Damage to buildings in Latur earthquake

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A comprehensive assessment of damage caused to residential buildings in Latur earthquake is presented. The buildings, which are mostly non-engineered, have been classified based on the materials used for construction and their performance during the earthquake. The possible causes of damage, and the shortcomings in the prevalent construction practices have been clearly identified. On the basis of the analysis presented, it has been concluded that the performance of these buildings can be significantly improved through the use of simple earthquake-resistant features. The information presented herein may be useful in developing practical strategies for rehabilitating and retrofitting existing buildings in this region.

AN earthquake measuring 6.4 on Richter (IMD) caused widespread damage in the south-eastern region of Maharashtra. The main shock, which occurred at 3:56 a.m. on 30 September 1993, was preceded by several dozen fore-shocks over the previous one year, while after-shocks have also occurred at frequent intervals since the main shock. Interestingly, the epicentre of the earthquake lies in Zone I of the relevant Bureau of Indian Standards code[1], which implies lowest probability of large earthquakes in this region (Figure 1).

This earthquake seriously affected buildings and other infrastructure in Latur and Osmanabad districts of Maharashtra. It resulted in the death of over 9,000 people and damaged property worth several crores of rupees. In some of the badly affected villages, a significant percentage of residents perished and all residential constructions were either severely damaged or destroyed. Limited damage was also caused in the adjoining districts and the shock was felt as far away as Bombay and Madras. Since the magnitude of damage is disproportionately high for magnitude 6.4 earthquake, it is essential to thoroughly understand the causes for this damage.

The authors visited the affected region about one week after the main shock. Following an extensive survey, residential constructions found in this region were divided into different types. Each type of construction was examined in great detail to determine the causes of damage and to identify weakness in constructions. This report first identifies the construction practice prevalent in the affected region followed by a scrutiny of the performance of buildings in the following section. Possible causes of damage are also discussed and the strengths and weaknesses of each building type clearly identified.

The information presented here can be used for a comprehensive assessment of damage caused to buildings by Latur earthquake. It can also be used to assess the potential of damage in adjoining areas with similar construction practice. The analysis presented herein should prove instructive in developing earthquake-resistant guidelines for future constructions, as well as practical strategies for rehabilitating and retrofitting existing buildings in this region.

Prevalent construction practices

Latur and Osmanabad districts, as well as most regions in western India, overlie the Deccan traps (Figure 2) which are solidified basaltic lava flows. These flows are heavily fractured and weathered near the surface and black-cotton soil of variable thickness covers the flows at most locations. Abundant stone rubble formed by the weathering of basalt constitutes the basic construction material. Almost all buildings in this region are made of stone masonry, although modern materials such as kiln-baked brick and reinforced concrete are also used in some.

