A Numerical Study on Seismic Behavior of a Typical Rural House of Iran

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ABSTRACT:
More than 90 percent of almost 4 million rural houses in Iran do not have any lateral load resisting system. A large amount of fatalities in recent earthquakes in Iran, like Bam (2003) and Zarand (2005), was due to collapse of such houses. It points to the need of more research in this area. In this paper, the seismic behavior of one of the most vulnerable types of such houses is studied through a comprehensive numerical model. The adobe blocks are modeled as separate elements connected to each other by contact elements to represent the role of mortar between the blocks. The explicit method is selected as the solving procedure and different sources of nonlinearity are considered in the analysis. The model is then analyzed for different base excitations, including ground motions recorded during Bam earthquake. The results show damage patterns which are comparable with those observed in real earthquakes.

KEYWORDS: 1- Adobe Houses 2-Finite Element Method 3- Contact Element 4-Seismic Loading 5- Iran

1. INTORDUCTION:

In Iran, many of rural houses are made up of adobe and masonry materials. Previous earthquakes have caused disasters in such houses. Wide destruction of such structures during even moderate earthquakes is indeed due to the lack of any reliable resisting system against lateral loads. Time to time, strong earthquakes such as Bam (2003) and Zarand (2005) earthquakes remind us about this fundamental problem regarding rural houses. In addition, almost all historical buildings are masonry structures, retention of which is important for governments. Growing attention of researchers to such structures may originate from above reasons.

Masonry structures are typically made up of some blocks jointed by mortar. The latter is the main weakness of such structures because the mortar used in masonry buildings is brittle and cannot bear tension. Laboratory tests on single joints show that dominant failure modes, such as sliding or separation begin from mortar [1-2]. Experiments on block assembly with mortar joints in both uniaxial and biaxial stress states have shown some basic mechanisms as slipping of joints, splitting of bricks and joints and diagonal cracking [3-4]. Combination of these mechanisms can lead to failure of a structure.

Two main approaches are proposed for numerical description of adobe or masonry material. The *macro-modeling* approach makes no distinction between blocks and mortar [5]. The material is assumed continuous and homogeneous and the effect of joints is considered in the material properties. The alternative method is *micro-modeling* approach which simulates blocks separately as a discontinuous assembly in their actual position. The blocks are connected together by interfaces. The constitutive model for interfaces is the main concern in this method and most of the efforts are concentrated on finding an appropriate formulation for interfaces in recent studies.

Page [6] was the first one who assumed the bricks to remain elastic and concentrated all non-linear behaviors on joints. He assumed two failure modes for joints, i.e., shear and tensile bond failures. In presence of compression and shear, the failure occurs in shear mode. However, when tension exists, the failure occurs in brittle mode without any load-carrying capacity over the tensile bond strength. Lotfi and Shing [7] and Lourenco and Rots [8] have proposed other interfaces using plasticity and fracture mechanics. All mentioned models use Mohr-Coulomb criteria as failure criteria. They use some internal variables to describe some post-peak phenomena. For example, Lourenco and Rots [8] added a cap model to the criteria to take into account the joint compaction.

Present research is devoted to numerical analysis of masonry houses of Iran made by adobe and mud in the framework of finite elements with micro-modeling approach. All non-linear behavior is assumed to occur in joints; and bricks are considered to remain elastic. Such assumption is appropriate for adobe/mud houses with poor mortar especially in aggressive environments.

The interfaces are modeled by a kind of hard contact with sliding and separation capability in tension. The purpose of the study is to learn about dynamic behavior and failure modes of a simple adobe/mud house. Numerical Simulation is performed using ABAQUS software [9], which provides the required features for modeling, such as different contact elements and different solving algorithms. The result of this research indicates different failure modes in a simple adobe/mud house and the procedure proposed has the capability to navigate the weaknesses of a masonry house.

2. METHODOLOGY

In micro-modeling approach each block is modeled in its actual position. In addition, joints are also modeled in their actual position so that an interface connects adjacent block faces. Figure 1 shows how bricks and joints are arranged in the model. Dynamic excitation is applied to the base of structure as an acceleration record which simulates the effect of earthquake on structure.

