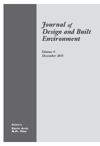
Journal of Design and Built Environment
Vol. 9, December 2011, pp. 1–16



NON LINEAR SEISMIC ANALYSIS OF MASONRY STRUCTURES

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Abstract

Nowadays, even though many new construction techniques have been introduced, masonry has got its own importance in building industry. Masonry structures fail miserably under lateral loading conditions like earth quakes and impact loads. The occurrence of recent earthquakes in India and in different parts of the world have highlighted that most of the loss of human lives and damage to property have been due to the collapse of masonry structures. Though an earthquake could not be prevented, the loss of life and property could be minimized, if necessary steps could be taken to reduce the damages on the existing masonry structures. This paper investigates the application ofNonlinear Seismic Analysis of a masonry building using ANSYS software and check the efficacy of retrofit measuresto protect the existing building.

Keywords: Earthquake, Masonry structures, Micromodelling, Finite element, Modal analysis, Transient analysis

Introduction

Masonry may be defined as the construction of building units bonded together with mortar. The units may be stones, bricks or precast blocks. Though many new construction techniques have been introduced, masonry retains its importance in the building industry. But masonry structures fail miserably under lateral loading like earth quakes and impact loads (Jagadish et. al, 2003). Due to its low strength, masonry was previously advised to be avoided in seismic zones. But IS 13828-1993 states that inclusion of special earthquake design and construction features may raise the earth quake resistance of the masonry structures and reduce the loss of life. Thus it is important to study masonry structures using Nonlinear analysis.This paper mainly concentrates on the Non linear Seismic Analysis of masonry buildings. In the Seismic zone map, India is divided into 5 seismic zones (Zone I - V). Zone V is most severe and zoneI is least seismic. Kerala State falls in zone II and III. Masonry buildings are the most common type of construction used for housing in Kerala State. Post-earthquake surveys have proved that the masonry buildings are most vulnerable to and have suffered maximum damages in the past earthquakes. Recently, it was observed that the frequency of occurrences of earthquakes in Kerala has increased. Though an earthquake could not be prevented, the loss of life and damage to property could be minimized. Steps could be taken to reduce the damages to existing masonry structures. The present work illustrates the procedure for Non linear seismic analysis of masonry building using ANSYS software (ANSYS, 2003). The effects of openings were also studied. The analysis can also check whether retrofitting of the existing building is required or not.

Fired bricks, concrete blocks and natural stone are used for the construction of masonry walls. The quality of masonry units should comply with the local and national requirements with regard to materials and manufacture, dimensions and tolerances, mechanical strength, water absorption, frost resistance, soluble salts content, fire resistance, etc. Mortar mix is a combination of cement and sand used to hold together the construction blocks. Different mix proportions of mortar are used in construction. For general building above ground, 1:5 is used. For portion below ground 1:3 can be used. The minimum allowable mix is 1:6 in seismic zones.

Earthquakes

Earthquakes cause horizontal and vertical ground movements and vibration. They are usually complicated due to forced and super imposed vibrations. For simplification of design, these movements are primarily subdivided into vertical and horizontal vibrations. The horizontal vibrations are much greater than vertical ones and hence they are considered in designing earthquake resistant structures. Usually earthquake loads are analyzed considering it as a time varying support motion given to the structure. The most useful way of defining shaking of ground during an earthquake is using the time variation of ground acceleration.

Ground vibrations during earthquakes cause inertia forces at locations of mass in the building. These forces travel through the roof and walls to the foundation. The emphasis is on ensuring that these forces reach the ground without causing major damage or collapse. Lack of structural integrity is one of the principle sources of weakness responsible for severe damage leading to collapse. The failure of the connection between two walls, between walls and roofs as well as walls and foundation has been observed. Of the three components of a masonry building (*roof*, *wall* and *foundation)* the walls are most vulnerable to damage caused by horizontal forces due to earthquake. Some of the damages are development of cracks near the openings, cracking of piers between adjacent openings, separation of orthogonal walls, and partial out of plane collapse of second storey walls. A wall also topples down easily if pushed horizontally at the top in a direction perpendicular to its plane. Walls that are inadequately anchored to the floor diaphragm can exhibit large diagonal cracks in the piers due to in-plane loads.

If the mortar joints are weak, as in lime mortar, the cracks follow the joint (Yoshimura and Kuroki, 2001).

The observations of structural performance of buildings during earthquakes provide volumes of information about the merits and demerits of the design and construction practices in a region. Some of the deadliest earthquakes that occurred across the world after 2005 are Haiti M7.0 (2010), SouthernSumatra, Indonesia M7.5 (2009), Eastern Sichuan, China M7.9 (2008), and Java, Indonesia M6.3 (2006).

