Nonlinear FEM Numeral Simulation of RC Shear Walls with Staggered Holes

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ABSTRACT: Shear walls with staggered holes (SWSH) are bad for structures, if they are applied in buildings, we should modify them. This paper mainly discusses their seismic performance and influence of different strengthened methods on them. Based on existed experiment results, Models of shear walls with staggered holes and 3 kinds of strengthened models are established with finite element software OpenSEES. The strengthened methods are (a) hidden beams be added between two adjacent floors; (b) Based on Method (a) the hole edges are strengthened with construclational columns; (c) Based on Method (a), the diagonal reinforcement is added in the wall limbs between holes and edge columns. The calculation results show that the ductility and load capacity of SWSH is much lower than regular shear walls, and all the 3 kinds of strengthened methods can improve it, especially (b) and (c) can improve seismic performance efficiently, and (c) shows better performance in later stage. Thus it is suggested that shear walls be strengthened with Method (b) or (c), if shear walls with staggered holes are applied in actual engineering.

Keywords: shear walls with staggered holes; OpenSEES; strengthened methods; FEM Analysis

1 INTRODUCTION

Shear walls are important anti-literal force members in tall buildings, which have the advantages of high rigidity and strong capacity. They enter the plastic state before frames under severe earthquakes, which can enhance damping factor of structures, and then consume the earthquake energy. Scholars had taken a great deal of research on shear walls. The affecting factors of shear walls anti-seismic is summarized to be axial compression ratio[1-2], span-to-depth-ratio of coupling beams[3], the height-width ratio of wall limbs[4], the construction of edge columns and wall limbs. [5-7]

The Chinese code states that [8], shear walls should be distributed regularly in structures, the doors and windows should be aligned vertically. However, the door and window holes may not be aligned vertically in actual engineering. If it is inevitable to apply the shear walls with staggered holes in actual engineering, the hole edges should be strengthened, or the holes be filled with lightweight materials to make the shear walls rule. So far, scholars had made much and intense research on rule shear walls, but the research on shear walls with staggered holes is not shown.

In recent years tall and super tall buildings are popular worldwide, especially in China, but since the Wenchuan and Yushu earthquake in China, the seismic design is increasingly valued by Chinese government, and the earthquakes disaster frequently occurred this century. Thus it is more and more important to study on earthquake and anti-seismic for structures. Till now, there are two ways of studying seismic design, experiment test and numeral simulation. Now researchers always combine the two ways to verify structure seismic performance, however, we cannot experiment on full-scale structures, then, it is necessary to use finite elements softwares.

Comparing with experimental tests, numerical simulation is effective, because it is impossible to do so many experiments to verify the tall buildings, and experiment tests may cost much money, the numerical simulation is able to saving costs, and the experimental specimen are always reduced scale structural models, they are different from the practical engineering. Thus it is necessary for engineers to use finite elements software to design and analyze structures.
Nowadays the softwares MSC.Marc [9], ABAQUS [10], Perform3D [11], Etabs ANSYS [12] are popular. These softwares are powerful in analyzing, but the costs are high, and the source codes are always unavailable, it may restrict the further in-depth research and discussion on their internal mechanisms and functionalities.

Unlike conventional commercial software, OpenSEES is for free and the source code is available, it enables people to conduct a secondary development, which can help to improve OpenSEES. Based on the existing experiments [3], different models of shear walls with staggered holes are established with the nonlinear finite element software OpenSEES, and the influence of different strengthened methods on shear walls are analyzed.

2 MODEL VALIDATION

Based on OpenSEES code, Xinzheng Lu had developed the layered shell element ShellMITC4, which is based on the theory of material mechanics. The layered element simplifies the three-dimensional nonlinear behavior of the shear walls into a shell situation by discretizing them into several fully-bonded layers in the thickness direction. Different material properties and thicknesses can be assigned to each layer according to the size of the wall and the distribution of reinforcing bars [13-14] (See Figure 1). The bars are smeared into one or more orthotropic layers according to their physical location and direction, as shown in Figure 2. Comparing to the conventional methods, it is easier to model shear walls with element ShellMITC4, and the computational efficiency is high.

