Seismic Performance of Steel Plate-Reinforced Concrete Composite Shear Wall

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SUMMARY
In tall buildings the reinforced concrete (RC) shear wall is one of the predominant structural components used to resist lateral loads induced by earthquakes around the world. Previous research demonstrated that shear walls displayed a sudden loss in lateral capacity due to the wall corner and web crushing in the plastic zone. In addition, it was found that large shear distortions in shear walls may lead to a low energy dissipation capacity. For this reason, some steel-RC composite shear walls have been developed and indicated to mitigate most disadvantages of RC shear walls. The structural members studied herein are steel plate-reinforced concrete composite shear walls (SPRCW) by numerical analysis methods. The primary parameters vary in the axial load ratio, the ratio of steel plate and the ratio of web reinforcement in RC shear wall. Numerical analytical results indicate that, compared with the conventional RC shear walls, SPRCW has an evident improvement in the lateral load carrying capacity and ductility, especially in the energy dissipation capacity. In addition, the axial load ratio and the ratio of steel plate have more significant effects on the ductility and carrying capacity. The ratio of web reinforcement of RC wall has negligible effects on the component performance, but it would be still required to provide lateral support to the concrete and embedded steel plate.

Keywords: steel plate-reinforced concrete composite shear walls, ratio of steel plate, seismic performance, energy dissipation

1. INTRODUCTION

In tall buildings the reinforced concrete shear wall is one of the predominant structural components used to resist earthquakes around the world. Previous research demonstrated that shear walls displayed a sudden loss in lateral capacity due to the wall corner and web crushing in the plastic zone. In addition, it was found that large shear distortions in shear walls may lead to a low energy dissipation capacity (Sittipunt and Wood, 1995). For this reason, several kinds of steel-RC composite shear walls have been developed and indicated to mitigate most disadvantages of RC shear walls due to the advantageous characteristics of such two kinds of material (Deierlein, 2000; Gan, 2008; Zhou, 2010; Cao, 2011). The basic conclusions of these composite shear walls include the significant increase of load carrying capacity and ductility. As well, such composite components exhibit superior behaviour characteristics, particularly with respect to energy dissipation capacity and damage patter.

The structural members studied herein are steel plate-reinforced concrete composite shear walls (SPRCWs) with the steel plate embedded in the RC wall, and mechanical connectors such as shear studs attached on both sides to coordinate the deformation between steel plate and RC wall. SPRCWs offer several advantages relative to conventional RC walls. In particular, they can lead to high shear stiffness, smaller thickness and less weight. The SPRCWs located on the bottom of super high-rise building possess relatively high ductility for its whole seismic performance.

For the modelling of SPRCW elements, the common approach is to use finite element analysis procedures and apply them in micro model of the wall details. Although the finite element method can model individual parts in a full three-dimensional representation, and interface elements are also typically used to capture the effects of bond slip between different parts, the commercial software typically available for these purposes has shown difficulty in accurately capturing the nonlinear behaviour of concrete, particularly the unloading and reloading behaviour of concrete components.

Zhou et al. (2010) described the application of finite element procedures to assessing the seismic performance of a composite steel-concrete wall. The material modelling of the RC wall was done according to the Cyclic Softened Membrane Model (CSMM) (Mo, 2008), and the steel plate elements were tied to the concrete elements only at the locations of shear studs. Some hypothetical composite steel-concrete walls were analysed, but they were lack of experimental verification. Vecchio et al. (2011) developed the Disturbed Stress Field Model (DSFM) to enable the analysis of steel-concrete composite panel elements. The authors reported good agreement for the pre- and post-peak displacement responses, post-peak ductility, damage, and ultimate failure mode.

Although some buildings have been built using CSPSWs and some design provisions considered in the latest design codes, there still has a limited research on such kind component's seismic performance. In the present paper, the numerical analytical method is similar to that employed in Zhou et al. (2010). The numerical models are calibrated in OpenSees based on the experimental results of SPRCW under cyclic loading. The primary analytical parameters vary in the ratio of axis load, the ratio of steel plate and the ratio of web reinforcement in RC shear wall. Conclusions and recommendations are drawn accordingly.

