



# IMPROVING THE EARTHQUAKE RESISTANCE OF SMALL BUILDINGS, HOUSES AND COMMUNITY INFRASTRUCTURE

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## ***Who sponsored this booklet?***

World Bank, through their Multi-Donor Trust Fund office in Banda Aceh, Indonesia identified a need for a “Field Manual” to assist KDP engineers in improving the standard of seismic resistance in houses and community infrastructure.

The New Zealand Agency for International Development (NZ Aid) funded the preparation of this booklet.

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## **Disclaimer**

The information and advice contained in this booklet is provided as training material and general guidance to assist trained engineers in improving earthquake resistance. Every effort has been made to ensure the accuracy of the information. The information is intended for trained engineers and is not a substitute for specific engineering advice. AC Consulting Group Ltd accepts no liability.

## ***Purpose of this booklet***

The booklet presents a series of recommendations for improving the earthquake resistance of houses, small buildings and other structures:

The recommendations cover:

- The basic principles of earthquake resistant construction
- Guidance for improvements to design and detailing practice for small engineered buildings and infrastructure
- Guidance for design and detailing for non-engineered buildings
- Guidance on improvement in construction quality (materials and workmanship) and construction monitoring (we emphasise the importance of quality materials, construction and thorough construction inspection).

Types of buildings covered include:

- Traditional non-engineered single-storey houses (with masonry walls and practical columns)
- Small scale community buildings (maximum two storeys, maximum occupancy 50 persons)
- Other community infrastructure.

These improvements are neither difficult nor expensive; some however require a change in mindset. Most improvements are incremental; together they will make a significant improvement.

The knowledge gained from this series of recommendations will assist you to explain good practice to foremen and tradesmen, to correct their poor practices and to reject any sub-standard workmanship. We encourage you to educate home and business owners on the importance of seismic resisting construction.

Copies of this booklet can be downloaded from [www.aconsulting.co.nz](http://www.aconsulting.co.nz)

### **Specific Engineering of larger structures is not covered.**

Whilst buildings of greater than two storeys and buildings with special functions or unusual features are not covered the basic engineering principles remain valid for these and other larger buildings. We strongly recommend an experienced engineer is consulted when designing larger buildings in earthquake zones as there are other aspects of earthquake-resistant design which must also be considered.

Of particular importance to earthquake engineers is the principle of ductility (the ability of a structure to deform but still sustain its load and dissipate energy for several load cycles after initial yield during an earthquake) and the necessity of following the strict detailing rules to ensure a building actually behaves in a ductile manner. Designers will need to comply with relevant building codes when designing larger buildings. Many universities offer courses in the design of earthquake resistant buildings.

## **Introductory Comments**

### **The Purpose of Earthquake Engineering**

The purpose of earthquake engineering is to:

- Avoid the loss of lives resulting from the collapse of infrastructure or a building in a major earthquake (a *design* earthquake or *ultimate limit state* earthquake)
- Limit personal injury and building damage (including contents) in moderate earthquakes (serviceability limit state earthquake). Infrastructure / building should be fully functional after a clean up
- Minimise damage and disturbance to residents in moderate and minor earthquakes
- Maintain the key function of the infrastructure / building
- Protect the lives of those outside the building
- Protect other property & the environment.

Note:

- The best way to protect lives is to ensure the building does not collapse
- Many traditional buildings are constructed of brittle materials and are likely to fail in a sudden, brittle manner
- For brittle buildings there is a clear threshold, below which little visible damage occurs; above which collapse is likely
- Sudden brittle failures such as shear failures are the main cause of collapses and should be avoided.

### **Earthquake Resistant Construction**

For a building to be earthquake resistant it must be:

- Configured well
- Detailed well
- Constructed well.

Weakness in any one of these will result in a less-earthquake resistant building.

### **What is a Moderate Earthquake?**

The New Zealand Code defines a moderate earthquake as a Richter magnitude 6.5, occurring 20km from the site. Other codes have similar definitions. This is equivalent to Modified Mercalli Intensity 8, with peak ground accelerations of approx 0.50g ( $\pm 0.15g$ ).

MM8 is described: ***Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Falls of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.***

## ***The Great Sumatra-Andaman Earthquake (26 December 2004)***

**In Banda Aceh this was a moderate earthquake (as shown by the shaking and damage).**

- The 2004 earthquake was slightly smaller than a “design” earthquake for Banda Aceh as defined by SNI 03-1726 (refer Recommendation No. 24)
- Most single and two storey buildings including those of traditional construction did survive
- The 2004 earthquake caused extensive cracking and other damage in many buildings.
  
- The 2004 earthquake should be viewed as a wake-up call
- It is dangerous to assume any buildings with cracks will be safe in the next earthquake
- It should be looked upon as an opportunity to make changes and improvements and a reason to improve on traditional construction where this has proven to be unsatisfactory.

### **General Observations of Existing Buildings in Aceh**

General observations of a large number of one and two storey buildings in Aceh (some had survived the earthquake well, some had not) showed:

- Timber buildings performed well
- Steel framed buildings performed well (with some exceptions)
- Well-detailed reinforced concrete buildings performed well
- Masonry buildings with confinement and adequate connections performed reasonably well
- Poorly detailed and constructed masonry buildings performed poorly – this includes many relatively new *middle class* houses
- Poorly constructed reinforced concrete buildings performed poorly
- Poorly constructed masonry buildings performed poorly.

To summarise, the move to *modern* materials has led to a reduction in seismic resistance. If buildings are to be constructed from either masonry or reinforced concrete there must be the knowledge to design them and the skills to construct them to a high standard.

### **Acknowledgement**

We wish to acknowledge and thank the Earthquake Hazard Centre, School of Architecture, Victoria University of Wellington, New Zealand and the New Zealand Society for Earthquake Engineering for allowing us to reproduce several of their diagrams in this booklet.

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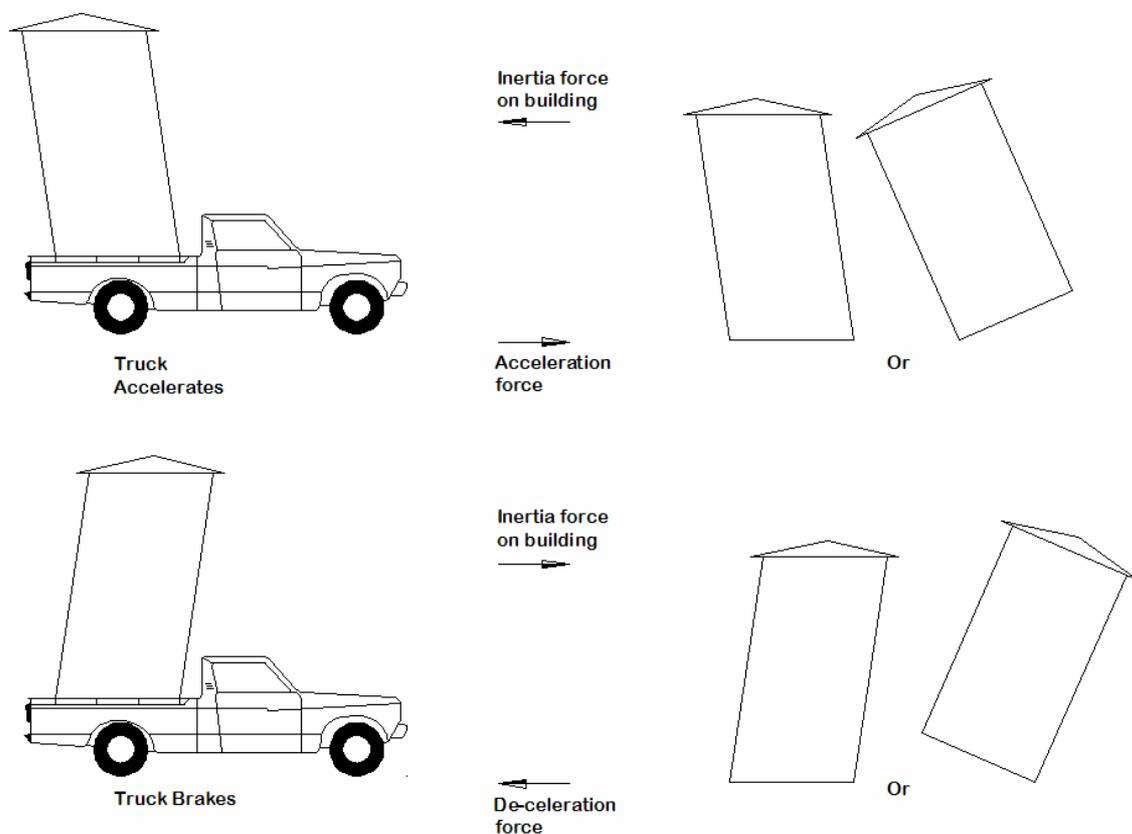
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# Recommendation No. 1: Buildings must Resist Horizontal Loads from Any Direction

