THE BAM, IRAN EARTHQUAKE OF 26 DECEMBER 2003

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Abbreviations:

BHRC	:	Building and Housing Research Centre of Iran
EEFIT	:	Earthquake Engineering Field Investigation Team
EERI	:	Earthquake Engineering Research Institute
EMS-98	:	European Macroseismic intensity Scale of 1998
GMT	:	Greenwich Mean Time
GSI	:	Geological Survey of Iran
IAEE	:	International Association for Earthquake Engineering
ICG	:	International Centre for Geohazards
ICHO	:	Iranian Cultural Heritage Organization
IFRC	:	International Federation of Red Cross and Red Crescent
IIEES	:	International Institute of Earthquake Engineering and Seismology
IRCS	:	Iranian Red Crescent Society
OFDA	:	Office of US Foreign Disaster Assistance
MHUD	:	Ministry of Housing and Urban Development
Ms	:	Surface-Wave Magnitude
Mw	:	Moment Magnitude
RC	:	Reinforced Concrete
UNFCCC	:	United Nation Framework Convention on Climate Change
UNOCHA	:	UN Office for the Coordination of Humanitarian Affairs
USAID	:	US Agency for International Development
USGS	:	United States Geological Survey

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1 Introduction

1.1 Preamble

A large earthquake with a magnitude of Mw=6.6 (USGS[3]) struck the city of Bam, located approximately 1000km southeast of Tehran, at 05:26:56 local time (01:56:56 GMT) on Friday 26th December 2003. The earthquake destroyed most of Bam city and the nearby villages and according to the latest estimates the official death toll exceeded 26,000 with more than 30,000 injuries and 75,000 left homeless.

After the earthquake a field investigation was organised by Halcrow Group Limited. as part of its commitment to improving our understanding of the hazards presented by natural disasters. The author of this report, a member of the Special Structures group within Halcrow, undertook a field investigation from 11th to 17th of January 2004. The mission started in Tehran with the author attending a joint meeting of EERI's 'Learning From Earthquakes' team, sent to investigate the Bam earthquake, and members of International Institute of Earthquake Engineering and Seismology (IIEES). The author then spent the next three days in Bam city and the surrounding areas. This report is primarily based on the observations made during this visit, though data from other sources is also used to enlighten the discussions and to provide supplementary information.

The earthquake was strongly felt in the provincial capital of Kerman, about 190km (120 miles) Northwest of Bam, however the main damage from the earthquake was limited to a relatively small area near to Bam city, within a 20-30 km radius. In the Bam area the majority of the buildings that suffered extensive damage were of one or two storeys construction and were built from mud bricks or other masonry materials.

This earthquake highlighted the particular vulnerability of other cities in this earthquake region and in general the built environment in Iran. The dramatic scale of the casualties associated with a relatively small affected region underlines the fact that urgent measures need to be taken to safeguard the increasingly urbanised population from the real risk posed by future earthquakes.

1.2 Scope of Investigation

The main purpose of this investigation was to visit the earthquake stricken region of Bam to record and comment upon the causes of the various types of damage observed in the buildings and other structures and to determine what lessons can be learnt from this earthquake. This report also provides supplementary data on the seismological and geological background of the region and briefly touches on socio-economical effects of earthquakes.

1.3 Overview of observations

The fact that the earthquake occurred at 5:26am local time on a Friday morning during the Iranian weekend when most people were asleep in their homes provides one of the main reasons for the high death toll. At the time of the visit the search and rescue efforts had already finished although many families were still looking for missing relatives and in many places bulldozers were still working to remove rubble and debris. Most of the survivors were living in tents provided by the various aid agencies. At Bam city centre there was a scene of devastation with the majority of buildings reduced to small hills of rubble, blocking alleyways and preventing easy passage. Fortunately, the main streets due to their greater width were reasonably clear though covered by a thick layer of dust.

The earthquake damage was concentrated in Bam where the total number of people directly affected was estimated to be approximately 200,000. Few buildings survived without major damage and one of the main losses in the earthquake was a major cultural heritage site and the world's largest mud-brick structure, known locally as Arg-e Bam (Bam citadel), which suffered extensive damage. In addition to mud-brick buildings which suffered effects ranging from severe damage to total collapse, many other types of buildings also exhibited similar degrees of extensive damage. This can be attributed to the poor materials and construction that are common features of these structures. The few buildings whose performance was satisfactorily in the earthquake were of a superior design and construction, among these some steel structures with braced frame lateral load resisting systems.

The main hospitals in the city were all severely damaged and out of service following the earthquake and other critical facilities such as the main fire station also suffering collapse. Although there was no significant damage to the main routes into Bam a few hours after the earthquake access to the city became practically impossible as a consequence of people, trying to assist the relief effort, travelling by car from other neighbouring cities creating traffic grid-lock.

The agro-economic losses to the city were also significant since the Qanats, which are ancient underground irrigation systems and the main source of agricultural water for Bam's world-famous date trees, were severely damaged and the water in many of them was no longer conducted.

The extensive damage suffered by Bam contrasts strongly with small satellite towns and cities such as Baravat, a small city less than 5km to the east of the Bam (see Figure 18 for the location), that suffered much less extensive or serious damage.

2 Geological and Seismological Features

2.1 Regional Tectonic

The Iranian plateau is part of the major Eurasian plate with the tectonic setting of the region dominated by the collision of the Arabian, Eurasian and Indian plates (Figure 1). The Arabian plate is moving northward against the Euroasian plate at a rate of approximately 30 mm/year with deformation of the Earth's crust taking place across a broad zone 1000 km wide, that spans the entire region of Iran and extends into Turkimanestan in the Northeast of Iran [3]. Earthquakes occur as a result of both reverse faulting and strike-slip faulting within the zone of deformation.

Convergent movement between the Eurasian and Arabian plates is accommodated by the Zagros ranges along the boundary of the colliding plates. This takes place in the form of rising mountains in conjunction with fault movements at depth within the earth. However, because of the diffuse nature of this deformation (i.e. simultaneous movements along a number of sub-parallel faults over a wide area) the intensities of these tremors are generally low. A different regime is seen in the interior parts of Iran. In the Central-East area strike-slip movements are the dominant deformation pattern. In contrast to that of the Zagros Thrust zone, seismic activity associated with central Iranian faults is sporadic being much more localized and occurring with significantly higher magnitudes. Similar mechanisms are responsible for large magnitude earthquakes in other regions of the country [9].

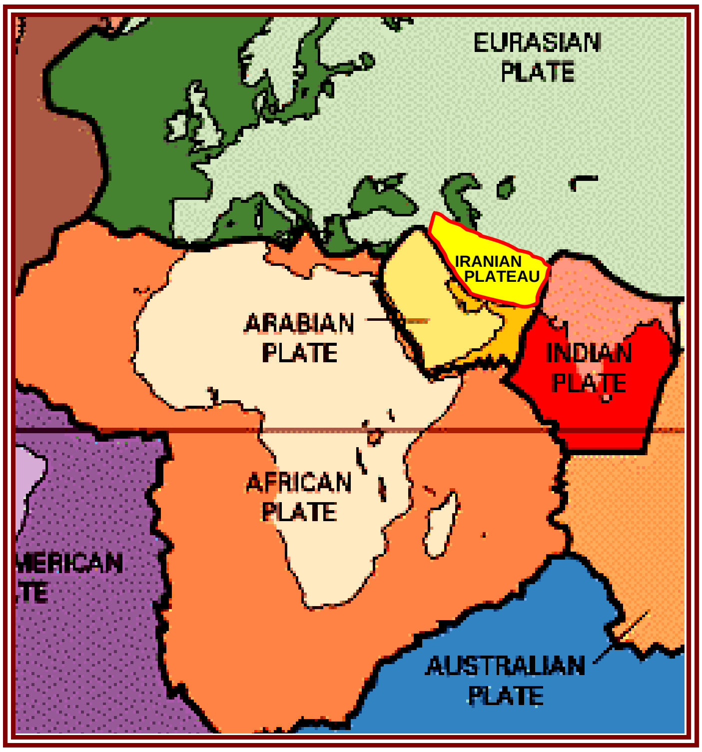


Figure 1: Tectonic setting of the region

2.2 Geology of Bam region

The Bam area is part of the Lut-e-Zangi Ahmad desert that has hot summers with temperatures up to 50 ^{o}C and winters with below freezing temperatures. The geomorphology of the region also includes a range of mountains to the North of Bam extending northwest and also the Jebal-e-Barez mountain range to the Southwest of Bam extending in a Northwest-Southeast direction. Water sources within these mountain ranges are the main suppliers for the Qanat system in Bam, Baravat and their satellite villages. The seasonal Posht-Rood river that flows to the North of Bam city is dry during much of the year.

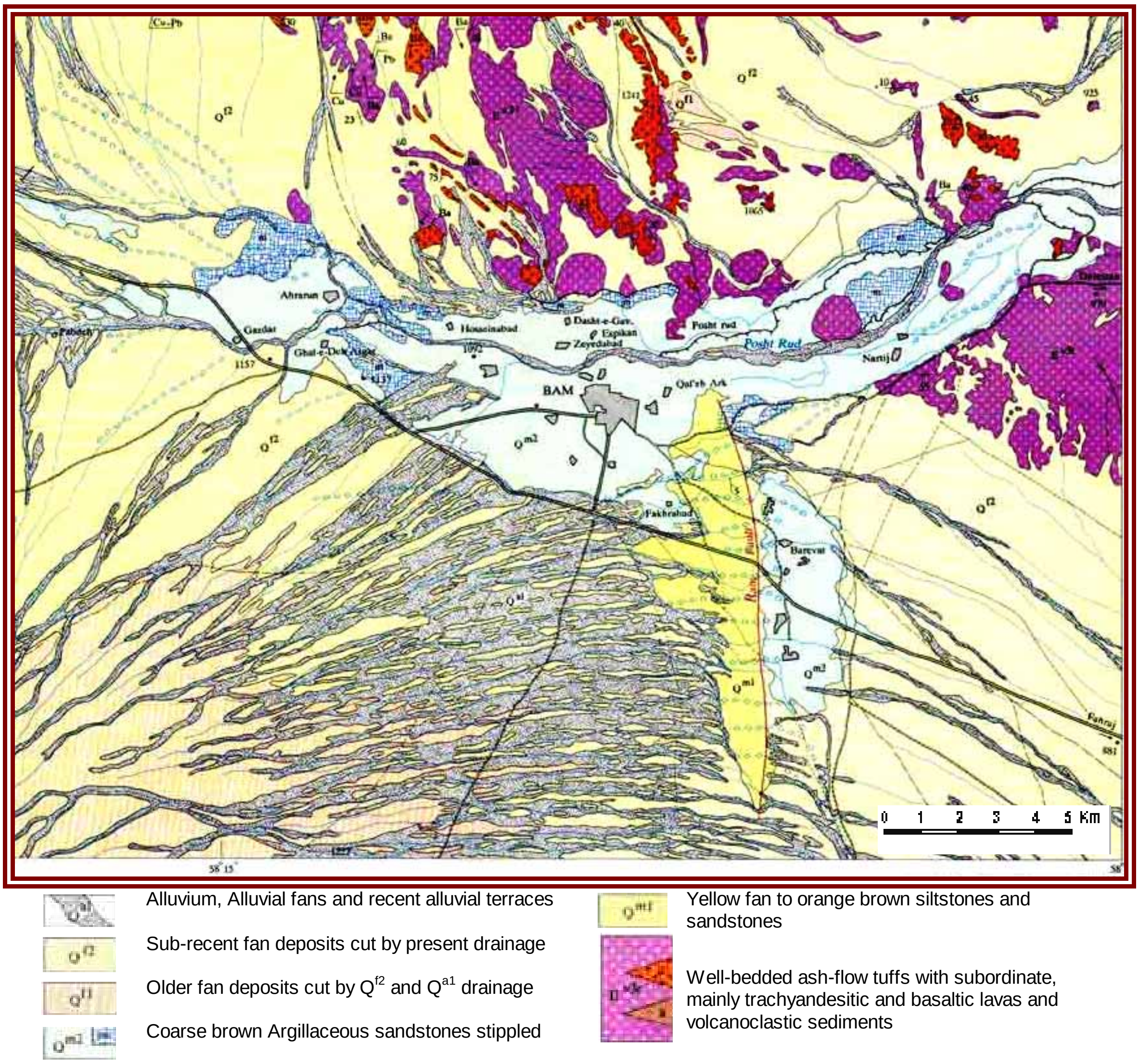


Figure 2: Regional geology of Bam city (The limits of the map are about 58.14-58.30E and 29.00-29.12 N)

The geology of the region is dominated by lithologies ranging from recent Quaternary alluvium to Eocene volcanic rocks [4]. Figure 2 shows the geological map of Bam and its vicinity based on 1:100,000 Bam geological map sheet published by Geological Survey of Iran (GSI) [10]. As can be seen Bam and Baravat and surrounding areas are covered by coarse brown sandstone deposits. The northeast area of the Arg-e Bam is founded on tuff and traciandesite rocks while other parts are built on alluvial deposits [11]. The thickness of alluvium in Bam varies between 0 and 30m. The main tectonic feature in the area is the Bam fault that can be identified on the geological map, between Bam and Baravat, along the line separating older fans (Q^{m1}) from younger sediments (Q^{m2}).

2.3 Historical seismicity of the region

In the central east area of Iran deformation from tectonic activities takes place along faults, which have predominantly North-South and Northwest-Southeast directional trends. Although no major historical or recent earthquakes have been reported near Bam or along the Bam Fault, northwest of Bam and within a range of 150km there have been several destructive earthquakes during past 30 years. The major faults in this region include the Nayband fault with a North-South trend, the Kuh Banan fault which trends Northwest-Southeast and the Gowk fault that starts at the junction of the two aforementioned faults and trends in a North-South direction towards the Jebal Barez mountains in the

Southwest of Bam, as shown in Figure 3. In the past 20 years five earthquakes on an 80km section of the Gowk fault system have been associated with strike-slip surface ruptures [7]. The total length of the Gowk fault is about 16km that is topographically marked by a narrow linear valley that joins several deep depressions along the border between the Kerman plateau and Dasht-e-Lut.