2. TEST AND NUMERICAL VERIFICATION OF SPRCW

Jiang et al. (2012) tested nine high-strength RC shear wall specimens with high axial load ratios, with the primary intent of studying the compressive behaviour of conventional RC shear walls, steel reinforced concrete (SRC) walls and SPRCWs. The specimen SPRCW-1 was chosen as verification study case. The dimensions and steel reinforcement details are shown in Fig. 2.1. The actual strengths of concrete, rebar and steel obtained via material property tests are shown in Table 2.1.

Table 2.1 Actual parameters of materials (unit: MPa)

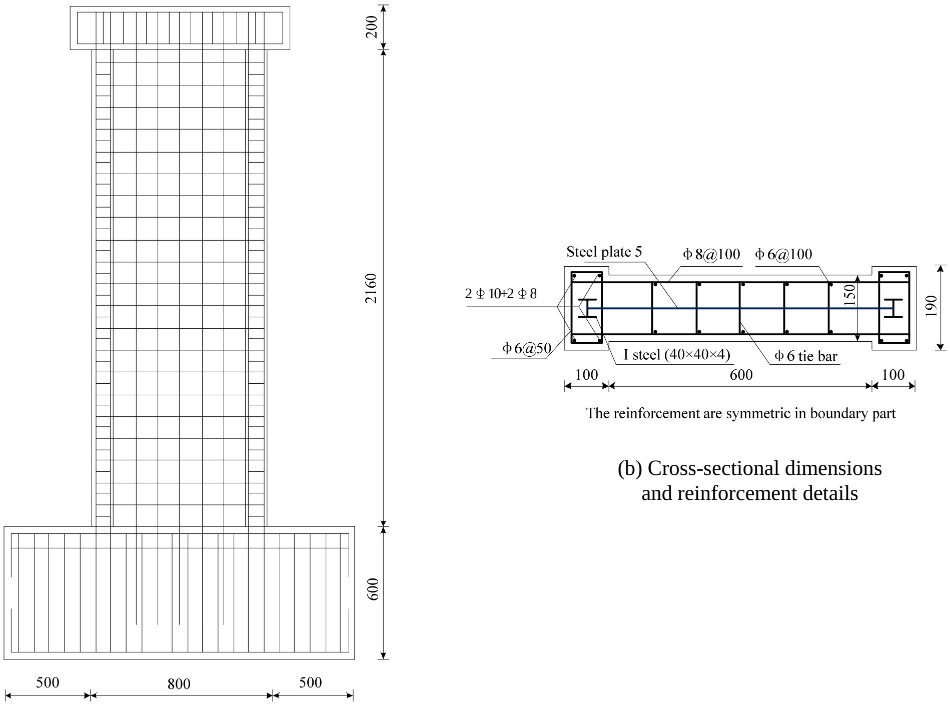
Materials	Yielding strength	Ultimate strength	Modulus of elasticity	Concrete
Rebar Φ6	298.3	407.1	2.10×10^5	Concrete cubic compressive strength is 84.1MPa, and axial compressive strength is 59.7MPa.
Rebar Φ8	291.2	431.5	2.09×10^5	
Rebar Φ8	446.3	593.7	2.00×10^5	
Rebar Φ10	436.1	595.3	2.00×10^5	
I steel 4	334.0	454.9	2.06×10^5	
Steel plate 5	309.5	415.0	2.06×10^5	

The cyclic loading tests of the specimen are simulated by OpenSees, and the numerical analytical elements and materials are listed in Table 2.2. The behaviour of shear studs connecting the RC wall and embedded steel plate are simulated by the command "equalDOF", which will make the nodes of RC wall and steel plate elements with the identical coordinates have the same motion. To be note, this assumption may be unsuitable when there is not enough shear studs to connect the steel plate and RC wall. Although the model described above has shown good performance in predicting the behaviour of SPRCW components considered in the validation studies, it does have some limitations. For example, it can not address out-of-plane stability and bond slip between RC wall and steel plate.

The specimens are modelled by the finite element mesh, as shown in Fig. 2.2. According to the original tests, the vertical load with a value of 2180kN was exerted on specimens and kept constant through the whole analysis process. The reversed cyclic loads were then applied under displacement control based the test loading protocol.

