Study on lateral-force resistance performance of cross-slanted corrugated steel plate shear wall

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Abstract. In this paper, a cross-slanted corrugated steel plate shear wall is proposed, and its lateral-force resistance performance is analyzed by finite element method. The results show that the cross-slanted corrugated steel plate shear wall (CCSPW) can effectively suppress the out-of-plane buckling of the infilled steel plate. Therefore, the CCSPW has larger initial stiffness and excellent ductility. In addition, the ultimate bearing capacity of the designed cross-slanted corrugated steel plate shear wall is 2.26 times that of the flat steel plate shear wall (FSPW), and is 2.09 times that of the single oblique corrugated steel plate shear wall (SCSPW).

1. Introduction

The steel plate shear wall, developed in the 1970s, has been widely used as an effective lateral-force resistance system for high-rise buildings and bridges [1]. With the deepening of research, the types of steel shear wall are more and more, and the performance is getting better and better. In recent years, the corrugated steel plate shear wall has attracted increasing interests, mainly focusing on enhancing out-of-plane stiffness, strength, ductility and high energy dissipation [2, 3].

In 2002, Chan and Khalid [4] performed finite element analysis on three types of steel plate shear walls, named flat steel plates, cross arrangement trapezoidal corrugated plates and vertical arrangement trapezoidal corrugated plate respectively. The results showed that the shear strength of the vertical arrangement trapezoidal corrugated plate shear wall was higher than that of the other two types of shear walls, laying the foundation for the research and application of corrugated steel shear wall. According to the different corrugated forms, corrugated steel plate can be divided into folding corrugated steel plate, trapezoidal corrugated steel plate and sinusoidal corrugated steel plate [3, 5]. Among them, the trapezoidal corrugated steel plate shear wall has been studied a lot [3-7], while the reports of other forms are relatively little. Lan et al. [8] studied the folding shear wall. The results showed that the critical buckling load of the triangular corrugated steel plate shear wall was significantly higher than that of the flat shear wall. What’s more, the triangular corrugated steel plate shear wall demonstrated high rigidity and high ultimate bearing capacity. Dou et al.[9] studied the shear buckling behavior of sinusoidal corrugated steel plate shear wall by finite element method. The results showed that, for the sinusoidal section steel shear wall, the buckling form only had overall buckling and local buckling and no interaction buckling occurred. The authors also pointed out that the wavelength had a greater effect on the buckling load of the steel wall. Zhao et al.[10] studied a single-layer sinusoidal corrugated steel plate wall and obtained the effects of different structure parameters of the corrugated plate on elastic buckling load and lateral stiffness of the corrugated steel plate shear wall.
In this paper, a cross-slanted corrugated steel plate shear wall is designed by using two layers of sinusoidal corrugated steel plates. The two corrugated steel plates are arranged obliquely. The finite element software ABAQUS is used to study its lateral-force resistance behaviors and the stress mechanism is analyzed. In order to have a better understanding of the advantages of the designed cross-slanted corrugated steel plate shear wall, it is compared with the flat steel plate shear wall and the single oblique corrugated steel plate shear wall.

2. Characteristics of the cross-slanted corrugated steel plate shear wall

The overall structure of the cross-slanted corrugated steel plate shear wall is shown in Figure 1 (a), which mainly consists of frame column, frame beam, slanted corrugated steel plate and end plate. The parameters of the sinusoidal corrugated steel plate are shown in Figure 1 (b). Two slanted corrugated steel plates are bolted or welded in the factory. The connection form of infill steel plate and frame is revealed in Figure 1 (c). The infill steel plate is first welded to the end plate, and then the end plate is bolted to the flange of frame column and beam. In addition, the welding connections process is finished in the factory in advance, not like the traditional manufacture of steel structure connections. Therefore, the construction of end-plate connection is convenient, fast, insensitive to the season, and easy to be high quality.

3. Finite element model

3.1 Mode size

Figure 2 shows the simulation model of the proposed cross-slanted corrugated steel plate shear wall (CCSPW). Its overall dimension is 3000 mm × 3000 mm, as shown in Table 1. CCSPW consists of the infilled corrugated steel plates, two frame columns and one frame beam. The frame column and beam are H-shaped steel. In addition, to better illustrate the lateral-force resistance performance of the proposed steel plate shear wall, the flat steel plate shear wall and the single slanted corrugated steel plate shear wall are modeled as shown in Table 1.
Figure 2. Finite element model of the cross-slanted corrugated steel plate shear wall.

Table 1 Main parameters of the three finite element models (unit: mm).

| Model type                                      | Name | L   | H   | q  | a  | t_w |
|------------------------------------------------|------|-----|-----|----|----|-----|
| Flat steel plate shear wall                    | M-1  | 3000| 3000| -  | -  | 5   |
| Single slanted corrugated steel plate shear wall| M-2  | 3000| 3000| 300| 60 | 5   |
| Cross-slanted corrugated steel plate shear wall | M-3  | 3000| 3000| 300| 60 | 5   |

3.2 Element selection and material parameters

In order to better reflect the local buckling of the beam column and the plastic hinge at the end of the frame. The infilled steel plate, beam and column are modeled using shell elements, that is the S4R (4-node, reduced integral) unit.