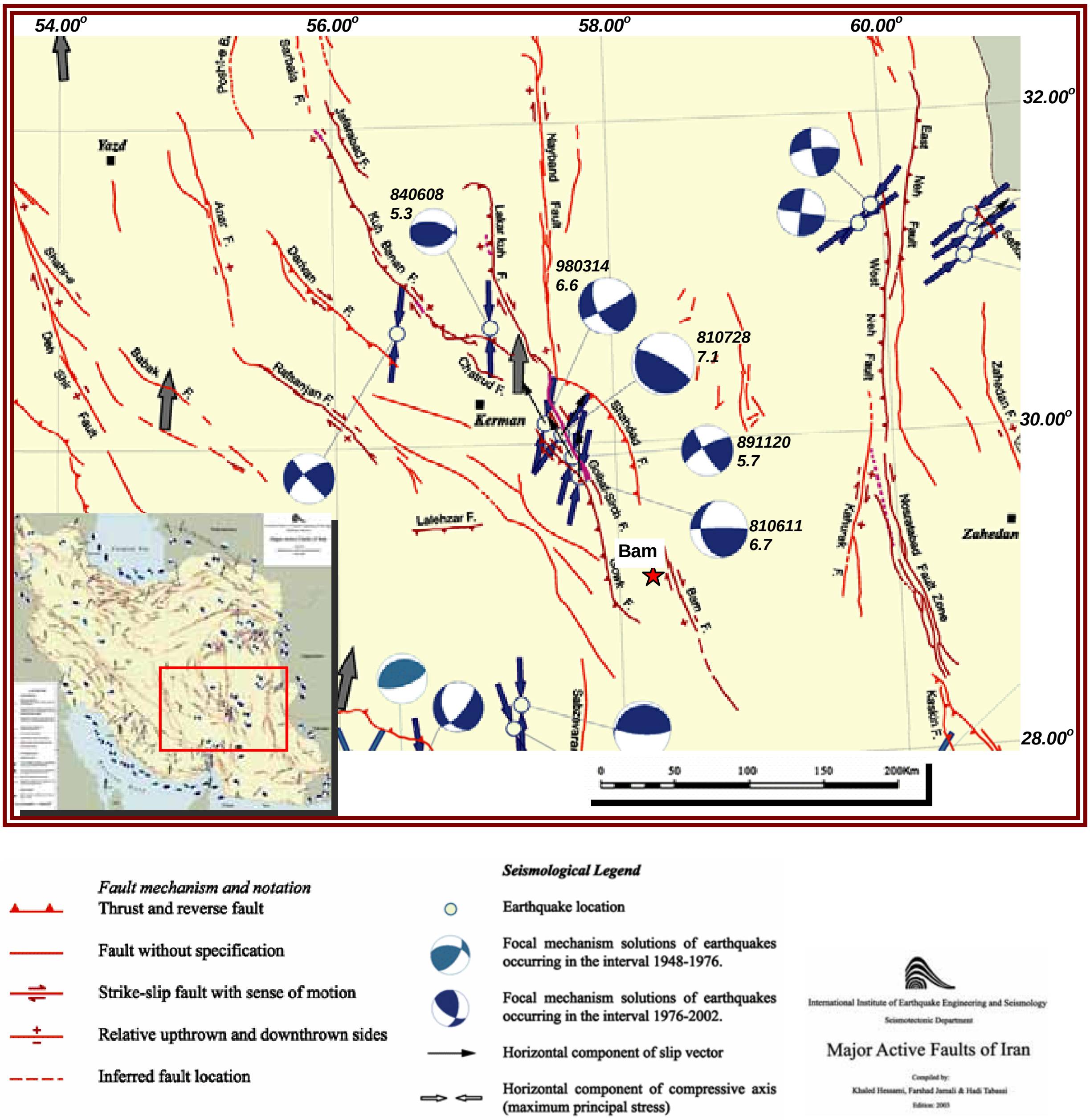


Figure 3: Regional seismology of Bam city (Courtesy of IIEES [5], The dates and magnitude of the earthquakes have been reproduced from references [6] and [7])

Five major earthquakes in recent years are shown in Figure 3 of which four are associated with the Gowk fault. The Golbaf Earthquake (1981) (M_w 6.6) destroyed Golbaf City and surrounding villages with 1100 deaths and more than 4000 injured and produced a 15km surface rupture. This earthquake was followed a month later by the Sirch Earthquake (1981) (M_w 7.1) with 65km of discontinuous surface ruptures that destroyed Sirch and the surrounding villages with approximately 1300 deaths. The lower magnitude South Golbaf Earthquake (1989) (M_w 5.8) had much reduced consequences with 4 deaths and 45 injured and was associated with an 11km surface rupture. Similarly the Fandoga (north Golbaf) Earthquake (M_w 5.4) was associated with 5 deaths and about 50 injured and ruptured along a 20km section in northern Golbaf [1,2,7].

There are also historical earthquakes reported in the region: The Sirch-Hassan-abad 1877 earthquake (M_s 5.6), about 130km Northwest of Bam, destroyed many villages in Sirch, Abgarm and Hashtada, the Laleh Zar earthquake (1923) (M_s 6.7) that killed 200 and the Golbaf earthquake (1949) (M_s 6.0) [2].

2.4 Recorded Ground motions

The Iranian strong ground motion network consists of around 1000 digital instruments dispersed around the country. Out of the 78 instruments within a 300km radius of Bam, the main shock of the Bam earthquake was recorded by at least 24 instruments. The specifications of the stations and their recorded accelerations are reported in Table 1. The maximum uncorrected accelerations recorded at Bam station (58.35E, 29.09N) were 0.82g, 1.01g and 0.65g in the longitudinal (East-West), vertical and transverse (North-South) directions, respectively. The recording instrument was located on the ground floor of two-storey Governor's office building in Bam and importantly has recorded a ground motion very close to the epicentre. Despite severe damage experienced by the building (see Figure 38) there was only minor damage in the room where the instrument was located, as reported by BHRC[11]. Uncorrected ground accelerations for the main shock recorded in Bam station are shown in Figure 4. These records show severe vertical and fault normal accelerations in Bam city with maximum corrected accelerations of 980 and 778 cm/s^2 corresponding to a peak ground velocity of 124 and 40 cm/s and a peak ground displacement of 34 and 8 cm, all respectively for horizontal fault-normal and vertical components [11]. The duration of the strong motion based on Evolution of Arias Intensity with 5 to 95% evolution was about 8 seconds for the fault-normal component [12]

STATION	Dist-ance (Km)	Geographical Coordinates		Uncorrected PGA(cm/s/s)			Epicenteral Distance		Station Altitude m	Station Azimuth	
		E	N	L	V	T	NEIC	IGTU		L	T
Bam	0	58.35	29.09	799	989	636	10	14	1094	278	8
Abaraq	49	57.94	29.34	171	88.8	111	54	47	1644	72	162
Mohamad Abad	49	57.89	28.9	124	70.7	71.4	44	60	1961	350	80
Jiroft	76	57.74	28.67	40.3	31.8	28.3	68	88	275	240	330
Joshan	136	57.6	30.12	25	17.5	36.6	143	127	1650	142	232
Andoohjerd	139	57.75	30.23	32.1	14.9	34.4	148	130	851	200	290
Sirch	146	57.55	30.2	31.1	14.6	29.7	153	137	1685	30	120
Golbaf	107	57.72	29.88	30.8	13.7	29.5	114	99	1698	150	240
Kerman2	181	57.07	30.28	19.2	8.32	30.6	187	175	1755	140	230
Kerman1	184	57.04	30.29	18.8	9.4	25	190	178	1767	175	265
Qale Ganj	181	57.87	27.52	21	14	25	171	195	439	210	300
Nosrat Abad	178	59.97	29.85	19.8	13.2	23.9	185	168	1115	284	14
Kahnooj	143	57.7	27.94	23.5	9.24	18.6	133	157	556	20	110
Cheshme Sabz	192	56.42	29.46	23.4	9.15	11.1	192	194	2581	65	195
Rayen	104	57.44	29.59	21.5	23	18.1	108	102	2195	334	64
Shahdad	160	57.69	27.52	20.5	8.49	13.6	169	150	515	78	168
Bardsir	195	59.97	29.85	19.8	13.2	23.9	199	194	1115	284	14
Mahan	149	57.29	30.06	12.7	7.87	13.2	155	143	1864	150	240
Lale Zar	157	56.81	29.52	13	8.04	12	158	158	2822	65	155
Ravar	284	56.79	31.26	12.5	6.15	12.6	292	275	1244	320	50
Zarand	257	56.05	29.42	12.2	6.4	12.6	263	250	2088	145	235
Horjand	210	57.15	30.67	6.68	6.04	12.2	226	229	2320	110	200
Bolvard	226	56.05	29.42	10.1	3.83	10.5	226	229	2088	145	235

Table 1: Records of Main shock of the Bam earthquake 26 December 2003 from Iran Strong Motion Network [11]

The earthquake epicentre has been reported by the United States Geological Survey (USGS) to be located at 29:00N-58.34E, about 185km Southeast of Kerman [13]. This implies that the epicentre of the earthquake was only a short distance from Bam (29:09N-58.35E) and to the South of the City. The focal depth of the earthquake is reported to be about 7km (BHRC [11]) to 10km (USGS [13]). Studies by Talebian et al [15] based on interferograms derived from coseismic satellite maps suggest that the fault responsible for the Bam earthquake was a blind strike-slip fault located about 5 Km to the west of the visible surface traces of the Bam fault. Accordingly the causative fault extends beneath the Bam City from the south.

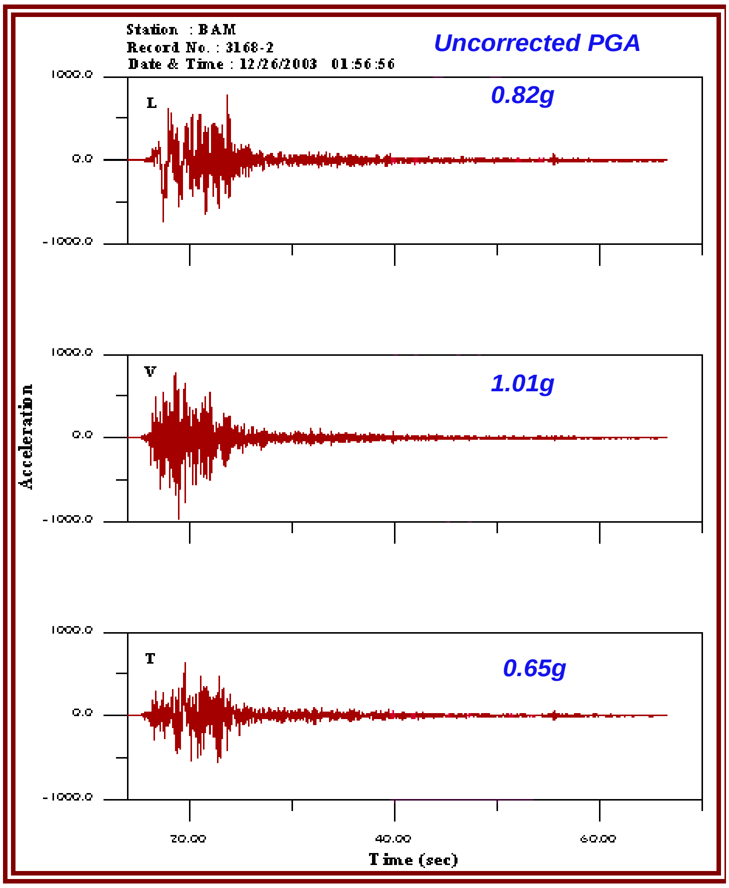


Figure 4: The accelerographs for the main shock of Bam earthquake recorded in Bam station [11]

A pre-shock was recorded in Bam station about 53 minutes before the main shock. This pre-shock had a maximum horizontal acceleration of 0.017g and maximum vertical acceleration of 0.08g, with an estimated depth of 10km. The pre-shock was sufficiently strong that a small proportion of the population (according to survivors of the earthquake) took precautionary measures by staying out of their homes.

More than 60 aftershocks were recorded in the 6 days following the main shock. Bam digital instruments functioned for up to 1 hour and 20 minutes after the earthquake, until running out of memory, and managed to record 9 aftershocks. The largest aftershock happened about one hour after the main earthquake with a magnitude of 5.3. Another aftershock with a magnitude of 4.6 was recorded about 12 hours after the main shock at the Mohammad-Abad and Abaragh stations. About 30 hours after the main shock another instrument was installed by BHRC in Bam. This instrument recorded 5 aftershocks with magnitudes ranging between 3 and 4 during the 5 days following installation [11].

From Table 1 it can be seen that the recorded peak ground accelerations rapidly attenuate as the distance from the epicentre increases. This can be seen in terms of the macroseismic intensity distribution in Figure 5.

3 Overall Damage Pattern

Damage from the Bam earthquake was mainly concentrated in Bam City and the surrounding villages. Strong motion attenuation in the East-West (i.e normal to Bam fault) direction was significantly higher than in the north-south direction. An estimate of population directly affected by the Bam earthquake is shown in Figure 5,where a comparison of earthquake intensity and the population density, within a radius of 100km from the epicentre, is also depicted. This intensity is shown based on European Macroseismic intensity Scale of 1998 (EMS-98) with a total affected population estimated to be 145,500 [14]. Figure 5 shows that most of the population centres other than Baravat and Bam's satellite villages (less than 10km from Bam city) fall beyond the high intensity zones which correlates well with damage observed during field observations. For instance, severe damage was seen inside Bam City, Esfikan village (North of Bam) and Khaje-Asgar village (immediately Northwest of Bam), while much less damage was seen in Nartij village (about 8km Northeast of Bam). Also the damage in the town of Baravat which is virtually connected to Bam at its east edge was moderate.