Table 2.2 Elements and analytical parameters of SPRCW specimen

Components	Elements	Materials	Notes
Boundary Parts	Displacement Based Beam-Column Element	Concrete: Concrete02	The concrete material of confined effect for core area and unconfined effect for cover layers are considered in boundary parts.
		Rebar and steel: Steel02	
RC wall	Quad Element	Plane Stress Concrete Materials	
Steel Plate	Quad Element	J2 Plasticity Material	



(b) Cross-sectional dimensions and reinforcement details

(a) Elevation of specimen

Figure 2.1. Elevation of specimen and cross-sectional views and reinforcement details (unit: mm)

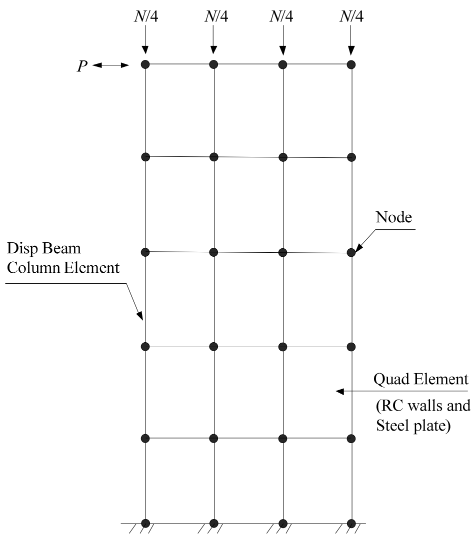


Figure 2.2. Finite element modelling of specimen

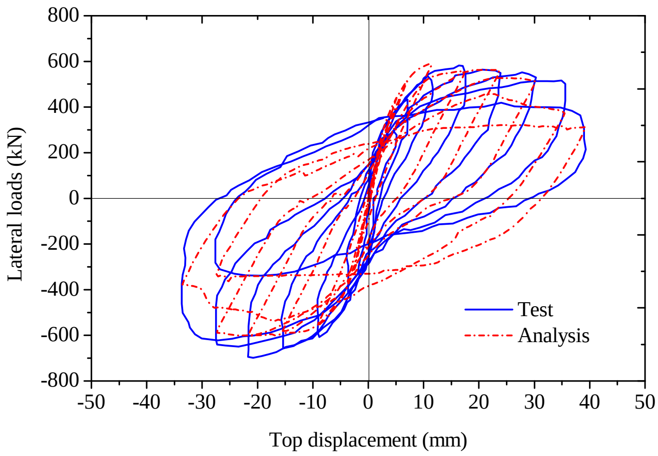


Figure 2.3. Analytical and test load-displacement curves

Experimental and analytical results of the lateral force-displacement curves of the SPRCW are shown in Fig. 2.3. It can be seen that good agreements are obtained for the pre-peak stiffness, post-peak stiffness and carrying capacity. The analytical model tends to overestimate energy dissipation in the later stages of post-peak response. This is may be a result of the interfacial slip between the embedded steel plate and RC wall not being considered. The analytical model assumes sufficient anchorage has been provided.

3. NONLINEAR ANALYSIS OF SPRCWS WITH DIFFERENT PARAMETERS

With respect to geometrical modelling, the same model as described in Section 2 is used to investigate the seismic performance of SPRCWs with different parameters. Regarding material properties, the same set of concrete, rebar and steel as given in Table 2.1 are used for the analysis here. According to the latest code for design of composite structure in China, the main parameters included in this study are the axial load ratio, the ratio of steel plate and the ratio of web reinforcement of RC wall. The effect of shear studs is not considered herein because of the assumption of sufficient anchorage. All of analytical models followed the same displacement-controlled cycles shown in Fig. 3.1.

