbedded into the walls as well as used to support floors (Figure (22)).

Figure 22. Collapsed section of the main gateway showing imbedded timber reinforcement of the Khesht wall.

To begin to understand what may have been done in the past with earthen construction in response to earthquakes it is helpful to begin by looking not only at what fell, but what did not. For this we turn to the chineh garden walls around the date palm orchards throughout the city. The chineh garden walls are generally about two to two-and-a-half meters high and 50-100*cm* thick at the base with a batter reducing them to only a few cm thick at the top. Most of the date palm groves in Bam and in Barakat are surrounded by walls of this type. The Iranian chineh construction found in Bam is characterized by a series of bands of

clay that are about 50*cm* high that represent each "lift" in the construction process. These lifts were constructed along the wall from one end to the other, and then made smooth and level on the top before proceeding with the next lift, see Figures (3), (5), (23) and (24).

Figure 23. Chineh garden wall, probably of recent origin, in Baravat (near to Bam). This wall shows the cracks that commonly exist in chineh walls, and how the layered construction helps to ensure stability by allowing the cracked sections of the mud layers to perform like large blocks of masonry.

Figure 24. South-facing outside wall of the stables courtyard showing how the layering of the chineh walls has interrupted the cracking and collapse of sections of the wall, thus helping to maintain the stability of the partly undermined upper part of the wall.

This differs from Northern European cob construction, which lacked such clearly defined horizontal interfaces between the lifts. There may have been a number of reasons for this construction detail in chineh, such as water shedding, but one structural reason for it may have been that it served to stop the continuous propagation of vertical cracks through the wall, a problem that is all the more acute in a dry climate. Because they are constructed only of uncompressed dried mud, they began their life with many vertical cracks and checks from the initial drying out process. In fact, the Getty Seismic Adobe Project report states: "Substantial cracks nearly always exist in historic adobe buildings as a result of past earthquake activity, wall slumping, or foundation settlement. Cracked walls are a typical feature of these buildings" [18].

Throughout history, Iranian builders would have striven to avoid the negative structural effects of this inevitable cracking as much as possible. This would have been done for stability in general, not just because of earthquake risk, but the earthquake risk may have contributed to the evolution of the system that was used, while the local limitation on resources would have limited the builders to the use of unfired earth. The horizontal control joints in the chineh walls thus may be a result of this effort to control the effects of crack propagation by interrupting the progression of cracks through what would otherwise have been a uniform material.

Many chineh walls, both ancient and modern, did prove to be remarkably durable in the 2003 earthquake. As one approaches the Arg, passing through areas of gradually increasing damage, these walls are seen to have remained standing even when nearby houses and multi-story steel frame buildings were collapsed. Near the Arg, the damage to the garden walls is clearly greater, but large sections of them have nonetheless remained standing that were both parallel and perpendicular to the direction of the earthquake waves. Also, many of the walls of the unmaintained and unrestored structures mentioned above that survived the earthquake largely intact were of chineh construction, see Figures (3), (5), (11), (18), (20), (24), and (27). Both those walls, and the ancient walls of Khesht construction survived intact, with a few minor exceptions, whereas, as mentioned above, it was those walls in the Arg where chineh was later reinforced with Khesht that the damage was observed to be the greatest, see Figures (7), (16) and (17).

When examining the historic evolution of the chineh with its control joints, it may be relevant to also turn to the construction practices that evolved in ancient Rome. In Rome the surviving archeological remains are filled with walls of a form of natural pozzolanic cement. These great lumps of material have

shown a remarkable durability, but one feature in many of these walls stands out. Every meter and a half or so was a horizontal band of fired brick masonry that extended through the walls. The early Roman bricks were essentially a flat thin tile. The original purpose of these bands is not known from any literature source, and archeologists often differ in their interpretations, but it is clear that they did function as "crack stoppers". By interrupting the uniform matrix of the natural cement with the bedded layer of bricks in mortar, the inevitable cracks that occurred in the cement layer were interrupted, giving added stability to the walls, see Figure (25).

Figure 25. Long Wall, Hadrian's Villa near Rome showing the bands of brick that were laid into a wall constructed with natural cement with a tile facing. The crevices are the result of the later chipping out of the bricks for re-use.

In the Arg-e Bam, some of the chineh walls had a band of adobe bricks in between the lifts at the base of the wall. In one of the eastern rampart walls, there appears to have been a row of adobe bricks between each of the several lifts. These may have served a similar function as the Roman bricks even though they were not fired bricks. At the *UNESCO-ICOMOS-ICHO* Workshop, one delegate, Archibald Walls from the *UK*, reported that there are other sites in Iran that do have horizontal bands of bricks laid into walls of chineh.

These and other Iranian examples are worth exploring for further information on the effectiveness of such horizontal bands of masonry laid into earthen walls, but the lesson to be learned is that what we sometimes only think of as architectural details originally may have been developed to serve more practical structural needs. This point is reinforced by the following example in Istanbul: during the 1999 Koçaeli earthquake, the only part of the ancient city walls to collapse was a tower that had been completely reconstructed in new masonry only a few years before, see Figure (27).

The next tower, see Figure (26) - despite its heavily decayed and cracked condition - remained standing. The surviving ancient tower had horizontal brick bands that extended through the rubble stone core of the wall. The restorers of the new tower only placed the brick bands on the surface of the wall as a veneer, constructing the tower with thick walls of rubble set

Figure 26. Surviving portion of the original Istanbul city walls. The cracks and broken section pre-dated the 1999 earthquake.

Figure 27. The reconstructed tower that collapsed during the 1999 earthquake. The bands of red brick on the wall were fake veneers, rather than full layers.

Figure 28. The unrestored Khale Dokhtar, a small Arg (or citadel) on the riverbank opposite the Arg-e Bam that survived the earthquake with the collapse of some arches. The high walls of the massive structure otherwise survived intact (Termites and other insects were also in evidence where the collapses occurred.)

Figure 29. ICHO model of the Arg-e Bam after recent restorations prior to the earthquake.

in mortar clad with cut stone. The lesson that can be learned from this event is that for ancient buildings, structural design and construction practices are part of an integrated system, not separate or unrelated features. The hidden parts of the ancient walls are every bit as important as what can be seen on the surface. Illustrative of this fact, the pre-modern builders most likely understood the importance of the simple concept of crack-stopping since it was one of the few measures that they had at their disposal to improve the stability of the ancient construction in the desert environments.

8. Conclusion

In summary, it appeared to be that the collapse of the Arg-e Bam was largely a result of the internal collapse of the walls resulting from a catastrophic loss of the cohesion of the earth deep within its walls. The initial impression was that the 20th century restoration work itself performed far worse than the ancient work, but it was not always the newer work that failed per se, but the combination of the new and old. In fact, it appeared that the newer work often failed as a result of the internal collapse of the older work on which it was founded.

While it does not explain all that happened, the termite damage is symbolic of the larger issue of the role of time and change in both the science and the art of building conservation. It was only after noticing this infestation that I began to focus on the other aspects of internal wall degradation - the dryness and lack of cohesion of the earthen cores, the decay and consumption of the reinforcing timbers and fiber reinforcements, the existence of small and large voids between vertical layers in the walls, and the evidence that thick earthen walls had burst open before they collapsed. When all of these elements are put together with the particular characteristics of this earthquake with its high frequency vertical vibrations, the collapses of the walls from the inside-out appears to be a plausible explanation for a great part of what happened.

If, after further research, these explanations into the causes of the collapses in the Arg described here are substantiated, it is important then to ask: what are the implications of these findings, not only for the future restoration work in the Arg, but also for the other cultural heritage sites in Iran and throughout the Middle East and North Africa? If, after a 50 year program of restoration, such a seemingly robust earthen monument can be shaken down in 12 seconds, we need to understand why the kind of post-elastic stability described in the Getty research did not occur. Many, of Iran's most splendid monuments are of earthen construction behind their exterior surfaces of carved stone and ornate ceramics. In an earthquake, if the inner layers shift and settle in response to earthquake vibrations, the outward pressure could lead to a blowing out of the walls at their base, causing collapse of the structures. Standard structural retrofit analysis and techniques may neither fully account for this risk, nor mitigate it.

In order to make the best use of the knowledge that can come from an investigation of the damage sustained by the Arg-e Bam, it is important first to understand, as the Getty researchers did, that the destruction of such monumental earthen architecture from shaking of this magnitude should not be taken as

a forgone conclusion or as a condemnation of the use of unfired earth as a building material. What the destruction of the Arg does provide, however, is the cautionary message: Buildings are not always as they seem to be when looked at from the outside. This message is particularly profound when it comes to earthen architecture. The transition of the walls of the Arg from horizontally bedded layers to separating vertical segments resulted from centuries of erosion and renewal, but the external look of the walls had changed little over that time. It took an earthquake to open the walls up and reveal that the internal composition of the wall was no longer the same as it had been when originally constructed.

More than any other building material, unfired clay can change over time from cumulative effects of the short repeating cycle of erosion and renewal, and also from a gradual deterioration of the hidden core of the walls, not only from termites, but also from rising damp, water intrusion from the top and sides, differential settlement, gradual compaction, and gradual chemical or mineralogical changes to the matrix of the material. Although of particular importance when dealing with unfired earth, these causes of deterioration can affect many different building materials.

The visual symbol of this earthquake to the world has become the dramatic juxtaposition of the "before" and "after" images of the Arg-e Bam (Figure (1)). However, for the future of both construction with adobe and the conservation of earthen architecture, the symbol should also be the ancient earthen structures around the Arg that did not collapse, see Figure (3), (11), (20) and (28). Without having had modern-day maintenance or restoration, at the time of the earthquake, these structures were closer to the structural form of their original construction dating from centuries past. Having survived the earthquake intact, they stand today as examples of earthen construction that proved to be capable of resisting a major earthquake better even than some of the new steel frame buildings that did collapse. The age of an historic structure thus may be less of a factor than modern-day changes to its fabric, including, ironically, modern efforts to strengthen and restore that ancient fabric.

If this is true, we may need to look no further than some of these modern-day construction and conservation practices to begin to find a solution to the problem. It is at this level that the fate of the Arg becomes intertwined with the fate of the modern town that stood along side. The houses in which people died were modern houses. Their walls may have been of Khesht, but many also had roof beams of steel, and floors or roofs of fired brick. If both the twentieth century restorations in the Arg and the new houses in the town suffered more than the untouched ancient abandoned earthen ruins in the desert nearby, then the problem had less to do with earthen construction per-se than it had to do with the particular form of earthen construction that was practiced in modern Bam. Therefore, both restoration practices and new building construction practices need to change, and some of the guidance for how they should be changed may be found in the heritage of the nation itself, rather than only between the covers of engineering textbooks.

With so many deaths having occurred in buildings with earthen walls, occurring together with the collapse of such a symbolically important monument, these two phenomena have been fused in the eyes of many around the world. Life safety concerns with adobe construction are now tragically highlighted, creating a problem for the conservation of other earthen sites in seismic areas, all of which are now at greater known risk than before the Bam earthquake. By coming to understand the collapse mechanisms in the Arg, one can go beyond the level of blaming a construction material for the poor performance of construction systems. If one stops at the material in the determination of the causes of failures, all discussion stops, and the fundamental need to determine all of the necessary ingredients that constitute earthquake safety will not be achieved.

Although it would seem that it should be easier to design and construct safe structures out of steel and concrete, in practice, this earthquake, as well as other recent earthquakes in Mexico, Turkey, India, Morocco and many other countries, have tragically proved that safety can be elusive, even with modern materials. In many parts of the world, unfired earth is the most available and economical building material. It is also deeply imbedded as part of the history and culture of Iran and the region. While it may be more challenging to construct safe structures using unfired earth, that does not mean that it cannot or should not continue to be done.

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References

1. In Farsi, “Arg” Means “Citadel”.
2. Leroy, T., Kimbro, E., and Ginel, W. (2002). “Planning and Engineering Guidelines for the Seismic Retrofitting of Historic Adobe Structures”, The Getty Conservation Institute, Los Angeles.
3. Hubert, G. (2004). “Technical Mission to Bam and Its Citadel”, In UNESCO-ICHO Joint Mission to Bam and Its Citadel, ICHO, 37p.
4. The Official Death Toll is About 26,000, and Unofficial Counts Have Risen as High as 43,000.
5. Data from IIEES, Iran (http://www.iiees.ac.ir/English/bank/eng_recent.html)
6. Iran Strong Motion Network (ISMN) (2004). http://www.bhrc.gov.ir, and Ashtiany, M., et al, Preliminary Observations on the Bam, Iran, Earthquake of Dec. 26, 2003, EERI.
7. The Inter-Atomic Forces that Give Clay its Cohesiveness of Clay, that Allows it to be Such a Useful Building Material, are Dependent on the Presence of moisture.
8. An Example of this, Similar to the one Remembered, can be Found in: Marcelino Gonzáles Cano, Restauración Arquitectónica De Estructuras Arqueológicas En Áreas Sísmicas: El Caso De Mixco Viejo, Guatemala, (1976), Figures (7) and (8).
9. Photographs by James Blair for t he National Geographic Magazine (1974). Courtesy of the National Geographic Society.
10. IBID.
11. Aerial Photograph in The Bam Citadel, a Comprehensive Report, ICHO, (2004). Page 26, Dated 1996 (the same image as used on the Workshop Poster).
12. As Shown in a Photograph in the UNESCO-ICHO Joint Mission to Bam and Its Citadel, ICHO (2004), p80.
13. Ed Crocker of the USA Recommends “That the Fibrous Material be Soaked with Borates. This in Fact could have been done Historically Since Borax is Common in Desert Deposits. Borates Destroy the Digestive Enzyme of Termites and other Invasive Critters. It is also Inexpensive and
14. For a Further Discussion of the Historical Variability of Earthquakes at a Given Site, See: Piero Pierotti, ed, A Manual of Historical Seismography, (Published in English and Italian), University of Pisa, Edizioni Plus (2003).
15. Ferruccio, F. (1997). “Local Seismic Culture”, Ancient Buildings and Earthquakes, European University Centre and Council of Europe, Also See Piero Pierotti, Op Cit.
16. For more information, see R. Langenbach, Bricks, Mortar and Earthquakes, APT Bulletin, 31:3-4, (1989), available on the web at www.conservationtech. com.
17. Arthur Neve, Thirty Years in Kashmir (London) (1913), p38, Quoted in Ibid. It is Interesting to Note That This Historical Kashmiri Construction Has Subsequently Provided an Influential Model for the Modern Development of a Similar Rein-Forcement System for Rural Earthen Construction in the Rest of India and then later in Nepal, which is Now Embodied in the Indian and Nepali National Building Codes. (L., Randolph, op cit, and interviews with Anand Arya of University of Roorkee, India, and Richard Sharpe of New Zealand.)
18. Getty Report op cit, p80.

Bibliography

- Ashtiany, M., et al (2004). “Preliminary Observations on the Bam, Iran, Earthquake of Dec. 26, 2003”, EERI.

- Ferruccio, F. (1997). “Local Seismic Culture”, Ancient Buildings and Earthquakes, European University Centre and Council of Europe.

- Hubert, G. (2004). “Technical Mission to Bam and its Citadel, in UNESCO-ICHO Joint Mission to Bam and Its Citadel, ICHO.

- ICHO (2004). The Bam Citadel, a Comprehensive Report.

- ICHO (2004). UNESCO-ICHO Joint Mission to Bam and Its Citadel, ICHO.

- IIEES, Iran (www.iiees.ac.ir/English/bank/eng_recent.html).

- Iran Strong Motion Network (ISMN) http://www.bhrc.gov.ir,

- Langenbach, R. (1989). “Bricks, Mortar and Earthquakes”, APT Bulletin, 31:3-4, This and other papers

are available on the web at www.conservationtech.com.

- Pierotti, Piero, ed (2003). "A Manual of Historical Seismography", (published in English and Italian), University of Pisa, Edizioni Plus.

- Leroy, T., Kimbro, E, and Ginell, W (2002). "Planning and Engineering Guidelines for the Seismic Retrofitting of Historic Adobe Structures, The Getty Conservation Institute, Los Angeles.

- Tolles, Leroy, Kimbro, E., Webster, F., Ginell, W. (2000) Seismic Stabilization of Historic Adobe Structures, The Final Report of the Getty Seismic Adobe Project, The Getty Conservation Institute, Los Angeles.

Performance of Lifeline Systems in Bam Earthquake of 26 December 2003

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ABSTRACT: *At 5:26 am local time, Friday, December 26, 2003, an earthquake with moment magnitude 6.5 hit the city of Bam in southeast Iran. The earthquake caused more than 26,000 deaths, 30,000 injuries, and left 70,000 homeless. It caused extensive damage to residential and commercial buildings and emergency response facilities. In contrast to the inflicted human loss and suffering and extended building damage, lifeline systems, although damaged, performed much better. Transportation systems, i.e., roads, bridges, railways, and the airport, although slightly to moderately damaged, were generally operational soon after the earthquake to support emergency response and recovery effort. There were several breaks in the water distribution systems and minor damage to deep wells. However, the traditional qanat systems, which bring water from foothills tens of kilometers away via underground tunnels, were mostly damaged. The Bam area is served via connection to countrywide electric grid system. There was little damage to high voltage transmission lines and towers and minor damage to electric equipment in the main substation. Numerous concrete poles were damaged in the distribution system. There was nonstructural damage to telecom central offices. The main reason for the good performance of the lifeline facilities was that most of them are located outside the zone that was heavily damaged. Another reason is that they are newer facilities and in general more engineering has been used in lifeline facilities design and construction when compared with that for residential buildings.*

Keywords: Earthquake; Lifeline; Water tank; Qanat; Electrical Substation; Airport

1. Introduction

Continuous functioning of lifeline systems, such as transportation system, water distribution, waste-water and sewage systems, electric generation, transmission and distribution networks, communications systems, and gas and petroleum distribution systems, is essential for the well-being of urban communities. The need for lifeline systems is even more crucial immediately after occurrence of a major natural or man-made hazard such as an earthquake. Thus, proper design, construction and maintenance of lifeline systems with respect to their availability, performance, and reliability during and after natural hazards are critical and needed [1, 2]. Lessons learned from the performance of lifeline systems in natural hazards [3, 4, 5] help support achieving this goal. The purpose of this paper is to summarize the performance of lifelines in the recent Bam earthquake.

On Friday December 26, 2003 at 5:26 *am* local time, a moderate earthquake with moment magnitude 6.5 hit the city of Bam and its surrounding areas in Kerman province in southeast Iran. The epicenter of the earthquake was located at 29.00*N*, 58.34*E* in the ancient city of Bam. The rupture occurred on the known and mapped dipped Bam fault which runs through the city of Bam. The Bam fault, though known, had no known earthquake activity in recent

times. The earthquake had a focal depth of 10*km* and an estimated rupture length of 20*km*. There was no evidence of rupture reaching the ground surface. However, there is strong evidence that the fault rupture reached the city of Bam.

The earthquake caused extensive damage to residential, commercial, governmental, religious and educational buildings. In the old parts of the city of Bam more than 90% of traditional adobe buildings collapsed. A large number of new buildings, mostly unreinforced masonry but also engineered buildings, collapsed or had extensive damage, which require their complete demolition. The earthquake impacted area had a total estimated population of 200,000 with about 90,000 in the city of Bam. The earthquake caused more than 26,000 deaths, 30,000 injuries, and left 70,000 homeless. The high ratio of death to injuries is due to the timing of the earthquake, when most people were in bed, and large number of people living in traditional adobe buildings and unreinforced masonry buildings where earthquake motions cause brittle failure and sudden collapse of buildings. In contrast to the devastating human loss and suffering and extensive damage to buildings, the lifeline systems, though damaged, performed relatively better.

By invitation of the Geological Survey of Iran, *GSI* (www.gsi.org.ir), the Norway's Centre of Excellence, International Centre for Geohazards, *ICG* (www.geohazards.no), sent a team of experts on a post-earthquake reconnaissance mission to Bam in January 2004 [1]. The *ICG* in turn invited the first author from Risk & Reliability Engineering, to join the *ICG* team in this effort. The team was in Bam about one month after the occurrence of the earthquake. The team documented its finding on the, earthquake, causative fault, and impact of the earthquake in a report to *GSI* [6]. This paper summarizes damage and performance of lifelines in this earthquake. The lifelines considered in this paper are water systems; transportation networks, including roads and bridges, railways, and airports; electric transmission and distribution systems; and communication systems.

2. Water Systems

2.1. Water Distribution System

The city of Bam uses drinking water from about 12 deep wells. The water is distributed to residential, commercial, industrial and other users via a water distribution system. The system is made of buried pipelines, mostly concrete cement pipes, and several underground and above ground water storage tanks. There is no water treatment plant in Bam. At the locations of several storage tanks chlorine mixture is added to water for chemical treatment [7].

There was report of damage to a number deep wells and also several pipeline breaks throughout the city. Due to collapse of the buildings and breakage of connecting pipes, at users ends, water had to be brought by tanker trucks to the tents and shelters and other users after the earthquake. Overall the storage tanks performed well. Figures (1) shows an elevated concrete water tank, located near the old section of the city close to the earthquake rupture where the damage was high. The tank experienced severe stress and deformation at the column-beam connections.

2.2. Qanat System

Qanats are the traditional water systems used in Iran over centuries. A qanat consists of an underground tunnel dug into competent sediments and a linear series of vertical wells that provide access for inspection and repairs. Figure (2) shows the design principles of a qanat. The underground tunnel would bring water from foothills of mountainous area tens of kilometers away. The wells are typically about 30*m* to 50*m* apart. Sometimes several qanat branches are joined together and continued to the designated area via one qanat branch. Figure (3) shows aerial photo of several qanat branches.

There are 126 chains of qanats in the Bam region, of which 62 to 64 serve the twin cities of Bam and Baravat. The chains of qanats bring water to the city from foothills of mountainous area west and south-west of the city (Jebal Barez) tens of kilometers away, Figure (4). The wells are about 20 to 50*m* apart. The water from each well is led toward the city via the connecting underground tunnel. The wells are about 70*cm* to 90*cm* in diameter, and are as deep as 100*m* closer to foothills to about 5*m* to 15*m* closer to the city. The tunnel cross section is usually in rectangular shape about 70*cm* to 100*cm* in width and 150*cm* to 200*cm* in height. The under ground tunnel eventually reaches the ground surface, and the water is then led to farms and gardens via small manmade creeks, Figure (5). In Bam area the qanat water is mostly used for agriculture and date tree gardens. There are about 1,600,000 date trees in Bam and its vicinity and the export of Bam dates to other parts of Iran and rest of the world is a major source of income and livelihood for citizens of Bam. The qanat water is sometime stored in traditional underground reservoirs, as shown in the last two picture on Figure (5).

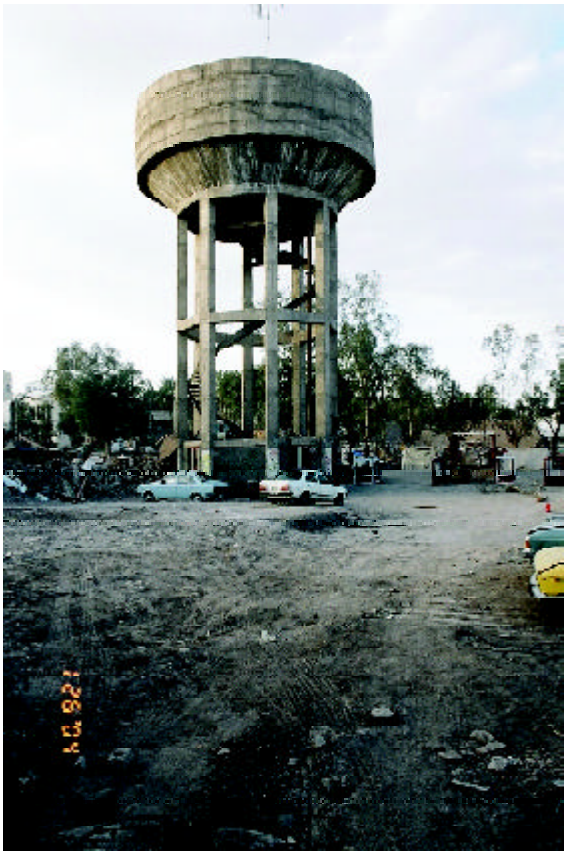

Figure 1. Elevated concrete water tank located in near the old section of the city where the damage was high. The tank experienced severe stress and deformation at the column-beam connections.

More than 55 chains of qanats had various levels of damage mostly to their wells and underground tunnels closer to the city and the quake epicenter. The damage was in the form of failure of the underground tunnel walls and wells, blocking the water to reach the ground

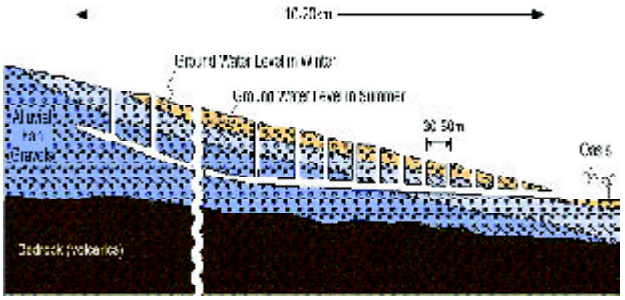

Figure 2. Principles of water transport by a qanat.

Figure 3. Aerial photo of several chains of ancient qanat systems, which typically bring water from foothills of mountainous area to more dried desert towns and villages in Iran.

Figure 4. Snow-capped Jebal Barez mountain range is located in southwest of city of Bam as seen from Azadi hotel in Bam. About 126 qanat chains bring irrigation water from foothills of Jebal Barez to Bam region.

Figure 5. Once the qanat chain arrives at its destination, the underground tunnel reaches the ground surface (top and middle left pictures). From there the water is distributed via man-made channels and brought to farms and date palm gardens. Damage to the channels is noted in the middle and lower right pictures. The qanat water sometime is stored in traditional underground reservoirs (bottom two pictures).

surface. One should note that the wells as well as the underground tunnels are not reinforced and are basically vertical and horizontal holes in the ground. Even without earthquakes the wells and the tunnels need regular maintenance to remove the fallen soil from the well walls and tunnels. At the time of the team visit a number of qanat builders from other parts of Iran had come to Bam area to clean and reconstruct the damaged qanats, see Figure (6). In addition to damage to qanat chains, the distribution surfaces channels were damaged or closed off due to collapsed garden walls or other constructions.

Figure 6. The vertical wells, also used as access wells, are usually large enough for one person to be able to climb down (about 90cm across). Note the use of old tire at the entrance of one well. Damage to the qanat systems included underground tunnel collapse and closure (not shown), access well failure, which in turn causes the closure of the underground tunnel, damage to the channels. At the time of our visit a number of qanat builders had been brought from other parts of country to repair the very important qanats.

3. Electricity

There are no electric generating plants in Bam or the affected area. Bam and its vicinity are connected to the countrywide electric grid system. Main transmission lines, bring electricity from this grid to Bam area. There are four substations in the area: two in Bam, one in Baravat, and one in New Arg. The two in Bam are $230kV$ and $115kV$. Transformers are used to reduce the voltage to $220V$ for residential and commercial use.

There was no damage to main $230kV$ transmission lines. There was however damage to concrete poles in the distribution system and streetlights. Part of the damage to the concrete poles was due to collapse of adjacent walls and buildings. We observed series of poles to be out of plumb. Damage to transformers on distribution poles was reported [8], see Figure (8).

The $230kV$ substation in Bam experienced some damage. There was some damage to porcelain insulators and bushings at this substation. The wall around the substation collapsed. The office/control building in the substation structurally performed well, see Figures (8) and (9). This substation was about $5km$ distance from epicenter. At the time of our visit (one month after the earthquake), electricity had been restored throughout the city, even in the area where there was severe to complete building destruction.

4. Transportation Systems

4.1. Roads

There is a main two-way highway-connecting city of Bam to Kerman on the northwest and Zahedan and Iranshahr on east and southeast of Bam. This road crosses the Bam fault scarp. Very minor damage to road embankments and surface cracks in the main highway close to Bam fault scarp were observed. For the most part, roads and streets were usable immediately after the earthquake, see Figure (10).

Cross-country bus lines are the main mode of transportation for masses in Iran especially outside the major cities. The last picture of Figure (10) shows the roof of a bus terminal building collapsed onto several busses.

The bridges over a Bam river, called Posht-e-rud, performed relatively well. Figure (11) shows one of the main bridges over the river. There are signs of vertical movement in the base of the support walls/ columns. Damage to the pipeline on the side of the bridge is observed. All of the three main bridges were operational for service after the quake.

4.2. Airport

The main terminal building at the Bam airport had moderate damage, but the runway was operational immediately after the earthquake, see Figures (12). The steel frame terminal building was moderately damaged, but it withstood the quake. The masonry infill walls were damaged. The false ceilings were severely damaged. There was moderate damage to stairway to the second floor. There was nonstructural damage to airport control tower (broken windows). The airport runway had little damage and came to be extremely useful for emergency response and recovery effort. Hundreds of flights from inside of Iran and around the world landed in this airport immediately after the earthquake to bring search and rescue teams and equipment as well as much needed medical, food, blankets, tents and other supplies.

4.3. Railway

The construction of railroad to Bam had just been completed but the railroad had not been used prior to the quake. The passenger terminal located some $25km$ south of the city was under construction and had some damage. There was no damage to the rail tracks. There was light damage to embankment. The railroad was extremely useful for bringing supplies and help to Bam immediately after the earthquake, see Figure (13).

5. Gas and Petroleum

There is no petroleum pipelines installed in the affected area. Even though a large number of small and large cities in Iran have natural gas distribution system, Bam and the affected area did not have a gas transmission and distribution system at the time of the quake. One should note that, fires following earthquakes are very common and existence of underground gas pipelines and their ruptures due to earthquakes could lead to major conflagration. Even though there were reports of at least seven fires after the earthquake, lack of a natural gas system and wood constructions did prevent a conflagration in the city.

The gas stations and heating gas suppliers bring their material via tankers to the city. Fortunately, there was no gas station in the old section of the city, which experienced severe shaking. The gas stations in the city, Figure (14), were in operation at the time of our visit (one month after the earthquake).

Figure 7. Damage to transmission line towers was not observed. Concrete and wooden poles are used to bring electricity from substations to users. Pole top transformers convert the electricity to 220V. Many distribution poles were damaged. A large number of distribution poles and street light poles were out of plumb after the earthquake.

6. Communications

The team did not get to visit the central offices at Bam and Baravat, but there was report that the telecommunication central offices had mostly non-structural damage as well as damage to unanchored equipment. The main telecom towers mostly survived the quake. Some communication towers located on the roofs of the collapsed buildings were also damaged, see Figure (15).

Figure 8. The 230kV substation experienced minor damage. The wall surrounding the facility collapsed. In the process it hit the concrete poles and caused their failure. A number of porcelain isolators were b roken. The office/control room did not seem to have been damaged structurally.

7. Summary and Conclusions

There were minor cracks on the main Kerman-Bam-Zahedan highway close to the Bam fault scarp crossing. The bridges over Posht-e-rud river had none to light damage and were available for use right after earthquake. The airport terminal steel moment resisting frame building had moderate damage, mostly to the masonry infill and non-structural elements, false ceilings, partitions, and architectural features. The runways had minor cracks, but were available for plane taking off and landing and proved extremely

Figure 9. Damage to various electric equipments in the 230kV substation is observed in the above pictures. At the time of our visit (one month after earthquake) the electricity was available throughout the city, even though most of the users' buildings had been severely damaged to use the electricity.

Figure 10. There were minor damage to roads and highways. There were some damage to road embankment and surface cracks cracks in the main highway close to Bam fault scarp. For the most part roads and streets were usable immediately after the quake. The roof of bus terminal building collapsed onto several busses.

