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Finite element analysis on the collapse of infill walls with holes and different length-to-height ratios *

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Abstract: Wenchuan earthquake damage survey displayed the major structures of buildings suffered only small damages, but it was common that infill walls suffered heavy damages or even collapse. To study the failure forms and collapse mechanism of infill walls in an earthquake, the influence of opening or length-to-height ratio on shake-resisting capability of filling walls was analyzed, and measures to improve the anti-collapse ability of infill walls were put forward. The numerical simulations on collapse process in earthquake were carried out by using ABAQUS software. We used 5 single story and single span models. It is revealed that the rigidity and compressive capacity of infill walls are reduced because of the infill walls with holes and the increases of length-to-height ratios. Adding constructional columns and horizontal beams can ensure structural integrity and improve the anti-collapse ability of the wall.

Keywords: finite element analysis; collapse; length-height ratio; rigidity

1 Introduction

Masonry-infilled reinforced concrete frames can be found in many parts of the world. The infill wall as a non-structural component is always neglected in the design and its influence on the major structure is usually not considered. An infill wall is simplified as a linear load applied to the major frame. Its influence on the natural period of the frame structure is considered through a reasonable period reduction factor. Researchers have suggested that infill walls have led to the collapse of buildings [1-3] and may affect the response of frames detrimentally [4]. Researchers have also suggested that masonry infill panels may be beneficial [5-12].

The damage of an infill wall not only affects the structural functionality but also cause life-threatening in severe cases. The related survey showed that the damage and collapse of infill walls are more common than those of a major structure, and length-to-height ratio and openings of an infill wall are two important factors on its collapse [13,14]. After Wenchuan earthquake, many infill walls collapsed or severely damaged and how to improve the anti-collapse ability of buildings or structures is an extremely rewarding subject [15-16].

Finite element software ABAQUS was used to conduct a simulation analysis on 5 single-story and single-span models, to investigate the influence of opening and length-to-height ratio on the collapse of infill walls in earthquake, find their failure forms and collapse mechanisms. A series of specific anti-collapse measures were put forward through the simulation, which provide references for future anti-seismic designs and the collapse analysis of masonry structures,
2 Analysis models

2.1 Parameters of models

The mortar and the blocks are modeled respectively based on the distinct element method\(^{[17]}\) without considering the bond slip between them, their all degrees of freedom are coupled, and 5 infill wall models are built. The masonry walls of single story have a height of 3.0 m. The columns and beams have a cross section of 500 mm × 500 mm and 500 mm × 250 mm. The infill walls have a height of 2.4 meters. The reinforced concrete lintels have a size of 2 400 mm × 190 mm ×190 mm on the top of opening. The blocks of infill walls are ordinary small concrete blocks, the major block size is 390 mm × 190 mm × 190 mm, and auxiliary blocks size is 190 mm×190 mm × 190 mm. Other parameters are seen in Table 1 in detail. Constitutive relations for beams, constructional columns and blocks are linear elasticity, considering only contact nonlinearity. These material properties are seen in Table 2 in detail.

<table>
<thead>
<tr>
<th>Model</th>
<th>L/m</th>
<th>H/m</th>
<th>L/H</th>
<th>lmax/m</th>
<th>h/m</th>
<th>Construction measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>4</td>
<td></td>
<td></td>
<td>1.7</td>
<td></td>
<td>Adding the structural column</td>
</tr>
<tr>
<td>Model 2</td>
<td>6</td>
<td></td>
<td></td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 3</td>
<td>6</td>
<td></td>
<td></td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 4</td>
<td>4</td>
<td></td>
<td></td>
<td>1.7</td>
<td>1.6 × 1.2</td>
<td>Adding the structural column and horizontal collar beam</td>
</tr>
<tr>
<td>Model 5</td>
<td>4</td>
<td></td>
<td></td>
<td>1.7</td>
<td>1.6 × 1.2</td>
<td></td>
</tr>
</tbody>
</table>

2.2 Simulations of mortar

The deformation and failure of actual masonry mortar are related to not only the characteristics of material itself, but also the deformation and movement of blocks that are connected with the mortar in earthquake. The failure criterions for the vertical mortar joint and the horizontal mortar joint are different due to various plumpness of mortar joint. So the actual mechanical deformation of the mortar in a mortar joint is very complicated and uneven. In order to simplify the models, we assume that the deformation of the mortar includes only three main directions: one normal deformation and two tangential deformations. The mortar is simulated by mortar spring that the thickness is zero in this work. According to the existing criterions\(^{[18]}\), the shear strength of mortar is 0.06 MPa, and the tensile strength of mortar is 0.07 MPa. When the shear stress and the normal stress of mortar reach shear strength and tensile strength respectively, the mortar spring broke.

