Chapter 27
Alternative Methods in Numerical Modelling of Earth Masonry Under Seismic Loading

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27.1 Introduction

27.1.1 Background

Masonry buildings have been very popular as a low-rise structural type due to a series of advantages such as relatively low cost, availability of materials, thermal efficiency, sound insulation and adequate durability.

Masonry construction is dated back to the ancient era for the construction of dome structures, temples, load-bearing low-rise buildings, etc. Even at present, masonry construction is popular among the house builders. However, conventional masonry material manufacturing consumes a considerable amount of natural resources and the production process emits significant amounts of CO_2 to the atmosphere. This leads to a set of environmental issues which in turn warrants a need of alternative building materials such as earth-based masonry.

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With the aim of promoting sustainable construction technology, earth has been re-introduced as a raw material for the wall construction of low-to-medium-rise buildings. In the past two decades, several researchers have established the engineering properties of rammed earth (RE) and compressed stabilized earth blocks (CSEB). Most of the studies have given the emphasis on strength properties due to static loads. Performance of earth masonry under dynamic loading is yet to be established with detailed studies. Most of the dwellings are constructed using masonry materials. Since such masonry buildings have not been designed for seismic loads and those are highly vulnerable to seismic events, and hence, the severity of the damage is substantial which could even result in some fatalities.

Therefore, there is a necessity of investigating dynamic performance of earth masonry structures in regions of moderate seismicity to enhance the seismic capacity. The dynamic properties of structural elements made out of earth masonry such as rammed earth and compressed earth blocks (stabilized/un-stabilized) have been investigated rarely with experimental studies. Further to that, numerical studies with computer modelling have occasionally been carried out on earth masonry. Such numerical analysis will be made useful by validating with experimental results, so that more resource intensive and repetitive laboratory trials for varying types of masonry could be minimized.

In this paper, attention has been paid for analysing alternative numerical models using two different computer softwares. Further the experimental data have been used to validate the numerical results and find their limitations.

27.1.2 Aim and Methodology

The aim of this study is to develop numerical models using different computer software and then use currently available experimental results to validate and to find their limitations.

27.2 Numerical Studies Carried Out on Masonry Structures

Dolatshahi and Aref (2011) did a comprehensive numerical model with explicit computational procedures available in "ABAQUS" software because in the implicit analysis, several researchers found that numerical model cannot follow the masonry wall up to failure due to convergence issues. Therefore, the numerical model results were limited. From this method, bidirectional cyclic deformation of masonry walls

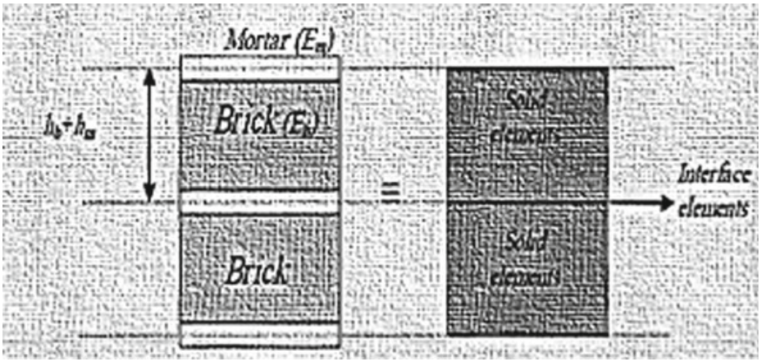

Fig. 27.1 Detailed model of brick and mortar (Dolatshahi and Aref (2011)

could be studied. The main objective of this study was to investigate the failure modes of un-reinforced masonry walls for various loading directions. Bricks and mortar were modelled as solid (C3D8R) and plane interface elements (COH3D8), respectively. Bricks were expanded by half the mortar dimension in both directions as in Fig. 27.1, and they were divided into two parts for capturing the exact behaviour and crack propagation of the wall.

For the joints, elastic and plastic behaviour were assumed. The failure modes for in-plane and out-of-plane loading were the diagonal crack and rocking mode, respectively. The numerical model was validated with past experimental studies.

