



EARTHQUAKE-RESISTANT MASONRY BUILDINGS

Basic Guidelines for Designing Schools in Iran



**Division of Educational Policies and Strategies
Support to Countries in Crisis and Reconstruction**

EARTHQUAKE-RESISTANT MASONRY BUILDINGS

Basic Guidelines for Designing
Schools in Iran

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The 1990 World Conference of Education for All set the challenge of progress towards basic education for all, but man-made and natural disasters have been a barrier to the achievement of this goal. Natural disasters such as floods, hurricanes and earthquakes destroy hundreds of school buildings and other educational facilities every year, causing death and injury to children and disruption to the ongoing process of education.

We cannot prevent natural disasters from striking, but we can prevent or limit their impact by making buildings strong enough to resist their destructive forces. In the case of earthquakes, it is possible, as this study demonstrates, to neutralize their harm by applying basic engineering and planning principles that are inexpensive and not beyond the skills of most building industries.

UNESCO is in an ideal position to provide assistance in this field because of the specialized expertise available to it as well as its central position as forum for the collection and dissemination of international experience in order to achieve capacity building. UNESCO regularly publishes specialized studies and guidelines on various aspects of disaster prevention, such as cyclones resistance, fire prevention, safety in playgrounds etc. all of which can be downloaded from the UNESCO website: www.unesco.org. In this connection I am heartened to learn that the International Institute of Earthquake Engineering and Seismology in Iran, which UNESCO helped to establish in 1989, has published a Farsi edition of the Educational Building Report No.13 dealing with Protection of Educational Buildings Against Earthquakes, which was published by UNESCO in 1987.

In major crises, UNESCO ensures that there are relevant technical advisers to strengthen local capacities through training, installing functioning systems and team building. This was the case in Bangladesh, where UNESCO's role in pooling international and national resources to provide better buildings and improved satellite systems helped to mitigate the effects of the devastating cyclone which hit the country in 1990.

I am confident that this study will contribute towards the success of current reconstruction plans after the devastating earthquake which hit the states of Qasvin, Zinjan and Hamadan last June. However, the work of UNESCO does not stop here. Effective management in post-conflict situations requires reinforcement of national planning and management capacities for education in terms of institutional, physical and human resources. This is where we should now direct our attention and joint efforts.

Kacem Bensalah
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UNESCO, Paris

Masonry is the most important construction material in Iran. It has been used for public and residential buildings in the past several thousand years. A great number of well-preserved old masonry structures still exist proving that this form of construction can successfully resist loads and environmental impact.

Although some specific features have been invented during the course of time to improve the seismic behaviour of masonry buildings, such as connecting stones and tying of the walls, masonry construction remains, even today, the most venerable part of existing building stock. This is not only the case in developing countries, but it is also the case in the most developed regions of Europe and the USA.

Extensive research has been carried out during the last decades in universities and building research stations in many parts of the world on the behaviour of masonry buildings under earthquake action and the way structures can be designed to resist it. This booklet presents some of the most important aspects of this research relating to masonry construction.

It consists of three main chapters. The first chapter deals with how buildings respond to the lateral and shear stresses generated by earthquakes. The most common structural failures, such as sliding shear, cracks, overturning etc. are illustrated and the concepts of bracing, tying and anchorage are presented as the engineering devices to avoid them.

Chapter two discusses earthquake resisting solutions in some detail beginning with simple systems to more complex ideas, such as rigid frames, x-bracing and shear walls.

Chapter three presents some of the new research findings on the effect of seismic forces on masonry buildings. Performance specifications for fired bricks, concrete blocks and natural stone are explained and three common forms of improved masonry construction systems, namely reinforced masonry, confined masonry and reinforced cavity walls are described and illustrated. The general principles governing detailing principal building elements such as walls, floors, roofs etc are explained and guidelines on how to devise plan configurations with inherent seismic resistant qualities are presented.

A survey of school buildings damaged by the Qasvin earthquake was carried out as part of the preparations for this study. The results of this survey, in the form of photographs and notes, is included in the Annex.

Figures are used to illustrate most of the design ideas and the use of technical jargon has been limited to make the text accessible to a large readership. Especial attention has been paid to the protection of non-structural building elements such as partitions, windows etc. which are frequently overlooked by designers, but which cause disruption and are costly to replace.

Not everything related with the subject could have been included. Many important issues, notably strengthening masonry buildings against earthquakes and repairing the damage caused by them are missing. A book list has been included to help readers seeking information on this and other issues not covered in the booklet.

Many kind people in Iran helped the writer in various ways. He wishes to record his thanks particularly to Dr. M. Arbabzade, architect at the Organization for the Renovation, Development and Equipment of national Schools, Dr. S. Eshghi, Head of Special Structures Department at the International Institute of Earthquake Engineering and Seismology and to Dr. S. Mutawef, Research fellow at the Management and Planning Organization for their assistance and encouragement.

I. How Buildings Respond to Earthquakes

An earthquake is the vibration of the earth's surface that follows a sudden release of energy in the crust..

During an earthquake, the ground surface moves in all directions. The most damaging effects on buildings are caused by lateral movements which disturb the stability of the structure, causing it to topple or to collapse sideways. Since buildings are normally constructed to resist gravity, many traditional systems of construction are not inherently resistant to horizontal forces. Thus design for earthquakes consists largely of solving the problem of bracing a building against sideways movement. The actions illustrated in Figure 1 demonstrate combinations of the vertical gravity effects with the lateral effects of earthquakes.