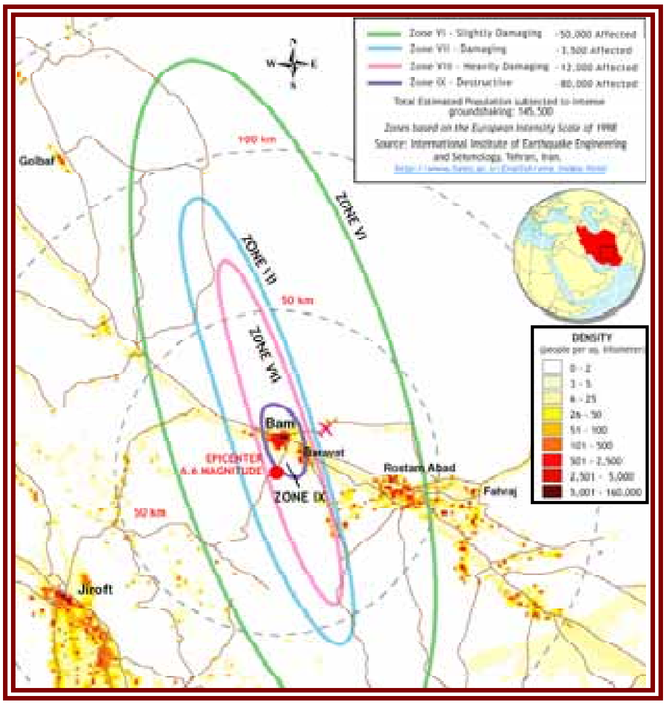


Figure 5: Macroseismic intensity and estimated affected population [14]

The following subsections present an overall view of the distribution of earthquake damage including ground failures and damage to lifelines.

3.1 Ground movements

Ground failures and deformations were not significant in the Bam Earthquake. Ground movements were observed at the intersection (see Figure 6) of the Bam fault and Bam to Baravat main road that runs almost normal to the fault (see Figure 2). However, these movements were generally small and produced only surface cracks on the road and on the adjacent ground on either side.

Other minor surface ruptures have been reported in the south of Bam, some 5km west of Bam fault in Figure 6, and also in the north of Bam [15].

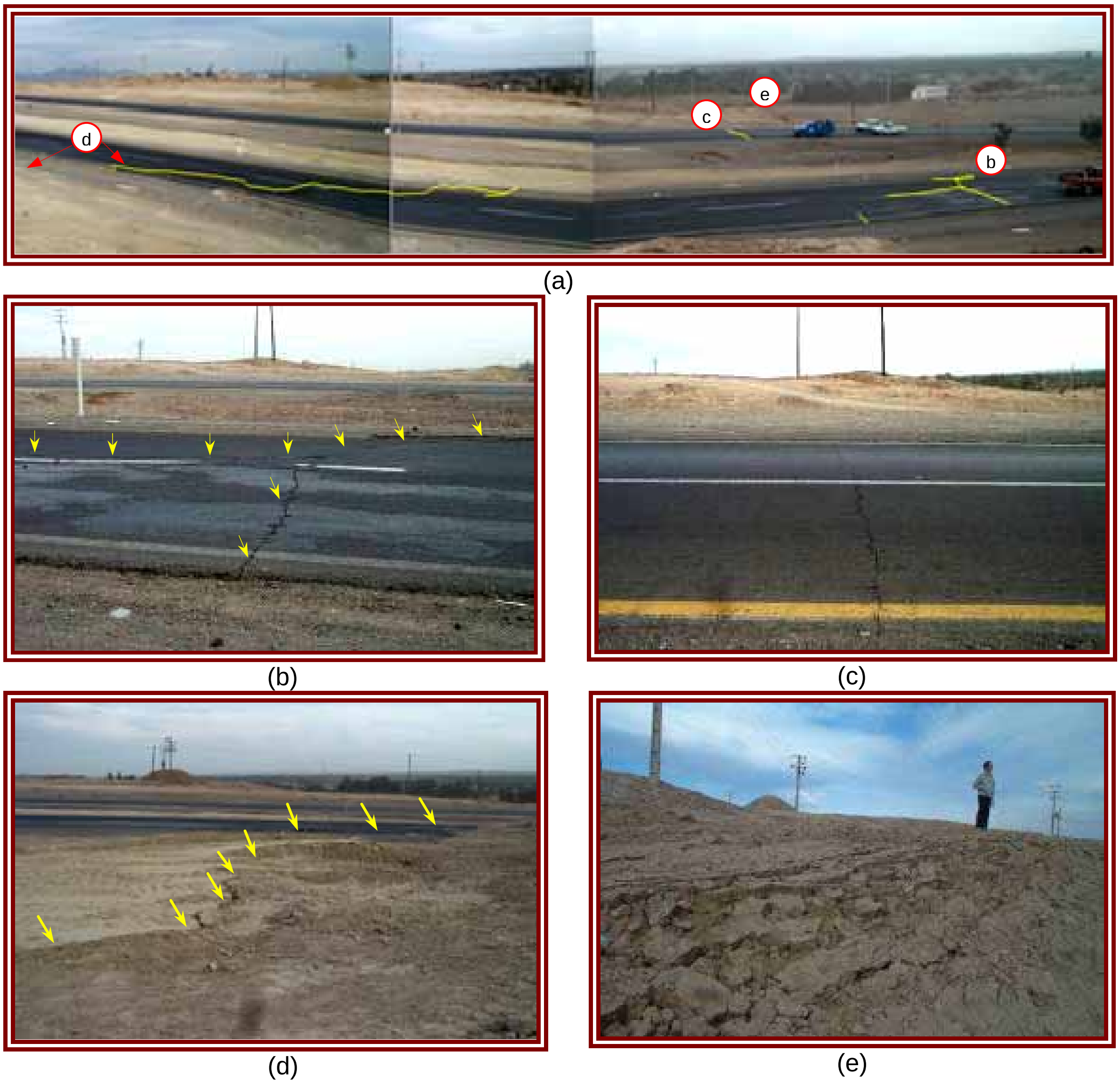


Figure 6: Ground movements along the Bam fault on the Bam-Baravat road and nearby ground (a) panoramic view on Bam-Baravat road from south with cracked areas highlighted (b), (c) Close up view of cracks in south and north band of the road (d) Cracking in the ground on the south side of the road (e) a shattered zone of fissures on the north side (Yellow lines and arrows show the location of cracks)

3.2 City of Bam

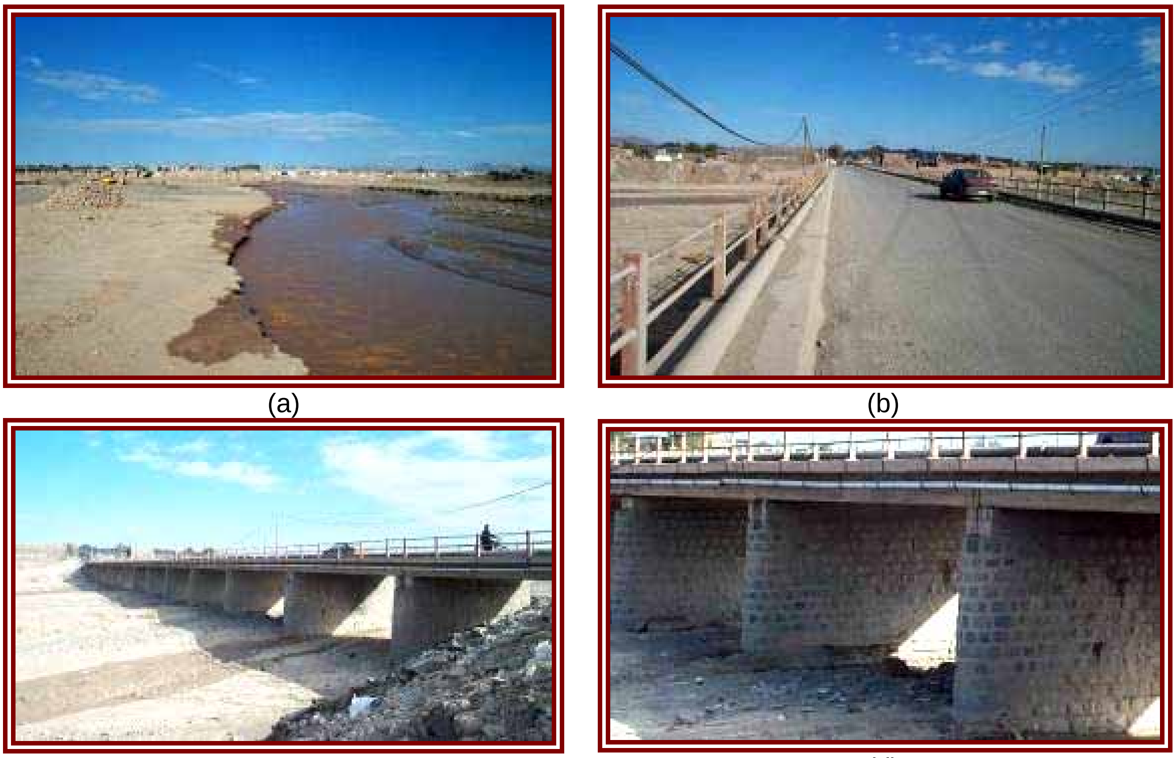
In overall terms the damage observed in the city of Bam varied depending upon location and building construction. The damage was very severe in the old part of the city in the Northeast and around Bam Citadel where the construction was dominated by adobe type building structures. Severe damage was also observed in newly constructed parts of the City in the Southeast. The aforementioned areas were densely populated while most of the Southern and Western parts had dual land use with many so called 'garden-houses' with palm trees planted in large courtyards. The damage in these latter areas was comparatively low, varying between 30% and 70%. More details of buildings behaviour are given in section 5.

3.3 Lifelines

Lifeline infrastructure in the earthquake stricken region and within the city of Bam performed reasonably well during the earthquake, with the exception of the Qanats, a traditional irrigation system, which suffered severe damage. The damage to roads, bridges, railway and airport was minor.

The new railroad to Bam passes the city to the South with the main station located about 25km from Bam and under construction at the time of the earthquake. There was no damage to the tracks or the station.

Figure 7 shows the main bridge in Bam which provides access to the satellite villages to the North of the city. Minor cracks on roads appeared near to the fault zone as seen in Figure 6. However, in the city itself, many streets and most of the alleys were blocked after the earthquake due to debris from the damaged buildings.



(a) (b) (c) (d)

Figure 7: Posht Rood seasonal river (a) and the main bridge in the north of Bam (b-d). No sign of damage to the bridge was observed. The pipeline beneath the deck (c,d) was displaced in a couple of points while the main pipeline on the deck appeared to be intact (b).

Damage to the airport building is shown in Figure 8. Part of the facade on the top of the building and sections of the false ceiling collapsed and cracks on the walls were observed outside and inside of the building. The airport was out of operation for a few hours after the earthquake due to damage to the airport control tower but later played a major role in the rescue and relief operations. Many flights from inside and outside the country landed in the airport in the early days after the earthquake.

Power transmission, electricity and telecommunication networks, and water distribution system also suffered minor damage. Figure 9 shows one of the main telecommunication towers in Bam. Many electricity poles within the city were damaged due to the collapse of adjacent buildings, however at the time of the visit the electricity had been restored. There were also reports of damage to the wells, underground water storage tanks and pipelines providing water to the city. Some elevated water tanks were observed standing with only minor damage to their columns.

Figure 8: Bam Airport: Damage to the airport building in form of cracks and partial failure of non-structural fixtures. The first two rows show views from the outside of the building with the bottom row showing the inside of the building.

3.3.1 Qanats

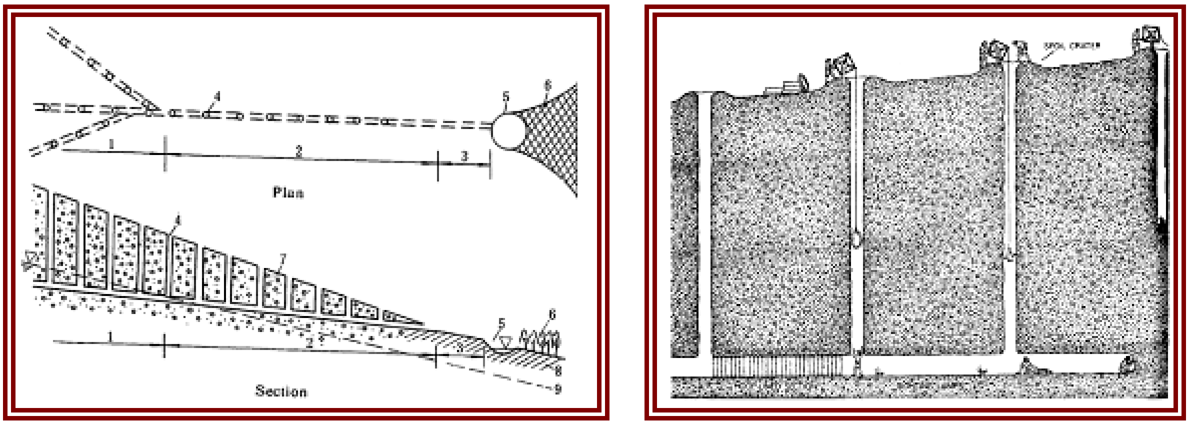
Some 3,000 years ago the Persians learned how to dig underground aqueducts that would bring mountain ground water to the plains. From Persia the technique was exported to neighboring countries. Nowadays, *qanat*s can be found in Japan, China, Central Asia, and Pakistan, and westwards to North Africa, Spain and even South America.

Figure 9: One of the main telecommunication towers in Bam which survived the earthquake

Qanats are subterranean tunnels that tap groundwater and lead it to human settlements and agricultural lands under gravity. The system consists of a tunnel that is intersected at regular intervals with hand dug airshafts that provide oxygen for the diggers and cleaners who maintain the channels. The advantage of qanats is that they provide continuous water flow when operated, and although subject to seasonal fluctuations, the system is reliable for long periods. They provide a sustainable technique for extracting groundwater without exhausting the water storage in the ground and played a tremendously important role in the spread of irrigated agriculture and the establishment of sophisticated settlements in dry areas [16].