India is prone to great earthquakes. Major earthquakes which occurred in India are Bhuj M7.7 (2001), Chamoli M6.5 (1999), Jabalpur M6.0 (1997), Killari M6.4 (1993) and Uttarkashi M6.6 (1991). From the damages observed in buildings due toearthquakes, it is seen that severe or significant damages occurred on those masonry buildings which were constructed without seismic provisions (IS 1905, 1987). Brick masonry buildings were more vulnerable to earthquakes than RC buildings. The main damage patterns consisted of shear cracks in wall, mainly starting from corners of openings; partial out of plane collapse of walls; partial caving – in of roofs due to collapse of supporting walls andshifting of roof from wall.The common failure modes of masonry (Agarwal and Shrikhande, 2007) are:

A. Sliding shear failure

It results in a building sliding off its foundation or on one of the horizontal mortar joints. It is caused by low vertical load and poor mortar. If the building is adequately anchored to the foundation, the next concern is for adequate resistance of the foundation itself, in the form of some combination of horizontal sliding friction and lateral earth pressure. The dislocation of a lightly attached roof is also an example of this type of failure. A wall with poor shear strength, loaded predominantly with horizontal forces can exhibit this failure mechanism. Aspect ratio for such walls is usually 1:1 or less (1:1.5).

B. Diagonal cracks

Diagonal cracks occur in masonry walls when the tensile stresses, developed in the wall under a combination of vertical and horizontal loads, exceed the tensile strength of the masonry material.

C. Non structural failure

While structural elements of a building are the prime concern for earthquake resistance, everything in the building construction should resist earthquake forces. Nonstructural walls, suspended ceilings, window frames and fixtures should be secure against movement during the shaking actions. Failure here may not lead to building collapse, but it still constitutes danger for occupants and requires costly replacements or repair. Interior partitions, curtain walls, wall finishes, windows and similar building elements are often subjected during earthquakes to shear stresses, for which they do not have sufficient resistive strength. The most common damage resulting from this is breakage of window panes and cracks in internal plaster and external rendering. Possible remedies are to isolate the window frames from the surrounding walls by the introduction of flexible joints and to reinforce the plaster or to pre crack it by introducing control joints (grooves).

D. Failure due to overturning

The critical nature of the overturning effect has much to do with the form of the building's vertical profile. A wall that is too tall or too long in comparison to its thickness is particularly vulnerable to shaking in its weak direction. Thus the tendency of a wall to topple when pushed in the weak direction can be reduced by limiting its length-to thickness and height to- thickness ratios.

Seismic codes

Ground vibrations during earthquakes cause forces and deformations in structures. Structures need to be designed to withstand such forces and deformations. Seismic codes help to improve the behaviour of structures so that they may withstand the earthquake effects without significant loss of life and property. Procedures outlined in seismic codes help the design engineers in the planning, designing, detailing and constructing of structures. An earthquake-resistant building has four virtues namely: (a) Good Structural Configuration: Its size, shape and structural system carrying loads ensure a direct and smooth flow of inertia forces to the ground. (b) Lateral Strength: The maximum lateral (horizontal) force that it can resist is such that the damage induced in it does not result in collapse. (c) Adequate Stiffness: Its lateral load resisting system is such that the earthquake-induced deformations in it do not damage its contents under low-to-moderate shaking. (d) Good Ductility: Its capacity to undergo large deformations under severe earthquake shaking even after yielding is improved by favourable design and detailing strategies.Seismic codes cover all these aspects.

Seismic codes are unique to a particular region or country. They consider the local seismology, accepted level of seismic risk, building typologies, and materials and methods used in construction. They are indicative of the level of progress a country has made in the field of earthquake engineering. The first formal seismic code in India, namely IS 1893, was published in 1962. The Bureau of Indian Standards (BIS) has the following seismic codes for masonry buildings: IS 1893 (Part I): 2002, IS 4326 –1993, IS 13828–1993, IS 13920–1993, IS 13935–1993, and IS 1905–1987. These standards do not ensure that structures suffer no damage during earthquake of all magnitudes. But, to the extent possible, they ensure that structures are able to respond to earthquake shakings of moderate intensities without structural damage and of heavy intensities without total collapse.

Lessons learnt from the Earthquake Damages in buildings

Earthquake damage points out the inadequacies of the prevalent design and construction practices in the region. The buildings constructed using proper earthquake resistant measures based on the lessons from various earthquakes have certainly helped in minimizing the degree of damages. The observation of damage behaviour of buildings during earthquakes confirms the direction of modern code provisions. Following are the summary of the lessons learnt (Bruneau, 1994; Jagadish et al, 2003; Jain, 1992; Kuwata et al, 2005; Yoshimura and Kunoti, 2001).