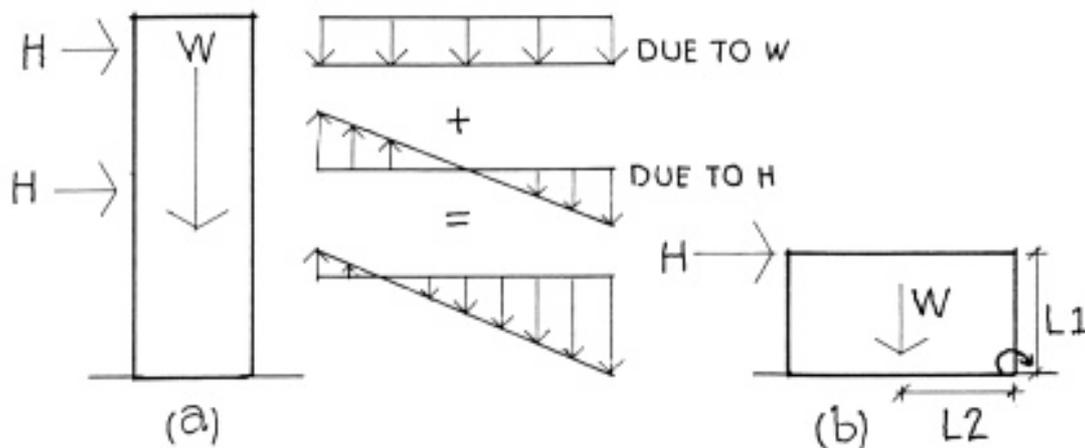


Figure 1. Effects of combining horizontal and vertical loads.
Net overturning moment = $(H \times L1) - (W \times L2)$

In most buildings this system consists in some combination of horizontal distribution elements, such as roof and floor diaphragms and vertical bracing elements such as shear walls and rigid frames.

An earthquake shakes the whole building. A major design consideration must therefore be that of tying the building together to prevent it from being shaken apart. This means that the various separate elements must be positively secured to one another. The detailing of construction connections is a major part of the structural design for earthquake resistance.

Separation Joints

When the building form is complex, various parts of the building may move differently, which can produce critical stresses at the points of connection between parts. Often the best solution is to provide seismic separation joints to ensure independent movements of the parts, as shown in Figure 2. The width of the joints should not be less than 30 mm. When the building height exceeds 9 m the width of the joints is to be increased by 10 mm for each additional height of 3 m.

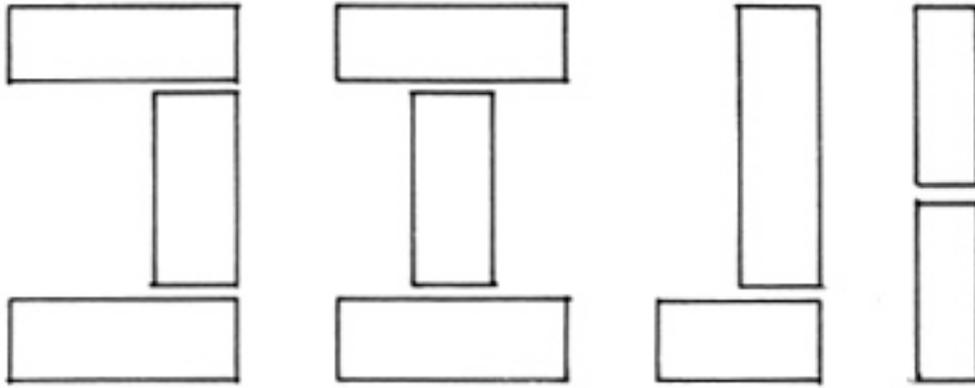


Figure 2. Separation joints

Common Modes of Structural Failure

Earthquakes subject the structure to a series of vibrations which cause additional bending and shear stresses in structural walls. Four modes of failure which must be guarded against are illustrated in Figure 3.

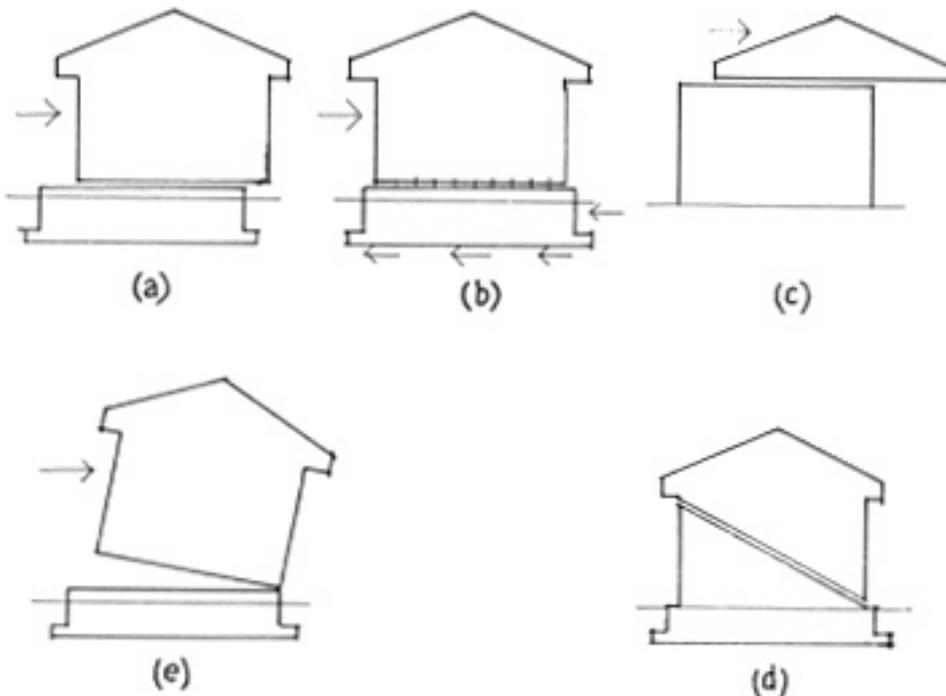


Figure 3. Typical failure modes of masonry walls subjected to seismic loads.