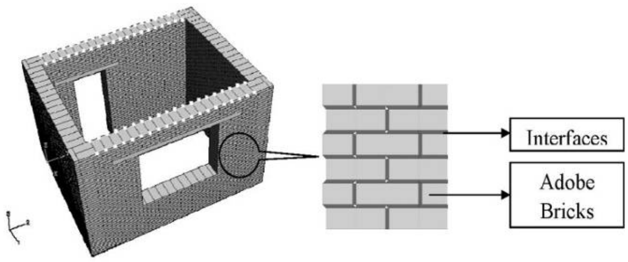

Fig. 1. Bricks and joints arrangement in model

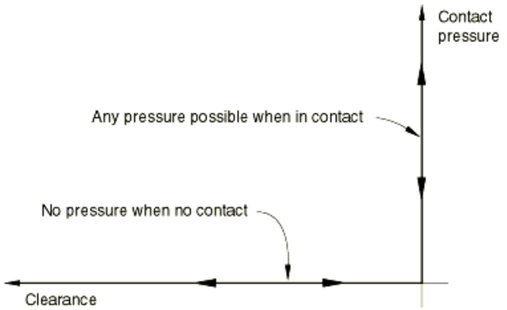

Fig.2.Normal behavior of contact elements

In ABAQUS, contact elements are used to simulate the interfaces. Zero thickness elements selected among available contact elements. Each contact has two normal and tangential behaviors. The normal behavior in compression is so that adjacent faces will remain connected and can bear compressive stress but cannot bear tension. When normal stress becomes zero the faces separate and a crack forms. Figure 2 shows the normal behavior of contact elements in tension and compression.
Mohr-Coulomb criteria is used as yielding criteria for tangential sliding (Fig. 3). If stress exceeds the shear limit obtained from the criteria, two faces begin to slide on each other and shear stress will be retained constant depending on the normal stress value. Penalty method is used as constraint enforcement algorithm. This method does not add any new parameter to the finite element solution, instead adds some displacement constraints to the problem. Frictional coefficient defines the tangential characteristic of the contacts and should be introduced to the

software as input. The frictional coefficient value depends on roughness and physical characteristics of the faces in contact.

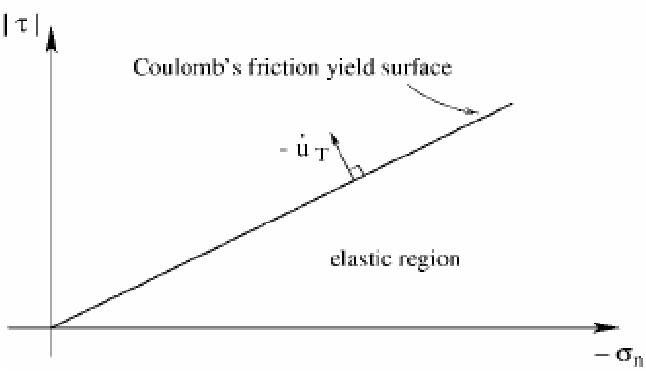

Fig. 3. Mohr-Coulomb criteria

Explicit method is chosen as solution procedure. The method is conditionally stable but if it is stable the solving procedure will be faster than implicit method. For stability of the solution a parameter is set for each solution named stability limit. The time steps for each integration stage should not be greater than stability limit. The parameter depends on parameters like minimum size of elements in model, density and modulus of elasticity and is defined by expression below:

$$\Delta t_{stable} = L^e \sqrt{\frac{\rho}{E}} \qquad L^e\text{: minimum element size} \quad \rho\text{: density} \quad E\text{: modulus of elasticity} \tag{2.1}$$

3. VERIFICATION OF THE MODEL

Figure 4 shows the crack patterns in two identical masonry walls subjected to lateral displacement in an experiment done by Velmertfoort *et al* [10] in 1992. Later, the results of this experiment were used by Lourenco and Rots [8] to verify their numerical modeling using micro-modeling procedure. Their results are shown in Figure 5 in which the cracks in some parts of the wall were predicted. Properties of the model are also shown in Table 1.