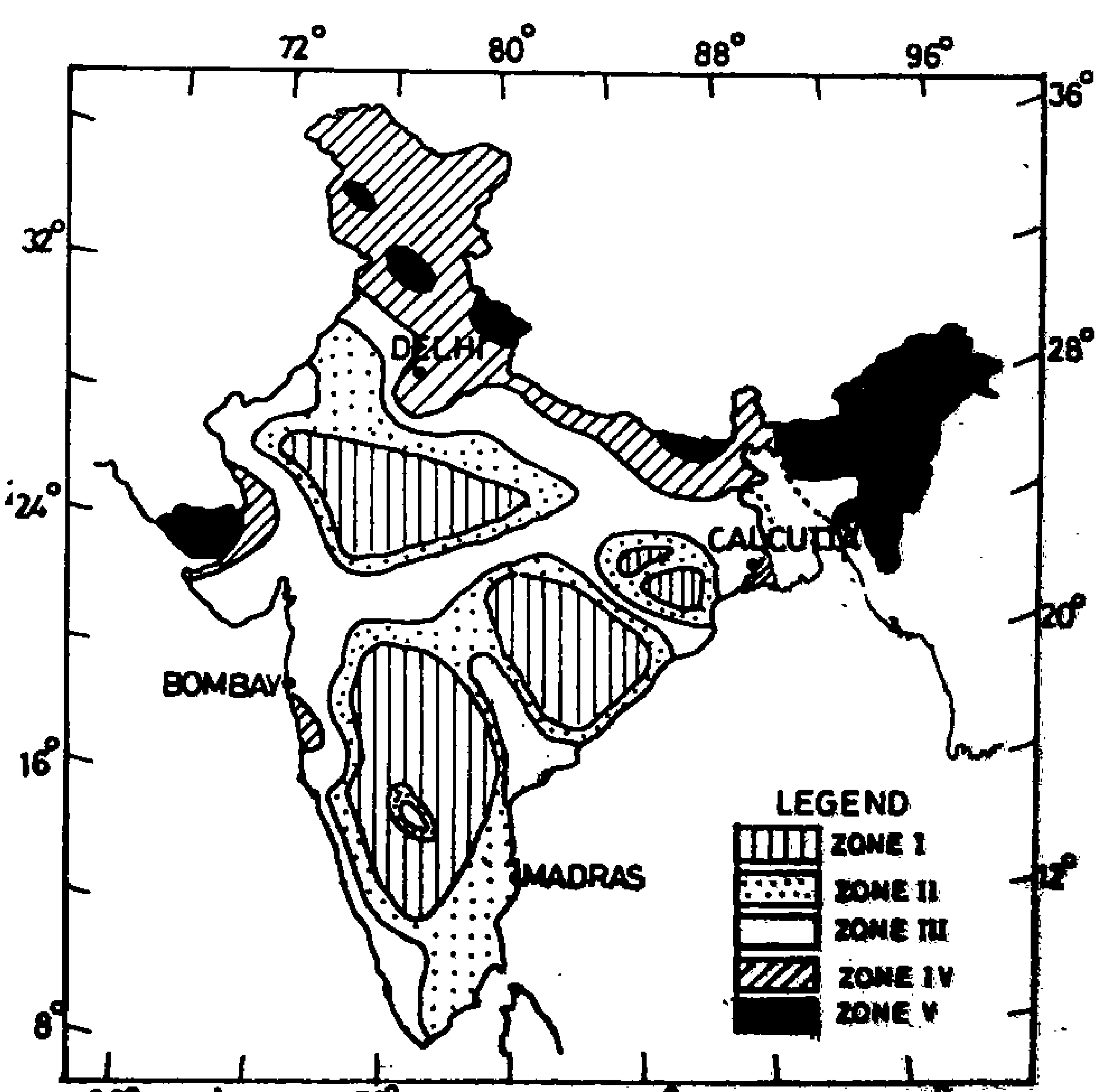

Figure 1. Seismic zoning map of India[1].