Figure 3-a, sliding shear, results in a building sliding off its foundation or on one of the horizontal mortar joints. It is caused by low vertical load and poor mortar. If the building is adequately anchored to the foundation, the next concern is for adequate resistance of the foundation itself, in the form of some combination of horizontal sliding friction and lateral earth pressure as shown in Figure 3-b. Sliding shear failure can also occur within the building structure, a classic case being the dislocation of a lightly attached roof shown in Figure 3-c. Figure 3-d illustrates another mode of failure, namely diagonal cracks in masonry walls when the tensile stresses, developed

in the wall under a combination of vertical and horizontal loads, exceed the tensile strength of the masonry material. Figure 3-e illustrates the effect of overturning moments. This may result in the building tipping over. The critical nature of the overturning effect has much to do with the form of the building's vertical profile. Buildings that are relatively squat in form are unlikely to fail in this manner, while those with tall, slender forms are vulnerable as shown in Figure 4.



Figure 4. Overturning effects of horizontal loads.

Nonstructural failure

While structural elements of a building should be the prime concern for earthquake resistance, everything in the building construction should resist forces generated by earthquakes. Nonstructural walls, suspended ceilings, window frames and fixtures should be secure against movement during the shaking actions. Failure here may not lead to building collapse, but it still constitutes danger for occupants and requires costly replacements or repair.

Interior partitions, curtain walls, wall finishes, windows and similar building elements are often subjected during earthquakes to shear stresses, for which they do not have sufficient resistive strength. The most common damage resulting from this is breakage of window panes and cracks in internal plaster and external rendering. A possible remedy for the former is to isolate the window frames from the surrounding walls by the introduction of flexible joints; the latter can be avoided by reinforcing the plaster or to precrack it by introducing control joints (grooves).

Site Failures

Figure 5 shows five common site failures that may occur during an earthquake. If significant in dimension site failures can cause damage to fences, retaining walls, pavements, drains and other buried piped services.

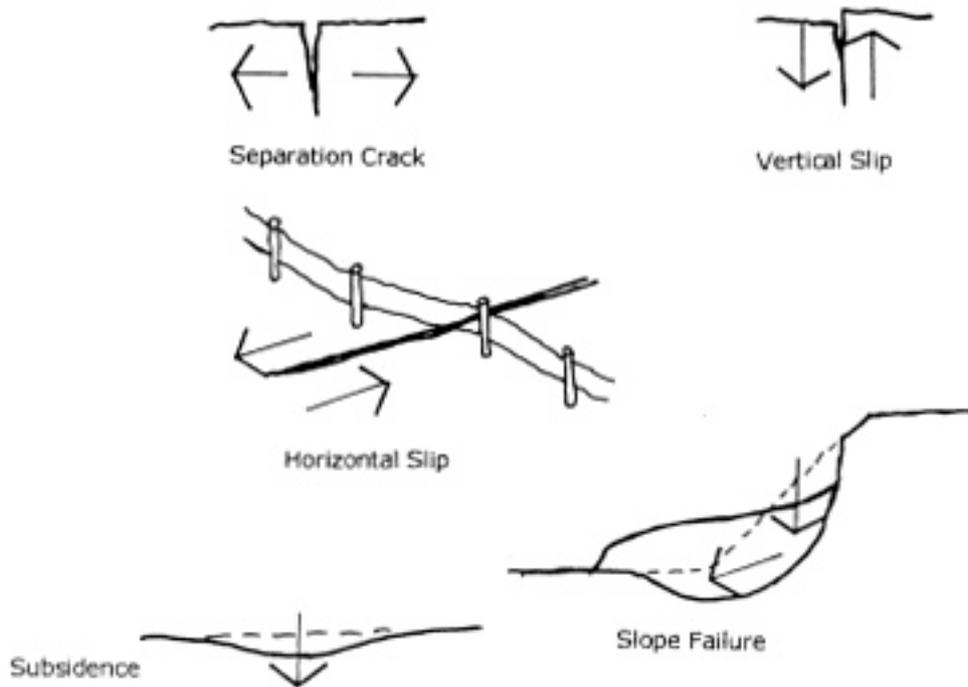


Figure 5. Common forms of site failures.

Foundation Failures

Site failures described above can cause damage to the building foundations. If the supporting ground moves, the foundations will move.

It is essential that the foundation system move in unison during an earthquake. When supports consist largely of isolated column footings, it is advisable to add ties of the type illustrated in Figure 6 in order to achieve this and to enable the lateral loads to be shared among all the independent footings.

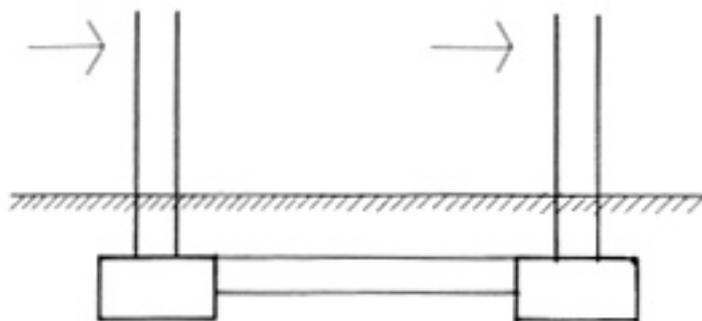


Figure 6. Tying of isolated foundations to ensure common lateral movement

II. Lateral Force-Resisting Systems

Most of our techniques of building construction focus on direct resistance of gravity forces. This is a natural result of our own experience with gravity acting on our bodies and of our handling the elements with which we build. We thus tend to produce constructions that are vulnerable to the effects of horizontal forces. Figure 7-a illustrates such a structure, a fence post, designed to resist gravity loads but is vulnerable to the horizontal load conditions shown in Figure 7-b.

