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Nonlinear Analyses of Stiffened Steel Plate Shear Walls Considering Gravity Effects

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Abstract

Steel Plate Shear Walls (SPSWs) are lateral load resisting systems that consist of a boundary frame and an infill steel panel. Due to the construction time limit of high-rise buildings in China, SPSWs could not wait to be installed after the floors are in place, and the wall system has to undertake part of the vertical loads along with lateral loads. Therefore, SPSWs are needed to avoid buckling during construction and under the serviceability limit states, meanwhile remain elastic under the frequent earthquake load. In this paper, elastic buckling analyses and nonlinear pushover analyses are conducted on a set of stiffened and comparative unstiffened SPSWs with varying design parameters such as number and layout of stiffeners and gravity effects, in order to investigate the global behavior of stiffened SPSWs considering gravity effects and propose design recommendations. Channel stiffeners are adopted as they provide higher out-of-plane and torsional constraint than plate stiffeners do. Results show that compared with unstiffened SPSWs, SPSWs with limited number of channel stiffeners can have higher lateral strength and significantly higher lateral stiffness and less out-of-plane displacement. Especially when gravity effects are considered, the advantages of channel stiffened SPSWs is more outstanding compared to unstiffened SPSWs.

1. Introduction

Steel plate shear walls (SPSWs), which is composed of thin infill steel panel and boundary elements, has high lateral stiffness and strength, thus ideal for resisting the lateral loads in mid to high-rise buildings. Due to high slenderness and imperfection in fabrication, the steel panels usually buckle early under low level of shear load and thus loss part of the capacity and stiffness. In Japan and some European countries, steel plate shear walls are heavily stiffened to postpone or even prevent the elastic buckling. In North America, however, steel plate shear walls are usually unstiffened due to the high labor cost associated with adding stiffeners, which are called special plate shear walls. The wall panels are then prone to buckle elastically, which generally will not affect the ultimate shear strength very much, since most of it relies on the large inelastic capacity from the tension field action. However, Canadian design code (CAN/CSA 2009) and American Institute of Steel Construction seismic design guidelines (AISC 2010) all require that infill panel only resists the lateral loads, while the boundary columns of the SPSW system resist

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the vertical loads. In order to comply with this requirement, the field construction sequence has the main frame columns and beam elements erected first, and steel panels are then installed or attached to the main frame elements. However, this sequence may lead to a significantly longer duration of construction.

Due to the construction time limit of high-rise buildings in China, SPSWs could not wait to be installed after the floors are in place, so the wall system has to undertake part of the gravity loads along with lateral loads. In addition, Chinese design code doesn’t allow the panel to buckle during construction and under the serviceability limit states, and the structure also should maintain elastic under the frequent earthquake load. Two major issues that arise when the tension field action is developed in a typical unstiffened SPSW include large out-of-plane deformations and unpleasant sounds from the buckling of the infill panels. In addition, significant pinching sometimes appears in the envelope curve of unstiffened SPSW due to the early buckling of unstiffened steel plates with an attendant reduction in energy consuming capacity, whereas stiffened SPSWs exhibit better seismic resistance characteristics. Furthermore, the demands and reactions on the boundary elements increase because of the development of tension field action. Cases of failures of the boundary elements or their connections have been reported in the tests conducted on unstiffened SPSWs by Elgaaly et al. (1993), Driver et al. (1998), Astaneh-Asl (2001), and Park et al. (2008). As a result, SPSW stiffeners could be utilized, in the proper arrangements, to prevent early buckling, reduce the pinch effect, and reduce the resultant forces in VBEs, so as to achieve a more economic design.

