NUMERICAL AND PARAMETRIC STUDY OF CONCRETE FILLED STEEL PLATE COMPOSITE SHEAR WALLS WITH T-SHAPED STIFFENERS

B. L. Jiang[1], S. Y. Ji[2], Y. M. Li[3] , H. W. Yang[4]

[1] *PhD Student, School of Civil Engineering, Chongqing University, jiangbaolong@cqu.edu.cn*
[2] *Associate Professor, School of Construction Management and Real Estate, Chongqing University, jishuyan@cqu.edu.cn*
[3] *Professor, School of Civil Engineering, Chongqing University, liyingmin@cqu.edu.cn*
[4] *PhD Student, School of Civil Engineering, Chongqing University, 1814766653@qq.com*

Abstract

Concrete filled steel plate composite shear walls are composed of two exterior steel face plates with concrete infilled. The concrete core is attached to the steel face plate using mechanical connectors like studs and tie bars. The composite shear walls were developed to reduce wall thickness, to enhance constructability, and to enable rapid construction by eliminating the use of formwork and reinforcing bars. In this paper, a concrete filled steel plate composite shear wall with T-shaped stiffeners was introduced, which used T-shaped stiffeners as the main mechanical connectors. The numerical simulation by using the analytical software OpenSees was conducted for the concrete filled steel plate composite shear walls with T-shaped stiffeners under cyclic loading, and the accuracy of the simulation was verified against available test results. Then a parametric study was performed to study the effect of variables such as axial compression ratio, aspect ratios, steel content ratio. The analysis results illustrated that with the increasing axial compression ratio the bearing capacity of shear walls was slightly improved, but the degradation of stiffness was accelerated. With the increase of aspect ratio, the initial stiffness and peak load of the shear walls decreased dramatically, but the deformation capacity was improved. As the steel plates, especially the end plates, were thickened, the deformation capacity of composite shear walls was improved significantly.

Keywords: concrete filled steel plate composite shear wall, numerical study, parametric analysis

1. Introduction

Concrete filled steel plate composite shear walls are composed of external steel plate and internal filled concrete, and these two materials work together through the connection such as tie bars, T-shaped stiffeners, etc. The infilled concrete prevents early buckling of the steel plate, while the steel plate provides restraint for the concrete. Meanwhile, the steel plate can be used as framework during construction. This kind composite shear wall has the advantages of large bearing capacity, good seismic performance and convenient construction. Therefore, concrete filled steel plate composite shear wall is a high-performance lateral force-resistance structural member for high-rise building structures.

A series of studies for this type of concrete filled steel plate composite shear wall have been carried out by many scholars. This type of component was first applied to special structures such as offshore structures [1], and later gradually used in building structures as floor slabs, vertical and lateral force-resistance components [2, 3]. Eom *et al.* [4] carried out quasi-static cyclic loading tests on the isolated and coupled double skin composite walls with rectangular and T-shaped cross sections connected by tie bars, and the main failure location of the shear wall in the test was the bottom of the wall. Nie *et al.* [5] conducted a series of theoretical and experimental research. The results indicated that concrete filled double-steel-plate composite wall has good bearing capacity, lateral stiffness, ductility and energy dissipation capacity, and therefore is a new type of composite shear wall with superior seismic performance. Cheng *et al.* [6] conducted seismic performance tests and numerical simulation studies on the composite concrete and double steel plates shear walls with binding bars. Through the analysis of the key parameters, such as the aspect ratio and axial compression ratio, the law of the influence of these parameters on the seismic performance of the shear wall was obtained. Zhang *et al.* [7, 8] conducted test research and numerical simulation on the bundled lipped channel–concrete composite wall. The research demonstrated that this type of composite wall has good seismic performance, and proposed a calculation formula for compressive bending and shear bearing capacity for this type of composite wall.