Figure 7-c shows the simple solution of burying the post a sufficient distance into the ground to protect it from overturning. A solution for structures more complicated than simple posts is shown in Figure 7-d where the base is spread in order to increase the moment arm for the gravity-developed stabilizing moment illustrated in Figure 1-b. External bracing may be applied to individual structures as shown in Figure 7-e.

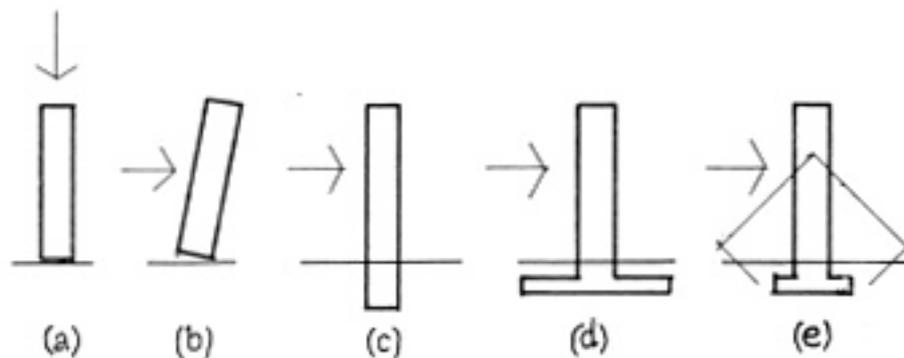


Figure 7. Resistance to overturning.

When they consist of separate elements, as shown in Figure 8-a, building frames of the traditional post and beam system lack lateral force resistance. For a single bay of such a system, stability may be achieved by:

- Strengthening the connections between the elements of the frame to make them moment resistant (Figure 8-b).
- Providing bracing in the shape of the letter (X) as shown in Figure 8-c.
- Building rigid infill walls between the columns (Figure 8-d).

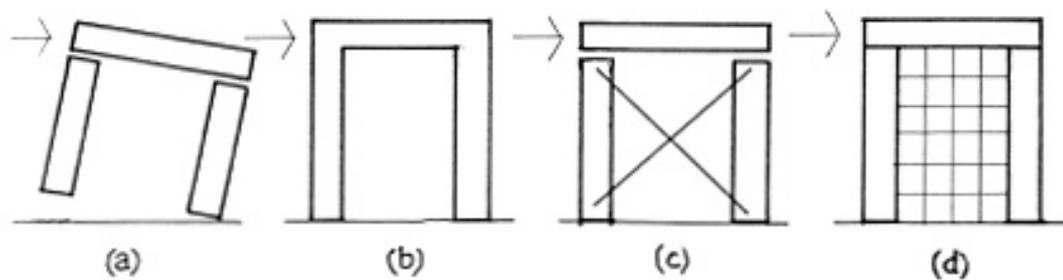


Figure 8. Bracing the laterally unstable post and beam structure.

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The solutions illustrated above are modifications applied to existing gravity-resisting supports in order to develop external stability. Other factors that influence the building's response to lateral loading effects of earthquakes are:

Building Sites

High-risk sites of the types illustrated in Figure 5 and locations with low bearing capacity soils such as expansive clay, loose sand, unstable hillsides etc. should be avoided.

Weight of the Construction

Heavy buildings are a seismic hazard. Buildings, particularly the roof and the floors should be kept as light as structurally possible.

Building Form

Symmetrical buildings of relatively simple form usually perform better than complex shapes where walls are asymmetrically distributed on the plan.

Stiffness of Non-structural Elements

It is recommended to reinforce non-structural partition walls with 4-6 mm diameter bars placed in the bed joints with a vertical spacing of not more than 600 mm.

Where weather conditions necessitate the use of reinforced concrete pitched roofs the masonry gable end walls should be anchored to the uppermost tie beams. If the height of the gable wall exceeds 4 m, intermediate tie beams should be added at intervals not exceeding 2 m, as shown in Figure 9.

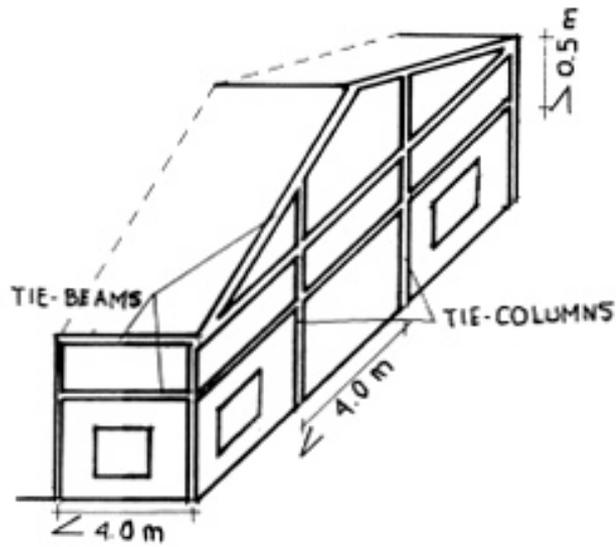


Figure 9. Method of tying gable walls.

III. Designing Masonry Buildings for Earthquakes

Masonry has been popular through the ages for its fire resistance, its thermal capacity and its durability. However the combination of weight, stiffness and weakness against tensile forces makes traditional masonry buildings highly vulnerable to earthquakes. This is not only the case in developing countries but it is also the case in the most developed regions of the world.

Vibrations caused by earthquakes generate additional loading. Shear stresses develop which cause damage to structural elements. Since masonry, which can be stressed relatively high in compression, is weak in resisting bending and shear, collapse is often the result. Consequently, masonry has, for a long time, been considered unsuitable in earthquake resisting constructions.