Figure 11. A bridge over the Posht-e-rud performed relatively well. There are signs of vertical movement in the base of the support walls/columns. Damage to pipelines is observed.

Figure 12. The engineered steel frame terminal building at Bam airport was moderately damaged. The masonry infill walls were damaged. The false ceilings were severely damaged. The airport runway had little damage.

Figure 13. The passenger terminal was under construction and had minor damage. There was no damage to rail tracks. There was light damage to embankment.

Figure 14. Gas stations in the city of Bam were in operation at the time of our visit.

Figures 15. The main telecom towers mostly survived the quake. Some communication towers located on roof of the collapsed buildings were also damaged.

useful for bringing immediate emergency management operations to the affected area. The national railway system had been extended to Bam. The passenger terminal building was under construction and had minor damage. The rail tracks had none to light damage (embankment).

The railroad was also available and useful for emergency response and reconstruction effort. There were several breaks in the water distribution systems and minor damage to deep wells. The age-old traditional qanat systems, which bring water from foothills tens of kilometers away via underground tunnels, were mostly damaged. Out of the more than 60 qanat chains that served the twin cities of Bam and Baravat, only a few survived the earthquake. The agricultural activities in the Bam area (mainly date tree and citrus gardens) are totally dependent on the water transported to the area by these qanats from the foothills of Jebal-e-Barez Mountains. The importance of qanats to the livelihood of the people of Bam cannot be underestimated. The city is where it is because the fault that caused the earthquake also provided the conditions for the access to water for agricultural activities (daybreak of the qanats occurs on the

surface expression of the Bam lineament).

The area is served via connection to countrywide electric grid system. There was little damage to high voltage transmission lines and towers. There was minor damage to electric equipment in the main substation. Numerous concrete poles were damaged in the distribution system. There was nonstructural damage to telecom central offices.

The damage pattern of the earthquake was nearly symmetric about a line 3 km to the west of the surface expression of the Bam fault, and the damage attenuated rapidly with distance from this line. There was very little or no damage at distances greater than 5 km from the reference line [6]. The main reason for the relatively good performance of the lifeline facilities was that most of them are located more than 5*km* from this reference line (e.g. airport, railway, train station, electrical substations). The qanats were damaged in the area between the reference line and surface expression of the Bam fault. Qanats typically have daybreak at locations where there is a sudden change in the ground elevation level (and the water table). These sudden changes in surface topography usually occur because of the existence of faults underneath. The correlation between access to water and proximity to earthquake-generating faults is a problem that needs to be studied further.

Another reason might be that for the most parts they are newer facilities. In general more engineering has been used in lifeline facilities design and construction when compared with that for buildings (e.g. concrete water tank, airport, railway station, telecommunication facilities). The observations confirmed that well-designed and constructed structures would have survived with only minor damage the severe earthquake shaking levels experienced during the Bam earthquake.

In summary, with the exception of qanats, lifeline systems by far had less damage than buildings. Having said that, there was still significant damage to lifeline facilities. More attention must be paid to non-structural elements and equipment installations in lifeline facilities.

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References

1. Moghtaderi-Zadeh, M., Wood, R.K., Der Kiureghian, A., and Barlow, R.E. (1982). "Seismic Reliability of Lifeline Networks", *Journal of the Technical Councils, ASCE*, **108**(TC1).

2. Taylor, C. editor (1991). "Seismic Loss Estimates for a Hypothetical Water System, A Demonstration Project", *ASCE Technical Council on Lifeline Earthquake Engineering Monograph No. 2*.

3. Zadeh, M., Larsen, T., Scawthorn, C., Van Anne, C., and Chan, T.K. (1993). "Effects of Hurricanes Andrew and Iniki on Lifelines", *Proceedings of the ASCE Conference on Hurricanes of 1992*, Miami, Florida.

4. Goltz, J.D. editor (1994). "The Northridge, California Earthquake of January 17, 1994: General Reconnaissance Report", NationalCenter for Earthquake Engineering Research, Technical Report NCEER-94-0005, Buffalo, New York.

5. Beavers, J. editor (2003). "Advancing Mitigation Technologies and Disaster Response for Lifeline Systems", P*roceedings of the Sixth U.S. Conf. and Workshop on Lifeline Earthquake Engineering*, ASCE Technical Council on Lifeline Earthquake Engineering Monograph No. 25.

6. Nadim, F., Lindholm, C. Remseth, S., Andresen, A., and Moghtaderi-Zadeh, M. (2004). "Bam Earthquake of 26 December 2003: ICG Reconnaissance Mission", ICG Report 2004-99-1, Also Posted at www.geohazards.no.

7. Eshghi, S., Zare, M., Assadi, K., Razzaghi, M., Ahari, M., and Motamedi, M. (2004). "Reconnaisance Report on 26 December 2003 Bam Earthquake", (in Persian), International Institute of Earthquake Engineering and Seismology, Tehran, Iran.

On the Nonstructural Elements and Their Behavior in the Bam Earthquake of 26 December 2003

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ABSTRACT: *Regarding the importance of the nonstructural elements in the vulnerability of buildings, and the extensive damages of some of these elements in recent earthquakes, particularly the Bam event, in this paper at first the characteristics of nonstructural elements are briefly reviewed, with emphasis on the Iranian buildings; then the seismic design, vulnerability, and upgrading of these elements are explained and discussed as a state-of-the-art review; and finally, the results of a thorough survey performed on the behavior of and the damages sustained by these elements, particularly the architectural ones, in the city of Bam because of the December26, 2003 earthquake are presented. Finally, based on the results of this survey some recommendations are made which can be useful for modification of the "Guidelines for the Seismic Retrofit of the Existing Buildings", which is used presently in the country as the only official reference in this regard.*

Keywords: Bam; Nonstructural; Seismic safety level; Design provisions; Vulnerability; Upgrading techniques; Seismic retrofit; Risk mitigation

1. Introduction

Nonstructural elements are those elements in a building which are supposed not to participate in carrying the applied loads to the structural system, including the seismic forces. These elements can be divided into four main categories:

1. Architectural elements
2. Mechanical facilities
3. Electrical and communicational facilities
4. Interior equipments

The characteristics of elements in each of the abovementioned categories are not only different from those of other categories, but also are quite numerous and distinct within each category, particularly in the case of architectural elements. This great variety of characteristics has made the study of their seismic behavior much more difficult than the building structural elements. This can be claimed to be one reason behind the fact that the seismic study of these elements has started much later than the studies of structural elements. Another reason is the discarding of structural engineers with regard to the design of nonstructural elements as they are usually believed to be designed by architects or by the designers of mechanical and/or electrical facilities. The main reason has been obviously the fact that the total collapse of or severe damage to the building structures in past earthquakes has diverted the attention of building engineers from the vulnerability of the nonstructural elements. However, these elements have shown their high vulnerability, even in recent earthquakes, in which the level of structural damages has been comparatively low.

Past earthquakes have proven that the nonstructural elements are highly vulnerable, if not designed for earthquake excitations. The consequences of the nonstructural elements vulnerability can be summarized as follows:

- Direct damages
- Premature collapse of the building
- Creating post earthquake fires
- Spreading hazardous materials
- Interrupting the rescue activities

A brief explanation on each of the above mentioned consequences is given here. Since the costs of construction and/or installation of the nonstructural elements versus their relative volume of the whole construction work are usually much more than those of the building structures, the financial loss due to the direct damage to the nonstructural elements can be relatively high, even when there is no structural damage. This is particularly true in the case of industrial buildings in which the building cost itself is very little in comparison with the costs of interior equipments.

The premature collapse of a building by the nonstructural elements may be accelerated by the uncounted for contribution of these elements to carrying of the lateral seismic load. Damage to either mechanical or electrical systems can easily result in fires. Some samples of these fires have been observed in the Bam earthquake as discussed in section 4 of this article.

Spreading the hazardous material is another consequence of damage to mechanical facilities. This is particularly true in industrial buildings, in which various chemicals are used.

Interrupting the rescue activities because of damage to the nonstructural elements is a case which has occurred in some hospitals in the past earthquakes. A similar case occurred in Bam airport, in which damage to the nonstructural elements interrupted the operation of the Control Tower as discussed in section 4.2 of the paper.

As mentioned before, the study of seismic behavior of the nonstructural elements has started much later than the structural elements of buildings. One of the first attempts in this regard was a workshop held by Earthquake Engineering Research Institute (*EERI*) in 1983 with the objective of reviewing and evaluating the status of nonstructural elements [6]. The studies continued since then in various forms from mathematical modeling to retrofitting techniques to their effect on the emergency function of an essential building. For example, Henry and Stein (1987) conducted a comparative study of the effects of cladding panel modeling [14]. They studied the macroscopic effects on the behavior of a two story, one bay frame with a single cladding panel at mid-height when cladding panels are structurally incorporated into the analysis. The results indicate that incorporation of cladding panels results in a dramatic reduction in a structure's natural periods of vibration.

In early 90s the Applied Technology Council (*ATC*) held a seminar and workshop on Seismic Design and Performance of Equipment and Nonstructural Elements in Buildings and Industrial Structures, in which several issues with regard to the nonstructural elements were addressed. As an example, the seismic performance database based on the study of more than 100 major facilities and many smaller facilities and hundreds of buildings located in the strong-motion areas of 42 earthquakes that have occurred in California, Latin America, Europe, Asia, and the Pacific region since 1971 can be mentioned [52]. More examples of the studies reported in that workshop, which were published later as the *ATC*-29, are mentioned in section 3 of this paper.

In a state of-the-art report by Soong [43] the seismic behavior of nonstructural elements the importance of nonstructural issues in seismic design and performance evaluation was emphasized [43]. In a study on the nonstructural damage from the Northridge earthquake by McKevitt, et al [25] potentially hazardous nonstructural damage was pointed out with more emphasis [25]. As a good example of detailed analytical studies on the seismic behavior of the nonstructural elements the study by Pantelides, et al [33] can be mentioned. They worked on the development of a loading history for seismic testing of architectural glass in a shop-front wall system. In their work a systematic analytical study of the effect of the *S*00*E* component of the 1940 *E*l Centro earthquake on the response of a one-storey glass and aluminum shop-front wall system was presented. The seismic response of a one-storey commercial building comprised of three reinforced masonry walls, a glass and aluminum shop-front wall system, and a steel bar joist metal deck roof system was determined using the *ABAQUS* and *SAP* 90 finite element packages [33].

One of the first experimental works on the nonstructural elements was conducted by Negro and Colombo [32]. They made some full-scale pseudodynamic tests on a four-storey framed structure designed according to Eurocode 8, with different infill configurations. Their results showed that an irregular distribution of the panels yields unacceptably large damage in the frame. In addition, it was shown that even a regular distribution of infills can lead to irregular behavior of the frame [32]. Another experimental study was conducted on the seismic horizontal force of nonstructural systems mounted on the buildings using a shaking table [27].

In that study the nonstructural systems mounted on two conditions of main structures, fixed base and isolated structures, were examined using several earthquake motions. The acceleration responses of the nonstructural systems, the amplification factor relative to the input ground accelerations, and the horizontal force coefficients were observed, and comparison between the experimental results and the 1997 *UBC* and the 1997 *BCJ* design codes were also conducted [27].

In the second seminar of *ATC* on the nonstructural elements, held in 1998, Seismic Design, Retrofit, and Performance of nonstructural components were discussed. As a sample of studies presented in that seminar, whose contents were published as the *ATC* 29-1, the work reported by Porter and Scawthorn [34] can be mentioned, in which the seismic reliability of critical equipment systems such as fire protection systems in high-rise buildings was studied [34]. In that study attaining seismic reliability was reported to involve several steps, including: 1) modeling the equipment and the system they constitute with regard to seismic performance, 2) assessing the risk posed by failure of the equipment due to a major earthquake, 3) determining an appropriate criterion, or level of reliability, and 4) cost effectively assuring the reliability.

The seismic response of nonstructural systems mounted on the suspended pendulum isolation (*SPI*) devices was also studied by shaking table test [26]. As compared to the results of the reference fixed structures, it was found that the utilization of the *SPI* system produced the significantly low acceleration amplification factors of supported nonstructural systems. The *SPI* system also gave relatively constant amplification factors along the natural period of nonstructural systems and over the various input ground excitations. Comparison between the experimental results and two nonstructural design stipulations of the 1997 Uniform Building Code and the 1997 Building Center of Japan was also conducted to show that the horizontal force coefficients of nonstructural systems mounted on isolated structures are sufficiently lower than the maximum provided design values [26].

Following the work of Yanev, [52], Kao, et al [16] developed a nonstructural damage database. That database provides information on earthquake-caused damage to nonstructural elements in buildings and other facilities from the 1964 Alaska earthquake to the present. It contains nearly 3,000 entries encompassing more than 50 earthquakes [16].

Recently the nonlinear analysis of nonstructural components was studied by Villaverde [50]. He proposed a design-oriented simplified method for the seismic design of nonlinear nonstructural components attached to nonlinear building structures. His method is based on a previously developed simplified procedure for linear systems that is analogous to the reduction of response spectrum ordinates by a ductility factor and involves the use of reduced natural frequencies and augmented damping ratios to linearize the nonlinear systems [50].

More recently the nonstructural seismic preparedness of Southern California hospitals was taken into consideration [51]. They tried to assess the level of adoption of nonstructural seismic hazard adjustments by hospitals in Southern California, and to identify the factors that led to adoption of these adjustments. Results provide evidence that hospitals in Southern California have partially implemented a variety of earthquake preparedness and mitigation activities. However, many adjustments specific only to earthquake hazard were not commonly implemented, and this is cause for concern [51]. Finally, very recently the effect of damage to nonstructural elements in a hospital evacuation was studied [38]. Based on a study on the 1995 Kobe earthquake they have reported that the immediate nonstructural damage, after even a moderate earthquake, can put a hospital at serious risk [35].

It is seen that the nonstructural elements have been looked at by researchers from many different viewpoints. However, the ongoing research shows that there are still some problems with regard to these elements which need more investigations. Among these, the studies done on the three following subjects are of more importance, since they are more related to the "seismic risk mitigation" as the main goal: 1) the seismic design provisions and recommendations, 2) the seismic vulnerability evaluation, and 3) the seismic upgrading techniques. The works done with regard to these subjects are reviewed in detail in section 3 of this article to help making better decisions on the future works in this field. However, before the review, it is helpful to have a brief explanation of the characteristics of the nonstructural elements, which make them different from the structural elements, particularly in the case of Iranian buildings. These are discussed in section 2 of the paper. After the review in section 3, the behavior of nonstructural elements in the Bam earthquake is studied in section 4, and finally based on the Bam observations some discussions and

recommendations are presented in section 5 of the paper, which are useful for revising the corresponding chapter in the "Guidelines for the Seismic Retrofit of the Existing Buildings", which is used presently in the country as the only official reference in this regard.

2. Characteristics of the Nonstructural Elements

In spite of different specifications for various kinds of the nonstructural elements, these elements have some general physical characteristics which make them different from the structural elements from the seismic behavior point of view. Furthermore, in the case of Iranian construction styles, and also because of some cultural fact in Iranian lifestyle these elements have some particular features which can not be found in conventional types of building construction and use in other countries.

2.1. General Characteristics

Most of the nonstructural elements have the following general mechanical specifications which makes them different from the structural elements, such as steel or reinforced concrete members, which are generally utilized for seismic resistant design of buildings:

- High initial stiffness
- Low ultimate strength
- Brittle behavior subjected to dynamic loads

Masonry nonbearing walls and partitions, façades and claddings, mechanical pipings, and some of interior facilities, which are attached to the building such as cupboards and shelves, are all samples of the nonstructural elements having the abovementioned characteristics. The first specification makes the whole building structure stiffer than the building skeleton alone. This means a lower natural period which usually results in higher seismic forces received by the building. Obviously, these high seismic forces will act on all elements showing resistance against the loads, regardless of being structural or nonstructural. The high imposed forces to the nonstructural elements on the one hand, and their second and third specifications, namely the low ultimate strength and brittleness, on the other, will make these elements to get damaged or even fail just in the very first moments of earthquake excitations. It is notable that if the nonstructural elements are not permitted to act as parts of lateral resisting system to participate in carrying the lateral seismic loads, the value of the seismic forces received by the whole building system would be much less, as the stiffness of the building skeleton alone is lower than the combined structural and nonstructural system.

Another adverse effect of the participation of the nonstructural elements in carrying the lateral loads raises from the non-uniform distribution of these elements in the plan of the buildings, which is almost inevitable. This non-uniformity on the one hand, and the high stiffness of these elements, on the other, can causes the building center of stiffness to be much farther of the building center of mass than what has been considered in the design based on the building skeleton alone. This uncounted eccentricity can make the even a building with regular and symmetric structural system behave torsional, and this additional torsion in turn can result if excessive damage or even collapse of the building.

The two abovementioned facts have encouraged many researchers and designers to work on the idea of isolating the nonstructural elements from lateral load bearing system of the building. This isolation idea can be easily applied if the nonstructural elements are lightweight, but if these elements are heavy, which is the case for most of architectural nonstructural elements in Iranian buildings, the isolation idea can not work well. This problem is discussed in the following subsection with more details.

2.2. Particular Features of the Nonstructural Elements in Iranian Buildings

In the case of Iranian buildings there are some particular features which make the nonstructural elements of these buildings different from those of other countries, especially US and Japan as the two developed seismic countries. Some of these differences are due to the different building construction styles in Iran and the US, and some others relate to the lifestyles in the two countries, which is basically a cultural problem. Regardless of their roots, these differences are of great importance as the Iranian codes have been developed and are still being developed mostly based on the *US* corresponding documents. These features are different depending on the category of the nonstructural elements as follow.

2.2.1. Architectural Elements

This group has the most different features from the corresponding group in developed seismic countries, and is the most problematic group among the nonstructural elements in Iran. The particular features

of this group are:

- Heavy weight
- Low inherent integrity
- Weak connection to supporting structure

The external walls and internal separating walls and partitions, made of massive brick masonry, as well as the stone facade or cladding, particularly the 3*cm* brick finishing of the external walls, are samples of architectural components having all of the abovementioned characteristics. Internal veneer, such as ceramic tiles, and internal walls and ceiling finishing are samples of components having the second and the third characteristics. The top wall and the parapet cornices are the sample components having the first and the third characteristics. Finally, window frames are the sample components which have the third characteristics in Iranian buildings.

2.2.2. Mechanical and Electrical Elements

This group of the nonstructural elements can be considered as the second problematic group because of the following features:

- Having various manufacturing standards
- Mostly installed without any specific standard

In fact, most of the major mechanical and electrical equipments, such as *HVAC*, are imported from abroad, and in many cases from the northern European countries, which are not earthquake prone, and accordingly do not have any specific seismic provisions. Furthermore, although these countries usually have high installation standards, the installation in Iran is done mostly by non-expert people who do not follow the installation instructions properly, and therefore, even if the equipment is from a seismic prone counties, and has the required anti-seismic installation instructions those measures usually are not actually implemented.

2.2.3. Interior Equipments

This group has also some differences with those in other seismic countries, particularly the *US*. These differences are as follow:

- They either are, or are occupied by fragile objects, particularly in the case of house internal ornaments
- They are mostly heavy and are installed as hanging objects from the ceilings in many parts of the building

These two features have basically cultural roots, for example having several old glass or ceramic jars or other similar objects, and also big and heavy chandeliers in almost all rooms, particularly in more luxury houses is an Iranian tradition.

The special features discussed in this section make the use of design guidelines and also evaluation criteria and retrofitting measures, developed by other countries and discussed in the following section of the paper, inadequate in many cases, and therefore, some more appropriate methods and techniques are required to be developed.

3. Studies on Seismic Design, Evaluation, and Upgrading of the Nonstructural Elements

As mentioned in section 1 of the paper several studies have been performed on the nonstructural elements since late 70*s*. However, among these studies those related to the seismic design, vulnerability evaluation, and retrofitting techniques are more important for the "seismic risk mitigation" purposes. Therefore, in this section of the article a state-of-the-art review on the seismic design, evaluation, and upgrading of the nonstructural elements is presented.

3.1. Seismic Design Provisions and Recommendations

The first seismic design provisions for nonstructural components in buildings can be found in the 1978 *ATC* 03 report. These provisions were discussed to some extent in the *EERI* [6] publication based on the workshop held in April 1983 with the objective of reviewing and evaluating the status of nonstructural elements as considered factors in seismic design and construction, with emphasis on the status of and need to improve implementation of research [6]. In that workshop four issues were discussed, which include life hazards, structural relationships, institutional roles, and economic losses.

Sakamoto, et al [37] proposed some methods for aseismic design of nonstructural elements based on experiments and field surveys [37]. Their work basically was focused on exterior walls and partitions, particularly falling of broken glass, and to some extent on the environmental design. Hirosawa, et al [15] presented a state-of-the-art report on seismic design of building equipment and nonstructural components in Japan [15]. They reported various kinds of damage to the nonstructural elements, including broken windows and water storage tanks, loss of exterior and interior finishing, and battered furniture. They also mentioned that in reinforced concrete buildings, the nonstructural walls have often caused a brittle failure of structural columns, with displaced doorway sashes preventing people from entering or exiting.

In an overview of the building code seismic requirements for nonstructural elements Porush [35] suggested some replacements for some the Uniform Building Code provisions [35]. Also Lai and Soong [19] proposed some seismic design recom-mendations for the secondary structural systems [19]. They showed that by selecting an optimum damping of the support, the maximum acceleration of the secondary system can be minimized and that this damping ratio is relatively insensitive to the earthquake input. On the other hand, the relative displacement between the secondary system and the structure can always be decreased by increasing the support damping. Compromises thus need to be made when there is a conflict in achieving the best global secondary system performance.

Haupt [13] discussed the barriers and challenges in developing seismic code rules for equipment and non-building structures. He has mentioned that developing requires the identification of the disparate groups involved, defining and making concrete the appropriate interface parameters between the definition of seismic effects and acceptance criteria, developing tiered acceptance criteria consistent with defined hazard, and developing long-term relationships among organizations preparing rules. Some simplified procedures for seismic design of nonstructural components were also proposed by National Center for Earthquake Engineering Research (*NCEER*) [40], in which an assessment of the current code provisions of that time was also done. In their assessment the 1978 *ATC* 03 report provisions, adopted with some minor changes by the 1991 *NEHRP* Recommended Provisions that were used as the basis for the first generation seismic force provisions for the design of nonstructural components in codes and manuals of that period were critically evaluated, and improved procedures were proposed for incorporating of the dynamic characteristics of the supporting structure as well as the nonstructural components.

In another *NCEER* report the research accomplish-ments on the code development for nonstructural components have been discussed [42]. Focusing on the 1991 NEHRP (National Earthquake Hazard Reduction Program) provisions, he tried to identify their shortcomings, and to recommend revisions which would bring them more in line with the state-of-the-art knowledge of the time in this area. His revisions were recommended within the framework of the equivalent lateral force format for practical applicability. Villaverde [48, 49] also proposed a replacement for the seismic code provisions for nonstructural components in buildings [48, 49]. He tried to develop a procedure to determine in a rational but simple way the lateral forces for the seismic design of nonstructural components attached to buildings based on the results of studies on seismic response of secondary systems. It takes into account the dynamic interaction between the structure and the nonstructural component, the level above the base of the structure of the point or points where the nonstructural component is attached to the structure, and the number of such attachment points. It uses, in addition, the design spectra specified by building codes for the design of the structure as the earthquake input to the nonstructural component.

Sucuo lu and Vallabhan [46] worked on the behavior of window glass panels during earthquakes [46]. Based on the review of glass damage observed in past earthquakes and previous research on the seismic performance of glass components they evaluated the seismic design code procedures proposed for mitigating the damage sustained by glass components. They developed some analytical procedures for calculating the in-plane deformation capacity and out-of-plane resistance of window glass panels subjected to seismic excitation, and proposed some simple practical procedures for the design of glass panels against earthquake effects. Their procedures account for the inter-storey drift displacements and floor responses of multi-storey buildings as well as the mechanical properties of the window glass.

Freeman and Kehoe [11] performed a review on the *NEHRP*-94 Recommended Provisions, in which two alternate methods for determining the horizontal seismic force for architectural, mechanical, and electrical components is suggested: one method specifies a constant acceleration over the height of the building, and the other assumes a linear distribution of acceleration over the height. Comparing with the 1994 Uniform Building Code (*UBC*-94) seismic design provisions, in which the lateral forces on nonstructural components and equipment are calculated by a formula based on the assumption that the horizontal acceleration of the component is constant over the height of the building, Freeman and Kehoe tried to judge the *NEHRP* recommended provisions by the recorded data from the instrumented buildings subjected to earthquakes [11]. Freeman [10] also tried to summarize the provisions of the Tri-Services guidelines to be used as a basis for performance-based engineering of nonstructural components [10]. (The

1982 edition of "Seismic Design for Buildings" manual by the Departments of the Army, Navy, and the Air Force is generally referred to as the Tri-Services manual, and it its supplements, "Seismic Design Guidelines for Essential Buildings" (1986) and "Seismic Design Analysis for Buildings" (1996), dynamic analysis procedures for nonstructural components are presented that account for both elastic and inelastic response of the building to earthquake ground motion. Those design manuals provide criteria for two levels of earthquake motion, methods for approximating floor response spectra, performance requirements of nonstructural components, and design examples.)

Gurbuz, Wu, and Wittchen [12] reviewed the evolution of the requirements for design of nonstructural components and their anchorage, including *UBC*-94, *UBC*-97, and the draft International Building Code (to be *IBC*-2000 later) and showed that classical design and anchorage practice for some heavy equipment may not meet the *UBC*-97 or *IBC*-2000 provisions [12]. A similar study on the development, evolution, and application of the earthquake design force for nonstructural elements was also done by Bachman, and Drake [3] based on the *UBC* and the *NEHRP* provisions. Bachman [2] also presented a comparison of design forces for typical applications for the *UBC*-94, *UBC*-97, and *IBC*-2000, and mentioned that one primary difference is that the *UBC*-94 forces are to be used with working stress design and the *UBC*-97 and *IBC*-2000 forces are to be used with strength design. Therefore the *UBC*-97 and *IBC*-2000 design forces are typically 1.4 times greater than those found in the *UBC*-94.

Kehoe and Freeman [17] also criticized the procedures for calculating seismic design forces for nonstructural elements by comparing *UBC*-94 and *UBC*-97. They studied the effects of the significant changes in *UBC*-97, including the introduction of an *R* factor for nonstructural elements, the use of soil factors in determining the design force, and the variation of the design force over the height of the building, by comparison of design forces between the *UBC*-94 and the *UBC*-97 for rigid and flexible elements, and by comparison with dynamic analysis and building response data. They claimed that the comparisons results do not provide justification for the radical changes in the *UBC*-97. On this basis they proposed restoring the provisions of the *UBC*-94 with some minor modifications, including inclusion of an amplification factor on the design acceleration for roof-mounted elements and improved procedures for calculations of amplification of flexible or flexibly mounted equipment based on the procedures developed in the Tri-Services manual. They also made some recommendations for further research to improve the design procedures.

An interesting case of seismic design of intricate exterior cladding systems was reported by Krakower, et al [18]. In their report it is mentioned that successful seismic design of intricate exterior cladding systems requires awareness of many factors. When some or all of the factors are not considered, the design and construction of the cladding may affect the construction schedule and may result in incompatibility between the cladding and structural systems that lead to unsatisfactory seismic performance. Working on the reconstructed historic House of Hospitality in San Diego's Balboa Park, which has a complex decorative cladding system of about 3000 highly ornamental pieces of glass fiber reinforced concrete (*GFRC*) cast from molds of the salvaged original staff plaster ornamentation, they mentioned that a refinement of the cladding support occurred after the start of construction to improve the constructability and compatibility of the design. Based on their report the seismic design of the *GFRC* cladding structural system faced conflicting parameters, some of which forced the design and construction team to develop a few typical framing and anchorage details that could be used in a variety of potential support conditions. Once these details were established, the testing program was defined and anchor capacities were obtained. They also mentioned that all of the building systems in the vicinity of the cladding had to be accounted for in order to develop the strategy to simplify the structural system [18].

Another interesting issue with regard to the design of the nonstructural elements is the design responsibility as discussed by McGavin and Gates [22]. Referring to California hospital design their recommendation is a systems approach rather than a component by component approach as is currently the case. They also gave some suggestions how the responsible professionals might be brought into the building design industry [22]. A very interesting case, which was related to the 1994 Northridge earthquake, was reported by McGavin, et al [23]. Based on their report following the 1994 Northridge earthquake the City of Los Angeles established working groups in numerous areas to study the need

for possible changes to building ordinances within the jurisdiction of the city. One of the groups was dedicated to studying nonstructural issues, including suspended ceilings. Numerous interests were represented in the nonstructural studies, including the City of Los Angeles, the Division of State Architect, engineers, architects, property owners, academic researchers, and industry representatives. The findings of the suspended ceiling subcommittee were presented to the city for proposed amendments to Chapter 16 (Article 1, Sections 1638 through 1641) of the Los Angeles Municipal Code [23].

McGavin and Patrucco [24] proposed nonstructural functional design considerations for healthcare facilities. Subsequent to the 1971 San Fernando earthquake, California passed its first Hospital Seismic Safety Act mandating that hospitals remain functional. Testimony to the California Seismic Safety Commission following the 1994 Northridge earthquake led to the passage of a second version of the Hospital Seismic Safety Act of 1994 (*SB*1953 Alquist). *SB*1953 is a model code for all jurisdictions in earthquake prone areas where hospital function is a concern. Mentioning the lack of a universally accepted language, code, or definition of what constitutes function or operation McGavin and Patrucco claimed that the majority of owner supplied equipment in the hospital, some of which is life support equipment, receives little or no consideration for seismic qualification. Based on this belief they addressed definitions of function and methods of qualification to better attain a reasonable level of confidence for function for building nonstructural systems and critical owner supplied equipment. They also proposed a "seismic lifeboat" concept that for saving health care providers significant capital outlay over more difficult and questionable methods of attaining function required by *SB*1953. They claimed that their seismic lifeboat concept for health care facilities would make it possible for acute care hospitals to be able to provide basic life saving procedures as well as basic first aid to in-house patients and walk-in injured after a damaging earthquake with a high degree of confidence.

Staehlin [45] also worked on seismic design and performance of nonstructural components in hospitals by discussing the design requirements by the State of California, Office of Statewide Health Planning and Development (*ISOHD*) along with the observed performance of these components during the Northridge earthquake, January 17, 1994. Singh, et al [41] tried to present simplified methods for calculating seismic forces for nonstructural components. Their details of calculating the seismic acceleration coefficients are different, stemming from a study of the response of several buildings analyzed for an ensemble of recorded ground motions. They compared forces calculated by their proposed approach with those calculated according to the *NEHRP*-97 and the UBC-97 provisions, and also with the forces that could have been caused in the nonstructural components by the 1994 Northridge earthquake. Their provisions proposed to reduce the force required for rigid components and to increase forces on the flexible or flexibly mounted components. Finally, Drake and Bragagnolo [4] also described the development, evolution, and application of the earthquake design force provisions of the *UBC*-97 and the *NEHRP*-97 for elements of structures and nonstructural components. Their claim is that engineers and architects need to become informed regarding a variety of earthquake design force provisions.

3.2. Seismic Evaluation Methods

The first studies on seismic evaluation of the nonstructural elements started just a few years after the first works on their seismic design. Reitherman [36] did a study on reducing the risks of nonstructural earthquake damage, and presented a practical guide which was published by the *U.S.* Federal Emergency Management Agency (*FEMA*) as *FEMA* 74. This *FEMA* series booklet provides practical information to owners, operators, and occupants of office and commercial buildings on the vulnerabilities posed by earthquake damage to nonstructural items and the means for mitigating these problems. The booklet has two specific objectives: 1) to aid the user in determining which nonstructural items are most vulnerable to earthquakes and are of most concern, and 2) to point the way toward implementing cost-effective countermeasures.