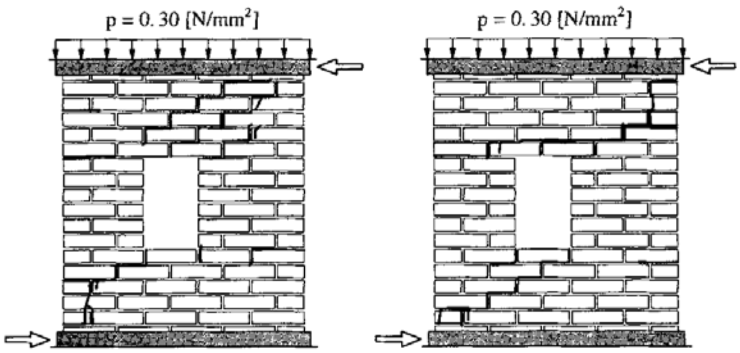

Fig. 4. Crack distribution observed in experiment [10]

Table 1. Properties of the Lourenco and Rots model [8]

Brick Dim. mm	E (N/mm^2)	Element type	Number of Elements in a Brick	Imposed Displacement mm	Vertical Load (N/mm^2)
204×98×50	16700	8 Nodes cubic Linear	4×2	25	0.3

Here, the same wall is used to verify the proposed model. Figure 6 shows the deformed shape of the wall under the same displacement. The pattern of the cracks shows very good conformity with those observed in experiments (Fig. 4) and shows the capability of the proposed procedure.

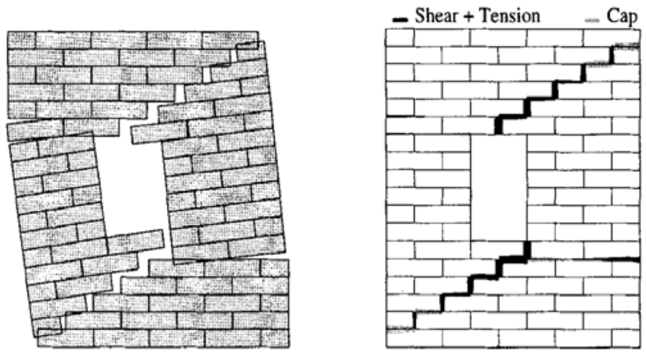

Fig. 5. Prediction of cracks by Lourenco and Rots [8]

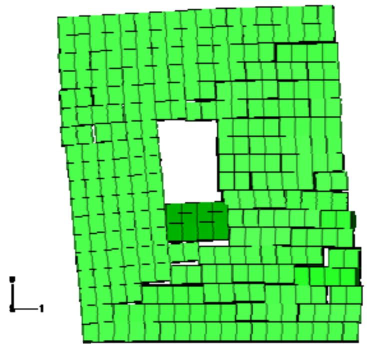

Fig. 6. Prediction of cracks in this study

4. SIMULATION OF A SIMPLE ADOBE HOUSE

Rural houses of Iran can be classified to nine different types [11]. Adobe/mud houses with wooden flat roof are among the major types. They are spread all over the country and large amount of population live in this type of houses. In the present research a simple type of adobe/mud house is selected for simulation. Brick and mortar are used in most of types of rural houses in Iran and the simulation can easily be generalized to other types of houses. The selected typical house has a simple plan and two openings. The geometry of the model is shown in Figure 7.

Bricks are arranged in the way done in practice. Each brick is modeled by a single solid element. There are several arrangements of bricks in corners (where two perpendicular walls meet) which can be used in practice. Here, an appropriate type of connection is assumed in corners (Fig. 8). This means that the bricks are arranged in a way which provides good connection between walls. It is obvious that the type of connection of walls has crucial effect on the structural response and may change the dominant failure mode.