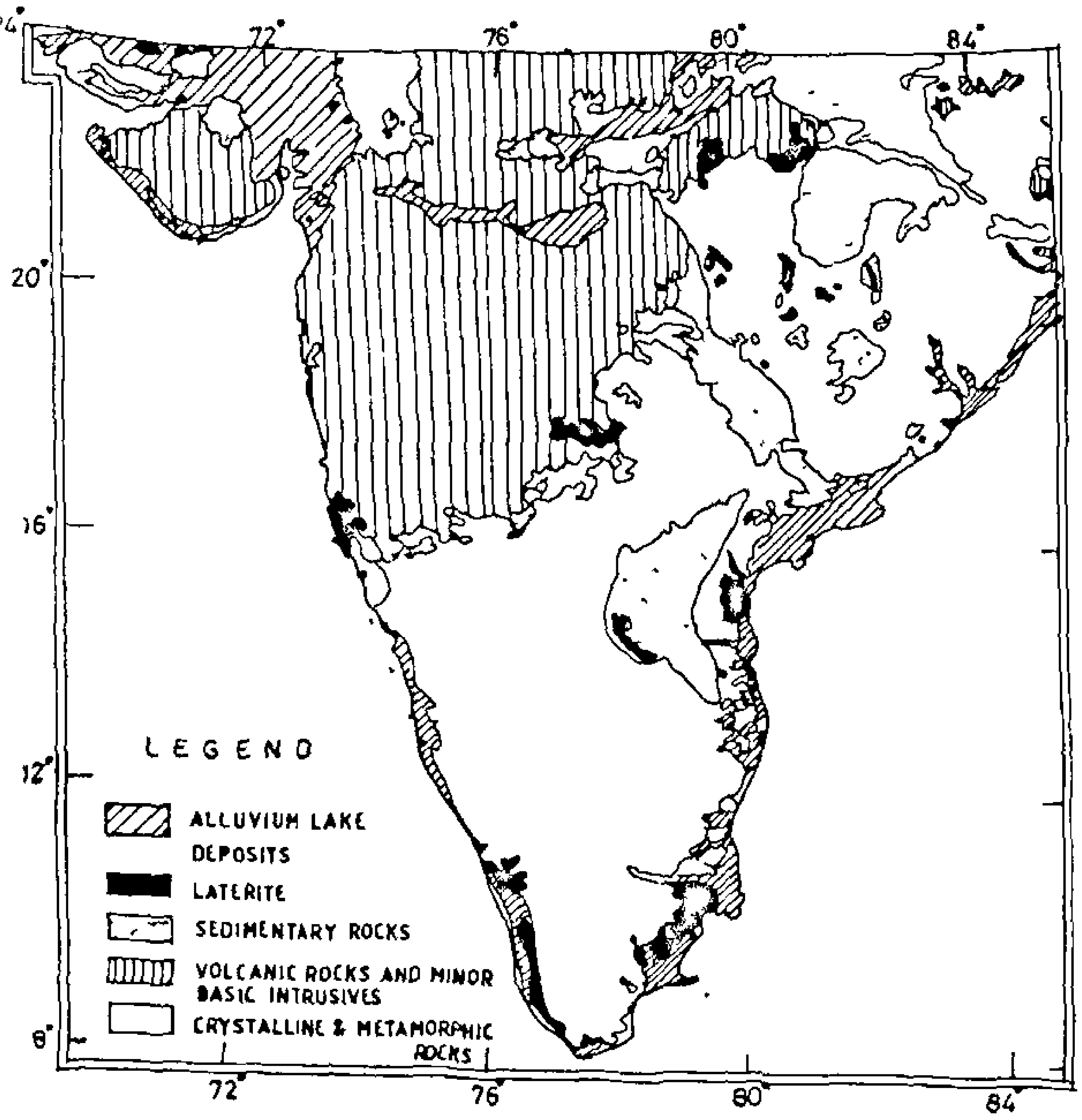

Figure 2. Map showing principal lithological groups[1].

Almost all buildings in the most severely affected areas are non-engineered constructions, i.e. built without specialized engineering assistance. On the basis of the materials used in construction, the buildings can be divided into two main types: (i) buildings with mud mortar and (ii) buildings with cement mortar. Some recent constructions, designed by qualified engineers and constructed under their supervision, have been classified separately as buildings with earthquake-resistant features. A brief description of the main features of the different types is given next.

Buildings with mud mortar

These are single-storied traditional buildings having stone masonry walls with mud mortar used as the binding material. The foundations in these buildings are provided by extending the walls downward to the hard rock level. At locations where the black-cotton soil is deeper than 4–5 m the walls are extended to a depth of about 4 m to act as a foundation. The stone masonry walls are typically about 600–1000 mm thick. The stone rubble blocks that are used in these constructions have rounded edges and are not usually shaped into rectangular blocks. The masonry pieces vary in size from 100 mm to even 600 mm along their longest axis. The inside wall surfaces in rooms are made smooth by interlocking the masonry blocks properly, whereas the outside surface is generally made smooth with small rubble pieces and mud filling (Figure 3).

Wooden planks or galvanized iron sheets supported on wooden joists are most commonly used as roof. A thick layer of mud (up to 300 mm thick) is often placed on the roof to provide insulation. In older constructions, the joists are supported on wooden columns at regular intervals along the walls. The wooden frame and columns are tied together to act as an integral unit (Figure 4). In most new constructions, however, the joists rest directly on the walls. In these constructions, there is no continuity between the roof and the members that carry its weight (Figure 5), making the structure vulnerable to earthquake forces.

Buildings with cement mortar

Both stone and brick masonry houses, mostly non-engineered, have been constructed in this region using cement mortar as the binding material. The building dimensions are similar to mud mortar buildings but the walls are 600–1000 mm thick even with brick masonry (Figure 6). The walls in stone masonry constructions have field stones of greatly varying sizes and shapes. Some brick masonry buildings have stone masonry between the lintel and roof level (Figure 7). The foundations of all these buildings are similar to those of the corresponding mud-mortar buildings, provided by extending the walls below the ground level.

Several of the buildings had traditional roofs using wooden planks and a layer of mud. In all buildings that were inspected, the weight of the roof was carried by the walls and no alternate vertical load-carrying system was used. In some brick masonry constructions using cement mortar walls, the roof consisted of reinforced concrete slabs, typically 75 mm to 100 mm thick. While it was not possible to examine the details of their reinforcements, they obviously had adequate strength.