In the past, most of the research on stiffened steel plate shear wall was focused on the effects of stiffeners on the behavior of the wall panel, while not much emphasis has been placed on the interaction between the stiffened panel and the boundary frame members. Grondin, Elwi et al. (2002, 2003) conducted analyses of steel plates with tee-shape stiffeners under uniaxial compression and combined uniaxial compression and bending. Consequently, they presented that sudden loss of load-carrying capacity existed with plate buckling, and stiffener to plate area ratio and plate slenderness ratio were significant on the strength of stiffened steel plates. Alinia’s study (2005,2007,2009) showed that the stiffened steel plate would have the maximum buckling and post-buckling strength if stiffeners were optimally designed. And an optimum amount of stiffeners should be used to have sufficient rigidity and deformability. Also, he concluded that it is preferable to select parallel unidirectional stiffeners than bidirectional cross stiffeners. Tsai, K.C.et al. (2010) used horizontal restrainers on the web plate of a narrow steel shear wall to reduce the force demands on the boundary column by limiting the magnitude of the out-of-plane buckling of the web plate. S.Sabouri-Ghomi’s (2012) test results showed that, installation of stiffeners improved the energy dissipation capacity and shear stiffness of steel plate obviously while its effect on the steel plate shear strength was minor. Alavi et al. (2013) conducted several 1/2-scaled single-story experiments and studied the behavior of diagonally stiffened steel plate shear walls with and without central perforation. Experimental results showed that the diagonal stiffeners improve hysteretic behavior of the steel shear walls, especially when the edge stiffeners are used in the panel. Nie J.G. et al. (2013) conducted three 1/5-scaled four-stories experiments to investigate the seismic behavior of steel plate shear walls with U-shape stiffeners, with and without openings. The results showed that stiffened steel plate shear walls exhibit satisfactory seismic behavior. Wang M. et al. (2015) proposed T type rib stiffened low yield point steel plate shear wall through the FE model analysis. The results showed that the proposed

SPSW could effectively improve the energy dissipation capacity and ductility, lessen the impact of tension field on the columns, and also had better load-carrying capacity and smallest out-of-plane deformation.

As for the influence of vertical load of the SPSWs, only little of former research focus on this field. Vertical loads from columns were included in some experimental research, the cyclic test of a four-story SPSW conducted by Driver et al. (1998), vertical loads of a magnitude representing reasonable unfactored gravity loads for a typical building at the lowest story were applied at the tops of the columns, but no comparison was made to explain the influence of the vertical load. The test conducted by Nie J.G. et al. (2013) also applied the vertical load at the tops of the columns, but the boundary columns are concrete filled steel tube (CFST) columns which has a high degree of axial stiffness. Elgaaly et al. (1997) compared the shear-carrying capacity of unstiffened SPSW with and without vertical load through the FE model analysis. The results show that the vertical load affects little, but perhaps because the magnitude of vertical load was small and the comparison only focus on the ultimate strength of the infill panel, the conclusion couldn't be applied generally. Guo Y.L. et al. (2014) investigated the behavior of steel plate shear walls (SPSWs) with pre-compression of the frame columns by FE method. They presented that the pre-compression from frame columns must be considered in design since that the compression impaired the shearing capacity significantly. And they proposed a reduction coefficient of shear-carrying capacity of SPSW due to pre-compression as a design reference.