Drake and Richter [5] performed a study for earthquake hazard mitigation of nonstructural elements in *U.S.* postal service facilities [5]. That paper presented a description of work in progress to identify potentially hazardous nonstructural elements in the *U.S.* Postal Service (*USPS*) facilities and to provide recommendations for upgrade of elements and supports for the life safety level. That work was supposed to be incorporated into the Applied Technology Council's *ATC* 26, a handbook for practicing structural/ earthquake engineers and *USPS* staff engineers to evaluate existing *USPS* facilities.

Arnold (1998) worked on the requirements for nonstructural components for the *NEHRP* guidelines for the seismic rehabilitation of buildings [1]. He acted as the team leader for the development of the requirements for Architectural, Mechanical and Electrical Components for the *NEHRP* Guidelines for the Seismic Rehabilitation of Buildings (*FEMA* 273). In that paper the methods by which a range of performance levels and objectives was accommodated is discussed. Other issues outlined are the scope of the nonstructural components to be considered, the categorization of nonstructural components as acceleration-sensitive or deformation-sensitive, issues relating to means of egress, the nonstructural damage states, and the definition of the operational and collapse prevention levels of performance. Some comments about the difficulties of developing a performance-based set of provisions for nonstructural components are also provided.

3.3. Seismic Upgrading Techniques

The work on seismic upgrading of the nonstructural elements started almost a decade later than the first works on their seismic design. Lagorio [20] published a book entitled "Earthquakes -- an architect's guide to nonstructural seismic hazards for members of the architectural profession. The book covers some of the latest developments in earthquake hazards reduction prior to the time of its publication. It is divided into the following sections: 1) Earthquake Causes and Effects, 2) General Aspects of Building Performance, 3) Site Investigation, 4) Site Planning, 5) Building Design, 6) Nonstructural Building Elements, 7) Existing Buildings, 8) Urban Planning and Design, 9) Recovery and Reconstruction, 10) Earthquake Hazards Mitigation Process, 11) Recommendations and Summary, and 12) 1989 Loma Prieta Earthquake in the Santa Cruz Mountains of the San Francisco Bay Area Region. An index is also included.

Merz and Cumming [29] presented some recommendations for installation of suspended acoustical ceiling in moderate- and low-risk seismic areas. Following the installation guidance for seismic restraint of suspended ceilings in *UBC* Standard 47-18, which has its origins in a 1972 Ceilings and Interior Systems Construction Association (*CISCA*) Recommended Standard for Seismic Restraint of Direct-Hung Suspended Ceiling Assemblies, and its development for the splay wire restraint requirements in *UBC* 47-18 and their modification during the intervening years for the lateral force design levels specified for Seismic Zone 4 (California), Merz and Cumming discussed the background of the those ceiling restraint provisions and provided separate recommendations for ceiling installation in Seismic Zones 0-2.

Masek and Reitherman [28] performed a study on problems in the implementation of nonstructural earthquake hazard reduction efforts. In that study the authors express their general agreement with the frequently made statement that reducing nonstructural vulnerabilities is cost effective and necessary to reduce significant risks. However, they claim that their experience over the past decade indicates that the barriers to actual implementation are often overlooked. So, the purpose of that paper is to present a summary of solutions to problems that can inhibit implementation of earthquake damage mitigation programs for equipment. Their observations are based upon studies conducted involving in excess of 30 million square feet of processing, manufacturing, computer equipment, mechanical/electrical equipment, and office space. Projects have included design of equipment for new facilities, design of retrofit seismic restraints, and third-party review of restraint designs by others. At the end of that paper some suggestions are drawn from the experience of the authors in working with contractors, facility and risk managers, equipment vendors, and maintenance personnel.

Selvaduray [39] worked on nonstructural hazard mitigation for schools, which was published as *NCEER*-93-0015 report. That report tries to define "nonstructural" and provide the motivation for nonstructural hazard mitigation. It is also tried that typical examples of nonstructural damage during earthquakes are described, with a special emphasis on damaged incurred by schools. Also hazard reduction techniques that are applicable to schools are described, with specific recommendations on what can be done in the office and classroom environment, how the potential of hazardous materials incidents occurring can be reduced, and how mechanical equipment can be anchored.

Fierro, et al [9] presented a practical guide for reducing the risks of nonstructural earthquake damage, which was published as the third edition of *FEMA* 74. That guide was developed to fulfill several different objectives and address a wide audience with varying needs. The primary intent was to explain the sources of nonstructural earthquake damage in simple terms and to provide information on effective methods of reducing the potential risks. However, the

recommendations contained in that guide are intended to reduce the potential hazards but cannot completely eliminate them. A few years later Fierro and Perry [8] made a further discussion on FEMA 74. Mentioning that *FEMA* 74, Reducing the Risks of Nonstructural Earthquake Damage -- A Practical Guide, was written to help both the layperson and the engineer to understand, evaluate, and mitigate the risks associated with nonstructural earthquake damage, that paper presents a history of the development of the original document and subsequent revisions, including the third edition by Wiss, Janney, Elstner Assocs., Inc., published in September 1994. Mentioning that the document includes 39 upgrade details that are all categorized as either "Do-It-Yourself" or "Engineering Required" and that the document also includes a Nonstructural Inventory Form, a Checklist of Nonstructural Earthquake Hazards, and a table of Nonstructural Risk Ratings; their paper provides some suggestions for their use in surveying nonstructural earthquake hazards. The authors tried to cover a sample facility inventory using the methodology of *FEMA* 74, and include a summary of suggested improvements and modifications in light of recent developments.

Eidinger and Goettel [7] performed a study on the benefits and costs of seismic retrofits of nonstructural components for hospitals, essential facilities and schools. The cost effectiveness of seismic upgrades of nonstructural components at hospitals, emergency operation centers, city halls, and schools were examined in that paper. They provide examples for bracing of fire sprinkler pipes, upgrades of suspended ceilings, installation of flexible utility connections between buildings, anchoring of equipment, steam pipe upgrades and window retrofits. Also Lama [21] presented some practical guidelines for seismic retrofitting of *HVAC* systems. In that paper Lama deals with the methods developed that allow the contractor to retrofit on *HVAC* equipment, piping and ductwork a seismic system that is practical, economically feasible, proven, and trouble free. He also mentions in his paper that proper snubbing and cable sway brace systems for floor mount and suspended systems, which have no moving parts, are designed not to interfere with the acoustical and vibration systems that are mandated by the Mechanical Engineers and Acoustical Consultants for the *HVAC* systems. These systems also should meet the requirements of the structural engineering community for the foreseeable future.

Meyer, et al [30] worked on retrofit seismic mitigation of mainframe computers and associated equipment as a case study. Their work is a case history of a completed seismic restraint program at a raised floor data center. Their restraint system employs splayed tension cables from the equipment to the concrete floor slab, and anchored equipment includes mainframe computers and related equipment. That paper outlines the three major steps in an actual nonstructural mitigation project including analysis, design, and installation. The analyses included time history dynamic analysis to study the effects of various design parameters on the acceleration of the anchored equipment, and the loads on the anchoring system. The design included consideration of anchor bolts, cable stretch implications, and pre-tensioning. The installation issues included constraints due to obstacles, difficulties in attaching to the equipment, working in a fully operational facility, and cost controls. They also discussed the quality control through testing, submittals, and inspection.

Thiel, et al [47] worked on the seismic retrofit of nonstructural components in acute care hospitals. In that work they mention that the Office of Statewide Hospital Planning and Development (*OSHPD*) has developed technical provisions for the seismic retrofit of acute care hospitals, and that under *SB* 1953 acute care hospitals must be either certified as, or retrofitted to be, life-safe by 2008 and must be capable of maintaining operations following an earthquake by 2030. They also mention that the provisions for nonstructural systems and components are an integral part of the requirements adopted by the Building Standards Commission to meet these performance objectives. These requirements have two distinct aspects: 1) the delineation of the specific systems included in the various performance levels, ranging from the lowest, Nonstructural Performance Category *NPC*-1, to the highest, *NPC*-5, and 2) the technical standards used to achieve the performance. The *OSHPD* modified Division *III-R* -- Earthquake Evaluation and Design for Retrofit of Existing State-Owned Buildings and Existing Hospital Buildings -- of Part 2, Chapter 16, Title 24 is to serve as the standard to be consistent with those standards to be used for other state buildings. That paper presents the technical details of the standard and discusses its application, particularly to typical equipment.

Recently the near-fault issue was taken into consideration. Soong, et al [44] studied the near-fault seismic vulnerability of nonstructural components and retrofit strategies. In their paper they mention that the

seismic design of buildings has been well developed and is being continually updated and improved, yet, nonstructural components housed in buildings are rarely designed with the same care or under the same degree of scrutiny as buildings. As a result, buildings that remain structurally sound after a strong earthquake often are rendered unserviceable due to damage to their nonstructural components, such as piping systems, communication equipment and so forth. They also mention that the September 21, 1999, Chi-Chi, Taiwan, earthquake further demonstrates the importance of controlling damage to nonstructural components in order to ensure their functionality during and after a major earthquake. In that paper they assessed damage to some critical facilities during the Chi-Chi earthquake, and addressed two important issues associated with seismic performance of nonstructural components: seismic vulnerability and rehabilitation strategies.

Based on the review presented in this section of the paper it is seen that although several studies has been performed since early 80s on various issues related to the nonstructural elements in the field of earthquake engineering, the occurrence of every new earthquake has created some new ideas which has changed or modified the previously published regulations, guidelines and recommendations. The Bam earthquake is not an exception in this way, and the study and investigation on the behavior of the nonstructural elements in this earthquake can be very useful for the possible required modifications which should be applied to the existing seismic design guidelines, evaluation procedures, and retrofitting techniques to make them more appropriate for the country use. This investigation is presented in the next section.

4. Behavior of the Nonstructural Elements in the Bam Earthquake

The December 26, 2003 earthquake of Bam with magnitude of 6.5, which hit the city of Bam, town of Baravat, and several surrounding villages in Kerman province, destroyed more than 70% of the buildings in the stricken area, and also caused extensive nonstructural damages to the buildings which were remained structurally intact. The observed cases of nonstructural damages are mainly architectural. There are also some cases related to the internal equipments, and just a few cases of electrical or mechanical components. In this section of the paper the damages to nonstructural elements are reviewed based on their categories.

4.1. Architectural Components

The major damages to the architectural components were observed in masonry walls and partitions, internal and external façade and veneers, and particularly stairs. Some damages to false ceilings, glass finishing and windows and doors glasses, parapets and other attachments were also observed as follow.

4.1.1. Exterior Walls Masonry

Several cases of damage to external wall masonry were observed, of which some samples are shown in Figures (1) to (4). It is seen in Figure (1), which is related to the recently constructed Emdad Khodro building located beside the Kerman-Zahedan road, that the external walls in the second story and a part of it in the first story of the building have fallen out. This building had a serious case of pounding as it is shown in the next pictures. The broken glasses of the window in the first story are also visible in the picture. Note that there is no sign of the interlocking between the remained wall in the second floor with the one formerly perpendicular to that, which is now fallen

Figure 1. Collapse of the external walls made of brick masonry in Emdad Khodro building (Photo by M. Hosseini).

out. Also note that in the middle bay at the second story the internal shelf has fallen inward the building. It is also notable that the roof parapet of the building did not get damage, which can be basically because of its short height.

Another case of damage to the external walls is shown in Figure (2), which is related to Khormaye Shargh (East Date) export company. The complete collapse of the end wall of the refrigerating hall is seen in the figure. It is also seen that one wall of the motor house beside the hall has collapsed. A close up of this fallen wall is shown in Figure (3). Examination of the building showed that there was not any internal stabilizing column or external buttress in that end wall. In the case of the motor house wall just its inherent weakness and little integrity with other walls can be the main cause of collapse.

Other samples of the external walls failure are shown in Figures (4) and (5). The little integrity of these walls and their weak connections with the structures are believed to be the main causes of failure in these cases.

Figure 2. Complete collapse of the external wall of the refrigeration saloon of Khormaye Shargh (east date) export company made of concrete block masonry (Photo by M. Hosseini).

Figure 3. Complete failure of the external wall with partial collapse of the ceiling in the motor house of Khormaye Shargh export company (Photo by M. Hosseini).

Figure 4. Collapse of external walls in an under construction R/C building, whose skeleton remained i ntact after the quake - Note to the fallen out window as well (Photo by M. Hosseini).

Figure 5. Collapse of the external wall masonry in the second and third stories of a 3 story steel structure building - the roof parapet has fallen as well (Photo by M. Hosseini).

4.1.2. Yard Walls

Several cases of failure of yard or surrounding walls were observed. Two samples, one brick wall and one hollow concrete block masonry are shown respectively in Figures (6) and (7).

The main reason behind the collapse of these yard walls, as it can be seen in Figures 6 and 7, is in addition to their inherent weakness, the lack of, or the long distance between buttresses [loghaaz-haa].

Figure 6. Toppled brick wall - Note to the fallen parapets as well (Photo by M. Hosseini).

Figure 7. Toppled concrete block (partially brick) wall (Photo by M. Hosseini).

4.1.3. Interior Walls and Partitions

Many cases of failure or severe damage to the interior walls and partitions were observed. Two samples are shown in Figures (8) and (9). It can be seen in Figure (8) that although the wall material is gypsum, which is a relatively light material, and although the prefabricated panels are usually of higher quality in comparison with the in situ construction, the lack of integrity and weak connection to the ceiling have caused the failure of the wall. In the case shown in Figure (9) it seems that the very little thickness of the partition has been the main cause of the failure.

4.1.4. Facades

The most popular facade in Bam, as in many other cities in Iran, has been the fine brick masonry cover, called usually the 3*cm* brick facade. The stone tiles are the second some popular materials used as the

Figure 8. Severely damaged interior wall made of gypsum panels (Photo by M. Hosseini).

Figure 9. Severely damaged interior partition (Photo by M. Hosseini).

facade in Bam. Several cases of damage to the 3*cm* brick facades and other brick facades were observed, of which a few samples are shown in Figures (10) to (16). Stone facades have also got damaged in many cases, a sample of which is shown in Figure (17). As it is seen in Figures (10) to (16) no specific pattern can be found for the damage of brick facades. They have got damaged in different building elevations with various forms and areas.

It is noticeable in Figures (11) and (12) that the window glasses have remained intact while the brick facades have gotten severely damaged. It is also notable that the parapet of the logistic building of (formerly) Azadi Hotel (presently Iran Parsian Hotel) has not fallen, which can be because of its little height. It should be noted as well that the Iran Parsian Hotel is located far from the causative fault of the earthquake comparing with the Hijab intermediate school or the city electric substation. However, this building suffered extensive nonstructural damages.

Figure 10. Damage to the so called 3cm brick facade in the second story of the Hijab girls' mid school (Photo by M. Hosseini)

Figure 11. Damage to the so called 3-cm brick facade in the first story of the office building of the city electric substation (Photo by M. Hosseini).

Figure 12. Damage to the brick facade in the top part of the walls in the logistic building of Azadi Hotel (Photo by M. Hosseini).

An interesting point, which is visible in Figure (13), is the lack of cohesion between the main wall masonry and the brick façade. The very clean surface of the concrete block masonry of the wall in this figure shows clearly this lack of cohesion. In the special case shown in this figure it seems the vertical box profiles of the top fence have prevented the façade form the complete collapse. Other interesting point is the detachment of the group of bricks with the used mortar behind them, which are stuck together and made a big piece of debris. It is obvious that falling of such a big piece from a high elevation can be very harmful to the subjected people. Nevertheless, this type of integrity between the bricks and the mortar can help their retrofit as described in section 5 of this paper.

Figure 13. Damage to the brick facade in a yard wall (Photo by Mahmood Hosseini).

Another interesting point can be seen in Figure (14), which shows the fallen brick façade of a residential building. It is seen that in spite of the failure of the façade and the pop out of the windows, the upper part of the façade, which covers the parapet wall had remained almost intact. This can be related to the good cohesion of the brick with the used mortar and also of the mortar with the concrete horizontal tie behind it. (The concrete tie has helped the building to survive the quake.)

Contrary to the cases shown in Figures (10), (12), and (14), the case depicted in Figure (15) shows the failure of the brick facade in the lower part of the building. A reason behind this scattered location of the damaged façade in building elevation can be the non-uniformity of construction work, particularly the used mortars. Figure (15) also shows the failure of the staircase roof (penthouse) which was a very

common case observed in the Bam buildings as is discussed in more detailed in the following section of the paper.

Figure (16) depicts a unique case of facade or finishing of a yard wall. It is seen that the masonry of the wall has two separate parts, an inner layer and an outer layer. The inner layer is itself a 3*cm* brick facade, a part of which shown in Figure (13), and the outer layer seems to be a combination of brick masonry and hollow concrete block masonry, finally plastered with a layer of cement mortar. The bricks on the wall, which their larger faces are exposed in the picture, seem to be a filler layer between the two main layers of the wall!

The sample of damaged stone façade is shown in Figure (17). The scattered locations of the detached tiles of the façade on the elevation of the building

Figure 14. Failure of the brick facade in the external wall of a residential building - note to the popped out windows as well (Photo by M. Hosseini).

Figure 15. Damage to the brick facade in lower part of the two story residential buildings - Note to the collapsed penthouse as well (Photo by M. Hosseini).

Figure 16. Damage to the plastered brick and block facade in a yard wall (Photo by M. Hosseini).

Figure 17. Damage to the stone tiles facade in Ban k Mellat building (Photo by M. Hosseini).

indicate again the non-uniformity of the construction work. The interesting point is the detachment of the group of tiles with the used mortar behind them, which are stuck together and make a big piece of debris. This case of stone tile failure was also observed in brick façade as shown in Figure (13).

4.1.5. Stairs and Staircases

Stairs and staircases are among the most vulnerable nonstructural elements, and therefore, are among the most harmful elements in the aftermath of an earthquake as well. Several cases of damage to stairs and the roof structure of the staircases (penthouses) were observed in the Bam earthquake. Some of these cases are shown in Figures (18) to (21) in addition to Figure (15) discussed in the previous section.

It is seen in Figure (18) that the skeleton of the stair case roof has lost its integrity. The same problem

is visible in Figures (19) and (20). In a very recent study entitled "Post-Earthquake Quick Inspection of Damaged Buildings in Bam" (Moghadam and Eskandari, 2004) it is reported that in almost 75% of the inspected buildings the main reason of collapse of the penthouses has been the lack of structural system or lack of structural integrity [31]. They also states that according to the inspection in more than 25% of cases both stairs and their sidewalls have been damaged, in more than 20% of cases just the sidewalls were damaged, while the stair itself was undamaged, and in less than 10% of cases, the stair has been damaged, while its sidewall was undamaged.

Figure 18. Severely damaged staircase roof in the office building of the city electric substation-Note to the broken glasses as well (Photo by M. Hosseini).

Figure 19. Damage to the staircase roof in the three story building of Azadi Hotel (Photo by M. Hosseini).

Figure 20. Severely damaged staircase in a commercial building (Photo by M. Hosseini).

Figure 21. Severely damaged or totally collapse penthouses in the residential complex two story buildings (Photo by M. Hosseini).

4.1.6. False Ceilings

The most important building in which this kind of nonstructural damage was observed was the Bam Airport Terminal. It can be realized in Figures (22) and (23) that although the false ceiling parts seem not to be heavy, because of their high length, on the one hand, and the strong vertical component of the ground motion, on the other, they have suffered from a kind of buckling instability, resulted in their falling down.

Figure 22. The deformed parts of the false ceiling in the Bam Terminal Building (Photo by Mahmood Hosseini).

Figure 23. The false ceiling of the Bam Terminal Building, of which some part have fallen down because of instability (Photo by M. Hosseini)

4.1.7. Interior Veneers

As it is expected there are several types of interior veneers use in the Bam buildings, and almost all types have suffered severe damages. Some samples of damages are shown in Figures (24) to (30). Figures (24) and (25) relate to the Bank Refah Karegaran (The Workers Welfare Bank) building in which several kind of damage to the nonstructural elements were observed including the damages to the interior veneers such as the finishing gypsum layers on walls and ceiling and stone tiles finishing on walls. A reason behind the failure of gypsum layer finishing is the potentially weak line of the electric wire protection tubes as is discussed in section 4-2 of the paper.

The scattered locations of these damages again show the lack of uniformity in the construction process, which was also observed in the facades as discussed before. It is noticeable that in spite of

Figure 24. Severely damaged gypsum layer finishing of the interior wall of the Bank Refah Karekaran building (Photo by M. Hosseini).

Figure 25. Severely damaged gypsum layer finishing of the interior wall of the Bank Refah Karekaran building (Photo by M. Hosseini).

Figure 26. Severely damaged gypsum layer finishing of the ceiling of the Bank Refah Karekaran building (Photo by M. Hosseini).

Figure 27. Severely damaged stone tile finishing of the interior wall of the Bank Refah Karekaran building (Photo by M. Hosseini).

Figure 28. A big part of gypsum veneer of the ceiling has separated and fallen (Photo by M. Hosseini).

having a mezzanine part in this building as shown in Figure (24), which makes building an irregular one, its structural behavior has been almost satisfactorily. It is also notable in Figures (24) and (26) that the sizes of the fallen parts of veneers are quite large and it is obvious that the debris with this size can be seriously harmful to the people, considering particularly the height of the ceiling. This size problem is also observable in Figure (28), which shows a part of ceiling of which a big part of gypsum veneer has separated and fallen.

Figures (29) and (30) show the damages to the interior veneers in the Azadi (Iran Parsian) hotel. The veneers of the upper part of almost all of columns in the lobby were damaged as shown in Figure (29). There were also some damages to the ceramic tile veneers in the bathrooms of the hotel as shown in Figure (30). An interesting point is that just a small part of the column veneer as shown in Figure (29) was damaged, while the lower part which is covered

Figure 29. A sample of damages to the veneers of the columns tops in Azadi (Iran Parsian) hotel (Photo by M. Hosseini)

Figure 30. A sample damages to the ceramic tile interior veneers in the bath rooms of Azadi (Iran Parsian) hotel (Photo by M. Hosseini).

by glass mirror has remained intact. It is not easy to give a reason for this case. This reasoning difficulty is also true for the form of damage in the tile veneer shown in Figure (30).

4.1.8. Glass Facades and Windows

Several cases of damages to the glass facades, thick glass doors, or window glasses were observed, of which a few samples are shown in Figures (31) to (37). The scattered locations of the broken glasses in Figure (31) show again the non-uniformity of the material and construction process. In Figure (32) in addition to the broken glasses of windows the cracked and partially fallen parapet of the Emergency Section of the city hospital is also noticeable. In Figure (33) the size of the broken parts of the thick glass door of Bank Refah Karegaran (The Workers Welfare Bank) can be realized by comparison with the size of the pen cap in the middle of the picture in light blue color.

Figure 31. Damage to th eglass facade of trade and tourism building (Photo by M. Hosseini).

Figure 32. Damage to the glasses of widows in the Emergency Section of the city hospital (Photo by M. Hosseini).

Figure 33. Splashed Parts of the broken thick glass door of Bank Refah Karekaran building (Photo by M. Hosseini).

Figure (34) shows the broken window glasses of a building, while no crack can be seen on the veneer of the walls. The same case is seen in Figures (35) and (36). This shows that the window glass is more vulnerable than the brittle facades. Nevertheless, in

Figure 34. Damage to the glasses of widows in the second story of a residential building (Photo by M. Hosseini).

Figure 35. Damage to the glasses of widows in Bank Saderat Iran building (Iran Import Bank) (Photo by M. Hosseini).

Figure 36. Damage to the glasses of widows in the second story of a residential building - Note to that horizontal damage line in the façade at the level of roof (Photo by M. Hosseini).

Figure (36) a horizontal crack at the level of roof can be seen in the façade which has created because of the movement of the parapet. In fact, this has been that commence of the parapet failure, but because of the short height and relatively high thickness of the parapet it has survived the quake. A similar condition can be seen in Figure (37) in the building located at right, while in the one at left in addition to the breakage of all window glasses the parapet has collapsed as well.

4.1.9. Parapets and Other Attachments

Some samples of damaged or collapsed parapets were discussed in the previous part of the paper. In this part some more cases of damage to parapets and attached tablets and bill boards are discussed as shown in Figures (38) to (41). It is seen in Figure (38) that all

parapets in the front elevation of the building have collapsed, while in the other direction the relatively high and slender parapet has survived. This shows the high directivity effect of the earthquake.

Figure 37. Damage to the glasses of widows in the second story of a residential building (Photo by M. Hosseini).

Figure 38. Collapse of parapets in the Iran Insurance Company building (Photo by M. Hosseini).

Figure 39. Partial collapse of parapets in a two story building (Photo by M. Hosseini).

The directivity effect is also visible in Figure (39) in which again just parapets in some specific directions have collapsed, while in other direction they have survived. Figure (40) shows another case of complete collapse of parapets in a two story residential building. Note that in this building the window glasses have remained almost intact. This is because of higher resistance of glasses to out of plane forces in comparison with the parapets, on the one hand, and the directivity effect of the quake, on the other.

Figure (41) shows the collapsed tablets and bill board of a commercial building. Regarding the relatively low weight of the bill boards it can be claimed that the connection between the boards and their frames have not been strong enough to resist the earthquake shock. A part of the stone façade of the parapet has also failed, which is basically because of the failure of the whole parapet from that point to right (not completely shown in the picture). This again confirms the directivity effect of the earthquake.

Figure 40. Complete collapse of parapets in a two story building (Photo by M. Hosseini).

Figure 41. Collapse of tablets and bill boards in a commercial building (Photo by M. Hosseini).

4.1.10. Windows and Door Frames

An almost newly observed phenomenon in this earthquake was the popping out of the windows and some door frames. Some samples of these cases are shown in Figures (42) to (44). This phenomenon can be due to the lack of enough connection between the windows and doors frames and their surrounding walls. In some cases, like the one shown in Figure (44), the popped out window has caused the failure of a part of the wall above it. The absence of the spandrel beam can be also another reason behind the poping out phenomenon and the consequent partial failure of the surrounding walls.

Figure 42. The windows in Iran Khodro building popped out of walls (Photo by Mahmood Hosseini).

Figure 43. A popped ou t window in the electric substation office building (Photo by M. Hosseini).

Figure 44. A popped out window in a one story residential building (Photo by M. Hosseini).

4.2. Mechanical and Electrical Facilities

The cases of damage to mechanical and electrical facilities of building were not observed so much in this earthquake. Nevertheless, the observed cases had very adverse consequences.For example, the failure of these facilities in the Bam Airport Terminal and particularly its control tower resulted in the interruption of the airport operation for several hours. It could be understood from Figure (45) that some of electrical facilities and control equipments have malfunctioned because of the high shock of the earthquake resulted in their operation interruption. A sample of damage to the electrical facilities of the airport is shown in Figure (46). The main reason of this damage has been the failure of supporting structure (the false ceiling).

Figure 45. The failure of mechanical and electrical facilities and interior equipment of the Bam airport control tower (Photo Source: http://www.irna.ir/melli/bam/photo_index6.htm)

Figures(47) and (48) show some samples of damage to the electrical facilities. Figure (47) shows the failed light fixtures in the office building of the city electric power substation. The main reason behind this failure is the weakness of connections. Other case of damage to electrical system is shown in Figure 48, which depicts the pull out of the protective tubes of electric wires in the office building of the city electric power substation. The main reason behind

this kind of failure seems to be the potential weak lines in the finishing due to the presence of the wire protection tubes, which are in fact some mainly hollow spaces. The partial failure of the ceiling in Figure (48) is also notable. This has been in fact an inspection access window, which has detached form the ceiling again because of weak connection.

As in many of the past earthquake this event had also some cases of post earthquake fires, which were mainly due to the damage to the electrical facilities. Figure (49) shows a partially burnt shop, which caught fire because the failure of its electrical facilities. The fire caused of the deformation of the broken glass pieces as shown in Figure (50).

Figure 46. The failed smoke detector of the Bam airport (Photo by M. Hosseini).

Figure 47. The failed light fixtures in the office building of the city electric power substation. (Photo by M. Hosseini).

Figure 48. The pulled out protective tubes of electric wires in the office building of the city electric power substation (Photo by M. Hosseini).

Figure 49. A partially burnt shop which got in fire because the failure of its electrical facilities (Photo by M. Hosseini).

Figure 50. The deformed pieces of glass due to the fire occurred in the shop shown in Figure (49) (Photo by M. Hosseini)

4.3. Interior Equipments

Several kind of the interior equipments were damaged in the Bam earthquake as shown in Figures (51) to (53). Figure (51) shows the semi fallen blackboard of a classroom, that obviously have had weak connection to the wall. However, it should be noted that even if it had a strong connection (a bigger nail or

hook), still, because of the inherent weakness of the wall finishing and even the wall masonry, it would have detached from the wall because of notching phenomenon. The same weakness problem can be seen in Figure (52) which shows the toppled shelves of a shop. The fallen part of the gypsum finishing of the ceiling at the right corner in Figure (51) is notable, as in the safety rules, which should be followed inside a building in the time of earthquake, corners are usually suggested as the safer locations comparing to the other places in a room. The partial failure of the upper part of the wall on the right in Figure (52) is also notable. Figure (53) shows the entirely messed interior equipments of another shop in which the collapse of the stone veneer of the left wall is also visible.

Figure 51. The semi-fallen blackboard due to the weak connection (Photo by M. Hosseini).

Figure 52. The toppled shelves of a shop board due to their weak connection (Photo by A.S. Moghadam).

Figure 53. The entirely messed interior equipments o f a shop (Photo by M. Hosseini)

5. Discussion and Recommendations

By paying attention to the various patterns of damage to the nonstructural elements, presented in the previous section, some facts can be realized, and based on some of these facts some recommendations can be made:

- The directivity effect was quite noticeable in the Bam earthquake, as in many cases of two similar walls or parapets in a building one had completely collapsed, while the other one has survived almost intact.
- The weakness of non load-bearing masonry walls (either exterior or interior), and particularly their weak connections to the main structure was quite evident. Therefore, it is necessary to provide some reliable connections between the walls and partitions and the main structure of the building. This problem is critically important when the wall is supposed to act as and active infill. It can be claimed that many of the framed building failures have been due to the collapse of their infills before the failure of the frame structures. Even if the wall is supposed not to contribute to carrying of the lateral load, still it should be attached in a clever way to the structure so that while isolated from the lateral load bearing system, it can remain in its place, and particularly it can withstand the out of plane loads acting on it.
- The yard walls, which are supposed to carry just their own weight, should also have enough lateral resistance. This can be provided by some vertical ties which anchor the wall to its foundation (the wall should have a suitable foundation anyway), or by closely spaced buttresses [loghaaz-haa].

- Facade, particularly the large stone plates and the 3*cm* bricks, should be securely attached to the corresponding walls. A notable point in this regard is that a group of small tiles or bricks, stuck to the mortar behind them, make it possible to retrofit these kinds of facade with a reasonable amount of supporting ties system, by an external structure.
- Glass façade should be also made safe against earthquake. This can be done in three different ways: 1) using the shatterproof glasses, 2) using some kind of very soft materials around the glass plates in their frames to accommodate their movement without breakage, and 3) using an overall framed structure for the whole glass facade and putting it on a rocker-roller supporting system.
- The parapets and tablets or bill board should have reliable supporting structure securely attached to the main building structure. If the use of light weight materials is encouraged in the country vulnerability of these kind of attachments will be greatly reduced.
- The interior veneers and finishing should be also securely attached to their corresponding walls. It is suggested that the use of integrated sheet veneers is encouraged. This will decrease the vulnerability of the interior veneers to a great extent.
- The connecting methods of the interior equipments to the main structural elements or other parts of the building, recommended or suggested by other countries, including the *US*, are not appropriate for the Iranian buildings, particularly in the cases of concerning the masonry walls. This returns back to the inherent weakness of walls masonry mentioned in section 4 of the paper. It is suggested that these equipments are attached to the walls by some kind of ties which can pass through the wall and can be secured in the other side of the wall.
- Staircases and penthouses are among the most vulnerable nonstructural elements in Iranian buildings. It is suggested that the supporting structure of stairs is prevented from contri bution to carrying of the lateral loads. This will help not only the structural system to have a more reliable seismic behavior, but also the staircase itself to sustain less damage.

