Analysis of Seismic Behavior of Four-side Partially Connected Steel Plate Shear Wall

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Abstract. Four-side partially connected steel plate shear wall is the structure that frame and plate are incompletely connected. Through the analysis of mechanism, it shows that, when compared with traditional completely connected steel plate shear wall, the partially connected one causes less additional bending moment on frame. In order to further learn about the behavior of partially connected steel plate shear wall, this paper used FE modeling method on ABAQUS. The paper analyzed the influences of the frame-plate connection ratio and the height-thickness ratio of steel plate on the behavior of unstiffened four-side partially connected steel plate shear wall, and investigated the function of three different forms of stiffeners on partially connected steel plate shear wall.

1. Introduction

Steel plate shear walls (SPSW), which have been developed since early 1970s[1], are good lateral resistant systems. With distinguished mechanical performance like good earthquake resistant, easy to assembly and high economical efficiency, SPSWs are widely applied in modern high-rise buildings. In recent year, there come out different kinds of steel plate shear walls, and the researches about SPSWs are deeper and wider. The research on seismic performance of thin steel plate shear wall is especially a hot issue. Thin steel plate shear wall, which has great strength after elastic buckling, has great potential in earthquake resistance. However, the formation of tension field on plate brought by yielding will cause large additional bending moment on frame, which is harmful to the security of frame. In order to solve this problem, some modifications for thin SPSW have been proposed, such as SPSW with hole or slit[2-4] and SPSW only connected with beam[5-7].

Partially connected steel plate shear wall (PCSPSW) has been proposed in recent years as a novel structure. Fu, Wei, et al. [8-10] did some research on partially connected buckling-restrained steel plate shear wall, and Yang [11] investigated the performances of PCSPSW. As a kind of new structure, on the one hand, PCSPSW can reduce the additional bending moment on frame. On the other hand, PCSPSW is comfort with assembly conception, which means it is easy for installation and maintaining. So, the research of PCSPSW is important for designing and practice in engineering.

2. Characteristic of four-side partially connected steel plate shear wall

The steel plate in four-side partially connected steel plate shear wall isn’t connected completely to the frame, (as shown in figure 1, the black bold lines and shadow represent the connection between plate and frame). The parameters of PCSPSW, the connection ratio between plate and column/beam ($a_1/a_2$), and the height-thickness ratio of steel plate ($\beta$), are defined by formulas (1)–(3).
The height-thickness ratios of the plate in this paper are between 400 to 900, which belong to thin steel plate shear wall category. In the thin steel plate, the elastic buckling always happen firstly, then some areas begin to yield and tension fields are developed. If the frame of SPSW is strong enough, the post-buckling strength of steel plate can be hundreds times of the elastic shear stress\[12\]. So, in seismic designing, thin steel plate, which has an advantage in energy dissipation, can protect the frame as the first line of defense. However, the additional bending moment, which is caused by tension field, will make the beams and columns prone to bending, leading the frame to fail first. Besides, the curving beams and columns will inhibit the development of tension field in plate.

Partially connected steel plate shear wall can reduce the additional bending moment caused by the formation of tension field. As it is shown in figure 2, the force on the column caused by plate can be decomposed into the lateral force and vertical force, and the lateral force causes additional bending moment$(M_a)$, which can be described by formula (4) and (5). It is obvious that additional bending moment$(M_a)$ is related to steel yield stress($f_y$), the angle between tension field and vertical member($\theta$), and the connection length between plate and frame($c$). Theoretically, additional bending moment should be decreased, because the connection length in PCSPSW is smaller than ordinary SPSW. Hence, PCSPSW lowers the requirement of frame, which saves the usage of steel and decreases the weight of structure to improve the earthquake resistance.

$$M_a = \frac{1}{6} q c^2$$  \hspace{1cm} (4)
$$q = f_y \cos \theta$$  \hspace{1cm} (5)

3. Finite element modelling

In order to analyze the seismic performance of partially connected steel plate shear wall, ABAQUS was used for modelling and stimulating hysteretic behavior. In the model, frame components and steel plate are all made of four-nodes shell element(S4R), the dimension of grid is 100mm×100mm. All beam-column joints are supposed as rigid-joint, and steel plate are connected to the frame through ‘Tie’. Bilinear hardening plastic constitutive model (figure 3) is employed for steel. The behavior of modelling accord with Von Mises criterion.