## Earthquake Loads

- Earthquakes cause ground shaking
- The severity of earthquake loads is dependent on location – refer to the local building standards or loadings code
- Ground shaking induces inertial loads in building elements; stronger ground shaking or heavier building elements result in greater loads
- Earthquake loads are predominantly horizontal (there is also a vertical component)
- Earthquakes can strike from any direction
- Earthquake loads are cyclic
- Imagine you are standing on the back of a truck and the truck suddenly accelerates, then brakes sharply, accelerates again, breaks again and repeats the cycle several times. It is difficult to remain standing
- Now imagine a building on the back of the truck. Many traditional masonry buildings with weak mortar will collapse. Tall slender buildings will topple over
- Buildings that are not too heavy, modestly proportioned, with good connections and properly attached to their foundations will remain on the truck undamaged
- Note that even well-engineered earthquake-resistant buildings cannot be expected to withstand the very large forces associated with a tsunami.



## Resisting Earthquake Loads

In order to resist loads from any direction buildings must be able to resist loads from two orthogonal directions (at right angles). Designers usually consider the x and y directions separately. An earthquake load, from any direction can be resolved into x and y components which can be resisted by the structure in these two directions.

Loads can be resisted by:

- Moment-resisting frames
- Braced frames
- Shear walls
- Frames infilled with masonry (recommended for one- and two-storey buildings only).

Some buildings have shear walls in two directions; others have moment-resisting frames in two directions; yet others have shear walls in one direction and moment-resisting frames in the other.

**At concept design stage ensure you have elements (walls or frames) to resist lateral loads in two orthogonal directions. There must be enough elements in each direction; they should preferably be spread over the length and width of the building.**

## Earthquake Displacements and Loads

Earthquakes cause ground shaking; the ground beneath a building is displaced laterally. The loads in the upper part of the building are generated inertia effects of this displacement. The resulting shear forces and bending moments in a building are (generally) a maximum just above foundation level (slender flexible buildings can behave somewhat differently).

### Earthquake loads are a function of:

- Seismic Zone – and proximity to fault line
- Building mass
- Buildings period of vibration – generally a function of height and type of bracing element
- Properties of foundation materials (soil or rock)
- Structural type configuration, material, degree of ductility, damping)
- Building category (Risk and Importance factors)
- Special factors.

### Points to note:

- Stiff buildings and stiff elements such as shear walls attract more load than flexible elements such as moment-resisting frames
- Heavy elements such as tile roofs result in greater loads than lighter elements
- The seismic zone has a major effect on the *design* earthquake load as does distance from fault line
- Subgrade type (Soil, Rock, etc) also has an effect
- Avoid combining different types of elements to resist loads in the same direction
- Structural weaknesses, weak and brittle materials, poor connections and plan irregularity reduce the ability of a building to resist any horizontal loads

- **Even well designed earthquake-resistant buildings suffer some structural damage in moderate to large earthquakes – we must design and detail buildings to ensure they do not collapse even when damaged**
- To design buildings for no damage in large earthquakes would be very expensive and impractical.

## **Ductility**

Ductility is the ability of a structure to sustain its load and dissipate energy for several load cycles after initial yield, i.e. it can carry the gravity loads without collapse.

A ductile structure or element generally fails by yielding in tension. Designers must detail ductile members to avoid failure in shear or compression.

Design codes allow lower seismic loads to be used when designing a well-detailed ductile structure, compared to the loads used in designing an elastic structure.

Single and two storey structures are generally designed as elastic structures.

Buildings must also be designed to carry wind loads and these are always sustained elastically.

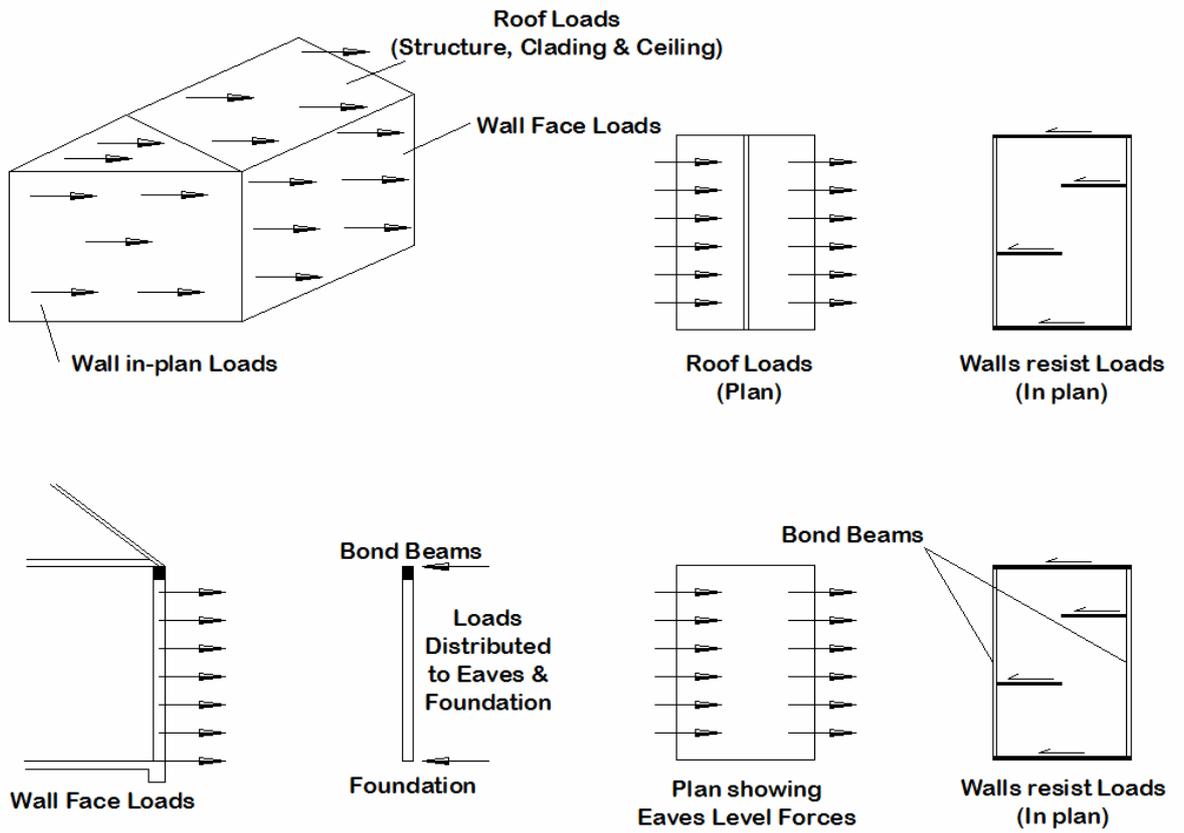
It is good practice to apply ductile detailing to all buildings, even those designed to be elastic; a building with some ductility will perform better in an earthquake than a non-ductile building.

