NUMERICAL ANALYSIS OF A TYPICAL DOME-ROOF ADOBE BUILDING UNDER EARTHQUAKE EXCITATIONS

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ABSTRACT

After the Bam earthquake and its severe losses, the engineering community was forced to pay special attention to the seismic vulnerability of traditional structures. Therefore, with the aim of reducing such devastations to minimum, a multi-phase research project was defined at Sharif University of Technology to study the vulnerability and retrofit these structures. In the third and fourth phases of this project, a typical 2:3 scale adobe building with dome roof was chosen for study, making use of shaking table facilities. The tests included both un-retrofitted and retrofitted states and considerable seismic performance improvement was observed in the latter. In the present study, seismic response of the aforementioned experimental specimens is numerically simulated. The results of the numerical modeling indicate that the retrofitted building can tolerate up to 250\% of the excitation without collapse. Moreover, it was observed that the vertical component of the excitation has marginal effects of the failure model of the model but it considerably intensifies the experienced damages. These conclusions could not be made because of the limitations of the shaking table capacity.

Keywords: Adobe buildings, Dome roof, Numerical simulation, Seismic retrofit

INTRODUCTION

In developing countries, a large percentage of houses in rural areas are masonry buildings and a significant percentage of the population of these countries live in these buildings (Khosravifar and Mousavi, 2006). The buildings, due to the low cost and ease of manufacture, are abundant in all the villages (Housing foundation report, 2003). Figure 1 shows the average annual casualties from earthquakes in Iran over the past decays. Observations from past earthquakes suggest that the dominant construction in all areas with heavy casualties had been adobe structures which showed very poor behavior against earthquakes (Khosravifar and Mousavi, 2006).

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Figure 1. Earthquake casualties in Iran over the past 120 years (Khosravifar and Mousavi, 2006)

Casualties of the Bam Earthquake on Dec. 26, 2003 led a group of experts in earthquake engineering come together and a project was defined to study the seismic behavior of rural houses in Iran in the Department of Civil Engineering, Sharif University of Technology. This study is the eighth phase of that research series. In this phase, the numerical modeling and assumptions are calibrated against an adobe panel tested by Masaeli (Masaeli, 2009). In the following, an adobe building with a domed roof retrofitted with steel mesh and rebar tested by Yekrangnia (Yekrangnia, 2009) is numerically investigated. After that a parametric study is done over the calibrated adobe building and the results are elaborated in terms of failure modes, walls’ drift and strains in the retrofitting elements.

**MODELLING METHODS AND ASSUMPTIONS**

This section presents the methodology and assumptions of finite element analysis. ABAQUS software was used for this purpose (ABAQUS user’s Manual) and the simplified micro modeling approach was utilized in modeling (Annecchiarico et al., 2010). Therefore, half of the mortar thickness was assigned to the upper bricks and the other half to the lower bricks (Lourenco et al., 1998). Dynamic explicit method was implemented in the numerical analyses. Eight-node solid elements with first-order shape function and reduced integration was used and the mesh of 30mm consisting of 124000 elements was selected for analyses.

Adhesion of clay mortar was defined as contact elements properties (ABAQUS user’s Manual). Both the shear and tensile failure were considered for zero-thickness contact elements. Quadratic stress criterion was used for damage initiation of adhesive contact elements based on equation (1) and the evolution of damage is based on effective displacement (ABAQUS user’s Manual). Damage variable (D) shows the rate of exponential softening after the first occurrence of the failure. The damage magnitude is obtained from the equation (2) (ABAQUS user’s Manual).

\[
\left(\frac{t_x}{t_x^0}\right)^2 + \left(\frac{t_y}{t_y^0}\right)^2 + \left(\frac{t_z}{t_z^0}\right)^2 = 1
\]

(1)

\[
D = 1 - \left(\frac{\delta_m^0}{\delta_m^{max}}\right) \left\{ \frac{1 - \exp\left(-\alpha\left(\frac{\delta_m^{max} - \delta_m^0}{\delta_m - \delta_m^0}\right)\right)}{1 - \exp(-\alpha)} \right\}
\]

