Disaster Mitigation for Low-cost Housing

1. Introduction

> Given the potential magnitude of seismic forces and general level of construction practices, it is not surprising that when an earthquake occurs, people are often safer in an open field than they are in buildings that are supposed to shelter them. Earthquakes rarely kill people, but buildings do--unless specific precautions are taken.[1]

Earthquake disasters throughout the world have taken more than one million lives in this century (not including the high toll in the China earthquake of July 1976). By far, the greatest number of victims were low-income people in developing countries. More than 80% of the deaths resulted from the collapse of small unreinforced adobe and masonry structures.[2] The heavy loss of life and property can be significantly reduced through improved building design and construction methods and by proper siting. Any attempt to establish guidelines, however, must take into consideration the cultural patterns and socio-economic conditions in developing countries as well as technical capabilities.

The need for a low-cost technology to reduce earthquake damage to structures is particularly great in many of the countries included in this housing profile, located as they are along major plate boundaries where seismic activity is frequent. While general principles in seismic design will be discussed in this paper, the focus will be on low-cost, earthquake-resistant construction.

2. Causes of Earthquake Damage

Four basic phenomena account for earthquake-induced damage: ground shaking, ground rupture in fault zones, ground failure, and tsunamis. A structure located astride a ground rupture in a fault zone would almost certainly be damaged by the resulting vertical or horizontal offset. Likewise, buildings may be destroyed as a result of ground failure which can take the form of landslides, earth lurch, settlement or liquefaction. In the latter condition, silty or sandy soils saturated with water lose their shear strength when subjected to vibration. Support systems such as water lines, sewers, transportation and communication lines are particularly liable to damage in ground failures. Tsunamis, high velocity seismic seawaves, can cause devastation in coastal communities.

1 Architects and Earthquakes (Washington, D.C.), p.x, Introduction.

2 Resa Razani, "Seismic Protection of Unreinforced Masonry and Adobe Low-Cost Housing in Less Developed Countries: Policy Issues and Design Criteria," p.1.

Most earthquake damage is caused by ground shaking, and it is the principal consideration in earthquake-resistant design. When the earth moves suddenly, seismic waves (body and surface waves) emanate from the source of disturbance, with surface objects responding to the resulting vibration. Such factors as earthquake location and depth of focus (most damaging earthquakes are at a shallow depth of less than 20 miles), length of fault break (major determinant in duration and magnitude of the earthquake), and local soil conditions (firm soils amplify ground vibrations less than soft soils, for example) have an effect on the extent of ground shaking.

Due to its geologic environment, Peru can serve as an example of a country in which all four earthquake-related phenomena are potential hazards. There was no observed surface faulting in the disastrous 1970 earthquake when the epicenter was located offshore; however, recent faults are widespread and there was surface faulting in the 1946 Ancash and the 1969 Pariahuanca earthquakes. Nor was there a tsunami in 1970, though tsunamis have accompanied previous earthquakes in Peru. The great destruction in 1970 was due principally to the poor performance of buildings (mainly poorly constructed adobe dwellings) in ground shaking and to the unstable terrain, which accounted for the massive loss of life in the Huascaran debris avalanche and for widespread damage from failure of geologic foundations in river valleys and coastal regions.

3. Effect of Earthquake on Structures

The characteristics of ground motion which particularly interest the architect or structural engineer are duration, amplitude of ground shaking, frequency and its division into vertical or horizontal components of motion. Buildings should be able to withstand extended periods of large amplitude ground motion without collapse.

Ground motion from seismic waves is transmitted to buildings through their foundations. The inertia of a building's mass resists motion applied to its base, thus creating inertial forces [F(force)=M(mass) times A (acceleration)]. The inertial forces, which exist in every component of the building, act in the direction opposite to that of ground motion. Vertical loads are normally provided for in building construction and are thus not considered in earthquake design; horizontal inertial forces must be provided for, however, in order to give a structure adequate lateral resistance.