Most of the losses of lives are due to the collapse of houses constructed in traditional materials like adobe, unreinforced bricks, stone and the like without adequate earthquake resistant measures. Therefore, effort should be made for creating general awareness about the technology of earthquake resistant design and construction. The pattern of damage reveals that if the earthquake resistant measures as specified in building codes are adopted buildings are quite safe from seismic viewpoint. The layout of buildings should be as simple as possible and there should not be any sudden change in the distribution of mass or stiffness. Light weight building material such as bamboo, timber and PVC are to be used in highly seismic areas. Avoid construction of heavy structures on the roof. The building frame should have adequate ductility to permit energy dissipation through plastic deformations. Proper detailing of joints for all type of construction should be made. In precast and wood buildings joints are the vulnerable locations of failure. Hard foundation is found to be suitable for all types of buildings. Construction of buildings on loose soil such as fill should be avoided unless proper care is taken in the foundation design. Loose sand with high water table subjected to violent ground shaking may lead to liquefaction. The liquefaction causes differential settlement, tilting or sinking of buildings. Shallow foundation deteriorates due to weathering. Isolated footings undergo differential settlement. Tall buildings resting on piles withstood the earthquakes well. Settlement on hill tops prone to landslide should be avoided. For important and tall buildings proper dynamic analysis should be carried out. Buildings such as hospitals, fire stations, communication buildings etc. should be designed and constructed for earthquake resistance, so as to remain functional after an earthquake for quick relief operations.

Nonlinear Seismic Analysis

The nonlinear seismic analysis of masonry structures is carried out using time – history analysis using ANSYS (2003). Three models were prepared for the non linear seismic analysis. Each model was subjected to three different magnitude of vertical load on the top of the wall.

- Model 1: Brick masonry wall of dimension 3.6m x 3.0m
- Model 2: Brick masonry wall of dimension 3.6m x 3.0m with an opening of size 1.5m x 1.0 m at the centre.
- Model 3: Brick masonry wall of dimension 3.6m x 3.0m with an opening of size 1.5m x 1.0 m at the centre and a concrete beam around the opening.

Steps involved in the analysis (ANSYS, 2003) were collecting material parameters like Young's Modulus, Poisson's ratio, density etc., modelling the masonry structure, meshing the model, applying the boundary condition, determining the Vibration characteristics (Performing Modal Analysis), performing Transient Analysis and comparing the results with the permissible values. The basic mechanical properties of masonry are strongly influenced by the mechanical properties of its constituents namely, brick and mortar. Table 1 gives the properties of different materials and table 2 gives the stress – strain data of brick (Kaushik et al, 2007; Hemant, 2007). Figure 1represents the stress – strain curve of brick.

Modelling of Masonry Structure

The numerical modelling of masonry structures using FEM is computationally very demanding task because: (1) the typological characteristics of masonry buildings do not allow the use of simplified static schemes, (2) the mechanical properties of the material lead to a widely non linearbehaviour whose prediction is very tricky.

The finite element modelling of masonry is of two types (Lorenco et al, 2004):

In heterogeneous modelling the units and mortar are considered separately. This approach suits small size models. Because of the complexity of modelling

Table 1. Properties of different materials

Description	Young's Modulus (kN/mm^2)	Poisson's Ratio	Density (kg/m^3)
Brick	5	0.2	2100
Mortar	2	0.15	2162
Concrete	30	0.2	2400
Steel	200	0.3	7850

Table 2. Stress – Strain data of brick

Strain	0.000	0.001	0.002	0.003	0.004	0.006
Stress MPa	0	5	8	11	12.5	15

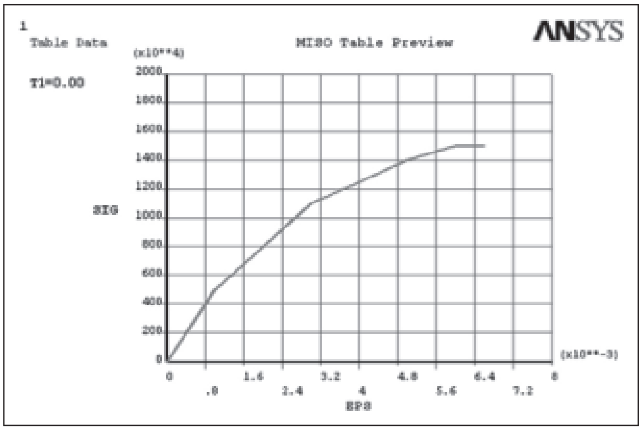

Figure 1. Stress – Strain curve of brick

the analysis cannot beperformed in economical time ranges.

Homogeneous modelling can be applied for the large scale models. The masonry units, mortar elements are assumed to be smeared and they are assigned as an isotropic or anisotropic material. In this modelling it is necessary to have test results of large masonry part containing adequate number of units and mortar combinations.