At present, the various researches on the above-mentioned composite shear wall include researches on different cross-sectional forms, steel plate layouts, and connection methods. However, there is still a lack of research on the concrete filled steel plate composite shear wall with T-shaped stiffeners. Therefore, based on OpenSees software, this paper firstly carries out a numerical simulation of quasi-static cyclic loading test of a concrete filled steel plate composite shear wall with T-shaped stiffeners. Then, the numerical simulation results are compared with the experimental results to verify the feasibility of the numerical simulation. Finally, numerical simulation is conducted to analyze the effect of different parameters on seismic performance of the shear wall with T-shaped stiffeners.

2. Description of tests used for validating numerical models

In the experimental study [9], a quasi-static cyclic loading test was carried out on four specimens of concrete filled steel plate composite shear wall with T-shaped stiffeners. And the Specimens SW3 was selected to verify the feasibility of the numerical simulation. For this type of shear walls, the edge adopted built-in T-shaped steel components, and the middle segment adopted a mixed connection method of T-shaped stiffeners and tension bolts. The specimen with a cross-section of 1000mm× 100mm consists of two steel plates with a thickness of 2 mm in the middle. The diameter of the tension bolts of the specimen was 5mm. The calculated height and shear span ratio was 1570 mm and 1.57, respectively. The axial compression ratio n of Specimen SW3 was 0.24. The axial compression strength of concrete f_c was 31.8 MPa, and the steel yielding strength f_y was 384 MPa. Details of Specimen SW3 were given in Fig. 1 and Fig. 2.
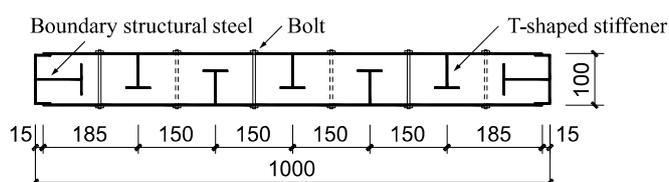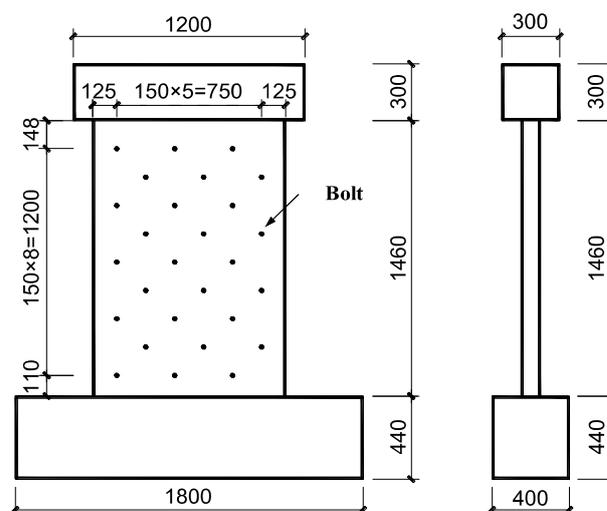
Fig. 1 – Sectional configuration of SW3 (unit: mm)

Fig. 2 – Elevation of SW3 (unit: mm)

The general arrangement of the test setup is illustrated in Fig. 3. The axial force was first applied to the specimen by a vertical hydraulic jack, and remained constant when it reached the predetermined value. Afterwards, the specimen was tested under axial load subjected to cyclic lateral loading. The lateral force was controlled by the load before yielding, and then by the displacement. Taking the displacement $\varDelta_y$ at yielding as the step difference. Two cycles were repeated for every displacement level until the specimen was broken, and the displacement increment was $\varDelta_y$.
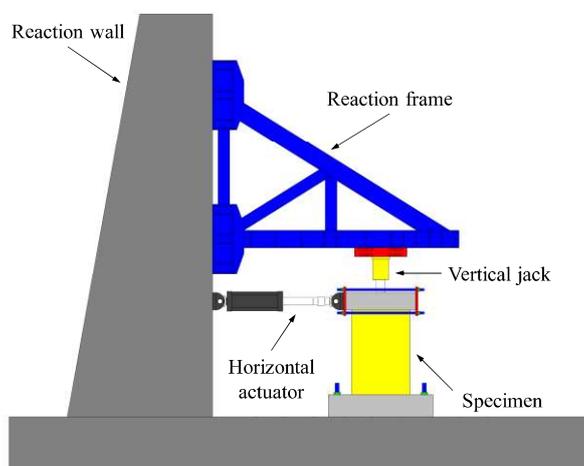
Fig. 3 – Test setup