The elastic properties and mass of structures cause them to develop vibratory motion when activated by dynamic stresses. In general, less deformable, rigid structures have shorter periods of vibration than flexible structures. It is important in seismic design to determine the probable frequency of ground motion as well as the natural period (rate of oscillation) of the structure in order to avoid resonance which can occur, particularly in tall buildings with complex deflections, when ground motion coincides with the building's natural period.

The ability of a structure to withstand seismic stresses depends on its capacity to absorb or transfer the energy released in an earthquake. When a building is able to recover its original shape after deformation, it has remained within its elastic range of deformation. Beyond this range, in the inelastic or plastic range, fracturing can occur. Materials with a limited plastic range are "brittle;" those which can withstand considerable inelastic strain (absorb energy) are "ductile." Ductility depends on design as well as on materials.

The Earthquake Insurance Classification of the Pacific Fire Rating Bureau, USA, types buildings according to anticipated damage as summarized below:

Class	Relative Damage-ability	Structure
A I	1.0	Small wood-framed structures as dwellings, not over 300 sq m and three stories.
A II	1.5	One story, all steel. Single or multi-storied steel frame, fireproof concrete, exterior concrete panel walls, concrete floors and roof, moderate wall openings; otherwise Class A V.
A III	2.0	Single or multi-storied concrete frames, concrete floors, walls, and roofs, moderate wall openings, otherwise Class V.
A IV	4.0	Large wood frames and other wood frames not included in Class I.
A V	4.0	Single or multi-storied steel frames, unreinforced masonry exterior panel walls, concrete floors and roofs.

Class	Relative Damage-ability	Structure
A VI	5.0	As Class V but with reinforced concrete frames.
A VII reduced basic rate	5.0	Walls cast in place or precast reinforced concrete, reinforced blocks, or reinforced bricks with floors and/or roofs other than reinforced concrete (reinforcement must be adequate).
A VII	7.0	Buildings with unreinforced bearing walls with lime mortar and certain multi-storied steel or concrete structures with wood floors or unusually poor design features.
A VIII	Collapse hazards in moderate shocks	Bearing walls unreinforced above, hollow clay tiles or unreinforced hollow concrete blocks.
B Special rate	0.5 to 2.0	Buildings which can resist earthquake of 1906 type with minimum to slight property damage.

Note: 1) Category A buildings are generally without specific lateral force bracing systems.

2) Unfavorable foundation conditions and/or hazardous roof tanks can increase earthquake hazards considerably.

Source: "Building in Earthquake Areas." Overseas Building Notes. No. 143, April 1972.

4. Building to Resist Earthquake Forces: Siting

Assessing the seismic risk of a location for safe siting of structures involves consideration of many factors: e.g., presence of faults, history of earthquake activity; geological conditions (record of landslides, ground settlement and warping, inundation by flooding or tsunami); physical properties of foundation soils (density, water content, shear strength, attenuation values). While generalizations concerning siting may be misleading, some comments can be made. Sites where there is a possibility of surface faulting, landslides, flooding or other hazards or where weak foundation conditions exist should be avoided if possible, or provision made in the design and construction of buildings for the mitigation of potential hazards. Structures sited in a seismic region must be constructed to withstand effects of strongest anticipated ground motion. When siting large structures, the failure of which could affect large numbers of people (dams, nuclear reactors, etc.), detailed geological-engineering studies of the area would be required.[1]

5. Building to Resist Earthquake Forces: Design

Lateral forces which are concentrated at roof and floor levels are transferred to other levels through vertical elements such as columns, producing critical shear and bending forces in these elements. Gravity load changes, caused by lateral drifting of the roof, add to bending. The use of lateral stiffening agents such as cross beams or walls acting in plane shear (those parallel to direction of ground motion) reduce drift, alter force distribution patterns.

