13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2563

IMPLICATIONS OF DESIGN AND CONSTRUCTION DECISIONS ON EARTHQUAKE DAMAGE OF MASONRY BUILDINGS

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SUMMARY

The Kutch earthquake striking at 8:46 AM. on January 26th, 2001 proved disastrous for the Indian state of Gujarat. Building structures rolled on the ground killing thousands of people and the earthquake poured a calamity of intense misery down the spine of the Indian nation. This unfortunate event provided a sad opportunity to civil engineers and architects to introspect into what went wrong from the point of view of the performance of the civil engineering structures even after standard guidelines for design, construction and strengthening of structures exist in the country. Indeed, there are many diverse factors whose combined effect determines the degree of damage in a structure. In last fifteen years India faced six damaging earthquake which revealed the implications of design and construction decisions on damage of buildings. Present paper is based on the damage survey conducted by the authors after these earthquakes and brings out some special observations on factors affecting the damage. Some of these are not even attended by the codal provisions. This information gives additional in-depth information about increased vulnerability to buildings. The study will be useful for disaster mitigation in future and for further research needed.

EARTHQUAKE EFFECTS

An earthquake is a natural phenomenon, it causes a complex ground motion that for computational ease can be resolved into, two horizontal and one vertical component of ground vibration. The main effects of the earthquake are ground shaking, ground failure, tsunamis and fire. The ground motion causes the vibration in any structural system standing on ground. This shaking generates horizontal and vertical inertia forces in the structural system and in its contents because of the mass they have. This is called dynamic loading that involves several reversals of loads. This means earthquake force continuously changes its magnitude and direction till the structure vibrates. Most buildings are able to resist vertical loads, but are unable to resist lateral loads, because it tries to over turn the buildings. As a result the buildings are subjected to tensile and shear stresses in addition to compressive stresses. This leads to destruction of these man made masonry structures, as these materials are weak in tension.

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BEHAVIOR OF BUILDINGS DURING PAST EARTHQUAKES

The type and extent of damage to the structure during an earthquake depends on the strength of the materials, used for construction, the structural system, joint details, quality of construction, the foundation stability and strength, maintenance, besides the intensity of earthquake shock. In past all over the world about 75% of fatalities attributed to earthquake are caused by collapse of buildings Coburn A. [1]. Out of these about 70-80% of victims died due the collapse of masonry buildings. These masonry building include adobe, mud, stone and brick building. Worldwide fatality data shows a slight reduction with time, because total number of fatalities in the year 1900-1949 had average fatalities of 16,000 per year, which reduced to 14,000 per year in next 50 years. The trend is good, as in nineties the fatalities were 11,600 per year. However this reeducation is insufficient, if it is compared with increase in world population that is doubled in every fifty years. As the population is more in developing countries they are becoming more vulnerable to earthquake risk as compared to developed / industrial countries. Moreover industrial countries are putting enough efforts for disaster mitigation by adopting earthquake resistant technologies for their structures Coburn [1], Nigam [2].

BUILDING PRACTICES

In any region building construction is controlled by four major factors, economic conditions, social and cultural aspects, climatic requirements and availability of material. In India building construction practice has wide varieties ranging from Ekra to Reinforced Concrete. However most common types are earthen, stone and brick buildings. In any developing country, most of the population lives in these buildings. The masonry is used with reinforced concrete framed structure also as non-structural material. However, the objective here is to discuss the masonry buildings that are load bearing structures. These buildings are having box like system of walls. These walls support all load coming on the building. Material wise buildings can be classified as follows.

- **a.** Random rubble field stone in mud mortar
- **b.** Sun dried bricks in mud mortar or earthen buildings
- **c.** Dressed stone in weak mortar including mud mortar
- **d.** Burnt bricks or prescast cement concrete blocks in weak mortar including mud mortar
- **e.** Burnt bricks or cement concrete blocks in rich mortar
- **f.** All above types in combination timber frame

The above six classes can further be classified in number of types of buildings depending upon the roof /floor system like having inclined roof of heavy stone tiles or tin sheet or asbestos sheet, flexible floor/roof, rigid brick masonry floor/ roof, prefabricated floor/roof, concrete foor/roof.
However, on the basis of behaviour shown by various types of buildings during past earthquakes they could be classified in three categories Bose P.R. [3].

Engineered Buildings

These buildings are designed and constructed to resist seismic forces in addition to gravity loads as per existing knowledge of earthquake resistant technology. Some of the traditional buildings in earthquake prone areas will also be classified as engineered building.

Semi Engineered Buildings

These buildings are mostly designed and constructed to resist gravity loads only, as per codal provisions of the country, may be because of lack of knowledge of earthquake resistant technology. Beside this it includes the well-constructed building using strong materials by qualified builders on the basis of experience and not having any earthquake resistant measures.