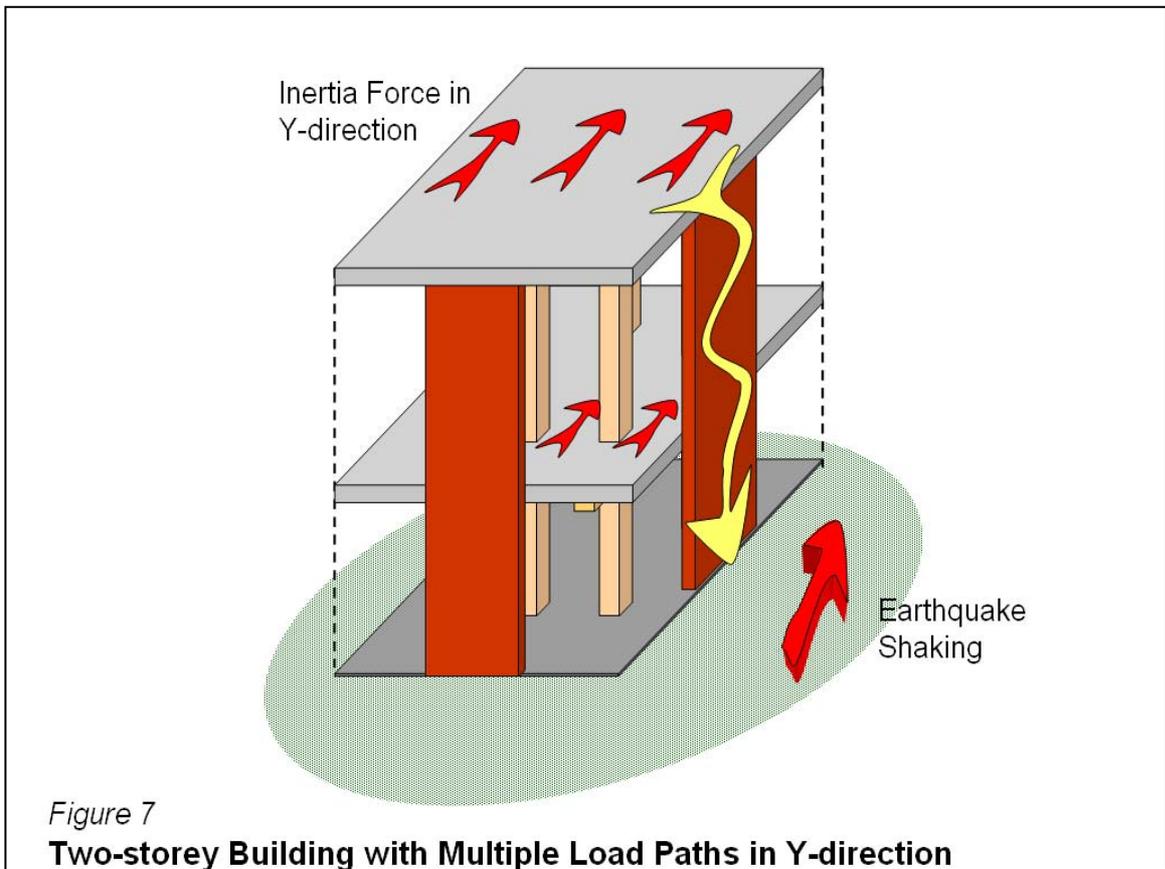
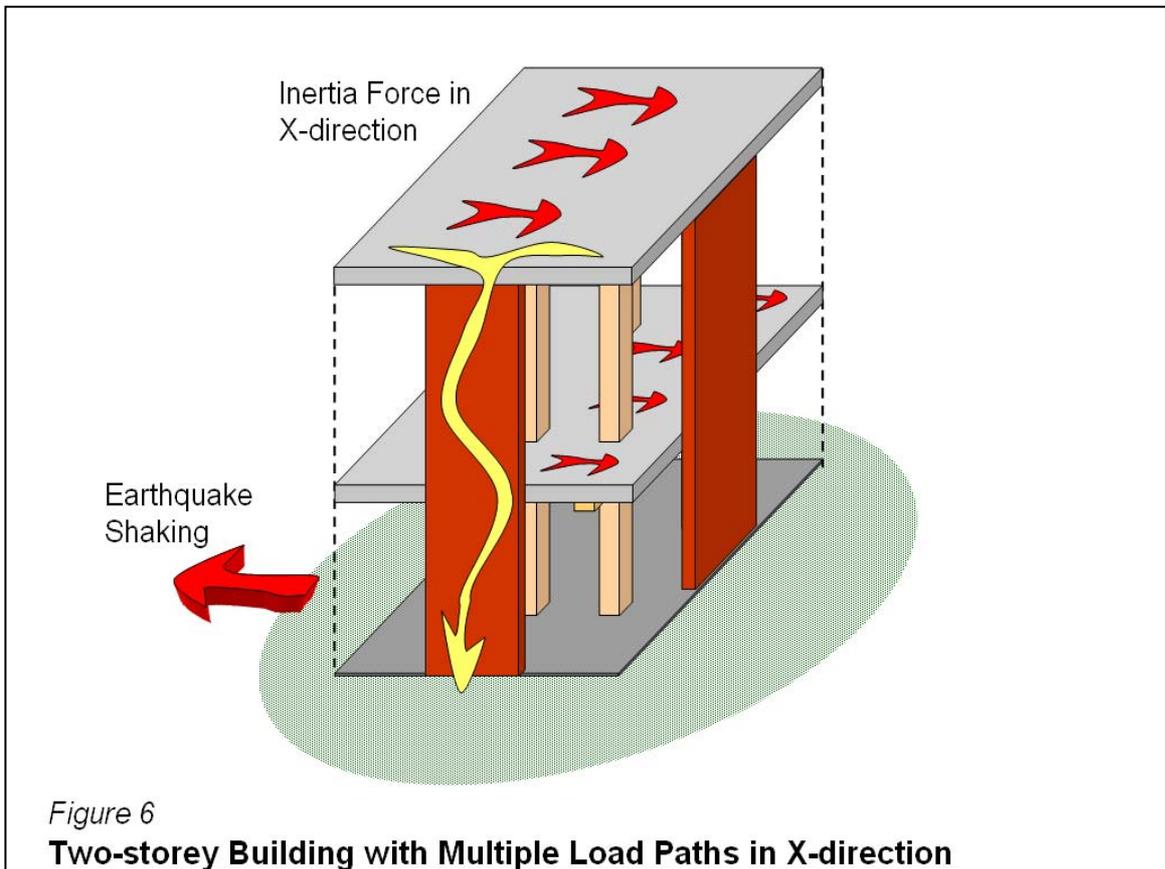
(Note: a brittle material or element will fail suddenly once it has passed its elastic limit.)