In a shear wall system, a diaphragm (roof or floor acting as a horizontal beam) must be able to resist the inertia forces generated within it as well as a portion of those generated within the walls perpendicular to ground motion. A sheer wall must be able to resist its own inertia forces and those transferred to it. Proper connections between the two components are a third indispensable element.[2] Structures must be tied together so that components act as a single unit.

The choice of building shape is of critical importance in seismic design. The strongest configuration is a square, with rectangular shape acceptable if the proportion of long wall to short is 2.5:1. For uniform stress distribution, the structure should be balanced: parallel walls

1/ See Bolt, Geological Hazards, pp. 46-49.

2/ See A Methodology for Seismic Design and Construction of Single-Family Dwellings for a further discussion of how these components function.

approximately equal in weight, strength and height. Ideally, wall openings should match in parallel walls. The wings of buildings of irregular shape ("L", "T", or "U") may experience different movements, thus creating torsion (twisting around an axis). Failures are most common at points where wings connect. Torsion may also occur in a flexible section of a rectangular house with a stiff off-center. If a house must be built in an irregular configuration, a lightweight "crush" section between wings is recommended.

The observance of calculated separation distance between buildings is probably more important in high-rise than in low structures because of greater deformation in the former. The required distance between any two structures is determined by a formula based on calculated drift values. Even smaller structures should be far enough apart that people evacuating their homes in an earthquake would not be hit by debris from collapsing houses once they are outside.

The relationship between structural and nonstructural components must also be considered. While the effect of nonstructural elements on structural portions is most significant in cases where the former provide unexpected stiffness (e.g., non-bearing masonry walls, stair-framing), the horizontal displacement and shearing and racking action in structural elements due to drift may have a critical effect on nonstructural components and must be compensated for.[†] Such nonstructural additions as cantilevered balconies, cornices, parapets, railings create potential hazards unless properly anchored. Chimneys require special attention so that combustible material will not be near an earthquake-damaged flue.

Low-cost housing should be limited to one or two stories (preferably one in adobe construction) with floor and roof weight kept to a minimum. Low walls have the advantage of lighter weight and a lower center of gravity.

A building concept growing in acceptance in the United States, which may have applicability for developing countries, is earth-sheltered construction. Houses built partly underground are significantly more energy efficient than are those of conventional construction. While research to test the disaster resistant potential of such housing is limited, the advantages in such hazards as windstorms and fires appear obvious. Developers of earth-sheltered construction believe seismic performance would also be improved since underground structures would tend to move with ground motion rather than resisting it and creating inertial forces. As in other types of seismic construction, roofs would need firm anchoring,

[†] Architects and Earthquakes, pp. 55-67.

and areas with unstable terrain or subject to flooding would be unsuitable building sites.

6. Building to Resist Earthquake Forces: Components and Critical Connections

While it is essential that the various parts of a building be adequately connected in order to provide structural integrity, each component requires attention in planning and construction to ensure satisfactory performance during an earthquake. The use of proper construction techniques is very important; poor building practices can undermine good design.

6.1 Foundations

A strong foundation can dampen earthquake effects. The following guidelines are suggested:

- Base of foundation should be below top soil and frost level (at least 45 cm).
- Foundations should not span both soft and hard ground.
- Foundations of separate wings should also be separate.
- Resisting walls of adobe buildings should rest on wall foundations extending above ground level to protect against moisture.
- Wall footings should be continuous with building tied into footings.
- Footing width should be 1.5 times wall thickness or at least 35 cm for single-story house.
- Water pipes and drains require special attention to avoid escape of water into foundation soil during an earthquake.
- Care must be taken in backfilling building and sewer excavations to prevent earth settlement adjacent to building.

6.2 Walls and Openings

Unreinforced bearing walls of masonry and adobe, in such common use in many developing countries, are particularly susceptible to earthquake damage, the failure being due to racking shear (initiated by cracks at points of high stress such as corners of openings), out-of-plane bending from transverse forces, or a combination of both. Faulty connection between roof and walls and walls and foundations is another cause of failure. Filler walls within load-bearing frames have the same structural weakness.