6. Conclusions

Based on the matters discussed in the previous sections of this paper it can be concluded that:

- ❖ Almost all of the nonstructural elements in the existing building of the country are moderately to highly vulnerable to the probable future arthquakes. Therefore, the retrofit of these elements is a necessity parallel with the retrofit of the structural systems of the existing buildings.
- ❖ Infill walls and staircases are the most vulnerable architectural elements. It is strongly suggested that these elements are separated from the lateral load bearing system of the building.
- ❖ The connecting methods of the interior equip ments to the structural systems, recommended by other countries, including the *US*, are not appropriate for the Iranian buildings, particularly in the cases concerning the masonry walls. Some appropriate methods, like the one mentioned in section 5 can be developed.
- ❖ The proposed recommendations are useful aids for completion and modification of the third volume of the present "Guideline for Seismic Retrofit of the Existing Building" which is now under revision by the *IIEES*.
- ❖ The use of lightweight materials and integrated sheet veneers should be encouraged in the country. This will be a very effective way for reducing the seismic vulnerability of these nonstructural elements.
- ❖ Some of the suggestions and recommendations, discussed in the paper for retrofit of the nonstructural elements need new research projects, particularly the experimental ones, to achieve the reasonable solutions.

References

1. Arnold, C. (1998). "The Requirements for Nonstructural Components for the NEHRP Guidelines for the Seismic Rehabilitation of Buildings, ATC 29-1", *Proceedings of Seminar on Seismic Design*, Retrofit, and Performance of Nonstructural Components, Applied Technology Council, Redwood City, California, 433-444.

2. Bachman, R. (1998). "Building Code Seismic Design Provisions for Non-Structural Components", ATC 29-1, Proceedings of Seminar on Seismic Design, Retrofit, and Performance of

Nonstructural Components, Applied Technology Council, Redwood City, California, 7-14.

3. Bachman, R.E. and Drake, R.M. (1998). "Design Force Provisions for Nonstructural Elements and Model Codes", *Proceedings of the Sixth U.S. National Conference on Earthquake Engineering [Computer File]*, Earthquake Engineering Research Inst., Oakland, California, p.12

4. Drake, R., Bragagnolo, M., and Leo J. (2000). "Model Code Design Force Provisions for Elements of Structures and Nonstructural Components, Earthquake Spectra, **16**(1), 115-125.

5. Drake, R.M. and Richter, P.J. (1990). "Earthquake Hazard Mitigation of Nonstructural Elements in U.S. Postal Service Facilities", *Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*, Earthquake Engineering Research Inst., El Cerrito, California, **3**, 21-29.

6. EERI (1984). "Nonstructural Issues of Seismic Design and Construction", *Earthquake Engineering Research I nstitute (EERI)*, 84-04, Berkeley, California, p. 122.

7. Eidinger, J. and Goettel, K. (1998). "The Benefits and Costs of Seismic Retrofits of Nonstructural Components for Hospitals, Essential Facilities and Schools, ATC 29-1", *Proceedings of Seminar on Seismic Design*, Retrofit, and Performance of Nonstructural Components, Applied Technology Council, Redwood City, California, 491-504.

8. Fierro, E.A. and Perry, C.L. (1998). "Development and Usage of FEMA 74, Reducing the Risks of Nonstructural Earthquake Damage: A Practical Guide, ATC 29-1", *Proceedings of Seminar on Seismic Design*, Retrofit, and Performance of Nonstructural Components, Applied Technology Council, Redwood City, California, 421-431.

9. Fierro, E.A., Perry, C.L., and Freeman, S.A. (1994). "Reducing the Risks of Nonstructural Earthquake Damage: A Practical Guide", FEMA 74, Federal Emergency Management Agency, Washington, D.C., **1**, 3rd ed. (Superseded the 1985 edition).

10. Freeman, S.A. (1998). "Design Criteria for Non-Structural Components Based on Tri-Services Manuals, ATC 29-1", *Proceedings of Seminar on Seismic Design*, Retrofit, and Performance of Nonstructural Components, Applied Technology Council, Redwood City, California, 15-29.

11. Freeman, S.A. and Kehoe, B.E. (1997). "Review of Proposed Design Accelerations for Nonstructural Elements", *Proceedings Fourth Conference on Tall Buildings in Seismic Regions: Tall Buildings for the 21st Century*, Los Angeles Tall Buildings Structural Design Council and Council on Tall Buildings and Urban Habitat, Los Angeles, California, and Bethlehem, Pennsylvania, 291-302.

12. Gurbuz, Orhan; Wu, Sheng; Wittchen, Scott, Review of Requirements for Design of Nonstructural components and their anchorage, ATC 29-1, *Proceedings of Seminar on Seismic Design*, Retrofit, and Performance of Nonstructural Components, Applied Technology Council, Redwood City, California, pages 71-77, 1998.

13. Haupt, R.W. (1992). "Problems, Barriers, and Challenges in Developing Seismic Code Rules for Equipment and Non-Building Structures, ATC-29", *Proceedings of ATC-29 Seminar and Workshop on Seismic Design and Performance of Equipment and Nonstructural Elements in Buildings and Industrial Structures, Applied Technology Council*, Redwood City, California, 99-105.

14. Henry, R.M. and Stein, C. (1987). "A Comparative Study of the Effects of Cladding Panel Modeling", *Mathematical Modelling*, **8**, 560-565.

15. Hirosawa, M., Mizuno, H., and Midorikawa, M. (1991). "State-of-the-Art Report on Seismic Design of Building Equipment and Nonstructural Components in Japan, NIST SP 820, Wind and Seismic Effects", *Proceedings of the 23rd Joint Meeting of the U.S.-Japan Cooperative Program in Natural Resources*, Panel on Wind and Seismic Effects, National Institute of Standards and Technology, Gaithersburg, Maryland, 397-412.

16. Kao, A.S., Soong, T.T., and Vender, A. (1999). "Nonstructural Damage Database, MCEER-99-0014", *Multidisciplinary Center for Earthquake Engineering Research*, Buffalo, N.Y., p. 59.

17. Kehoe, B.E. and Freeman, S.A. (1998). "A Critique of Procedures for Calculating Seismic Design Forces for Nonstructural Elements, ATC 29-1", *Proceedings of Seminar on Seismic Design, Retrofit, and Performance of Nonstructural Components*, Applied Technology Council, Redwood City, California, 57-70.

18. Krakower, M., Donaldson, M.W., and Court, A.B. (1998). "Simplifying Complex GFRC Cladding Structural Systems in Seismic Hazard Zones: A Case Study, ATC 29-1", *Proceedings of Seminar on Seismic Design, Retrofit, and Performance of Nonstructural Components*, Applied Technology Council, Redwood City, California, 215-228.

19. Lai, M.L. and Soong, T.T. (1992). "Optimum Seismic Design of Secondary Structural Systems, ATC-29", *Proceedings of ATC-29 Seminar and Workshop on Seismic Design and Performance of Equipment and Nonstructural Elements in Buildings and Industrial Structures*, Applied Technology Council, Redwood City, California, 229-239.

20 Lagorio, H J., (1990). "Earthquakes--an Architect's Guide to Nonstructural Seismic Hazards", *John Wiley & Sons*, Inc., New York, p. 312.

21. Lama, P.J. (1998). "Practical Guidelines for Seismic Retrofitting of HVAC Systems, ATC 29-1", *Proceedings of Seminar on Seismic Design*, Retrofit, and Performance of Nonstructural Components, Applied Technology Council, Redwood City, California, 445-454.

22. McGavin, G.L. and Gates, B. (1998). "Earthquake Design Consideration for Nonstructural Components ... Who is Responsible?", *Proceedings of the Sixth U.S. National Conference on Earthquake Engineering [computer file]*, Earthquake Engineering Research Inst., Oakland, California, p. 5.

23. McGavin, G.L., Lai, J., and Ikkanda, S. (1998). "City of Los Angeles Proposed Ordinance Changes for Suspended Ceiling Systems Prompted by the 1994 Northridge earthquake, ATC 29-1", *Proceedings of Seminar on Seismic Design, Retrofit, and Performance of Nonstructural Components*, Applied Technology Council, Redwood City, California, 277-282.

24. McGavin, G.L., Patrucco, H. (1998). "Nonstructural Functional Design Considerations for Healthcare Facilities", *Proceedings of the Sixth U.S. National Conference on Earthquake Engineering [Computer File]*, Earthquake Engineering Research Inst., Oakland, California, p. 11.

25. McKevitt, W.E., Timler, P.A.M., and Lo, K.K. (1996). "Nonstructural Damage from the Northridge Earthquake", *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*.

26. Marsantyo, R. et al (1999). "Shaking Table Test on the Seismic Response of Nonstructural Systems Mounted on Base Isolated Buildings", *Proceedings of the Second World Conference on Structural Control, John Wiley & Sons*, Chichester, England, New York, **2**, 1101-1110.

27. Marsantyo, R., Shimazu, T., and Araki, H. (2000). "Experimental Work on the Seismic Horizontal Force of Nonstructural Systems Mounted on the Buildings", Proceedings of the 10th Earthquake Engineering Symposium, Architectural Institute of Japan, Tokyo, Paper No. G3-22, **2**, 2635-2640. This study has been also published as (2000) "Dynamic Tesponse of Nonstructural Dystems Mounted on Floors of Buildings" in the *Proceedings of the 12th World Conference on Earthquake Engineering [computer file]*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 1872.

28. Masek, J.P. and Reitherman, R.K. (1992). "Current Problems in the Implementation of Nonstructural Earthquake Hazard Reduction Efforts, ATC-29", *Proceedings of ATC-29 Seminar and Workshop on Seismic Design and Performance of Equipment and Nonstructural Elements in Building s and Industrial Structures*, Applied Technology Council, Redwood City, California, 53-59.

29. Merz, K.L. and Cumming, L. (1992). "CISCA Recommendations for Installation of Suspended acoustical Ceiling in Moderate- and Low-Eisk Seismic Areas, ATC-29", *Proceedings of ATC-29 Seminar and Workshop on Seismic Design and Performance of Equipment and Nonstructural Elements in Buildings and Industrial Structures*, Applied Technology Council, R edwood City, California, 87-97.

30. Meyer, J.D., Soong, T.T., and Hill, R.H. (1998). "Retrofit Seismic Mitigation of Mainframe Computers and Associated Equipment: A Case Study, ATC 29-1", *Proceedings of Seminar on Seismic Design*, Retrofit, and Performance of Nonstructural Components, Applied Technology Council, Redwood City, California, 149-163.

31. Moghadam, A.S. and Eskandari, A. (2004). "Post-

Earthquake Quick Inspection of Damaged Buildings in Bam", *to be published in the International Journal of Seismology and Earthquake Engineering, Special Issue on the Bam Earthquake.*

32. Negro, P. and Colombo, A. (1997). "Irregularities Induced by Nonstructural Masonry Panels in Framed Buildings", *Engineering Structures*, **19**(7), 576-585.

33. Pantelides, C.P., Truman, K.Z., Behr, R.A., and Belarbi, A. (1996). "Development of a Loading History for Seismic Testing of Architectural Glass in a Shop-front Wall System", *Engineering Structures*, Volume **18**(12), 917-935.

34. Porter, K.A. and Scawthorn, C. (1998). "Appropriate Seismic Reliability for Critical Equipment Systems --an Approach Based on Regional Analysis of Financial and Life Loss, ATC 29-1", Proceedings of Seminar on Seismic Design, Retrofit, and Performance of Nonstructural Components, Applied Technology Council, Redwood City, California, 393-420.

35. Porush, A.R. (1992). "An Overview of the Current Building Code Seismic Requirements for Nonstructural Elements, ATC-29", Proceedings of ATC-29 Seminar and Workshop on Seismic Design and Performance of Equipment and Nonstructural Elements in Buildings and Industrial Structures, Applied Technology Council, Redwood City, California, 17-31.

36. Reitherman, R. (1985). "Reducing the Risks of Nonstructural Earthquake Damage: A Practical Guide", Earthquake Hazards Reduction Series 1, FEMA 74, Federal Emergency Management Agency, Washington, D.C., p.87.

37. Sakamoto, I., Itoh, H., and Ohashi, Y. (1984). "Proposals for Aseismic Design Method on Nonstructural Elements", *Proceedings of the Eighth World Conference on Earthquake Engineering*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, **V**, 1093-1100.

38. Schultz, C.H., Koenig, K.L., and Lewis, R.J. (2003). "Implications of Hospital Evacuation After the Northridge", California, Earthquake, Annals of Emergency Medicine, **42**(4), 604-605.

39. Selvaduray, G.S. (1993). "Nonstructural Hazard Mitigation for Schools, NCEER-93-0015", Proceedings from School Sites: Becoming Prepared for Earthquakes, Commemorating the Third Anniversary of the Loma Prieta Earthquake, National Center for Earthquake Engineering Research, Buffalo, N.Y., 2-29--2-34.

40. Singh, M.P. et al (1993). "Simplified Procedures for Seismic Design of Nonstructural Components and Assessment of Current Code Provisions, NCEER-93-0013", *National Center for Earthquake Engineering Research*, Buffalo, N.Y., **1**.

41. Singh, M.P., Moreschi, L.M., and Suarez, L.E., (1998). "Simplified Methods for Calculating Seismic Forces for Nonstructural Components, ATC 29-1", *Proceedings of Seminar on Seismic Design*, Retrofit, and Performance of Nonstructural Components, Applied Technology Council, Redwood City, California, 43-56.

42. Soong, T.T. (1994). "Code Development for Nonstructural Components", Research Accomplishments, 1986-1994, The National Center for Earthquake Engineering Research, National Center for Earthquake Engineering Research, State Univ. of New York at Buffalo, 137-143.

43. Soong, T.T. (1995). "Seismic Behavior of Nonstructural Elements--State-of-the-Art Report", P*roceedings of the 10th European Conference on Earthquake Engineering*, A.A. Balkema, Rotterdam, **3**, 1599-1606.

44. Soong, T.T., Yao, G.C., and Lin, C.C. (2000). "Near-Fault Seismic Vulnerability of Nonstructural Components and Retrofit Strategies", *Proceedings of International Workshop on Annual Commemoration of Chi-Chi Earthquake*, National Center for Research on Earthquake Engineering, Taipei, Taiwan, 100-111, **II**, Technology Aspect.

45. Staehlin, W. (1998). "Seismic Design and Perfor mance of Nonstructural Components in Hospitals, ATC 29-1", Proceedings of Seminar on Seismic Design, Retrofit, and Performance of Nonstructural Components, Applied Technology Council, Redwood City, California, 469-473.

46. Sucuoglu, H. and Vallabhan C.V.G. (1997). Behaviour of Window Glass Panels During Earth quakes, Engineering Structures, **19**(8), 685-694.

47. Thiel, C.C.Jr., Zsutty, T.C., and Tokas, C. (1998). "Seismic Retrofit of Nonstructural Components

in Acute Care Hospitals: Title 24, Part 2, Chapter 16, Division III-R Requirements, ATC 29-1", *Proceedings of Seminar on Seismic Design, Retrofit*, and Performance of Nonstructural Components, Applied Technology Council, Redwood City, California, 475-489.

48. Villaverde, R. (1996). "A Proposed Replacement for the Seismic Code Provisions for Nonstructural Components in Buildings", *Proceedings of the Eleventh World Conference on Earthquake Engineering, Pergamon*, Elsevier Science Ltd., Oxford, England, Disc 2, Paper No. 643.

49. Villaverde, R. (1997). "Method to Improve Seismic Provisions for Nonstructural Components in Buildings", *Journal of Structural Engineering*, **123**(4), 432-439.

50. Villaverde, R. (2000). "Design-Oriented Approach for Seismic Nonlinear Analysis of Nonstructural Components", *Proceedings of the 12th World Conference on Earthquake Engineering [Computer file]*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 1979.

51. Whitney, D.J., Dickerson, A., and Lindell, M.K. (2001). "Nonstructural Seismic Preparedness of Southern California Hospitals", Earthquake Spectra, **17**(1), 153-171.

52. Yanev, P.I. (1992). "The EQE Earthquake Data Base and the Performance of Equipment and Non-Structural Components, ATC-29", *Proceedings of ATC-29 Seminar and Workshop on Seismic Design and Performance of Equipment and Nonstructural Elements in Buildings and Industrial Structures*, Applied Technology Council (ATC), Redwood City, California, 107-118.

The Behavior of Special Structures During the Bam Earthquake of 26 December 2003

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ABSTRACT: *On 26 December 2003 an earthquake of magnitude Ms = 6.5 with a focal depth of about 8km occurred in southeastern Iran. The earthquake caused intense ground shaking throughout the affected area. Special structures such as on-grade steel oil tanks, elevated tanks, and industrial equipment were damaged during the earthquake. This paper presents the results of an investigation of the behavior of these special structures in Bam. Strong motion characteristics as recorded by accelerograms are discussed, as well as the failure modes of structures and components located within the affected area. An investigation into the response of an electrical transformer was carried out as a case study of a simple system.*

Keywords: Bam earthquake; Special structures; Critical Facilities; Damage assessment; Water tank; Oil tank; Electrical substation

1. Introduction

In recent decades, seismic disasters have claimed a significant number of victims and caused physical damage and direct economic loss. Each earthquake also causes indirect loss and economic impact such as environmental pollution and work stoppages because of damage to special structures and equipment. The Bam earthquake in southeastern Iran on 26 December 2003 (Ms = 6.5) occurred at 05:26:26*am* local time. The epicenter of the earthquake was at 29.01*N*-58.26*E*, southwest of the city [1]. The focal mechanism of the earthquake was reported as strike slip and the focal depth was about 8*km* [2]. The Bam fault, in a nearly north-south direction, passes from the vicinity of Bam city (less than 1*km* east of Bam) between the cities of Bam and Baravat.

Special structures such as elevated water tanks and electrical facilities were damaged during the event and some industrial complexes were closed as a result of heavy structural and/or non-structural damage.

2. Strong Motion Characteristics

The ground motion time histories of the Bam event were recorded by 23 stations of the Iranian National Strong Motion Network [3]. The closest instrument to record the earthquake was located in Bam itself with a focal distance of about 12*km*. The corrected acceleration histories of both horizontal and vertical components of the main earthquake recorded at the aforementioned station are shown in Figure (1).

Based on the recorded data at Bam station, the peak ground acceleration of the horizontal component of the earthquake were 775cm/sec^2 for perpendicular and 623cm/sec^2 for parallel components to the fault direction. Peak ground acceleration of the vertical component was 992cm/sec^2 [1]. The damage distribution of structures in the earthquake affected region, and data recorded at Bam station, indicated the directivity effect of near-fault ground excitation [1].

3. Distribution of Special Structures

As shown in Figure (2), several essential facilities and industrial structures are located in the focal region and various types of industrial and special structures experienced the strong ground motion in the earthquake affected area. A significant number of industries are concentrated in the Bam Industrial Region, 1*km* south of the city. The structural system of the main industrial buildings in this region is

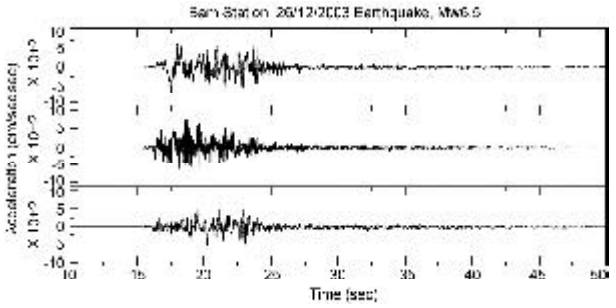


Figure 1. Corrected acceleration history of Bam Earthquake recorded at Bam station [1].

generally steel moment resisting gable frames or industrial frames with light-weight sloped truss systems.

There is a chemical plant belonging to the Roghan Jonoub Company next to the Bam Industrial Region that features six on-grades cylindrical and three elevated steel oil tanks. The 230/132kV electrical substation of Bam, one of the most important facilities in the stricken area, is located along a highway between Bam and Baravat, less than 5km from the faulting fissure.

4. The Response of Structures

4.1. Water Tanks

4.1.1. Elevated Tanks

A concrete elevated tank approximately 20m in height and 350m^3 in capacity was located at Bam Fire Station. The tank was designed and constructed about 32 years before the seismic event and earthquake induced loads were not taken into account during the design process. A tower with six rectangular columns supported the tank with the columns joined with rectangular beams at different elevations. Brick infill walls approximately 2.5m in height were constructed between tower columns to make an office beneath the tank, see Figure (3) .The tank was nearly empty at the time of the earthquake.

The response of RC elevated water tanks in past earthquakes shows that beam-to-column joints in these types of structure are susceptible to ground shaking [4]. Following the Bam earthquake, the *RC* tower of the aforementioned tank cracked, but did not collapse.

Inaccurate detailing was the major reason for the tank damage. As shown in Figure (4), the concrete column cracked near the beam-to-column connection and the longitudinal reinforcing bars buckled at that position. The main reason for this type of damage was the lack of transverse bars on the critical length of the column near the beam-to-column connection, which has a high potential for plastic hinge formation. Although, according to the Iranian concrete code (*ABA*) [5], the maximum allowable spacing between stirrups is 250mm, the spacing between transverse stirrups in the tower *RC* columns was much greater. Another failure mode of the tower was damage to beams adjacent to the column joint, in which the crack penetrated to the column, see Figure (5).

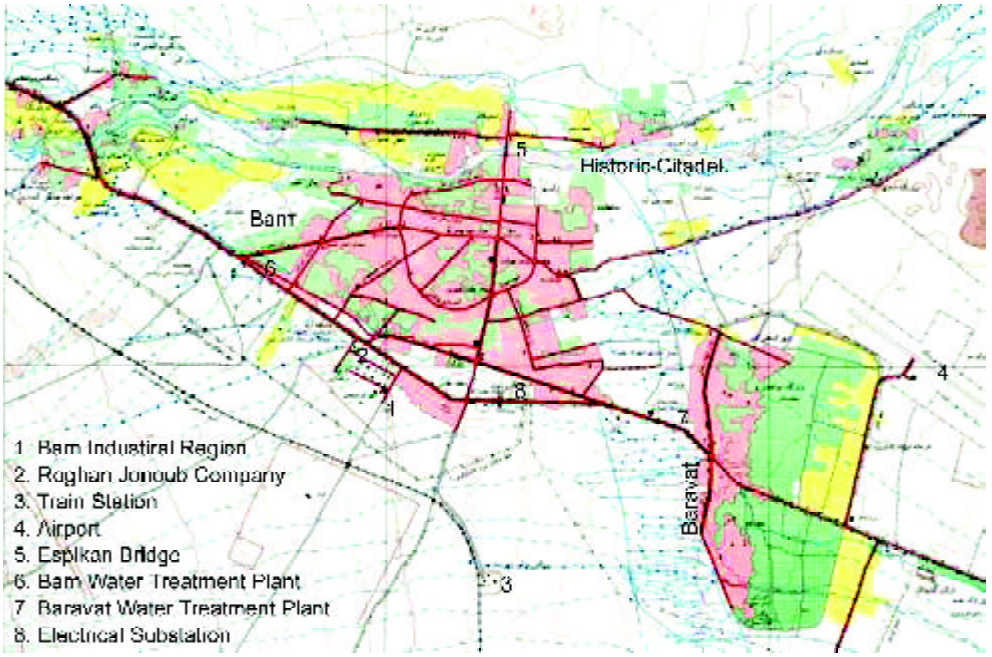


Figure 2. Locations of major urban and industrial facilities.

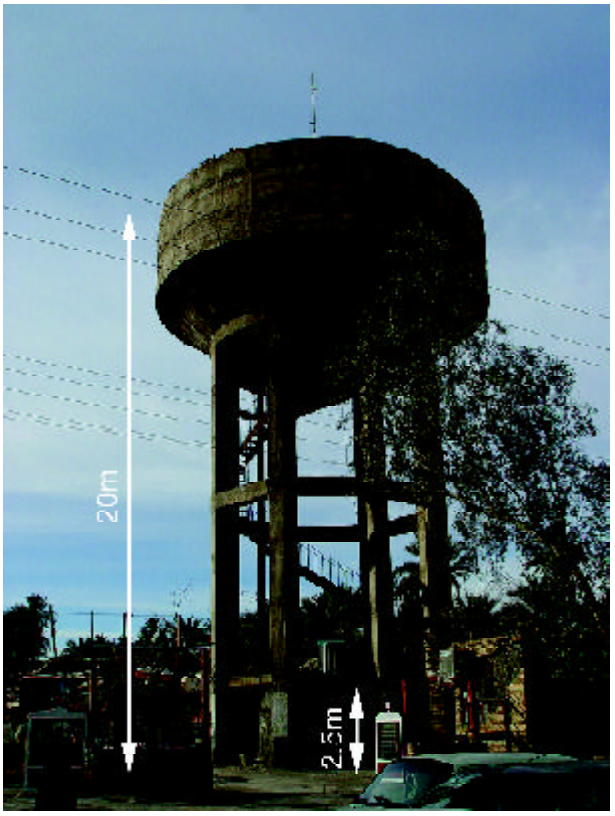


Figure 3. General view of the Bam elevated RC tank.

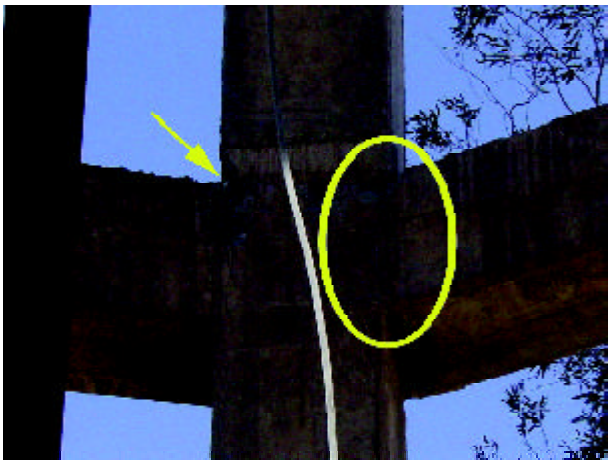
Figure 4. Inaccurately detailed cracked RC column [1].

Several steel elevated water tanks experienced the strong ground motion, but most of them suffered no damage. Buckling of the slender bracing and rupture of poorly detailed bracing connection were common failure modes in damaged steel elevated tanks.

4.1.2. Underground Tanks

The Bam water treatment plant is located about 2*km* southwest of the city. There are three underground tanks at the site. The tanks had no visible structural

(a)



(b)

Figure 5. Damage to beam next to column joint.

damage. Soil settlement of about 10*cm* took place in the earth fill of each tank and tensile cracks were observed at the top of the earth fill, see Figure (6). None of the buildings in the plant suffered serious damage and the plant was operable after the earthquake.

The Baravat water treatment plant is constructed over the Bam fault. There were two underground water tanks at this plant. Both tanks are stone masonry. Before the seismic event, both tanks worked at full capacity, but the plant suffered major damage to tanks and annex structures during the earthquake and was forced to shut down. All of the annex buildings, including the chlorination building, collapsed completely, see Figure (7). These structures were un-reinforced brick masonry buildings. Leakage from the tank wall and bottom occurred after the earthquake and cracks were also found at construction joints on the masonry retaining walls surrounding the tank, see Figures (8) and (9).

(a)

(b)

Figure 6. Settlement and tensile cracks observed in tank earth fill.

Figure 7. Collapse of chlorination building.

Figure 8. Leakage of water from tank wall.

4.2. Bridges

In general, bridges sustained little or no damage. The most affected bridge, Espikan Bridge north of Bam near Arg-e Bam, sustained little damage. Espikan Bridge is a uniform bridge with an *RC* deck and stone masonry columns and 14 spans across the Poshtrood River, see Figure (10). As shown in Figure (11), the RC bent caps of the bridge cracked with the longitudinal movement of the deck in the north-south direction. No visible damage occurred to

Figure 9. Cracks observed at construction joints of surrounding wall

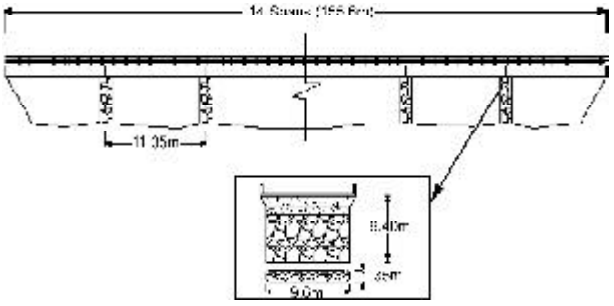


Figure 10. Espikan Bridge.

the deck slab as a result of the pounding of separate parts of the superstructure thanks to sufficient joint width and the bridge was in service after the earthquake.

The Darzin Bridge also experienced longitudinal movement of the superstructure and the stone abutment cracked as a result of settlement of the abutment, see Figure (12). However, the bridge was still safe for use after the earthquake. No structural damage occurred to other observed bridges in the affected region.

4.3. Industrial Frames

Steel gable frames are common in industrial structures

(a)

(b)

Figure 11. Damage to RC bent caps from deck movement.

Figure 12. Settlement of Darzin bridge abutment.

in Iran. Several steel gable frames in Bam Industrial Region and some other industrial sites near the epicenter subjected to strong ground motion. No significant structural damage occurred in gable frames, but non-structural damage was observed. Light-weight roofs, good design and acceptable

supervision during construction are some reasons for the good behavior of these structures during Bam earthquake. Failure modes in these structures are described below.

4.3.1. Damage to Annex Buildings

As shown in Figure (13), failure of annex buildings was a typical damage mode for industrial structures with annex buildings. Annex buildings are generally brick masonry low-rise buildings constructed with adjacent gable frames without joints. Failure of annex buildings was, in most cases, caused by torsion due to asymmetric distribution of resistant walls or pounding of an adjacent industrial structure.

Figure 13. Damage to annex building of an industrial frame [1].

4.3.2. Damage to Infill Walls

Failure of infill walls was the most common damage mode of industrial structures. The main reason for this mode of failure was lack of horizontal anchors and/or wall posts to restrain the infill walls to the structure. As indicated in Figure (14), inaccurate detailing of the anchor connections to the structure and lack of overlap length caused failure of infill walls.

4.4. Equipment

Equipment in industrial plants and critical urban sites such as power station suffered heavy damage. The major reason for this, especially in industrial sites located at Bam Industrial Region was the collapse of mechanical buildings. Mechanical buildings in most observed plants were un-reinforced brick masonry buildings with inaccurate detailing and weak materials that are seismically vulnerable. During the earthquake,

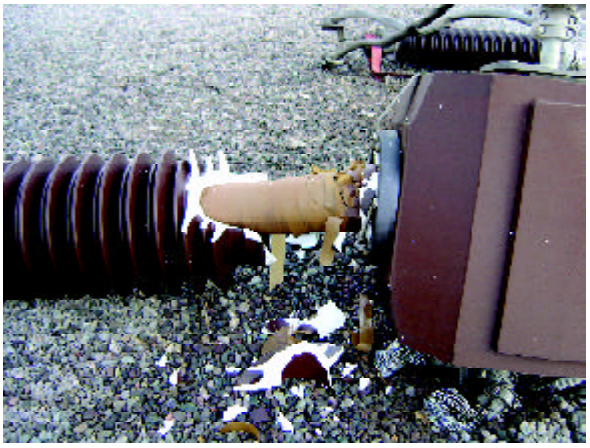
Figure 14. Failure of infill walls due to inaccurate detailing of anchors [1].

the collapse of mechanical buildings caused heavy damage such as the rupture of connected pipes and residual deformation of equipment components, see Figure (15). Damage to equipment resulted in the closure of industrial plants after the main earthquake.