We select the stiffness of spring based on concrete material to model mortar, which uses coarse aggregate (similar to a block element) as the basic element from micro mechanism of concrete material. The mortar material (similar to the mortar of mortar joint) is used as the spring\(^{[19]}\) between elements. The normal force \(N\), tangential force and steering forces between discrete elements are given by

\[
\begin{align*}
\Delta F_n &= \begin{bmatrix} k_{11} & 0 & 0 \\
0 & k_{22} & k_{23} \\
0 & k_{32} & k_{33} \end{bmatrix} \begin{bmatrix} \Delta u_n \\
\Delta u_r \\
\Delta \theta \end{bmatrix}, \\
\Delta M &= 
\end{align*}
\]

where \(k_{11} = EA/l_{ij}, k_{22} = 12EI/l_{ij}^3, k_{23} = -6EI/l_{ij}^3, k_{33} = 4EI/l_{ij}^3\), and \(l_{ij}\) is a unit distance between \(i\) and \(j\). \(E\) is the modulus of elasticity of the element material, \(A\) is the cross-section of element, \(I\) is the inertia moment of element.

2.3 Connection and contact

The infill wall and the beam-column are connected with reinforcement. The axial connection in the software ABAQUS is used to simulate the connection, which has a component of relative translation momentum, but not restrain relative rotation\(^{[20]}\).

Compared with traditional finite element analysis, simulation of an infill wall must be related to the
interface of each component. In this work, the contact algorithm in the ABAQUS/Explicit is used to simulate the interface of blocks or between the blocks and the ground. Tangent contact is defined to ensure tangential relative slippage between the surfaces and it also determines the internal frictional force. Coulomb friction is chosen and the friction coefficient is 0.09. The normal contact is defined to ensure embedding depth between two contact surfaces and the key is to determine the pressure-depth curve. Hard contact is selected in the paper, the two surfaces begin to contact when embedding depth varies from a negative value to zero, and creates a contact pressure. The contact restriction is relieved when the contact pressure turns into zero or a negative value.

The existing damping dissipates the energy of the structure, which makes the frame structure stay still ultimately after the blocks in the infill wall come off. After blocks come off, it is important to find the final balance when the damper of mortar becomes invalid, which is the ultimate aim of the simulation of infill-wall collapse. Otherwise, the structure will shock near the balance because the kinetic energy of blocks is not dissipated. The paper uses the Rayleigh damping model after a simplified approach to adjust and determine the mass damping coefficients based on the conservation of structural energy after being calculated.

2.4 Seismic excitation

As the ground was simplified into a rigid element and the blocks were solid elements. The connections were complex between the rigid element and the solid elements, so the bottom wall and the frame column bottom were subjected to the seismic loads in the form of acceleration waves. The rigid ground played a part in undertaking the blocks that broke off.

The input earthquake acceleration in the numerical simulation was the Wolong wave (recorded by the record in the Wenchuan Wolong Station of the China Earthquake Center when Wenchuan earthquake hit on May 12, 2008). Seismic waves of 10 s in the east-west direction and the north-south direction were selected without considering their vertical acceleration. The acceleration time-history curves are shown in Fig. 1. The peak value of acceleration is 0.957 g in the east-west direction (parallel to the wall). The peak value of acceleration is 0.655 g in the north-south direction (perpendicular to the wall). Seismic loadings are acting on the bottom of the wall and the column with the bidirectional acceleration waves. The spread directions of input seismic waves are shown in Fig. 2.

![Fig.1 Acceleration time-history of seismic waves in a) the east-west direction; and b) the north-south direction](image)
3 Results and discussion

3.1 Effect of length-height ratio

The length-height ratio is 1.7 and the flexible connection for the infill wall and the structural column is researched in the paper in Model 1. The connection played a role in the connection of the blocks, which made the masonry-infill frame structure keep the structural integrity during the earthquake. The failure of the wall is shown in Fig. 3. Just a few blocks slip slightly when the earthquake was over.

Model 2 was built to analyze the influence of the length-height ratio on shake-resisting capability of the infill wall, which had a length-to-height ratio of 2.5. A few cracks started to appear on the wall at the seismic time \( t=6.5 \) s in Model 2. The number of the cracks increased suddenly and the blocks bulged outward at the seismic time \( t=7 \) s. The cracks of the wall were all horizontal cracks in the simulation and the positions of the cracks were near the mortar joint where the infill wall and the beam-column were connected with steel ties. This is because the rigidity of mortar was much larger than the steel strength under the earthquake and horizontal lacing bars would bend owing to the anchoring force of mortar. The tensile strength of the mortar was lower and tension failures of mortar happened easily in the deformation process of steel tie. Finally, the blocks came off due to losing the felting effects of the mortar. The damage is shown in Fig. 4. Compared with Model 1, the infill wall in Model 2 was destroyed and collapsed in a large amount. This is because the length of horizontal reinforcement increased when the length of the wall was longer, the deformation ability increased and the tensile stress in the horizontal mortar joint increased, which caused the mortar failure under tension.

