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A Review Study on Performance of Stone Masonry Building Under Earthquake

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Abstract — *Many masonry structures collapsed or were severely damaged during the recent destructive earthquakes occurred in worldwide. This paper evaluates the review study of various researchers on seismic performance of masonry buildings during the earthquakes and behaviour of masonry buildings under seismic action. The traditional masonry buildings without any earth quake resisting features have proved to be the most vulnerable to earthquake forces and had suffered maximum damage in past earthquakes. Therefore, it is necessary that realistic stone masonry houses as are being constructed in rural and hilly regions should be tested dynamically for evaluating various seismic strengthening measures in order to prove their effectiveness. Most of masonry buildings were formed with random or coursed stone and mud brick walls without any reinforcement. Many of these buildings were damaged or had collapsed. The cracking and failure patterns of the buildings are examined and interpreted according to current provisions for earthquake resistance of masonry structures. Masonry being a brittle material will undergo sudden failure under lateral loads causing large amount of damage to human life and property. Therefore to make the masonry ductile it has to be reinforced with a material that gives warning before failure and resists damage. The present paper makes a review on seismic performance of reinforced masonry structures.*

Keywords- *Indian Earthquakes, Masonry Building, Seismic Performance.*

I. INTRODUCTION

In the last decades, vulnerability of masonry structures to earthquakes has focused the attention of politicians, researchers and structural engineers to prevent losses of human lives and damages to the buildings. These problems are of most relevance in old urban and rural nuclei in which masonry buildings are particularly prone to seismic actions. Past earthquakes demonstrated that especially old stone masonry buildings suffered severe damages, due to the poor seismic resistance of the shear walls [Chiostrini, Galano and Vignoli, 1998].
For structural engineers a main problem is the mechanical characterization of old masonry walls, i.e. shear strength and deformation parameters should be predicted. Knowledge of the textures and the properties of blocks and mortar are often insufficient to these previsions; so, experimental tests should be performed to achieve a reliable estimation of the above masonry's characteristics. Several past researches have been performed on this topic but the literature concerning experimental studies on stone masonry walls with chaotic texture is rather sparse.
Masonry is generally a highly durable form of construction. Stone masonry is a common technique used for the construction of buildings, retaining walls and buildings. In general, masonry may be defined as a structural assemblage of masonry units with a binding material known as mortar. Stones, bricks and concrete blocks are the most common types of masonry units. Since stones and bricks are used in the masonry construction, they increase the thermal mass of the building thus protecting the building from fire. So masonry is called as non-combustive product. Masonry structures can withstand the normal wear and tear for centuries. Masonry being a brittle material will undergo sudden failure under lateral loads causing large amount of damage to human life and property. Therefore to make the masonry ductile it has to be reinforced with a material that gives warning before failure and increase its resistance under later loads.

II. SOME INDIAN EARTHQUAKES

India has had a number of the world's greatest earthquakes in the last century. In fact, more than 50% area in the country is considered prone to damaging earthquakes. The northeastern region of the country as well as the entire Himalayan belt is susceptible to great earthquakes of magnitude more than 8.0. The main cause of earthquakes in these regions is due to the movement of the Indian plate towards the Eurasian plate at the rate of about 50 mm per year. Indian subcontinent has suffered some of the greatest earthquakes in the world with magnitude exceeding 8.0. For instance, in a short span of about 50 years, four such earthquakes occurred: Assam earthquake of 1897 (magnitude 8.7) (Oldham, 1899), Kangra earthquake of 1905 (magnitude 8.6) (Middlemiss, 1910), Bihar-Nepal earthquake of 1934 (magnitude 8.4) (GSI, 1939), and the Assam-Tibet earthquake of 1950 (magnitude 8.7) (CBG, 1953). Significance of such earthquakes can be gauged from the fact that in his famous book on Engineering Seismology (Richter, 1958) Professor C.F. Richter (known for the Richter scale) devotes an entire chapter entitled "Some Great Indian Earthquakes" to introduce the nature of earthquakes: the book has no similar chapter for great earthquakes in other regions of the world. Fortunately, since 1950 only moderate size earthquakes have occurred in India which is no reason to assume that the truly great earthquakes are a thing of the past. Some major Indian earthquakes are discussed below:

2.1 Bihar-Nepal earthquake of August 21, 1988

The earthquake of Magnitude 6.6 struck at 4 hrs 39 m 11.25 sec (IST) with its epicenter in Nepal near the Bihar-Nepal border (Lat 26.775 and long. 86.609) in close proximity to 1934 earthquake epicenter. The focal depth is estimated to be 71 km. The maximum intensity of VIII+ was observed at Darbhanga and Munghyer in Bihar and Dharan in Nepal. This earthquake has taken 281 lives in Bihar and nearly 650 lives in Nepal. The total number of injured persons in Bihar are 3767. It damaged/ collapsed 1.5 lacks houses/buildings in Bihar alone [Paul, Thakkar et al. 1988].

At Darbhanga the high intensity was mainly attributed to the soft alluvial soil and liquefaction resulting in large scale subsidence of soil while in Dharan the high intensity is attributed to amplification of ground acceleration due to hill and hill slope. The recent r.c.c. constructions with codal; provision have shown better performance while old and poorly built load bearing unreinforced masonry brick buildings performed badly. Large scale liquefaction of ground was observed in the Gangetic plane resulting in ground subsidence. Mud houses and brick houses laid in mud mortar were affected most in the villages. Severe damage to old masonry buildings having jack arch construction were observed. Framed construction have shown better performance.

2.2 Uttarkashi Earthquake of October 20, 1991

An earthquake of magnitude 6.6 shook the districts of Uttarkashi, Tehri, and Chamoli in the state of Uttar Pradesh on October 20, 1991 at 2:52 hours (GSI, 1992; Jain et al., 1992). The death toll was estimated to be around 768 persons, with about 5,066 injured. The area has one of the lowest population densities in the state, and hence the rather low number of deaths and injuries. The maximum intensity of IX on the MM scale was assigned to an area of about 20 square km. This earthquake provided excellent ground motion records (acceleration versus time history) in the area (e.g., Jain and Das, 1993): maximum peak ground acceleration of about 0.31g was recorded at Uttarkashi. Ground motion records showed that in the Himalayan region, the motion has significantly higher amount of high-frequency contents. During the earthquake, collapse of houses with R.C. roof slab supported on weak random-rubble stone masonry clearly demonstrated the disastrous results of often neglected walls and columns vis-à-vis slabs and beams. Several 4-storey buildings in Uttarkashi (not designed or detailed by engineers) with R.C. frame and stone infills sustained the earthquake rather well! This was due to the presence of significant number of infills from foundation to the top of the building which acted as shear walls. From such examples, one could easily and incorrectly get carried away to conclude that all R.C. buildings in general are good for earthquakes. To sober one down, top two storeys of the 3- storey State Bank of India R.C. frame building collapsed; clearly illustrating the disaster those R.C. buildings can cause if not done right. An important bridge on the strategically important Uttarkashi-Harsil route collapsed; causing disruption of traffic for several days (e.g., Murty and Jain, 1997).

The earthquake caused enormous destruction of houses and loss of life, killing nearly 770 people and injured nearly 5000, mostly all due to collapse of random rubble residential houses. The affected region lies between seismic zone IV and V according to seismic zoning map of India. The maximum affected area was Uttarkashi, Tehri and Chamoli districts. Telecommunication and power supply were badly effected due to damaged telephone and electric poles. Rubble stone masonry houses in mud mortar close to the severely effected area were totally collapsed and others got severe damage. Many school and health buildings were also damaged.

Figure 1: Damage to stone masonry houses and Collapse of the housing colony at Gawana

Many houses were severely damaged/collapsed. Gawana steel lattice bridge located about 6 km from Uttarkashi on road to Gangotri collapsed, severely affecting the relief and rescue operations immediately after the earthquake. Widespread rock falls landslides/rock slides were observed mostly along the road causing heavy damage to hilly roads and blocking it.