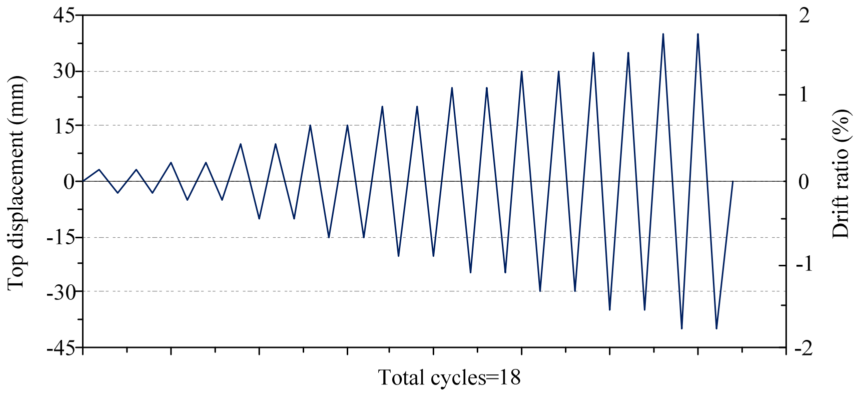
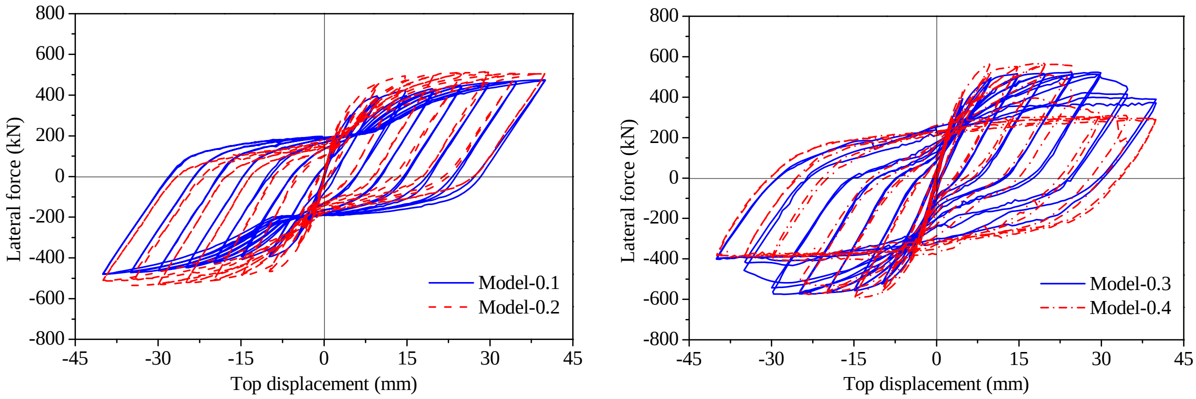


Figure 3.1. Top lateral displacement history of all analytical models

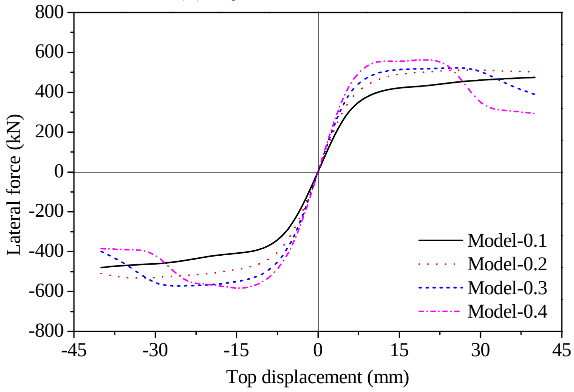
3.1. Axial load ratio

The SPRCWs are usually located on the bottom of super high-rise building. To obtain the enough ductility for its seismic performance, the axial load should not be beyond the limit value. Four levels of axial load were selected in the study to investigate their effect on the behaviour of SPRCWs. These design values varied from 0.1, 0.2, 0.3 to 0.4, and the corresponding vertical loads were 537kN, 1074kN, 1611kN and 2148kN, which considered the effect of structural steel and steel plate.

A comparison of load-displacement curves of both hysteresis and skeleton curves with different axial load ratio are shown in Fig. 3.2. Similar to the conventional RC walls, the results suggest that axial loads have an obvious effect on the ductility. SPRCWs subjected to high level vertical loads show increase in the initial stiffness and slight enhancements of load carrying capacity. In contrast to SPRCW with the axial load ratio of 0.2, the increase of carrying capacity only 9.8% can be obtained that subjected to the axial load ratio of 0.4. The skeleton curves show that the vertical loads has a considerable effect on the post-peak strengths of SPRCWs. The evident strength degradation could be attributed to the occurrence of concrete crushing. The enhancements of vertical loads lead to a quick damage of concrete and thus further decrease of SPRCW capacity. This conclusion is also validated in experimental results (Jiang, 2012). Load-displacement responses for RC wall and steel plate are shown in Fig. 3.3. When the SPRCW subjected to low level vertical loads (the axial load ratio of 0.2), the RC wall provides the majority of carrying capacity, and there is an enhanced trend for steel plate with the loading displacement increased. Compared with SPRCW loaded under the axial load ratio of 0.4, the concrete crushed when the loading displacement reached beyond 30mm approximately and the steel plate plays a significant role in the later analysis. This phenomenon also can be found in hysteresis curve of SPRCW with the axial load ratio of 0.4 and it is similar to the steel component hysteresis in the later loading stage.