The following modelling strategies can be adopted depending on the level of accuracy, simplicity desired and application field. (1) Detailed micro modelling: Units and mortar joints are represented by continuum elements whereas the unit-brick interface is represented by discontinuous elements. Figure 2 shows the detailed micro-modelling. (2) Simplified Micro-modelling: Expanded units are represented by continuum elements whereas the behaviour of the mortar joints and unit-mortar interface is lumped in discontinuous elements. These interface elements represent the preferential crack locations where tensile and shear cracking occur. Figure 3 shows the simplified micro-modelling. (3) Macro-modelling: units, mortar and unit-mortar interface are smeared out in the continuum. Figure 4 shows the Macro-modelling. Macro modelling is more practice oriented due to the reduced time and memory requirements as well as user friendly mesh generation. This type of modelling is most valuable when a compromise between accuracy and efficiency is needed.

The present work uses detailed micro modelling. The main advantage of detailed micro modelling is that almost all the failure modes can be considered. But it is not convenient for the modelling of whole masonry structure, because the number of elements required can be huge, and consequently the cost of calculation time increase tremendously. Memory requirements are also very high (Lorenco, 1996; Lorenco et al, 2004).

The element used for modelling the brick units, mortar and concrete was Solid65. Solid65 is used for the 3-D modelling of solids with or without reinforcing bars (Figure 5). The solid is

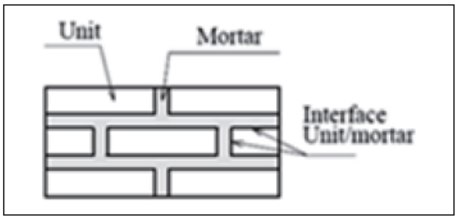

Figure 2. Detailed Micro- modelling

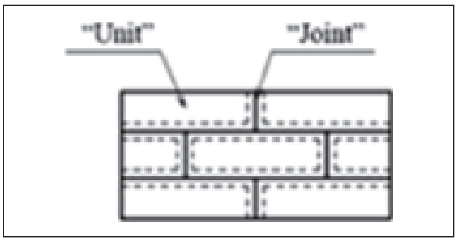

Figure 3. Simplified Micro modelling

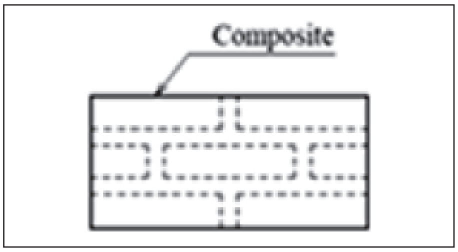

Figure 4. Macro- Modelling

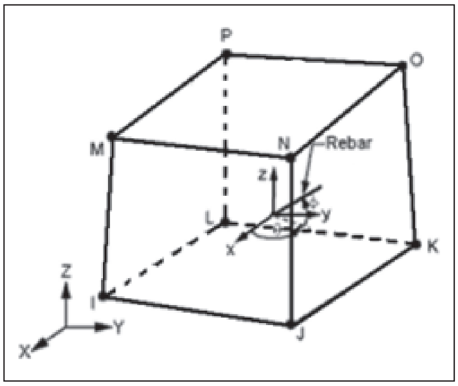

Figure 5. Solid 65

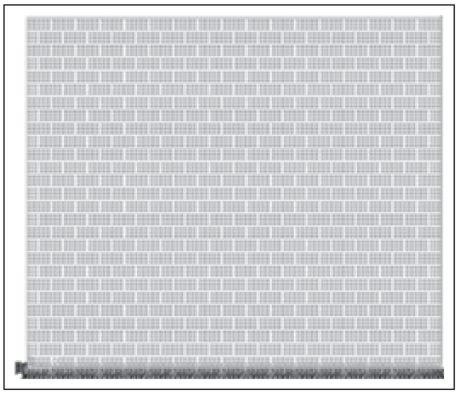

Figure 6. FEM model of the masonry wall (Model 1)

capable of cracking in tension and crushing in compression. In concrete applications, for example, the solid capability of the element may be used to model the concrete while the rebar capability is available for modelling reinforcement behaviour. The element is defined by eight nodes with degrees of freedom at each node: translations in the nodal x, y, and z directions. Up to three different rebar specifications may be defined. The most important aspect of this element is the treatment of nonlinear material properties. The concrete is capable of cracking (in three orthogonal directions), crushing, plastic deformation, and creep. The rebar can sustain tension and compression, but not shear. They are also capable of plastic deformation and creep.

The next step is to model the masonry wall and assign the properties and element type (ANSYS, 2003). The next step is meshing of the model. Figure 6, 7 and 8 show the FEM models of model 1, model 2 and model 3 in ANSYS.