However, in the last few decades, considerable research on the behaviour of masonry walls and buildings subjected to seismic actions has been carried out in many countries. Use of strong mortars, high strength masonry, added reinforcement, improved detailing and the introduction of good anchorage between masonry walls and floors and roofs have enhanced the resistance of masonry to seismic stress. These improvements enable the masonry building to act as a box-type structure. Vertical gravity loads are transferred from the floors and roof, which act as horizontal tension elements, to the bearing walls, which support the floors and act as vertical compression members. During earthquakes, however, floors and roofs act as horizontal diaphragms that transfer the seismic forces, developed at floor levels, into the walls. In addition to this, floors and roofs connect the structural walls together and distribute the horizontal seismic forces among the structural walls in proportion to their lateral stiffness. Tie (ring) beams are provided at floor levels to assist the floors in connecting the structural walls.

Masonry Materials

Masonry Units

Fired bricks, concrete blocks (hollow or solid) and natural stone are used for the construction of masonry walls. In all cases the quality of masonry units should comply with the local national requirements with regard to materials and manufacture, dimensions and tolerances, mechanical strength, water absorption, frost resistance, soluble salts content, fire resistance, etc.

Stone units should be square dressed with parallel faces. Random rubble is not adequate in earthquake zones. Hollow concrete blocks should meet the following requirements:

- The holes of hollow units should not exceed half the volume of the unit.
- The minimum thickness of shells is 15 mm.
- The vertical webs should extend over the entire horizontal length and width of the unit.

Mortar

The minimum allowable mix is 1 part of cement to 4 parts of sand, or 1 part cement to 1 part of hydrated lime and 5 parts of sand.

Concrete Infill

The concrete mix used to fill holes of hollow concrete blocks where steel bars are placed should be not weaker than 1:2:4. The maximum aggregate size for blocks with 50 mm voids is 10mm; for blocks with 100 mm voids 20 mm.

Reinforcing Steel

Plain or deformed bars may be used for structures, reinforced masonry and confined masonry. Especially shaped prefabricated ladder-type or truss-type reinforcement is to be used in mortar bed-joints, as shown in Figure 10.

The vertical distance between reinforcements should not exceed 600 mm. The reinforcing bars should be anchored adequately into the tie-columns or intersecting walls. Minimum thickness of mortar cover above reinforcing bars should be 15 mm.

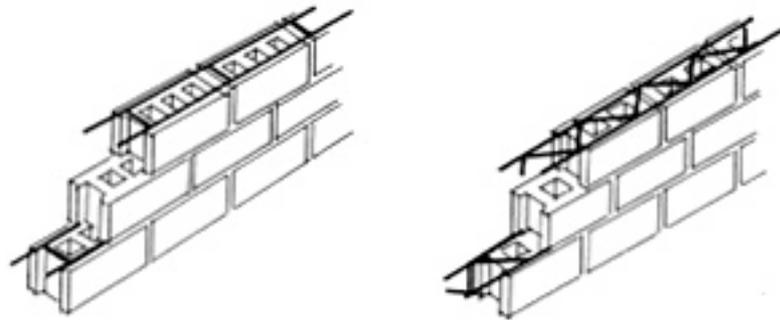


Figure 10. Typical bed joint reinforcement.

Construction Systems

Unreinforced Masonry

This form of construction is not considered earthquake resistant and its use should be disallowed.

Reinforced Masonry

Two systems of reinforced masonry are in common use:

1. Reinforced hollow units masonry.

This is achieved by placing bed joint reinforcement of the type illustrated in Figure 10 at 600 mm centres, and vertical bars as shown in Figure 11. The holes containing the vertical bars are filled with concrete as the construction of the wall progresses.

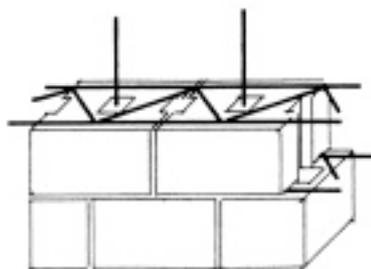


Figure 11. Reinforced hollow unit masonry

2. Reinforced cavity masonry.

As shown in Figure 12, this system consists of two leaves of masonry units, separated by a cavity into which the vertical and horizontal reinforcement is placed and the cavity is filled with either concrete infill or mortar. The leaves are usually 100 mm thick and the cavity 60-100 mm.

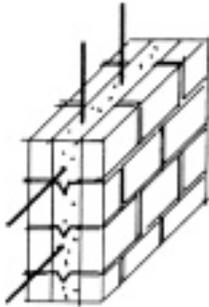


Figure 12. Reinforced grouted cavity masonry construction.

Confined Masonry

This is a construction system where masonry structural walls are surrounded on all four sides with reinforced concrete (Figure 13).

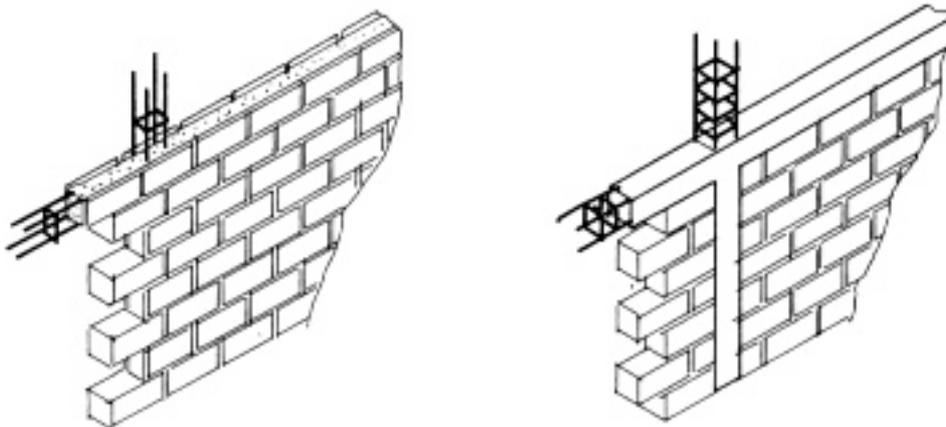


Figure 13. Methods of confining masonry.