According to “Code for Seismic Design of Buildings”, the concrete structural columns should be added when the width of masonry-infill wall is twice larger than the story height. The length-to-height ratio was 2.5 and the width of the infill wall was twice larger than the story height in Model 2. In order to increase the anti-collapse ability of the infill wall with more length-to-height ratio, the concrete structural column was added in the middle of the wall in Model 3. Cracks appeared in the wall at the seismic time \( t=8.5 \) s and a longer horizontal crack was near the mortar joint where steel tie was set. A few shear cracks appeared in the wall and only one block fell off. The damage was shown in Fig. 5. Meanwhile the structural column divided the infill walls, reducing the length of reinforcement strip, decreasing the deformation of the infill wall and reducing the impact of the mortar layer due to tension.
The displacement time history curves on the top of the column of Models 1 to 3 without openings are shown in Fig. 6. The displacement on the top of the column in Model 2 is larger than in Model 1. The maximum displacement parallel to the wall is 5.76 mm in Model 2, which is 2.31 times larger than that in Model 1 in the direction. The maximum displacement perpendicular to the wall is 6.44 mm in Model 2, which is 1.76 times larger than Model 1 in the direction. The results suggest that with a larger length-to-height ratio, reciprocal constraints between the infill wall and the major frame are reduced, the relative displacement of the structure increases, the degree of damage increases and the security decreases. The curves of Model 3 show that adding the structural column imposes constraints on the structure and this reduces the displacement of the structure effectively. The earthquake damage research shows [21] that the anti-shear capacity of the structural column on the infill wall does not improve remarkably, but helps prevent sudden collapse of the structure under an earthquake.

The structural columns are added to improve the deformation ability and ductility significantly. They expend a portion of earthquake energy by deformation and friction slip after cracks appear in the wall, reducing the earthquake disaster of the infill wall frame structure.

3.2 Effect of the opening

At the seismic time $t=6.5$ s, the blocks form stagger displacement and begin to come off on both sides of the window, and the whole performance of infill wall begins to decrease in Model 4. At the seismic time $t=7.5$ s, the wall begins to collapse at a large scale. At the seismic time $t=10$ s, the wall collapses completely, as shown in Fig. 7c. The blocks atop the wall do not fall off because they are connected to the beam. The horizontal lacing tie near the edge of the hole can not be connected to the component effectively such as the structural column, which relieves the restraint on the blocks. In the end the infill wall collapses completely, as shown in Fig. 7.

In Model 5, only one auxiliary block becomes loose and falls over in the earthquake. The diagonal cracks appear at the left side of the opening and a long horizontal crack is produced at the joint between the opening and the beam. The wall remains uninjured during the earthquake, as shown in Fig. 8. In the meantime, the structural column and the diagonal collar beam expended a portion of seismic energy to reduce the injury of the major frame and infill wall, stopping or delaying the collapse of the structure and reducing the loss of the earthquake.

![Fig. 5 Damage of Model 3](image)

**Fig. 5 Damage of Model 3**

![Fig. 6 Displacement-time curves of the top of columns: a) parallel to the wall; and b) perpendicular to the wall](image)

**Fig. 6 Displacement-time curves of the top of columns: a) parallel to the wall; and b) perpendicular to the wall**
The time history curves of displacement atop the column in Models 1, 4 and 5 are shown in Fig. 9. The maximum displacement parallel to the wall is 5.84 mm in Model 4, which is 2.35 times larger than that in Model 1 in the direction. The maximum displacement perpendicular to the wall is 7.65 mm, which is 2.06 times larger than that in Model 1 in the direction. The results show that some structural measures are needed to restrain the blocks near the hole, that fall over firstly when an earthquake happens. This deprives the necessary integrity of the infill wall, causing destruction and collapse of the wall prematurely. The anti-seismic performance of the infill wall in Model 5 is much better than that in Model 4 obviously, because the wall is divided by the structural column and the horizontal collar beam to prevent the expansion of cracks after cracks appear in the wall. This limits the displacement and skidding of the blocks and maintain the bearing capacity of the walls.

4 Conclusions

1) By the discrete element method, the mortar is simplified to three-dimensional mortar spring with normal deformation and shear deformation, which can reflect the crack of mortar joint and slippage of blocks very well. So the discrete element method applies to simulating and analyzing the collapse of masonry-infill walls.

2) Increasing the length-to-height ratio of infill wall reduces the anti-collapse ability of infill walls. Adding the structural columns in the middle of wall can increase its integrity and anti-collapse ability.
3) The ultimate loads of the walls are reduced because of the holes, and strengthening measures should be taken in order to improve the ductility and earthquake resistance capacity. Adding the structural columns and horizontal collar beams can limit the slip of blocks and increase seismic performance of the structure.

References


Fig. 9 Displacement-time curves of the top of columns: a) parallel to the wall; and b) perpendicular to the wall.