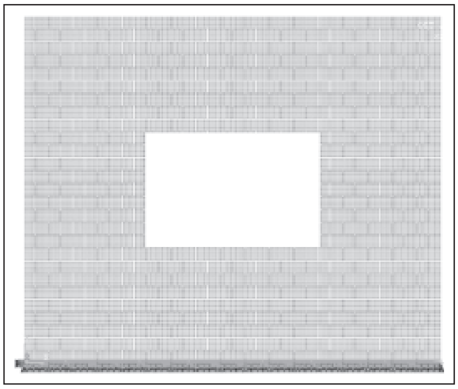

Figure 7. FEM model of the masonry wall with opening (Model 2)

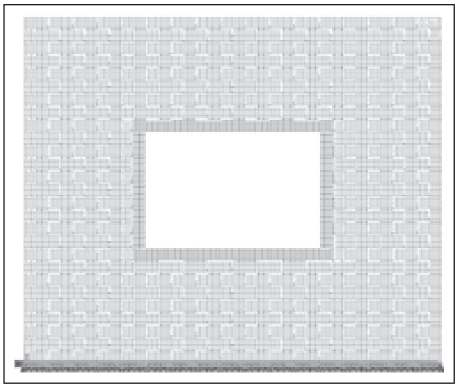

Figure 8. ANSYS model of a masonry wall with an opening and a concrete beam around it (Model 3)

Modal Analysis

Modal analysis provides the vibration characteristics (natural frequencies and mode shapes) of a structure. In ANSYS, a modal analysis is also the starting point for other, more detailed, dynamic analysis, such as harmonic response or a transient analysis. The natural frequencies and mode shapes are important parameters in the design of a structure for dynamic loading conditions. MODAL analysis in ANSYS is a linear analysis. Any non linearity, such as plasticity and contact (gap) elements, are ignored even if they are defined. Different mode extraction methods are available. Block Lanczos method is selected in the present paper.

A modal analysis was carried out for the three models prepared and the first ten natural frequencies were obtained. Table 3 shows the natural frequencies of the three models for first ten modes.

When a structure vibrates, it oscillates according to some form. Any typical system has an infinite number of modes. Such modes can be compared to some basic modes, or fundamental modes. The first three modes are the fundamental modes. They are generally the most important, as they most stress the structure; they are the two flexural modes (along two directions, orthogonal to each other) and the third torsional mode. It is important to study the oscillation of system, because it lets one understand whether the structure was well-designed. Figure 9, 10 and 11 shows the first three mode shapes of three models.

Transient Analysis

Time history and response spectrum are the two basic methods commonly used for the seismic dynamic analysis. The time history method is relatively more time consuming, lengthy and costly. The response spectrum method is relatively more rapid, concise and economical. However, time history method must be employed when geometrical and / or

Table 3. Natural frequencies of three models

SL NO	MODEL 1 Natural Frequency (Hz)	MODEL 1 Maximum displacement (cm)	MODEL 2 Natural Frequency (Hz)	MODEL 2 Maximum displacement (cm)	MODEL 3 Natural Frequency (Hz)	MODEL 3 Maximum displacement (cm)
1	0.81	0.043	0.75	0.046	0.90	0.043
2	2.64	0.058	2.23	0.058	3.01	0.060
3	5.05	0.047	4.80	0.046	7.29	0.050
4	7.71	0.063	7.42	0.080	8.75	0.039
5	8.76	0.063	8.34	0.056	9.70	0.093
6	11.63	0.042	8.76	0.039	10.10	0.070
7	14.06	0.048	12.59	0.050	15.71	0.049
8	15.80	0.064	16.18	0.094	19.11	0.072
9	17.73	0.091	17.03	0.067	19.26	0.106
10	18.13	0.068	17.14	0.071	19.63	0.068