The models use Q345 Steel, whose Elasticity modulus (E) is 2.06×1011MPa, Poisson ratio ($\nu$) is 0.3. The sizes of frames keep the same (beam: H488×300×11×18, column: H550×300×11×18), and all the panel sizes of steel plates are 3m×3m. To investigate the influences of connection ratio and height-
thickness ratio, fifteen models of unstiffened partially connected steel plate shear wall are calculated, the detail dimensions are listed in Table 1. In addition, three models of stiffened PCSPSW are built based on model PCSPSW2-3, whose connection ratio is 0.5, height-thickness ratio is 600. The types of stiffening are X-shape stiffening (PCSPSW-2-3-X), crossing stiffening (PCSPSW-2-3-Y) and groined stiffening (PCSPSW-2-3-Z). (which are shown in figure 5) Thickness of stiffeners is 5mm and the height is 100mm.

The load are applied on models by two steps. First step: constant axial pressure 600kN is applied to the top of each column. The axial compression ratio is 0.105. Second step: low cyclic horizontal load is applied to the beam end through displacement control method (loading curve is shown in figure 4).

| Model Number | Thickness of plate (mm) | Height-thickness ratio of plate | Connection length (mm) | Connection ratio |
|--------------|-------------------------|-------------------------------|------------------------|-----------------|
| PCSPSW1-1    | 3.5                     | 857                           | 3000                   | 1               |
| PCSPSW1-2    | 3.5                     | 857                           | 2250                   | 0.75            |
| PCSPSW1-3    | 3.5                     | 857                           | 1500                   | 0.5             |
| PCSPSW1-4    | 3.5                     | 857                           | 750                    | 0.25            |
| PCSPSW1-5    | 3.5                     | 857                           | 375                    | 0.125           |
| PCSPSW2-1    | 5                       | 600                           | 3000                   | 1               |
| PCSPSW2-2    | 5                       | 600                           | 2250                   | 0.75            |
| PCSPSW2-3    | 5                       | 600                           | 1500                   | 0.5             |
| PCSPSW2-4    | 5                       | 600                           | 750                    | 0.25            |
| PCSPSW2-5    | 5                       | 600                           | 375                    | 0.125           |
| PCSPSW3-1    | 7                       | 429                           | 3000                   | 1               |
| PCSPSW3-2    | 7                       | 429                           | 2250                   | 0.75            |
| PCSPSW3-3    | 7                       | 429                           | 1500                   | 0.5             |
| PCSPSW3-4    | 7                       | 429                           | 750                    | 0.25            |
| PCSPSW3-5    | 7                       | 429                           | 375                    | 0.125           |

4. Analysis of the results from finite element calculation

The influences of connection ratio, height-thickness ratio and stiffening type are discussed in this section.

4.1. Influence of connection ratio

Skeleton curve, which is actually the locus of the maximum horizontal force reached in each loading cycle, reflects the relationship between force and deformation. The figure 6 is the skeleton curve of
unstiffened PCSPSW, which shows that there are about four phrases in displacement-load curve: elastic phrase, yielding phrase, hardening phrase and failure phrase. With the same height-thickness ratio, PCSPSW with smaller connection ratio experiences shorter elastic phrase, but longer hardening phrases. The structures with different connection ratio begin to fail under the similar displacement. Besides, the degradation of stiffness is more remarkable in later period, when PCSPSW system has higher connection ratio. Generally speaking, the bearing capacity of PCSPSW decreases with the reduction of connection ratio. The stiffness and bearing capacity are significantly decreasing when the connection ratio is lower than 1/2.