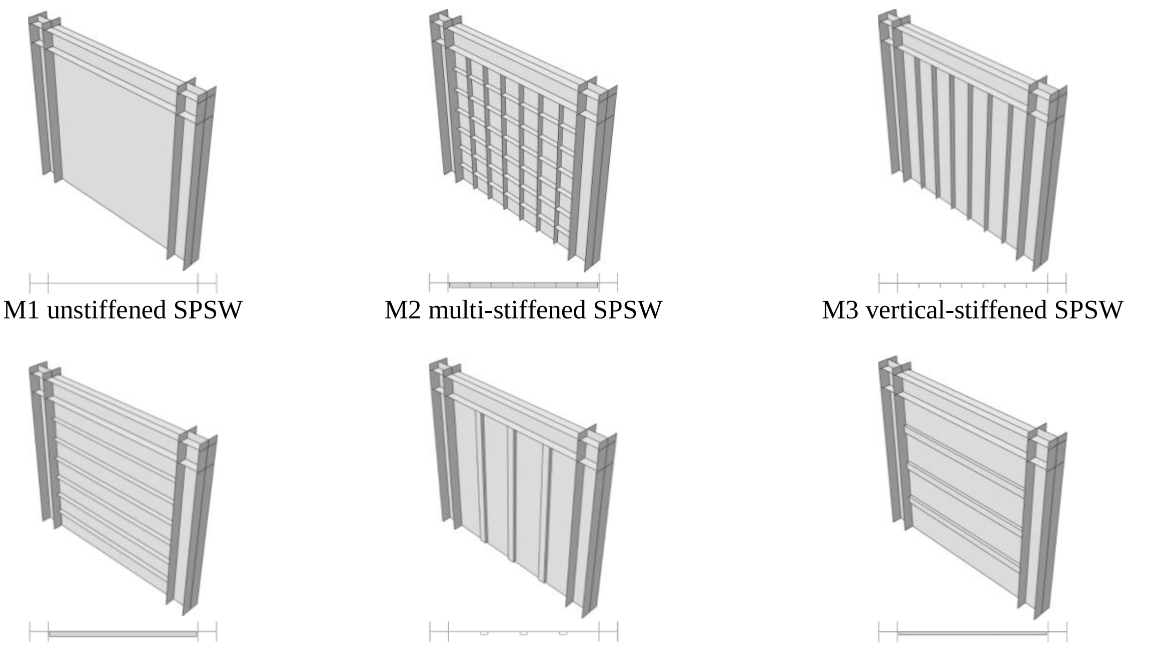
Based on the above discussions, the main objectives of this paper include the study of the influence of stiffeners under vertical and lateral loads, and the evaluation of the effectiveness of stiffeners with different number and layout. To achieve these objectives, a number of SPSWs having different infill panels are numerically analyzed using the finite element method. In addition, a series of SPSWs are also analyzed to consider the effect of vertical load in the study. Both elastic buckling and nonlinear pushover analyses are performed. The influence of infill walls on the behavior of frames is also studied by comparing the behaviors of moment frames acting as SPSW boundaries and acting alone (bare frames without infill panels).

2. Method of the study

2.1 Design of models

A series of single-story single-bay SPSW models includes the un-stiffened SPSWs as well as the SPSWs with various types of stiffeners (see Fig. 1) are considered for this research. Both elastic buckling and inelastic pushover analyses are performed, with emphasis on the behavior of the boundary elements as well as the wall panels, and the results were compared to identify the optimum performance. In addition, the discussion were not limited to the normal designed models, the analysis of the models with weak columns were also conducted to confirm the efficacy of stiffened SPSWs. Besides, since the convenient construction and economy consideration, the properties with vertical loads were also studied. The new type of stiffened steel plate shear wall system with sparsely-spaced channel stiffeners was proposed based on the analysis results.

The unstiffened steel plate shear wall is built first and composed of an infill steel panel, with the dimensions 3000mm×3000mm×5mm, boundary columns (400×400×25×30) at both sides and boundary beams (400×300×25×35) at the top side, as shown in Fig.1. Boundary frames are designed according the principle that the plastic hinge of frames occur after the yield zone of unstiffened infill panel spread onto the whole panel, that is to say, the tension field action can be fully developed. The stiffened steel plate shear wall is built with the same dimension and the stiffeners all on one side of the steel panel for easy fabrication. The stiffeners in multi-stiffened infill panel are bidirectional arranged, and it is designed to ensure the panel can reach the material yield before geometrical buckling by bidirectional arranged. The stiffeners in unidirectional flat stiffened models are the same with multi-stiffened models. The quantity of channel stiffeners is only half of the flat stiffeners. And the stiffeners are designed to fulfill the minimum required moment of inertia. There is a 30 mm gap at each side of the stiffener to allow the relative deflection between steel panel and stiffeners, and also for the convenience of fabrication.