The use of stabilized adobe and locally available reinforcing materials (e.g., split cane, bamboo, wire mesh) can significantly improve seismic resistance of adobe walls. The extension of reinforcement into adjacent walls and foundations provides structural unity.[1]

Walls can be strengthened, too, by the use of a ring beam to tie walls together, thus preventing tensile cracking at upper corners.

Wall openings, which require effective reinforcement to prevent failure of adjacent piers, should be kept small and a minimum of one meter away from corners and from each other. (See illustration.) Ideally, doors should open to outside to allow quick evacuation of buildings in an earthquake.

Care must be taken to avoid damaging structural members (columns, walls, slabs) in the installation of piping.

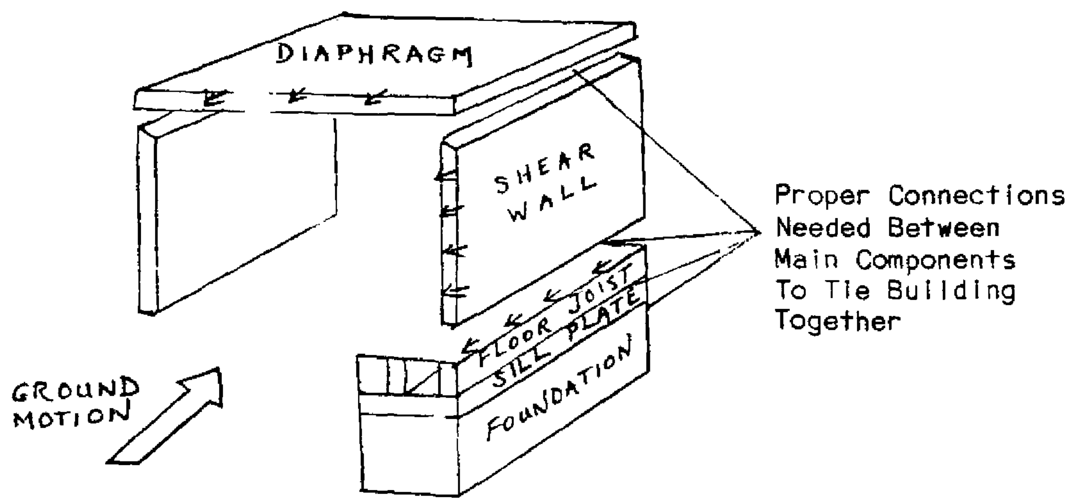
6.3 Roofs and Upper Floors

The collapse of heavy roof systems in earthquake-damaged houses is a major cause of death and injury. Failure may be due to insufficient strength, inadequate connections, or rupture of supporting walls or columns. The system's configuration determines the type of failure. The rupture of the bottom chord in a roof truss, for example, may cause walls to fall outward. On the other hand, the separation of abutting walls can result from the failure of a roof to act an a unit and to transfer loads to lateral (shear) walls. (See illustration.) The roof or floor elements must be provided with sufficient in-plane stiffness to enable them to act with diaphragm action in transferring lateral forces.