Non Engineered Buildings

These are poorly built buildings using local weak materials like mud, stone, unburnt or burnt bricks and timber etc. Most of these buildings are private dwellings built by local artisans or contractors or by the owner himself, without any technical knowledge of building design and construction. These buildings are not engineered to resist the lateral forces generated by earthquakes.

TYPES OF DAMAGES

Earthquakes are intelligent faultfinders. They always look for any mistake committed by designer or builder. Even well designed building may not behave well if it is not well constructed and maintained. However as the type indicates engineered buildings will withstand a shock well may be with economically justified repairable damage without any collapse. Semi engineered buildings may show large amount of damage and even partial collapse to complete collapse may be there. Non-engineered building is the easiest target for earthquake that will be destroyed by it. It is natural that the extent of damage will also depend on the intensity of shock and location of building. It is essential to look into the type of damages that have occurred in such low cost buildings during past earthquakes. Different types of damages in such types of buildings are briefly presented herewith [4].

Nonstructural damages

The non-structural damages do not impair the strength or stability of a structure but may sometimes be the sources of falling hazards.

- Cracking and overturning of parapets
- Falling of plaster
- Cracking and overturning of partition walls
- Cracking and falling of ceilings
- Falling of loosely placed objects

Damages in Roofs and Floors

- Dislodging of roofing material
- Separation and fall of roof truss from supports
- Complete roof collapse due to the collapse of supporting structure
- Failure of the joints connecting columns and girders in wooden trusses
- Failure of wooden gable frames due to the rupture of bottom chords

Damages in Bearing Walls

- Failure due to longitudinal shear
- Failure due to bending in the transverse plane
- Failure of gable end masonry walls
- Failure of spandrel beams
- Failure due to torsion
- Failure of masonry arches
- Separation of walls at corners and T-junctions
- Delamination and bulging of walls leading to their collapse in stone walls
- Outward overturning of walls

Damages in Foundations

- Failure of foundation due to inadequate depth
- Differential settlement
- Sliding of foundation at slopes

The irregularity of building increases the above listed damages in all buildings

IMPLICATIONS OF DESIGN AND CONSTRUCTION DECISIONS

Location Landscape and Soil Type

Location plays a very important role is earthquake damage. It involves associated seismic risk and site soil condition. Any type of soil failure may lead to building damage. If the building is located next to a depression or open drain damage will be more to the building. In Kutch earthquake such behaviour was noticed in one building complex of Samkhyali Bose P.R. [5], where twelve similar housing units of two storeys were located on a site in the outskirts of the Samakhyali town in the Rapar taluka of Gujarat state. This triangular site is located roughly along a drain. A level difference of around three metre existed between the drain, which was running parallel to one side of the site, and the ground level at the site of construction. Seeing to the area it could be appreciated that the ground before the construction of the buildings would have been undulating. For providing a flat surface to the construction site these undulating tracts of land were filled up with soil. Along the side adjoining the drain a random rubble stone masonry retaining wall of nearly one and a half m. height was constructed. The visual examination of the site showed that the filled up soil at the site was not adequately compacted. Even the original soil up to a particular depth below this filled up soil may not have been in an adequately pre-consolidated state as the site was used for agricultural purposes before the construction of these structures. It was noticed that damage was more in the buildings located along the drain as compared to other buildings. One building was totally destroyed where even the retaining wall along it failed and suffered damage Figure 1.Similarly in Haritpawan Gurukul of Swaminarayan a residential high school having reinforced concrete framed structure, at Ganga Rampar near Bhuj having three wings showed more damage to its west wing along a deep drain Figure 2. Similarly if the building is located on hillock the damage will be more. This was noticed in Latur Osmanabad earthquake Sinvhal A., Bose P. R.et al [6] and in Kutch earthquake Figure 3. It seems the energy of waves which are coming to the side of depression or at the top of hillock and the energy of the waves reflecting back from there is getting cocentrated. Further it is well known that damage will be more on loose filled ground. However other reasons can further intensify the damage at such locations Bose P.R. [5].

Building Material, Quality of Construction and Maintenance

Heavy material contributes to high seismic forces. Low strength material which has no or very less tensile and shear strength is more prone to damage. Weak Binding material like mud mortar will cause more damage as compared to cement sand mortar. Weaknesses of construction include improper bonding between walls, unfilled joints between bricks, out of plumb walls, lack of curing etc. Well-maintained building shows a better behavior. Even reinforced concrete building may show more damage due to lack of maintenances.

Architectural Design Decisions

It includes building configuration i.e., its form and shape in plan and elevation; location -and size of major structural elements; number location and size of openings; and connection details of non-structural elements with main structural system. Complex, asymmetrical, irregular shape, less number of walls or columns, long walls without any cross walls, large or many openings in masonry walls cause more damage because of tensional effects and less shear resisting capacity. It is said that building is destroyed on paper by the designer before it is built, because of its size and shape in plan and elevation.