As mentioned before, the electrical substation was one of the critical facilities of the affected area. It is composed of two sections for $230kV$ and $132kV$. The equipment in this station sustained heavy damage. In general the extent of damage in the $230kV$ section was greater for the $132kV$ section. More than 13 bushings in the $132kV$ section cracked and collapsed, see Figure (16). Both $132kV$ and $230kV$ transformers moved due to the sliding response of equipment. One $230kV$ transformer moved about $40cm$ from its original position. The movement of transformers caused the base rails to sustain plastic deformation. Figure (17) indicates the sliding response of the $230kV$ transformer to ground shaking.

Figure 15. Damage to equipment in the collapse of mechanical buildings [1].

(a)



(b)

Figure 16. Damage to bushings at Bam substation.

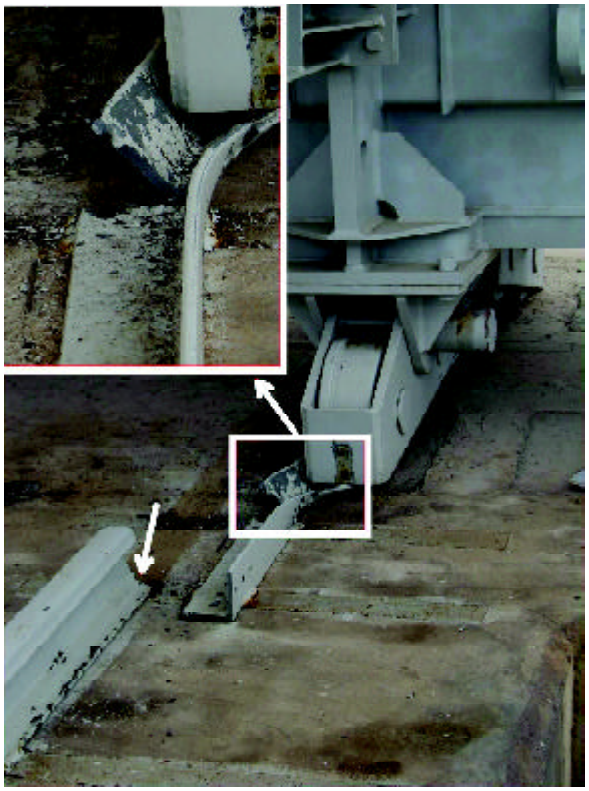


Figure 17. Displaced 230kV transformer [1].

4.5. Cylindrical Oil Tanks

Three out of six on-grade steel oil tanks at Roghan Jonub Company (see part 3) experienced leakage of liquid from roof-to-wall junctions from sloshing during the quake. Other damage modes such as elephant foot buckling, rupture of rigid piping, and tank were not observed in these tanks. Figure (18) shows the leakage of oil from on-grade tanks.

Figure 18. Leakage of oil from tank due to sloshing [1].

A cylindrical on-grade gasoline tank next to Bam electrical power station, which was nearly empty, suffered heavy damage. Rigid piping connected to the tank ruptured, probably from the inaccurate erection of the pipes, see Figure (19).The tank foundation was damaged due to tank uplift, but shell buckling did not occur, see Figure (20).

4.6. Elevated Oil Tanks

Elevated oil tanks at the Roghan Jonub plant were severely damaged and failed to contain the oil because of the failure of piping connections, see Figure (21). Also, as shown in Figure (22), a tank tower column punched the tank shell.

Figure 19. Rupture of pipe connections.

Figure 20. Damage to tank foundation due to tank uplift.

Figure 21. Leakage of oil due to rupture of pipes [1].

Figure 22. Punching of tank shell [1].

4.7. Critical Facilities

4.7.1. Airport

Bam Airport is located north of Bam between Baravat and Arg-e-Jadid. The control tower of the airport was closed because of heavy non-structural damage, see Figure (23). Since no structural member suffered serious damage the airport brought back to full operation with the use of a portable control unit. Non-structural components also suffered heavy

(a)

(b)

Figure 23. Damage to airport control tower.

damage in the earthquake.

Most masonry infill walls at the airport cracked, Figure (24). Some false ceiling panels concealing power cables and such fell. No structural damage occurred due to the pounding of adjacent blocks, but finishing surfaces cracked or fell off at construction joints. The facade bricks of the terminal building fell off and damaged equipment and air conditioners, see Figure (25).

Figure 24. Damage to masonry infill walls at airport.

Figure 25. Damage to air conditioners.

4.7.2. Train Station

The Bam train station is under construction at a site south of Bam city. The structural system of the main terminal is a moment resisting *RC* frame with light-weight space trusses for the ceiling. Infill walls in the main building were cracked and facades were damaged from the strong ground motion, see Figure (26). Figure (27) shows shear cracks that occurred at some beam-to-column connections in the one-story *RC* frames.

Figure 26. Damage to façade at the Bam train station.

(a)

(b)

Figure 27. Shear cracks observed on beam-to-column joints at train station.

5. A Case Study of the Response of an Electrical Transformer

The response of a transformer to pulse-type near-fault base excitation was considered. The transformer is the rigid block shown in Figure (28), which can oscillate about the centers of rotation (o and o'). The block may

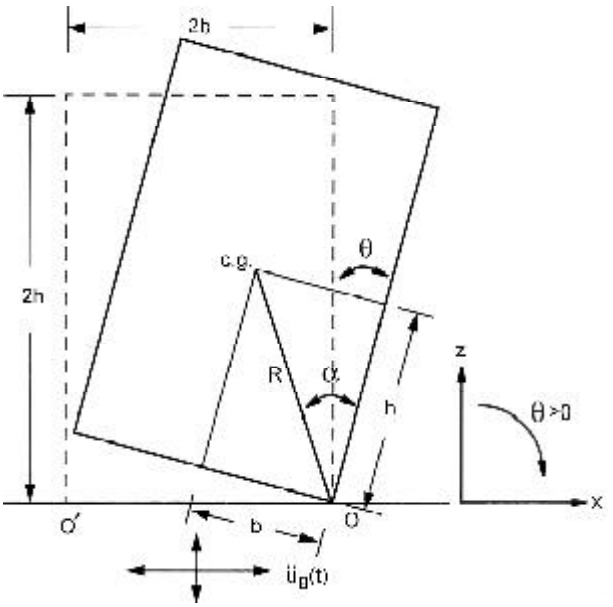


Figure 28. Schematic of a rigid block in rocking motion [6].

translate with the ground, slide or rocking, depending on the level and form of ground excitation [6].

Shenton [7] showed that, depending on the width-to-height ratio of the block, static friction coefficient and magnitude of base acceleration, there is a slide-rock mode of oscillation in addition to pure slide and pure rocking modes. Assuming that the coefficient of friction, μ, is greater than $\tan\alpha$ (α = slenderness), the horizontal acceleration required to induce rocking should be at least $a_p = g.\tan\alpha$. Assume that the rigid block in Figure (27) is about to enter rocking motion due to positive base acceleration, where $p^2 = 3g/4R$ and $R = (b^2+h^2)^{0.5}$ and p is almost equal to $2rad/sec$ for electrical transformers [6].

Makris and Roussos [6] proposed the following approximate expression to estimate the minimum acceleration which can make a rigid block overturn:

$$\frac{a_{po}}{\alpha g} \approx 1+\beta\frac{\omega_p}{p} \qquad (1)$$

where $p^2 = 3g/4R$ and $R = (b^2+h^2)^{0.5}$; a_{po} is the minimum overturning acceleration of the pulse; α is the angle of slenderness; and p is almost equal to $2rad/sec$ for electrical transformers [6]. For one-sine pulse-type excitation, β is equal to 1/6.

In view of the relatively long duration of the coherent pulse, the range of interest of the frequency ratio, ω_p/p, for electrical equipment with $p = 2rad/sec$ (such as electrical transformers), is $0<\omega_p/p<3$. Within this range of oscillation, the minimum overturning acceleration spectrum of cycloidal pulses is nearly linear. The ground motion acceleration history of the Bam event in the fault-normal direction, indicated in Figure (2), was modeled as a one-sine pulse type excitation and the acceleration, velocity and displacement history of such an excitation can be given as follows:

$$\ddot{u}_g(\tau) = \omega_p \frac{p}{2} sin(\omega_p\tau), 0 \le \tau \le T_p \qquad (2)$$

$$\dot{u}_g(\tau) = \frac{v_o}{2} - \frac{v_o}{2} cos(\omega_p\tau), 0 \le \tau \le T_p \qquad (3)$$

$$u_g(\tau) = \frac{v_o}{2}\tau - \frac{v_o}{2\omega_p} sin(\omega_p\tau), 0 \le \tau \le T_p \qquad (4)$$

Consider the pulse duration of $T_p = 1.3sec$ and a velocity amplitude of $V_p = 1.6m/sec$, which are approximations of the duration and the velocity amplitude of the first main pulse of the record. The equivalent pulse-type motion is indicated in Figure (29).

Using the approximate (Eq. (1)) and equivalent pulse (Eq. (2)) the ω_p/p ratio is approximately equal to 2.4, which is less than 3. Thus we obtain:

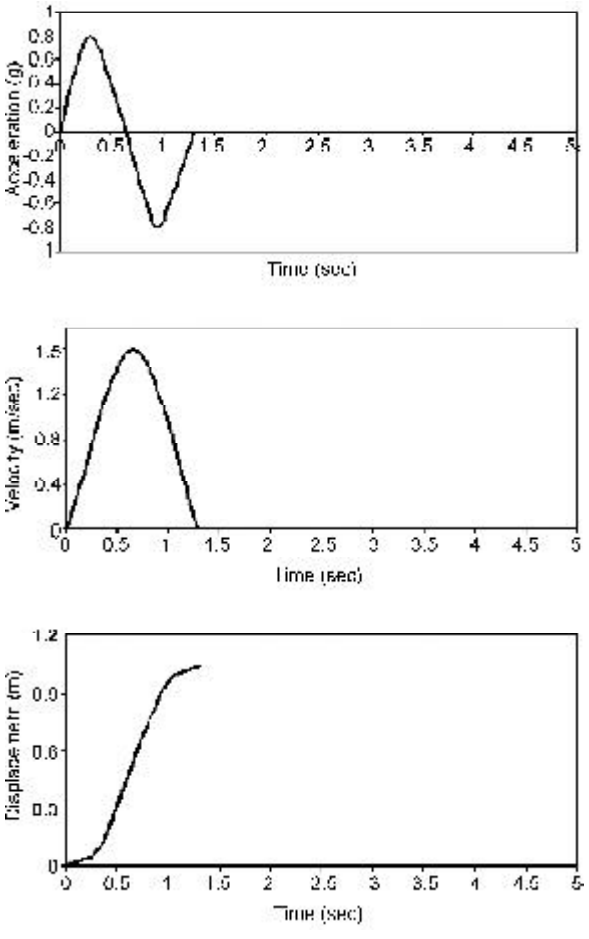


Figure 29. Fault-normal component of acceleration, velocity and displacement modeled as a pulse motion.

$$a_{po} = g\,(1+2.4\times 1/6)=1.4g\alpha \qquad (5)$$

The plot of a_{po} for various slenderness ratios is shown in Figure (30).

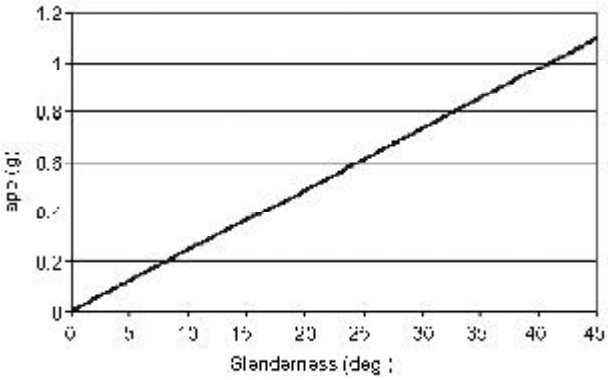


Figure 30. Plot of "apo" versus slenderness.

As indicated in Figure (29), the peak ground acceleration required for the overturning of a transformer of $\alpha = 25°$ is $0.61g$, which is less than the *PGA* of the Bam earthquake in the fault-normal direction. It seems that the existence of base rails and connections to the transformers was the main reason for the stability of the transformers in the Bam station.

6. Conclusion

The seismic event of December 26, 2003 in south-eastern Iran imposed heavy damage to special structures and critical facilities in the earthquake affected area. Inaccurate detailing and use of weak materials were reasons for damage to many industrial structures.

Complete or partial collapse of mechanical buildings caused serious damage to equipment.

The *RC* tower of an elevated water tank cracked, but steel elevated water tanks suffered no serious damage. There was no visible structural damage to the Bam *RC* underground water tank, but the underground masonry tanks at Baravat water treatment plant cracked. Inadequate erection of oil tank rigid piping caused the rupture of piping connections and subsequent leakage of liquid.

No visible structural damage occurred to industrial gable frames, but nonstructural components of these structures were severely damaged. Although bridges sustained little or no damage, longitudinal movement of the superstructure was a common damage mode in bridges.

In conclusion, damage to industrial and critical facilities caused a heavy direct and indirect economical and social impact.

References

1. Eshghi, S., Zare, M., and et al (2004). "The Reconnaissance Report of Bam Earthquake", *International Institute of Earthquake Engineering and Seismology*, 2004/01, Tehran, Iran, (in Persian).

2. Eshghi, S. and Zare, M. (2003). "Bam (SE Iran) Earthquake of 26 December 2003, Mw6.5: A Preliminary Reconnaissance Report", www.iiees.ac.ir.

3. Building and Housing Research Institute (2004). "Preliminary report on Bam Earthquake".

4. Rai, D.C. (2001). "Performance of Elevated Tanks in Mw 7.7 Bhuji Earthquake of January 26th, 2001", www.ias.ac.in/epsci/sep2003/Esb1513.pdf.

5. Management Organization (2000). "Iranian Concrete Code (ABA)", Standard No. 120, Rev. 1, Tehran, Iran.

6. Makris, M. and Zhang, J. (1999). "Rocking Response and Overturning of Anchored Equipment under Seismic Excitation", PEER 1999/06.

7. Shenton, H.W. (1996). "Criteria for Initiation of Slide, Rock, and Slide-Rock Rigid-Body Modes", *J. of Engng. Mech.*, Div. 122, 690-93.

Reconnaissance Report on Bam Earthquake Social and Public Policy Issues

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ABSTRACT: *May, 2004 the "Learning from Earthquakes" program of the Earthquake Engineering Research Institute sent a team of researchers on a reconnaissance mission to Iran and the site of the Bam earthquake (December 26,2003). The purpose of this team was to study social science and policy aspects of the earthquake impact, relief and recovery phases. Interviews were conducted with a wide range of stakeholder groups including victims and those responsible for public and private recovery activities. Observations were collected related to transitional housing, mental health, economic and social recovery and the planning process for permanent reconstruction. Particular attention was paid to innovative programs and policies developed in response to this earthquake disaster.*

Keywords: Earthquake; Iran; Social Impact; Disaster Recovery; Post-earthquake reconstruction; Economic recovery; Transition housing

1. Introduction

The Earthquake Engineering Research Institute (*EERI*) through the “Learning from Earthquakes” program sponsors technical reconnaissance missions to study the effects of damaging earthquakes throughout the world. A team of engineers and seismologists was sent to the site of the Bam earthquake shortly after the event to study evidence of the event and subsequent physical damage. This article summarizes initial findings from a second reconnaissance trip to Iran and the earthquake-stricken area, carried out from May 8-16, which focused on societal impacts five months after the Bam event, early recovery activities, longer-term recovery planning, and public policy aspects of earthquake loss-reduction in Iran. For this report, fact-finding meetings were conducted with many organizations, including the International Institute of Earthquake Engineering and Seismology, which hosted the *EERI* team; *UN*-affiliated organizations; national-level entities concerned with loss reduction and disaster response and recovery; international non-governmental organizations (*NGOs*); local *NGOs* in Bam, city and provincial government officials and agencies; and health care and mental health professionals.

2. The Social and Policy Context

Response and recovery activities following the Bam earthquake were influenced in important ways by four broader societal factors: the 1979 revolution; the Iran-Iraq war, which lasted from 1980 to 1988; the experience of other recent earthquake events in Iran, especially the *M* 7.2 1990 Manjil-Rudbar earthquake, which killed 37,000; and the distinctive characteristics of Iran’s governmental system.

The 1979 revolution, which established the Islamic Republic of Iran, resulted in significant policy shifts and in the creation of new governmental institutions. One cornerstone of the Islamic revolution was a focus on rural development and the provision of services to residents of small towns and villages, which had been seriously neglected under the previous regime. Such services included the distribution of

grants, low-interest loans and building materials, as well as land and technical assistance for the improvement of rural housing. The Housing Foundation, a quasi-governmental organization established following the revolution, was given major responsibilities in the area of rural redevelopment. The responsibilities of the Housing Foundation also extended to both post-war and post-disaster reconstruction-for example, through financing homes destroyed in war and disasters and providing temporary shelter for war refugees and disaster victims. Consistent with this mission, the Foundation is now directing post-earthquake residential reconstruction in Bam.

The Iran-Iraq war, which resulted in the deaths of an estimated 600,000 Iranians, required Iranian society to develop capacity in such areas as the provision of emergency medical care and reconstruction and recovery-related services. Skills and capabilities developed during eight years of war, like those employed in rural development initiatives, were readily transferable to earthquake response and recovery.

Both before and after the revolution, Iran had experienced a number of damaging earthquakes, which also fostered the development of response and recovery capacity within Iranian society. The 1990s decade was a particularly active seismic period; three major damaging earthquakes occurred in rural areas of the country in 1997 alone. While the Bam event differed from earlier earthquakes in that it affected a relatively urbanized population, lessons learned in responding to and recovering from recent seismic events were in many respects applicable to the Bam disaster. The 1990 Manjil earthquake proved to be a watershed event in terms of policies it helped set in motion, including a 1991 law that established the Natural Disaster Headquarter (*NDH*) under Iran's Ministry of Interior. That law gave the Department of Interior full authority for the management of seismic hazards, including the coordination of disaster response, reconstruction, and recovery.

Finally, response- and recovery-related policies and practices following the Bam earthquake must be understood within the context of Iran's centralized governmental system. While local government elections were introduced in the late 1990's, theoretically increasing local-level participation in political decision-making, authority for governmental programs and policies remains overwhelmingly at the national level, with implementation carried out through provincial offices of national ministries such as Health and Housing. Consistent with Iran's overall governmental structure, the major responsibility for post-disaster reconstruction and recovery resides with the central government, although, as discussed below, efforts are being made to involve the population of the disaster-stricken region in the recovery process.

3. Societal and Economic Impacts

3.1. Earthquake Casualties

As tends to be the case in major disasters, early reports on the earthquake's death toll appear to have overestimated the number killed. While the numbers are still not finalized, revised figures now indicate that 26,271 people died in the quake-although some continue to dispute that death count. Over 20,000 people were injured and an estimated 120,000 were made homeless. The dead included Bam's foremost singer, many writers and scientists, farmers and bazaaris, and an estimated 560 teachers and 200 health professionals, accounting for almost one-fifth of the city's teachers and one-third of its health workers. The survivors include an estimated 2,000 widows, 1,600 widowers, 1,200 orphans and 3,000 children with one parent. About 400 people were permanently disabled. Efforts to obtain more detailed data on patterns of mortality and morbidly, such as gender and age breakdowns and injury severity, so far have been unsuccessful. Follow-up work is needed to collect and analyze epidemiological data.

The high death and injury toll can be attributed to the time of day the earthquake occurred and to the extreme vulnerability of the built environment in the greater Bam region. The earthquake, which took place before dawn when most residents were still asleep, caused the immediate collapse of residential structures, the vast majority of which were of adobe construction. Asphyxiation due to dust inhalation and the cold December temperatures undoubtedly also contributed to the deaths of survivors who were trapped under the rubble.

It also appears that most residents were unaware of the magnitude of the earthquake threat in the region and thus were unprepared when the earthquake struck. There were significant foreshocks in the hours leading up to the earthquake, and some residents warned others or left their houses during the night to seek shelter outdoors, but most people remained in their homes. Residents now question whether some sort of warning should have been issued to the public when those smaller earthquakes occurred.

Residential Damage. Damage to residential structures was very severe, leaving approximately

95% of the homes within the city of Bam and a large proportion of dwellings in the surrounding villages uninhabitable. Nearly all of the housing in Bam and in eight to ten villages within about 10*km* of Bam must be replaced. The high vulnerability of residential structures to the earthquake was largely due to the existence of adobe and non-engineered buildings, which accounted for 80% of the building stock. Additionally, rapid and uncontrolled development in recent years resulted in the construction of many unsafe buildings.

3.2. Educational Institutions

Iran's very young population includes many school-age children. Forty eight percent of the population of Bam was under the age of 20 before the earthquake. Schools in Bam and the surrounding region were destroyed or very severely damaged. Before the earthquake, there were about 32,000 students, 3,200 teachers, and nearly 300 schools in Bam. Hundreds of teachers and 8-10,000 students were killed in Bam and surrounding areas.

3.3. Impacts on the Economy and Population of the Region

Business impacts were comparable in scale and severity to impacts on households; at the time of the May reconnaissance trip, very few business establishments were operating in Bam's commercial districts. Some businesses had been reestablished in containers and makeshift sheds outside the city; however, many of these businesses gravitated to Bam from outlying areas. Many more prosperous and established businesses relocated to other cities, such as Kerman, the provincial capital. Bam is a regional agricultural center that is known for its high-quality dates, citrus crops, henna and dairy products. Many of the 400 surrounding villages have close economic ties with Bam. The economies of these communities were already severely stressed before the earthquake due to a six-year drought. Because of the extensive damage that had been done to the qanats, an irrigation system distinctive to the region, there was great concern that these high-value crops would be lost. However, repairs to the irrigation system progressed well, and this year's crops will likely not suffer as a consequence of the earthquake.

The "New Arg" industrial complex east of the city is another engine for the local economy. Prior to the earthquake, 1000 workers at an automobile plant in this complex were laid off, creating ripples throughout the community. Even before the earthquake, unemployment was about 20 percent.

Arg-e-Bam, the 2,000-year-old Bam Citadel, is a major resource and important tourist destination that attracted numerous tourists to Bam every year. The Citadel, which was of adobe construction, was very extensively damaged. *UNESCO* and other international organizations are currently considering ways of rehabilitating and restoring the Citadel, both because of its enormous cultural significance and because of its economic value for the region. How that restoration will be planned and financed has yet to be determined. In its current degraded state, the Arg is highly vulnerable to water damage, and additional deterioration is virtually certain unless steps are taken immediately to protect the Citadel complex. The Arg has long been a living symbol of Bam, and many among the population feel an intense sense of attachment to the site. Plans for recovery must thus consider the cultural, economic, and social value of this unique complex.

Bam is located along a major drug-smuggling route, serving as a conduit point for drugs smuggled out of Afghanistan and bound for Europe. Although there are of course no exact figures, drug transport clearly contributes to the informal economy of the region. The trade is responsible for significant safety and health problems among the already demoralized population. It is also a major contributor to high incarceration rates for males in the region.

The earthquake dealt a severe blow to public finances in Bam and surrounding communities. The city of Bam is currently experiencing a severe budget deficit-a shortfall that reportedly will be made up at a later time by the central government.

Major population shifts have occurred as a consequence of the earthquake. At the time of the earthquake, the greater Bam area consisted of the city itself, with a population of approximately 86,000, as well as numerous surrounding villages with a total population of 100,000 residents. City and village economies were tightly integrated, with villagers bringing goods to sell and working in Bam, and the city providing services, such as warehouse services for dates, health care, and other services, for the surrounding region. The earthquake disrupted the regional economy, causing many survivors to leave the area on at least a temporary basis, while stimulating migration into the city from surrounding regions, as villagers came to the city in search of temporary housing and other disaster-related services. Thus,

despite the high death toll, the population of Bam is larger now than it was before the earthquake.

4. Status of Early Recovery Activities

While much has been accomplished since the earthquake, conditions remain desperate in Bam, and a host of problems persist. The earthquake had a devastating impact on community institutions. In addition to causing widespread residential and commercial damage, the earthquake destroyed or severely damaged all schools, hospitals, and health care facilities in the impact area. Virtually every household was touched in some way by the earthquake. Recovery activities thus must address all aspects of community life, including homes, businesses and economic activity, education, and health and social services.

The Red Crescent Society and the Iranian military played key roles in the initial response and the provision of emergency aid to affected populations. Additionally, there was an enormous outpouring of charitable giving from the general population, overseas Iranians, Islamic charitable organizations, and other donors. In an unprecedented move, after the earthquake, the government of Iran invited international aid organizations into the country and lifted visa and passport restrictions following the earthquake. This resulted in a large-scale convergence of aid-giving organizations into the impact region and ensured an abundance of relief assistance for victims while also creating major coordination problems. In an effort to better co-ordinate relief activities, the impact region was divided into fourteen geographic sectors, and different Iranian provinces and aid organizations assumed responsibility for service provision to individual sectors. This system provided a management framework and ensured a steady flow of resources and volunteers during the post-impact period. This arrangement was to be replaced by management by the province of Kerman at the end of May.

In contrast, intermediate-term and especially longer-term recovery planning has not been as well coordinated. International *NGOs* are gradually leaving the earthquake-stricken area, and while some recovery-related needs are being addressed, others are being neglected. Many of those contacted during the reconnaissance visit cited problems with various aspects of "transition planning", such as how to ensure continuity of services when agencies leave the area and how to manage the transition from temporary shelter to intermediate-term temporary housing.

Relief, reconstruction and recovery activities are being managed through a Ministry of Interior Council consisting of 24 organizations, including governmental ministries, the Red Crescent Society, and international organizations, with representation from the Bam City Council. The task force composition follows guidelines established in the new disaster management system, which had been developed in May 2003. The new system was designed to integrate agency activities across the hazards cycle, encompassing mitigation, preparedness, response, and recovery activities. Reconstruction is being financed through a range of sources, including the national government; the Islamic Development Bank; *UN* agencies such as *UNESCO* (for the Arg-e-Bam project) and *UNDP*; a $300-400 million loan from the World Bank, and private charitable donations.

4.1. Temporary Housing and Residential Reconstruction

At the time of the second reconnaissance trip, the vast majority of displaced households were still living in tents, most of which had been provided by the Red Crescent Society. At the insistence of residents, the majority of these tents had been placed on private property near homes that had been destroyed. Other tents were erected in congregate camps, while still others were located on streets adjacent to former dwellings. Tent camps are being used mainly to house former renters and migrants from the nearby villages. The tents are very small, and the vast majority have no capacity for cooling, with temperatures currently rising to over 100 degrees. There are no bathroom facilities; instead, displaced residents must use collective toilets and showers.

Under the general direction of the Department of Interior and the supervision of the Housing Foundation, approximately 18,000 temporary housing units have been constructed, and plans were underway to move residents into these units beginning in late May. Like the tents, temporary housing units are very small (3 x 6 meters); the units are being constructed both on private property and in large complexes. Bathroom and sanitary facilities are either single-stall temporary toilets located near tents and temporary structures, or in some instances consist of groups of stall joined together. The shower is usually in the stall, using the toilet for a drain. The sewerage and wastewater are not treated. Concerns have been expressed regarding the congregate toilet/shower facilities, both because

women may be reluctant to use them owing to modesty concerns, and because no funds have been allocated to maintain the facilities.

Plans for the provision of approximately 20,000 units of permanent housing are well under way, again under the direction of the Housing Foundation. Housing reconstruction is expected to take between two and a half and three years. In an arrangement that blends governmental and private-sector initiatives, the central government will provide the financing for residential reconstruction through a combination of grants and loans to homeowners. However, to retain control over the rebuilding process, the government will also screen contractors, review designs, and select builders who will then make their services available to residents through a government sponsored "housing bazaar" designed to allow property owners to select builders who will meet their personal and budgetary requirements. Government agencies will provide a range of services to residents, from debris removal and site preparation to design review, inspections, and the enforcement of price controls to prevent price-gouging. At the same time, homeowners will be able to choose contractors and builders as well as home designs and building materials, within constraints set by reconstruction authorities.

Housing reconstruction is already under way in the villages surrounding Bam. Much of this work is being done by international *NGOs* that have contracts with the Housing Foundation, which provides the designs. Individual organizations take responsibility for providing the foundation, steel frames and ceilings in the villages to which they are assigned. Typically the masonry work and basic finishing is left to the owner. For example, Relief International is constructing 1060 steel-frame houses and Swiss Caritas is building 430 reinforced concrete frame houses in 13 villages in the impact region. The footprints of these units range from $43m^2$ to $85m^2$ depending on the size of the household.

4.2. Businesses and Schools

Business reconstruction is being coordinated through the Ministry of Finance and Trade. Plans for rebuilding businesses resemble those for residential structures. Business owners will receive a grant totaling approximately $1,200, plus a loan of $60 per square meter of reconstruction. The reconnaissance team was unable to determine whether there are specific plans that target business recovery.

Schools were back in session within a few days after the earthquake, operating out of tents provided by *UNICEF* and other organizations. Initially, rather than dividing students by grade, separate schools were set up for all male and female students. School is now being held in metal tents and other temporary structures. Some students left the area after the earthquake and are presumably in school in other cities. Approximately 80% of Bam's surviving students are at least registered for school. However, attendance is lower than before the earthquake, particularly for boys, many of whom are no longer interested in school. Those in charge of the schools have reportedly tried to provide a supportive environment for the students, rather than returning immediately to the regular curriculum. Nevertheless, at the time of the reconnaissance visit students were still finding it difficult to concentrate on schoolwork.

School reconstruction is being coordinated through the "New Construction and Improvement of Schools", program, which is part of the Ministry of Education. No government aid is available for private schools, many of which were of even poorer construction than the public schools. A considerable amount of school reconstruction is being financed by international *NGOs*, Iranian donors, and Iranian expatriates. The cost of rebuilding a school ranges from $100,000-300,000.

4.3. Health and Mental Health Issues

Impacts on the health and psychological well-being of residents have been severe. Since so many health-care professionals lost their lives in the earthquake, many health services are now being provided by health-care workers from Kerman, Tehran, and other parts of the country. Medical residents have reportedly been especially eager to volunteer in order to provide care to residents of the impact region. A temporary hospital is operating in Bam, but patients requiring surgery must go to hospitals in Kerman.

With funding from *UNICEF* and the Mental Health Department of the Ministry of Health, a large-scale project has been established to provide psychosocial support to residents of the impact area. Training for psychosocial intervention in disasters had already been under way prior to the disaster; a "train-the-trainers" workshop for mental health service providers had been held in Tehran just a month before the earthquake.

The psychosocial intervention program established after the earthquake involves extensive outreach and needs assessment throughout the impact region, beginning with "tent visits" conducted by trained

mental health professionals. These visits are followed by a series of group counseling sessions for children and adults identified through screening, focusing on such problems as anxiety and avoidance behavior. Longer-term individual counseling is provided for more severe psychosocial problems. The program also offers a range of other services, including the provision of crisis care, training of teachers and school counselors, referrals, and broad public awareness programs.

As is the case with medical personnel, a large number of mental health professionals from the province, the capital, and other parts of Iran have made their services available for earthquake victims. As of the May visit, of the more than 53,000 individuals who had been screened, nearly 26,000 had been referred to group counseling sessions, and more than 3,000 sessions had been held. Approximately 550 mental health professionals had been involved with the program as of Mid-May, and about 45 professionals were active in providing services each week.