2.3 Jabalpur Earthquake of May 22, 1997

This earthquake is the first moderate earthquake (magnitude 6.0) to have occurred close to a major Indian city in recent times: Jabalpur has a population of about 1.2 million people (Jain et al., 1997; Rai et al., 1997). It provided some indication of what type of seismic performance to expect out of modern Indian constructions. The maximum intensity was upto VIII (in a very small area); most parts of Jabalpur town experienced shaking intensity of VI and VII. Numerous R.C. frame buildings of three-four storeys with brick infills performed well even though these may not have been designed for earthquake forces: this is because the brick infill walls acted as shear walls and took most of the seismic loads in such buildings. On the other hand, several similar buildings but with open-first storey (i.e., few or no brick infills in the ground storey) showed heavy distress to the ground storey columns: such buildings could have collapsed due to failure of ground storey columns if the shaking had been stronger or lasted for a longer duration. Another interesting feature of the earthquake was heavy damage to a very large number of two and three storey brick-masonry residential buildings belonging to different government agencies: e.g., the ordnance factories, Department of Telecom, railways, etc. Such buildings did not have any earthquake resistant features. Damage to mumtys (staircase projection above the building roof) in such houses posed a major problem. Most medium and large towns in the country now have a huge inventory of R.C. frame buildings with open first storey (to accommodate vehicle parking), and two-three storey brick masonry housing units; such buildings could cause major disasters in future earthquakes affecting Indian cities.

2.4 Bhuj Earthquake of January 26, 2001

The earthquake of Magnitude 6.9 occurred on January 26, 2001 and has caused widespread damage to variety of buildings and many of them have collapsed. Total deaths reported were 19500. For the first time in India large number of urban buildings including the multi-storey buildings at Bhuj, Ahmedabad, Gandhidham and other places have damaged/ collapsed. The mushrooming of multi-storey buildings without any consideration of earthquake resistant design and construction practices has generated a countrywide debate about its seismic safety. It has caused damage to the common type of load bearing buildings and RCC framed buildings.

Most of the rural construction of mud, adobe, burnt brick and stone masonry either in mud or cement mortar have shown severe damage or collapsed. The stone masonry buildings undergo severe damage resulting in complete collapse and pileup in a heap of stones (Fig. 2). The inertia forces due to roof/floor is transmitted to the top of the walls and where the roofing material is improperly tied to the wall, it will be dislodged. The weak roof support connection is the cause of separation of roof from the support and lead to complete collapse. At many places the height of the random rubble stone masonry walls in mud mortar/ poor cement mortar was about 5.0m.

Figure 2: Damage to stone masonsry houses and Collapse of two storey stone masonry building Bachau

2.5 Jaisalmer Earthquake of April 9, 2009

A moderate earthquake (M5.0-5.9 termed as moderate) struck the Thar Desert near Jaisalmer in Jaisalmer district, Rajasthan on 9 April 2009 at 07:16 AM local time. It had a magnitude of 5.1 and was felt in a large part of the region along the India-Pakistan border.

At least six people were injured in the Jaisalmer area after being hit by falling masonry or after jumping from buildings in panic. This earthquake was felt strongly for 15-30 seconds knocking out power at Jaisalmer, displacing loose household items and sending people running outdoors; some jumped off the roofs of houses in panic. Students preparing to sit year-end examinations ran out of examination centres. The walls or roofs of at least a dozen buildings reportedly collapsed and at least 3,000 buildings developed cracks. Stones were dislodged from a wall inside the Sonar Killa near the Suraj Prol and fell near the entrance of a school but no one was hurt. Stones were also dislodged near the southern side of the fort. A decorative "chhatri" above the Retiring Room on Platform 1 at the Railway station collapsed. The strongest effects are reported to have been experienced in the Sheo Panchayant in Jaisalmer district. Strong shocks were also perceived at Ramgarh in Jaisalmer district and at Shiv tehsil in Barmer district. The earthquake was felt at Barmer where people went outdoors. Tremors were experienced at Bikaner, Fatehgarh, Jaipur, Jalore, Jodhpur, Khuiala, Mohangarh, Pokaran, Sankra, Sirohi, and Vinjorai. Outside Rajasthan, tremors were felt in at Bhuj, Khavda and other parts of Kachchh in Gujarat and at Hyderabad, Khairpur Mir, Sanghar, Sukkur and Umarkot in Pakistan's Sindh province. Mild tremors were also felt in high-rise buildings as far as Delhi, nearly 650 kilometres to the north-east.