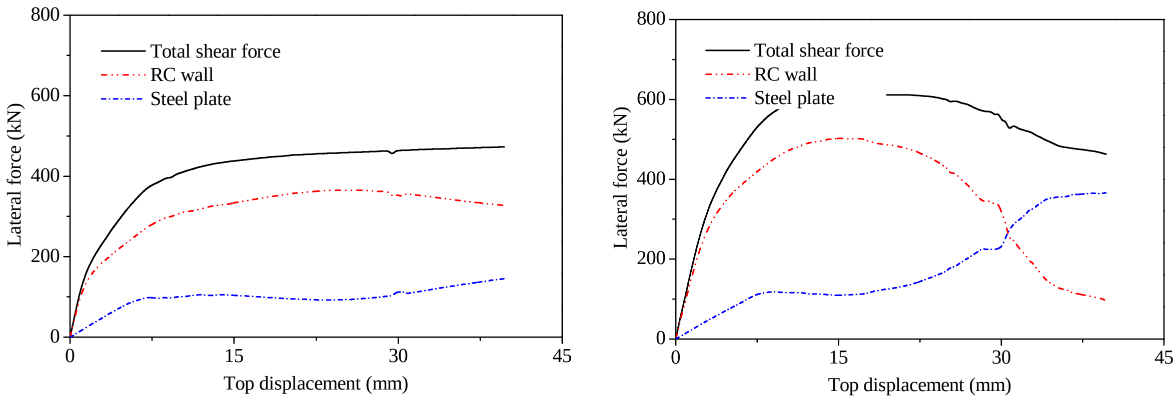


(a) Hysteretic curves



(b) Skeleton curves

Figure 3.2 Load-displacement curves for different vertical loads



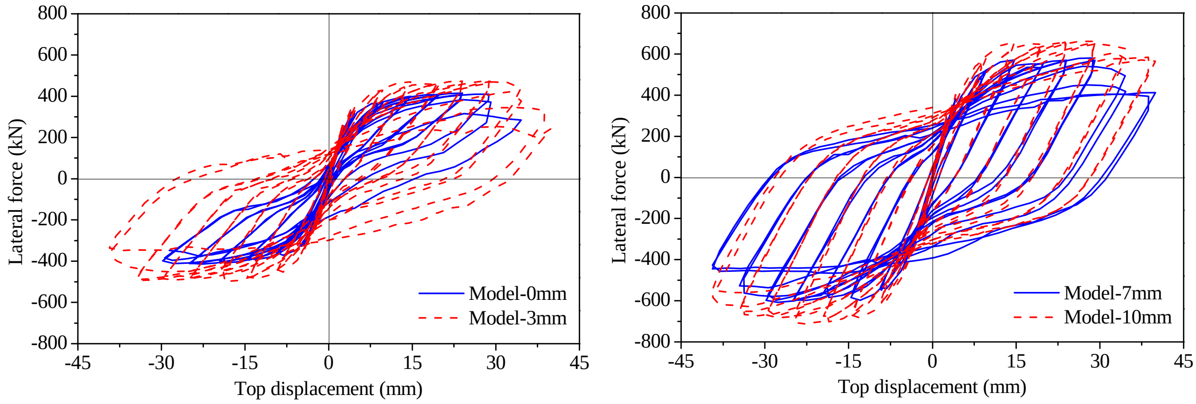
(a) Axial load ratio of 0.2 (b) Axial load ratio of 0.4