M1 unstiffened SPSW M2 multi-stiffened SPSW M3 vertical-stiffened SPSW

M4 horizontal-stiffened SPSW M5 vertical channel stiffened SPSW M6 horizontal channel stiffened SPSW

Figure 1: Model description

2.2 Model description

The Q235 and Q345 conventional structural steel are, respectively, selected for infill panel (including the stiffeners) and frame members materials. The elasto-plastic stress-strain relation is used to define the constitutive behavior for both materials with the elastic modulus E=206 GPa and poison's ratio υ=0.3. The yield stresses are 235Mpa and 345Mpa for Q235 and Q345 materials respectively and the von-mises criteria is used to define the yielding of infill panels and boundary frames.

Finite element models are developed using the FE software ABAQUS. The infill panel, boundary frames and stiffeners are all modeled using S4R elements, which are the four nodes shell elements with reduced integration. The implicit approach is used for eigen-value analysis and nonlinear pushover analysis.

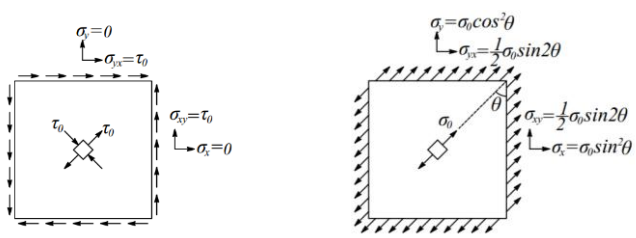
The infill panel is considered to be connected directly to the frame members. The bottom of infill panel is assumed to be anchored to the ground rather than to an anchor beam. To simulate the fix support conditions at the column bases, the bottom nodes of both flanges and webs are restrained from displacement in all directions. Likewise, all degrees of freedom are restrained at the bottom nodes of the infill panel. To replicate the effects of the concrete slab of floors, all beam webs are also restrained against movement in the out-of-plane direction. A reference point is generated in each model, and it is coupled to the left side edge of the boundary beam. In the elastic buckling analysis, a concentrated force is applied at the reference point to receive the eigenvalue and the buckling shape. In the nonlinear push-over analysis, a displacement boundary condition is applied at the reference point, and the system would be pushed until the desired lateral drift, which is 2% drift in this paper.

Initial imperfections need to be considered in the FE analysis of SPSW models to consider the initial out-of-plane deformations that occur in the infill panel in practice. To account for this effect, an initial imperfection pattern corresponding to the first buckling mode of each infill plate with small peak magnitude (1/750h in this paper) is applied as the initial conditions of SPSW models.

3. SPSW models under lateral load without vertical load

3.1 Two load-carrying modes of the infill panel

When the infill panel bears shear load, it works in shear load-carrying mode before buckling, as is shown in Fig. 2(a). When the infill panel occurs buckling, it becomes into tension field load-carrying mode with the increase of out-of-plane displacement as the story drift angle is increasing, as is shown in Fig. 2(b).