Meillyta (2012) studied the performance of un-reinforced masonry walls with openings under horizontal loads by developing load–drift relationship. Finite element (FE) method (ABAQUS "software" with explicit solver), continuum elements and inelastic constitutive model (Drucker Prager) were chosen to numerically model the un-reinforced masonry wall. Interaction between the bricks was modelled using normal and tangential behaviour available in interaction module in ABAQUS. Static friction coefficient value of 5 and kinetic friction coefficient value in between 0.5 and 0.75 were used in modelling. The bottom face of the masonry was restrained for all translating degrees of freedoms. The model was validated using the load displacement results from an experimental un-reinforced masonry (URM) wall without openings.

Tarque et al. (2012) studied the non-linear seismic behaviour of adobe structures with numerical analysis since the experimental tests are costly and due to their limitations. The numerical model was validated with the experimental studies done at the Pontificia Universidad Católica del Perú by Blondet et al. (2006). The concrete damaged plasticity model was used in which the adobe was considered as an isotropic material. Further, the adobe masonry can be considered as a homogeneous material because adobe and mortar are basically made of mud. The material properties were obtained by Tarque (2011) in the plane cyclic test on adobe walls. The numerical model was subjected to an acceleration recorded at the base level in the experimental studies. The numerical model was validated fairly well with the experimental results under the crack pattern, failure mechanism and displacement response. The poor connection between the wooden beams of the roof and the adobe walls were simulated by reducing the element length to avoid the physical connection at the wall corners.

Betti et al. (2014) investigated the ability of estimating the seismic performance of un-reinforced buildings among different numerical models and analysis methods. The experimental model was a two-storey building tested on the shaking table under increasing natural ground motions. The first numerical model was built with the finite element method through a macro-model technique. The second numerical model was built using a macro-element approach. The main results of numerical and experimental studies have been compared. It has been concluded that FE model is able to predict damaged areas, initial collapse mechanism and collapse load.

The macro-element model is able to predict the collapse load accurately, but not the actual collapse mechanism. This method can be used only if the out-of-plane damage mechanisms are not initially activated. However, it can fairly estimate the fundamental dynamic response parameters by 6 degrees of freedom models. Therefore, paper suggested following both numerical and experimental approaches for the traditional, poor connected masonry buildings and locations like flexible floors where the global box behaviour cannot be assured.

Illampas et al. (2014) calibrated and validated a numerical model for adobe masonry building which is subjected to horizontal loading. For the experimental investigation, 1:2 scaled un-reinforced adobe masonry building was built and load was applied onto the rear wall using a hydraulic jack. The displacements were measured at the upper section of the rear wall, the façade and the side wall.

Experimental results concluded that adobe masonry structures subjected to horizontal loading are affected critically due to weak bonding between mortar joints and masonry units and lack of effective diaphragmatic function at roof level. Initiation of the damage was due to stress augmentation at the window corners and abutments of timber members. Further, the cracks formed were closed completely, leaving a damage indication with the removal of applied loads and they re-opened with re-applied loads. This observation reminds that an adequate inspection of earthen structures should be carried out after seismic events.

According to the experimental data, a 3D FE model was developed and calibrated with force–displacement response and failure mode. Isotropic damage plasticity constitutive law was adopted for numerical simulation. The FE analyses revealed that the global structural behaviour was affected by tensile response, and the structural behaviour of adobe masonry buildings subjected to horizontal loading is sufficiently accurate. For further investigation on the dynamic performance of adobe structures, the calibrated FE model was subjected to a time history analysis of a real earthquake.