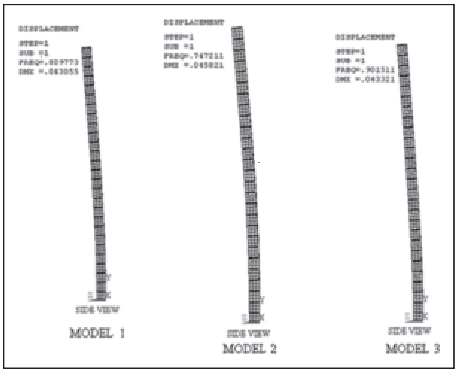

Figure 9. Mode shape for the first natural frequency

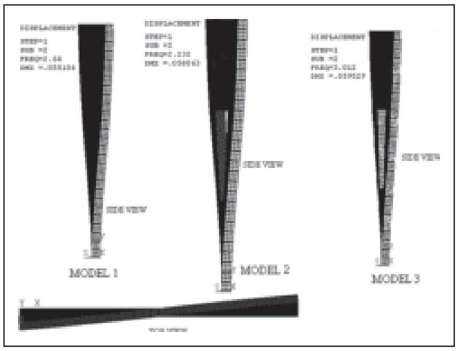

Figure 10. Mode shape for the second natural frequency

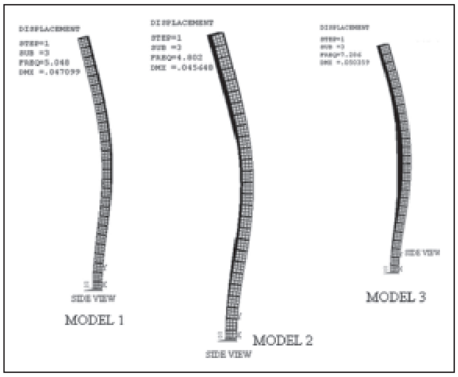

Figure 11. Mode shape for the third natural frequency

material non linearities are present in the structural system. Nowadays, it is more convenient to use time- history method due to advances in computer hardware and software.

Transient dynamic analysis (or Time – History Analysis) is used to determine the dynamic response of a structure under the action of any general time dependent loads. This is used to determine the time varying displacements, stresses, strains and forces as it responds to any combination of static, transient and harmonic loads. The time scale of loading is such that inertial or damping effects are considered to be important.

Transient dynamic analysis in ANSYS is not too difficult. The geometry and finite element model is created in the usual manner in PREP7 with loads and boundary conditions being applied in the SOLUTION phase. There are various types of analysis options such as FULL, REDUCED, MODAL SUPERPOSITION. In the present thesis, the FULL method option is used and on entering the solution phase, transient option is selected. Then the required data and damping values are entered and finally the solution is activated (ANSYS, 2003).

Once the modal analysis is completed, the next step was to carry out the transient analysis using as input, the acceleration-time data of earthquake. In this paper, Bhuj earthquake (January 26, 2001), whose acceleration time data was used, had magnitude of between 7.6 and 8.1 on Richter scale. It killed around 20,000 people, injured 167,000 people, destroyed 400,000 houses and damaged around 700,000 houses. Many multi storey buildings in Ahmedabad collapsed (Jagadish et al, 2001).

Transient Analysis was done for two separate cases. (1) In plane, where acceleration was applied to the base nodes in a direction parallel to the longer side of the wall. (2) Out of plane where acceleration was applied perpendicular to the longer side of the wall. From the transient analysis, it was observed that the maximum stress was obtained during the 11.477th second of the earthquake in both the cases mentioned above and the corresponding acceleration was 0.39g. Figure 12, 13 and 14 gives the stress distribution diagram obtained from the transient analysis of the three models. The result also shows that as the vertical loading on the top of the wall is increased, the maximum equivalent stress developed on the wall increases. The circle indicates the position of the maximum equivalent stress developed on the masonry wall. This is the point where the first crack appears.

A. Acceleration in X-Direction – In Plane

In this case, the acceleration data of the Bhujearthquake was applied to the base nodes of the masonry wall in a direction parallel to the longer side of the wall. Each model was subjected to three different magnitudes of vertical loading on the top of the wall. The maximum equivalent stress was found to be developed during the 11.477th second of the earthquake with a corresponding acceleration of 0.39g. Table 4 shows the stress details which includes the X, Y and Z stress components, shear stress in XY, YZ and XZ planes and von mises stress of the three models respectively during the 11.477th second of the earthquake.