4.4. The Bam General Plan

In Iran, centralized planning is carried out according to a 20-year National Master Plan that is divided into a series of five-year plans. The earthquake occurred near the beginning of a new planning cycle, and as a consequence of the Bam event, seismic loss reduction is now being emphasized in planning nationwide. The general plan for Bam was essentially complete at the time of the earthquake. A consulting firm in Tehran was preparing it for the Ministry of the Housing. The Bam City Council submitted comments on 26 issues within five days of the earthquake so that it could guide recovery. In particular, the City Council wants to maintain the scale of buildings and desert ambiance of the reconstructed city, and they want the Arg-e-Bam restored.

Although the City Council offered a broad array of recovery and reconstruction recommendations to central government representatives shortly after the earthquake, the general plan for the city has been developed in Tehran for the Ministry of Housing. Local government must “sign off” on the plan, but its own influence on the planning process has been minimal. The reconstruction cannot begin until the plan is completed. Land-use patterns are expected to alter little in the aftermath of the earthquake, except for minor changes, such as the widening of streets.

The preservation of Bam's distinctive urban form as a "garden city" of single-family homes located within date groves, as well as restoration of the Arg-e-Bam, are major issues for reconstruction planning. Debates can be anticipated over such topics as the use of adobe in reconstruction in this highly seismic region. A number of conferences and workshops have already been held under the auspices of the *UN* and other agencies to identify “lessons learned” as a result of the earthquake. A conference on Bam reconstruction is scheduled to be held in Italy, probably in September. At that meeting, both the Bam reconstruction plan and overall risk management strategies will be discussed.

5. Overarching Issues

The sections above have attempted to provide a broad picture of both earthquake impacts and the status of recovery activities five months after the earthquake. Over the course of its activities, the team also identified a series of more general issues affecting the impact region and Iranian society more generally. Those issues center on the role of the public and civil society institutions in the reconstruction process; public awareness and risk communication; and effective coordination of response and recovery activities, including the need to better manage the transition between response-related and short- and longer-term recovery strategies.

5.1. Public Participation

There is a broad recognition of the importance of public participation in the reconstruction and recovery process. Local residents, *NGOs*, international organizations, and Iranian government officials all acknowledge the need for such participation. The challenge for the earthquake-stricken areas and for Iranian society more generally is to find ways of widening public participation in what to date has been a centralized, top-down governmental framework. Following the earthquake, mechanisms were developed to encourage such participation, but it is unclear at this time whether they will be implemented and to what effect. What was described by the media as a “riot” that took place in Bam in early March can be seen as a reflection of public frustration with the recovery process and unmet promises of aid and of the public’s need for a more direct voice in the recovery process. The unrest was also a reflection of high rates of unemployment among significant sectors of the population, especially young people.

5.2. Public Communication and Hazards Education

A second overarching concern centers on the need for more effective public risk communication, both within and outside the impact region. As noted earlier, Bam residents had little awareness of the earthquake threat prior to the time the earthquake occurred. In the aftermath of the earthquake, there is a clear need for public education on topics ranging from the likelihood of aftershocks to earthquake prediction science, recommended earthquake preparedness measures, and the importance of adhering to earthquake resistant codes and standards during the reconstruction process. Rumors abound concerning the causes of the December earthquake and the possibility of future seismic activity--again evidence that the public's demand for accurate information is not being met. Local *NGOs* have criticized the limited dissemination of information related to reconstruction, and some city and provincial government agencies are mobilizing to publish newspapers, distribute posters and hold information sessions in public meetings or through the media. However, these efforts also require better coordination.

5.3. Interagency Coordination and Transition Strategies

The earthquake revealed strategic gaps in post-earthquake response and recovery. While as indicated earlier, many response activities were managed well, individuals consulted for this report also pointed to the lack of more rapid and localized search and rescue capability as a major problem following the earthquake. Some hypothesized that the high death toll can be attributed at least in part to the absence of local search and rescue capacity in the affected region. Search and rescue activities are carried out by the Red Crescent Society, which needed time to send personnel into affected areas. As is often the case, international search and rescue teams arrived too late to play a role in lifesaving operations.

Due to poor information sharing, lack of trust among some organizations, and other factors, many agencies are working independently of one another, rather than coordinating their activities. This has resulted in duplication of efforts and confusion for those seeking services. Efforts at establishing mechanisms to link aid-related organizations with one another have been complicated by organizational factors, such as frequent turnovers in personnel. Organizations that might have been expected to play a larger role in recovery decision making, such as the Bam City Council and local *NGOs*, frequently lack both the resources and the authority to become more actively involved in official recovery efforts. This last-mentioned issue is again a reflection of a general absence of mechanisms for incorporating community participation into the governmental decision-making process.

Disaster scholars have long noted that transitions through the phases of response, early recovery, and longer-term recovery are generally not well-managed. Some individuals contacted during this reconnaissance visit argue that this is also the case for the Bam earthquake. Those directly involved in early recovery activities have noted that strategies are needed to ensure that transitions are well-timed, that resources are made available when they are needed, and that the public is kept up-to-date and has the opportunity to participate in the recovery process.

6. Research Needs

The Bam earthquake raises many questions that should be addressed in future social science and policy research. Studies are needed to analyze factors associated with mortality and morbidity in this event and to assess the post-earthquake search and rescue process. Follow-up research is needed to better understand longer-term impacts upon the surviving population, including psychosocial impacts, and to track the social and economic recovery process for households and businesses. Special attention should be paid to at-risk populations, such those who suffered very severe losses, disrupted families, and youth. The Bam event also provides a significant opportunity for economics-based research on disaster losses, costs, and recovery. It will also be important to document decision-making, policy development, and policy implementation affecting the reconstruction of the Arg-e-Bam historic complex. Additionally, research is needed to evaluate the provision of services to affected populations, including mental health care, temporary and permanent housing aid, and assistance provided to businesses. Studies assessing the effectiveness of governmental aid programs and policies could provide valuable lessons both for Iranian society and for other nations. Finally, systematic research is needed to document the extent to which this event results in changes in earthquake loss reduction policies and practices within Iran, including public education and preparedness programs, the implementation and enforcement of earthquake-resistant design and construction practices, and what changes, if any, take place with respect national, provincial, and community loss-reduction programs.

A United Nations Strategy for Support to the Government of the Islamic Republic of Iran Following the Bam Earthquake of 26 December 2003

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ABSTRACT: *After the earthquake on 26 December 2003 with magnitude 6.3 which struck the historic city of Bam and its surrounding villages and took the lives of nearly 26,500 people, left over 25,000 injured and about 75,000 homeless; the United Nations agencies in the Islamic Republic of Iran have worked closely with the Government to respond to the immediate needs of the affected people, by undertaking a rapid needs assessment and launching a Flash Appeal to address the urgent and immediate needs of the affected population, and to facilitate a smooth transition from the immediate rescue and relief phase to a medium and long-term reconstruction and recovery phase. The UN has committed itself to supporting the Government not only in the provision of short-term relief, but also in long-term reconstruction, recovery and risk reduction. UN Secretary-General Kofi Annan offered support for an international conference on the reconstruction of Bam as well as organizing an international workshop on earthquake disaster risk management. Recognizing the value of a concerted UN approach that complements the Government's reconstruction and disaster risk reduction efforts, the UN System in consultation with its national and international partners has prepared a strategy document, using methods of social research such as participant observation, case studies, the use of key informants, group discussions and individual in-depth interviews. The strategy builds on past efforts of the UN System in the Iran and on the UN Flash Appeal of 8 January 2004. It outlines UN support to the Government of Iran for reconstruction, rehabilitation and risk reduction over the next five years, and details specific activities in the short, medium and long term.*

Keywords: Bam earthquake; Rescue, Relief; Recovery; Reconstruction; Disaster; Risk management; United nations; UNDP; Iran

1. Introduction

On 26 December 2003, a powerful earthquake with *Ms* = 6.3 struck the historic city of Bam and its surrounding villages. It took the lives of nearly 26,500 people, left over 25,000 injured and about 75,000 homeless. Approximately 85 percent of the houses, commercial units, health and educational facilities and administrative buildings in the city and surrounding villages were either severely damaged or completely destroyed. The 2,500 year-old historic citadel of Bam (Arg-e-Bam), an internationally famous heritage site, was almost completely destroyed, dealing a severe blow to the economic prospects of the Bam

region and the livelihoods of its people.

In the aftermath of the earthquake in Bam on 26 December 2003, the United Nations agencies in the Islamic Republic of Iran have worked closely with the Government to respond to the immediate needs of the affected people. At the request of the Government, UN agencies undertook a rapid needs assessment and launched a Flash Appeal to address the urgent and immediate needs of the affected population, and to facilitate a smooth transition from the immediate rescue and relief phase to a medium and long-term reconstruction and recovery phase. The Flash Appeal was launched by the *UN* Under-Secretary-General Jan Egeland in Bam, Geneva and New York on 8, 9 and 12 January respectively.

The *UN* has committed itself to supporting the Government not only in the provision of short-term relief, but also in long-term reconstruction, recovery and risk reduction. In his letter of 5 January 2004 to the President of Iran, *UN* Secretary-General Kofi Annan offered support for an international conference on the reconstruction of Bam. The Secretary-General also proposed an international workshop on earthquake disaster risk management.

International experience has shown that when appropriate technical support is provided early on in the recovery effort, risk management and reduction considerations can be factored into all recovery and reconstruction initiatives from the beginning; discouraging the reconstruction of risk, and laying the foundation for more sustainable recovery and longer-term development. In a highly disaster-prone country such as the Iran, the successful reconstruction of Bam would provide a good opportunity not only to reduce vulnerability to future earthquakes in Bam but also in other areas equally or more vulnerable to earthquakes and other natural disasters.

While it is unlikely that the financial support from the *UN* will match the resources that will be allocated by the Government, regional and international financial institutions and other international agencies, the *UN* System with its experience, technical expertise and long history of involvement in natural disaster risk reduction issues is uniquely positioned to provide both technical and coordination assistance to the reconstruction programme on a sustained basis.

Recognizing the value of a concerted *UN* approach that complements the Government's reconstruction and disaster risk reduction efforts, the *UN* System in consultation with its national and international partners has prepared a strategy document. The strategy builds on past efforts of the *UN* System in the Iran and on the *UN* Flash Appeal of 8 January 2004. It outlines *UN* support to the Government of Iran for reconstruction, rehabilitation and risk reduction over the next five years, and details specific activities in the short, medium and long term.

1.1. The Challenge of Rebuilding Bam

The long-term reconstruction and recovery for Bam programme will be a major challenge for the people of Iran. The reconstruction effort will be a massive exercise requiring a multi-sectoral approach ranging from rehabilitation of livelihoods and the local economy, to restoration of water, health and sanitation systems, to the rebuilding of critical infrastructure, to housing and social sector reconstruction etc. It will require significant financial resources, skilled human resources and innovative institutional arrangements, and will involve a wide range of actors at the local, provincial, national and international levels. Initial estimates indicate that the long-term recovery will take a number of years, and that it could cost anywhere between US$700 to $1,000 million. Although most of these resources will have to be gathered by the Government of Iran, the international community can provide critical support to some of the more strategic areas.

1.2. Challenges to Disaster Risk Management in Iran

The devastating effect of the Bam earthquake has brought back into focus the fact that Iran is highly vulnerable to natural disasters. On the Global Seismic Hazard Map, Iran, which is crossed by two major fault lines, stands out as one of the most earthquake prone countries in the world. The country however, is not only exposed to earthquakes but also to frequent flash floods and recurrent drought. Annually, Iran suffers an average of 2,393 deaths, or about 3.4 percent of the global annual total of about 70,000 deaths. Yet with a population of 73 million, Iran represents only about 1.25 percent of the global population.

The country has significant technical expertise in almost all aspects of disaster risk management. It is host to internationally renowned institutions such as the International Institute of Earthquake Engineering and Seismology (*IIEES*). Iran also has some of the best-developed building codes. Seismicity across almost the entire country has been well studied and mapped. In addition, much work has been done

on seismic zonation of the country as a whole, and on micro-zonation of urban areas, such as Tehran. Yet this wide range of technical expertise and know-how has not translated into adequate action for disaster risk reduction. A preliminarily analysis indicates that some of the challenges that the practice of disaster risk management faces in Iran are:

- Inadequate emphasis on comprehensive disaster risk management vis-à-vis disaster relief
- Lack of awareness among decisions makers in key development sectors of disaster risk management issues
- Absence of multi-disciplinary approaches to assessing and managing disaster risk
- Inadequate compliance with building regulations and inadequate training for construction workers and labourers
- Lack of appropriate techno-legal and techno-financial regimes for disaster risk management
- Insufficient application and use of existing scientific and technical knowledge in Iran to wards enhanced city planning, seismically safe construction and disaster risk reduction actions.

2. Towards a Consolidated UN Strategy

2.1. Past UN Initiatives on Disaster Risk Management in Iran

Over the last decade, *UN* agencies in Iran have worked on a wide range of disaster risk management initiatives. While these initiatives have made important contributions, they leave much to be desired. The following are some of the key activities undertaken in the past:

- Preparation of guidelines for earthquake disaster management: after the Manjil earthquake of 1990, *UN-HABITAT* and *UNDP* collaborated with the Housing Foundation of the Islamic Revolution to prepare detailed guidelines for earthquake disaster management. The guidelines include regional and urban planning and design; production of building materials; quality control; design and construction of engineered and non-engineered earthquake resistant buildings; and upgrading of existing and earthquake damaged buildings.

- *UNDP-UNESCO* joint project to assist in the establishment of the International Institute of Earthquake Engineering and Seismology (*IIEES*): Based on the decision taken by the 24th Session of the *UNESCO* General Conference representing the will of the international community to build capacities in Iran and the region, *UNDP* and *UNESCO* launched a project (*UNDP/IRA/* 90/009) to support the establishment of *IIEES*. The project included training of *IIEES* technical staff as well as provision of equipment for seismic monitoring and forced vibration testing of existing structures for research purposes.
- Development of an Integrated National Disaster Management Plan (*INDMP*): The objective of this project was to develop a plan that would provide a strong basis, at the national level, for the sustained protection of population, property and d evelopment achievements in Iran. The *UNDP* project emphasised need for improved organizational coordination mechanisms; disaster implication checklists for major development projects; establishment of effective communication and information systems; and the enhancement of earthquake awareness in urban areas. The project also introduced a coherent structure for emergency management at the national, provincial and local levels in preparedness, mitigation and recovery phases. The decree introducing the Plan was approved by the Council of Ministers on 6 April 2003.
- Capacity development for national disaster response and coordination: The aim of this joint *UNDP*-Iranian Red Crescent Society project was to reduce the loss of lives from natural disasters by improving national disaster response capability and coordination.

2.2. The UNDAF Process

The United Nations Development Assistance Framework (*UNDAF*) is an essential component of the *UN* programme for reform introduced by the Secretary-General in 1997. As a strategic five-year planning framework for *UN* development operations and assistance at the country level, the *UNDAF* provides a collective, coherent and integrated *UN* System response to key national priorities and needs as outlined in the Common Country Assessment, and within the context of the Millennium Development Goals (*MDGs*) and the Millennium Declaration.

Iran's first *UNDAF* (2005-2009), which is scheduled for finalisation in mid-2004, identifies "sustainable development, energy efficiency and disaster risk management" as one of the five priority areas, and envisages "reduced disaster risk from hydro-meteorological and geophysical hazards in

Iran" as one of the key outcomes of *UN* collaboration. Some of the strategies adopted by the various *UN* agencies in the wake of the Bam earthquake are being written into the *UNDAF* document to ensure that the agency country programmes address some of the disaster risk reduction challenges highlighted by the Bam earthquake.

3. Key Elements of a Consolidated UN Strategy, Methodology

While it is unlikely that the financial support from the *UN* will match the resources that will be allocated by the Government, regional and international financial institutions and other international agencies, the *UN* System with its experience, technical expertise and long history of involvement in natural disaster risk reduction issues is uniquely positioned to provide both technical and coordination assistance to the reconstruction programme on a sustained basis. The following are three distinct but inter-related elements of the proposed *UN* Strategy:

- In the short term, very specific and targeted technical support to the start-up phase of the reconstruction and recovery programme (February-May 2004).
- Sustained technical and coordination support to the Government for the duration of the reconstruction programme to help ensure efficient and sustainable recovery and long-term disaster risk reduction (May 2004-December 2005).
- Capacity building for mainstreaming disaster risk reduction into development processes at local, provincial and national levels (2004-2009).

3.1. Methodology of Development

In development of *UN* strategy Paper a number of social research methods for identifying community needs such as participant observation, case studies, the use of key informants, group discussions, and individual in depth interviews were used.

3.2. Technical Support to the Start-Up Phase of the Reconstruction and Recovery Programme (February-May 2004)

In the first five months following the earthquake, the *UN* System has worked closely with the Government of Iran, local and provincial authorities, the affected communities, private sector and subject matter specialists to provide technical inputs for the reconstruction programme for Bam through: focused workshops, and technical consultations on sectoral themes such as health, water and sanitation, education, livelihoods, shelter, protection of vulnerable groups, urban redevelopment and planning, conservation of cultural heritage, etc; provision of local and international expertise and experience; demonstration projects; advocacy initiatives, and capacity building and training programmes on a variety of subjects for both reconstruction managers and members of the affected communities. Key *UN*-supported activities in this phase have included:

- Technical workshop on the management of reconstruction programmes (25-26 February)-The workshop brought together members of the Steering Committee for the Reconstruction of Bam, senior Government and *UN* officials and post-earthquake reconstruction experts from Iran, Japan, India and Turkey. Participants shared experiences, lessons learnt and advice on the technological, financial and institutional arrangements for reconstruction; site selection and land tenure; s helter sector reconstruction; rebuilding critical infrastructure; and urban redevelopment and planning. Recommendations from the workshop were submitted to the Steering Committee for the Reconstruction of Bam for inclusion in the Government's reconstruction programme for Bam.
- Technical consultation on emergency measures to safeguard Bam's cultural heritage (10-17 March)-The *UNESCO*-Iranian Cultural Heritage Organization (*ICHO*) consultation reviewed plans for the conservation of heritage structures in need of immediate stabilization, and developed preliminary guidelines for the zonation of the Bam's historical quarters.
- Training workshops to support education managers and teachers/educators (April-May 2004)-Workshops in the series focussed on: capacity building for education management in post-crisis situations; communication skills; basics of school health; formal and informal technical and vocational education; etc.
- Workshop on lessons learned from the health response (11-13 April 2004): The workshop, organised by *WHO*, allowed for an analysis of the lessons learnt and best practices from health response to the Bam earthquake. Topics of discussion included: immediate emergency medical care, delayed medical care, management of dead bodies, communication disease

urveillance and control, water and sanitation, national and provincial responses etc. Recommendations from the workshop were presented at the *OCHA* workshop on lessons learned from the response operations in Bam (14-15 April).

- Workshop on lessons learned from the response operations in Bam (14-15 April)-Given the magnitude of the disaster, the immediate response to the Bam earthquake was impressive. The workshop, organised by *UN-OCHA* and the International Search and Rescue Group (*INSARAG*), provided and opportunity for a systematic analysis of those aspects of the immediate response that worked and those that did not. Recommendations from the workshop were presented at the *INSARAG* conference in Tunisia in April.
- Technical consultation on urban redevelopment and planning for the "new" city of Bam (15 April) -The workshop provided an opportunity for members of the Steering Committee for the Reconstruction of Bam, the Bam city planners, representatives from key Government departments, technical and scientific organisations, *UN* agencies and civil society to discuss issues such as long-term disaster risk management, creative recovery and the preservation of cultural heritage, in the context of urban redevelopment and planning. Concepts such as a "child-friendly city' and a "healthy city" were also explored. As a result of the workshop, a decision has been taken at the national level to make microzonation studies mandatory before the start of all future redevelopment and planning exercises.
- Preparation of technical guidelines for the conservation, restoration and management of Arg-e-Bam and other historic monuments in Bam (18-20 April)-The consultation resulted in the preparation and adoption of detailed guidelines for the mid-to-long-term conservation, restoration, and management (including risk preparedness, presentation, tourism development, and capacity building) of the Arg-e-Bam and other historic monuments.
- Workshop on livelihoods recovery and reconstruction (1-2 May)- The workshop explored livelihoods rehabilitation strategies for various sectors including shelter, agriculture, health, education, industry and tourism. Economic reactivation of micro-enterprises and self-help groups, and community integration in the reconstruction process as an interim economic recovery tool also featured heavily in the discussions. In follow-up to the workshop, ILO and UNDP, in collaboration with the Kerman Chamber of Commerce and the Bam City Council will conduct rapid surveys to assess the labor market and business opportunities in Bam.
- Consultation on social sector and basic services recovery (3-4 May)- The *UNICEF*-supported workshop was held as the first in a series of participatory consultations involving the authorities, *NGOs* and the people of Bam on recovery strategies for water and sanitation provision, health and nutrition, education, child and family protection and psychosocial support. "Child-friendly city" and "healthy city" concepts were also discussed in detail.
- Meeting on professional partnerships (4 May): Reconstruction is likely to involve thousands of architects, engineers, planners and builders from across the country. Most of these specialists belong to professional associations such as engineers and architects associations. The half-day meeting provided a networking oppor tunity for members of various professional associations involved in the physical reconstruction of Bam. Partnerships and networks between the various associations at the regional and national levels would allow for transference of cutting-edge knowledge that could be cross-linked to the practical initiatives being undertaken. It could also help improve efficiency and cost-effectiveness, result in a unified strategic framework for decision making on issues of common concern, reduce duplication of efforts, and ensure better division of responsibilities.
- Meeting on public-private partnerships for reconstruction (5 May): The meeting brought together public and private sector representatives. Topics of discussion included enhanced market access for the products from the affected areas; training and capacity building of skilled workers; and financing for reconstruction.
- Technical workshop on lessons learned from re construction programmes in Iran (6 May) - The workshop was an opportunity for disaster management specialists and reconstruction managers in the country to share experiences

from past reconstruction programmes, identify lessons learnt and best practices, and brainstorm on strategies for disaster risk assessment and risk reduction in Iran.

- Technical workshop on appropriate building technology designs, construction and delivery mechanisms for shelter and public lifeline infrastructure (8-9 May)- International experience has shown that a wide variety of building construction technologies are often introduced into post-disaster reconstruction activities. While some of these technologies may meet the requirement of rapid delivery and high earthquake resistance, many will not lend themselves to easy replication and integration into the local construction industry because they do not correspond to the needs and lifestyles of the affected people. The workshop showcased a range of building technology options that are earthquake resistant, cost-effective and locally appropriate for the Bam region. It provided an opportunity for policy-makers, reconstruction managers, engineers, architects and contractors to consider the pros and cons of different building technologies for Bam reconstruction. In follow-up to the workshop, resource materials for seismically safe design and construction are being developed and will be disseminated through a number of smaller, hands-on training workshops for the various categories of building workers.

3.3. The Key Recommendations from Technical Workshops and Consultations

3.3.1. General

- The local authorities (municipal governments) should play a central role in planning and implementation of the reconstruction program. Reconstruction effort can be used as an opportunity for the empowerment and capacity building of the local government.
- Continuity of leadership of the reconstruction program at all levels-policy, programme design as well as implementation levels-should be ensured.
- The institutional arrangements for the reconstruction program should reflect strong ownership of the program at the provincial and local levels. The reconstruction program should continue to derive strength from high-level political support.
- While ensuring smooth and rapid recovery in the affected area, the institutional arrangements for the reconstruction program should also pave the way for longer-term disaster risk reduction.
- Special attention should be paid to the most vulnerable groups (such as orphans, women headed households, lone survivors in the family, severely injured and permanently disable), affected by the earthquake. The institutional arrangement should provide for a review of the situation of these vulnerable groups after every six months for the next several years.
- "Participation" of the affected communities in decision-making and implementation is a key success factor in making any reconstruction and recovery program sustainable. The institutional arrangements should make use of existing structures at the local level (such as village Islamic councils) to ensure participation at all levels and at all stages of decision making. Appropriate methodologies, tools and techniques need to be devised and applied to ensure effective participation.
- The civil society organizations should have an important role in the institutional arrangements for t he reconstruction program. As required, their capacities also need to be developed to play an appropriate role in the reconstruction program.
- Recognizing that a reconstruction program requires a different (quicker and flexible) way of operating, appropriate operational guidelines/ manuals should be developed for the implementation of the program.

3.3.2. Urban Redevelopment Planning, Site Selection and Land Tenure

- Given the proximity of Bam to seismically active fault lines, the location of some of the critical facilities will have to be revaluated and if required, changed to safer location. Overall, it is likely that the reconstruction will follow a combination of reconstruction on the same site and relocation of some of the critical buildings to a new location.
- The main cause of extensive damage to Bam city was due to bad quality of construction. Therefore the main emphasis will have to be on improving the quality of construction to ensure adequate level of earthquake resistance.
- In the newly reconstructed Bam, the issues of security of tenure for the inhabitants will have to be addressed. The security of tenure of not

only the permanent inhabitants of Bam but also those living on rented land and property needs to be ensured.

- Land and property ownership records (through existing official registration documents, aerial maps, mutual confirmation by local people etc.) should be systematized in order to avoid competing claims at later stages of the reconstruction process. It may be useful to set up an Area Development Authority to deal with day-to-day problems and disputes that might emerge as the reconstruction progresses. The government has already taken steps by brining in a legislation to stop the buying and selling of l and in Bam area (during the reconstruction phase) to avoid any ownership disputes.
- Appropriate arrangements need to be put in place to ensure enforcement of safety standards and building codes. The architects and engineers need to be made responsible for the safety of new buildings. Approved drawings of the newly constructed buildings in Bam city should be digitized and kept for posterity in government records.
- The process of urban redevelopment and planning after an earthquake is a complex one. It will be beneficial for a team of relevant officials to visit Gujarat and to learn from the experience of reconstruction of urban centers after the Gujarat earthquake.
- The process of debris removal should be seen as an opportunity to improve the habitat of affected communities. Several potential uses of the debris can be explored such as salvaging of reusable house building components and construction of flood protection dykes.
- The reconstruction program also offers opportunities to promote improved environment management practices and to reduce vulnerability to other natural hazards. In the case of Bam, there is an opportunity to introduce water management practices that help re-charge ground water resources. Like wise, application of roof water harvesting and wastewater-recycling processes can also be explored.
- Urban redevelopment planning should be closely linked to economic recovery processes in the affected area. There should be adequate emphasis on making the exiting livelihood options more resilient as well as exploring new livelihood options.

3.3.3. Shelter Sector-Appropriate Delivery Mechanisms

- The linkage between temporary or intermediate shelter and permanent needs to be carefully examined.The experience of past reconstruction programs in some countries indicates that temporary shelter should be used to buy some extra time for building permanent shelters. It is not always advisable to easily upgrade or integrate a temporary shelter into a permanent one.
- Shelter sector reconstruction is likely to be the largest component of the reconstruction program. It should be closely linked to local economic recovery and enhancement of livelihood options.
- Systems for producing locally appropriate, low cost building materials (such as stabilized earth blocks) need to be put in place. A lot of technological innovation has taken place in other countries. Possibilities of technology transfer from other countries can be explored.
- Buildings codes, in their existing format, are not easily understandable to local builders and contractors. Easily understandable and locally usable guidelines and manuals need to be developed for earthquake resistant construction.
- Training programmes for a large number of supervising engineers need to be instituted to facilitate the delivery of safe housing at such a large scale.
- Financial mechanisms to support delivery in shelter sector should be linked to application of earthquake safety standards. An appropriate system of incentives and disincentives needs to be put in place.
- There should be a provision for retrofitting owner built new houses that are not built to earthquake safety standards.
- While owner-driven housing reconstruction has its merits, it may not always be possible to apply this approach. The house-owners may be pre-occupied with their other livelihood activities and may not be able to participate in the reconstruction activity. Therefore, a combination of owner-driven and contractor-driven approach should be adopted. There may be other innovative approaches such as establishment of family cooperatives for owner-driven construction that can be explored.
- The assistance package to the affected house-

holds can be structured in such a way that it is more targeted towards the less affluent, less privileged and the most vulnerable groups.

- While promoting low-cost and locally appropriate technologies, aspirations of the affected population should be taken into account.

3.3.4. Rebuilding Critical Infrastructure and Enhancing Standards of Safety

- For all critical infrastructure performance based codes need to be established.

3.3.5. Response

- A comprehensive planning process for disaster risk management, taking into account national and international capacities should be put in place.
- A permanent, full-time structure for disaster management should exist.
- In particular, managers should be given a chance to participate in simulation exercises of large-scale emergencies with the participation of international actors.
- More "discipline" on the part of internationals such as contacting with local authorities chosing one contact point should be taken.
- Proactive information sharing should be followed up.
- The Government needs to establish stronger institutional mechanisms to deal with international assistance.
- More effective mechanisms should be available to decline offers for assistance and/or prevent unwanted assistance from reaching the country.
- More commitment should be put by agencies and donor Governments towards respecting a) the will of the Government, b) the indications provided by the United Nations and c) existing technical standards.
- The involvement and participation of beneficiaries is indeed fundamental.
- A number of practical and easy-to-implement procedures for a greater participation of beneficiaries should become standard for international agencies.
- During emergencies, information management is as important as the provision of actual relief as sistance.
- Informing the affected population in the immediate aftermath of the disaster (and even before) is extremely important.

The detail recommendation and proceedings of the workshops can be obtained from the *UNDP* office in Tehran.

3.4. Sustained Technical and Coordination Support for Sustainable Recovery and Long-Term Disaster Risk Reduction (March 2004-December 2005)

The main focus in this phase is on supporting the Government of Iran in the implementation of the Bam reconstruction programme. Efforts will be targeted to gathering additional financial and technical resources for the institutional arrangements, strategies and plans that the Government has put in place, and on managing, tracking and coordinating the use of these resources. The *UN* will also use the opportunity to draw attention to the importance of all aspects of earthquake disaster risk management, with particular emphasis on identifying best practices and lessons learned from the Bam earthquake. Key activities during this phase include:

- ***Establishment of a Public Information System***

The aim of the initiative is to empower the affected communities through enhanced access to information resources on disaster recovery and reconstruction programmes and projects. The *UNDP*-supported project will entail mapping of potential community learning and information sharing points; collection and collation of data for an electronic Central Resource Database Centre; design and development of an Information Bank and query-based portal for the generation of various information products for the print and electronic media; and the establishment of *ICT* kiosks in various locations throughout the affected areas to provide families with information on Government policies and activities, updated damage reports, entitlements, land status, rehabilitation schemes etc.

- ***Educational Materials for Earthquake Risk Preparedness (May-December 2004):***

The loss of around 12,000 student and teachers and destruction of several schools in Bam earthquake has highlighted the high vulnerability of schools and children. It has also highlighted the need for earthquake-preparedness training in schools. *UNESCO* and *IIEES* are supporting the development of a school-text that will contain: success stories from the Bam earthquake survivors on the efficacy of the earthquake preparedness training; information on seismicity and seismic hazards in the region; and basic earthquake-preparedness training information.

- ***Training Sessions and Workshops in the Education Sector (May-December 2004)***

These *UNESCO*-supported workshops will cover: communication skills; access to psychosocial support for school-aged children, including treatment and care; basic health education; life skills training, inclusive education for orphans; etc

- ***International Conference for the Reconstruction of Bam (September 2004)***

As proposed by the *UN* Secretary-General, once the Government of Iran has formulated its strategy for the long-term reconstruction programme in Bam, and has put in place institutional arrangements to manage the reconstruction, the *UN* will assist in organising a forum for the Government to present its strategy to the international community. The forum will provide an opportunity for the Government of Iran and its partners to discuss the different proposals outlined in the strategy, from technical, financial, institutional and social perspectives.