(2)

The amount of stress after the first occurrence of damage depends to parameter “D” which is obtained from equation (3) (ABAQUS user’s Manual). Moreover, damage evolution curves in is displayed in Figure 2 and the state of traction matrix in each increment is presented in equation (4).
\[
t_n = (1 - D) \bar{t}_n, \quad \bar{t}_n \geq 0
\]
\[
t_s = (1 - D) \bar{t}_s
\]
\[
t_t = (1 - D) \bar{t}_t
\]

\(\bar{t}_n = \frac{\delta_0}{t_0}, \bar{t}_s = \frac{\delta_0}{t_0}, \bar{t}_t = \frac{\delta_0}{t_0}\)

\[
t = \begin{bmatrix}
t_n \\
t_s \\
t_t
\end{bmatrix} = \begin{bmatrix}
K_{nn} & K_{ns} & K_{nt} \\
K_{ns} & K_{ss} & K_{st} \\
K_{nt} & K_{st} & K_{tt}
\end{bmatrix} \begin{bmatrix}
\varepsilon_n \\
\varepsilon_s \\
\varepsilon_t
\end{bmatrix} = K\varepsilon
\]

In the above equations, \(t\) and \(\varepsilon\) and \(\delta\) are the nominal stress, nominal strain and relative displacement, respectively. Indices \(n\) and \(s\) indicate tangential direction along the surface in two principal directions and the index \(t\) is normal to the surface. “\(o\)” superscript represents the maximum amount of the related parameter. \(\delta^0\) is the effective relative displacement during the first occurrence of failure, \(\delta_{mf}\) is the effective relative displacement in complete failure, \(\delta_{max}\) is the maximum value of the effective relative displacement in loading time history and \(\alpha\) is the dimensionless parameter which represents the failure evolution rate.

Adobe blocks were considered as perfectly elastic because in many cases, due to unconfined state of adobe blocks and also weak mortar/strong block walls in Iran, the damages are mainly concentrated at the locks interfaces i.e. mortar. (Dehghan, 2007), (Yekrangnia, 2009). Proper damage properties with the 1cm maximum deformation and maximum quadratic stress criterion with exponential softening were attributed to the adobe contact elements (Hasani, 2010). Table 1 shows mechanical properties of adobe which have been determined from the standard tests on adobe materials carried out previously (Masaeli, 2009).

Table 1. Modeling parameter values defined within the model

<table>
<thead>
<tr>
<th>Adobe elastic modulus (MPa)</th>
<th>Internal friction coefficient</th>
<th>Mortar tensile strength (t^0_t) (kPa)</th>
<th>Mortar shear strength (t^0_s, t^0_f) (kPa)</th>
<th>Adobe density (k\delta/\rho_m^3)</th>
<th>Adobe Poisson’s ratio</th>
<th>(\delta_{mf}) (cm)</th>
<th>(\alpha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>107</td>
<td>0.6</td>
<td>1.8</td>
<td>5.88</td>
<td>1667</td>
<td>0.25</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

MODEL DESCRIPTION

Figure 3 shows views of the experimental specimens (Masaeli, 2009), (Yekrangnia, 2009). The building is 2:3 scale adobe block with dome roof. The specimens were base-excited by intensifying Zarand (2005) earthquake records. The retrofitted specimen was retrofitted with 8 horizontal rods (22mm in diameter) drilled into the walls and bolted on the walls surfaces. The expected function of these rods was tying parallel walls and preventing them from outward overturning. Moreover, to improve walls in-plane strength, welded steel mesh was put on one side of the walls. The mesh covered less than a half area of walls and connected to them by some shear keys drilled through walls at important locations (Yekrangnia,
2009). The unretrofitted specimen collapsed in 125% of the scaled earthquake, while the retrofitted one tolerated the record of 175% intensity (Masaeli, 2009), (Yekrangnia, 2009).