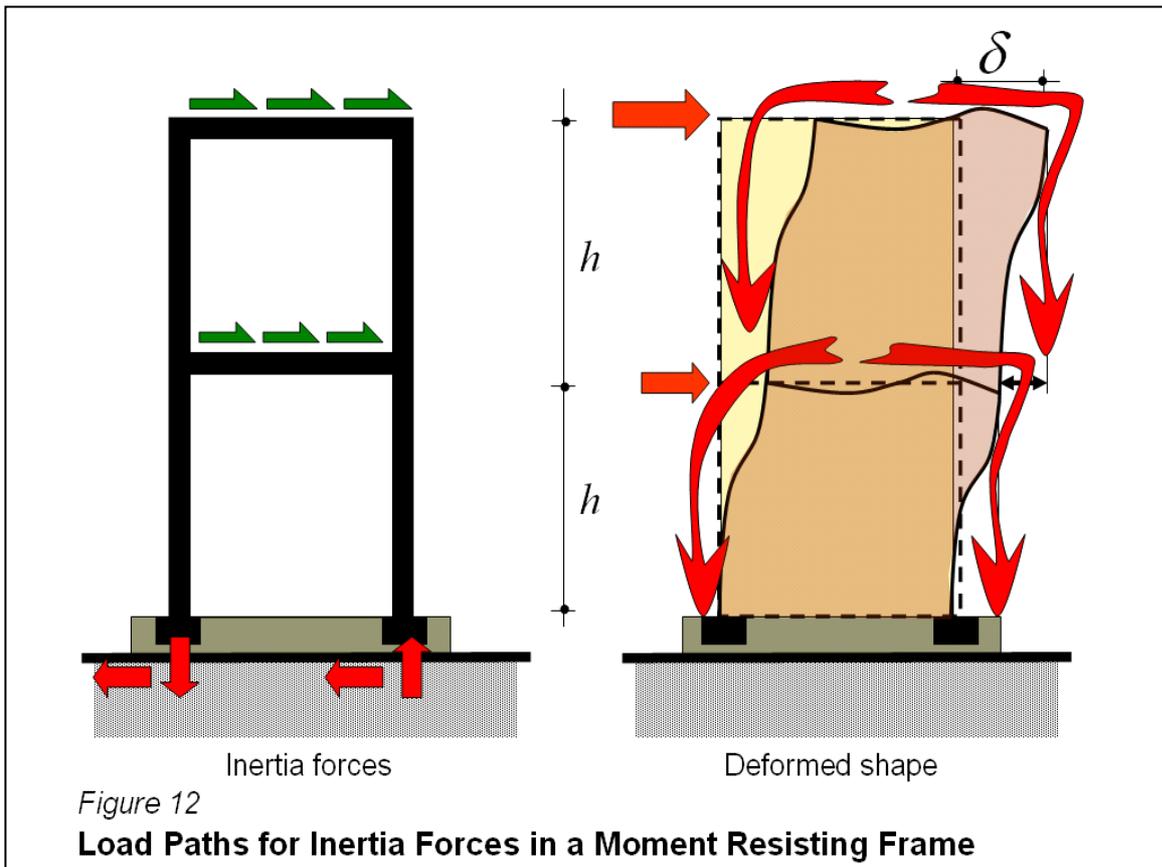
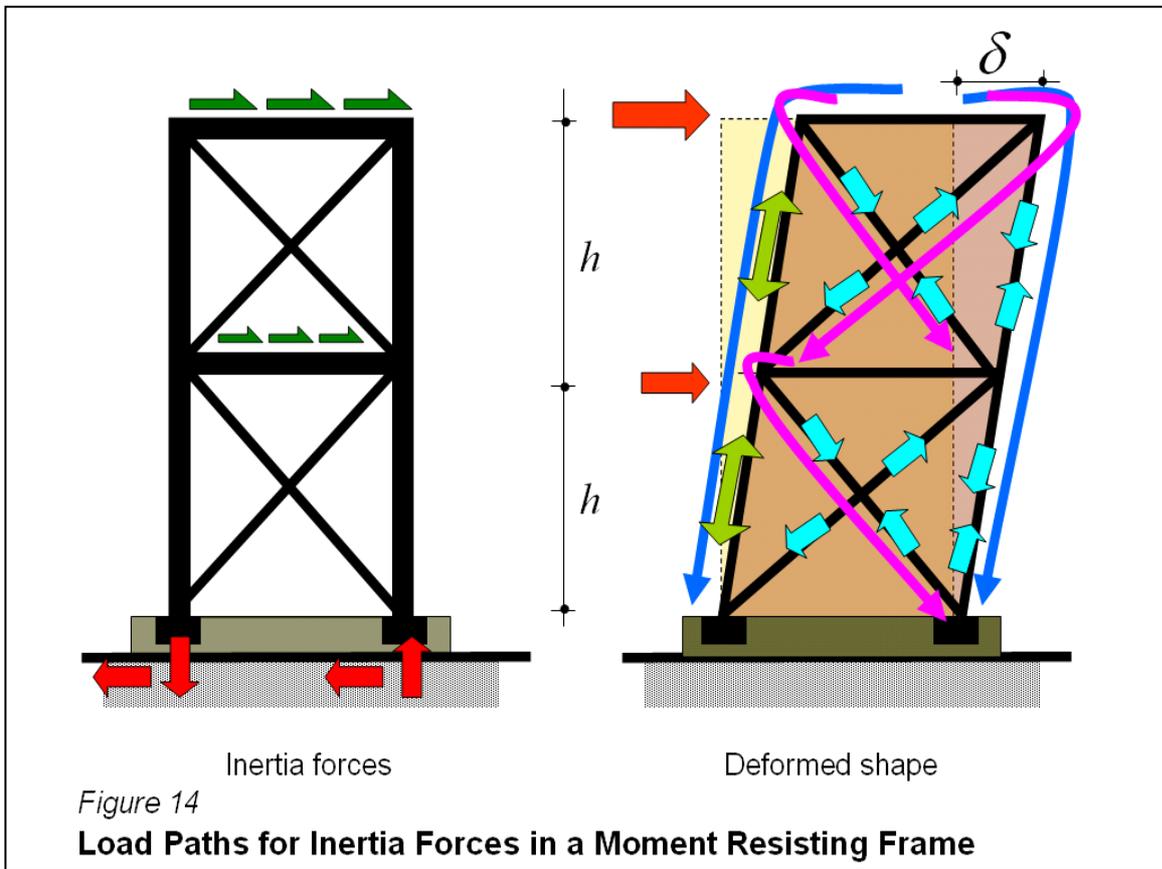
## **Recommendation No. 2: Horizontal Forces must be Transferred to the Ground (Seismic Load Paths)**

### **Understanding seismic load paths**

- An earthquake generates inertial forces in a building
- We must clearly define the load path to transfer these forces from all elements to the ground
- Load paths must be continuous; all forces must be transferred to the foundations.
  
- **Roofs** are a major load
- The roof structure must be braced to distribute loads to the walls (a diaphragm is a common way to achieve this)
- This load is then carried by side (in-plane) walls or moment-resisting frames to the foundations.
  
- **Walls** are a major load
- Face loaded walls (walls perpendicular to the earthquake load) transfer their loads up to the eaves (or bond beam) and down to the foundation
- The eaves loads follow the roof load path as above
- Some load is transferred horizontally to walls and columns
- Side walls (parallel to earthquake) resist loads in shear (and bending)
- The total load is transferred to the foundations and back to the sub-grade.
  
- All loads must be carried to the **foundations**; foundations must transfer the horizontal loads to the sub-grade.
  
- **Other loads** to consider include building contents, especially where the building is used for storage, machinery and water tanks
- Note that as earthquakes can strike from any direction, these principles must hold for all directions.







## **Recommendation No. 3: Alternative Concepts for Resisting Lateral Loads**

**Primary systems to resist lateral loads include:**

- Shear Walls
- Moment-resisting frames
- Braced frames
- A building may have different systems in different directions
- Note that slender columns carry gravity loads only; they are too flexible to resist lateral loads
- Each system has advantages and disadvantage
- Construction materials also affect the choice of structural system.
- Reinforced concrete walls (shear walls) on well designed foundations are probably the best system to resist seismic loads in low to medium rise construction. Some engineers always use RC shear walls
- However they are expensive, require expensive foundations and limit the internal layout.
- Moment resisting frames only perform well if they are correctly designed (take account of cracking which occurs)
- Stiff infill walls, if not separated will alter the load paths and negate the design effort.

**The building designer must select a combination of the above elements to achieve resistance in two orthogonal directions.**

### **The Importance of Strong Columns**

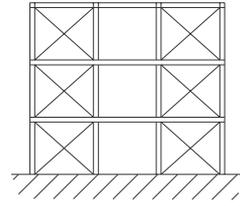
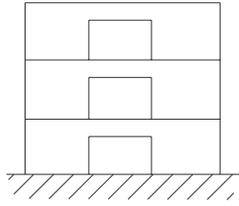
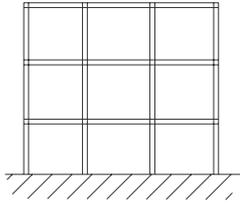
Experience has shown that columns are vulnerable to failure in earthquakes. Possible reasons include pressure to design slender columns and lack of ties (or too large spacing of ties) in reinforced concrete columns.

When a column is damaged there is a high probability that the building will collapse.

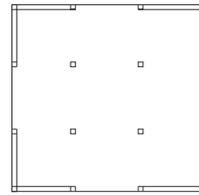
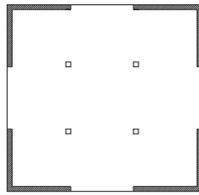
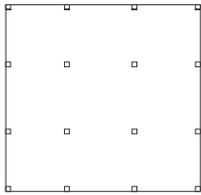
### **Recommendation**

- Ensure columns are stronger than beams
- Ensure R.C. columns have an adequate number of ties (refer Recommendation No. 19).

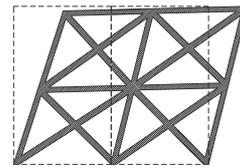
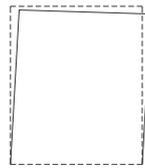
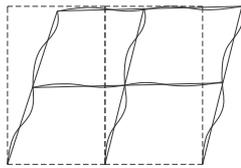
ALTERNATIVE CONCEPTS FOR  
RESISTING LATERAL LOADS



ELEVATION



PLAN



DEFLECTED SHAPES (ELEVATION)

MOMENT RESISTING  
FRAME

SHEAR WALL

CROSS BRACED FRAME

## **Recommendation No. 4: Configure Buildings to Resist Loads**

### **Building Configuration**

In order to survive a moderate to strong earthquake a building must be:

- Configured well
- Detailed well
- Constructed well.

All three are important. If a building is poorly configured this increases the strength demands on structural members and exposes any weaknesses in detailing or construction quality.

Building codes tend to concentrate on detailing; the designer must ensure the configuration is satisfactory.

### **The Importance of Symmetry**

The client, architect and engineer must agree on the building configuration. There will always be compromises to be made.

Seismic resisting elements should be arranged in a reasonably symmetric manner. The importance of this increases with building height.

The main elements which resist seismic loads (e.g. walls or frames) should be distributed symmetrically and evenly, in both directions over the plan area of the building. Walls and frames should preferably be placed on the building's perimeter. If these elements are concentrated in one area they will cause torsion (twisting forces) in the building; which can lead to failure.