2.6 Nepal "Gorkha" earthquake of April 25, 2015

One measuring M7.8 on the Richter scale hit Nepal at midday on the 25th April 2015, causing thousands of deaths and widespread damage. It measured IX (violent) on the Mercalli scale; the impact made worse by underlying poverty. Geology, urbanisation and building quality are the three main risk factors in Nepal and there is need for good governance and disaster preparedness in this active seismic area. However, the earthquake was a little smaller and farther east than had been expected and is seen as a warning for future events. The earthquake occurred at a depth of 15km due to subduction of the Indian plate beneath the overriding Eurasian plate. It happened approximately 80km northwest of Kathmandu, in the Gorkha district (Figure 1). Here the Indian plate moves northwards at an annual rate of 45mm, forming part of the Himalayan uplift. Much of the energy was transmitted 120km eastward towards Kathmandu, so the epicentre was at the western end of the affected region. GPS surveys show that the Kathmandu valley was raised 1m and that Kathmandu itself is now 80cm higher. Mount Everest sank 3cm and areas north of it have also lowered as the released strain allowed land to settle.

III. LITERATURE REVIEW

The earthquakes are un-preventable and unpredictable. Earthquake causes vibratory ground motion caused by waves originating from a source of disturbance inside the earth. These are generally associated with active tectonic features. Large numbers of earthquakes occur but only those earthquakes, which affect structures and disrupt the normal way of life, are of engineering importance. The loss of life and property occurs directly from failure of structures and may also take place due to indirect causes such as failure of water supply, fire caused by short circuiting of electric wires or kitchen fires, release of poisonous gases, release of radiation, flooding through failure of dams and embankments or due to tsunamis. The energy contained in different waves of different frequencies varies significantly. When such seismic wave strikes a structure resting on ground causes it to vibrate in horizontal and vertical directions. Intensity of vibration depends on the relative frequencies of ground motion waves and the structure, and the energy content associated with the frequencies. The vibratory ground motion causes additional moment and shear in the structure. If a structure is not designed for the additional forces, the structure may be severely damaged/ collapsed.
The detailed review of literatures related to seismic analysis of structures is very vast area. This literature review point out the brief review of the seismic analysis of masonry structures.

Krishna Naraine and Sachidanand Sinha (1989), studied the behaviour of unreinforced masonry under compressive cyclic loading both perpendicular and parallel to the bed joint. The specimens were instrumented for the measurement of axial and lateral displacements along the fixed gauge lengths. The experimental results have a major drawback that the readings were not consistent in the case of loading parallel to the bed joint; it causes the formation of wider cracks near the edge of the specimens. In the three types of tests, at the first time the load increased steadily to failure and then the specimen tested under cyclic loading. In the final case loading and unloading was repeated several times. The failure mode varies depends on the orientation of the bed joint.

Yan Zhuge et al. (1998) , conducted nonlinear dynamic analysis of unreinforced masonry. Developed an analytical model and study the response of unreinforced masonry to in – plane dynamic loads including earthquake loading. This analysis is considered as a nonlinear finite element program. The model is able to performing both static and time history analysis. The global behaviour of the building is studied by the use of a SDOF model, which is a FEM of masonry under dynamic loading. The analytical model has been developed for carrying out the time history analysis of the URM under seismic loads. At the time of testing, the vertical compressive stress is taken as constant and the horizontal loads increased gradually up to failure. All the failures depend on the stress state acting on the joints.