A schematic view of various components of a qanat and its construction procedure is shown in Figure 10.

Before 1950s qanats were providing 70% of the water supply in Iran. Since then their role has been reduced by the introduction of modern water supply methods such as deep wells and large dams. As a result qanats were meeting only 10% of the water demand in Iran in year 2000 [20]. However in some regions such as Bam, the qanat system still plays a substantial role in the socio-economic life of the people of the region.



(1) Infiltration part of the tunnel
(2) Water conveyance part of the tunnel
(3) Open channel
(4) Vertical shafts
(5) Small storage pond
(6) Irrigation area
(7) Sand and gravel
(8) Layers of soil
(9) Groundwater surface

Figure 10: Qanats: ancient water supply systems. Schematic view of qanat's components and its construction procedure [18]

Qanat chains can easily be spotted on aerial photos, and even satellite images, by a row of small circular holes, each one the top of an access shaft. A chain of qanats in the northwest of Bam city is shown in Figure 11, using an image from the IKONOS Satellite.

Before the Bam Earthquake on 26 December 2003, there were more than 120 qanats in the Bam region. Of the 65 qanats supplying water to Bam's world-famous date gardens, 25 experienced some local collapse and subsequently dried up. The remaining qanats suffered damage approaching 40 to 50% in the form of collapsed access shafts and underground tunnels and closure of open channels due to the collapse of walls and surrounding buildings. Even 42 days after the earthquake only 3 qanat chains were repaired with water flowing again. At this time there were reports stating that it would probably take another three to four months to repair the rest of the qanats [19]. The agro-economic effect on the Bam region was therefore particularly severe due to dependency on agricultural products such as dates.

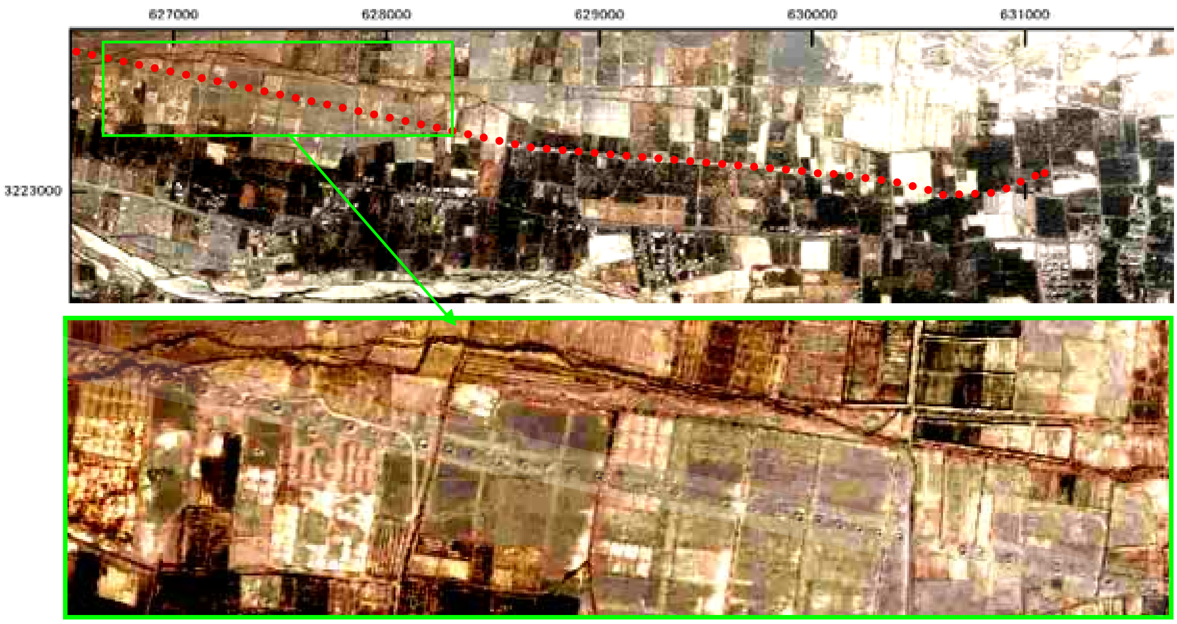


Figure 11: A chain of qanat in the northwest of Bam city (dotted line in top picture) as imaged by IKONOS Satellite on 27 December 2003, and an enlarged part (bottom picture) where the openings of the access shafts are visible

Figure 12 shows an active qanat in Bam and in Nartij village in northeast of Bam and a dried qanat in Baravat at the time of visit to the region.

Figure 12: (a,b) An active qanat in Bam city showing the outlet below a residential building standing after the earthquake (c,d) an active qanat in Nartij village, northeast of Bam, (e-h) A dried qanat in Baravat with outlet to an open channel, distribution point, access facility at street level and the access shaft further up in a nearby field (i) Access Shaft for an old qanat near Nartij Village

3.4 Other effects

Despite the fact that the most of the area near to Bam has a high proportion of loose sand and silt deposits there were no reports of damage due to liquefaction after the earthquake. This can be attributed to the low level of ground water in most parts of the region. Some evidence of liquefaction was however reported by IIEES to the north and northeast of Bam, near a river bed. The latter was based on aerial photos taken two days after the earthquake [4].

Some minor effects from landslides in the form of separated earth blocks and falls in dry natural drainage channels were observed in southeast of Bam and near to Baravat (Figure 13). Most of the banks of these natural drainage channels are already cracked due to the hot climate and are prone to separation or slide failures.

Figure 13: A minor landslide and a fall in southeast of Bam, near to the Bam-Baravat main road

4 Damage to Arg-e-Bam

4.1 Historical background

Arg-e-Bam (Bam Citadel) is the oldest and largest mud-brick structure in the world and thought to be around 2000 years old. The complex is located in the Northeast of the modern city and historically was the old city of Bam, partly inhabited until 180 years ago. The Arg was built out of clay, mud brick, straw and trunks of palm trees at the foot of a huge rocky outcropping and is surrounded by a rampart, consisting of 38 towers, and deep trenches that provided an effective defensive barrier against possible attack.

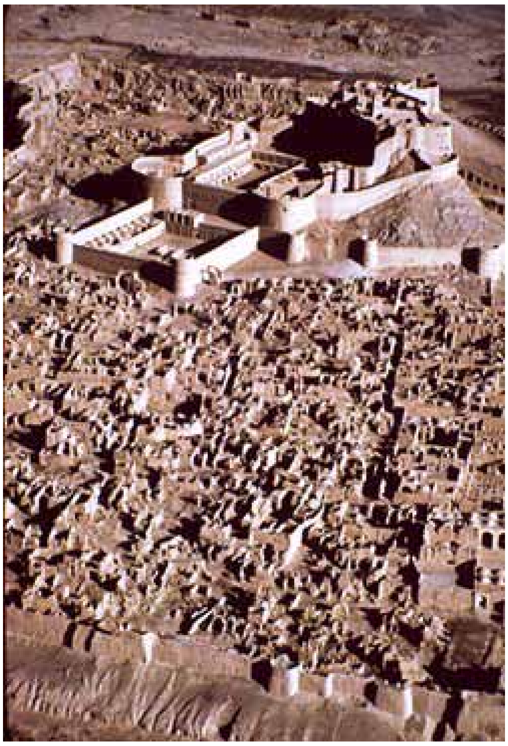


Figure 14: Aerial photo from Arg-e-Bam before major repair in 1977 (courtesy of www.argebam.ir [21])

The complex covers an area of about 200,000m^2 and incorporates three specific sections (Figure 15). The first section is the largest and was used for residential buildings, shops and public places. The second section that was surrounded by a second set of walls was the military section and provided a secure base and accommodation for higher rank military personnel. The third section located on the higher ground in the north of the complex was separated from the military section by another inner wall. This latter area was the official residence of the governor of the Arg and had five stories [23].

Since 1973 routine repairs were conducted on Arg to conserve this magnificent ancient mud brick structure and before the earthquake on 26 December 2003 it had become one of the most popular tourist destinations in the southeast of Iran. Figure 14 and Figure 16 show some views of the Arg-e-Bam before the earthquake.

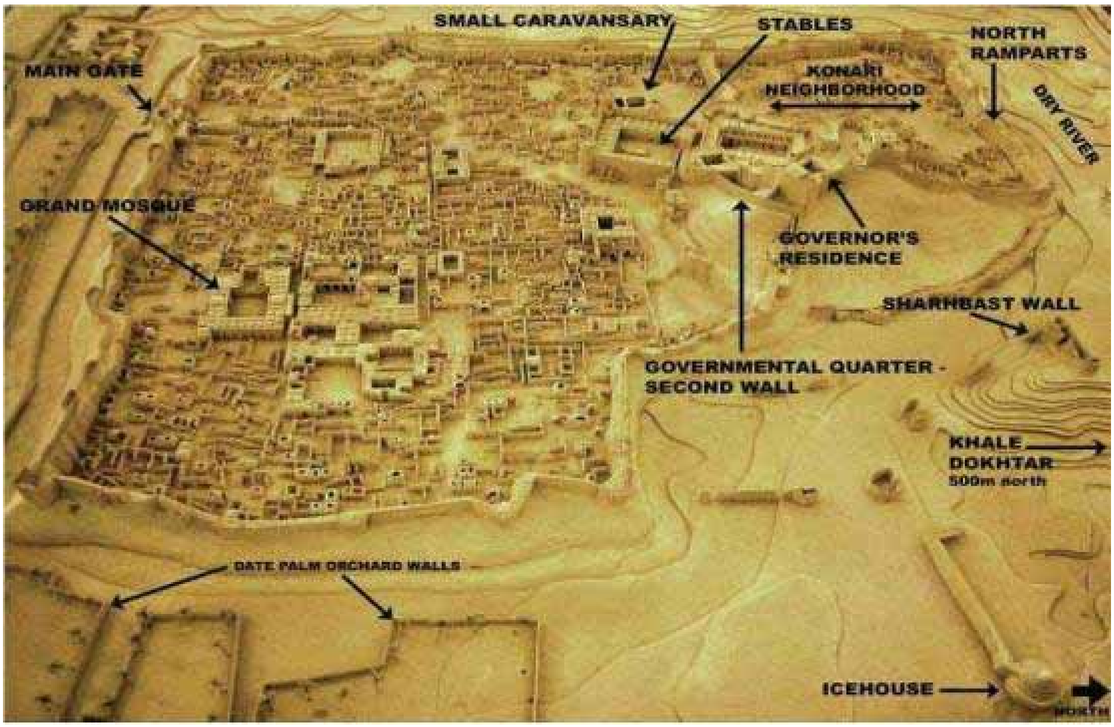


Figure 15: Iranian Cultural Heritage Organization (ICHO) Model of the Arg-e Bam prior to the earthquake (adopted from Langenbach, 2004 [21])

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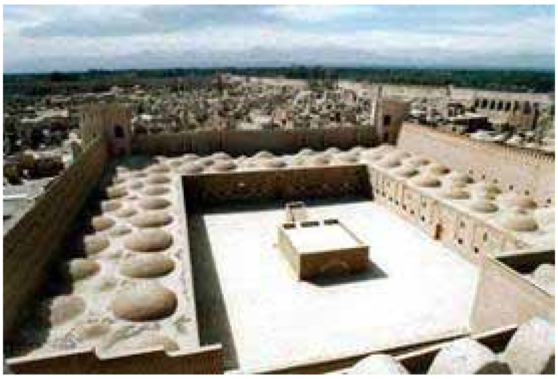
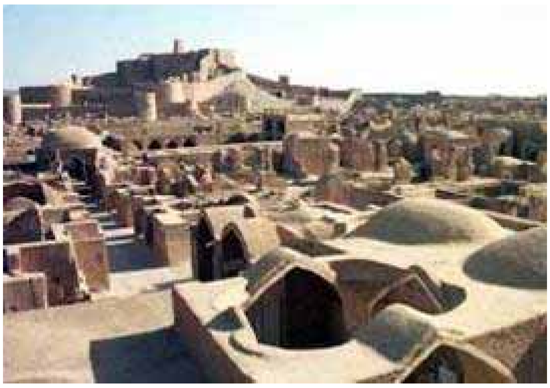
Mashgh Square



Stables

General view



General view

Figure 16: Arg-e-Bam before Bam Earthquake ([23],[24])

4.2 Damage extent

Visiting the site shortly after the earthquake gave a shocking insight into the extent and scale of the damage to Arg-e Bam. Approaching from the Southwest, some parts of the external walls of the complex were reduced to rubble, barely resembling the shape of the original construction. By climbing on top of their remains one could clearly see the complex's debris filled courtyard. For someone who had not visited the site before the earthquake, but knowing that the Arg had been a main tourist attraction in the region, it was clear that major destruction had taken place. However the full extent of the destruction only became clear by reference to earlier photographs, such as those in Figure 16, which are a testament to the Citadel's magnificence and grandeur prior to the earthquake.

When the earthquake struck during the early hours of the morning, only two guards and a conservator were in the complex. Only the conservator survived. Since most of the structure collapsed it is clear that the death toll would have been much higher if the earthquake had occurred during daylight hours when many more people would have been working or visiting the site.

Despite the known weaknesses of unreinforced adobe construction under large earthquake forces, the causes and the type of damage observed at Arg-e Bam have yet to be studied in depth. The fact that this structure had been standing undamaged for around 2000 years has been taken by some [1, 22] as evidence that the Bam region had not experienced any earthquake of a similar intensity to the Bam earthquake during this period. However, initial conclusions from some other studies indicate that the extensive conservation operations undertaken in recent years prior to the Bam earthquake, might have contributed to the extent of the damage experience by the original structure. Langenbach [21] notes that "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". Figure 17 shows damage to Arg-e Bam after the Bam earthquake.

Due to the historical importance of Arg-e Bam, restoration studies have been started. It is anticipated that seismic resistant considerations will play a major role in any restoration plan with recent studies [25] in other parts of the world providing valuable recommendations and guidance on improving the seismic performance of adobe construction. However because of its unique architectural characteristics and cultural value, special seismic studies would appear to be inevitable for Arg-e Bam.