(a) Shear load-carrying mode (b) Tension field load-carrying mode

Figure 2: Schematic diagram of two infill panel load-carrying modes

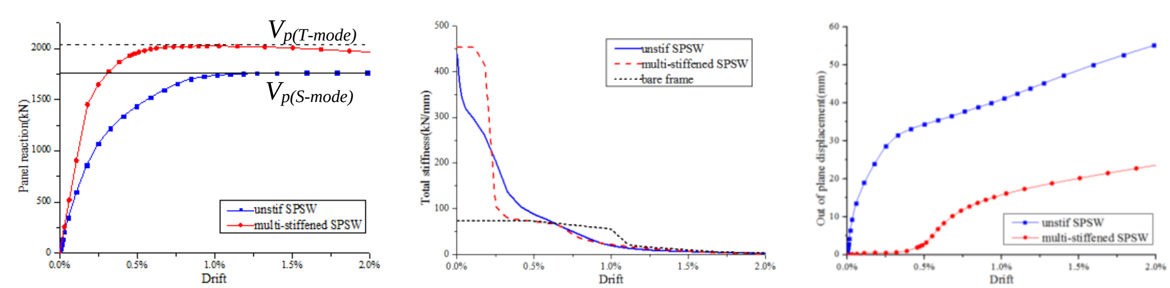
Based on their slenderness parameter as well as buckling and yielding behavior, infill panels in SPSW systems may be divided into slender, moderate, and stocky categories with respective early buckling, concurrent buckling and early yielding characteristics. Such a classification enables the accurate evaluation of the load-carrying modes of the infill panel, thus evaluate the behavior of the SPSW systems. For slender categories, especially high depth-thickness ratio panel, geometrical buckling happens much easier than material yielding, which is typical tension field load-carrying mode (Fig. 2(a)). If the boundary elements are strong enough to ensure development of tension field in the whole of infill panel, the shear capacity theoretical maximum of infill panel is calculated by Eq. 1. For stocky categories, such as low depth-thickness ratio or heavily stiffened panel, material yielding happens easier than geometrical buckling, which is typical shear load-carrying mode (Fig. 2(b)). Its shear capacity theoretical maximum is calculated by Eq. 2.

$$V_{p(T-\text{mode})} = 0.5\sigma_{yp} \sin 2\theta \cdot B \cdot t_p \approx 0.5\sigma_{yp} \cdot B \cdot t_p \quad (1)$$

$$V_{p(S-\text{mode})} = \tau_{cr} \cdot B \cdot t_p = \frac{\sigma_{yp}}{\sqrt{3}} \cdot B \cdot t_p \approx 0.577\sigma_{yp} \cdot B \cdot t_p \quad (2)$$

Where τ_{cr} is the infill plate shear stress, σ_{yp} is the infill plate yield stress, B and t_p are length and thickness of the infill panel. In addition, θ is the angle of tension field inclined respect to the vertical line as shown in Fig. 2(b).

Within the models considered in this paper, M1 and M2 are typical slender and stocky categories. In a typical unstiffened thin single-story SPSW, the buckling of infill panel occur early. The infill panel bears lateral load by tension field. For multi-stiffened SPSW, the buckling load is larger, and the infill panel bears lateral load by shear load-carrying mode. The comparison between the two models are shown in Fig. 3. In Fig. 3(a), the infill panel reaction is shown to be in good agreement with theoretical result, that the multi-stiffened panel reaction is about 15% larger than unstiffened panel. But multi-stiffened SPSW infill panel reaction experience a little decrease when the story drift exceeds 1%, since the shear load-carrying mode gradually turns into tension field one with the out-of-plane displacement increased after the inelastic buckling occurred. In Fig. 3(b), it is shown that there are obvious differences between stiffness curves of M1 and M2. The stiffness of M1 decreased continuously from beginning, since its early buckling. For M2, initial stiffness keeps in a higher level than M1 does, but decreases quickly as the infill panel begins to yield. When the yielding extended to the whole infill panel, the stiffness curve experiences a platform stage which is equal to the stiffness of bare frame. With the increase of the drift, boundary elements begins to yield and results in decrease of stiffness again until the ultimate capacity is reached. It is shown that there is no yield platform on stiffness curve of M1 other than M2, because thin infill panel needs larger drift for reaching its ultimate capacity through tension field load-carrying mode rather than Shear load-carrying mode. Therefore, the boundary elements start to yield with the yielding extended to the whole panel because of the larger internal force in boundary elements caused by frame bending effect with the larger drift. However, the infill panel of M2 can reach ultimate capacity with a smaller drift, and boundary elements can keep elastic until some region begins to yield. In Fig. 3(c), it is shown that M2 can constraint out-of plane displacement effectively, especially at the small drift stage, the out-of plane displacement of thin SPSW increases quickly while M2 does not appear obvious out-of plane displacement. The effectiveness of constraint the out-of-plane displacement at large drift is also considerable.