- ***International Seminar on Earthquake Disaster Risk Management (October 2004)***

The Bam earthquake has underscored the need for greater emphasis on earthquake disaster risk management not only in Iran but also in other earthquake prone countries of the developing world. As proposed by the *UN* Secretary-General, an international seminar on earthquake disaster risk management, held in the wake of the Bam earthquake could help stimulate more serious discussion on the need for careful and coherent planning to mitigate the impact of future disasters. The seminar could bring together experts and decisions makers from twelve to fifteen of the most earthquake prone countries to address real issues of concern, such as what financially and politically-viable mechanisms or programme approaches exist to reduce earthquake risk in mega-cities such as Tehran. The seminar would also be an opportunity for the Iran launch of *UNDP's* global report on "Reducing Disaster Risk: A challenge for Development".

4.4. Capacity Building to Mainstream Disaster Risk Reduction into Development Processes at Local, Provincial and National Levels (2004-2009)

Iran's development objectives clearly emphasise sustainable and equitable development. However, progress in this regard will only be possible when development policies and plans succeed in reducing vulnerability to natural disasters. A greater awareness of this, generated by the Bam earthquake, can be channelled towards the mainstreaming of disaster risk reduction approaches in national development policies and processes. Under the *UNDAF*, the *UN* system is developing a comprehensive programme in support of national disaster management efforts that will focus on: the mainstreaming of disaster risk management at the local, provincial and national levels; increased public participation in disaster risk management; and enhanced coping mechanisms of local communities to deal with natural disasters. The following are a few areas where the *UN* could work with the Government:

- ***Urban Earthquake Disaster Risk Reduction Programme for Iran***

Given the level of seismic activity in the country, and given the concentration of population and economic activities in urban areas, the level of earthquake risk faced by Iranian cities is very high. The Bam earthquake should act as a wake up call and mobilise concerted efforts for urban earthquake disaster risk reduction. Such efforts are already being made in Tehran. However, most of the ongoing work focuses on purely technical aspects. These efforts need to be mainstreamed into urban development policy making and greater emphasis needs to be put on public awareness raising. Ultimately, urban earthquake risk reduction issues will also have to be linked to issues of good governance. Over the next year, *UNDP*, capitalizing on its experience of governance issues in Iran, could help initiate an urban earthquake disaster risk reduction programme in Iran.

- ***Promoting an Appropriate Techno-Financial Regime for Disaster Reduction***

While there is easy access to engineering and technical solutions for earthquake-resistant buildings, few financial mechanisms exist in Iran to put these solutions into practice. Now would be a good time to explore possible kinds of financial support mechanisms or systems of incentives and disincentives that could be established to foster greater compliance with earthquake safety standards in all sectors.

- ***Promoting an Appropriate Techno-legal Regime for Disaster Reduction***

Iran has one of the best developed building codes for earthquake resistant construction? However, the rate of compliance, even in urban areas, is very low. Even

where the building designs follow building codes, the execution of those designs on construction sites is usually poor. Laying down interim standards and simple quality control methods for building materials, a construction method etc. is essential. It may be time to undertake a thorough review of the legislative and institutional arrangements for the enforcement of building codes in Iran.

- ***Enhancing Cooperation with the Government of Iran on Natural Disaster Response and Strengthening Disaster Response Capacities at Local, Provincial and National Levels***

The *UN* will contribute to strengthen capacity for natural disaster response at all levels in Iran. *OCHA* has developed a module for this training and is able to start at 6 to 8 weeks notice. The *UN* is interested in continuing the training of Iranian experts for the United Nations Disaster Assessment and Coordination (*UNDAC*) teams. Capacities of various Iranian agencies and departments to deal with the international community (search and rescue and health response teams etc.) in times of disasters will also be enhanced.

- ***Development of a Sub Regional Programme on Urban Earthquake Risk reduction:***

The *UNDP* Country Office is managing a ten-country preparatory assistance on disaster risk management in Central and Southwest Asia. As a part of the preparatory assistance, a multi-country urban earthquake risk reduction programme could be designed that would link selected mega-cities from the region that are earthquake prone, and foster an exchange of experiences, expertise and strategies on earthquake risk reduction. The Government of Iran has been very supportive of this preparatory assistance and has shown an inclination to play a leadership role.

- ***An Open Alliance for Earthquake Risk Reduction:***

The Bam earthquake has provided a challenge to governments to make the best use of existing know-how on earthquakes, and to integrate it into their development programmes. It has also provided an opportunity to the scientific and engineering community to provide more socio-economic and culturally compatible solutions to national needs. To facilitate discussion in this regard, *UNESCO, UNDP, ISDR* and *IIEES* (as the host institute in Iran) have agreed to form an alliance which will be open to a wider partnership among both Iranian and international institutions and organizations. The objective is to initiate a series of activities to protect people, building stock, lifelines and critical infrastructure from the impacts of future earthquakes. The alliance will advocate a shift in emphasis from post-disaster reaction to pre-disaster prevention and risk reduction actions. It will stress the importance of preventive approaches through the enhancement of research and knowledge capacities, the design and dissemination of risk mitigation measures as well as increased information, education and public awareness. The alliance's vision is: expanded scientific and applied research, technical infrastructures and capacities for implementation of an effective risk mitigation action; reduction of risk in all types of built structures; initiatives for earthquake risk mitigation in rural areas with emphasis on the provision of realistic, doable, affordable, simple methods and methodologies; and enhanced disaster preparedness through public awareness. In the short term, the alliance will ensure that post-Bam earthquake scientific and technical studies and investigations are conducive to the production of comprehensive and authoritative compendium on lessons learnt from the earthquake and guidelines for reducing future losses in similar cases. The long-term objective will be to enhance the monitoring of seismic activity; assessment of seismic hazards; investigation of geotechnical issues; improvement of building design, resilience of important public buildings, lifelines, critical infrastructure and historical monuments; and the promotion of earthquake preparedness and disaster management. The detail is given in a separate document in this issue of *JSEE*.

4. The Way Forward

Effective reconstruction and recovery of Bam will require concerted efforts by the local, provincial and national authorities, national and international *NGOs*, the *UN* and other international agencies. A number of regional and international organizations have shown an interest in contributing to different aspects of the reconstruction programme. Making the most of these inputs, however, will require close coordination. Within the *UN* system, efforts are being made to develop a collective, coherent and coordinated response through the *UNDAF*. Under the *UNDAF*, disaster management has been identified as a top priority by the *UN* and the Government. Sustainable reconstruction of Bam and disaster risk management in Iran will therefore guide the future programmes of the *UN* system.

On a more general level, the *UN* is committed to providing coordination support to the Government

and the international community throughout the reconstruction process. In the initial rescue and relief phase, the *UN* assisted the Government in coordinating the donor and *NGO* support by organizing sectoral meetings both in Bam and in Tehran. Through the *UN* Coordination Office in Bam and the Resident Coordinator's Office in Tehran, the *UN* System has continued to provide coordination assistance during the transition from the immediate rescue and relief phases to medium term recovery. Recognising that the recovery and reconstruction offer an opportunity for wider participatory planning processes at all levels, the *UN* System, in collaboration with the local authorities, has attempted to engage and bring together the earthquake-affected communities, local *NGOs* and the private sector in a series of consultative meetings, entitled "The Bam That We All Want". An Inter-Sectoral Recovery Manager has also been recruited to facilitate coordination between the various *UN*, national and international actors for the sustainable recovery and reconstruction of Bam.

Annex 1. Abbreviations and Acronyms.

FAO	Food and Agricultural Organization
ICHO	Iranian Cultural Heritage Organisation
ICRC	Iranian Red Crescent Society
IIEES	International Institute of Earthquake Engineering and Seismology
INDMP	Integrated National Disaster Management Plan
INSARAG	International Search and Rescue Group
ISDR	International Strategy for Disaster Reduction.
ILO	International Labour Organization
MDGs	Millennium Development Goals
MOI	Ministry of Interior
NDTF	National Disaster Task Force
NGOs	Non-Governmental Organizations
UNDAC	United Nations Disaster Assessment and Coordination Team
UNDAF	UN Development Assistance Framework
UNDP	United Nations Development Programme
UNDMT	United Nations Disaster Management Team
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UNFPA	United Nations Population Fund
UN-HABITAT	United Nations Human Settlements Programme
UNHCR	United Nations High Commissioner for Refugees
UNICEF	United Nations Children's Fund
UNIDO	United Nations Industrial Development Organisation
WHO	World Health Organization
YICLD	Yazd International Centre for Living with the Desert

Bam Earthquake: From Emergency Response to Reconstruction

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ABSTRACT: *This paper gives a brief explanation of the earthquake in Bam, casualties, as well as a report on rescue and relief operations, emergency shelters, temporary housing, and the country's plan for the reconstruction of the city, which includes, debris removal, rebuilding rural and urban residential and commercial units, reconstructing state and public buildings and facilities, schools, rural and urban water aqueducts and grid, establishing sewerage system, power network, and telecommunication system, supplying orchards and farmlands with water, renovating industries, reviving cultural heritage particularly the historical Bam citadel and the like.*

Keywords: Bam; Rescue and relief; Emergency shelters; Temporary housing; Reconstruction strategy; Construction Bazar; Local participation; Reconstruction funding

1. Introduction

The city of Bam is located at a vast plain in the southeast of Kerman province, 190*km* from Kerman toward the south. The city's plain has a slope from south west toward northeast with a gradient of about 1.2 percent. Bam has an area of 19,374 square kilometers and is 1,076 meters above the sea level. Avardi river flows in north of the city. Except the citadel, which is located at a 60*m* height, no natural structure can be found in Bam. Winds often blow from the northwest to the southeast. The city experiences 298 days of dry weather in average, while the rainy days stand at eight in average and at least three. The maximum temperature is 44 degrees centigrade in June, the minimum is -2 degrees centigrade, and the average annual temperature is 23 degrees centigrade. The annual rainfall is 62.5*mm*. The southern part of Bam is the room of rich underground waterbeds of which 51.5% is used in the city's aqueducts.

People financial resources have been mainly through farming and gardening as the city has big orchards of citrus fruits and palm groves. Bam's date is well known worldwide. According to the statistics, Bam had a population of 70,000 people in 1996 and its population in the rural and urban areas reached 142,376 people in January 2004 as shown in Table (1), according to Iran Census Center.

A destructive earthquake with a central depth of 10km and a magnitude of Ms 6.5 leveled the historical city of Bam and Barvat in the wee hours of September 26, 2003 at 05:26:56 local hours (01:56:56 *GMT*). The earthquake epicenter was located at 29.21*N*, 58.40*E* (*IGTU*). 80% of building has been completely destroyed while approximately 17% of buildings' structures have been totally damaged and cannot be used any longer and structures of about 2.8% of buildings have remained undamaged and 0.2% have experienced minor damages. Table (2) shows the buildings damage situation. Apart from residential and commercial units, most of the public and state buildings, urban facilities including water, sewerage, power, and telecommunication systems as well as irrigation and agricultural systems, gardens, streets and roads have been badly damaged and should be rebuilt. Also the historical citadel of Bam (Arge-Bam) was totally devastated.

Table 1. Population of Bam and Baravat.

No. of Outlined and Approved Plans	Mapping with Paint	Laying Foundations	Laying Mortar and Concrete	Reinforcing Foundations with Concrete	Erecting Skeleton	Fencing with Walls	Ceiling
95	19761	19279	8061	2908	1057	358	15

Table 2. Distribution of damaged buildings.

Total	59364	
Urban Residential	To be Reconstructed	26501
Commercial Units	To be Repaired	777
Rural Residential	To be Reconstructed	21711
Units	To be Repaired	7375

2. Rescue and Relief Operations

As the news broke, the responsible organizations such as Iran Red Crescent society, law enforcement forces, Basij, and volunteers from inside and outside the country rushed to the area and made every effort to rescue the people, transfer and treat the injured and help the quake-stricken people. The wounded people were transferred to Kerman and Tehran hospitals by planes and helicopters. The noble nation of Iran played its role again and did a praiseworthy task by offering relief. Relief workers removed the victims and wounded people from the debris with the help of machinery and people. The injured were transferred to the field hospitals or the above-mentioned hospitals. The dead were buried during traditional religious ceremonies in the newly-established Behesht-e-Zahra (*SA*) cemetery. As an emergency service, the Red Crescent Society distributed tents to house the survivors. Figures (1) show some scenes of the relief operation.

3. Emergency Shelters and Temporary Housing

Tents were distribution between the homeless people since the early other the event to provide them with the emergency shelters. Figure (2) shows some of these emergency shelters.

Interior Ministry and Kerman Governor General office were ordered to provide prefabricated buildings with an area of 18-20 square meters, equipped with water heater, air conditioning, sink, and sanitary ware to be erected in the area and camps for housing the survivors. Almost all the survivors were housed by June 12, 2004. Figure (3) show the construction of temporary housing units. Almost all of the homeless people were habituated in the temporary houses, either prefabricated or built-insitu till end of April 2004.

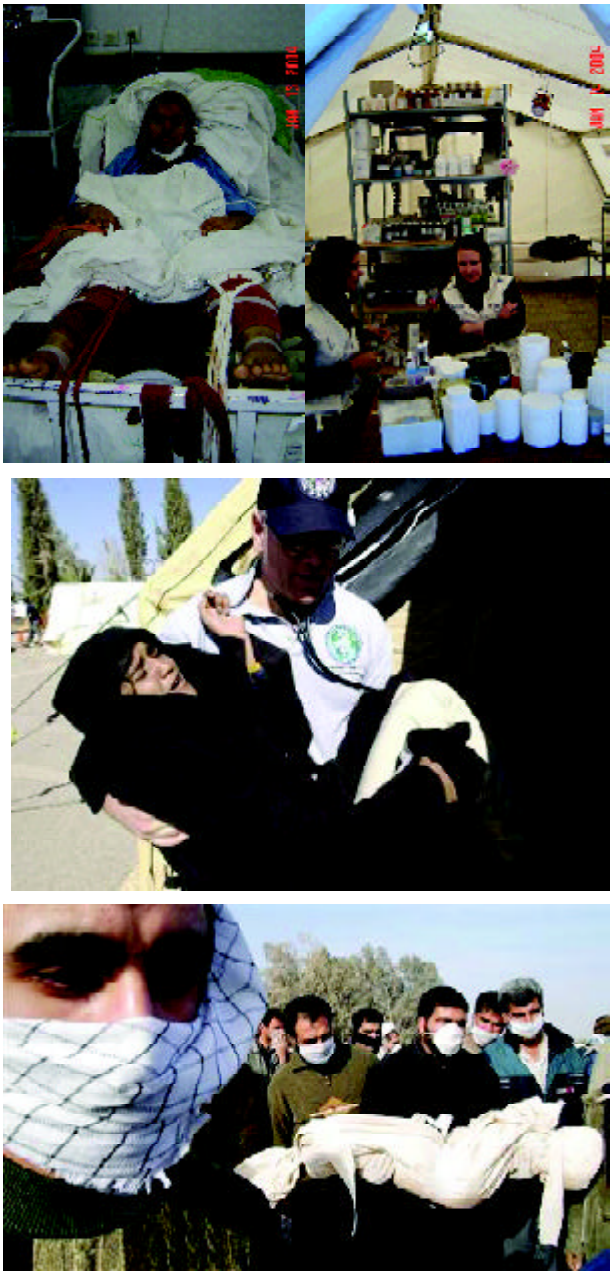


Figure 1. Relief workers removed the victims.

4. Bam Reconstruction

Following the proposal of the cabinet and order of President Seyed Mohammad Khatami, a headquarters for adopting policies and steering reconstruction of Bam was run and headed by Minister of Housing and Urban Development. Iran Housing Foundation (*IHF*) was appointed as the main executive organization for the reconstruction.

4.1. The Reconstruction Strategy

The headquarters decided on planning, providing financial sources, policymaking, executive operations, and supervision, which were briefed in the following topics:

a) On the pedestration area

b) In a camp

Figure 2. Emergency shelter.

Figure 3. A sample of insitu-built temporary housing.

1. Removing the debris in the city and suburban villages by the *IHF*
2. Reconstructing the city of Bam in its current location, observing local architecture
3. Reconstructing damaged residential and commercial units in the city and villages through:
   - Encouraging the owners of the units
   - Providing people with the necessary facilities to have information about construction technology
   - Promoting regional construction quality
   - Inviting university professors, consulting engineers, and contractors to render technical services including design and implementation Inviting suppliers of sand, and gravel, and concrete makers to set up plants in the region to meet the regional needs and supervise the supply
   - Establishing a workshop and exhibition area for offering technical and engineering services to people as well as consulting centers to offer technical information, map, stores, and construction materials centers to build resistant buildings for people to choose and buy, and to run workshop for rendering technical services related to construction operations. This is called the constration Bazar and its details are shown in Figure (4).
   - Preparing the ground for mass-constructors to build residential complexes in the areas where residential units cannot be constructed due to technical reasons
   - Hiring local people for reconstruction with the aim of creating job opportunities and promoting their technical know-how
   - Setting up Bam Architecture Council to issue orders on architectural designs and urban development in conformity with Islamic cultural, social, and regional values of Bam
   - Running laboratories to control the quality of construction materials
4. Inviting all state-run organizations to offer their proposals on reconstruction of devastated units with the aim of regional development
5. Feasibility study on plans and projects in Projects and Allocations Committee and making final decision in the headquarters
6. Using international help (foreign loans) for implementing development plans on water and sewage, power, irrigation, health, streets and roads, railroad, and schools
7. Managing reconstruction operations whose financial needs are met by foreign banks' loans
8. Authorizing Public and State Buildings and Facilities Executive Organization to do related task
9. Authorizing Ministry of Agricultural Jihad to manage reconstruction of the agriculture sector's infrastructures

Figure 4. Construction Bazar (Market) for the reconstruction of Bam.

10. Authorizing Ministry of Energy to manage reconstruction of water, sewerage, and power systems' infrastructures
11. Authorizing Ministry of Industries and Mines to manage reconstruction of industries
12. Authorizing Organization for Equipping, Developing, and Rebuilding Schools to manage reconstruction of schools
13. Authorizing the technical and engineering departments of the Islamic Revolution Guards Corps, Basij, and law enforcement forces to manage reconstruction of military centers and police stations
14. Planning for running websites to give necessary information
15. Ratifying the exgratia aid and banking facilities for residential and commercial units in the city and villages and for private units used by the public
16. Attracting financial aid of benevolent people to allocate for building schools and medical centers
17. Introducing qualified people to banks by the *IHF* for receiving banking facilities

The *IHF* also reserves the right to supervise reconstruction of buildings whose expenses are paid by non-governmental organizations, endowment institutes, and benevolent people. The executive organizations are obliged to offer their schedule and report their projects' physical progress to the *IHF*. The *IHF* is obliged to set up a secretariat to institutionalize reconstruction affairs. The secretariat is duty-bound to document all stages of reconstruction of Bam as the operations are progressed.

4.2. Debris Removal

After the rescue operations and housing the survivors ended, 17 provincial affiliates of the Housing Foundation and other executive organizations in the region were assigned (according to the agreed contracts) to remove debris and to prepare the land for reconstruction of residential and commercial units. Figure (5) shows the scene and Table (3) shows the statistics of the removed debris. The operation of removing debris in each case was started after the confirmation of the unit's ownership. To separate usable materials or goods from the debris, the owner was encouraged by some allocation to restore brick, iron profiles, etc.

Table 3. Progress of operations for removing debris.

Debris Removal in City and Villages	
No. of City's Bldg. (Commercial and Residential)	26501
No. of City's Bldg. Cleared of Debris	21634
No. of Rural Bldg. Cleared of Debris	4447
No. of Motor Vehicles Used Daily	Truck: 351; Dulldozer: 96

Figure 5. Debris removal.

4.3. Urban Reconstruction

Reconstruction operations of residential and commercial units have not started yet since the studies related to the comprehensive plan of Bam are not complete. The owners will be introduced to Bam and Baravat municipalities to receive permits for rebuilding their units when the first phase of Bam comprehensive plan is completed. The expenses of issuance of the permits will be borne and deposited in favor of Bam and Baravat municipalities by the *IHF*.

Each residential unit has an area of at least 80 square meters. The state allocations for residential and commercial units are shown in Table (4). The total low-interest loan and Grants for each house holes are 60 and 35 Million Rls., respectively.

Table 4. Budget allocation of low interest loan and grant (in 1000 Rials) for reconstruction and repair of residential and commercial buildings Bam and Baravat and rural area. (8500 Rials =1US$)

	Bam and Baravat: Reconstruction		Rural Area: Reconstruction and Repair
	Residential	Commercial	
Low-Interest Loan	60,000	1,300/m^2	45,000 (Reconstr) 15,000 (Repair)
Grant	35,000	10,000	15,000 (Reconstr) 3,000 (Repair)

The maximum amount of loan allocated to construction of fences for each unit is 20,000,000 Rials. In case, an owner demands for more built-up area, the executive organization introduces him to banks to receive more facilities. The *IHF* distributes building materials and prefabricated metal skeleton from grant found and the owners. As the permits are issued, the owners will be introduced to receive banking loan whose amount is decided by the *IHF* due to progress of construction in different stages.

4.3. Reconstruction of Rural Residential Units

Although banking facilities have not been offered so far, the reconstruction operations of 60-square-meter residential units in villages have started in accordance with the approved policies. Ex gratia aid and sources of the *IHF* have been used for the operations, and their progress are shown if Table (5).

Table 5. The progress of ex gratia and sources of IHF in reconstruction of rural units.

No. of Outlined and Approved Plans	Mapping with Paint	Laying Foundations	Laying Mortar and Concrete	Reinforcing Foundations with Concrete	Erecting Skeleton	Painting with Water	Ceiling
95	10764	10279	8867	2908	1057	358	15

4.4. The Technical and Human Resources for Reconstruction

For operation of reconstruction, several subsidiary headquarters and workshops have been equipped as shown in Table (6). A great volume of workforce was also assigned to the job as shown in Table (7).

Structural Drawing and details for 60 square-meter residential units that their construction will be supported by the government are shown in Appendix I.

Table 6. The equipped headquarters and workshops for reconstruction operation.

No. of Subsidiary HQ	No. of Material Labs	No. of Sand, Grave, Concrete, Skeleton Producing Workshop
17	7	17

Table 7. The assigned workforce in region.

Engineer	Technician	Office Worker	Others
104	95	99	1000

5. Conclusion

The construction bazar (exhibition and market), proposed by the Iran Housing Foundation, is an innovating way for employing the maximum contribution of local people, the present and future residents of the city, to the reconstruction process. However, for reconstruction of the rural area the proposed architectural plans should be informed to the people before any action take place in construction, so that they can observe if these plans are satisfactory to them.

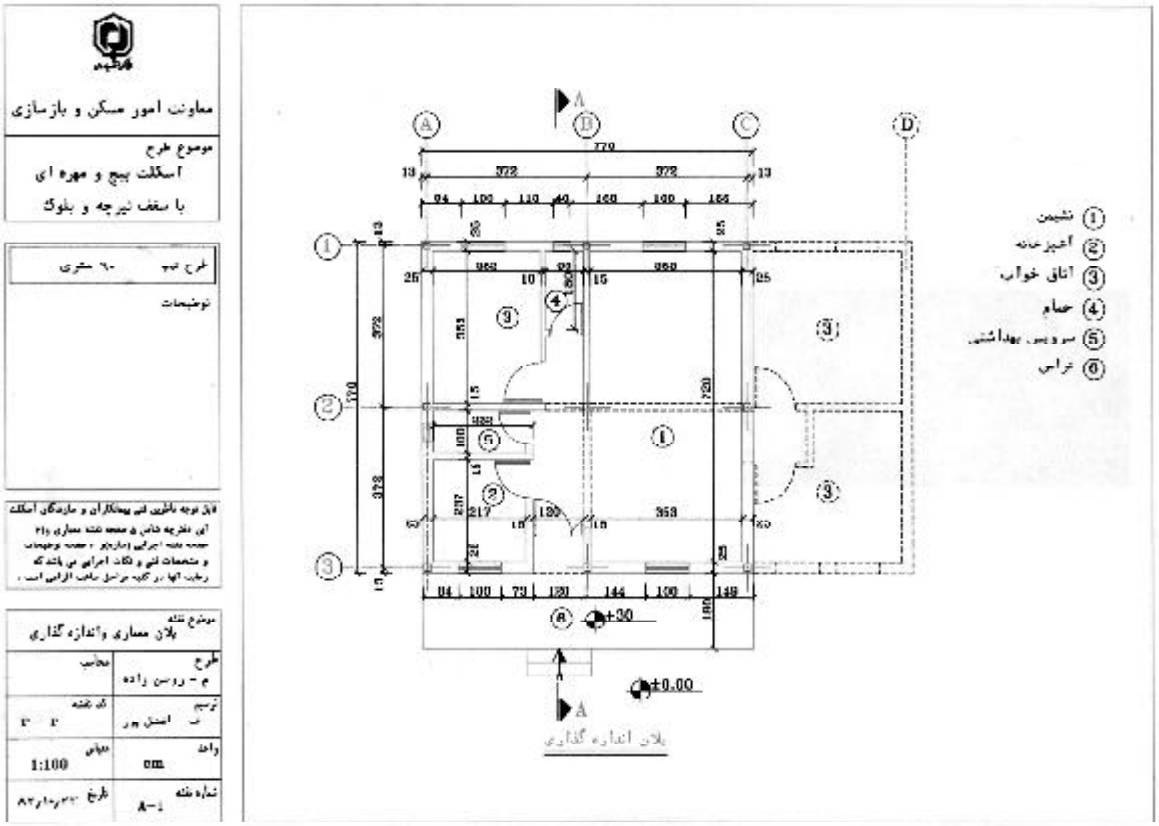
Acknowledgment

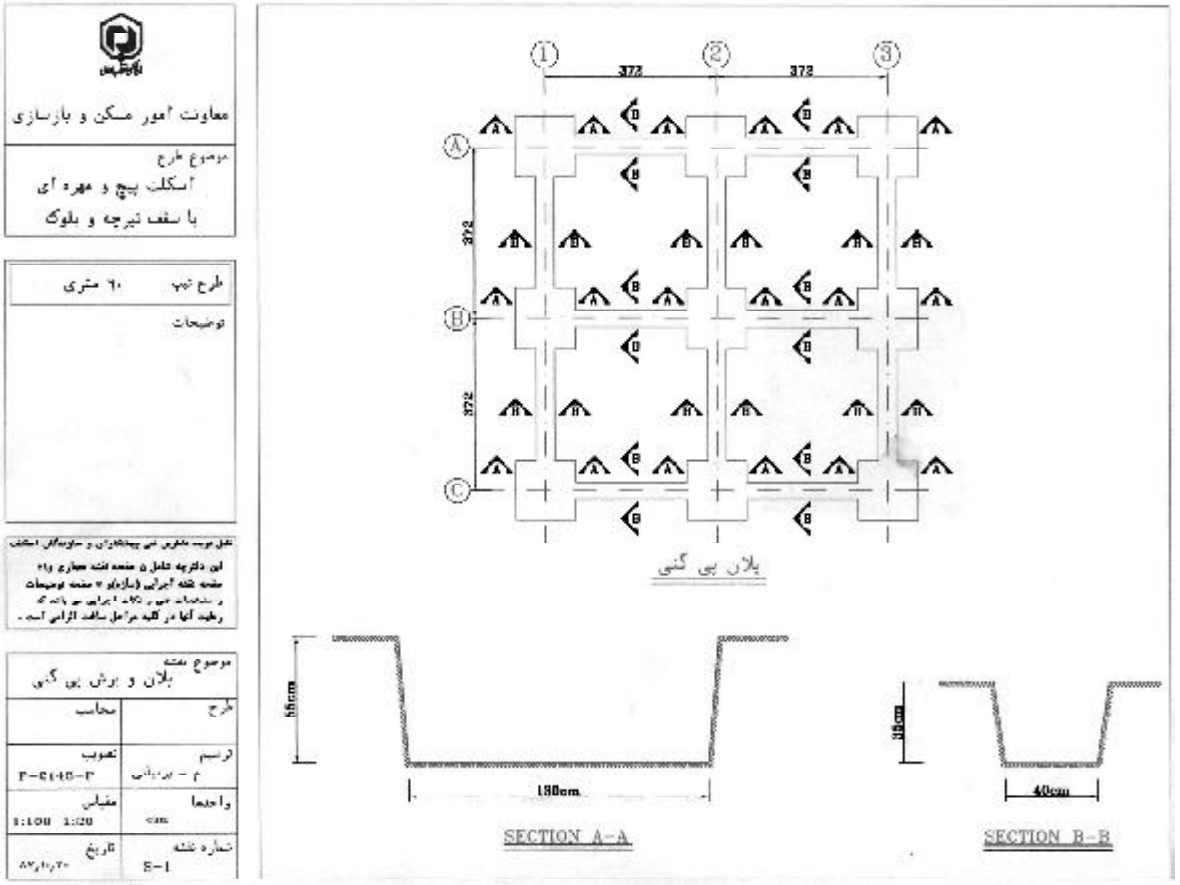
The authors wish to express their highest thanks to Mr. Saiidi-Kia, the president of Housing Foundation for his valuable efforts for the reconstruction of Bam, who has almost an authorship role in this paper. The authors are also grateful to professor M. Ghafory-Ashtiany, the president of the *IIEES* for his valuable comments.

References

1. ISC (2004). "The Results of the Places and Families Listing of Bam Earthquake Regions", The Iran Statistics Center (ISC).
2. The preliminary report of Bam city, Deputy of the Engineering Statute and Building Executing (2004). Ministry of Housing and Rural development.
3. The Maps of Type 60-Square-Meter Fastening Skeleton with Pole and Block- Iran Housing Foundation (2004).
4. Eshghi, S. and Zare, M. (2004). "Reconnaissance Report on 26 December 2003, Bam Earthquake", *International Institute of Earthquake Engineering and Seismology (IIEES)*, Tehran, Iran.
5. The Acts Collection of Bam Reconstruction Guidance and Policy Task Force.
6. The Collection of Work Progress Reports of the Iran Housing Foundation.

Appendix 1. Structural Drawing and details for 60 square-meter residential units that will be supported by the government.