Figure 6. Skeleton curves of unstiffened PCSPSWs

Figure 7. Curves of areas of hysteresis loops of unstiffened PCSPSWs

Figure 8. Curves of energy dissipation coefficient of unstiffened PCSPSWs

The curve of areas of hysteresis loops and the curve of energy dissipation coefficient are important indicator to evaluate the capacity of energy dissipation and earthquake resistance. Area of hysteresis loop, which is enclosed by a single circle of load-displacement curve, reflects how much the energy is consumed. Energy dissipation coefficient, which is the ratio between energy consumption and maximum elastic potential energy, reflects the energy-dissipating efficiency. It is shown in figure 7 that, when the connection ratio are lower than 1/2, areas of hysteretic loop are obviously lower. Through analyzing figure 8, it is found that curves of energy dissipation coefficient first grow then tend to be steady. When story drift is lower than 0.6%, PCSPSW with lower connection ratio has higher energy dissipation coefficient. When story drift is higher than 0.6%, but lower than 2.0%, PCSPSW with higher connection ratio has higher energy dissipation coefficient. When story drift is higher than 2.0%, where some damage happens on structure, the relationship between connection ratio and energy dissipation coefficient is affected by height-thickness ratio.
By observing the stress distribution and deformation, it is found that elastic buckling happens before yielding in steel plate. When yielding develops, tension field comes to be diagonally, whose shape is like an ‘X’. When connection ratio is higher than 1/2, the tension field in plate develops well. But, when connection ratio is lower than 1/2, only four corner zones yield and no full tension field is formed. Besides, the lower the connection ratio is, the larger the out-of-plane deformation is at the edges of plate. As for frame, areas of failure are at joints when connection ratios are low, but they prone to expand to the mid of beams or column with the increase of connection ratio. It is reasonable to infer that the decrease of connection ratio can relief the additional bending moment on the frame.

4.2. Influence of height-thickness ratio
It can be seen from skeleton curves (figure 6), the bearing capacity and the stiffness of PCSPSW are improved with the decrease of height-thickness ratio, and the influence of connection ratio is greater when height-thickness ratio is higher. From curves of area of hysteretic hoop (figure 7), it is found that, the higher the height-thickness ratio, the more energy the structure consumed. From curves of energy dissipation coefficient (figure 9), it is found that, when connection ratio is larger than 1/2, PCSPSW with lower height-thickness ratio has higher energy-dissipating efficiency. However, when connection ratio is lower than 1/2, the influence of height-thickness ratio on energy-dissipating efficiency is different under different story drifts.

![Figure 9. Curves of energy dissipation coefficient of unstiffened PCSPSWs](image)

The height-thickness ratio also has influence on stress distribution. In the steel plate with lower height-thickness ratio, yielding begins earlier, but yielding area is smaller. Besides, with the decrease of height-thickness ratio, the failure area in frame will transfer from joints to the mid of beams and columns. In addition, the maximum PEEQ (Equivalent plastic strain, reflecting the ductility and fracture tendency) appears on the corners of plate, when height-thickness ratio is low. With the decrease of height-thickness and increase of connection ratio, the maximum PEEQ in plate moves to the centre and becomes larger, sometimes it even more than 1, which means this area is broken.

4.3. Influence of stiffening type
Figure 10(a) is the skeleton curve of stiffened PCSPSW. It is shown that bearing capacity of X-shape stiffened PCSPSW is improved when compared with unstiffened PCSPSW, but the stiffness is prominently degraded in later stage. Groined stiffening is also helpful to improve bearing capacity and stiffness of PCSPSW, while crossing stiffening has no such function. It can be seen in the curves of area of hysteretic hoop (figure 10(b)) and the curves of energy dissipation coefficient (figure 10(c)) that groined stiffened PCSPSW has the best performance in energy dissipation, while crossing stiffening is the worst. Thus, earthquake resistance of groined stiffened PCSPSW and X-shape stiffened PCSPSW is better than crossing stiffened PCSPSW.
The stress distribution of plate shows that yielding in X-shape stiffened PCSPSW develop mainly around stiffeners, but the centre of plate doesn’t yield. Yielding areas of groined stiffening are mainly on the four corner areas and centre, and tension field develop diagonally. Yielding only happens on the corners of plate when it is crossing stiffened, and no integrated tension field is formed, which means crossing stiffening is unhelpful to energy dissipation. The stress distribution of frame shows that the stress in the mid of the beams and column decrease when PCSPSW is groined stiffened. But failure areas transfer from joints to the mid beams and column when PCSPSW is X-shape stiffened.