These houses always have one way roofs and two of walls are load carrying walls. Wooden joists are put on the walls in 50cm spaces (Fig. 7). Each joist is connected to bricks by contact elements because in practice they are simply put on the wall. Shell elements carry the mass of the roof. They are also connected to the joists by contact elements. This enables the sliding mode of the roof. All other details such as openings and lintel beams are considered in the model. The lintel beams are connected to adjacent bricks by contact elements. Table 2 shows the physical properties of the model.

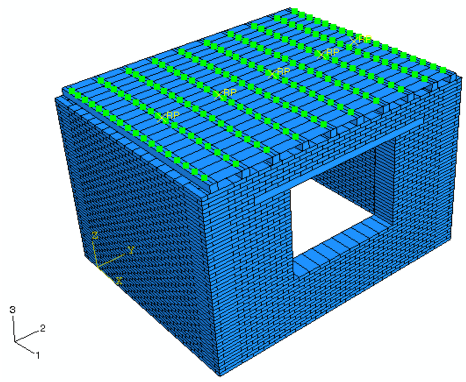

Fig. 7. Geometry of the model

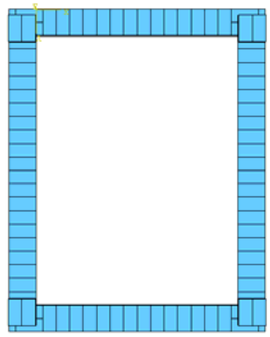

Fig. 8. Brick arrangement pattern in corners

Table 2. Physical properties of 3D house

Building Dim. m	E (N/mm^2)	Brick Dim. mm	Friction Coefficient	Density of Bricks Kg/m^3	Roof mass kg	Element type
4.8×3.8×3.0	2000	400×200×60	0.3	2100	4000	C3D8R

Dynamic loading is applied as base acceleration. First a simple record is applied at the base to draw the failure modes. The selected excitation is so that the value of acceleration in the base increases linearly until it becomes equal to **g** in a second. The record is rather intensive and imposes large displacements to the structure in order to extract failure modes. Figure 9 shows the deformed shape of the structure under base excitation in direction 2.
Failure modes occur as the displacement increases. The following order is how failure modes are observed in the model.

1. Sliding of Bricks
   First rows of bricks near base begin to slide in all walls. Relative displacement is greater in downer rows.
2. Diagonal Cracks
   Sliding of bricks in direction 2 opens a diagonal crack in walls parallel to the direction of excitation. The crack begins from base.
3. Corner Cracks in Openings
   As the displacement increases an inclined crack appears at the downer right side of the window and grows toward base (if the excitation pushes the structure to the right).
4. Out of Plane Bending Cracks
   In those walls which are perpendicular to the direction of the excitation and do not have any openings, bending cracks appear. They have a pattern which is like plastic hinges of slabs.
5. Corner Cracks Near Wall Junctions
   Such cracks tend to separate perpendicular walls. These cracks may occur sooner if the connection of walls is weak.

6. Cracks at the End of Lintel Beams
   These cracks begin from the beams at the top of openings and reach the roof.

Also, it can be concluded that, failure modes of the roof are not the dominant failure modes, even in severe large displacement excitations.