In order to ensure structural integrity, vertical confining elements should be located at all corners and recesses of the building, and at all joints and wall intersections. In addition, they should be placed at both sides of any wall opening whose area exceeds 2.5 m² (Figure 14.)

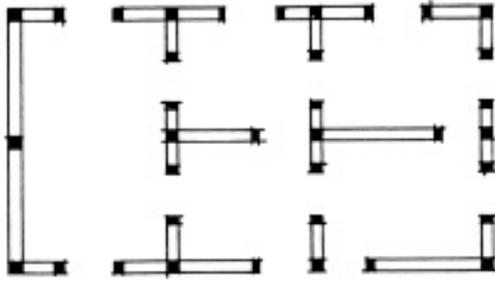


Figure 14. Typical distribution of vertical Confining elements in the plan of a building.

Walls

General Principles

- Walls are to be uniformly distributed along each principal axis of the plan.
- The minimum thickness of structural walls should be 240 mm. The total cross-sectional area of structural walls along each of the two axes should not be less than 3% of the gross floor area.
- Adequate foundations and good anchorage between walls and floors are essential.
- Distances between structural walls of reinforced masonry should not be more than 6m; distances in confined masonry should not be more than 8m.
- Partitions should be reinforced with 6 mm \varnothing bars placed at the bed joints with vertical spacing of 600 mm in order to prevent their out-of-plane instability. Partitions should be anchored to structural walls or tie columns with steel anchors.

Door and window openings

The sizes and positions of wall openings have strong effect on the in-plane resistance of masonry shear walls. When subjected to seismic loads, stress concentration takes place in the opening zones, causing cracking and deterioration of masonry. In order to improve the behaviour of masonry buildings when subjected to earthquakes, the following requirements should be met:

- Openings should, where possible, located in those walls which are subjected to smaller intensity of vertical gravity loads.
- An opening should be located not closer than 600 mm to the inside corner of its wall.
- On each storey, openings should be located in the same position along the vertical line.
- In order to provide uniform distribution of resistance and stiffness in two orthogonal directions, openings should be located symmetrically in the plan of the building.
- The tops of openings in the storey should be at the same horizontal level.

Lintels

Lintels should have a minimum of 250 mm bearing length at both ends to prevent local collapse due to crushing of supports during an earthquake. The width of a lintel should not be less than 150 mm.

If the distance between top of lintel and underside of beam above is less than 60 cm, the two should be united as shown in Figure 15-a. In the case of openings larger in area than 2.5 m², the lintel should be anchored to the tie columns as shown in Figure 15-b.

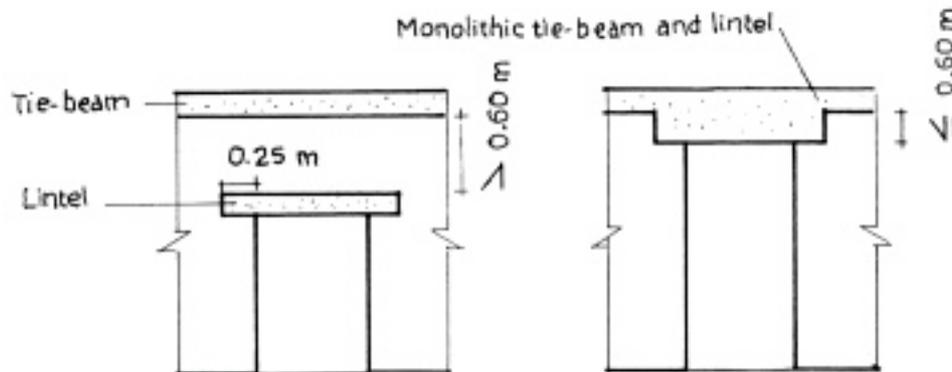


Figure 15. Typical details of lintels in seismic zones.

Double-Leaf Walls

- The traditional stone masonry construction with two outer layers of uncoursed irregularly sized rubble stones with an inner infill consisting of smaller pieces of stone bound together with lime mortar is not recommended in earthquake zones.
- Generally speaking, single-leaf walls should be preferred to double-leaf walls. Double-leaf cavity walls, where the cavity is filled with concrete, should be preferred to normal cavity walls, since they ensure monolithic behaviour of the wall under seismic conditions.

Floors and Roofs

During earthquakes, floors and roofs should act as rigid horizontal diaphragms, which distribute the seismic forces among structural walls in proportion to their stiffness. One of the main reasons for the poor behaviour of existing masonry buildings is a lack of proper horizontal diaphragm action of floor and roof structures and or lack of proper connections between them and the structural walls which carry them.

Use of timber floors and roofs in high-risk seismic zones is only recommended where the requisite carpentry skills exist and if specially designed details to ensure the integrity of these elements and their anchorage to the supporting walls.

Jack arches in lime mortar spanning between steel joists are adequate, provided the spans do not exceed 900 mm and steel cross bracing welded to corners of the outer joists above on the upper surface of the floor or roof is provided. Use of deformed bars for this is not allowed because they produce brittle welded joints.

In the case of reinforced concrete floors and roofs, two-way slabs are to be used in preference to one-way slabs. Connections to walls are to follow the details illustrated in Figure 16.