Buildings with earthquake-resistant features

A few buildings in the affected region were built using reinforced concrete frames with in-filled walls. One building that had brick masonry load-bearing walls with a lintel band was also observed. The reinforced-concrete building used square columns of about 250 mm size to carry vertical loads (roof weight). The beams were 300 mm to 400 mm deep and about 250 mm wide. The brick masonry building was constructed using 230 mm wide wall and a reinforced concrete band (100 mm thick) at lintel level. It was not possible to determine the details of reinforcement in the beam, columns, slabs, or the lintel band. In the buildings that were inspected, pile foundations up to a depth of about 4 to 5 m were found to have been used in black cotton soil

Performance under earthquake

An earthquake induces rapidly oscillating horizontal motion to the base of the buildings that results in the development of mass proportional inertia forces[2]. Heavier members, such as the roof in traditional constructions, apply a large lateral force to load-bearing walls and to columns on which they are supported. Similarly, thicker and heavier walls develop much larger inertia force than lighter walls. The deformation of walls caused by these forces in turn leads to shear and bending stresses in walls and columns.

The behaviour of each type of building under earthquake excitation has distinct characteristics. Evaluation of the response for the third type of building is of great engineering importance, as it can be used to evolve practical and, following the earthquake, *tested* techniques for retrofitting existing buildings, and for future constructions. None of the buildings that were examined showed distress at the foundation level. The traditional foundation systems appear to have adequate strength against earthquakes of the magnitude that occurred. No further discussion of the performance of the foundations will therefore be made in subsequent analysis.

Buildings with mud mortar

Mud mortar is known to have very poor shear and tensile strength. Consequently, the strength of walls to resist lateral forces that develop under earthquake excitation is very low. In addition, the mud layer on roofs of traditional buildings (Figure 4) has a significant mass and generates a very large inertia force. Consequently, the lateral strength to mass ratio for these buildings is very low. Therefore these constructions developed wall cracks or collapsed partially even at considerable distances from the most affected areas (up to 75 km from the epicentre). In regions close to the epicentre, almost all buildings constructed with mud mortar showed very severe distress or collapse of walls.

In buildings where the roof was supported on a wooden frame, the frame was usually found to be intact without any visible distress. The walls of fewer constructions of this type had collapsed compared to those supporting the roof weight. The wooden frame exhibited much better resistance to inertia forces produced by the roof mass than the load-bearing walls. The application of inertia force by the roof at the top level of walls, consequently, led to partial or complete collapse of buildings where the weight of roof was supported on walls.

In most buildings where the masonry blocks had excellent interlocking along the inner walls surface, damage to walls had initiated on the outer surface. The presence of cement plaster on the inside surface may have provided additional resistance against inward collapse of walls. Consequently, under earthquake excitation, such walls mostly collapsed on the outside rather than crush the inmates sleeping inside the house. This single factor had the most significant influence in lowering the fatality rate in spite of near total destruction of houses. In walls that were constructed without proper interlocking, the collapse direction had no apparent preference.

Buildings with cement mortar

A large percentage of buildings constructed using cement mortar was damaged in the most affected region. However, very few houses of this category had collapsed. These buildings, therefore, exhibited better resistance to the earthquake than the mud mortar buildings. This is of course expected; for cement mortar, if properly used, develops large resistance to shear force even though it may crack easily under tensile forces. The performance of these buildings, as a result, depends on the dominant stresses that develop in walls. Walls that are subjected to large shear forces are more resistant to earthquakes than walls subjected to large tensile forces. The presence of openings for doors and windows in a wall lead to development of very high shear and tensile forces at the corners, making the wall more vulnerable.

Most cement mortar buildings that were partially or fully destroyed had a traditional roof. The walls of these buildings had collapsed or developed large cracks at several locations (Figure 8). These cracks invariably included a corner of an opening, which was most likely the origin of crack. When the openings were very close to each other, these cracks had coalesced and resulted in partial collapse of the walls (Figure 9). It appears that the mortar strength controlled the performance against earthquake forces since no cracks were observed in masonry blocks.

In buildings that have reinforced concrete roofs, the roof slab acts as a diaphragm if it is properly tied to the walls. The diaphragm ensures that the walls on opposite side of a house move in tandem. Since the walls act as a combined unit, the earthquake resistance of these buildings is expected to be much greater than that of buildings in which the walls act independently. Very few houses that had roof slabs and cement mortar walls collapsed in the earthquake. Several constructions developed deep wall cracks originating from corners of the openings. These cracks were either horizontal caused by tensile forces, or diagonal caused by shear forces. In walls that had several openings close to each other, or where an opening was very close to an edge, the development of cracks had also led to partial collapse of the walls (Figure 10). However, such cracks did not usually imperil the integrity of the building, and injured very few inmates during the earthquake. Resistance

Figure 3. Typical wall cross-section in mud mortar constructions.