3. Analytical model and validation

3.1 Modeling

In this paper, OpenSees software was used to perform numerical simulation analysis on the concrete filled steel plate composite shear wall with T-shaped stiffeners. Displacement-based beam-column elements were used to simulate the compression and flexure characteristics of the shear wall. The shear wall was divided into 5 elements along the length of it, each element had 5 integration points along the length. Meanwhile, in order to make up for the inadequacy of the fiber model that cannot consider the shear deformation in the

3

shear wall simulation, the Section Aggregator combined section was used to consider the shear effect. The nonlinear shear effect of each section was simulated by defining the equivalent shear modulus of the section.

In the numerical analysis model, the concrete material adopted Concrete04 model in OpenSees. The skeleton curve of Concrete04 model is based on the concrete model proposed by Popovics considering the restraint effect. When the concrete elastic modulus E_c is equal to 4700 times the arithmetic square root of the concrete cylinder axial compressive strength f_c', it is the Mander model [10]. The unloading and reloading rules of Concrete04 model under compression are determined by the Karsan-Jirsa model, and Concrete04 model considers the mechanical properties of concrete under tension. The concrete strength used in the numerical simulation was converted from the actual measured value in the test.

The steel in the shear wall was simulated using the Steel02 constitutive model of OpenSees. The constitutive model is based on the Giuffre-Menegotto-Pinto steel model, which can reflect the Bauschinger Effect of the material. The strength and elastic modulus of the steel were obtained from the actual test, and the strain hardening rate was taken as 0.02.

3.2 Comparison between numerical simulation results and experimental results

Based on the above numerical simulation method, numerical simulation analysis was carried out on the Specimen SW3 of concrete filled steel plate composite shear wall with T-shaped stiffeners in the experimental study. The model parameters, boundary conditions, and loading procedure used in the numerical simulation were consistent with the experimental research. Compare the hysteresis curve and skeleton curve in the test results under quasi-static cyclic loading with the numerical simulation results, as presented in Fig. 4 and Fig. 5.
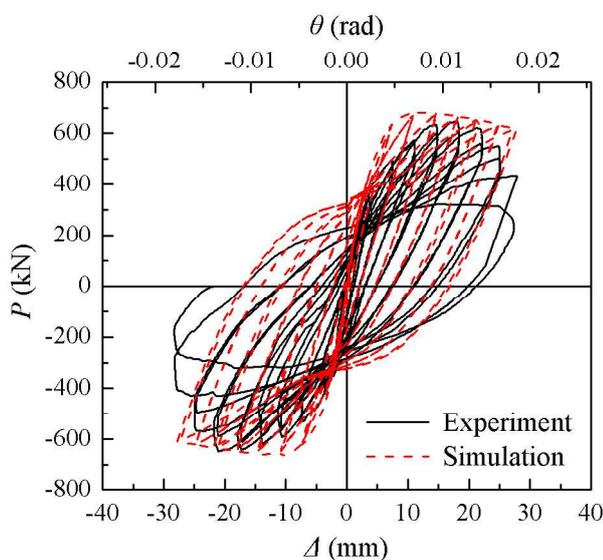