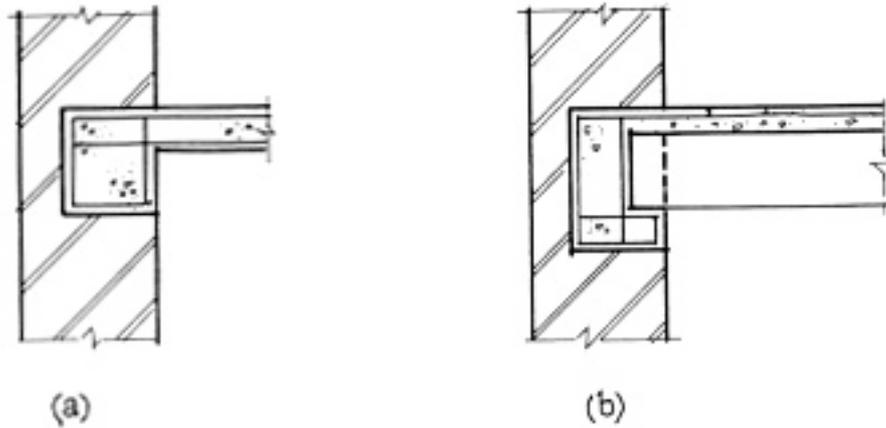


Figure 16.a. Cast in situ r.c. slab with tie-beam.
 16.b. Prefabricated slab with r.c. topping and tie-beam.

Tie Beams

The function of tie beams is to transfer horizontal shear induced by the earthquakes from the floor and roof to the structural walls. They connect the structural walls with each other and improve the rigidity of the horizontal diaphragms. Tie beams should not be smaller in section than 150 x 150 mm. The reinforcement should not be less than 4 no. 12mm ϕ with stirrups 6 mm ϕ at 200 mm centres. Reinforcement should be spliced and anchored at cornets and wall intersections. Bars should overlap by a minimum distance of 60 times the diameters of the bars.

Parapets should be reinforced vertically and horizontally. The reinforcement should be tied in with the reinforcement in the tie beam.

Cantilever Slabs and overhangs

These elements can cause harmful vertical vibration during heavy earthquakes. To reduce this, spans should not exceed those shown on Figure 17.

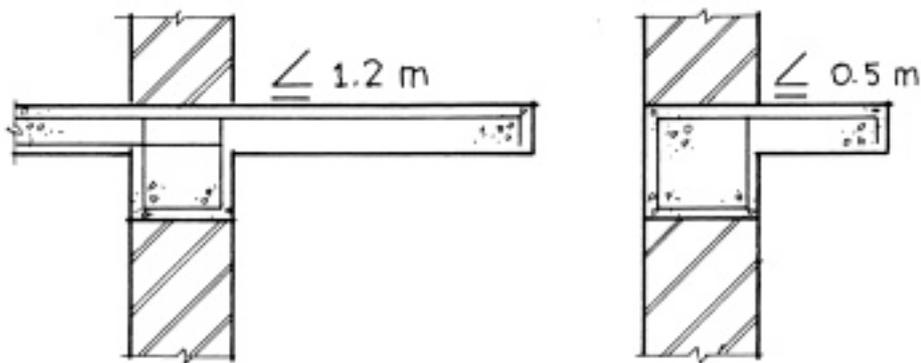


Figure 17. Typical details of cantilever slabs and overhangs.

Building Configuration

It is possible to improve the seismic resistance of a building by following these simple planning principles:

- The plan shape is to be kept simple; the length to width ratio should not exceed 4. If a building longer than this is required, separation joints as shown in Figure 2 should be introduced. The building structure should be as symmetrical as possible along each principal axis. A sufficient number of structural walls, with approximately the same cross-sectional area and stiffness, should be provided in each direction of the building (Figure 18).

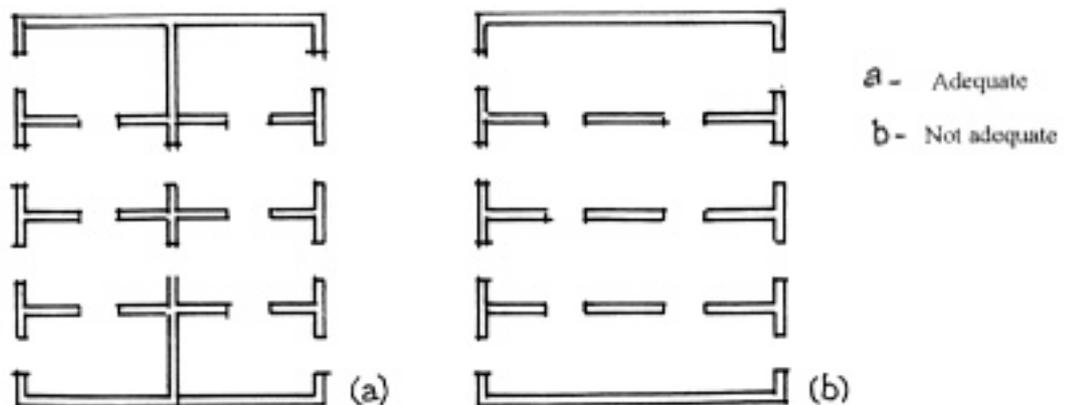


Figure 18. Distribution of structural walls in plan.

- If recesses are required, they should not exceed 25% of the overall dimension in the corresponding direction, see Figure 19.

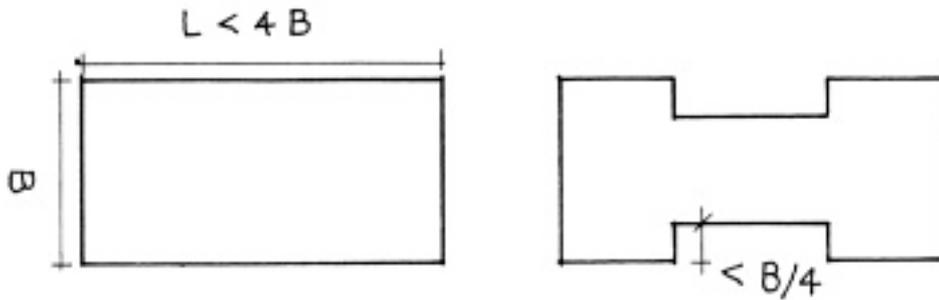


Figure 19. Masonry building plans in seismic zones.