Figure 10. Skeleton curves, Curves of areas of hysteresis loop and Curves of energy dissipation coefficient of stiffened PCSPSW

Besides, it is found that, for unstiffened plate, the maximum out-of-plane deformation inside plate, which is 237.3mm, is at centre. The maximum out-of-plane deformation at edges is 137.9mm. For X-shape stiffened plate, the maximum out-of-plane deformation inside plate, which is 269.5 mm, is not at centre. The maximum out-of-plane deformation at edges is 193.4mm. For crossing stiffened plate, deformation inside plate is small, and the maximum out-of-plane deformation at edges is 171.7mm. For groined stiffened plate, the maximum out-of-plane deformation inside plate, which is 144.3 mm is at centre. The maximum out-of-plane deformation at edges is 167.1mm. Therefore, X-shape stiffening will aggravate out-of–plane deformation, while groined stiffening is helpful to resist deformation. The maximum PEEQ in X-shape stiffened plate is 1.163, on the corners, which means that some rupture happen on them.

5. Conclusion
By analyzing the results of finite element simulation, following conclusions can be achieved.

- With the decrease of plate-frame connection ratio, the bearing capacity and energy dissipation of PCSPSW are reduced, the development of yielding is more inadequate, the tension field is slimmer, the out-of-plane deformation at edges of plate is larger, but the additional bending moment on the frame decreases. It is recommended that the connection ratio of PCPSW should be higher than 1/2, because the performances of the structure are declined significantly when connection is lower than 1/2.
- With the decrease of height-thickness ratio, the bearing capacity, stiffness and energy dissipation of PCSPSW increase, and yielding on plate happen earlier, but additional bending moment on frame increases.
- The influence of height-thickness ratio on energy-dissipating efficiency should be discussed according to connection ratio. It is recommended that height-thickness ratio and connection ratio should be considered comprehensively to design CPSPSW for high earthquake resistance.
- Different types of stiffening bring about different influences to PCSPSW. Under the same height-thickness ratio of stiffener, X-shape stiffening and groined stiffening are helpful to improve bearing capacity, stiffness, and energy dissipation, while crossing stiffening makes no difference in the performance of structure. Therefore, it is recommended that crossing stiffening should not be applied to strengthening PCSPSW.

References
[1] Guo Y, Zhou M. (2009) Classification and performance of steel plate shear wall [J]. Journal of Architecture and Civil Engineering, 26: 1-13.
[2] Bhowmick A K, Grondin G Y, Driver R G. (2014) Nonlinear seismic analysis of perforated steel plate shear wall. Journal of Constructional Steel Research, 94:103-113.

[3] Wei D, Wen P, Bian Z. (2006) Experimental investigation and simulation analysis of new steel plate shear walls with slit. Earthquake Engineering and Engineering Vibration, 26:129-133.

[4] Bai Y, Wang W, Zhang W, et al. (2018) Research on the hysteretic behavior of steel plate shear wall with slits. Process in Steel Building Structure, 20: 28-35.

[5] Xue Y, Su M, Ma D, et al. (2014) Hysteretic behavior analysis of vertically stiffened steel plate shear wall (SPSW) connected with frame beams. Steel Construction, 29: 1-7.

[6] Li G, Liu W, Lu Y, et al. (2015) Stressing mechanism and equivalent brace model for buckling restrained steel plate shear wall with two sided connections. Journal of Building Structure, 36: 33-41.

[7] Clayton P M, Berman J W, Lowes L N. (2015) Seismic performance of self-centering steel plate shear walls with beam-only-connected web plates. Journal of Constructional Steel Research, 106:198-208.

[8] Wei M W, Liew J Y R, Xiong M X, et al. (2016) Hysteresis model of a novel partially connected buckling-restrained steel plate shear wall. Journal of Constructional Steel Research, 125:74-87.

[9] Wei M W, Liew J Y R, Yong D, et al. (2017) Experimental and numerical investigation of novel partially connected steel plate shear walls. Journal of Constructional Steel Research, 132: 1-15.

[10] Fu X, Wei M, Zhang J. (2015) Mechanical and hysteretic behaviors of restrained steel plate walls connected to beam-column joints. Journal of Shenzhen University (Science and Engineering), 32: 221-230.

[11] Yang X, Xu G, Wei M, et al. (2018) Mechanical properties of steel plate shear wall connected to beam-column joints. Steel Construction, 33: 26-30.

[12] Chen G, Guo Y, Fan Z, et al. (2004) Cyclic test of steel plate shear walls. Journal of Building Structure, 25: 19-26.