Try to achieve symmetry in plan in two orthogonal directions.

Where an "L" or "U" shaped building plan is to be built the length to width ratio of the wings should be less than 3. Otherwise it is advisable to separate the wings and design them as separate structures.

It is also important to avoid vertical asymmetry in buildings of over one storey. The main lateral load resisting elements should be continuous up the building. Avoid changes in mass between floors (variance should be less than 50%) and similarly changes in lateral stiffness.

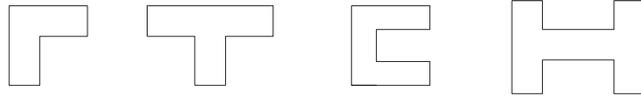
## **Other Design Considerations**

Earthquake resistance is not the designer's only concern. The designer and builder must also consider:

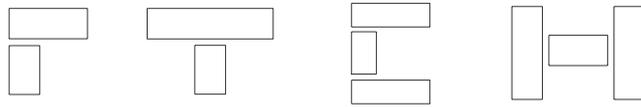
- Deflections, including thermal and other movements
- Fire resistance and fire egress; lightning protection
- Weather-tightness; control of surface water
- Durability (including insect attack) / stability of materials
- Economy of construction, speed of construction
- Sustainability
- Tropical design
- Thermal insulation; ventilation; energy efficiency
- Natural light
- Allowance for piped services
- Security, privacy, acoustic insulation
- Compatibility with local culture, religion and traditions
- Aesthetics
- Availability of suitable materials
- Availability of skilled labour.

BUILDING CONFIGURATION/  
STRUCTURAL WEAKNESSES

POOR PRACTICE

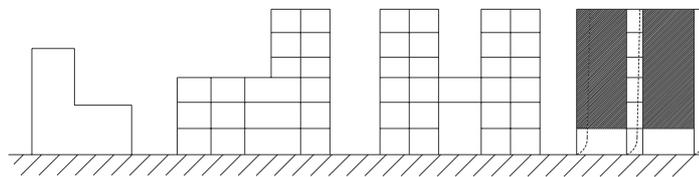


GOOD PRACTICE

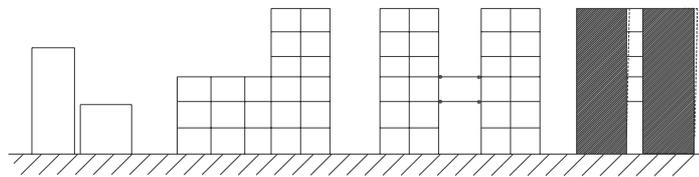


PLAN

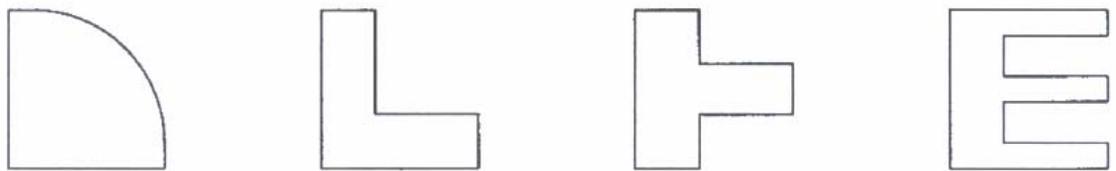
POOR PRACTICE



GOOD PRACTICE



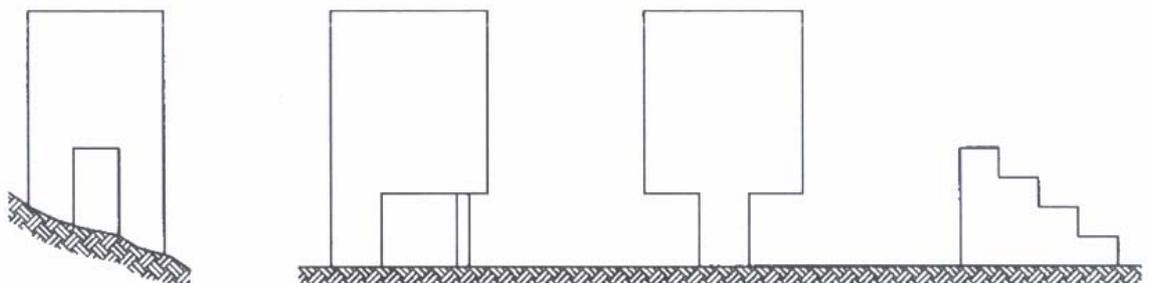
ELEVATION



Major lateral  
load resisting  
elements



a) Examples of Plan Irregularity



## **Recommendation No. 5: Ensure Building Elements are Tied Together**

**All building elements, including non-structural elements must be tied together.**

- We have discussed load paths above
- Seismic loads approach from any direction
- All building elements must be properly tied together to ensure that loads are transferred as assumed – whatever direction the loads are from
- Loads from any direction must be transferred
- Loads must be transferred over a number of cycles
- This includes slab to beam, slab to wall and wall and column to foundation joints
- Connections need to carry cyclic loads; materials that are strong in both tension and compression are necessary
- Brittle failure of connections must be avoided
- For reinforced concrete buildings continuous steel reinforcing is the simplest way to tie elements together
- Steel is a ductile material; it will hold the structure together over many cycles
- For other building materials use of steel connectors is recommended
- Glazing and cladding etc, must be connected to the structure to ensure it does not fall to the street below, injuring pedestrians
- Chimneys, parapets and other heavy masonry features, if they cannot be eliminated must be strongly connected to the main structure.

Brittle materials, such as masonry and mortar rarely stand up to cyclic loads.

### **Roofs should preferably be of light weight**

If heavy building materials are used at high level all connections must be carefully detailed and robust.

## Recommendation No. 6: Avoid Structural Weaknesses in the Building Configuration

The concept design and building configuration must avoid (or take account of) structural weaknesses including asymmetry in plan and elevation.

If possible the building should be symmetric.