Thakkar K Shashi et. al. (2000), Constructed full scale models of one storied stone masonry houses with two different combinations of strengthening measures and have been tested under progressively increasing intensity of shock on shock table facility. After the damage of models during shock table testing, these are retrofitted by existing techniques prescribed in the IS code and tested again. But the cracking in the piers of walls still occur. There is a good agreement in the region of cracking in the shock table tested model with that determined by finite element analysis. The injection of cementitous grout on localized damaged areas can restore the original strength and stiffness. The introduction of external horizontal tie bar to a wall can increase the strength and ductility of the model. Moreover, welded wire mesh in damaged region not only increases the lateral resistance of the wall but also prevents shear and flexure failures of the models.

Tianyi Yi et al. (2006), conducted different analytical approaches to investigate the response of unreinforced masonry. A nonlinear discrete crack finite element model was adopted. The nonlinear analytical methods are used for the analysis includes; a rigid body analysis, a two-dimensional nonlinear pushover analysis, and a three-dimensional nonlinear finite element analysis. This method predicts the nonlinear behaviour of the structure. Out-of-plane walls are considered for their additional vertical load capacity to resist overturning moments. The building is assumed to be dominated by shear deformations where flexural deformations are neglected. The rigid body analysis is good for a quick estimate, that the 3D nonlinear FE model is suitable for in-depth investigation of important projects, and that the 2D nonlinear pushover method is best for the seismic evaluation and retrofit of existing structures. The 3D nonlinear FE analysis is very time consuming, and thus is not suitable for daily design or evaluation projects. The rigid body analysis cannot recognize toe crushing and diagonal tension failure modes, and cannot predict deformations.

Y. Belmouden et. al. (2009), presented a novel equivalent planar-frame model with openings. The model deals with seismic analysis using the Pushover method for masonry and reinforced concrete buildings. Each wall with opening has been decomposed into parallel structural walls made of an assemblage of piers and a portion of spandrels. As formulated, the structural model undergoes inelastic flexural as well as inelastic shear deformations. The mathematical model is based on the smeared cracks and distributed plasticity approach. Both zero moment location shifting in piers and spandrels can be evaluated. The model can support any shape of failure criteria. An event-to-event strategy is used to solve the nonlinear problem. Two applications are used to show the ability of the model to study both reinforced concrete and unreinforced masonry structures. Simplified formulation of an equivalent frame model is arrived. The model permits to consider many relevant features of structural behavior such as structural wall coupling, zero moment location shifting, axial force–bending moment interaction, axial force–shear force interaction, and failure modes prediction. However, in the case of URM buildings, it is well known that smeared crack approach suffers from a few limitations.

Khaled Galal et. al. (2010), assessed the out-of-plane flexural performance of masonry walls that are reinforced with glass fiber-reinforced polymers GFRPs rods, as an alternative for steel rebars. Eight 1m and 3m full-scale walls were constructed using hollow concrete masonry units and tested in four-point bending with an effective span of 2.4 m between the supports. The walls were tested when subjected to increasing monotonic loads up to failure. The applied loads would represent out-of-plane loads arising from wind, soil pressure, or inertia force during earthquakes. One wall is unreinforced; another wall is reinforced with customary steel rebars; and the other six walls are reinforced with different amounts of GFRP reinforcement. Two of the GFRP-reinforced walls were grouted only in the cells where the rods were placed to investigate the effect of grouting the empty cells. The force-deformation relationship of the walls and the associated strains in the reinforcement were monitored throughout the tests. The relative performance of different walls is assessed to quantify the effect of different design variables. The range of GFRP reinforcement ratios covered in the experiments was used to propose a capacity diagram for the design of FRP-reinforced masonry walls similar to that of reinforced concrete elements.