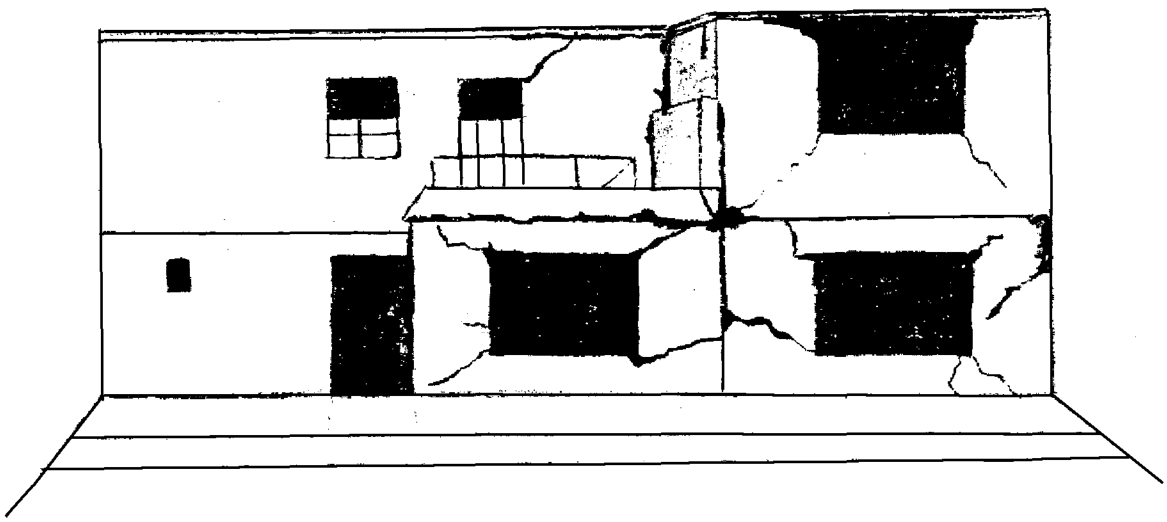
The substitution of lightweight roofing material (e.g., lightweight panel systems, corrugated asbestos sheeting, corrugated metal, grass or palm leaves) in low-cost housing for the commonly used tile or mud can greatly improve a building's seismic performance. A four-sided roof also offers advantages: the trusses more evenly distribute the weight of roof and earthquake forces; it requires less reinforcing and thus can be lighter; it eliminates need for a gable, which is a dangerous feature if not built cf lightweight material. All trusses should rest on the ring beam (not on the walls themselves) and be properly bolted.[2]

[1] Three methods of reinforcing adobe walls (a reinforced concrete system, the Modern Adobe System, and a cross-brace system) are discussed in detail by Frederick C. Cuny in Improvement of Adobe Houses in Peru.

[2] Cuny, pp. 23-24.

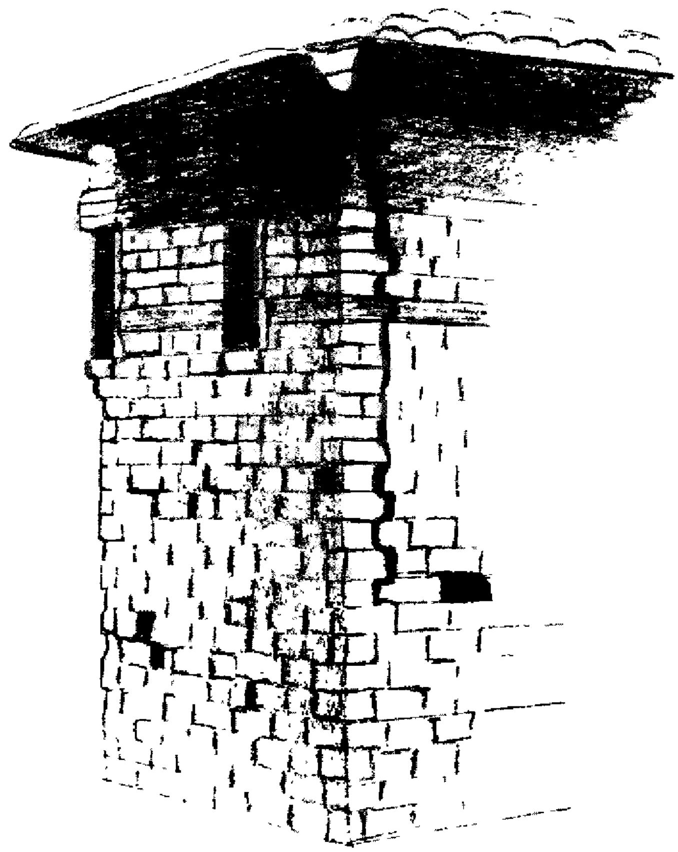


It is necessary in a lateral load-resisting system to use proper connections in order to transfer load through diaphragm, from the diaphragm to the wall, down through the wall by means of proper nailing of shear-resisting materials, proper connections of sill plates at the base and, when required, installation of hold-down anchors and proper reinforcing in footings. (<u>A Methodology for Seismic Design and Construction of Single-Family Dwellings.</u>)