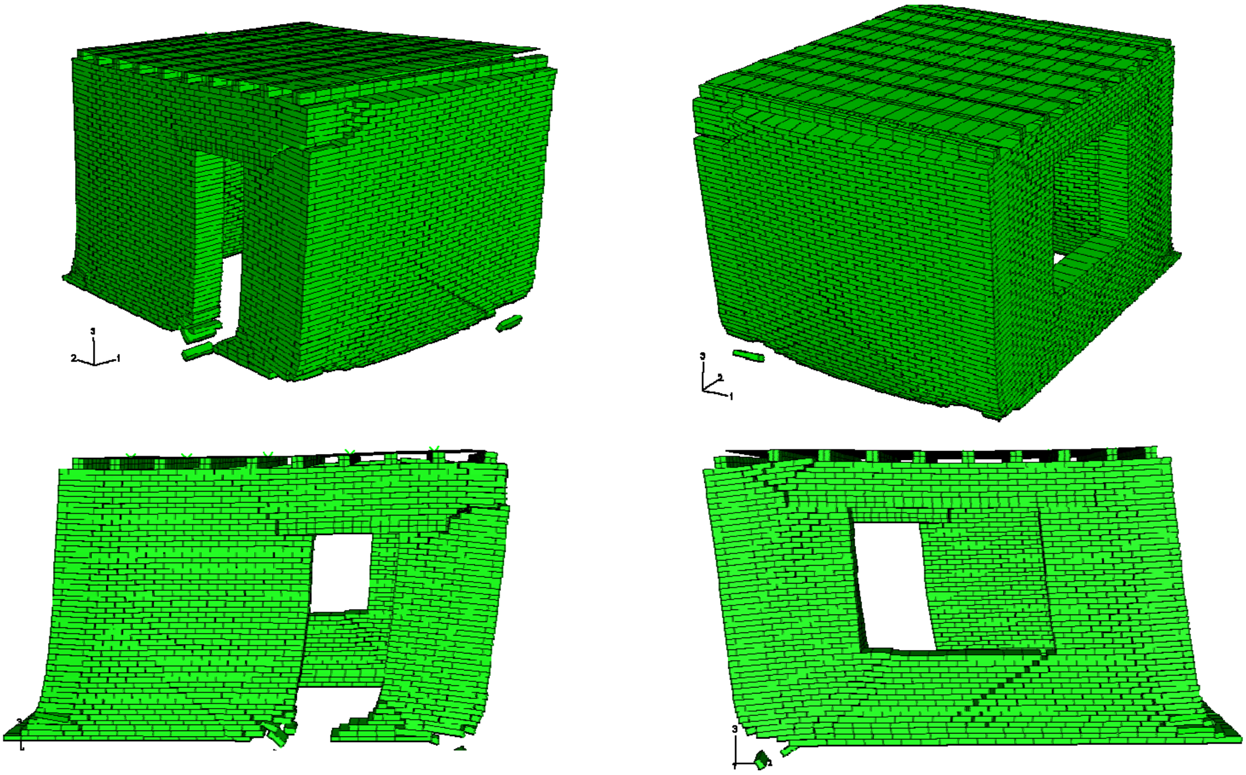

Fig. 9. Deformed shape of the 3D house under artificial excitation

As the next step, a real seismic excitation is applied to the model to investigate the effect of real earthquakes on the structure. Because the analysis procedure is very time consuming, a part of Bam earthquake record (2003) has been applied to the structure. The selected record is the main shock of Bam earthquake and lasts 7.57 seconds. Two components of the earthquake are applied in two perpendicular directions of the structure which are parallel to walls. More powerful component is applied parallel to those walls with openings (direction2). Figure 10 shows the selected records.

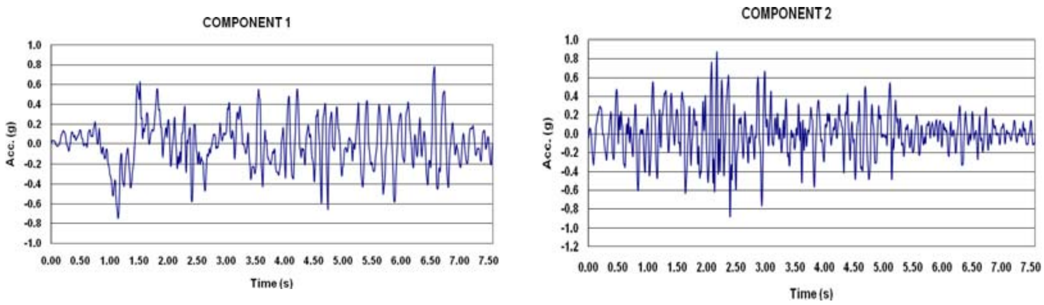

Fig. 10. Two components of the record applied to the model (Main shock of Bam 2003)

The deformed shape of the structure (Fig. 11) illustrates that previous failure modes are repeated in this excitation again. In addition second component of excitation (direction1) have caused those walls without any load to have greater out of plane deformation.