Ahmad N et. al. (2012), the performance of low-rise confined masonry (unreinforced masonry walls confined with horizontal and vertical lightly reinforced concrete elements) structures is assessed against earthquake induced site amplified strong ground motions using a probabilistic-based approach. The basic mechanical characteristics of structural material is obtained through experimental investigations on masonry material, structural walls and reduced scale structural models, which are employed for the design, mathematical modeling and seismic analysis of confine masonry structures. The seismic performance of two case study (two storey) structure types is assessed for various scenario earthquakes with moderate to strong ground motions. The typical confinement of masonry walls can avoid the total structural collapse in most of the strong ground motions thereby minimizing the occupant's injuries, however the damages to structures in large earthquake events are significant. Investigating on the seismic behavior of structures in scenario earthquakes show that the typical confinement of masonry walls ensure excellent performance of structures against earthquake induced ground motions, avoiding the structural collapse in most cases thereby ensuring safety of the occupants in even in larger earthquake events. In most of the test scenario earthquakes, the structures are found with slight to moderate damages in the form of cracking (more or less extensive) in masonry structural walls which may require repair in the form of cement grouting to restore the structure's lateral stiffness and strength. Due which the structures may cause significant economic losses in regions with moderate to high frequent seismicity. A ten percent increase in the wall density (when wall length is increased only) didn't cause appreciable difference in the seismic performance due to the reason that the better performance is governed by the deformation capacity (ductility) of the system.

J.Snoj et al. (2012), the seismic performance of existing masonry buildings were affected by different uncertainties. The experimental setup based on the measurement of ambient and forced vibrations on an old two storey masonry building. The vibration periods are estimated and which is based on two type of measurement, these are compared and seismic performance of the building is assessed for the near – collapse limit state. An existing masonry building's seismic analysis is very difficult criteria. The possibility to reduce the uncertainty in modeling is to measure ambient or forced vibrations. Time or frequency domain techniques are based on the estimation of natural frequencies.

IV. EFFECTS ON STONE MASONRY

Masonry buildings of brick and stone are superior with respect to durability, fire resistance, heat resistance and formative effects. Due to easy availability, economic reasons and the merits mentioned above stone masonry construction is widely used.

4.1 Causes of failure of masonry buildings

These buildings are very heavy and attract large inertia forces. Unreinforced masonry walls are weak against tension (horizontal forces) and shear, and therefore, perform rather poor during earthquakes. These buildings have large in plane rigidity and therefore have low time periods of vibration which results in large seismic force. These buildings fall apart and collapse because of lack of integrity. The lack of structural integrity could be due to lack of 'through' stones, absence of bonding between cross walls, absence of diaphragm action of roofs and lack of box like action.

4.2 Common type of damage in masonry buildings

All of them undergo severe damage resulting in complete collapse and pileup in a heap of stones. The inertia forces due to roof/floor is transmitted to the top of the walls and if the roofing material is improperly tied to the wall, it will be dislodged. The weak roof support connection is the cause of separation of roof from the support and lead to complete collapse. The failure of bottom cord of roof truss may also cause complete collapse of truss as well as the whole building.
If the roof/floor material is properly tied to the top walls causing it to shear off diagonally in the direction motion through the bedding joints. the cracks usually initiate at the corner of the openings. The failure of pier occurs due to combined action of flexure and shear. Vertical cracks near corner wall joints occur indicating separation of walls.
For motion perpendicular to the walls, the bending moment at the ends result in cracking and separation of the walls due to poor bonding. Generally gable end wall collapses. Due to large inertia forces acting on the walls, the masonry is either bulges outward or inward. The falling away of half the wall thickness on the bulged side is a common feature

V. CONCLUSION

A few generalized conclusions are summarized below:

- Masonry buildings belong to the most vulnerable class of structures which have experienced heavy damage or even total collapse in earthquakes.
- Non – linear seismic analysis is useful for assessing inelastic strength and deformation of the structure
- The strength capacity differs depends on the masonry parameters
- The seismic performance of reinforced masonry structures can be improved upon by proper selection of reinforcing material. Glass fiber, geosynthetic materials could be an alternative to the existing steel reinforcement to improve the ductile behavior of masonry structures.
- The different modes of failures are observed and these structures can be designed economically with high resistance to earthquake with nominal reinforcement. It was also observed that up to 10% increase in the overall density does not affect the seismic performance of the masonry structure since it is mainly governed by its ductility. It can also be observed that seismic performance of existing un reinforced masonry structures can be improved by adopting different retrofitting techniques.

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