Main entrance to Arg (south view)

West wall from outside

West wall from outside

View from the top of west wall to main courtyard

View from southwest to governmental sector

Close up view of governmental sector

Figure 17: Damage to the Arg-e-Bam after Bam Earthquake

5 Performance of building structures

5.1 Introduction

The Bam earthquake is by far the most devastating earthquake in the history of the region around Bam. Located at a relatively short distance from the epicentre Bam city experienced particularly intense local ground shaking with peak ground accelerations of 0.8g and 1.0g recorded for the horizontal and vertical components, respectively. Despite the enforcement of seismic code provisions in the region, many of the building structures were too old for their construction to be controlled by modern prescriptive standards. However due to the rapid growth of the population and rural to urban migration in the whole country during the last two decades, a significant proportion of the new building stock should have been designed and constructed taking account of the seismic requirements in the Iranian codes.

It is well known that the building construction practice in Iran and more specifically in small cities like Bam has been poorly regulated and monitored. There is clear evidence of this from the observations made after the Bam Earthquake. The widespread total damage to the majority of newly constructed buildings in the private sector contrasts strongly with the more limited damage to the few structures, mainly in the (well-regulated) public sector, that remained standing. This strongly suggests that poor construction practice played a major role in the vast destruction and high death toll within the city.

In the following subsections the seismic regulations in Iran are briefly discussed followed by a summary of observations made during the three day visit to Bam. No systematic approach was adopted to scan the damage extent in all areas; instead a combination of spot checks was undertaken on the different type of damage experienced by various buildings that form the bulk of building stock, accompanied by a walk through tour of the most devastated part of the Bam city. In addition to the Bam and Baravat cities, other major sites visited included Bam airport, New Arg and some of Bam's satellite villages to the North. Figure 18 shows the locations of these sites.

5.2 Seismic regulations and codes

Following the Buein-Zahra Earthquake of 1st September 1963 which killed more than 12000 people, the first Iranian regulations for seismic design appeared in the guideline "Seismic Safety Code for Building" published by the then Ministry of Housing and Reclamation in 1967. The seismic load calculation procedures for this code were subsequently published as "Standard No. 519, minimum loads for buildings" by the Planning and Budget Organization giving mandatory minimum loading standards for new building structures.

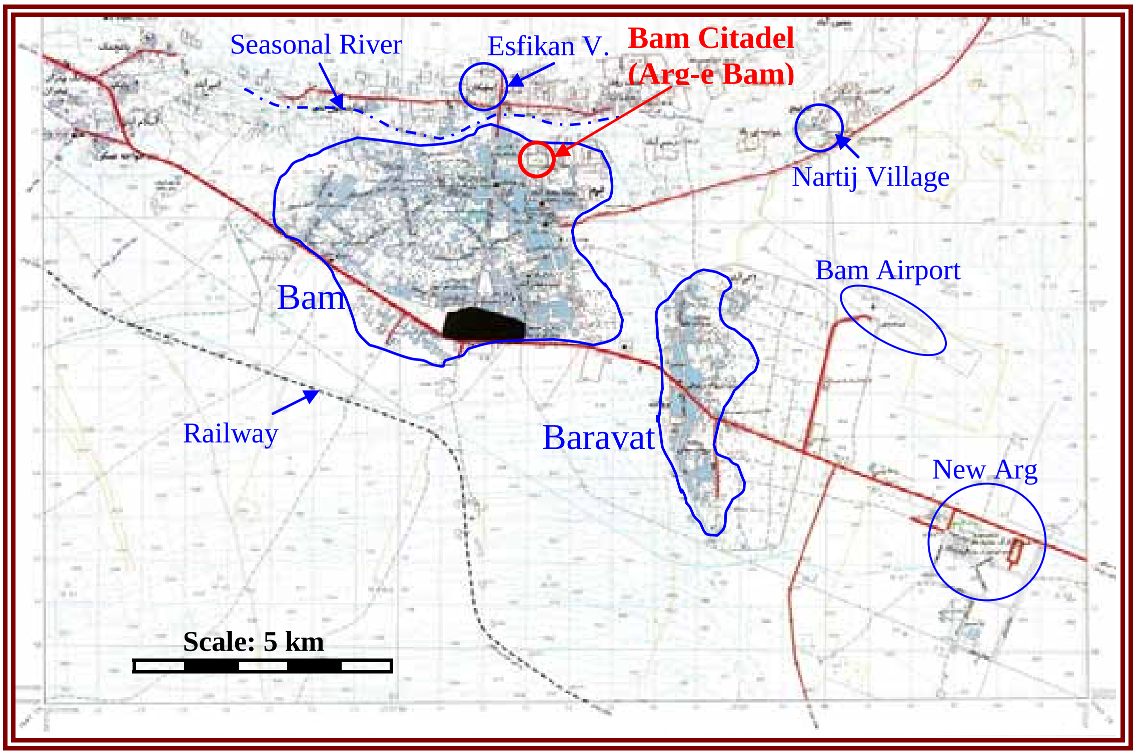


Figure 18: Relative location of the main visit sites

The first edition of the current "Iranian Code for Seismic Resistant Design of Buildings, Standard No. 2800" [26] was published by the Building and Housing Research Centre (BHRC) in early 1988 and since then has contained the official requirements for seismic design in Iran. The second edition was published in 1999 while the third edition is currently under final review for publication [27].

The current Iranian code [26] is published in three chapters and six appendices. The first chapter defines the general applicability criteria, classification of the structures in terms of their importance, form and structural system and also gives general design recommendations. Chapter two sets down rules for calculation of seismic loads and applies to all types of building structures except unreinforced masonry which is covered in chapter 3.

The code intent is to provide a level of seismic resistance for buildings such that they can resist low and medium earthquakes without any considerable damage to their structural system and withstand strong earthquakes without collapse. The design earthquake is defined as the one with less than 10% probability of occurrence in a 50 year period. For structures with high importance or those higher than 50m or having more than 15 stories a serviceability level earthquake also needs to be considered. This is defined as one with more than a 99.5% probability of occurrence in a 50 year period.

Generally the code excludes special structures such as dams, bridges, piers, marine and nuclear structures. Of special interest for this report, the code also excludes traditional structures made from mud bricks or clay and recommends that this type of construction should be avoided. However it recognises that in certain rural areas, where other materials are unavailable or uneconomical, this type of structure may be acceptable if provisions for seismic safety of such buildings based on special guidelines are followed. The code provisions are outlined below.

Minimum horizontal base shear is calculated based on equation 1:

$$\mathbf{V = CW} \qquad (1)$$

V: Base shear force (total seismic lateral forces in direction under consideration)
W: Total weight of the building (total dead load and weight of fixed installations) plus some of the live load
C: Seismic coefficient obtained from equation 2:

$$\mathbf{C = ABI/R} \qquad (2)$$

A: Design base acceleration (in terms of gravitational acceleration g)
B: Response coefficient of the building obtained from the design response spectrum and is calculated based on equation 3:

$$\mathbf{B = 2.0(T/T_0)^{2/3} < 2.5} \qquad (3)$$

T is the fundamental period of vibration of the building, and
T_0 is a coefficient dependent on the type of soil. For soil type IV in seismic zones 3 and 4, the value of B from equation 3 should be increased by 30%, but does not need to be more than 2.5.
I: Importance factor
R: Behaviour factor for the building (4<R<11, depending on the type of lateral load resisting system)
In calculating C in no condition should the B/R ratio be taken as less than 0.09.

The vertical component of the earthquake is only considered for balconies and cantilever parts of the structures. The main parameters for calculation of design base shear are given in Table 2.

Design Base Acceleration			**Characteristic period T_0**		**Building importance factor**		
Zone	Seismic Risk	A (g)	Soil	T_0	Group	Importance	I
1	Very high	0.35	I	0.4	1	High	1.2
2	High	0.30	II	0.5	2	Medium	1.0
3	Medium	0.25	III	0.7	3	Low	0.8
4	Low	0.20	IV	1			

Table 2: Main parameters for calculation of design base shear in Iranian Seismic Resistant Design Code (Standard 2800 [26])

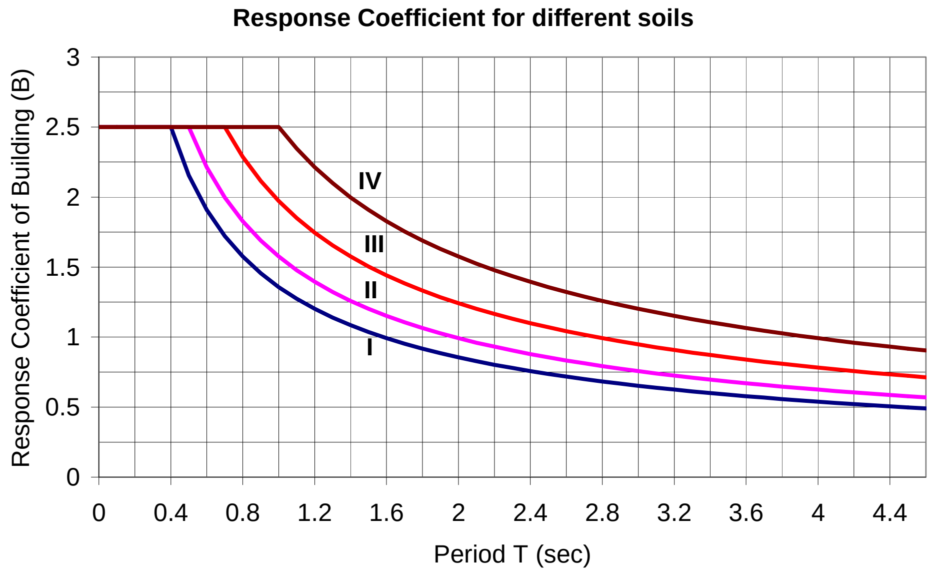


Figure 19: Response (spectral) coefficient of buildings in Iranian Seismic Resistant Design Code (Standard 2800 [26])

Chapter 3 of the Iranian seismic design code deals with un-reinforced masonry buildings that are built with fired bricks, concrete blockwork or rock with the number of storeys limited to 2. Horizontal ties are required for all buildings at two levels; firstly at the base level of all walls, these should be reinforced concrete ties, and secondly at the roof level, where the ties can be reinforced concrete or a standard steel section. Vertical ties are required for all building with two stories or those defined in the high importance category. Vertical ties are also required for one story buildings with medium importance in high and very high seismic zones. The maximum spacing for vertical ties should be less than 5m. Chapter 3 excludes reinforced masonry structures where the masonry material and reinforcing bars are used to resist compression and tension, respectively. Reinforced masonry is covered by code requirements in Chapter 2.

5.3 Building construction practice in the region

There are a number of factors affecting building construction in the Bam region such as cost, climate requirements and the availability of suitable materials. Types of construction range from mud-brick and adobe structures, fired brick masonry structures to reinforced concrete and steel structures. In terms of normal building practice, private homes are built by their owners who hire the builder and unskilled labour. There are no requirements for the registration of builders or contractors for these buildings and as a result there is no adequate system to prosecute negligent builders. However there is legislation in place requiring the production of construction drawings, for the control of construction by authorised professionals and for final approval of drawings by local authorities prior to the start of the construction. Nevertheless, in real terms, there is little control on the construction process itself. The situation is better for government buildings or those housing projects built by government where higher levels of construction control are normally implemented with the winning contractor tending to employ more skilled labour.

5.4 Building damage

The most dominant structural systems in the Bam region are:

- **Adobe buildings**: built from adobe materials and unfired mud bricks. Most of these building have a vaulted roof system.
- **Masonry buildings**: built from fired bricks or concrete blockwork as the main load bearing system and normally combined with a jack-arch roof system.
- **Steel structures**: Typical construction includes frame structures with steel beams and columns and sometimes a braced framing system to resist the lateral loads.
- **Reinforced concrete structures**: Only a limited number of these structures exist in Bam mostly used for public buildings or government offices.

Outside the city, in the villages and surrounding countryside, adobe and masonry buildings are the main structural types.

In the following subsections particular characteristics of various building types are discussed along with the various types of damage observed following the Bam Earthquake.

5.4.1 Adobe buildings

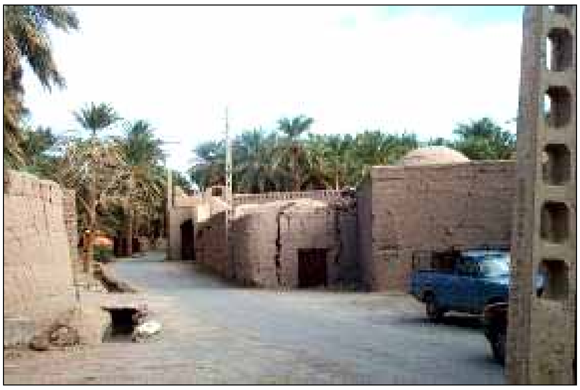
Adobe and mud bricks are one of the oldest and most widely used building materials in the southeast of Iran. The bricks that are dried in the sun are made of local clay, soil, mud and sand mixed with water and sometimes straw. The material is readily available and the construction practice is simple with the mortar and plaster consisting of the same material as the bricks. One of main characteristics of these traditional buildings, especially in the hot climate around the central and south-eastern deserts in Iran, is their domed or vaulted roof system. For these roof systems the final finished level may still be flat (see Figure 20). In this structural system thick and stiff walls provide the main load bearing system. During the past few decades there has been a substantial decline in the use of the mud brick construction in most urban and even rural areas, this is mainly due to the development of industrialised construction materials and methods. However mud brick buildings can still be found in large numbers in most of the cities, more specifically in the historical quarters, and remain the dominant architectural form in rural areas and villages.

Complex vaulted roof construction with flat finishing, resulting in a heavy roof

Double spanned vaulted roof sitting on thick walls*

Figure 20: An adobe building constructed from mud-bricks with a vaulted roof system. Flat and domed roof finishing has been used at different parts of the building (Bam City). Note that the fired bricks have been applied to form the facade in this traditional building.