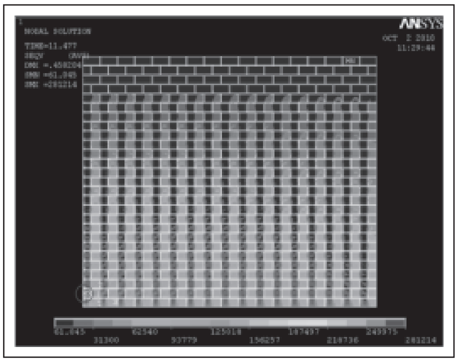

Figure 12. Stress Distribution of Model 1

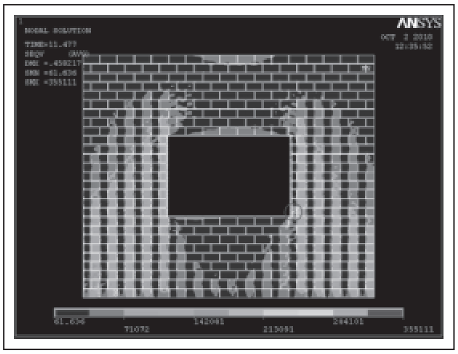

Figure 13. Stress Distribution of Model 2

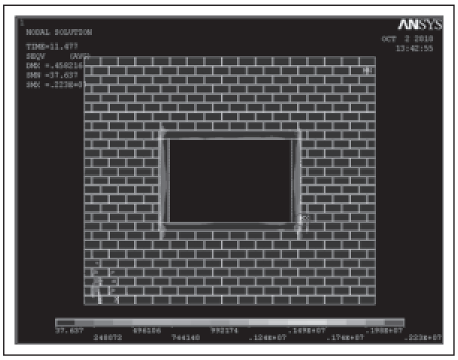

Figure 14. Stress Distribution of Model 3

Table 4. Maximum stress details for in plane motion

SL NO	DESCRIPTION	TIME (0 – 30 s)	ACCELERATION	STRESS (N/mm^2)			SHEAR STRESS (N/mm^2)			VON MISES STRESS (N/mm^2)
				X	Y	Z	XY	YZ	XZ	
I	**MODEL 1 - Wall without opening**									
a)	2kN/m	11.477	0.39g	0.080	0.056	0.023	0.057	0.010	0.014	0.285
b)	6kN/m			0.080	0.056	0.023	0.056	0.010	0.014	0.283
c)	10kN/m			0.079	0.056	0.023	0.056	0.010	0.014	0.281
II	**MODEL 2 - Wall with opening at the centre**									
a)	2kN/m	11.477	0.39g	0.130	0.067	0.029	0.086	0.012	0.018	0.363
b)	6kN/m			0.125	0.067	0.029	0.084	0.012	0.018	0.360
c)	10kN/m			0.122	0.066	0.029	0.082	0.012	0.018	0.355
III	**MODEL 3 - Wall with hole at the centre and a concrete cover around the opening**									
a)	2kN/m	11.477	0.39g	0.525	0.277	0.209	0.382	0.045	0.088	2.29
b)	6kN/m			0.519	0.273	0.206	0.376	0.044	0.087	2.26
c)	10kN/m			0.512	0.269	0.203	0.372	0.043	0.086	2.23

B. Acceleration in Z-Direction – Out of Plane

In this case, the acceleration data of the Bhujearthquake was applied to the base nodes of the masonry wall in a direction perpendicular to the longer side of the wall. Each model was again subjected to three different magnitudes of vertical loading on the top of the wall. The maximum equivalent stress was found to be developed during the 11.477th second of the earthquake with a corresponding acceleration of 0.39g. Table 5 shows the stress details whichincludes the X, Y and Z stress components, shear stress in XY, YZ and XZ planes and von mises stress of the three models respectively during the 11.477th second of the earthquake.

Discussion of Results

The following points were observed.

Three models of the masonry wall were prepared for the analysis. Each model was subjected to three different magnitudes of vertical loads (2kN/m, 6kN/m and 10kN/m) on the top of the wall. The result shows that as the magnitude of the vertical load increases, the equivalent stress increases in all the three models. The magnitude of the stress decreases from base to the top of the wall.

The duration of the Bhuj earthquake was 29.44 seconds. The maximum stress was developed on the masonry wall during the 11.477th second of the earthquake in

Table 5. Maximum stress details for out of plane motion

SL NO	DESCRIPTION	TIME (0 – 30 s)	ACCELERATION	STRESS (N/mm^2)			SHEAR STRESS (N/mm^2)			VON MISES STRESS (N/mm^2)
				X	Y	Z	XY	YZ	XZ	
I	MODEL 1 - Wall without opening									
a)	2kN/m	11.477	0.39g	0.188	0.440	0.045	0.266	0.073	0.081	0.917
b)	6kN/m			0.188	0.441	0.045	0.265	0.073	0.081	0.915
c)	10kN/m			0.187	0.443	0.045	0.265	0.073	0.081	0.913
II	MODEL 2 - Wall with opening at the centre									
a)	2kN/m	11.477	0.39g	0.323	0.627	0.058	0.271	0.066	0.155	1.340
b)	6kN/m			0.323	0.629	0.058	0.269	0.066	0.155	1.337
c)	10kN/m			0.322	0.632	0.058	0.267	0.066	0.155	1.332
III	MODEL 3 - Wall with opening at the centre and a concrete cover around the opening									
a)	2kN/m	11.477	0.39g	1.95	4.84	0.317	2.13	1.02	0.974	10.4
b)	6kN/m			1.94	4.86	0.316	2.12	1.02	0.974	10.4
c)	10kN/m			1.94	4.89	0.315	2.12	1.02	0.974	10.4

all the three models and the corresponding acceleration was 0.39g.

Transient Analysis was carried out for two different cases. Firstly, the acceleration of the Bhuj earthquake was applied in a direction parallel to the longer side of the wall (In Plane) and secondly, the acceleration was applied in a direction perpendicular to the longer side of the wall (Out of Plane).

