Finite Element Analysis On The Mechanical Behaviors Of New Cross-slanted Corrugated Steel Plate Shear Wall

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Abstract. In order to study the mechanical behaviour of the cross-slanted corrugated steel plate shear wall, the performance of the wall under one-way loading and low cycle loading was analyzed using the finite element analysis software ABAQUS. And the performance compared between flat steel plate shear wall (FSPW), single inclined corrugated steel plate shear wall (SCSPW) and horizontal corrugated steel plate shear wall (CSPW) was studied. The results show that the effect of self-buckling of the models of cross-slanted corrugated steel plate shear wall (CCSPW) is significant due to the interaction of two layers of corrugated steel plates. The yield bearing capacity, ultimate bearing capacity and out of plane deformation of CCSPW are better than those of CSPW, SCSPW and FSPW with the same thickness. The yield bearing capacity is 1.09 times of the same thickness of CSPW, 1.22 times of the same thickness of SCSPW. The ultimate bearing capacity is 1.25 times of the same thickness of CSPW, 1.57 times of SCSPW. And the out of plane deformation is 1/3 of the same thickness of CSPW. Under the low cycle loading, the hysteretic curve of CCSPW is shuttle shaped, full and stable. And there is no obvious "pinching" phenomenon in the whole loading process. Compared with CSPW, SCSPW and FSPW, The CCSPW has better hysteretic performance and energy consumption capacity.

1. Introduction
Steel plate shear wall is a new type of lateral-load resistance structural system developed in the 1970s. It is widely used in high-rise buildings and bridge engineering due to its superior seismic performance and convenient construction [1]. With the continuous further study, there are more and more types of new steel plate shear walls and their performance is more and more superior. The corrugated steel plate shear wall is developed based on the flat steel plate shear wall. The corrugated steel plate refers to the steel plate crimped to reduce the out of plane deformation by providing geometric rigidity. Due to the special structure, the corrugated steel plate shear wall can provide greater out of rigidity and restrain out of plane buckling to improve the buckling bearing capacity of the steel plate wall[2-3].

In 2005, domestic and foreign scholars have gradually increased the study on corrugated steel plate shear walls. According to the different corrugation forms, they can be divided into folded plate corrugated steel plate, trapezoidal corrugated steel plate, sine corrugated steel plate, etc.[3-4]. Lan Yinjuan et al. [5] studied the folded-plate shear wall. The results show that the critical buckling load of the three-folded corrugated steel plate shear wall is significantly higher than that of the flat plate shear wall, and its rigidity and the ultimate bearing capacity is also enhanced. Zhao Qiuhong et al. [6]...
conducted elastic buckling analysis and nonlinear pushover analysis on single-layer sine corrugated steel plate shear wall structures, and the influence of different parameters on the corrugated steel plate shear wall is obtained.

By intersecting two-layer corrugated steel plates obliquely, the cross-slanted corrugated steel plate shear wall was designed, and the performance of the wall under one-way loading and low cycle loading is analyzed by using the finite element analysis software ABAQUS, and flat steel plate shear wall (FSPW), single inclined corrugated steel plate shear wall (SCSPW), and horizontal corrugated steel plate shear wall (CSPW) were compared to study the performance advantages of cross-slanted corrugated steel plate shear wall (CCSPW).

2. Composition and construction of CCSPW

2.1. Model overview
The cross-slanted corrugated steel plate shear wall structure (CCSPW) is composed of two embedded corrugated steel plates inclined in different directions, edge members (beams, columns), and end plates, as shown in Figure 1. The corrugated form of the embedded corrugated steel plate is selected sine wave, as shown in Figure 2. The embedded corrugated steel plate is connected with the end plate to form a whole structure. This integral filling method can ensure that the steel plate wall has good rigidity, so that it can bear the horizontal load through the shear deformation of the steel plate and the tensile yield of the plate strip, and it can also bear the vertical load.