Figure 3.3. Load-displacement responses for RC wall and steel plate

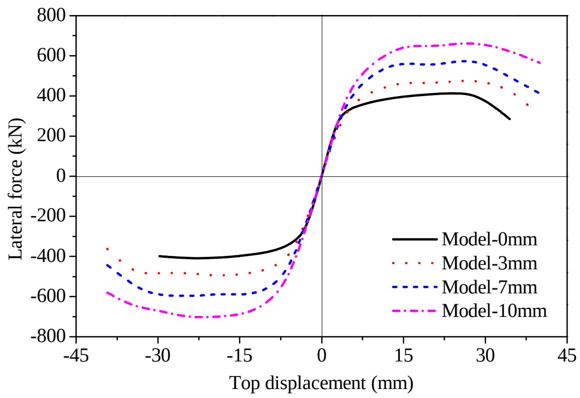
3.2. The ratio of steel plate

The behaviour of SPRCWs with different ratio of steel plate was investigated. The walls were modelled with vertical load of 1611kN and the same ratios of reinforcement (0.67% and 0.37% in the transverse and longitudinal reinforcement of wall web, respectively). The steel plate thickness varied from 0 to 10mm, which was slight more than the ratio constructed in practical engineering. To be noted, the thickness with 0mm means such kind shear wall is the conventional RC wall without the embedded steel plate.

The load-displacement curves of both hysteresis and skeleton curves are shown in Fig. 3.4. Clearly, the embedded steel plates are effective in contributing to the carrying capacity and ductility of SPRCWs. Compared with conventional wall, SPRCW with 3mm steel plate achieved 13.9% increase in peak strength, while the energy dissipation is improved obviously and the pinching effect also most disappears. Load-displacement responses for RC wall and steel plate are shown in Fig. 3.5. With the increase of the thickness of steel plate, it provided more carrying capacity, especially in the later loading stage. Again, the response plotted in Fig. 3.6 indicate that the vertical loads has a considerable for the strength degradation even the SPRCWs has a high level of the ratio of steel plate.