Shape of building units

The building units having asymmetrical irregular complex shapes are more prone to damage. Such buildings will suffer from damage due to torsion also. In Bhuj L- Shaped GK general hospital building collapsed in earthquake. Torsion was visible in a shop building having three-closed side and one open side with masonry columns in Killari Sinvhal A., Bose P.R. et al. [6].

Openings and Linear Planning

Too many openings may reduce the wall strength and masonry between openings may collapse during earthquake. In school and colleges a linear architectural plan is followed. At Bhuj in Lallan College in most of the building blocks having such linear plan front portion had too many windows and doors. This resulted in very long continuous beams supported on thick masonry piers at lintel level in both the storeys. Then again the masonry wall was raised on the top of this beam to support the transverse beams of T-beam floor and roof. This is a usual construction practice in schools and colleges to make the row of rooms in different phases. This sometimes causes discontinuity in the longitudinal beams also. This construction practice is adopted at most of the places due to lack of funds, whenever some money is received from some source few rooms are added to the existing building by college authorities. In these blocks the masonry pier collapsed which caused the collapse of longitudinal beams and then the entire floor and roof Figure 4. All structural elements built separately behaved separately without any monolithic connection. A small amount of vertical steel in the masonry piers and anchoring it to roof slab could have saved these buildings.

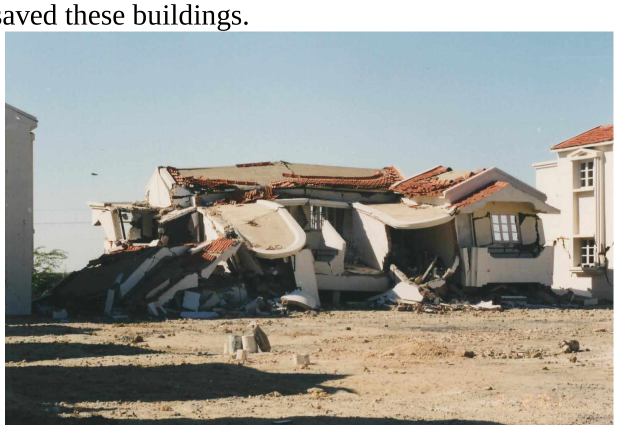

Fig. 1: Collapsed building built on drain side. Retaining wall at back also failed

Fig. 2: Maximum damage was found in the west wing located along drain

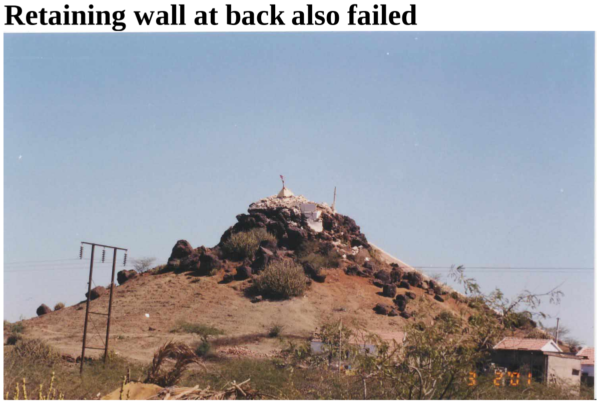

Fig. 3: Temple collapsed at the top of hillock while other masonry structures located on its foot remained standing near Bachau in Kutch.

Fig. 4: Collapsed two story college building had linear plan with too many openings in front.

Hybrid Structural System of Masonry and RC Columns

In developing countries it is a common practice to provide reinforced concrete columns in combination with masonry. It is provided as independent member just to replace masonry to get open spaces. Such columns are not designed to resist earthquake force and nominal steel is provided without ductile detailing Bureau of Indian Standards [7]. When earthquake occurs they attract lateral force beyond their capacity. This leads to catastrophic collapse or partial collapse Figure5.At present no special guidelines are available for such buildings, Bureau of Indian Standards [7-11].

Mixing of Materials

It is common practice that when family size is increased additional rooms are added in existing building and in traditional stone houses new material is used generally brick or concrete. Mostly such extension has no connection with old existing structural system.This new structural system simply slips from its place at the time of earthquake Figure 6-8 .

Fig. 5: Bachau Station Building showing the condition of a reinforced concrete column provided in masonry building.

Fig. 6: In Chamoli Earthquake, column raised on the top of the stone wall slipped from its place due to lack of connection.

Fig. 7: In Killari earthquake a brick wall raised to construct first floor on the top of stone wall without connecting it to old stone wall, simply slipped from first floor to ground.