3. Finite element model

3.1. Model size
In order to analyze the performance of the cross-slanted corrugated steel plate shear wall (CCSPW), a single-layer single-span steel plate shear wall was designed according to the design method of literature [11]. At the same time, the same size flat steel plate shear wall (FSPW), single inclined corrugated steel plate shear wall (SCSPW), and horizontal corrugated steel plate shear wall (CSPW) was also designed for comparison. The model column section size was H400×400×13×21, the beam section size was H500×300×11×15, and the geometric dimensions of the corrugated steel plate shear wall model were shown in Table 1.

| Types    | Number | Board width L/mm | Board height H/mm | Wavelength q/mm | Amplitude a/mm | Board thickness tw/mm |
|----------|--------|------------------|-------------------|-----------------|----------------|----------------------|
| CCSPW    | M-0    | 3000             | 3000              | 300             | 60             | 5                    |
| FSPW     | M-1    | 3000             | 3000              | -               | -              | 5                    |
| SCSPW    | M-2    | 3000             | 3000              | 300             | 60             | 5                    |
| CSPW     | M-3    | 3000             | 3000              | 300             | 60             | 5                    |
3.2. Element selection and material parameters
To study the out-of-plane buckling and failure modes of CCSPW, the SHEEL element was selected, and S4R elements (4 nodes, reduced integral) were used for each component. The Bauschinger effect was considered under the cyclic load. Therefore, the constitutive material model was strengthened by using the double-fold line. And the material yield criterion used the Von.Mises yield criterion. The tangent modulus in the strengthening stage was $1/100E$. The constitutive model was shown in Figure 3.

![Figure 3. Material constitutive model](image)

![Figure 4. Schematic diagram of steel plate shear wall loading](image)

3.3. Boundary conditions and load law
In order to simulate the constraint conditions at the bottom of the shear wall, the bottom of the embedded corrugated steel plate and the bottom of the frame column were completely fixed as shown in Figure 4. The loading surface of the steel plate wall is located at the end of the beam, and each index of the loading surface is coupled to a point outside the plane. The loading is carried out by controlling the displacement of the reference point, so as to avoid the stress concentration phenomenon when a single node is loaded. In the analysis, the vertical load was considered. The top surface of the column was coupled to a point to apply axial force, and the upper flange of the beam was uniformly loaded.

3.4. Meshing
The shape and size of the grid has a greater impact on the accuracy of the finite element simulation results. According to the trial calculation, quadrilateral shape was chosen. And the grid size of the frame was 150mm, the grid size of the corrugated steel plate was 100mm. Furthermore, to shorten the calculation time, the number of grids was reduced by coarsening the non-key research parts.

4. Analysis results

4.1. Lateral resistance performance
During the elastic stage, the bearing capacity keeps linear growth with the displacement shown from the load-displacement curve of the four types of specimens in Figure 5. After the bearing capacity reaches the yield bearing capacity, there is a slight increase. However, when the specimen M-2 is under compression, there is a significant decline after reaching the peak bearing capacity. And the bearing capacity of the other three types of specimens basically stabilized. The bearing capacity of specimen M-0 is significantly higher than that of specimen M-2 and specimen M-1 under compression. And its yield bearing capacity is 122% higher than that of specimen M-2 and 131% higher than specimen M-1; The ultimate bearing capacity is 157% higher than that of the M-2 compression specimen and 125% higher than that of the specimen M-1.

Figure 6 shows the load-displacement curves of specimens M-0 and M-3. The initial stiffness, yield load and peak load of specimen M-0 are similar to those of specimen M-3, and the ultimate bearing capacity of the former is significantly higher than the latter, 1.24 times that of the latter. The comparison of the two curves shows that the specimen M-3 has obvious yield inflection points, ascending phase and descending phase. However, the bearing capacity of specimen M-0 remains basically unchanged after reaching the peak value. Under the lateral load, it is always in the tension...
and compression mode, while the specimen M-3 mainly depends on the shear yield of the corrugated steel plate to bear the lateral load. When the displacement is loaded to a certain degree, The inner panel will produce large out-of-plane buckling, resulting in the failure of the steel plate wall, and the bearing capacity of the structure decreases significantly.

4.2. Hysteresis performance

Figure 7 shows the hysteresis curves of Specimens M-0, M-1 and M-2. And Figure 8 shows the hysteresis curves of Specimens M-0 and M-3. It can be seen from Figure 7 that in the initial loading stage of the flat steel plate shear wall specimen M-1, the load-displacement curve maintains a linear relationship, and the structure is in the elastic stage. As the displacement increases, the structure enters the elasto-plastic stage. The slope of the hysteresis curve is obviously reduced, and the hysteresis curve finally takes an inverse "S" shape, with obvious "pinching". There is also a sudden change in stiffness during the loading process. The bearing capacity of M-1 is obviously smaller than that of specimens M-0 and M-2.

Comparing the hysteresis curve of specimen M-2 with that of specimen M-1, The slope of the single stage hysteresis curve during forward unloading is not much different from that of M-1, but its slope during negative unloading is much higher than that of M-1. And the hysteresis loop area of specimen M-2 is larger than that of specimen M-1, indicating that the overall energy consumption performance of specimen M-2 is better than M-1.