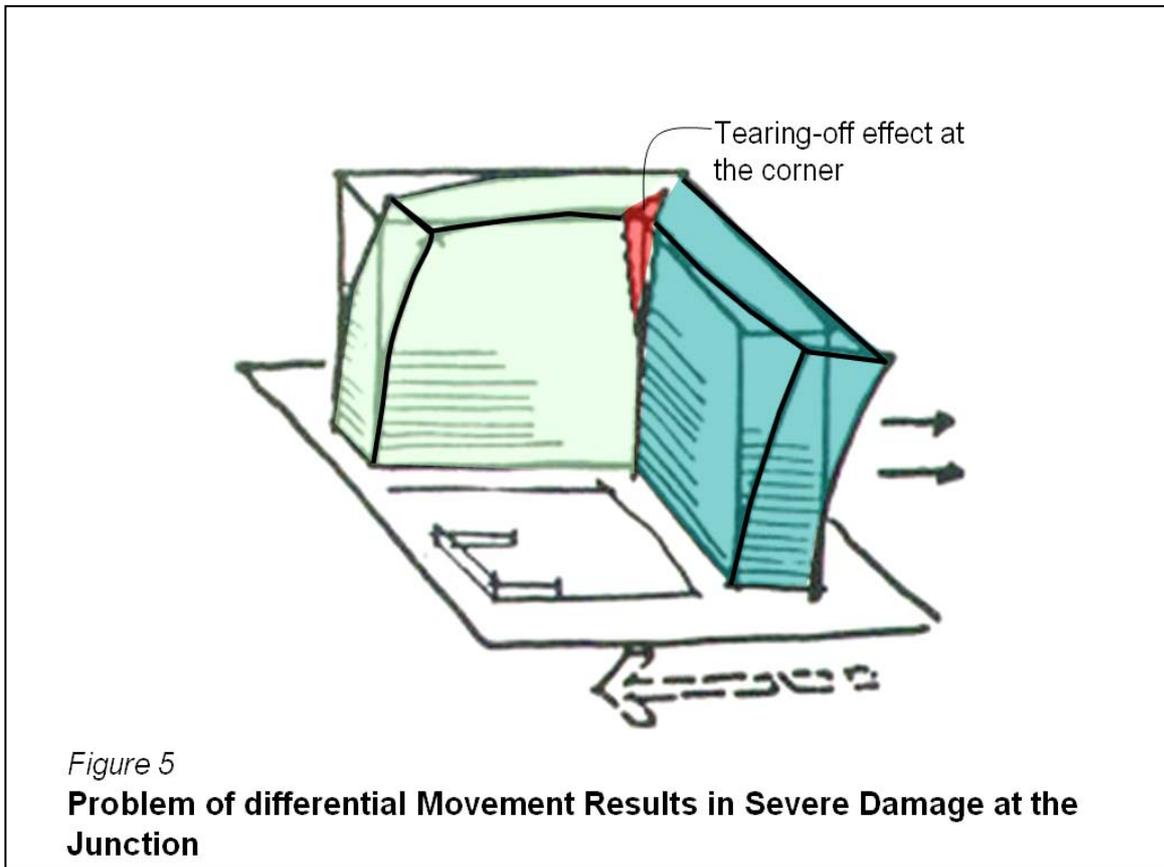
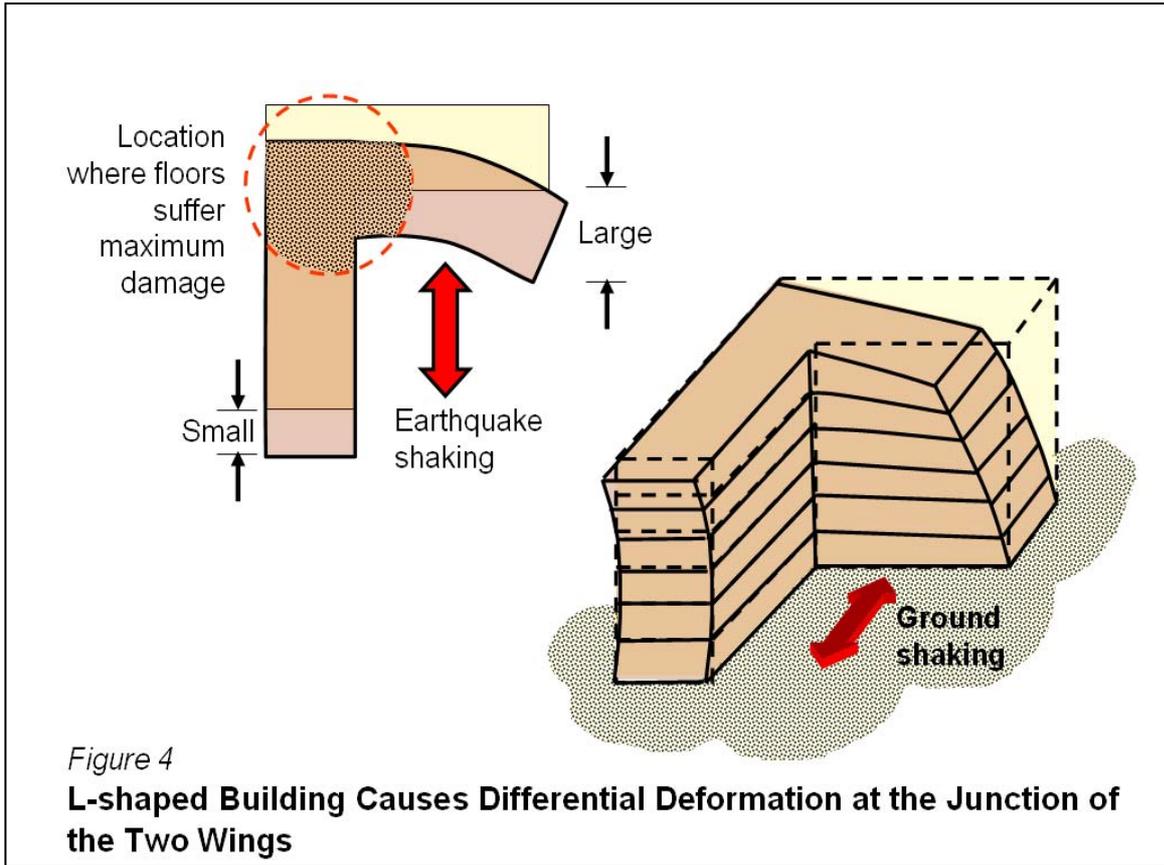
Try to achieve:

- Continuous load paths from roof to foundations
- Moderate dimensions of structural members i.e. avoid very slender columns, beams and walls (minimum dimensions are given in codes, texts and guidelines).
- Good connections between all elements, especially heavy elements
- Robust connections between structure and foundations
- Lightweight roof and other elements in upper portion of building
- Transfer of horizontal loads e.g. by use of floor diaphragms
- Good separation between adjacent buildings to prevent pounding
- Eliminate structural weaknesses such as stairs acting as struts (which redistribute seismic loads)
- Robust connections from main structure to dormer roofs, gables, other decorative features, parapets and chimneys.

Avoid:

- Soft storeys, i.e. a storey, often the ground floor, which is considerably less stiff than the other floors (refer Recommendation No. 16)
- Short column effect; where stiff part height infill panels concentrate the loads in short columns (refer Recommendation No. 15)
- Stiff *non-structural* elements that attract loads - this results in different loads paths to those assumed in design
- Asymmetry in plan leading to torsional eccentricity
- Asymmetry in elevation
- Pounding from neighbouring building, especially when floor heights do not coincide
- Large openings (doors and windows) adjacent to the corners of the building
- Large openings in diaphragm walls
- Poor connections between floor slabs and beams
- Concrete staircases which are connected to slabs at top and bottom; they must be connected at one level and allowed to slide at the other
- Heavy, weak and brittle materials in general
- Heavy roofs, especially in non-engineered buildings
- Drainpipes placed within slender columns –this practice is only acceptable if columns are sufficiently stout.

The earthquake resistance of a building must be considered from the beginning of the design process. It is much more difficult and rarely satisfactory to achieve this afterwards. If the architect requires an asymmetric building, it can still be analysed and designed to be earthquake resistant (however this is outside the scope of this booklet.)



## **Ensure adjacent buildings do not pound**

Building must have sufficient separation to ensure they do not pound together and damage each other in an earthquake.

Generally if framed buildings are separated by at least 0.01 H, pounding will not be a problem. (e.g. two 6-metre tall buildings should be separated by 60mm.) If the building floors are not aligned to within 20% vertical separation should be increased to 0.0125 H. For stiff shear wall buildings the separation distances can be reduced to 0.005 H and 0.0061 H respectively.

## **Other Issues**

Other issues can affect the overall performance in an earthquake.

- All exterior walls must be design to carry face loads (wind loads).
- Lintels over doors and windows must be properly designed.

## **Concept Design Report**

We recommend preparing a **concept design report**. This should describe:

- The primary structural systems
- The lateral load resisting system (shear walls, moment-resisting frames or braced frames)
- The loads used (seismic zone, wind zone, live loads)
- The soil conditions etc.
- Any potential structural weaknesses and note possible improvements.

## **Recommendation No. 7: Avoid Brittle Materials and Behaviour**

Brittle building materials such as un-reinforced brickwork, un-reinforced concrete blockwork and un-reinforced concrete should not be used in the primary vertical load and lateral load resisting elements.

Brittle materials tend to be stiff, weak and heavy. This means they attract more lateral loads than flexible elements. Most brittle buildings material carry loads in compression only as they have low tensile strengths.

In moderate earthquakes brittle materials tend to crack; this reduces their resistance to future lateral loads.

In larger earthquakes the brittle building materials usually fail in a sudden manner without giving any warning; after failure, brittle element often cannot sustain gravity loads, meaning the structure usually collapses.

In contrast ductile building materials are more flexible; they have the ability to sustain gravity loads without collapse (and to dissipate energy) for several cycles of lateral loads after initial yield.

Mild (and many modern high tensile steels) are ductile. Strengthening connections and columns with steel gives a structure a degree of ductility and often avoids collapse. Well-detailed timber structures are also ductile.

A fully ductile structure, usually of reinforced concrete or structural steel requires specific engineering design and detailing. Ductile engineering design is outside the scope of this booklet.

Where un-reinforced masonry is unavoidable ensure the mortar used is able to accommodate movement. A mortar made from cement, lime and sand can accommodate greater movement than pure cement/sand mortar; the lower strength associated with lime mortars is rarely a problem.

## Recommendation No. 8: Building Site and Foundations

### Avoid Potentially Hazardous Buildings Sites

Buildings should not be constructed directly above steep slopes which are liable to become unstable, or below slopes which are susceptible to landslides and rockfalls.

Do not build too close to river banks: as a guide buildings should be at least 6 metres from a riverbank *in flood*, and the floor should be at least 500mm above the *flood level*. For major rivers these figures are likely to increase.