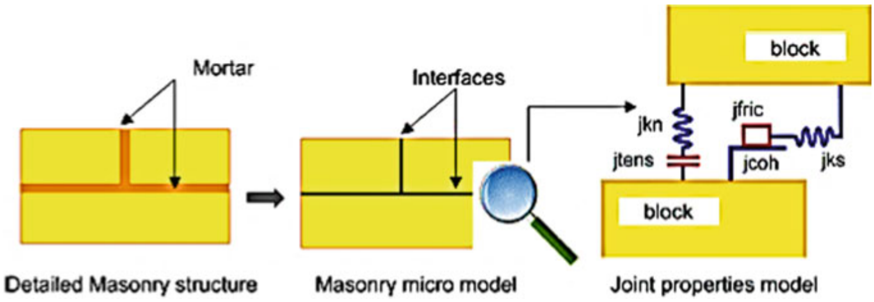

Fig. 27.2 Interface model (Çakti et al. 2016)

Ratnam (2014) has analysed dynamic behaviour of masonry wall panel of 1 m × 1.8 m with an opening made out of hollow cement stabilized soil interlocking blocks. Two masonry walls with and without reinforcement (sill and lintel band and vertical reinforcement) were tested to determine their in-plane cyclic performance. Lateral force was provided by a hydraulic actuator mounted horizontally at the height of the top surface of the wall. Lateral load and lateral displacement were measured. Further, a structural analysis program (SAP 2000) has been used to model reinforced and non-reinforced block walls and bamboo walls. It was concluded that lateral resistance and ductility of masonry walls were improved by the reinforcement.

Çakti et al. (2016) built a 1:10 scale model of the fifteenth-century Mustafa Pasha Mosque in Skopje and followed shake table tests. The experimental results of various dynamic excitations were used for the calibration of the discrete element model which represents masonry mosque and minaret by rigid blocks interacting via contact elements with tensile and shear bonds as in Fig. 27.2. Then, it was observed that numerical model can sufficiently simulate the time and frequency domain characteristics of low-level inputs and the damage regions. Generally, the discrete element approach can be used for the dynamic analysis of masonry structures which are relatively complex in laboratory conditions.

27.2.1 Summary of Idealizations Used in Numerical Modelling of Masonry Structures

- Micro- or macro-modelling technique was used.
- Bricks and mortar were modelled using C3D8R and COH3D8 elements in ABAQUS and shell elements in SAP.
- Bricks were expanded by half the mortar dimension in both directions.

- Explicit solver in ABAQUS was chosen as it is a computationally efficient and has low convergence problems over implicit method.
- Drucker Prager Plasticity Model or Concrete Damaged Plasticity Model was selected for quasi-brittle materials subjected to cyclic loads in ABAQUS.
- Interaction between the bricks was modelled using normal and tangential behaviour available in ABAQUS.

27.3 Experiments on Wall Panels

In this paper, experimental results of CSEB and RE wall panels which were subjected to time history and push over analysis, respectively, have been used for the comparison of two numerical applications.

27.3.1 Cement Stabilized Earth Blocks (CSEB)

Solid cement stabilized earth blocks which have been stabilized with 6% of cement were used as the main structural unit. Mortar joint thickness was 10 mm with cement: sand ratio of 1:6. According to the shake table capacities, wall panel dimensions were limited to 0.58 m × 0.58 m. Concrete layers were placed on the bottom and top of the walls for the confinement of the element. Two walls of the same size were subjected to moderate sized in-plane and out-of-plane seismic loading, and deflections were measured at the wall top, middle and bottom for each time increment of 0.00125 s.

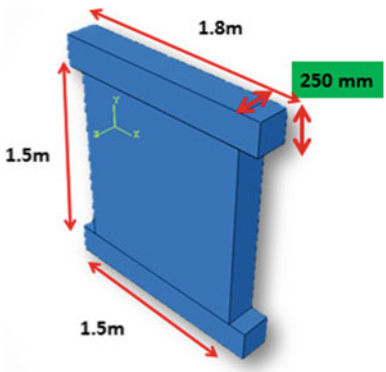

Fig. 27.3 Geometry of test specimens

27.3.2 Rammed Earth (RE)

Nabouch et al. (2016) constructed wall panels of size 1.5 m height × 1.5 m width × 0.25 m thickness by compacting earth layers using a pneumatic rammer. As shown in Fig. 27.3, top and bottom concrete layers were placed for the confinement of the element and to apply a horizontal load at the top of the wall. During the pushover test, vertical load of 0.3 MPa was applied on top of the beam to simulate the dead and live loads applied in a two storey building. The digital image correlation was performed to determine the displacement and crack propagation by comparing the images before and after the loading.