From the result, it is observed that the wall is more vulnerable to the earthquake wave hitting perpendicular to its longer side than to the earthquake hitting parallel to its longer side. The maximum stress was developed on the left side of the wall near the base in the first model in both In Plane and Out of Plane cases. In the second model, which consists of a rectangular hole of dimension 1.5m x 1.0 m, the maximum stress was found at the right bottom corner of the wall in both the cases. This is the region where the first crack is expected to start. In the second model, it can be seen that the maximum stress shifts from the left end near the base of the wall (in the first model) to the right end bottom corner of the holedue to the introduction of the hole. In the second model it can also be seen that the stress concentration is more near the corners of the hole. In the third model, most of the stress is taken by the concrete beam around the opening. Here also, the maximum stress is developed on the right bottom corner of the concrete beam in both the cases. In this model, the entire brick masonry portion around the concrete beam is protected. Only small magnitude of stress is developed on the brick masonry.

In the case of in-plane, the stress developed on the brick masonry portion is only 34.673 x 10^{-6} N/mm^2 and in the out of plane case it is 11.998 x 10^{-6} N/mm^2 which is less than the maximum permissible value of 0.35 N/mm^2. In the first model, the maximum stress developed in the in-plane case is 0.285 N/mm^2 which is less than 0.35 N/mm^2 which is the maximum permissible crushing/ compressive stress of brick masonry with mortar of 1:6 proportions. This shows that the brick masonry remains safe if the Bhuj earthquake hits in the above said direction. But in the out-of-plane case, the maximum stress developed was 0.917 N/mm^2 which is greater than the permissible value. So if the earthquake hits in the out of plane direction the above masonry will be destroyed. In the first model, it can also be seen that the maximum stress developed in the out of plane case is 3.22 times that of in-plane case. In the second model, the maximum stress developed in the in-plane case is 0.363 N/mm^2 which is slightly greater than 0.35 N/mm^2. In the out-of-plane case, the maximum stress developed was 1.340 N/mm^2 which is greater than the permissible value. So the second model will be subjected to damages in both the cases. In the second model, the maximum stress developed in the out of plane case is 3.7 times that of in-plane case. In the third model, the maximum stress developed in the in-plane case is 2.29 N/mm^2 which is less than the permissible value of 15 N/mm^2. In the out-of-plane case, the maximum stress developed was 10.4 N/mm^2 which is also less than the permissible value. So the third model will remain undamaged if the above said Bhuj earthquake hits the building in any direction. In the third model, the maximum stress developed in the out-of-plane case is 4.54 times that of in-plane case.

Conclusions

Heterogeneous modelling gives more accurate results that homogeneous modelling. But the heterogeneous modelling is time consuming, lengthy and costly. As the magnitude of vertical load on the top of the wall increases, the maximum stress developed on the wall increases. Also the magnitude of the stress is large near the base of the wall and decreases towards the top of the wall. Earthquake wave hitting perpendicular to the longer side of the wall is more vulnerable than that hitting parallel to the longer side of the wall. This is mainly due to the height to thickness ratio of the masonry wall. When the wave hit perpendicular to the longer side of the wall height to thickness ratio is much greater than when the wave hit parallel to the longer side of the wall. The equivalent stress for the first model is concentrated on the left bottom end and right bottom end near the support of the wall. But the maximum stress is developed on the left bottom end of the wall and the magnitude is 0.285 N/mm^2 for In Plane case and it is 0.917 N/mm^2 for the Out-of-Plane case when a vertical load of 2k N/m is applied. As the vertical loading is increased, the stress developed due to the earthquake in the wall decreases. The maximum permissible value of stress is 0.35 N/mm^2 and the wall remains safe in the In Plane case but fail miserably in the Out-of-Plane case. The first crack on model 1 appears to start from the left bottom end of the wall. By providing a protective concrete cover around the wall, we can prevent the damage on this masonry wall. In the second model, stress is concentrated near the corners of the opening in the wall. Also the maximum stress is developed near the right bottom corner of the opening. For the In Plane case the maximum stress developed is 0.363N/mm^2 and for the Out-of-Plane case it is 1.340 N/mm^2 for a vertical load of 2k N/m on the top of the wall. Here also the stress decreases as the vertical load on the top of the wall increases. The wall collapses in both the In Plane and Out-of-Plane case. The first cracks starts to develop from the bottom right corner of the opening. In the third model also the stress is concentrated near the corners of the opening in the wall. The maximum stress is developed near the right bottom corner of the opening on the concrete beam provided. For the In Plane case the maximum stress developed is 2.29N/mm^2 and for the Out-of-Plane case it is 10.4 N/mm^2 for a vertical load of 2k N/m on the top of the wall. Here also the stress decreases as the vertical load on the top of the wall increases. The maximum permissible value of stress is 15 N/mm^2 for the concrete and the wall remains safe in both In Plane and Out-of-Plane case. Only a small magnitude of stress is developed on the brick masonry. In the case of In Plane, the value of stress developed on the brick is only 34.673 x 10^{-6} N/mm^2 and in the out of plane case it is 11.998 x 10^{-6} N/mm^2. From the third model, it can be seen that provision of concrete beam around openings in the wall makes the existing unreinforced brick masonry safe against collapse.

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