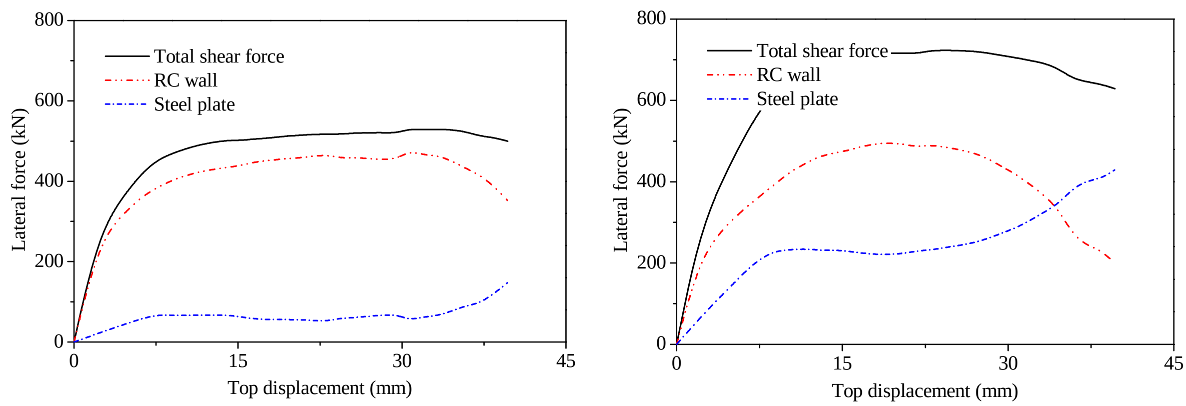


(a) Hysteretic curves



(b) Skeleton curves

Figure 3.4. Load-displacement curves for different thickness of steel plate



(a) 3mm steel plate (b) 10mm steel plate

Figure 3.5. Load-displacement responses for RC wall and steel plate

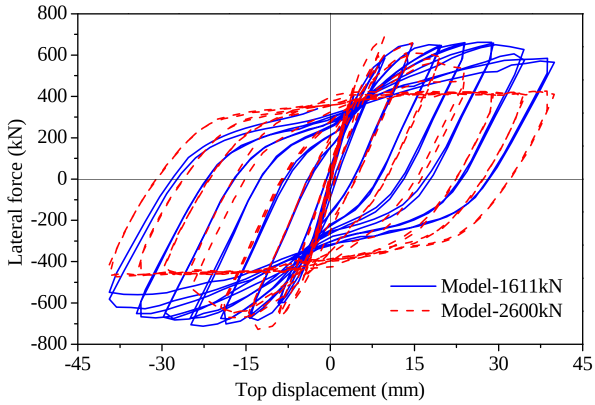
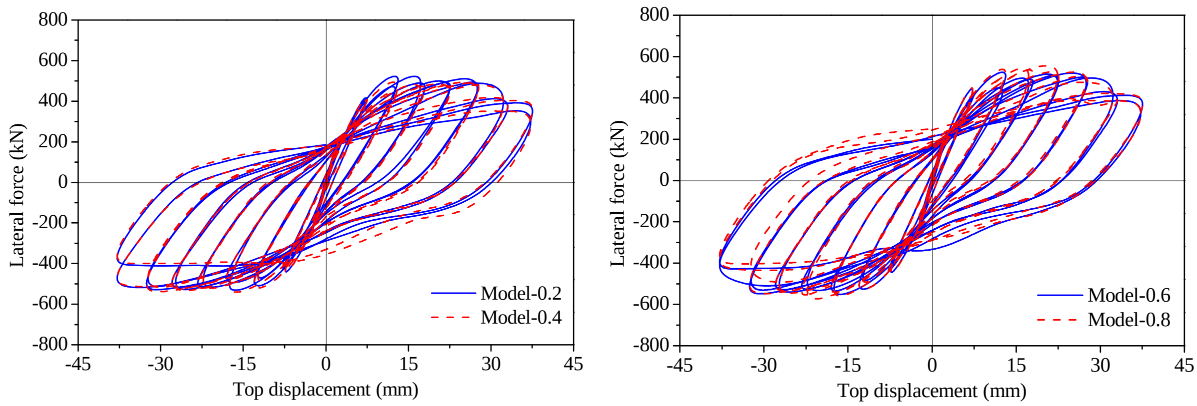


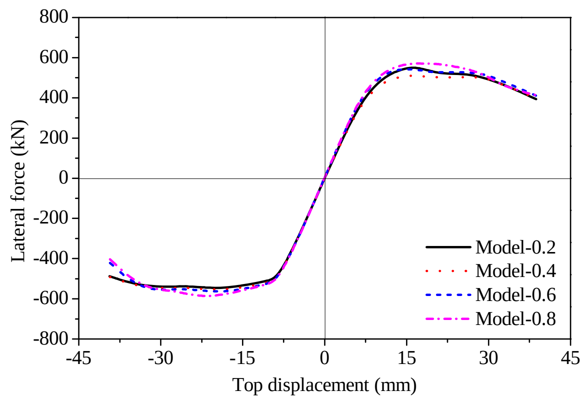
Figure 3.6. Load-displacement responses for different vertical loads with 10mm steel plate

3.3. The ratio of web reinforcement for RC wall

To study the effect of the ratio of transverse and longitudinal web reinforcement for RC wall, four SPRCWs were modelled with vertical load of 1611kN and the 5mm thickness steel plate. The walls were analysed with identical transverse and longitudinal web reinforcement of 0.2, 0.4, 0.6 and 0.8%, respectively.



(a) Hysteretic curves



(b) Skeleton curves

Figure 3.7. Load-displacement curves for different web reinforcement

Fig. 3.7 shows the load-displacement behaviour of both hysteresis and skeleton curves for different web reinforcement. It suggests that the ratio of web reinforcement for RC wall has a negligible effect on the load carrying capacity, initial and post-peak stiffness. By contrast, the calculations of hysteresis curves imply that reasonable increases in the amount of transverse and longitudinal web reinforcement are sufficient to improve the load carrying capacity for conventional walls as shown in Fig. 3.8. This phenomenon may attribute to the role of embedded steel plate. Compared with the ratio of steel plate, the ratio of web reinforcement for RC wall is in a low level and leads to a negligible effect for SPRCW's performance. Load-displacement responses for RC wall and steel plate are shown in Fig. 3.9. The results suggest that the increases of web reinforcement do not have a significant effect on either the RC wall or steel plate carrying capacity. Although the ratios of web reinforcement for RC wall may display a little role in the SPRCW system, it would be still required to provide lateral support to the concrete and embedded steel plate.