27.4 The Process of Numerical Modelling

The main steps of the dynamic analysis and the sequence of modelling the dynamic performance of earth walls using SAP and ABAQUS are shown in Figs. 27.4 and 27.5.

27.4.1 SAP

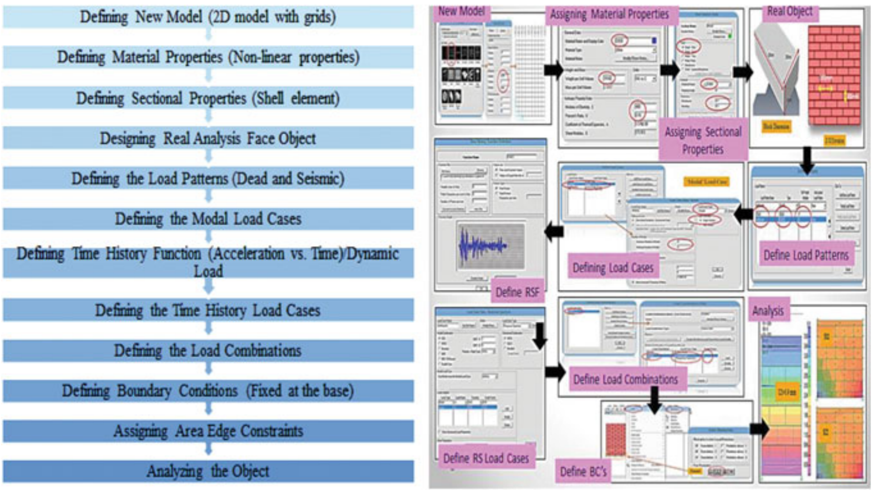

Fig. 27.4 Steps in SAP modelling

27.4.2 ABAQUS

The output of numerical analysis of CSEB and RE wall panels is presented in Table 27.1.

Table 27.2, illustrates the comparison of the results of numerical models of SAP and ABAQUS and other numerical modelling aspects.