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با سقف تیرچه و بلوک
طرح تیپ ۶۰ متری
توضیحات
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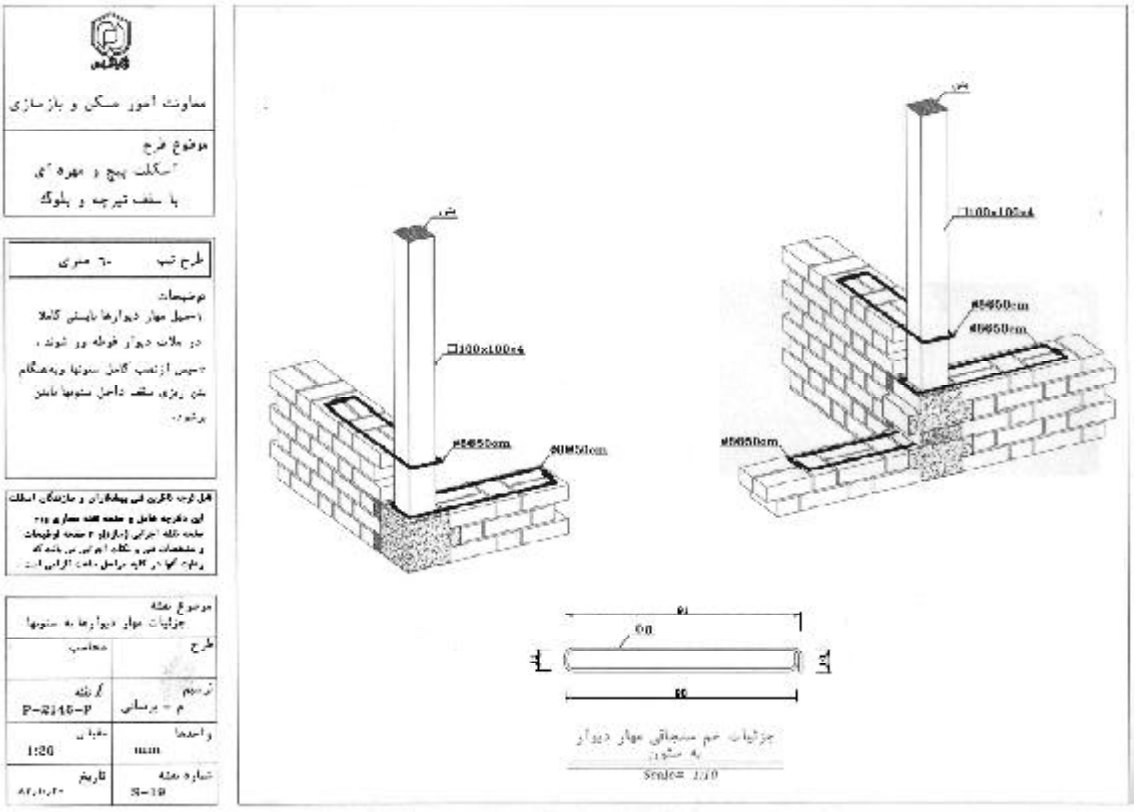
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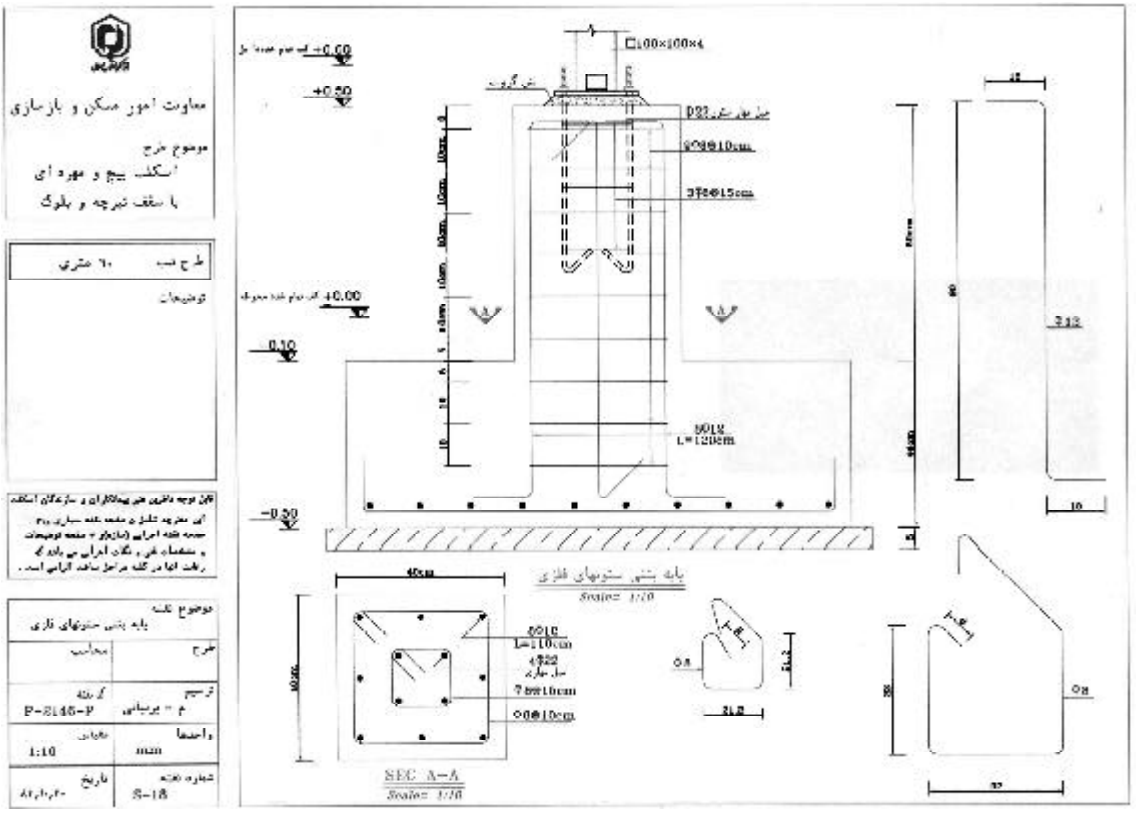
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موضوع طرح
اسکلت بتنی و مهره ای
با سقف تیرچه و بلوک
طرح شب ۶۰ متری
توضیحات
موضوع نقشه
پایه بتنی ستونهای فلزی
طرح
محاسب
ترسیم
م - پرتیانی
کروکی
P-S145-P
واحدها
mm
مقیاس
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شماره نقشه
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□100×100×4
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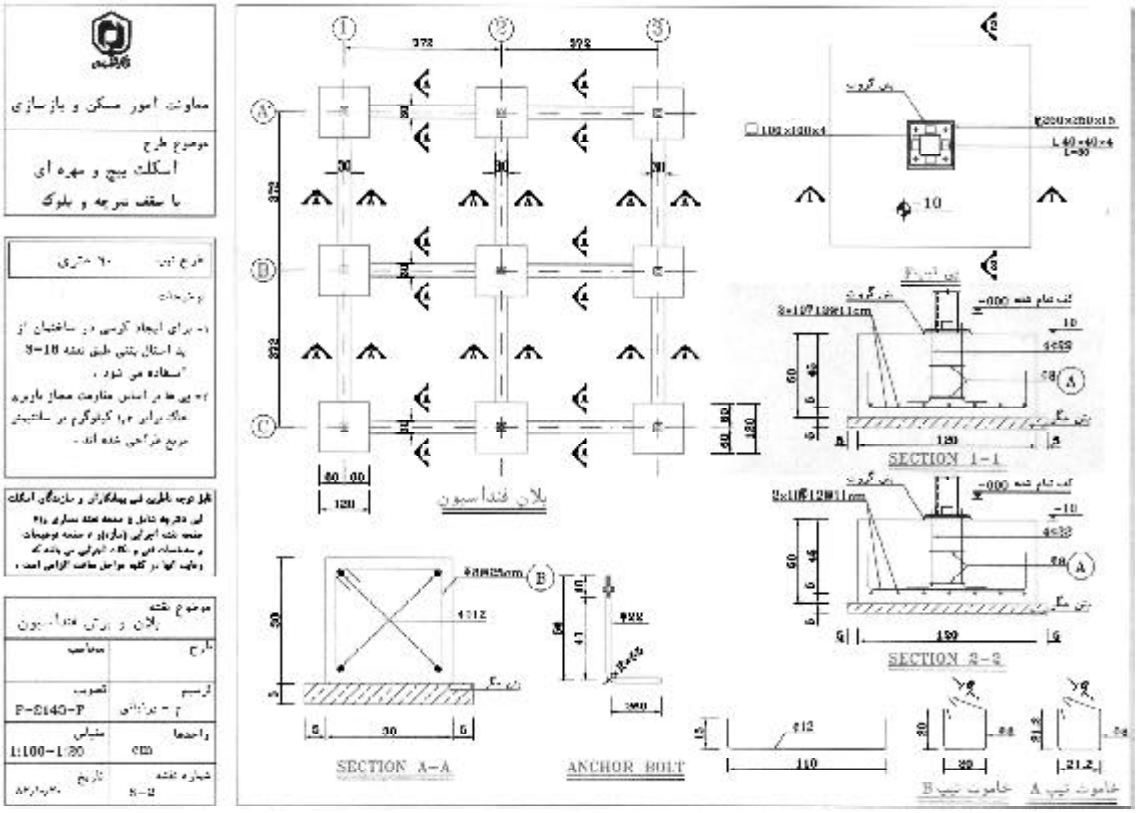
Scales 1/10
پایه بتنی ستونهای فلزی
Scales 1/10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موضوع طرح
اسکلت بتنی و مهره ای
با سقف تیرچه و بلوک
طرح شب ۶۰ متری
توضیحات
موضوع نقشه
پلان و برش فنداسیون
طرح
محاسب
ترسیم
م - پرتیانی
تصویب
P-S145-P
واحدها
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مقیاس
1:100-1:20
شماره نقشه
S-2
تاریخ
۸۲/۱۰/۲۰
372
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120
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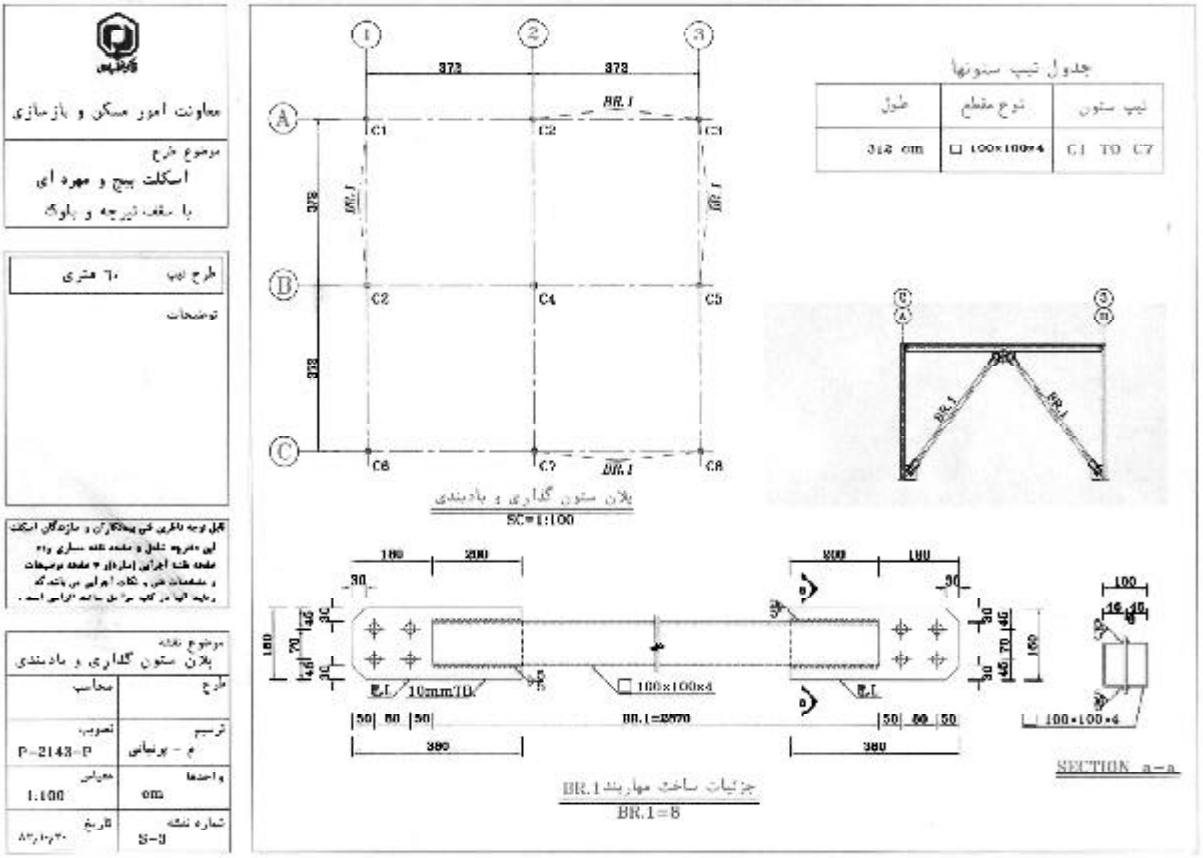
SECTION A-A
ANCHOR BOLT
SECTION 1-1
SECTION 2-2
خاموت تیپ A
خاموت تیپ B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موضوع طرح
اسکلت بتنی و مهره ای
با سقف تیرچه و بلوک
طرح تیپ ۶۰ متری
توضیحات
موضوع نقشه
پلان ستون گذاری و بادبندی
طراح
محاسب
ترسیم
م - پرنیانی
تصویب
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1:100
شماره نقشه
S-3
تاریخ
۸۳/۱۰/۲۰
جدول تیپ ستونها
تیپ ستون
نوع مقطع
طول
C1 TO C7
□ 100×100×4
312 cm
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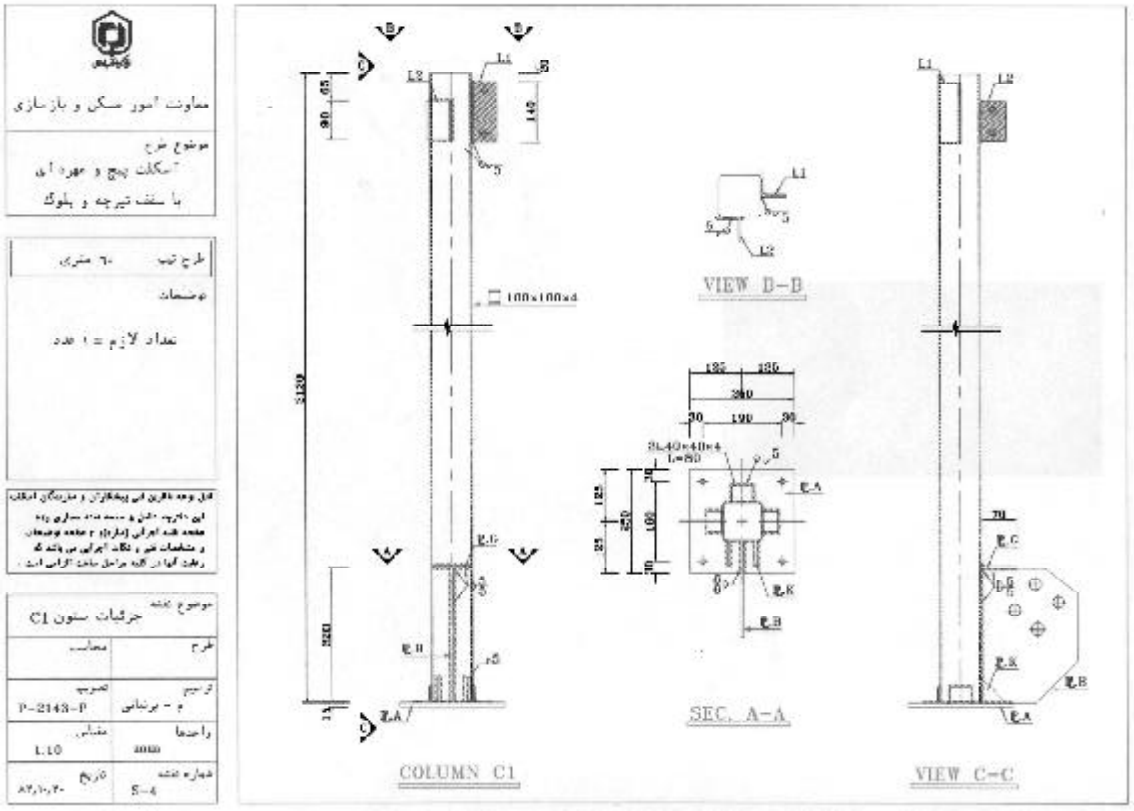
SC=1:100
جزئیات ساخت مهاربند BR.1
BR.1=8
SECTION a-a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موضوع طرح
اسکلت بتنی و مهره ای
با سقف تیرچه و بلوک
طرح تیپ ۶۰ متری
توضیحات
تعداد لازم = ۱ عدد
موضوع نقشه
جزئیات ستون C1
طراح
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م - پرنیانی
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شماره نقشه
S-4
تاریخ
۸۳/۱۰/۲۰
COLUMN C1
SEC. A-A
VIEW B-B
VIEW C-C

An Open Alliance of

The United Nations Educational, Scientific and Cultural Organization *(UNESCO)*

The United Nations Development Programme *(UNDP)*

The United Nations International Strategy for Disaster Reduction *(UN/ISDR)* and

The International Institute of Earthquake Engineering and Seismology *(IIEES)*

A Framework for Cooperation on Earhquake Risk Reduction

In the Islamic Republic of IRAN and Developing Countries

1. Overriding Considerations

The Bam earthquake disaster provides a unique window of opportunity to raise international awareness of the importance of the effective implementation of a comprehensive earthquake risk reduction program in Iran as well as in hazard-prone developing countries. It gives a challenge to the governments to make the highest use of the existing know-how on earthquakes and its integration into development programs. It also compels the scientific and engineering community to provide more socio-economic-cultural compatible solutions to national needs. Moreover, the public at large should become more concerned about the hazard and increase its own preparedness level. To initiate such an approach the United Nations Educational, Scientific and Cultural Organization (*UNESCO*), the United Nations Development Programme (*UNDP*) and the Secretariat of the International Strategy for Disaster Reduction (*UN/ISDR*) and the International Institute of Earthquake Engineering and Seismology (*IIEES*) as the host institute in Iran, decided to work in partnership with other organisations and professionals throughout the world to provide leadership for a series of activities that will protect people, building stock, lifelines and critical infrastructure from the impacts of the inevitable future earthquakes in Iran.

In the wake of the Bam earthquake, and based on the document "*UN* Strategy for Support to the Government of Islamic Republic of Iran following the Bam Earthquake of 26 December 2003". *UNESCO*, *UNDP*, *UN/ISDR* Secretariat and the *IIEES*, agreed to form an Alliance which will be open to a wider partnership among both Iranian and international institutions and organizations. They recognize that to improve human security and life safety in Iran as well as in developing countries by reducing the vulnerability to hazards and risks, including earthquake risk, is the overarching primary objective of the Alliance. This Alliance is expected to provide advise in the reconstruction process of Bam and in the prevention of future risks in similar cases.

Iran is recognized among the highly exposed countries to natural hazards, namely earthquakes. The risk of earthquake and other natural disasters is increasing in Iran as a result of population growth, urbanisation, alteration of the natural environment, climate change, vulnerable dwellings, public buildings and lifeline infrastructure. With further population growth, expanding public and private infrastructures, environmental changes and continuing trends towards urbanisation and industrialisation, the risks of greater tragedies stemming from natural hazards are expected to increase in the next years and over the current new century.

IIEES, *UNESCO*, *UNDP* and the *UN/ISDR* Secretariat underline that making disaster prevention and mitigation integral parts of development in Iran as well as in other hazard-prone countries requires a genuine shift in emphasis from post-disaster reaction to pre-disaster prevention and risk reduction

actions. Hence, the new emerging approach, to be spearheaded by the Alliance will stress the merit of preventive approaches through enhancement of research and knowledge capacities, the design and dissemination of risk mitigation measures as well as increased information, education and public awareness.

The Alliance affirms the importance of science and technology in laying the foundations for disaster risk management. As regards Iran, it notes that steady development in earthquake-related knowledge, research and technical applications has occurred since the 1990 Manjil earthquake. This trend ought to be further fostered. Above all the implications of this trend across the whole elements of the disaster reduction sectors and stakeholders should be ensured if significant risk mitigation is to be achieved in the final analysis.

Based on the above-mentioned considerations, the Alliance recalls that the establishment of the International Institute of Earthquake Engineering and Seismology in Tehran was founded on a decision taken by the 24th session of the *UNESCO* General Conference, representing the will of the international community to build capacities in Iran and in the seismically active regions to excel in earthquake risk mitigation. It recognizes that, since its establishment in 1990, the *IIEES* has gradually succeeded in meeting the challenge of developing into a Centre of Excellence in earthquake-related studies and the production of knowledge and know-how. Other Iranian competent agencies, including academic and public institutes, have a recognized role in furthering earthquake fundamental and applied research. Through *IIEES* and other competent Iranian institutions, there is more scientific knowledge and technological know-how than ever before to promote science-based disaster preparedness and prevention and to assist in designing and implementing risk mitigation strategies.

The Alliance emphasizes the importance of international cooperation in support of disaster reduction and in sharing knowledge and experience in disaster reduction practices. It is committed to facilitate the further expansion of the regional and international vocation of *IIEES* and other specialized Iranian institutions.

The Alliance notes with much regret the inertia and lack of effective action in enforcing building codes in Iran as well as in other countries. Furthermore, it considers the violation of earthquake-resistant construction norms in cities and rural areas worldwide which are at risk, as a major source of concern and risk and therefore calls for a zero tolerance of such a violation.

The Alliance is committed to encourage that part of post-Bam national and international aid for the reconstruction be used for long-term risk mitigation projects and activities. The Alliance stands prepared to provide technical advise to the Government and the Steering Council for the reconstruction of Bam.

The Alliance affirms the need for incorporation of components from ethic, science and education to culminate in a preventive culture as an integral part of disaster risk reduction strategy. This techno-ethic in its turn relies on techno-legal concepts.

The Alliance emphasizes that a coordinated approach should be systematically pursued in the design and implementation of the *UN* international initiatives related to risk reduction, as well as those involving specialized non-governmental entities, capitalizing and building on national capacities. The Alliance believes that a partnership of this kind could provide opportunities to *UN* Agencies and Bilaterals to make use of state-of-the art knowledge and experience gained from the post-Bam earthquake recovery and reconstruction into the developing country programme facing similar situations.

Vision

The Alliance affirms the following principles for action:

- Expanding scientific and applied research, technical infrastructures and capacities for implementa-

tion of an effective risk mitigation action;

- Reduction of risk of all types of structures, lifeline and infrastructure; especially low-cost traditional buildings, and ensuring that the future constructions are seismically safe;
- Enhancing the level of disaster preparedness by increasing public awareness and promoting collective prevention;
- Developing initiatives for the mitigation of earthquake risk in the rural areas with emphasis on the provision of realistic, doable, affordable, simple methods and methodologies.

2. Goals

The short-term goal is to provide useful contribution to: (i) a successful, rapid, and cost-effective recovery in Bam; (ii) the process for achieving an earthquake-resilient Bam with due consideration given to the social, cultural and economic aspects of the region; and (iii) the facilitation of the acquisition by *IIEES* of laboratory and other technical facilities to enable the Institute to meet growing challenges inherent to the process.

The long-term goal is to enhance disaster prevention and mitigation in towns and cities at risk as a national agenda to be adopted and pursued, making all new construction earthquake-resistant and implementing measures to reduce the vulnerability of the existing human and physical environment.

3. Partnership Activities and Initiatives

3.1. Post-Bam Earthquake Investigation and Restoration of Bam:

- Post-earthquake scientific and technical studies and investigations (earth sciences, water, environment, engineering) with a view to produce a comprehensive and authoritative publication on lessons learnt from the earthquake and guidelines for reducing future losses in similarcases. This publication will capitalize on the different findings from various post-earthquake reconnaissance and investigation missions that have been done on Bam.
- Promote the development and establishment of a "prototype facility" including a "prototype" school and a hospital using advanced technology such as base isolation, adapted to the culture, traditional architectural fabric and urban morphology of Bam.
- Contribution to the restoration of the 'Arg-e-Bam citadel" and other cultural heritage properties in the Historic City of Bam to protect the cultural identity and authentic characteristics of Bam.

3.2. Long-Term Earthquake Risk Mitigation

The Alliance should ensure that assistance is provided for the implementation of the following projects for earthquake risk mitigation:

- Implementation of a seismotectonic project through detailed investigations of active faults in the high hazard zones;
- Implementation of comprehensive seismicity studies and enhancing the capability of the Iran National Seismological Network (*INSN*) and the provision of a mobile seismological observation equipment.
- Implementation of seismic hazard zonation and microzonation studies for the most vulnerable inhabited areas;
- Implementation of a geotechnical microzonation project devoted to important cities;
- Activities on enhanced application of the integration of both traditional and new building technologies to be promoted in cities and rural areas at risk;
- Promoting activities related to the seismic safety of schools and educational institutions;
- Implementation of projects toward the seismic safety of lifelines and special structures, in order to prevent technological related disasters;
- Integration of seismic safety considerations into the work related to the restoration and strengthening of cultural heritage;
- Implementation of joint pilot projects focusing on integrating earthquake risk prevention in educational programmes at all levels;
- Implementation of pilot projects on the socio-cultural and economic aspects of earthquake risk mitigation in areas at risk and on aspects related to social behavior and public policy;

- Implementation of an appropriate techno-ethical and techno-legal regime for the enforcement of building codes and standards toward the effective implementation of risk reduction.
- Establishment in *IIEES* of a *UNESCO* Chair *UNITWIN* Programme on research and applications related to the assessment and mitigation of earthquake risk;
- Implementation of annual courses on "Aseismic Design and Construction of Structures" in IIEES for the benefit of the countries in the region;
- Preparation of a Report on above efforts to be presented during the *UN* World Conference on Disaster Reduction in Kobe, Japan, January 2005.

Bam Declaration and Recommendations

International Workshop on the Recovery of Bam's Cultural Heritage

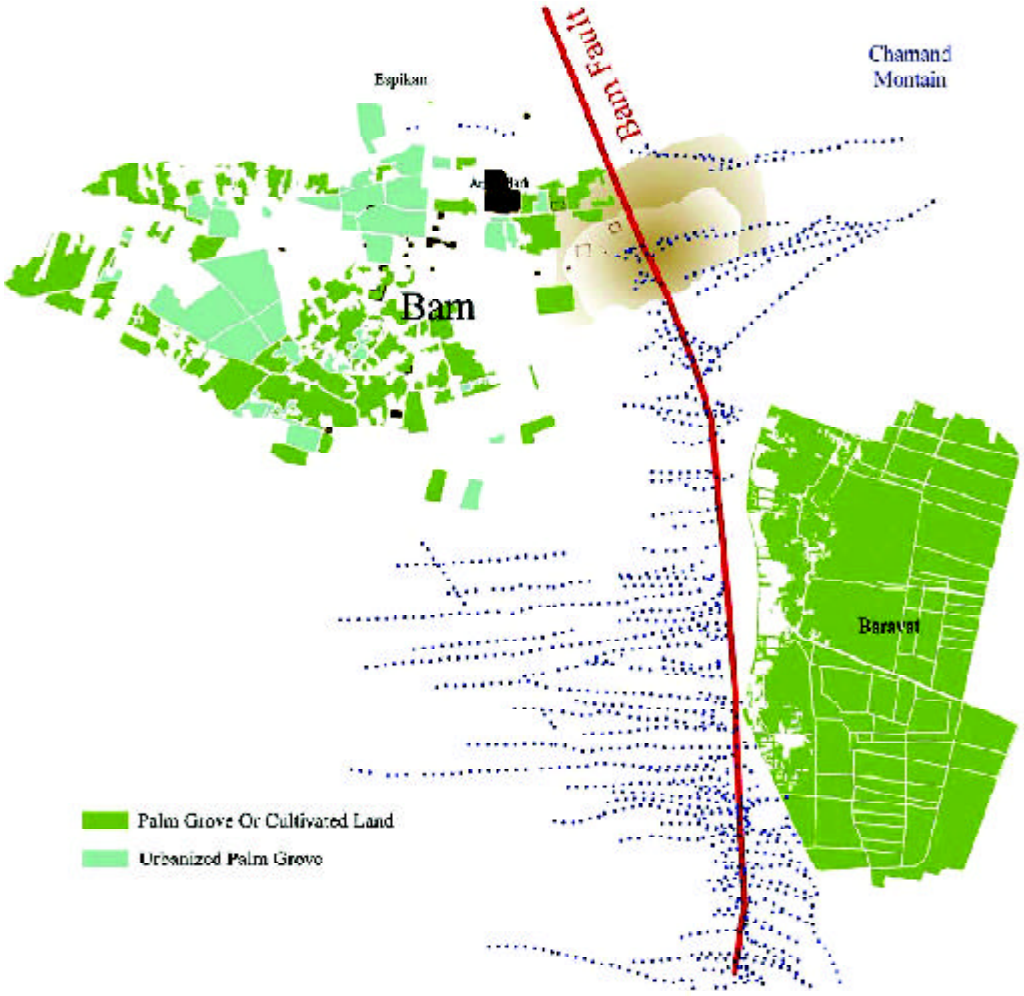
(17-20 April 2004, Bam, Islamic Republic of Iran)

1. Preamble

The devastating earthquake of 26 December 2003 in the historic desert city of Bam, Islamic Republic of Iran, caused the tragic loss of many lives and the destruction of an overwhelming part of its cultural heritage. This natural disaster stirred a strong sense of solidarity in the international community for the people of Bam. This wish to aid was also particularly strong amongst institutions and professionals in the conservation of cultural heritage.

On the occasion of the International Day of Monuments and Sites (18 April), the Iranian Cultural Heritage Organization (*ICHO*), the United Nations Educational, Scientific, and Cultural Organization (*UNESCO*), and International Council of Monuments and Sites (*ICOMOS*) organized an International Workshop for the Recovery of Bam's Cultural Heritage between 17-20 April 2004 in Bam. 38 international and 23 Iranian expert participants and representatives of local and national authorities, and 31 *ICHO* members, gathered from Canada, France, Germany, Iran, Italy, Japan, Peru, Spain, the United Kingdom and the United states of America, as well as representatives the Governments of France and Italy, International Centre for Earth Construction-Ecole d'Architecture de Grenoble-(CRATerre-EAG, France), the Getty Conservation Institute, World Monuments Fund, the International Centre for the Study of the Preservation and the Restoration of Cultural Property (*ICCROM*), *ICOMOS*, the World Bank, and *UNESCO*.

The workshop participants examined and reflected on the impact of the earthquake on Bam's heritage, notably Arg_e Bam and its related properties, the architecture and heritage assets which characterize this unique city, strategically located on the fringe of the desert;



pedagogical usage should be given priority. The appropriate cultural contexts and technological infrastructures can be instrumental in the dissemination strategies in this stage of implementation.

9.3 The urgent creation of a fund by *UNESCO* for streamlining assistance to Bam's heritage was recommended.

Finally, the participants of the Workshop expressed their deep appreciation to the Iranian Cultural Heritage Organization and the Iranian authorities, *ICOMOS* and *UNESCO* for jointly hosting and organizing this timely and important workshop. Furthermore, gratitude was expressed to the Government of Japan, *UNESCO* and its World Heritage Committee, and the World Bank, for their generous technical and financial assistance to realize this Workshop, and to the Governments of Canada, France and Italy, the Getty Conservation Institute, and the World Monuments Fund for their technical cooperation. Adopted in Bam, Iran, on 20 April 2004.

Distinguished reviewer of the papers in the JSEE special issue on Bam Earthquake.

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Editors would express their deep appreciation for their kind and Valuable cooperation in reviewing the papers within the time constraint in order to make this special issue to be printed on time, 7 month after the Bam earthquake.

GENERAL INFORMATION

SCOPE

Journal of Seismology and Earthquake Engineering is a quarterly journal that provides a forum for the publication of original papers in four general areas of Structural Earthquake Engineering, Seismology, Geotechnical Earthquake Engineering, and Seismotectonics. The editor's policy is to include at least one paper on each of the aforementioned topics as well as providing a balance between theoretic and design oriented contributions in each journal issue.

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4. Each paper should be provided with an abstract of about 100-150 words, reporting concisely on the purpose and results of the paper.
5. The SI system should be used for all scientific and laboratory data; if in certain instances, it is necessary to quote other units, these should be added in parentheses.
6. Tables, references and legends to illustrations should be typed on separate sheets and placed at the end of the paper.
7. Mathematical expressions and equations should be clearly printed. Particular care should be used in identifying unusual symbols or notations and to upper or lower case letters. Awkward mathematical notations and nonstandard symbols should be avoided.
8. References to published work should be numbered sequentially in order of citation and given in the text by a numeral within brackets, with a reference list, in numerical order at the end of the paper. Some examples are given below:

Books

5. Berberian, M. (1995). *"Natural Hazard and the First Earthquake Catalogue of Iran. Vol. 1: Historical Hazards in Iran Prior to 1990"*. IIEES, Tehran, Iran

Reports

10. Kaynia, A .M. (1993). "Stochastic Response of Pile Foundations", IIEES Report No. 72-93-2. International Institute of Earthquake Engineering and Seismology, Tehran, Iran.

Journal Articles

12. Miller, R.K., Masri, S.F., Dehghanyar, T.J., and Caughey, T.K. (1988). "Active Control of Large Civil Structures", *J. Engr. Mech., ASCE*, **114**(3), 1542-1570.

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