The failure mode of the retrofitted model under scaled Zarand record of 175% intensity is shown in Figure 4. As can be seen, the main damages are concentrated in the lower parts of the walls which are associated with stable frictional cracks. Moreover, the model experiences torsion from unsymmetrical distribution of the openings in the walls.

Comparison of the experimental results and the numerical analysis depicted in Figure 5 indicate the validity of the numerical modeling approach and assumptions. Also, as an example, the absolute maximum and average of top displacement of different walls of the numerical model under 175% of excitation level is presented in Table 2.
Figure 5. Comparison of the failure modes of experimental results and the numerical analysis

Table 2. Walls top displacement under 175% Zarand earthquake in the retrofitted model

<table>
<thead>
<tr>
<th>Wall</th>
<th>Absolute in-plane displacement (m)</th>
<th>Absolute out-of-plane displacement (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max.</td>
<td>Average</td>
</tr>
<tr>
<td>North</td>
<td>0.085</td>
<td>0.019</td>
</tr>
<tr>
<td>South</td>
<td>0.176</td>
<td>0.090</td>
</tr>
<tr>
<td>East</td>
<td>0.362</td>
<td>0.200</td>
</tr>
<tr>
<td>West</td>
<td>0.284</td>
<td>0.130</td>
</tr>
</tbody>
</table>

Comparison of strains in the retrofitting elements

During the tests, strain gauge mounted on the horizontal rebars (the rebars which controls out of plane displacement of walls as shown in Figure 6 has been monitored (Yekrangnia, 2009). Figure 7 and Figure 8 show the comparison of rods strain between the experimental specimen and the numerical model. As observed, strains occurring in the numerical model are in good agreement with the experimental results, except for bar 4. It should be noted that the strain-gauge on rod No. 8 during the test was destroyed and hence no experimental data is available on this rod (Yekrangnia, 2009).
PARAMETRIC STUDIES

Retrofitted building under 250% Zarand earthquake

Because of limitations of shaking table, the test was carried out up to 175% earthquake excitation (Yekrangnia, 2009). In order to evaluate seismic performance of the building up to collapse, the calibrated model was excited under 200%, 225% and 250% earthquake excitation. It was observed that 250% of Zarand earthquake excitation causes severe damages of the model. It is noteworthy that the main mode of failure in the model was the torsion and local cracks in the openings. The remarkable thing is that despite extensive damage in the model, the roof remained stable and the retrofitting plan completely restrains the upper part of building which caused the model work as an integrated part. Figure 8 shows the failure mode of the model under 250% of Zarand earthquake excitation.
The effects of vertical component of excitation

The shaking table of Sharif University of Technology can only apply the horizontal components of earthquake records. Therefore, only two horizontal components of Zarand earthquake record were applied to the both test specimens. In order to take into account the effects of vertical component of earthquake records, the calibrated model was excited under 175% and 200% earthquake records. It was observed that in 200% level, the model collapsed same as the level 250% without vertical component of record. Figure 9 shows the failure mode of model under 175% earthquake records with vertical component.

Figure 10 shows the out-of-plane relative displacement of top of the walls under excitation levels 175%, 250% and 175% having vertical record component. As it can be seen, the vertical component of Zarand earthquake has marginal effect on the failure mode of the building. Moreover, the out-of-plane displacements of the North-South and East-West walls are the same. This indicates that the parallel rebars which control out-of-plane displacements of the walls are efficient and the parallel walls react monolithically.
CONCLUSIONS

The numerical modeling of a previously-tested adobe building with dome roof was considered in this paper. The models were calibrated based on the result of experimental works; both showing the effectiveness of the implemented retrofitting pattern. The results of the parametric study show that the retrofitted building can tolerate up to 250% of earthquake excitation intensity. Furthermore, applying the vertical component of Zarand earthquake record has no considerable effect on the failure mode of the model.

REFERENCES


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