Consider what happens to rain that lands on or near the building. How does it flow away from the building? Are new drains required? If so, where do the drains discharge?

**Buildings must be founded in good ground. The foundations are arguably the most important part of the building.** A building on poor foundations cannot perform well in an earthquake.

- The sub-grade must be sound with an allowable bearing pressure of at least **100 kPa**
- Unstable ground should be avoided
- Poor soils result in a large increase in seismic forces
- The ground must be free from water at foundation level
- If surface water is present ensure suitable drainage is installed; the drain invert level must be deeper than the foundation level
- Building should not be placed directly over fault-lines
- If a building must be constructed in a designated *seismic hazard area* it should be subject to specific design (outside the scope of this Field Manual)
- Site investigation is an essential part of every design
- Soil types, changes in layers, depth to rock, depth of water table all effect actual loads
- **Buildings must be connected to foundations (they must not be allowed to fall off foundations).**

### Foundations

Foundations should be concrete – traditional rock foundations may be used for single storey buildings but they must be constructed to a high standard by experienced tradesmen.

For all foundations

- Foundations should be designed to be stronger than the building elements above – we must avoid foundation failures
- If possible use one type of foundation throughout: e.g. piles or shallow footings
- Individual foundations must be tied together in both directions
- Ground beams should be at least as deep as columns
- Consider settlement, especially differential settlement
- Ensure all bearing pressures etc are similar
- Consider consolidation and liquefaction of the underlying soils.

**Foundation failures frequently lead to collapse or at least total economic loss of the building.**

## **Recommendation No. 9: Reinforced Concrete Shear Walls**

### **Reinforced Concrete Shear Walls**

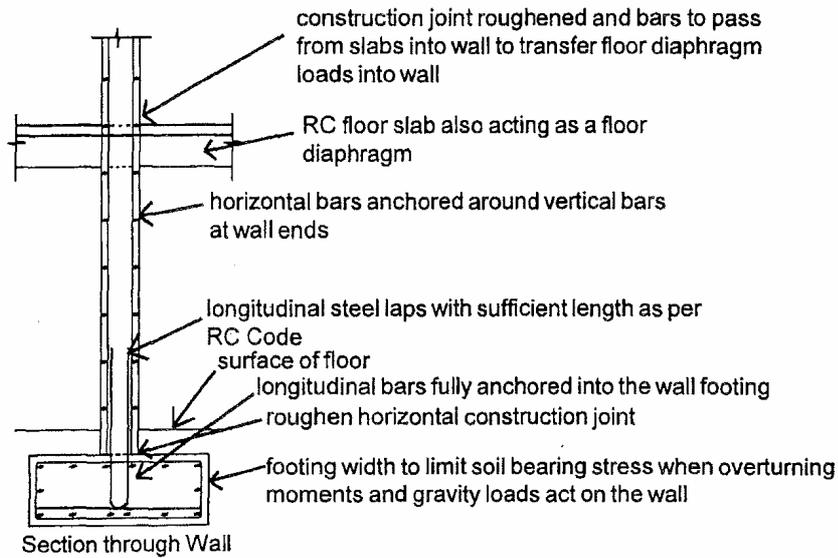
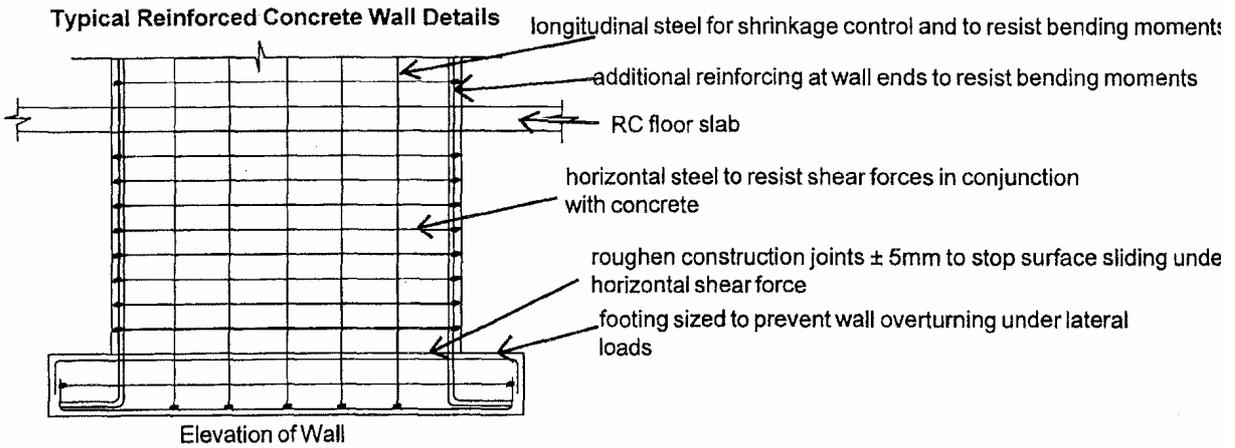
Reinforced concrete shear walls on well designed foundations are probably the best system to resist seismic loads in low to medium rise construction.

- They are less sensitive to design and construction detailing than moment resisting frames
- They are easier to control in terms of quality than brickwork or blockwork
- Walls should be distributed symmetrically and evenly in both directions (refer Recommendation No. 4)
- Walls should be continuous up the building (to ensure simple load paths)
- The footings must be sized to limit bearing pressures and prevent overturning
- Walls must be thick enough to resist face loads
- Size of wall panels must be limited to account for shrinkage (6 metres is a typical maximum length)
- Large openings in primary walls should be avoided; if large openings are required design and detail as a moment-resisting frame. Similarly avoid large openings close to corners of building.

### **Detailing - for a typical one or two storey building:**

- Minimum thickness 100mm; thicker walls will often be required
- Reinforcing steel must be in two orthogonal directions and be throughout length and height of wall
- Vertical steel; minimum bar size 10mm, maximum spacing 250mm (e.g. D10@250 for 100mm thick wall, minimum of 0.4% of gross concrete area)
- Additional wall reinforcement often required at wall ends
- Horizontal steel; minimum bar size 6mm, maximum spacing 300mm (minimum of 0.4% of gross concrete area)
- Roughen construction joints
- Ensure re-bar continuous through construction joints
- Ensure lap lengths are adequate and conform to codes
- Ensure floor diaphragms are well-connected to shear walls.

Note that for one and two storey buildings plywood shear walls can also be used.



# Recommendation No. 10: Moment-Resisting Frames

## Reinforced Concrete Moment-Resisting Frames

In order to perform well under earthquake loads the following guidelines must be followed:

- A moment-resisting frame consists of beams as well as columns
- Column - flat-slab systems rarely perform well in earthquakes
- Columns must be stronger than beams (in buildings of two or more storeys)
- Columns must not be too slender (adequate stiffness is required)
- In general beams in moment-resisting frames must be deeper than gravity-load-only beams
- Infill walls must be separated from frames
- Beam-column joints must include ties at close centres across joints (to prevent diagonal shear failure)
- Concrete strength must be at least 20MPa, preferably 25MPa
- If using high-strength steel ensure it is ductile and follow detailing rules (generally do not weld, thread, re-bend; comply with minimum bend radii)
- Supervise works to ensure re-bar is not omitted, and details are followed
- Note: In moderate to severe earthquakes some damage will occur in well-designed ductile frames; considerable damage will occur in poorly detailed frames!

### Good practice reinforcement detailing includes:

- Beam bar laps must be kept away from potential hinge regions
- Carry beam primary steel continuously through columns
- Bend beam bar end to vertical legs
- Ties are required in all beams and columns
- Reduce spacing of ties in beams at near column faces
- Column main bars to be at least D12
- Column splices to be at mid-height
- Bend column bar ends into columns
- Reduce spacing of ties in columns above and below beams (high shear zones)
- Column ties must continue through joints – closely spaced
- **Tie hooks must be 135°.**

## Beam-Column Joints in Reinforced Concrete Moment-Resisting Frames

Beam column joints are poorly understood. Inadequate joint shear reinforcement is a common cause of failure. Failed joints can lead to collapse.

Designers are under pressure to minimise member sizes. The joint becomes too congested with reinforcing steel. The builder omits some of the steel.

The joint should be stronger than the beam and the column. Design the joint steel before finalising the column size.

## Steel Moment Resisting Frames

Similar comments apply to steel moment resisting frames e.g. connections must be at least as strong as members.