To prevent this type of damage, wall openings should be smaller, better reinforced at corners; adequate tie-beams and sufficiently long lintels are required; connections between roof, wall, and floor levels must be stronger.

Source: Design, Siting, and Construction of Low-Cost Housing and Community Buildings to Better Withstand Earthquakes and Windstorms, p. 16.
(Drawing after photograph)



During an earthquake, roof fails to act as a unit and does not transfer loads to lateral (shear) walls. Instead, the frontal wall (with openings) receives roof thrust, separating it from lateral walls.

Source: Design, Siting, and Construction of Low-Cost Housing and Community Buildings to Better Withstand Earthquakes and Windstorms, p. 19.
(Drawing after photograph)

7. Building to Resist Earthquake Forces: Materials

As indicated above, different materials behave differently in the inelastic range. Ductile materials such as steel can undergo considerable permanent deformation without breaking. Such brittle materials as brick, glass and unreinforced concrete, on the other hand, experience sudden failure at or near the elastic limit. Seismic performance is improved by reinforcement of brittle materials and the use of ductile connections.

A lack of quality control in the manufacture of building materials (much of which is done on site) is often a problem in developing countries.

7.1 Concrete

Concrete is versatile, durable and fire-resistant, but it is weak in tension and therefore requires reinforcement with such materials as steel, fiberglass or bamboo. Steel rods, which are capable of absorbing tensile stresses, function particularly well with concrete. Care must be taken to see that reinforcements are properly positioned and anchored. Concrete should be thoroughly mixed in a special mixer, never on a soil face, and properly dried and cured. A main cause of failure of reinforced concrete members in an earthquake is the poor execution of concrete joints. Concrete joints should be located as specified (based on stress analysis) and kept clean during construction.

7.2 Masonry

Because of its low tensile strength, masonry (brick, stone) needs reinforcement. Mortars must be durable, especially in structures subject to extreme cold or structural stresses. Masonry walls should be securely tied to the reinforced concrete confining frames. A better anchorage is formed if the masonry wall is built before the columns and tie beam are concreted. Some common causes of masonry failure:[1]

- Excessive sagging (more than one thirtieth of thickness).
- Poor quality of mortar; carelessness in curing.

[1] Low-Cost Construction Resistant to Earthquakes and Hurricanes, pp. 104-105.

- Unsuitable bricklaying techniques.
- Incomplete filling between bricks.
- Use of fragile, poorly baked bricks.
- Improper arrangement of bond and placement of bricks.
- Failure to meet specifications for fastenings and separations between masonry and main structure.

7.3 Soil

The low cost and ready availability of natural earth account for its widespread use in many developing countries. A major weakness of adobe, its lack of moisture resistance, can be at least partly overcome by the use of high foundations, eaves, stucco covering and stabilization, the latter an important breakthrough in improving the durability of adobe blocks and bricks. The kind of asphalt used in stabilization is determined by the type of soil. Generally, those with sand and/or silt content of more than 45% are not suitable for reinforcement. Main construction faults affecting stability of adobe houses:[1]

- Poor adobe-making technique.
- Use of insufficiently dried adobe.
- Incomplete covering in horizontal layer and incomplete fill of vertical joints between blocks.
- Poor geometrical quality of the walls.
- Poor interlocking at wall intersections and lack of proper fastening.
- Walls built too rapidly (the maximum vertical rate should be one meter per day).
- Failure to lay courses along the whole contour of the walls (instead of in isolated panels), thus causing possible differential settlement.
- Lack of continuity in timber tie beams.
- Poor execution of wall coverings.