The material of infill steel plate is Q235 (Level B), while the frame beam and column are Q345 (Level B). Their tensile yield strengths are 235 MPa and 345 MPa, respectively. The Young’s modulus is $2.06 \times 10^5$ MPa and the Poisson ratio is 0.3. Thus, the infilled steel plate would yield firstly in theory. To simplify the process of the model, the ideal elastoplastic model is used. Before yielding, it is the ideal elastic material. After yielding, it is the ideal plastic material.

3.3 Boundary condition and load condition

The bind constraint was used to achieve the between column and infilled steel plate, and the I-shaped column are completely fixed at the bottom. The out-of-plane displacement of the load beam web is also limited. In addition, for analyzing the function of the infilled steel plate, the beam and column are hinged, and the connection between the infilled plate and the frame is simplified as rigid connection.

Moreover, the displacement loading control is adopted, and the ultimate loading state is taken when the lateral displacement of the loading point reaches 150 mm. In order to effectively prevent stress concentration caused by single node loading and better output the load-displacement curve of loading point, each index of the loading surface is coupled to a point outside the plane of the beam end, and the displacement load is directly applied to the coupling point.

Considering the influence of initial geometrical imperfections on the deformation of the steel plate, a certain geometric initial defect must be applied to the steel plate in the finite element modeling. The initial defect amplitude is 0.004 [11].
4. Analysis results

4.1 Effect of types of corrugated steel plates

The overall lateral load-displacement curve of the structure is shown in Figure 3 (a). It can be concluded that the lateral stiffness and ultimate bearing capacity of the cross-slanted corrugated steel plate shear wall structure are significantly higher than that of the flat steel plate shear wall and the single slanted plate corrugated steel plate shear wall. The ultimate bearing capacity of the designed cross-slanted corrugated steel plate shear wall is 2.26 times that of the flat steel plate shear wall (FSPW), and is 2.09 times that of the single oblique corrugated steel plate shear wall (SCSPW). The infilled flat plate achieves overall yield when it moves 9mm sideways. After reaching the peak bearing capacity, it is nearly stable. For the single slanted corrugated steel plate wall, the shear yielding occurs when the lateral displacement is small, which means its initial stiffness is small. When the lateral displacement is 14 mm, the full yield is achieved. At this stage, the lateral load is no longer supported by the shearing, but by the tensile force belt. After the displacement increases to be about 16 mm, the bearing capacity of the single slanted corrugated steel plate shear wall exceeds the flat steel plate shear wall. However, all of them have good ductility performance.

4.2 Study on the mechanism of cross-slanted corrugated steel plate shear wall

In order to better analyze the stress mechanism of the cross-slanted corrugated steel plate shear wall well, the stress cloud diagrams of different infilled steel plates under the load force are extracted and shown in Figure 4. For the flat steel plate shear wall (M-1), it can be concluded that the overall buckling occurs when the lateral displacement is small, resulting from a low plane stiffness. For the unidirectional oblique corrugated steel plate (M-2), it does not exhibit out-of-plane deformation when pulled along the direction of corrugation. When the corrugation is compressed and deformed, the infilled steel plate does not reach full shear yield. As the displacement increases, the corrugated steel plate would merge quickly in the force direction and the merged area is shaped like a "pleat". When the compression force is reversed, only little out-of-plane deformation emerges at the initial stage of loading due to the high out-of-plane stiffness of the infilled corrugated steel plate. However, after buckling, the out-of-plane deformation increases greatly, significantly exceeding the flat steel shear wall. Therefore, neither of them has worked fully.

For the cross-slanted corrugated steel plate shear wall (M-3), it utilized the advantage of single inclined steel plate wall under the working mechanism of tension and compression. When one side is pulled, the other side is compressed. Thus, the small out-of-plane deformation of the tension plate is used to restrain the out-of-plane deformation of the pressured plate. As a result, the stress distribution of the infilled steel plate is uniform, forming a self-defending buckling mechanism and demonstrating a high lateral bearing capacity and anti-buckling effect. From the above simulation results, it can be seen that the initial stiffness of the two-way inclined corrugated steel sheet wall structure is large, and the out-of-plane deformation of the infilled steel plate is small, which can effectively suppress the
buckling of the infilled steel plate, and can ensure that the structure does not buck in a large lateral load.

Figure 4 Development process of stress in panels: (a) M-1; (b) M-2; (c) M-3 distribution of tension stress; (d) M-3 distribution of compression stress.

5. Conclusions
In this paper, the effects of different infill steel plate types on the lateral-force resistance performance of corrugated steel plate shear wall are studied through finite element simulation method. The stress mechanism in the elastic and elastic-plastic stages is also analyzed briefly. The conclusive remarks are as follows:

(1) The cross-slanted corrugated steel plate wall functioned like a self-defending buckling component, which can bear the tension force as well as the compression force effectively. The simulation results show that the stress distribution of the infilled steel plate is uniform and the lateral bearing capacity is higher.

(2) Both the initial stiffness and the ultimate bearing capacity of the cross-slanted corrugated steel plate shear wall are enhanced significantly. The ultimate bearing capacity of the designed cross-slanted corrugated steel plate shear wall is 2.26 times that of the flat steel plate shear wall (FSPW), and is 2.09 times that of the single oblique corrugated steel plate shear wall (SCSPW).

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