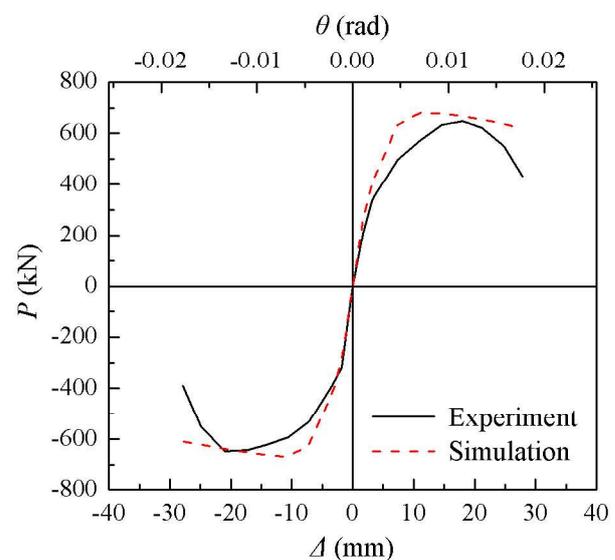Fig. 4 – Comparison of hysteretic loops

Fig. 5 – Comparison of skeleton curves

By comparing the hysteresis curve and the skeleton curve, it is observed that the shape of the curve in the numerical simulation results are roughly same as that in the test results, and the trend is similar. The difference between these two results of the yield point and the peak point load is about 5%. Moreover, the maximum difference in the slope of curve exceeds 20%. In the early elastic stage of the composite shear wall, the curves in the simulation results and the test results are in good agreement. It may be because the load is relatively small at this stage. The steel plate and concrete of the composite shear wall worked together, and the force state was consistent with the theoretical situation at this time. In the subsequent elastoplastic stage, the stiffness of the simulated values is slightly higher than that of the experimental values, and the displacement at the peak load point of the simulated value is smaller than one at the peak load point of the

4

experimental value. This may be due to the residual stress and slight deformation of the steel plate welding during the test. Meanwhile, the materials in the numerical simulation are ideal materials. The slip between steel plate and concrete cannot be considered, and it is assumed that the two materials can work well together. After the peak load, each cycle of the numerical simulation hysteresis curve is slightly fuller than that of the test, and the descending segment of the numerical simulation curve is gentler than that of the test. The main reason may be that the repeated loading of the test caused the accumulation of damage to the specimen. Firstly, the slip between the steel plate and the concrete will increase, and then the steel plate would be partially buckled or even cracked, and finally the concrete would collapse. However, the buckling effect of the steel plate before failure was not considered in the numerical simulation, and the bearing capacity of the steel plate will not decrease significantly until the concrete was crushed or the steel plate failed. Therefore, the hysteresis curve after the numerical simulation peak point is fuller, the pinch effect is small, and the bearing capacity decreases slowly.

In general, the numerical simulation results are in good agreement with the experimental results. The numerical simulation method and analysis model can better reflect the hysteretic performance and force deformation trend of concrete filled steel plate composite shear walls with T-shaped stiffeners. Therefore, the numerical simulation method and analysis model are suitable for the subsequent analysis of the influence of the parameters of this type of composite shear wall.

4. Parametric study

Based on the numerical simulation verification of the test results of SW3, the parameter analysis of concrete filled steel plate composite shear wall with T-shaped stiffeners was carried out through numerical simulation, which was used to further study the influence of various parameters, such as axial compression ratio, shear span ratio, steel plate thickness, on the seismic performance of this type of shear wall.

Table 1 – Parameters and analytical results of finite element models

Model	Plate thickness (mm)	Axial compression ratio	Shear span ratio	Yield displacement (mm)	Yield load (kN)	Peak load (kN)
SW1	3	0.12	1.57	6.80	750.60	829.09
SW2	2	0.12	1.57	6.25	530.98	611.09
SW3	2	0.24	1.57	6.22	568.12	666.95
SW4	2(3)	0.12	1.57	7.13	657.20	749.75
SW5	2	0.12	1	2.75	861.44	989.20
SW6	2	0.12	2	10.58	427.42	490.50
SW7	2	0.24	1	2.51	918.73	1045.48
SW8	2	0.24	2	10.17	454.54	519.13
SW9	2	0.36	1	2.60	949.44	1070.69
SW10	2	0.36	1.57	6.20	571.36	671.22
SW11	2	0.36	2	9.89	458.61	521.23

In the process of parameter analysis, a total of 11 concrete filled steel plate composite shear wall models, including the SW3 of the test simulation, with T-shaped stiffeners were established, and details of

5

model parameters are shown in Table 1. In the numerical simulation modeling, each model was set to the same material strength. The axial compressive strength f_c of concrete was 30 MPa, and the yield strength f_y of steel was 380 MPa. For the numerical simulation results, the equal energy method was used to determine the yield point on the skeleton curve of each model. The results are shown in Table 1.