In addition to mud-brick masonry construction there is another type of mud structure common in the Bam area locally known as "*Chineh*",that is used for the construction of walls. *Chineh* walls consist of layered clay which is specially prepared and cured by continuous massaging of the material by human feet, each layer being approximately 50 cm high (Figure 21). They have generally been used as garden or courtyard walls, but also in some locations as the main load bearing walls of residential buildings.



"*Chineh*" walls as part of courtyard wall (left) or bearing wall for houses (middle), Nartij Village

A man repairing his courtyard "*Chineh*" wall after the earthquake in Bam. The newly added layer can be distinguished by its darker colour.

Figure 21: "Chineh" (layered clay) construction in Bam region

From structural standpoint adobe structures are bulky and heavy. More importantly the roof can be very heavy due to the complex vaulted system, as seen in Figure 20, or due to additional weight accumulating by the application of insulating layers normally added every few years. Soil is a weak and brittle construction material and will disintegrate easily if subjected to strong vibration. Under seismic loads the heavy walls and roofs develop large inertia forces that cannot be resisted by walls often resulting in large cracks or collapse. Although the vaulted roofs perform well in transferring gravity loads, due to utilisation of mud bricks in compression, they are not well suited to transferring horizontal seismic loads or strong vertical seismic loads. The result is a sudden collapse of the structure with insufficient time for evacuation and a dusty atmosphere afterwards, further reducing the survival prospects for the victims trapped under the building. The majority of these buildings collapsed in the old district of Bam, leaving a flattened area.

Figure 22 to Figure 25 show damage to adobe buildings in the Bam earthquake observed at the time of visit. Severe damage to total collapse was seen in Bam city and Esfikan village while in Nartij village (see Figure 18 for locations) most of the buildings were standing with only moderate damage (Figure 21) with a smaller proportion suffering collapse (Figure 23). Although most of the buildings with vaulted roofs collapsed within the city, few had performed well and remained standing after the earthquake with only moderate damage. Vaulted roofs were also seen in fired brick masonry buildings, again in some cases with good performance. From those vaulted roof mud brick buildings that did not collapse it could be seen that most of the vault infills and end walls, perpendicular to the direction of vault axis, had collapsed. In some cases these infills and end walls were non-load bearing facade walls often made from fired-bricks and probably with a poor connection to the main structure (Figure 24). This suggests that the deformation mode of the vaulted roofs and their supports differs from those of the perpendicular walls, and the lack of a shear transfer mechanism between these two parts resulted in the separation and subsequent collapse of the walls.

Figure 25 shows damage to adobe buildings contrasted with that of modern masonry and braced steel frame structures in the old district of Bam. Though a relatively small number compared to all the building stock, there were many examples of these modern buildings which survived without collapse or even major damage. This shows that most of the lives in Bam city could have been saved, if good construction practice had been followed.

Figure 26 shows a good example of existing building practice in the city and lack of essential construction control. Apart from the poor materials adopted in the construction, the mixture of different structural systems has clearly contributed to the extent of damage.

Figure 22: Bam's old district, examples of total collapse of mud-brick buildings

Figure 23: Damage to mud-brick building in villages-(Rows 1 to 3: Esfikan Village, North of the Bam) 1st row: total collapse, 2nd row: Traditional sport facility (Zoor-Khaneh) with cracked domed roof, a collapsed mud-brick house and details of barrel vaulted roof, 3rd row a part of boys Guidance School, 4th row: damage in Nartij Village, northwest of Bam

Local shop buildings in Bam, near to Emamzadeh Ali Ebn-Hassan, with a barrel vaulted roof system. The buildings are standing but all facades, made from fired bricks introduced later and covering the front of the thick walls and roof have separated from main mud brick structure and collapsed.

Another example of adobe building with double spanned vaulted roof, standing after the earthquake showing damage to the fired brick facade

Adobe building damaged in old district of Bam city

Figure 24: Apparent weakness of vaulted roof structural systems in Mud-brick buildings

Figure 25: Damage to adobe buildings in contrast to other types of construction in the old district of Bam (left: a modern masonry building standing without major damage. Right: a steel structure with braced frame system with minor non-structural damage).

5.4.2 *Masonry buildings*

Masonry buildings constructed of fired bricks have become one of the most common construction methods in Iran since the early 1960's [28]. Masonry walls are the main load bearing structural elements, and more often than not, are combined with a partial steel frame consisting of a few columns in plan with steel beams spanning between the columns and walls. The most commonly used flooring system consists of steel joists (standard I beams) at approximately 1m spacing and fired brick jack-arches between the joists. This flooring system is also very common in steel structures. The other common floor system is one with the floor constructed from prefabricated reinforced concrete joists, about 50cm apart, with hollow bricks between the joists and an in-situ reinforced concrete slab topping (Figure 27). In central and south-eastern Iran fired brick vaulted roofs are also very common practice for the construction of masonry structures.

Figure 26: A combination of traditional and modern masonry construction materials and methods. Mud-brick walls (right) and fired brick walls (middle and left) has been extended in second floor by fired brick walls and vaulted roof (left) and jack-arch roof (middle). Second floor completely collapsed.

Since the introduction of modern seismic design codes in Iran, masonry buildings are now required to have horizontal and vertical ties (see section 5.2). The use of horizontal ties in Iran started in the 1960s and the use of vertical ties began in the 1970s [28]. However this practice took much longer to be implemented in rural regions such as Bam. Many of the older masonry buildings in Bam have been constructed without ties and even some buildings, constructed as recently as six months before the earthquake, were found to be without ties. Ties are required to connect various structural elements so that they can work together and maintain overall integrity under seismic action. For masonry structures without ties observed main failure types include: a) horizontal displacement of simply supported joists in jack-arch system resulting in collapse of arches between the joist (b) horizontal movement and slippage of the whole roof system on the walls resulting in total collapse of the building. In addition, poor material properties and workmanship were a common factor and a contributory cause to the damage experienced by many structures. Mortar materials used in older masonry buildings are lime-clay, lime-sand or lime-sand-cement. Although in more recent construction sand-cement is predominant, lime-sand is still used in some private houses.

Figure 27: Jack-arch flooring system in a steel frame structure (left) which is very common throughout Iran, and hollow brick-RC joist floor system in a masonry building the other common alternative (right). Pictures from Bam.

Figure 28 to Figure 32 show the damage to the typical masonry buildings without horizontal or vertical ties in Bam and Baravat. As a comparison Figure 33 to Figure 38 show the performance of those incorporating ties.

Figure 28: A residential masonry building without ties in Baravat in the same alleyway as Bagheri primary school in Figure 35. Construction finished about 6 months before the earthquake with a roof system of steel joists and brick arches with no structural system providing overall integrity. Heavy roof slippage over the walls resulted in collapse of walls and the whole structure. Poor materials and construction led to the collapse. The mortar used is lime-sand. Fortunately, the whole family escaped by being vigilant and sleeping outside after the initial pre-shock. Many other buildings of similar construction had completely collapsed in the same alleyway. Another example is shown in thelower right photograph.

Figure 29: Student's dormitory in Bam city centre. Many of the students were killed. The family is helping a student, who was injured during the earthquake, to collect her remaining belongings from a dangerously unstable building.

Figure 30: Razmandegan district of Bam. All the buildings in the district had recently been constructed, most of them consisting of masonry buildings with a jack-arch roof system without any ties. The majority of the buildings collapsed. In the building that can be seen standing in lower right corner photograph, horizontal ties could be clearly seen. This shows how proper construction practice could have made a difference to the outcome of this earthquake.

Figure 31: Kharazmi High school in Bam. Masonry building with a jack-arch roof system without ties that suffered total collapse.

Figure 32: Adab girls' school in Bam city centre. A typical example of masonry buildings with fire brick vaulted roofs. This building has a double spanned vaulted roof at two sides and a barrel vaulted roof in the middle. Both roof corners and most of the parapet on the end wall collapsed, but elsewhere the building survived without collapse. Also, damage to walls and roofs from the inside of the building, mainly in form of minor to large cracks, were observed.

Figure 33: Bonyad Maskan houses for teachers in Baravat. The buildings have vertical and horizontal ties. Some of the vertical ties were observed not to start from foundation level (top left). Walls surrounding the courtyard collapsed. Although the structure did not collapse it suffered structural and non-structural damage in the form of large cracks in the walls and the roof magnified by the poor quality of building materials and construction.

General view

Closer view

Details of poor martials and workmanship

Poor workmanship: Note the vertical bar that starts at one corner of the base and goes to opposite corner at top.

Concrete material no longer present in the vertical RC tie. Horizontal bars have also pulled out of horizontal RC tie.

Figure 34: Local market in Baravat, Masonry construction with vertical and horizontal RC ties. The longitudinal wall collapsed mainly due to the poor connection with the perpendicular walls and the very poor connection between horizontal ties at roof level. Note the poor quality of the concrete and construction of ties.

Figure 35: Bagheri Primary School in Baravat, One storey masonry building with ties. Standing without major damage. Parapets at the back of the building and a part of the surrounding wall have collapsed due to collapse of a building on the other side of the wall. Minor damage on inside walls.

Damage to the building viewed from outside

Damage observed from inside the building at the first floor level

Figure 36: Management office of Bam electricity: Masonry building with horizontal and vertical ties. Extensive damage to the walls in first floor with most of them showing diagonal or horizontal shear cracks. Damage at the second floor level was relatively minor and mainly non-structural. The rooftop staircase structure had collapsed totally due primarily to not connecting the beams to the middle column at second turning level. (further photographs on the next page).

Damage in second floor

Damage to staircase viewed from outside and inside the building

Details showing the poor concrete quality in vertical RC ties and generally bad workmanship

Figure 36: Management office of Bam electricity (continued from previous page)

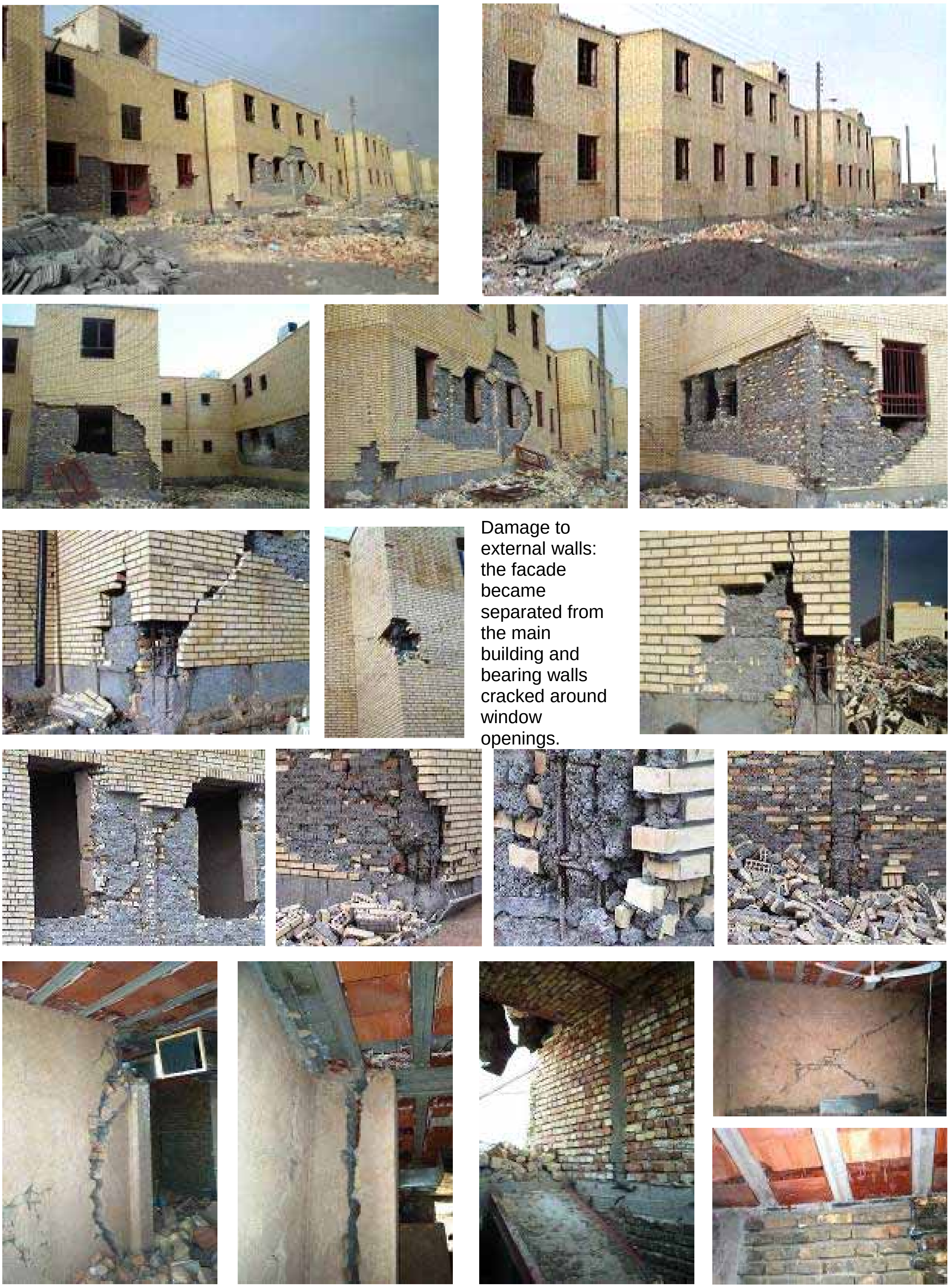


Figure 37: Housing and Urban Development Organization's new build to rent project in the southeast of Bam, about 1.5 Km west of the Bam fault line on the Bam-Baravat road. Most of the buildings suffered minor to moderate damage but some located in the east of the site were severely damaged. Most pictures in this collection are from a particular building showing severe damage. The buildings are of masonry type with horizontal and vertical ties and reinforced concrete joist-hollow bricks floor system.

Bonyad-Shahid masonry office building in Bam showing damage to parapets and inside the building. Overall moderate damage

Housing and Urban Development Organisation's Bam office. Another masonry building with a jack-arch roof system and ties experiencing collapse of parapets and moderate damage inside the building.