- Number of storeys and maximum building heights are to follow the recommendations in the table below.

Construction system	Height	No. of storeys
Confined masonry	12	3
Reinforced masonry	18	4

- The elevations should be regular (uniform), i.e. top-heavy facades where mass is concentrated at upper storeys should be avoided as shown in Figure-21.

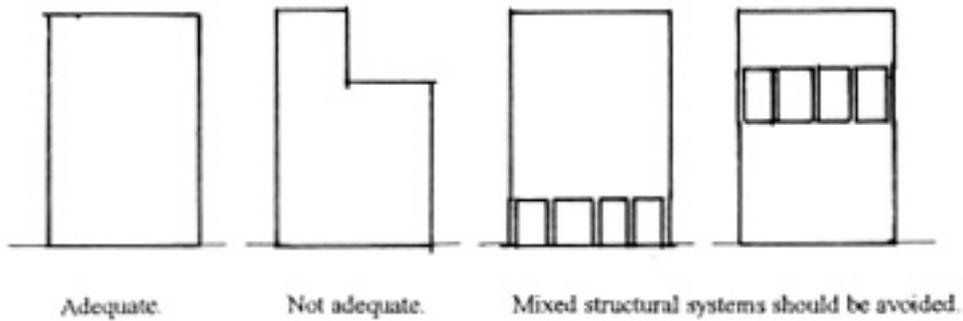
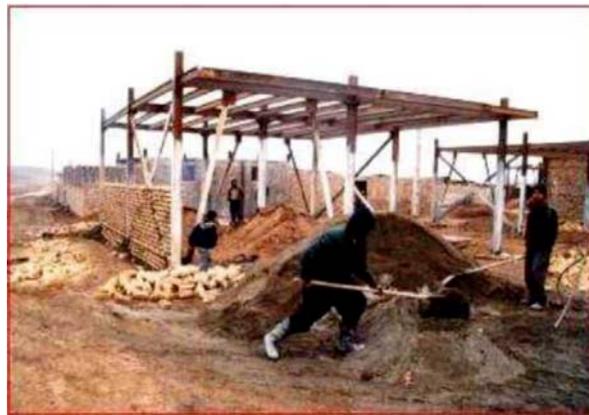


Figure 20. Building elevations in seismic zones.

The earthquake destroyed twenty-eight schools completely and damaged 137 others. A total of 16,526 pupils were affected.

The effect was felt most in the in rural areas where schools were built of unreinforced masonry. Structural failure resulted mainly from wall separation due to lack of lateral resistance and use of non-ductile materials and from dislocation of lightly attached heavy roofs. These forms of failure would have been avoided had the buildings been adequately conceived and constructed against earthquakes.

The photographs illustrate some of the positive and negative aspects of school building practice observed during the survey. They were taken during four days of fieldwork in the provinces of Qasvin and Hamadan in the first week of December 2002, five months after the earthquake.



1. Rebuilding the destroyed village of Abdoreh on the new site provided by the Housing Foundation. Bracings to walls and roof enhance the seismic resistant qualities of the structure.



2. New school on the site of the destroyed elementary school in the village of Farsajin. Tie columns anchored to the reinforcement of the foundations and, eventually, to the ring beam confine the masonry and provide lateral resistance to walls. Note heavy walls and untied roof of collapsed school.



3. New school at the village of Chuzé donated by the Japanese government. The timber structure is designed and supervised by Japanese engineers. Note the metal joints tying the brace to the truss and the eave beam.



4. Ruined classroom at destroyed village of Changorreh in the province of Qasvin. The school was built in 1970 of thick unreinforced brick walls carrying a heavy mud roof supported on timber joists.



5. School building at Dornian village in Hamadan province. Built of unreinforced walls, hence the failure under vertical shear force. The lightweight roof saved the building from total collapse.



6. District Education Office at Avaj in Qasvin province. Failure caused by stress concentration at edge of opening, because of untied lintel.



7. Hisar Wali 'Asr school in province of Qasvin. Cracks caused by Sliding shear in long boundary brick wall built without expansion joints.



8. Classroom at Gerbanlu village, Hamadan province. Horizontal crack in non-load bearing partition caused by lateral forces of the earthquake for which it was not designed.



9. Roof failure in Abdoreh. Traditional post and beam system with no rigid joints between discrete elements cannot resist lateral force.



10. Technical school at Avaj, Qasvin province is designed by ORDENS and constructed of confined masonry walls. It has survived the earthquake while a neighbouring building was totally destroyed. It has brick walls anchored to the foundations and to the rigid floors and roof by means of tie columns and ring beams.



11. The public bath building is the only standing structure at the destroyed village of Abdoreh. It has several cross- and longitudinal- walls, which act as rigid diaphragms and make the whole structure behave like a box system.

Most of the ideas presented in this booklet are based on laboratory tests and site observations illustrated in the following references.

Design for Earthquakes,

Authors: Ambrose and Vergun,

Publisher: John Wiley & Sons, 1999.

Protection of Educational Buildings Against Earthquakesⁱ

Author: Prof. A.S. Arya

Publishers: UNESCO Regional Office for Asia and the Pacific, Bangkok

Eurocode 8: Design Provisions for Earthquake Resistance of Structures

British Standards Institute, 1996

Structural Principles,

Author: I. Engel

Publisher: Prentice Hall, Inc., 1984

ⁱ Translated into Farsi by Abdolhassan Radeh and published by the International Institute of Earthquake Engineering and Seismology, Tehran 1993.