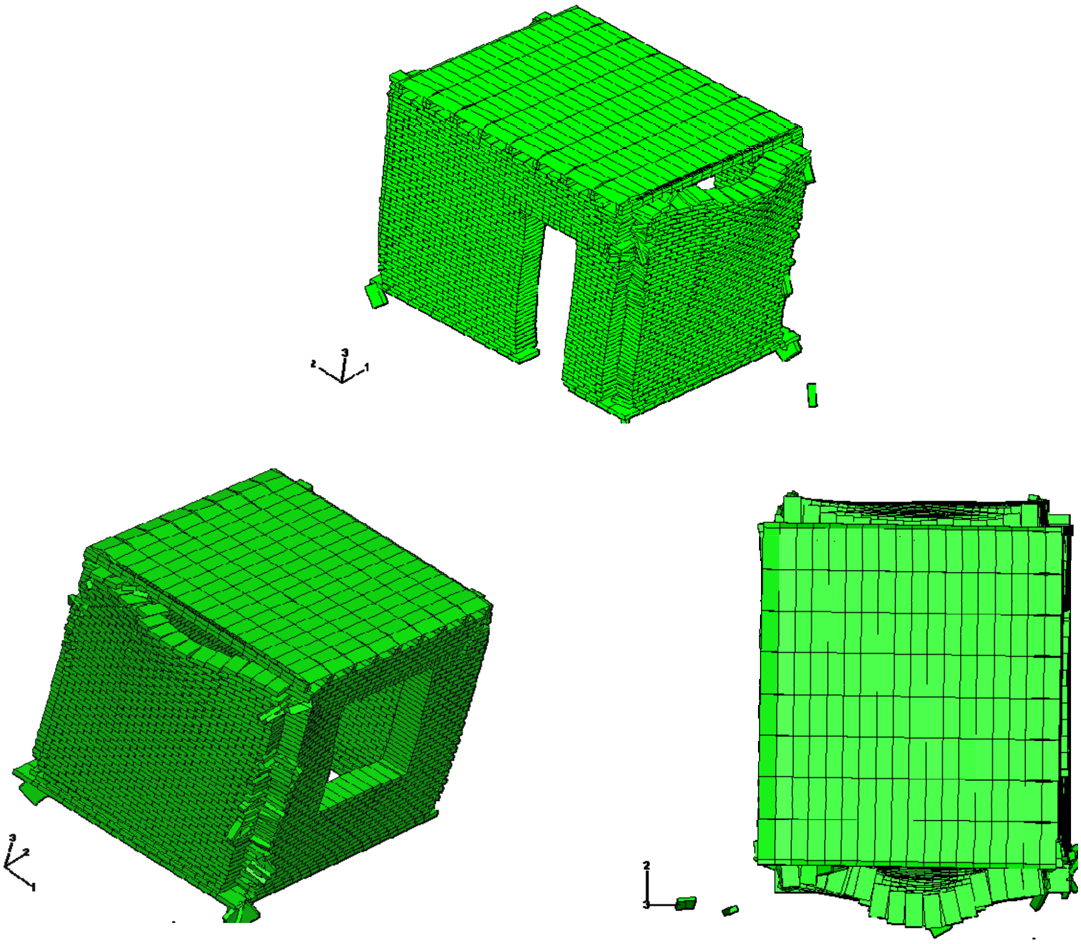

Fig. 11. Deformed shape of the 3D house under real excitation

5. CONCLUSION

Micro-modeling approach has been used as numerical approach for modeling of a simple adobe/mud structure. The results show that the methodology used in this study is an effective procedure to predict the behavior of a masonry structure subjected to dynamic loading and navigate the cracks and predict their pattern in a masonry house. The failure modes obtained from the modeling has been observed in damaged masonry buildings. Further studies are being performed on the subject.

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