Figure 4. Typical vertical load-carrying system in traditional constructions.

against such cracks can be greatly increased by strengthening the walls at the level of openings, i.e. at lintel level and sill level of windows and lintel level of doors.

Stone masonry buildings showed much greater distress than brick masonry buildings for both types of structure systems discussed here. There are two main reasons for this difference in performance. Firstly, the stone masonry walls had much lower lateral strength to mass ratio. Secondly, the stone masonry blocks usually consisted of weathered random rubble. The weathered layer on

Figure 5. Typical roof-wall connection in traditional constructions with load-bearing walls.

Figure 6. Brick masonry building showing size of walls and orientation of cracks.

the surface disallowed a good bond from developing between the masonry blocks and mortar. Under earthquake excitation, the surface of these rubble blocks acted as weak planes and delaminated easily, leading to easy propagation path for cracks.

Buildings with earthquake-resistant features

The main categories of earthquake-resistant houses found in the earthquake affected area are reinforced-concrete (RC) frame constructions and brick masonry constructions with lintel band. The RC frame constructions, if properly designed for ductility, are expected to withstand very severe earthquakes with repairable damage.[1] Buildings with lintel band offer protection against lateral forces by strengthening the walls at lintel level. Since most cracks tend to initiate from the corner of windows and doors at lintel level, the strength of the building

Figure 7. A building with both brick and stone masonry in the same wall

Figure 9. Partial collapse of brick masonry walls due to coalescence of cracks.

Figure 10. Stone masonry building with partial collapse of walls at corner.

Figure 8. Typical cracks in brick masonry walls.

against these cracks is significantly increased. Moreover, the lintel band is continuous over the building perimeter[4], and therefore, under earthquake excitation, it forces the building to behave as a box, resulting in all walls acting as an integral unit. This leads to much greater resistance to earthquake forces than is possible for brick walls that act independently or when the walls are coupled only through a roof slab.

The reinforced-concrete building that was examined in detail was situated in Killari, which is very close to the epicentre. Under the earthquake excitation, small cracks developed in half-brick thick partition walls, and

Figure 11. An undamaged building with lintel band surrounded by collapsed non-engineered constructions.

no significant cracks were observed in the beams and columns. The level of damage that was observed is consistent with that expected for this type of building under magnitude 6.4 earthquake.

A recently retrofitted building at Killari with lintel band performed quite satisfactory during the earthquake. A few superficial cracks were observed (about 2 mm wide and only plaster deep) at sill level of walls. Since in a building without any earthquake-resistant features, cracks are always formed at lintel level before sill level, the performance of this building clearly demonstrates the effectiveness of a lintel band. It is noteworthy that all other constructions surrounding this building were totally destroyed in this earthquake (Figure 11).

Discussions and conclusions

Buildings in the areas affected by the Latur earthquake can be divided into three types. The first consists of traditional buildings in which walls were constructed using stone-rubble masonry with mud mortar. The walls in these constructions had very low resistance to earthquakes and their collapse caused most of the fatalities. Load-bearing walls with cement mortar, used in the second type of buildings, equipped them better for earthquake resistance than mud mortar buildings. Although these buildings were also widely damaged by the earthquake, the extent of damage was limited. The buildings with earthquake-resistant features showed only superficial damage and demonstrated the adequacy of such constructions to withstand earthquakes similar to Latur earthquake.

Based on the investigation of damaged buildings in Latur and Osmanabad districts, the following conclusions can be drawn:

1. The foundations in traditional buildings, that are formed by extending the wall below the ground level, did not show any distress due to this earthquake. In new constructions using traditional materials, therefore, a foundation using the stone-masonry strip footing is adequate from earthquake considerations.
2. Buildings constructed using mud mortar walls have very poor resistance against earthquake forces, and collapse easily. This is due to improper interlocking of random-rubble stone masonry.
3. Traditional constructions, where the roof is supported on mud mortar walls, resulted in more casualty than constructions where the roof is supported on wooden frames. An alternate vertical load-bearing system, similar to the wooden frame, can therefore be used for retrofitting traditional constructions.
4. Buildings that are constructed using cement mortar do not possess adequate strength to withstand moderate earthquakes. The performance of future constructions using cement mortar can be improved by using the stone masonry blocks properly, and by providing a lintel band.
5. The performance of a building with lintel band, which is economical to construct, was at par with the performance of a RC frame building which is much more expensive. Furthermore, the local builders and masons can easily be trained to use this simple earthquake-resistant feature. Consequently, the use of lintel band must be encouraged to enhance the earthquake resistance of new constructions.

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