The ShellMITC4 element needs to define material PlaneStressUserMaterial for concrete and Steel01/02 for rebar, then discretize them into layers respectively. The overall procedure for defining the multi-layer shell element in OpenSEES is shown in Figure 3.

To verify the reliability of layered shell element, the model CW2 [3] is calculated. The columns, coupling beams and wall limbs are established with layered shell element ShellMITC4. The elevation draw and the reinforcement sectional draws are showed in Figure 4, and the comparison of calculating and test hysteric curves is showed in Figure 5. The material mechanic properties are shown in Table 1, and the axial force is 100kN, the compression ratio is 0.1.

![Figure 1. Multi-layer shell element.](image)

![Figure 2. Distribution of the rebar layer.](image)

<table>
<thead>
<tr>
<th>Floor No.</th>
<th>$f_y$ MPa</th>
<th>$f_c$ MPa</th>
<th>$E_c \times 10^4$ MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38.6</td>
<td>3.12</td>
<td>3.12</td>
</tr>
<tr>
<td>2</td>
<td>$\Phi 4=796.9^*$</td>
<td>38.7</td>
<td>3.38</td>
</tr>
<tr>
<td>3</td>
<td>$\Phi 6=311.3$</td>
<td>40.1</td>
<td>2.76</td>
</tr>
<tr>
<td>4, 5</td>
<td>$\Phi 4=278.3$</td>
<td>47.4</td>
<td>3.07</td>
</tr>
</tbody>
</table>

Notes: 1. the rebar elastic modulus is $2.1 \times 10^5$ MPa; $^*$For $\Phi 4$, there is no obvious yielding point, this value is the ultimate strength of the steel bar; $f_y$ is yield strength of rebar, $f_c$ is concrete compression strength, $E_c$ is concrete elasticity modulus.
Figure 5. Comparison of test curves and calculation curves.

The comparison result shows that the calculation curves are in good agreement with the test curves, it means that the ShellMITC4 element can simulate seismic response of coupling shear walls.

3 NUMERICAL SIMULATION AND ANALYZE

3.1 Shear wall models with staggered holes

The Chinese code states that [8], shear walls should be distributed regularly in structures, the doors and windows should be aligned vertically. In this section, we will study on the influence of staggered distance and staggered ways (SW4,5 are shear walls with staggered holes on the up 3floors, and SW6,7 are shear walls with staggered holes all through the structure).

Based on the CW2 specimen [3], finite element models are established to analyze the influence of different forms of staggered holes on shear walls. Among the models, SW1 is the CW2 specimen [3](Figure 3), SW2 and SW3 are also symmetry shear walls, coupling beam length is 600mm and 800mm(elevation draws shown in Figure 6a); SW4 and SW5 are symmetry at first two floors, but asymmetry at the upper three floors(elevation draws shown in Figure 6b). SW6 and SW7 are models with staggered holes through the whole shear walls (elevation draws shown in Figure 6c).

Table 2. Information of models.

<table>
<thead>
<tr>
<th>No.</th>
<th>Elevation</th>
<th>3-3</th>
<th>4-4</th>
<th>5-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW1</td>
<td>Figure 4a</td>
<td>Figure 4b</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SW2</td>
<td>Figure 6a</td>
<td>Figure 6a</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SW3</td>
<td>Figure 6a</td>
<td>Figure 6a</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SW4,5</td>
<td>Figure 6b</td>
<td>Figure 6b</td>
<td>Figure 6d</td>
<td>Figure 6e</td>
</tr>
<tr>
<td>SW6,7</td>
<td>Figure 6c</td>
<td>-</td>
<td>Figure 6d</td>
<td>Figure 6e</td>
</tr>
</tbody>
</table>

The comparison of skeleton curves for SW1-7 are showed in Figure 7.

Figure7a shows that, the initial stiffness and load capacity decreasing with the coupling beam span-depth ratio increasing, the stiffness and load capacity
reduces as the coupling beam length grows. Staggered holes does not affect the initial stiffness of shear walls, but the peak load comes early, the ductility is lower. The load capacity and ductility of SW4 and SW5 is lower than SW1, it means that staggered holes can bring negatively affect to seismic performance of shear walls, the peak load of SW2 is lower than SW1, but close to SW4, therefore, it is suggested that the shear walls with staggered holes be modified by extending its coupling beam length, which can make the shear walls regular (lightweight infilled material does not participate in force), if the staggered distance is short.