It is showed by comparing specimen M-0 with specimen M-2 that: (1) The bearing capacity of specimen M-0 under forward loading is obviously greater than that of specimen M-2. And the slope of the hysteretic curve when unloading is also obvious less than the slope of the specimen M-0. (2) The hysteresis curves of the two types of specimens did not appear to be pinched significantly during the entire loading process. When M-0 is forced in the positive and negative directions, the hysteresis curve is full and stable. And the area surrounded by the hysteresis loop is large, showing better energy consumption and ductility performance. It can be seen that the form of embedded steel plate has a significant influence on the hysteretic performance of the structure. The embedded plate is a corrugated shear wall. And its hysteretic performance, energy dissipation capacity and ductility are superior to flat steel plates.

From the comparison of the hysteresis curves of specimens M-0 and M-3 in Figure 8, it can be seen that: (1) At the initial stage of specimen loading, the area enclosed by the hysteresis loop is very small, and the two curves almost overlap. The load-displacement curve is straight, which shows that the structure is still in the elastic stage. (2) With the increase of displacement, the load-displacement curve no longer conforms to the linear relationship, and the hysteresis loop area gradually increases. At this time, the difference between the two becomes more obvious. The main difference is that the hysteresis curve of the specimen M-0 has a large slope, a large area surrounded by the hysteresis loop, and a small decrease in the bearing capacity. When the specimen M-3 was displaced about 50mm, the embedded steel plate basically failed to resist the lateral side. And the structural bearing capacity
decreased greatly. As the displacement continued to increase, the bearing capacity quickly dropped to 0.85Vmax, which was judged as structural failure. (3) The overall performance of the two types of specimens is that the hysteresis curve is basically shuttle-shaped. And there is no pinching during the entire loading process.

4.3. Skeleton curve

Figure 9 shows the skeleton curves and the pushover curves of specimens M-0 and M-3 which reflecting the mechanical properties of the structure and the decline of its bearing capacity. Figure 10 shows the skeleton curves of specimens M-0, M-1, M-2 and M-3. As can be seen from the comparison of the four curves in the figure, among the specimens M-0, M-1 and M-3, the bearing capacity and initial stiffness of a single specimen in positive and negative direction are basically the same. While the bearing capacity and initial stiffness of M-2 in positive and negative direction show large difference. All kinds of specimens have obvious elastic and inelastic deformation stages. During the elastic stage of specimens, the skeleton curve of M-0, M-3 basically overlap in both positive and negative directions, and their lateral stiffness is relatively larger than M-2 whose lateral stiffness appears relatively larger than M-1. Overall, the relationship between load and displacement of the four types of specimens shows a linear relationship.

With the increase of loading displacement, the structure enters the elastic-plastic stage. When the displacement is about 25mm, the bearing capacity of the specimen decreases in varying degrees and the decrease amplitude of the specimen M-2 m-3 is obviously greater than that of the specimen M-0 M-1.

5. Conclusion

A new type of cross-slanted corrugated steel plate shear wall (CCSPW) is proposed, and finite element analysis is carried out on CCSPW. Moreover, a comparison study was done between single inclined
corrugated steel plate shear wall (SCSPW), corrugated steel plate shear wall (CSPW), and flat steel plate shear wall (FSPW). Through the analysis, the main conclusions are as follows:

1. When CCSPW is subjected to lateral force, the tension plate provides out-of-plane restraint for the compression plate, which limits the premature buckling of the compression plate and makes the embedded steel plate reach shear yield. It is the same behavior when the compression plate is tensioned. The plate provides support to avoid excessive concentration of buckling ripples, and the two layers of steel plates interact to achieve the effect of self-anti-buckling.

2. The embedded steel plate form and the corrugated steel plate placement form have a greater impact on the overall mechanical properties of the structure. Under the action of low-cycle reciprocating load, the hysteretic curve of CCSPW is full and stable, basically in the shape of a shuttle. And there is no obvious "pinching" phenomenon in the whole loading process. The positive and negative initial stiffness and bearing capacity of the two are basically the same. Compared with CSPW, SCSPW, FSPW, it shows superior hysteresis performance and energy consumption.

Acknowledgments
The study was supported by A Project of Shandong Province Higher Educational Science and Technology Program (Grant No. J18KA206). Any opinions and conclusions expressed in this paper are those of the writers.

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