4.1 Axial compression ratio

Through the change of axial force applied to the top of the model, three groups of shear walls with the axial compression ratio n of 0.12, 0.24 and 0.36 were numerically simulated. Fig. 6 illustrates the comparison of the skeleton curves of each shear wall under different axial compression ratios.

(a) Shear span ratio λ=1　　　(b) Shear span ratio λ=1.57　　　(c) Shear span ratio λ=2
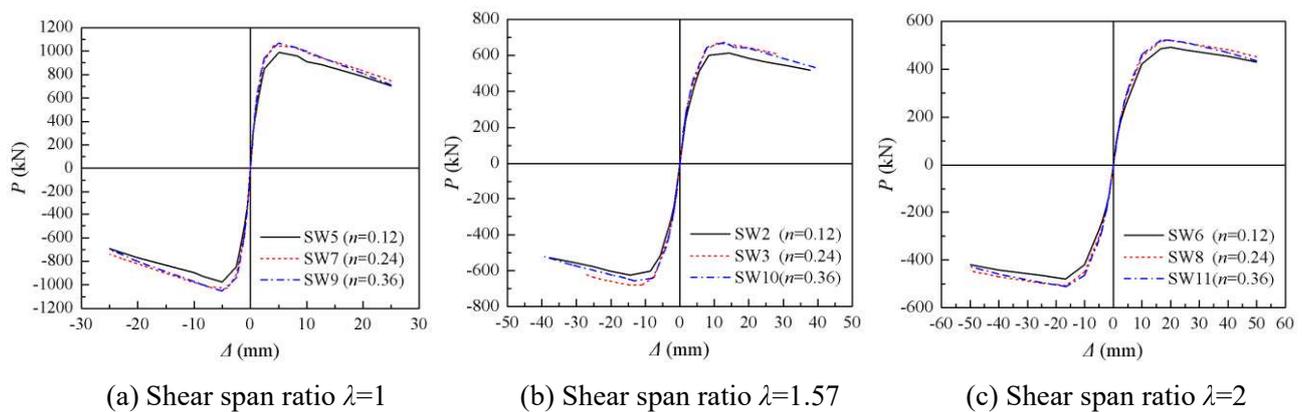
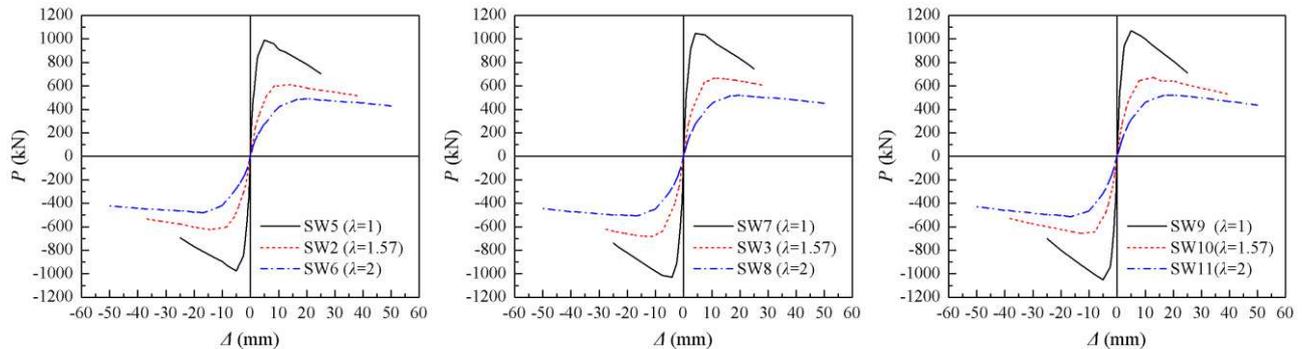Fig. 6 – Skeleton curves of composite shear walls with different axial compression ratios