Governor's office building in Bam. Masonry with horizontal ties, Apparently no vertical ties had been used in this building. Bam's accelerometer was based in this building before the earthquake.

A masonry building in Baravat under construction. No vertical ties at the first storey were observed

Esfikan Guidance school with 3 separate masonry buildings incorporating horizontal and vertical ties. One building completely collapsed (left) with the vertical ties standing and separated from the collapsed walls. Two other buildings are damaged but standing (middle), the internal damage is shown on the right.

A masonry building in Bam incorporating vertical and horizontal ties but with poor concrete quality.

Figure 38: Other examples of masonry buildings with ties

5.4.3 *Steel structures*

The Iranian seismic code only permits masonry structures up to two stories provided that they satisfy other specific limiting criteria. Beyond this limit steel frame structures are normally the first choice for engineers and owners, mainly due to the simplicity of design and construction. The single most important issue for these structures is the lack of welding quality control and generally poor workmanship. The secondary consideration is the lack of proper design due to the lack of seismic training for designers, in relation to the design of structural and also the non-structural elements. Some examples of performance of steel structures in the Bam Earthquake are presented below using photographs taken during the visit.

Many of the structures incorporating bracing systems to resist the lateral loads performed well and survived without collapsing and in some cases without any damage to their glassy facades (see Figure 44). Conversely, other steel structures in the same neighbourhood suffered total collapse or severe damage (Figure 40, Figure 43, Figure 45). Simple frame structures that were obviously badly constructed were among the most severely damaged structures. In some recently built steel structures flaws in the design and/or construction had caused excessive deformations resulting in extensive damage to the internal and external walls(Figure 41) or in the worst cases total collapse (Figure 42 and Figure 43).

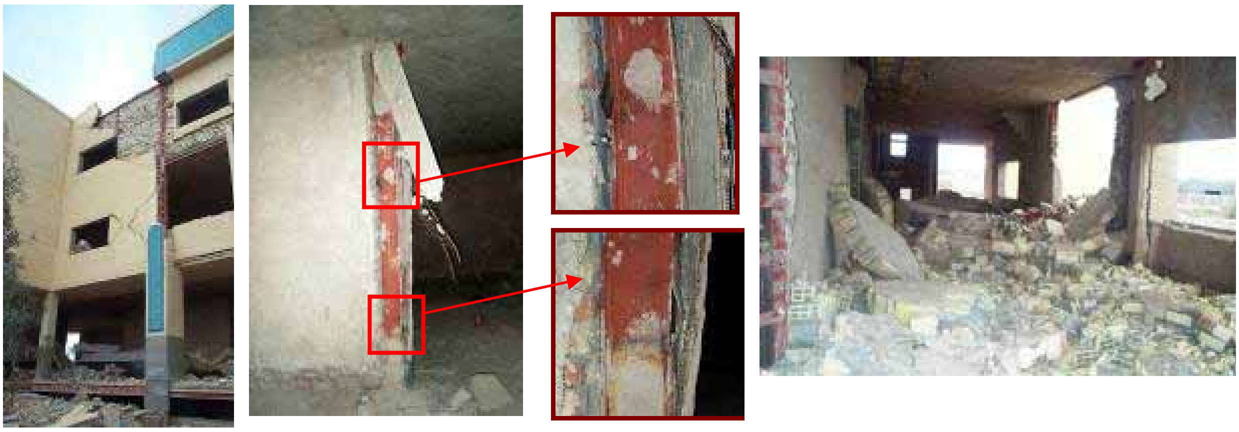
View from rear | View from front | View from side

Connection of bracing at beam-column joint | Details of ruptured beam-column connection | View from inside the bank building

Figure 39: Bank Mellat in Baravat of braced frame construction showing moderate structural damage and severe non-structural damage

Figure 40: An example of inferior construction of a steel structure located in the neighbourhood of Imam hospital in Bam. Note the irrational bracing configuration at the side of the building.

Front view | Rear view (steel frame erected) | Internal collapsed walls



Damage to external walls | Details of a buckled column in basement | Internal collapsed walls

Some details of steel frame | Severe damage to internal and external walls

Figure 41: Art and Cultural Complex building in Bam, under construction at the time of the earthquake. Braced steel frame structure in 3 storeys and one basement level, with hollow brick-concrete joist floor system. Severe non-structural damage to façade, infill and partition walls. Also at least one of the columns in the basement has buckled.

Kimia Building: Kimia Building is a combined residential-commercial building with braced steel frames in Bam city centre (Figure 42). The building roughly aligned to face a westerly direction had 5 stories above ground towards the front but only 4 stories in the rest of the building. Typical multi-functional buildings on the main streets of the city had a higher storey height in the first storey to satisfy commercial considerations. Bracing was visible on 3 sides of the building with a lift provided on the south side, for which the rooftop extension can be seen in the view from the south. In the southwest corner only two of the five stories could be seen after the earthquake as all the first three stories were flattened, however on the north side only the first two stories were flattened. It was noted that the spacing of the columns in south and north side frames are dissimilar. This together with the geometry of the bracings suggests a stiffness irregularity in plan. Another irregularity is the distribution of mass as the centre of mass is shifted toward the front of the building.

View from the north-west

View from the south-east

View from the west

View from the east

View from the south

View from the north

Figure 42: Kimia building in Bam. A braced steel frame structure with a maximum of five stories above ground level towards the front of the building (see Figure 43 for more details).

As it collapsed the building experienced a large lateral displacement, approaching 1/3 of the building dimension, toward the west (front). This can be seen in the view from the south (Figure 42), with the cross bracing seen in lower left corner of the view, actually being the bracing for the middle bay of the first storey in the original building configuration and now shown standing freely in front of the end bay. Also the size of this bracing compared to the others seen in the figure confirms that the building had a higher first storey. The building had also rotated in plan towards the north. Poor quality of welding is one of the main reasons attributed to earthquake damage observed in steel structures in Iran. For this specific building this is possibly one of the main reasons, however from the displacement mode of the collapse it is likely that the aforementioned irregularities of mass and stiffness also played a significant role.

View from north-east

Back of the building

Some close up views

Figure 43: Kimia building in Bam. A braced steel frame with a maximum of five stories above ground level towards the front of the building (see Figure 42 for different views).

Side view | Front view | Side view

Internal damage | Perspective | Side view

Side view | Perspective | View from back

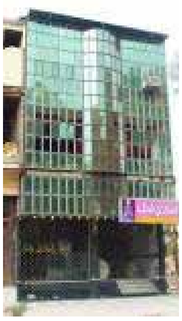
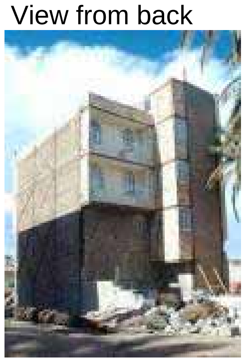
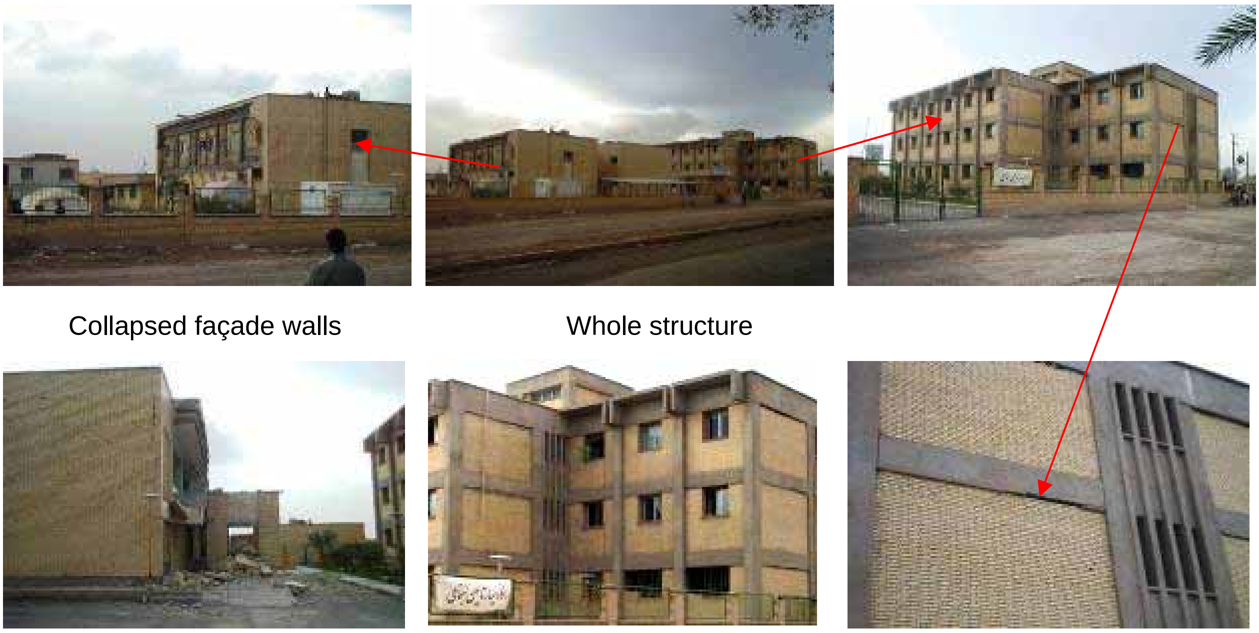
   

Figure 44: Good performance of some steel structures with a braced frame structural system opposite the Imam hospital in Bam (various views of the same building in each row, except lower row). Bracing in top left has buckled out of plane of the wall and detached from the top joint.

Figure 45: Performance of steel structures under Bam earthquake. Upper two rows: Braced frame structures that resisted major damage and collapse. Lower two rows: Unbraced and poorly constructed steel structures in jewellery market of Bam and surrounding area that suffered complete collapse.

5.4.4 *Reinforced concrete structures*

In Bam reinforced concrete structures were rare and of these very few, if any, were evident of being used for residential purpose, with the majority used for government or other communal buildings. A few examples of those visited are shown in the following figures. Generally they performed well and survived the intense force of the earthquake with only minor to moderate damage to non-structural members (see also Figure 51). However poor design, materials and construction quality caused severe damage and partial collapse of Imam Sadegh mosque in Bam as can be seen in Figure 53.



Collapsed façade walls — Whole structure

Walls around staircase collapsed — Damage to infill wall around windows — Separation of infill walls from beams

Figure 46: Main office of Social Security Organization in Bam. Reinforced concrete structure with damage to facade, staircase, and infill walls around window openings in first floor (interior of the building was not visited).

Figure 47: Bam's Emamat Telecommunication Complex in Zied square. RC frame structure with damage to facade at various locations. Otherwise the structure appeared to be intact. (interior of the building was not visited).

Outside view

Interior corridor, damage to walls

Inside view on upper floor showing collapse of infill wall next to a door opening

Separation of tiles in stairs

Damage inside the structure on the upper floor

Separation of the facade from the wall below a window

Figure 48: Baravat Telecommunication office- a three story RC frame structure, the damage is mainly non-structural. Most of the infill walls have worked with the frame to provide a lateral load path and suffered some moderate cracking with some collapsing during the earthquake.

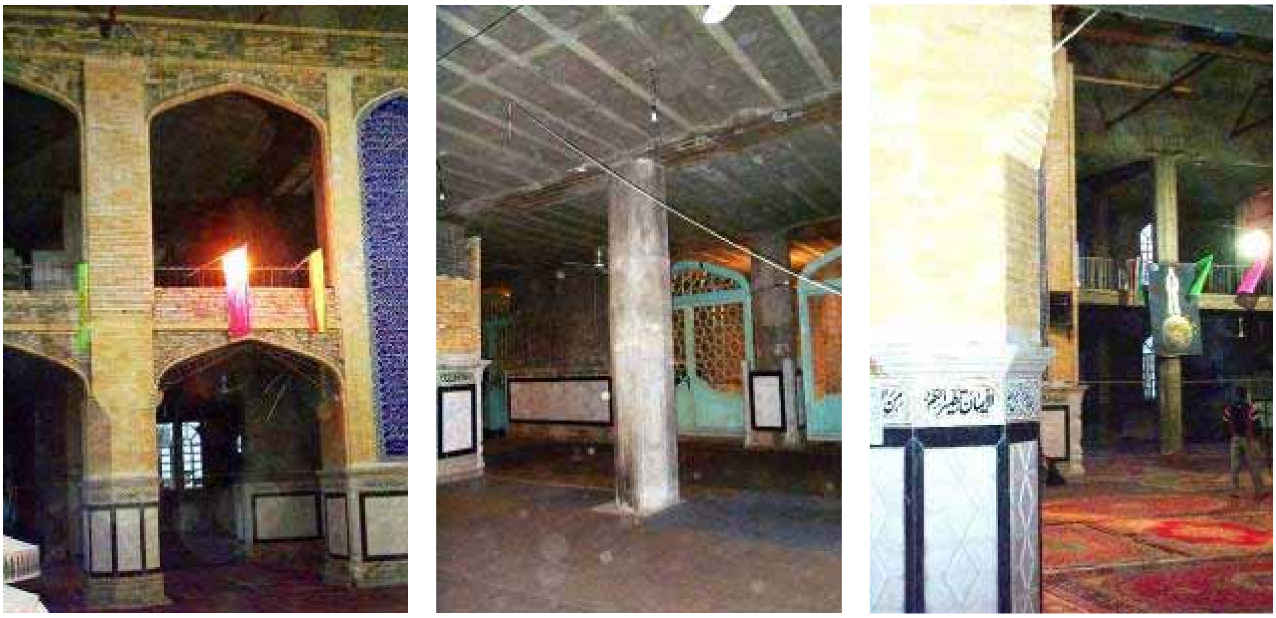
5.5 Other structures (Hospitals, Mosques and Mausoleums)

Performance of some non-residential buildings is shown in the following figures. These include Imam hospital, a new hospital under construction at the time of the earthquake, Jame mosque, Mausoleum of Emamzadeh Ali Ebn Al-Hossain, Imam Sadegh mosque and a cold storage facility in Esfikan village.