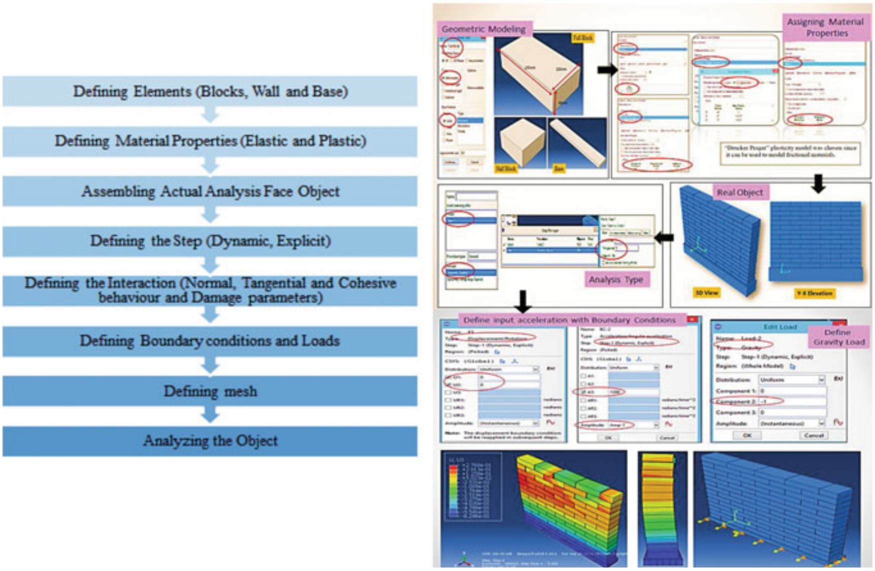

Fig. 27.5 Steps in ABAQUS modelling

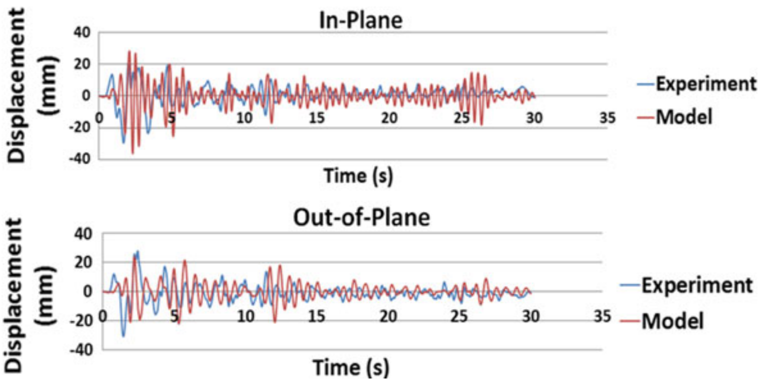

Fig. 27.6 Displacement versus time

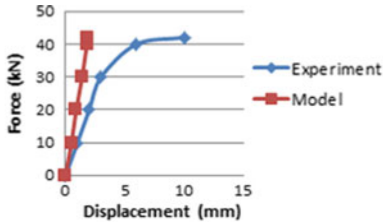

Fig. 27.7 Force versus displacement

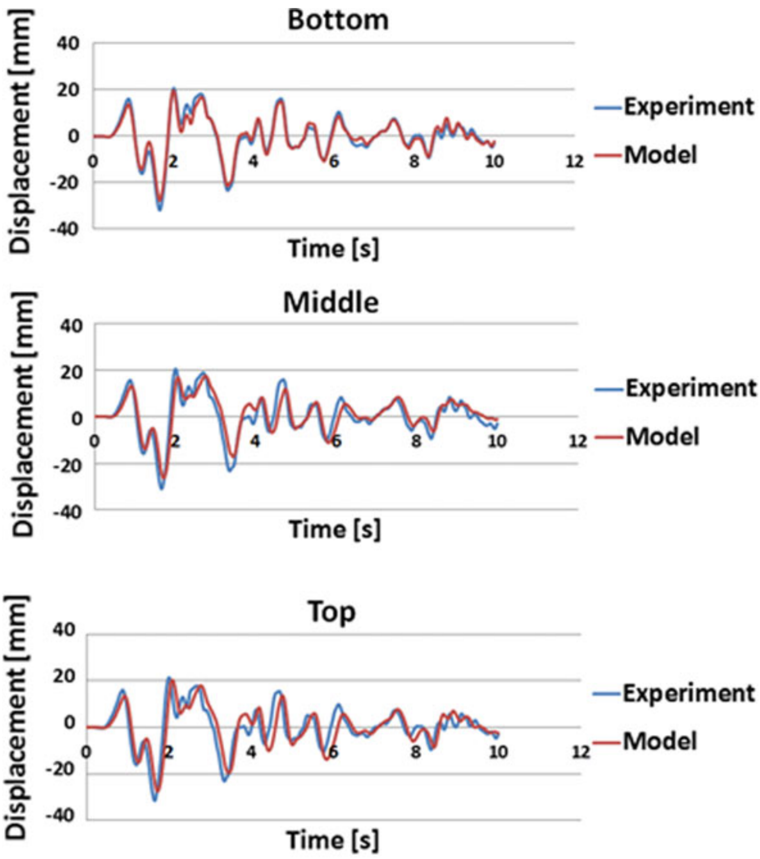

Fig. 27.8 Displacement versus time

Table 27.1 Numerical modelling results

	CSEB wall panel	RE wall panel
SAP	See Fig. 27.6	See Fig. 27.7
	Numerical displacement results in the middle and the top of the walls under the in-plane loading marginally coincide with the experimental results and for the out-of-plane loading, numerical results at the bottom and the middle of the walls also marginally coincide with the experimental results. The comparison graphs at the middle of the wall for in-plane and out-of-plane loading are shown in Fig. 27.6	For the top of the wall, numerical and experimental variation of the force versus displacement curve deviates with each other by more than 50%. The two curves for the experimental and numerical analysis are shown in Fig. 27.7
ABAQUS	Wall specimen was modelled using the solid element, concrete damaged plasticity model, dynamic explicit solver, tangential, normal, cohesive and damage interaction and applied the north–south component of the El-Centro earthquake in-plane and out-of-plane Numerical displacement results at the bottom, middle and the top of the walls under the in-plane and out-of-plane loading considerably coincide with the experimental results. The comparison graphs for out-of-plane loading are shown in Fig. 27.8	According to the above mentioned steps wall specimen was modelled using the solid element and pushover load was applied as point loads Under the in-plane loading, the experimental and numerical curves of force versus displacement converge to a greater extent as shown in Fig. 27.9

Table 27.2 Comparison of two computational models

Item considered	SAP	ABAQUS
Geometry modelling	Micro-macro 3D model	Micro-macro 3D model
Material properties	Anisotropic and Takeda hysteresis model	Elastic and concrete damage plasticity model
Assembling the actual element	Following grid pattern	Movement of elements
Defining the analysis type	Either modal or time history load case	Explicit solver
Interaction	Provide edge area constraints	Surface contact through tangential, normal, cohesive behaviour and damage
Defining the loads	Defining time history function	Defining displacement function and apply on the surface
Boundary condition	Fixed at the bottom (unless, huge distortions of the model)	Can apply displacement and acceleration constraints separately
Meshing the objects	Coarse mesh	Coarse mesh