7.4 Wood

Wood has good strength in both tension and compression, making it especially suitable for construction of bending-resisting elements. Among its many uses: wood joists and plywood panels for roofs and floors, sand-

[1] *Ibid.*, p. 110.

wich panels for exterior walls. It is not readily available, however, in all areas (e.g., coastal Peru) and, thus may be costly. Alternatives such as raw timber, cane, bamboo, palm or thatch may be substituted for some purposes. Protection is needed against moisture, fire and insects.

7.5 Metals

With high strength, stiffness and ductility, steel is widely used, as bars and wire mesh, for reinforcing concrete and masonry. Other uses of metals in low-cost construction include corrugated sheet metal of galvanized steel or aluminum for lightweight roofing and siding; steel connectors for bolting and anchoring; rods and cables for bracing.

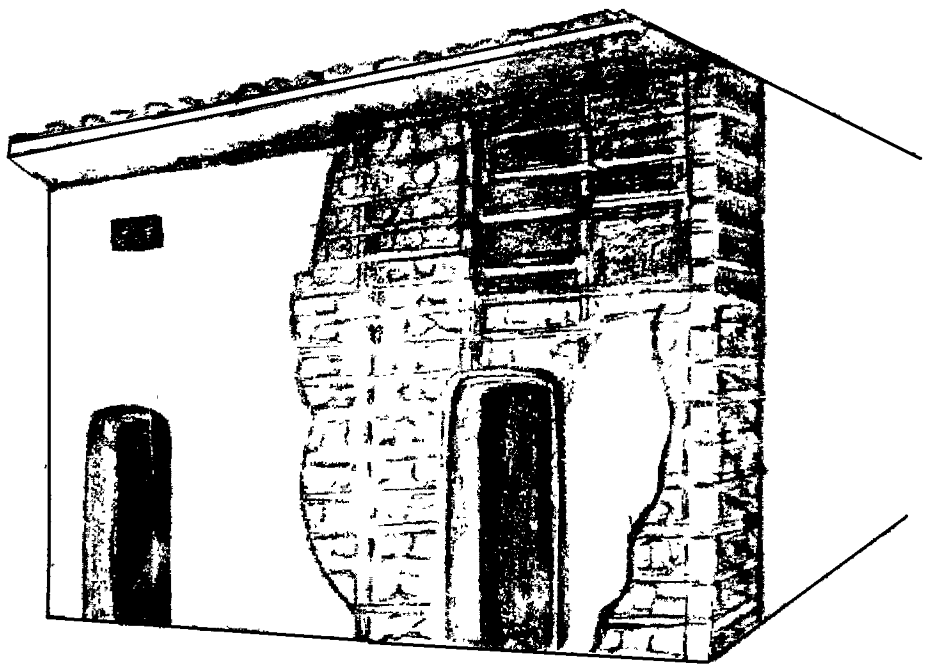
8. Building Codes

Progress in the development and implementation of low-cost, earthquake-resistant housing requires continued action in the areas of finance, design and construction, and education. Needed, too, is improvement and better enforcement of building codes in many earthquake-prone countries. The lack of feasible codes can often be attributed to the following problems:[1]