Figure 6. Overall procedure for defining the multi-layer shell element.

Figure 7. Skeleton curves for SW1-7.

3.2 Strengthened shear wall models with staggered holes

The analyze results above show that the staggered holes do affect seismic performance a lot. If it is inevitable to use the shear walls with staggered holes, the
hole edges should be strengthened, showed as Figure 8a, or the holes be filled with lightweight materials to make the shear walls rule, showed as Figure 8b.

Based on Chinese code [8], three kinds of strengthened shear wall models with staggered holes are established based on SW5 and SW7. Figure 9 is the diagram of SW5-1 and SW7-1 which is strengthened by hidden beams between holes the next two floors; Based on SW5-1 and SW7-1, constructional columns are arranged at the edge of holes, Figure 10; Diagonal reinforcement is arranged between holes and edge columns to make SW5-3 and SW7-3, see Figure 11. Figure 12 is the sectional draws of SW5-1-5-3 and SW7-1-7-3. Figure 13 shows the comparison of skeleton curves for strengthened shear walls with staggered holes and SW1, SW5.

Figure 8. Construction of shear walls with dragged holes.

Figure 9. Diagrams of SW5-1 and SW7-1.

Figure 10. Diagrams of SW5-2 and SW7-2.

Figure 11. Diagrams of SW5-3 and SW7-3.

Figure 12. Section reinforcement of 6-6 and 7-7.

Figure 13. Skeleton curves of strengthened shear walls with dragged holes.
We can see from the Figure 13 that, the hidden beams can improve the seismic performance of shear walls with staggered holes very well, the later strength is much higher, because there is a sudden change of lateral stiffness for shear walls with staggered holes, but the hidden beams can relieve the sudden change; The load capacity of SW5-2 and SW5-3 is higher than SW5-1, and the ductility seems to better which is shown in skeleton curves. The strength of SW5-2 is higher than SW5-3 in early stage, but when the displacement increase to 25mm, SW5-3 shows better performance on strength, SW7-2 and SW7-3 performs the same trend. It means that the diagonal reinforcement between holes and edge columns is able to improve the ductility of shear walls better, because the wall limb between holes and side beams is in complex stress, the diagonal rebar can improve the seismic performance especially the latter strength well.

Figure 14. Skeleton curves of SW5-1-3 and SW7-1-3.

Figure 14 shows the comparison of skeleton curves for shear walls with staggered holes throughout the model and the ones with staggered holes partly through the model. The initial stiffness is nearly identical, so we can see from the result that, different strengthened methods do not influence the initial stiffness. Comparing with SW5-1 and SW7-1, SW5-2 and SW7-2, SW5-3 and SW7-3, the strength of shear walls with staggered holes partly through the model is higher than that of shear walls with staggered holes throughout the model, but as the displacement grows, the strength of the latter one is higher than the former one.

4 CONCLUSIONS

Shear walls with different staggered forms and strengthened methods are established with nonlinear finite element software OpenSEES, the conclusion follows:

(1) The calculation curves are in good agreement with test curves, which means that the ShellMITC4 can simulate the coupled shear walls well [13-14];

(2) Based on the existed experiment results, shear wall models with staggered hole are established to analysis influence of the staggered distance, forms (shear walls with staggered holes throughout the model or ones with staggered holes partly through the model) to seismic performance. The analysis results show that the load capacity and ductility of shear walls with staggered holes are lower than the regulation shear walls. The farther the staggered distance is, the lower the load capacity appears to be. It is suggested that the shear walls with staggered holes be modified by extending its coupling beam length, which can make the shear walls regular (lightweight infilled material does not participate in force), if the staggered distance is short;

(3) This paper shows 3 different strengthened methods of shear walls with staggered holes which are with far staggered distance, they are: a the hidden beam be added between two adjacent floors; b Based on Method a the constructional column is added to the hole edges; c Based on Method a, the diagonal reinforcement is added in the wall limbs between holes and hidden columns. Comparing to the strengthened Method a, the other two methods show better performance. Method b shows better performance in early stage which is with larger load, and Method c shows better performance in later stage.

REFERENCES