Duration of analysis	Less than one minute	About half an hour
Displacements	Marginal convergence	Greater convergence

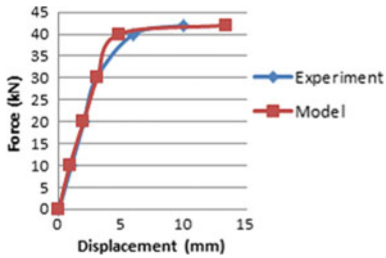

Fig. 27.9 Force versus displacement

27.5 Conclusion

Several attempts were made to assess the seismic performance of un-reinforced masonry with experimental and numerical studies using different computer softwares. The dynamic performance of earth masonry, in particular, was given a comparatively low attention by the past researchers.

Numerical analysis of dynamic behaviour of earth masonry will be given a higher prominence due to higher resource requirement needed for experimental studies. However, validation of numerical analysis with proper experimental programme presents more reliable results of the dynamic behaviour. This study has compared two different types of numerical modelling and proposed more reliable one.

In SAP, actual object was assembled according to the grid pattern using micro–macro-element approach. Masonry was assumed as anisotropic, and the Takeda hysteresis model was used. The bottom of the object should be fixed and edge area constraint must be applied to avoid model distortions.

In ABAQUS, actual object was assembled using 3D stress elements following micro–macro-element approach. Masonry was assumed as isotropic, and the concrete damage plasticity model was used. Surface interaction was applied through tangential, normal and cohesive behaviour and damage parameters. The dynamic explicit solver was used to analyse the object under displacement versus time function.

There are limitations in the SAP model to apply, true boundary and contact properties. Therefore, displacement values near the top and bottom of the wall do not coincide with experimental results. In the ABAQUS model, above limitations can be overcome, and hence, the results are considerably within the experimental values. Therefore, ABAQUS modelling of earth structures is good enough for evaluating their seismic performance compared to SAP models. But more sectional and material properties inherent to the actual structure should input in order to get accurate results and further solving time is much higher compared to SAP.

27.6 Future Work

In this paper, numerical comparisons were based upon the results of one type of experimental study. Therefore, better to confirm those observations with many experimental results by varying the parameters such as building height, wall thickness, scale of the structure, opening sizes, pre-compression load, block type, number of floors of the model and the interior structural arrangement of the model.

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