From the comparison of the skeleton curve, it is indicated that the axial compression ratio has some influence on the horizontal ultimate bearing capacity of the shear wall. By comparing the models with the axial compression ratio of 0.12 and 0.24, the horizontal peak loads of models SW7, SW3 and SW8 are 5%, 9% and 6% higher than models SW5, SW2 and SW6, respectively. Moreover, when the axial compression ratio increased to 0.36, the horizontal peak load increase of the shear wall is reduced to less than 3%, and the peak point of the skeleton curve is almost at the same position. It indicates that only when the axial compression ratio is in the middle and low range, it has a significant effect on the horizontal ultimate bearing capacity of the shear wall. But as the axial compression ratio increases, this effect becomes less obvious. Meanwhile, as the axial compression ratio of the shear wall increases, the displacement corresponding to the yield point of the shear wall and the peak point of the horizontal load decreases, but the difference is small and the effect is not obvious. However, the slope of the descending segment of the skeleton curve increases obviously with the increase of axial compression ratio, and the degradation of bearing capacity accelerates. It indicates that the deformation ability of the shear wall with smaller axial compression ratio is better. These laws are consistent with the results obtained by experimental research.

4.2 Shear span ratio

While keeping the section of the shear wall unchanged, by changing the horizontal loading point of the model and the height of the wall, the shear wall models with shear span ratio λ of 1, 1.57 and 2 were calculated and analyzed respectively. The calculation result is presented in Fig. 7. Through comparative analysis, it was indicated that increasing the shear span ratio under various axial compression ratios will significantly reduce the initial lateral stiffness and horizontal ultimate bearing capacity of the shear wall. Compared with SW5, SW7 and SW9 with a shear span ratio of 1.0, the ultimate load-bearing capacity of SW2, SW3 and SW10 with a shear span ratio of 1.57 is reduced by 36%~38%, and that of SW6, SW8 and SW11 with a shear span ratio of 2.0 is reduced by 50%~51%. Meanwhile, as the axial compression ratio increased, the degree of reduction gradually increases. Moreover, with the increase of the shear span ratio, the displacement of the yield point and peak load point of the shear wall continue to increase, the slope of the descending segment of the skeleton curve is also significantly reduced, and the destruction speed of the shear

6

wall gradually slows down. It indicates that as the shear span ratio increases, the deformation capacity of the shear wall increases.

(a) Axial compression ratio *n*=0.12 (b) Axial compression ratio *n*=0.24 (c) Axial compression ratio *n*=0.36

Fig. 7 – Skeleton curves of composite shear walls with different shear span ratios

4.3 Thickness of steel plate

On the basis that the external dimensions of the model section remained unchanged, the thickness *t* of all steel plates of SW1 was set to 3mm. Then, the thickness of the end channel steel and T-shaped steel plate of SW4 was set to 3mm, and the thickness of the other parts of the steel plate remained unchanged at 2mm. When other parameters are the same, the skeleton curve comparison of SW1, SW2 and SW4 is presented in Fig. 8.
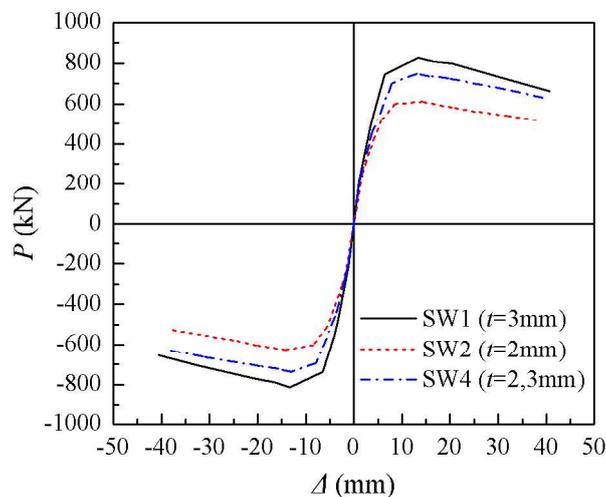

Fig. 8 – Skeleton curves of composite shear walls with different steel plate thickness