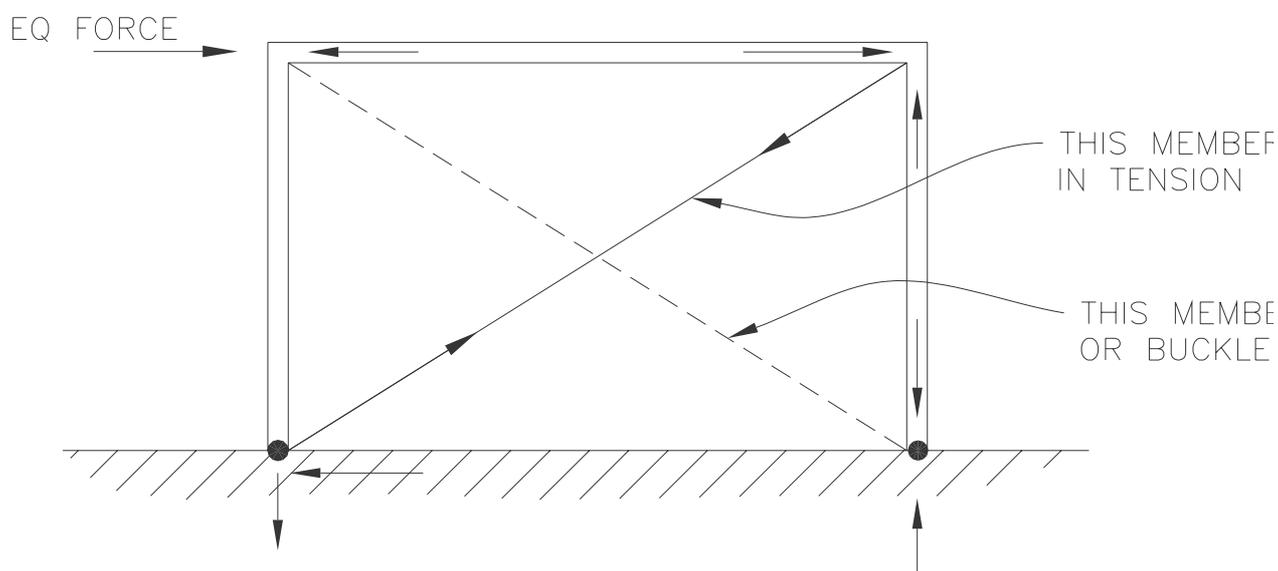
## Recommendation No. 11: Tension Braced Frames

### Cross Braced (Tension Braced) Frames

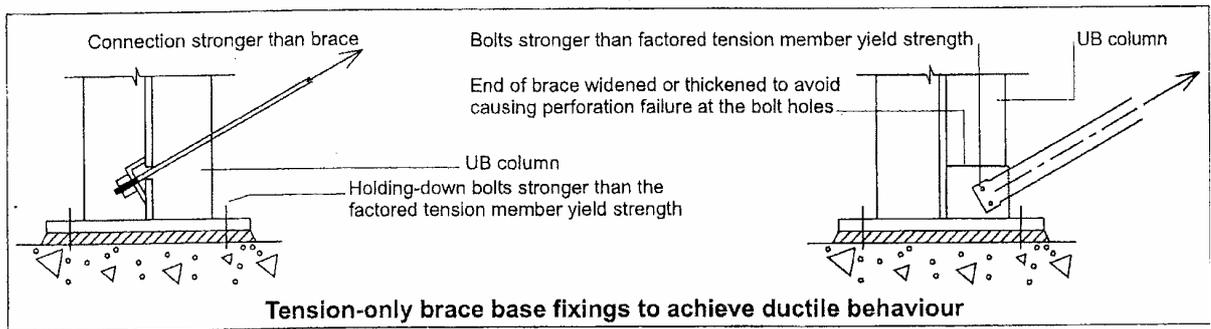
- Tension-only bracing is frequently used in low rise buildings (max two storeys)
- Tension-only bracing makes efficient use of steel, utilising its tensile strength
- When subject to lateral forces only the tension member carries load; the compression member carries no load
- As discussed above earthquake loads are cyclic; when the cycle reverses the opposite diagonal member carries the tension.

### The designer must:

- Ensure load paths are continuous
- Ensure failure is a (ductile) tension failure in brace
- Ensure all connections are stronger than member yield strength (typically 1.25x)
- Ensure the compression member does not influence the load paths; e.g. if braces are wire, cable or thin flats the compression member will buckle and not carry any load
- Diaphragm floors / roofs or bracing in plan should be used to transfer loads back to braced wall bays.



FORCES IN MEMBERS IN TENSION-BRACED FRAME



## Recommendation No. 12: Tension and Compression Braced Frames

### Tension and Compression Braced Frames

In this case both the tension and compression members carry loads simultaneously.

- Tension / compression bracing is frequently used in one and two storey buildings
- Braces are most commonly of timber or mild steel angles, i.e. members which can carry compression as well as tension
- The usual failure mechanism is buckling of the compression brace which transfers additional forces onto the tension member. This leads to failure of the tension member or of its connections
- It is preferable to detail overstrength connections to ensure the failure is in the tension member.

V braces, K braces and eccentric braces are variations of this system. They are not covered in this booklet.

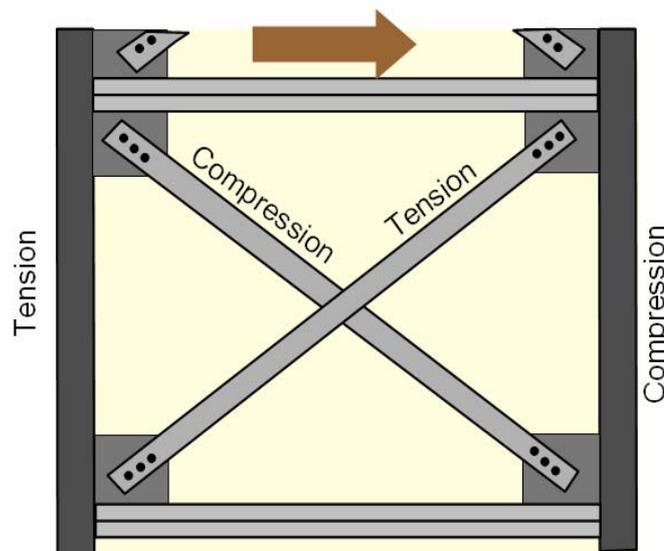


Figure 6  
Axial Forces in Members of a Braced Frame

## Recommendation No. 13: Diaphragm Floors

Diaphragm floors and roofs collect horizontal forces and transfer them to vertical elements - shear walls or frames.

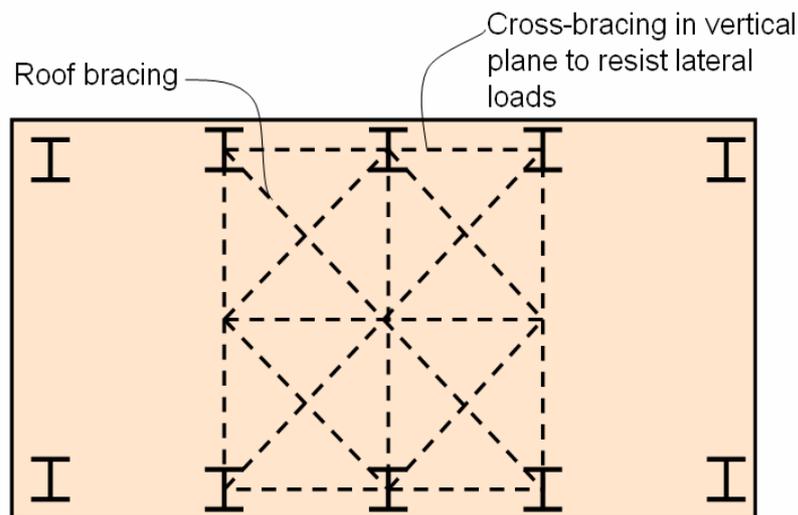
- A diaphragm can be considered as a horizontal beam spanning between two end walls or frames
- A diaphragm is defined as a member having a large ratio of area to thickness which distributes forces in its own plane.

A diaphragm may be:

- A reinforced concrete slab
- A timber / plywood floor
- Steel or timber cross-bracing in the floor.

**The designer must ensure:**

- The diaphragm must act as a single element
- Forces from the diaphragm must be transferred to the walls or frames below
- Connection must be detailed to be at least as strong as members
- Openings, especially larger openings affect the distribution of forces and must be detailed carefully.



*Figure 3*

**Plan View of Typical Tension-Only Bracing in Roof to offer diaphragm action**