Fig. 8: In Anjar, RCC framed building was under construction on the top of old stone masonry building when authors visited this highly damaged area.

Deterioration in Traditional Construction

With passage of time in rural areas pepole start making the buildings without following the norms of the reigional old construction practice which has inbuilt resistance against earthquake resistance.Sometimes this happens because of economic constrins.In killari old houses having timber frame inside stone walls were not collapsed even in the presence of heavy roof, and people were not killed while new houses built using only stone walls were razed to ground Figure 9 .

In Kutch area near Anjar the traditional village house consisted of random rubble stone masonry laid in mud mortar having central wall five metre high and sidewalls three metre high. At this level, transverse wooden beams are provided to create a storage attic. This is achieved with the help of wooden members split bamboo pieces, jute, bushes etc. to create storage floor figure 10. These houses suffered extensive damage due to high walls without earthquake bands and because of lack of integral action between various wooden members. In the walled city of Bhuj walls are made either of random rubble or of dressed stone and are laid in lime or mud mortar. The traditional timber roof is made almost in similar manner with attic. In Bhuj, being an urban area, this storage attic was converted into a living space like dinning space. Laying a layer of lime surkhi or cement mortar or plain makes this floor concrete above the old attic floor Figure11. These buildings were also collapsed or heavily damaged in old Bhuj.It seems that in some buildings the traditional roof was removed and replaced by reinforced concrete slab keeping the attic slab as it is. These buildings tumbled down due to heavy roof and flexible floor [12].

Renovation of Buildings

Renovation of building is very common especially in urban areas. At the time of renovation the structural system is disturbed and only vertical load is considered and earthquake is forgotten and most of the times walls are removed and vertical load is transferred to other walls. In Kutch at Gandhidham in Sindhi colony two story buildings built by Sindhi Resettlement Corporation in 1956, using hollow blocks of size 6"x8"x16", with reinforcement, looked intact, with some cracks only in the renovated building Figure 12.

Earthquake Resistant Masonry Buildings

The technology is available for making the earthquake resistant buildings, Manual ISET [13]. The buildings can be made earthquake resistant by introducing integral action, ductile behaviour and redundancy. For this earthquake resistant measures are needed like horizontal bands and vertical steel at corners and junctions of the wall and at jambs of the openings. Whenever these measures are used knowingly or unknowingly building survives without killing the people residing inside Figure 13,14.However sometimes these measures are used indiscriminately without care. Such buildings will not be able to resist the earthquake even with these measures due to mistake committed at the time of construction Figure 15,16.

CONCLUSION

There are many unattended factors and features which may intensify the damage at the time of the earthquake.Special care is needed at the time of analysis, design and construction of building to incorporate these at the time of execution of project.Gaps are thre in theretical knowledge and practical implementation.Agencies involved in disaster mitigation should try to identify the weaknesses introduced in the buildings by the people themselves and they are to be made aware of the implications involved with the decisions they are taking at the time of planning, designing or at the time of construction.

Fig. 9: In Killari in 1993 many traditional buildings with vertical timber frame inside survived the earthquake even with heavy roofs. Newly built houses without timber frame but with similar heavy roof of timber and earth were razed to ground.

Fig. 10: Traditional house in Kutch area showing high central wall and attic for storage.

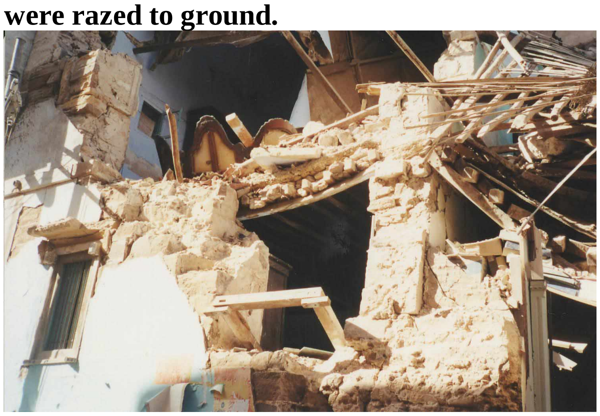

Fig. 11: In urban area attic of traditional house shown in Fig. 10 was converted into living space. Later traditional roof must have been replaced by concrete slabs. Such buildings killed many persons in Bhuj.

Fig. 12: At Gandhidham in this complex of well built row houses made of reinforced hollow block masonry, minor damage occurred only in the renovated house.

ACKNOWLEDGEMENT

Authors are thankful to Principal Delhi College of Engineering, Delhi, Prof. & Head, and Earthquake Engg. Deptt.Indian Institute of Technology Roorkee and National Institute of Disaster Management Delhi, for their support and encouragement. Authors are also thankful to all the officials and common public in the earthquake affected areas visited by them for their help, support and for the information provided by them.

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