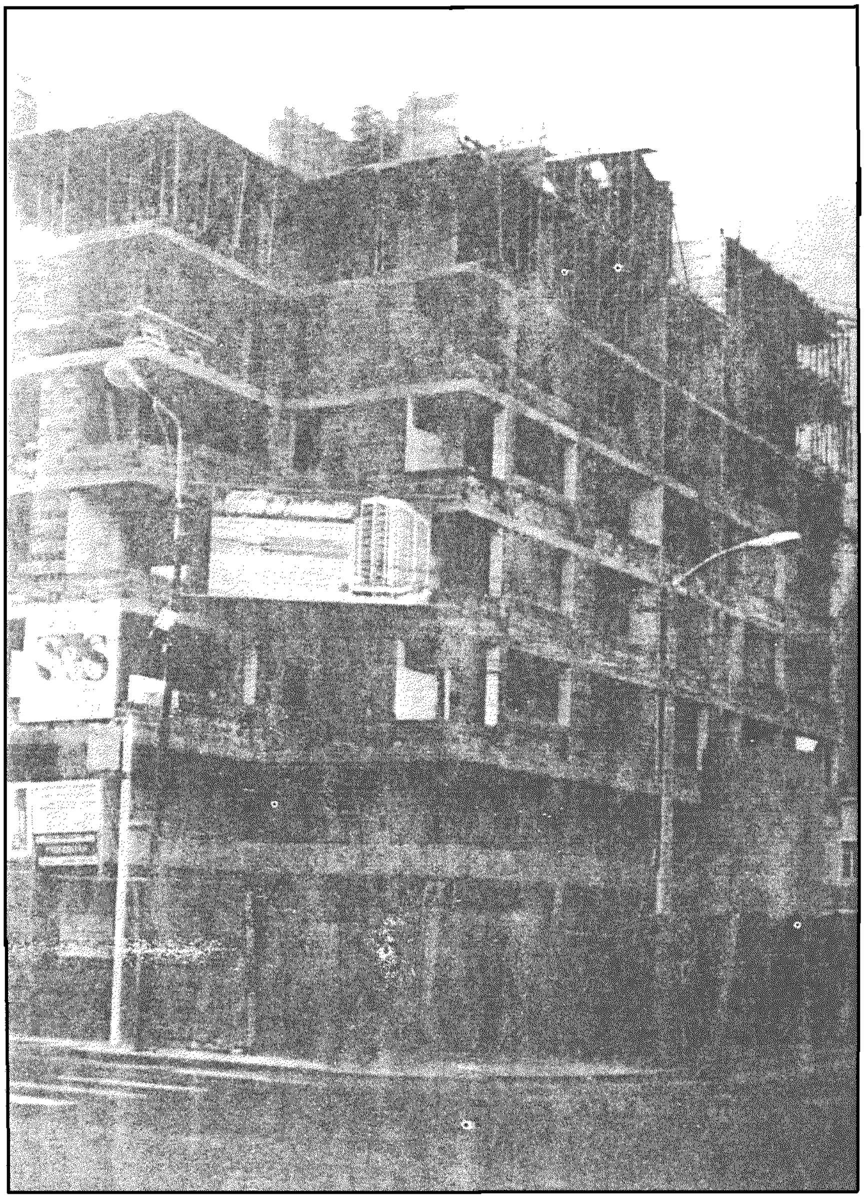
- Technical design limits are not known due to lack of study of local materials and construction systems.
- Geological and soil conditions have not have been adequately studied.
- Seismic records may not be available.
- A reliable system of inspection and enforcement may be lacking.

Building codes must be compatible with local conditions (which may vary from region to region within a country) and with local capabilities if widespread evasion is to be avoided.

[1] Design, Siting, and Construction of Low-Cost Housing and Community Buildings to Better Withstand Earthquakes and Windstorms, pp. 89-93.



Building facade showing traditional taquezal construction. The severe damage suffered by th's type of construction in the 1972 Managua earthquake resulted in great loss of life.



Multistory building under construction in Bogota, Colombia. This appears to be of a type of construction, common in many countries of Latin America, in which non-structural masonry walls and partitions are enclosed within a reinforced concrete structural frame. Although the integrity of this particular building cannot be assessed from a photo alone, the type of construction described is vulnerable to earthquake damage. (Photo by Oliver Davidson, Regional Preparedness Officer - Latin America and the Caribbean, US Office of Foreign Disaster Assistance.)