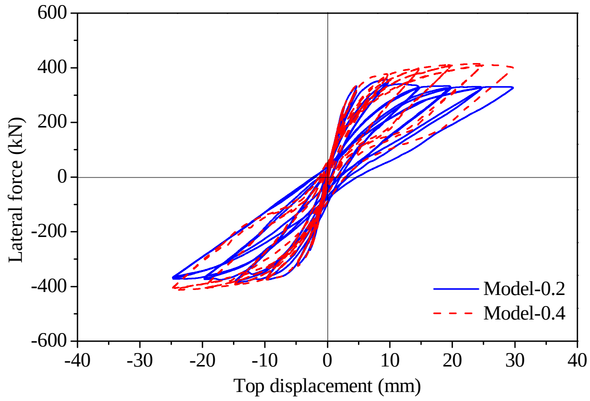
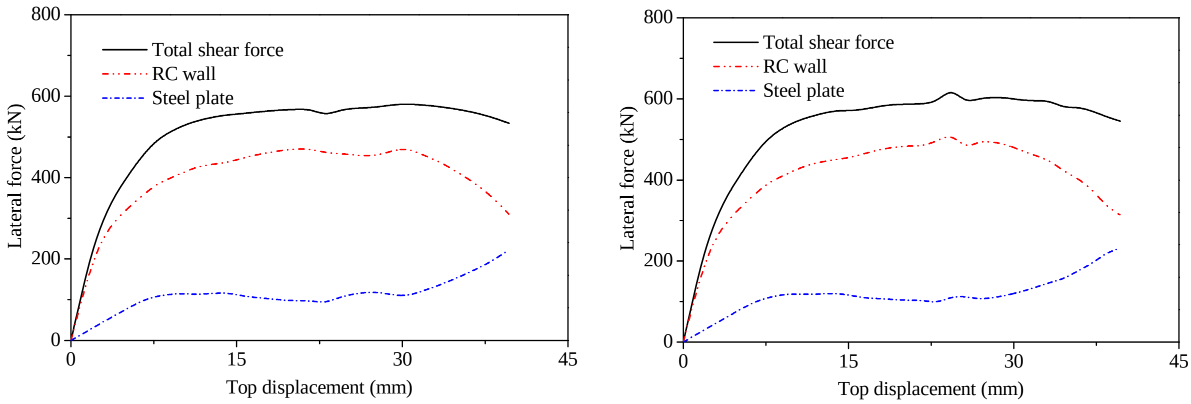


Figure 3.8. Load-displacement curves for conventional RC walls with different web reinforcement



(a) 0.2% web reinforcement (b) 0.8% web reinforcement

Figure 3.9. Load-displacement responses for RC wall and steel plate

4. SUMMARY AND CONCLUSIONS

In this study, the seismic performance of steel plate-reinforced concrete composite shear walls was studied. The verification study was undertaken, and a variety of parametric analyses for SPRCWs were carried out. The main conclusions can be drawn from the study:

1. Based on the verification study, it can be found that the plane stress concrete materials and J2 plasticity material can be successfully able to capture the nonlinear behaviour of SPRCWs. The analytical process is stable and computationally efficient under the reversed cyclic loading.

2. From the results of verification study, the analysis model tends to overestimate energy dissipation in the later stages of post-peak response. This is may be a result of the interfacial slip between the

embedded steel plate and RC wall not being considered. The analytical model assumes sufficient anchorage has been provided.

3. Compared with conventional wall, SPRCWs has a considerable increase in carry capacity and ductility. As well, the energy dissipation is improved obviously and the pinching effect also most disappears.

4. Axial loads have an obvious effect on the ductility. SPRCWs with high level vertical loads show increase in the initial stiffness and slight enhancements of load carrying capacity. The evident strength degradation attributed to the occurrence of concrete crushing can be found subjected to increased vertical loads. The ratio of steel plate is effective in contributing to the carrying capacity and ductility of SPRCWs. But vertical loads may be a considerable reason for the strength degradation even the SPRCWs has a high level of the ratio of steel plate.

5. The calculations of hysteresis curves imply that reasonable increases in the amount of transverse and longitudinal web reinforcement have a negligible effect on the load carrying capacity, initial and post-peak stiffness. Although the ratios of web reinforcement for RC wall may display a little role in the SPRCW system, it would be still required to provide lateral support to the concrete and embedded steel plate.

6. The individual load-displacement responses of RC wall and steel plate suggest that with the increase of axial loads and the ratio of steel plate, steel plate will provide more carrying capacity, especially in the later loading stage.

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