Figure 49: Imam Hospital in Bam, a single storey masonry building with a jack-arch roof system and inclined steel columns on the perimeter. Most of the building collapsed or was severely damaged. The Accident and Emergency Building collapsed due to the disproportionately thick and heavy roof, that buckled the external wall (left in1st and 2nd row). Three roof insulation layers can be seen (3rd row left).

Figure 50: A new hospital under construction at the time of the Bam earthquake, about 1.5km to the west of the Bam fault line on the Bam-Baravat road. The structural system is steel frame with precast two way spanning ribbed concrete floors. Some concrete blocks of infill walls, mostly in the top floor, collapsed but no structural damage was observed.

External view



Internal view

Figure 51: Jame Mosque in Bam. Reinforced concrete frame with joist and hollow brick RC slab roof and masonry infill walls. The central dome has a steel frame structure and is built from fired bricks. No sign of significant damage either on the interior or on the exterior of the structure or minarets.

Figure 52: Mausoleum of Emamzadeh Ali Ebn Al-Hossain In Bam. Complete collapse of the main dome and its supporting old walls in the interior part of the mausoleum. These walls were mainly made from mud bricks. A steel frame envelopes the building with a jack-arch roof system extending from the frame to interior masonry walls. The collapse of the main building appears to be the main cause of damage to the roof and external frame.

Front view

Rear view,

Front load bearing masonry wall

Concrete joist-hollow block roof

Figure 53: Imam Sadegh mosque in Bam: New construction with reinforced concrete beams and columns in the middle and load bearing masonry for the external walls. The wall at the back has collapsed as well as the part of roof which was supported by the wall. Very poor construction of reinforced concrete members and in many locations the reinforcement of the beams was left without any cover.

Figure 54: Emamzade Zied in Bam. Extensive damage to the sides of the main building which appear to be an extended part of an older section of the structure. The main building has not collapsed.

Figure 55: Khatam-Al Nabiein Cool Storage-North of Bam, located on the other side of the Posht Rood river across Bam's main bridge. The roof system is hollow bricks with reinforced concrete joists and slab. Internal steel frames providing shelving to the date packages were not properly designed for the heavy load of date packs. It is constructed from several independent two storey frames extending between the main walls with no positive connection tying them to each other or to the walls. The shelving floors are made from lumber, sitting on the steel beams. The shelving frame collapsed in its weaker out of plane direction due to inertia forces from the earthquake. The collapse of these shelving frames removed the support from the front of the building and resulted in building collapse.

5.6 Stairwell extensions

Due to the common failure of the rooftop extensions to staircase structures observed in the Bam Earthquake, this section collates and comments upon the available recorded incidents. The largest damage to these structures was seen in masonry buildings where the structure is merely an extension to the staircase walls and covered with a flat or inclined jack-arch roof spanning between the two side walls that run parallel to stair axis in plan. The other walls normally have large openings for a door to the roof top on one side and a window on the other side, which make the structure very flexible and weak in the direction parallel to these walls, unless a proper framing system is implemented. The figures below clearly show some case where the weakness in this direction has resulted in detachment of the whole staircase extension from the building below, large movements and also instances of collapse. The use of vertical and horizontal ties does not necessarily provide sufficient framing for the staircase extension to resist the earthquake force in the direction perpendicular to the stair axis.

Due to the importance of the staircase structures in providing safe evacuation from buildings, and since failure in these structures was a common occurrence in the Bam Earthquake the issue of proper design of these structures and the provision of clear design guidance needs to be considered by local authorities.

Baravat Telecommunication office

Undamaged in a reinforced concrete building

Bonyad-Maskan building in Bam

Figure 56: Examples of the performance of staircase extension structures in Bam earthquake. Good behaviour for reinforced concrete structures and collapse in masonry buildings.

Bonyad-Shahid building in Bam

Bam Electricity management office

Housing and Urban Development office building in Bam

No apparent damage in a steel frame structure (the continuity with structural system in steel structures can be seen in the skeleton of another similar building under construction to the left)

Figure 57: Examples of the performance of staircase extension structures in the Bam Earthquake for Masonry buildings

Figure 58: Examples of the performance of staircase extension structures in Bam Earthquake for Masonry buildings: Housing and Urban Development Organization's new 'build to rent' project. There were a large number of collapsed staircase extension structures in this project, only some examples are shown here.

6 Socio-economic effects

6.1 Introduction

Iran is known to be one of the most earthquake prone countries in the world. The Bam Earthquake was also one of the most severe earthquakes experienced in Iran in terms of human and economic loss for a small region. The devastation in Bam was beyond comprehension and shocked the whole country as well as people throughout the world. The direct and indirect consequences of the earthquake on the lives of people in Bam are obviously immense but difficult to measure and account for accurately. The earthquake stretched the disaster management capacity in Iran, despite the fact that the country suffers frequent large earthquakes that have claimed more than 140,000 lives during the twentieth century.

6.2 Search and rescue

Due to the enormous devastation caused by the earthquake and the fact that all the officials in the immediate neighbourhood were affected, the immediate official rescue operation took some time to organise and arrive in the region from the neighbouring cities. As the infrastructure in the city was effectively paralyzed the emergency response system of the city was also badly affected (see Figure 59). The earthquake struck early in the morning on a Friday which is an official weekend day in the country when practically everyone was asleep. In the early hours after the earthquake the survivors themselves desperately tried to help their family and neighbours who were missing or trapped. Within half an hour of the earthquake, the Iranian Red Crescent Society (IRCS) began to mobilise its emergency response teams and within two hours, the first IRCS search and rescue teams had reached Bam. Nearly 12,000 people were airlifted and taken to hospitals in other provinces. The IRCS also mobilised 8,500 relief volunteers [29]. In response to the earthquake international agencies were also mobilised in many countries and contributed to the search and rescue operations although reportedly the presence of international rescue teams was less effective than usual (about 30 people saved in 48 hours). This might be because the type of building material locally used produced more dust than usual reducing the chance of survival. The response and cooperation between Iranian authorities, Iranian Red Crescent Society (IRCS) and the international community was swift and exemplary [30]. In addition to the official operations many volunteers from various sections of Iranian society poured into the region to help those affected.

Figure 59: Bam's fire department and emergency response system after the earthquake

6.3 Shelter and food

Temporary shelters in the form of tents had been provided by the coordinated aid agencies. Most people preferred to establish their tent next to their destroyed or damaged houses, other were accommodated in existing open areas. Providing shelter in the early days was essential for survivors of the earthquake who were suffering from extreme emotional and physical distress. Bam region is dominated by a desert climate, which is characterised by warm days and cold nights, sometimes below freezing during the winter. At the time of the visit, electricity supplies were available in the tents and some longer term temporary shelters were being tested in different parts of the city. Some examples of temporary shelters are shown in Figure 60.

Steel frame temporary shelter is tested on-site in Baravat at the time of visit. No foundation was used for these test shelters. The roof system appears to be designed for a composite slab system. Some of the shelters at the back of the picture are shown covered by tent cloths.

Temporary shelters in Bonyad Maskan office in Bam. Portal frames with prefabricated wire mesh panels are covered with layers of concrete from inside and outside.

Another type of temporary shelter built using wire mesh panels and concrete cover

Prefabricated temporary shelter

Figure 60: Examples of temporary shelters which were being tested in Bam at the time of visit

At the time of the visit Bam city was divided into about 14 subdivisions and all the humanitarian efforts in each subdivision was coordinated with authorities in one of the provinces in the country. This appeared to be an effective approach for management of the relief efforts in a large disaster zone. The affected population in need of humanitarian and relief aid in Bam was estimated to be about 155,000.

6.4 Public services

As a result of the earthquake almost all public services, such as water, electricity, transport and health services in Bam were severely disrupted. Many people working in these public sectors were killed or injured. All three main hospital buildings in Bam were damaged beyond use. In addition all 95 Health Houses, 14 rural health centres and 10 urban health centres were destroyed and left out of service [29]. Temporary health centres and mobile hospitals were established by the government and international aid agencies near to hospitals as well as other suitable locations to respond to the various emergency and more general health needs.

6.5 Economic losses

The earthquake destroyed about 85% of the building stock in Bam. In addition the infrastructure throughout the city was severely degraded. Arg-e Bam, a jewel in Iran's cultural heritage, which had undergone significant repair and restoration during the past two decades, was destroyed. Preliminary estimates of economic loss from the earthquake is about US$1.5 billion, including direct damage of US$1.2 billion and indirect damage US$0.3 billion. However the human loss is incalculable. According to government sources the reconstruction of the city will take between 24 to 36 months, but previous experience has shown that it might take a decade or more to accomplish the reconstruction of a destroyed city which will also absorb a significant portion of the national budget.

7 Lessons learned and conclusions

Earthquakes are not new in Iran, there have been several powerful earthquakes during twentieth century claiming more than 140,000 lives, and no doubt Iran will continue to be hit with powerful earthquakes in the future. Earthquakes are a fact that everyone in the country now fully appreciates. Memories of the Buien-Zahra, Dasht-e Bayaz, Tabas, Golbaf and Manjil-Rubar earthquakes are unforgettable, not only for the people who survived these earthquakes but also the many others who have been touched by the news of the tragedy. With the power of media and technology nowadays earthquake news spread faster and deeper into every corner of the country and shakes up all members of society.

However, despite this knowledge the fact remains that the country appears powerless in dealing with the earthquake issue with little sign of improved national statistics with regards to seismic damage. Large death tolls and financial losses are still the main characteristics of Iranian earthquakes. In broader terms, this situation is common to most of the countries in the Middle East and Central Asia, such as Turkey, Armenia, India and China. It is interesting to note that four days before the Bam earthquake a similar magnitude earthquake struck California, where only a handful of people were killed. This clearly demonstrates that the knowledge to protect human life against earthquakes exists and the international community needs to focus on applying this knowledge to earthquake prone areas to minimize and mitigate the risks arising from major earthquakes.

Despite the history of tragic earthquakes, and their continuing recurrence in Iran, and the fact that the knowledge exists to deal effectively with the threat posed it appears that the issue of seismic risk has not to date been addressed particularly effectively. This failing runs through every level of society at individual and company levels and is reflected by local authorities, and central government. It is reasonable to ask why the obvious lessons of the earthquakes are being ignored. Perhaps the intermittent nature of devastating earthquakes tends to create a culture of acceptance of the status quo and failure to take responsibility in a society which has mainly focused on short term needs. It is obvious, that for any plan to work successfully this culture needs to change and the requrements for fundamental earthquake hazard reduction need to enter national consciousness at all levels of society and then be enforced with minimum tolerance of negligence.

The experience of Bam earthquake highlights once again similar causes and problems in the disaster preparedness system and the deficiencies in current construction practice, similar to most high casualty recent earthquakes. The following are specifically noted:

Existing structures:

- *Traditional buildings:* There were many old buildings in Bam which were built from mud-bricks at a time when no seismic design provisions were available. Most of these buildings completely collapsed during the earthquake. A considerable number of buildings in central and eastern provinces, more specifically in villages, are of this type and will not resist similar magnitude earthquakes. Therefore, it is essential that any earthquake hazard reduction programme in the region take these into consideration. Due to specific materials and construction forms the classic strengthening procedures might not be suitable and special studies are required to establish the appropriate course of action.
- *Non-engineered buildings:* These are building which are mainly built of masonry or a combination of masonry and steel without any specific seismic considerations. A good majority of the non-traditional buildings in many parts of Iran are of this type and are vulnerable to earthquakes. An active retrofit and renewal strategy should be formulated to encourage the owners to undertake retrofitting.

Construction practice and control:

In the Bam earthquake many buildings constructed during the last decade totally collapsed. The majority of these buildings were privately built houses. On the other hand fewer public buildings, especially those used as government offices collapsed, since these obviously benefited from better control over materials and construction practice. A number of observations and recommendations are made:

- Seismic design code: The implementation of the code is a major issue and there are several areas that need to be addressed. Firstly, proper and effective training has not been provided for many professionals who are generally only familiar with general building design and preparation of drawings without any seismic design considerations. Secondly, there are only limited official guidelines that accompany the code and clarify the use of code provisions for practicing engineers. It appears that providing background information and examples of the code provisions could greatly improve the successful implementation of the code. Thirdly the lack of construction control leads to poor construction and poor performance under earthquake loading.

- Lack of skilled labour and construction professionals: Most of the people working in the construction industry are unskilled and unlicensed. This results in poor material production and construction. A process should be implemented to train and licence professional working in construction.
- Lack of construction control: For many small projects, especially for private housing, the design engineer has the responsibility of supervising and approving the construction. However there is no effective control in this process and often the engineer only takes the role of approving the design drawings. An effort should be made to increase the awareness among the design professionals with respect to their legal and professional responsibilities and to include strict control of construction practice.

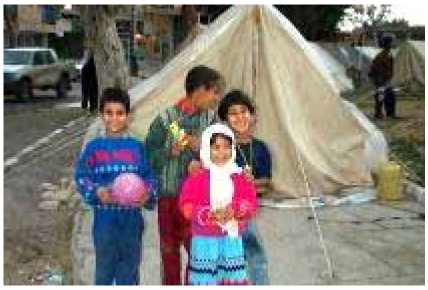
Emergency Preparedness:
Strategic plans should be developed to identify obstacles in emergency response at national and local levels for natural disasters with high number of casualties and damage. The most hazardous areas and the available resources in these areas need to be identified. Sufficient training should be provided for rapid response teams to be deployed to disaster zones in the shortest possible times. Public awareness education and exercises should be provided in high seismic risk areas.

Risk management and prioritisation
The actions identified in this report require significant investment over a prolonged period. In order to maximise the benefits it is necessary to identify the regions, localities, structural forms and particular facilities requiring the most urgent attention. This should be linked to a plan with budgets and programme that addresses both short term risk mitigation measures and longer term strategic actions that will create cultural awareness and responsible design and construction practices.

Last but not least, as a country with high seismic risk and with its own seismic characteristics it is also necessary to invest in scientific institutions and research facilities in earthquake engineering to pave the way for technical and professional people to tackle the country-specific problems in seismic hazard reduction.

Dedicated to the children of Bam









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