According to the simulation results of shear walls with different steel plate thicknesses, the overall trend of the skeleton curve of each shear wall is similar, and the shape of the curve is not much different. As the thickness of the steel plate increases, it also means that the amount of steel used in the same section will increase. Therefore, the initial lateral stiffness of the shear wall increases, and the yield load and peak load also increase significantly. Compared with SW2 with a thickness of 2mm, the yield loads of SW4 and SW1 are increased by 23% and 41%, respectively, and the peak load is increased by 22% and 35%, respectively. Meanwhile, it also indicates that the increase in the bearing capacity of SW4 relative to SW2 is greater than that of SW1 relative to SW4, while SW4 only increases the thickness of the end steel plate (about 20% of the total steel plate area) relative to SW2. This indicates that the end steel plate has a more significant influence

7

on the bearing capacity of this type of shear wall, and the bearing capacity of the shear wall can be effectively improved by increasing the thickness of the end steel plate.

5. Conclusion

Based on OpenSees software, numerical simulation and parametric studies on seismic performance of the concrete filled steel plate composite shear wall with T-shaped stiffeners were conducted. From the analytical results, the following conclusions can be drawn:

1) The trend of the hysteresis curve and the skeleton curve of the numerical simulation was consistent with the test, and the yield load and peak load were similar to the test results. It indicates that the numerical simulation results are in good agreement with the experiment to a certain extent. The numerical simulation method and analysis model can better reflect the hysteretic performance and the law of force deformation of concrete filled steel plate composite shear walls with T-shaped stiffeners.

2) The axial compression ratio had little effect on the stiffness and bearing capacity of concrete filled steel plate composite shear walls with T-shaped stiffeners. The stiffness and bearing capacity of shear walls with higher axial compression were slightly higher. However, the stiffness degradation was accelerated after the peak load, and the deformation capacity was slightly worse.

3) The shear span ratio had a significant effect on the seismic performance of concrete filled steel plate composite shear walls with T-shaped stiffeners. With the increase of the shear span ratio, the loading stiffness and horizontal peak load of the shear wall were greatly reduced, but the rate of stiffness degradation gradually slowed down and the deformation capacity is improved.

4) By increasing the thickness of the outer steel plate, the bearing capacity of the shear wall was significantly improved, and the end steel plate had a particularly significant influence on the bearing capacity of this type of shear walls.

6. Acknowledgements

7. References

[1] Link RA, Elwi AE (1995): Composite concrete-steel plate walls: analysis and behavior. *Journal of Structural Engineering*, **121** (2), 260-271.

[2] Wright HD, Gallocher SC (1995): The behaviour of composite walling under construction and service loading. *Journal of Constructional Steel Research*, **35**, 257-273.

[3] Hossain KMA, Wright HD (2004): Performance of double skin-profiled composite shear walls - experiments and design equations. *Canadian Journal of Civil Engineering*, **31**, 204-217.

[4] Eom TS, Park HG, Lee CH, Kim JH, Chang IH (2009): Behavior of double skin composite wall subjected to in-plane cyclic loading. *Journal of Structural Engineering*, **135** (10), 1239-1249.

[5] Nie JG, Hu HS, Fan JS, Tao MX, Li SY, Liu FJ (2013): Experimental study on seismic behavior of high-strength concrete filled double-steel-plate composite walls. *Journal of Constructional Steel Research*, **88**, 206-219.

[6] Cheng CL, Zhou DY, Zhu LM (2016): Numerical simulation and parameter analysis on seismic behavior of composite concrete and double steel plates shear walls with binding bars. *Journal of Hunan University (Natural Sciences)*, **43** (9), 10-17.

[7] Zhang XM, Chen ZH, Ren QY, Liu WT (2017): Study on finite element analysis and design method of composite shear wall with T-section double steel plates. *Building Structures,* **47** (S2), 241-248.

[8]   Zhang XM, Qin Y, Chen ZH (2016): Experimental seismic behavior of innovative composite shear walls. *Journal of Constructional Steel Research*, **116**, 218-232.

[9]   Zhang ML (2019): Study on seismic performance of concrete filled steel plate composite shear walls. *Master's Dissertation*, School of Civil Engineering, Chongqing University, Chongqing, China.

[10] Mander JB, Priestlet MJN, Park R (1988): Theoretical stress-strain model for confined concrete. *Journal of Structural Engineering*, **114** (8), 1804-1826.