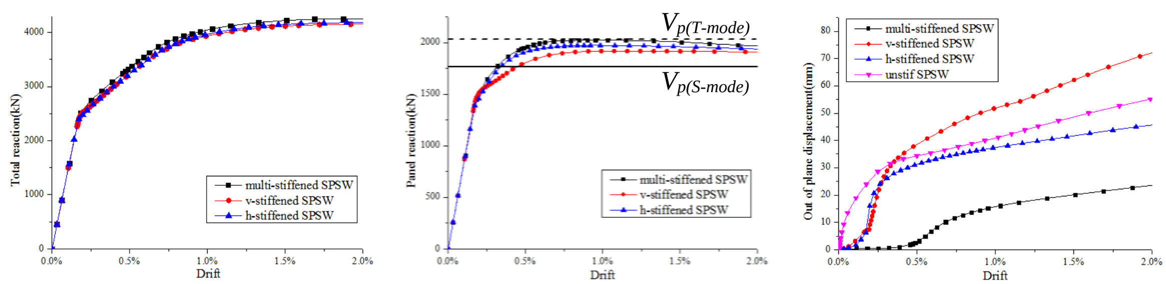
(a) Infill panel reaction SPSW reaction (b) Total stiffness (c) Out of plane displacement

Figure 3: Comparison between M1 & M2

3.2 Analysis of unidirectional stiffened SPSW

By comparing two typical load-carrying modes, it is found that the differences of the lateral capacity between them is not so important since that the lateral capacity of SPSWs are considered very high compared with other lateral resisting structure. But the initial stiffness and out-of-plane displacement should be paid more attention. And the comparison of the initial stiffness and out-of-plane displacement between the two models show significant difference. In practical application, the improvements of initial stiffness and the restriction of out-of-plane displacement are always needed. Firstly, the infill panels should ensure not to buckle and appear much lateral displacement in serviceability limit state, such as under wind load, in other words, improve the serviceability. And it also should be ensured to maintain elastic under the frequent earthquake load. Results of the previous model show that the load-carrying modes depend on how difficult the infill panel buckles. For stiffened infill panel, the length of short edge of subpanel has the main impact on buckling performance. Therefore, unidirectional stiffened SPSW models are considered for its easy construction and saving material, namely M3 and M4, which has the flat stiffener arranged vertically and horizontally.

The comparison results among M2, M3 and M4 are shown in Fig. 4. It is found that difference of capacity among three models is not obvious including total and infill panel capacity (see Fig. 4(a)(b)). For total capacity, the two unidirectional stiffened SPSW models show almost the same results. For infill panel capacity, axial stress in vertical stiffener is increasing by bending effect as lateral displacement increases gradually. So the vertical stiffener itself tends to be easier to buckle and experience large out-of plane displacement, thus lose restriction effect to the panel. This behavior makes infill panel buckled more easily and change the main shear load-carrying mode into tension field load-carrying mode gradually earlier. The feature does not appear in horizontal stiffened infill panel. And the angle of tension field in vertical stiffened infill panel is smaller than that in horizontal one, therefore, the lateral capacity is a little smaller. The out-of-plane displacement of vertical stiffened model is even larger than unstiffened model (see Fig. 4(c)). In Fig. 5, it is shown that the stiffener itself appears obvious deformation. As is known from the literatures, the large deformation of the stiffener itself would decrease the effectiveness of stiffeners and influence the hysteretic behavior significantly. The models considered in this paper are all single story, therefore, more shear than bending effect exists in structures. If bend effect is considered, behavior of flat stiffeners may be worse.



(a) SPSW reaction (b) Infill panel reaction (c) Out of plane displacement

Figure 4: Comparison between M2 & M3 & M4

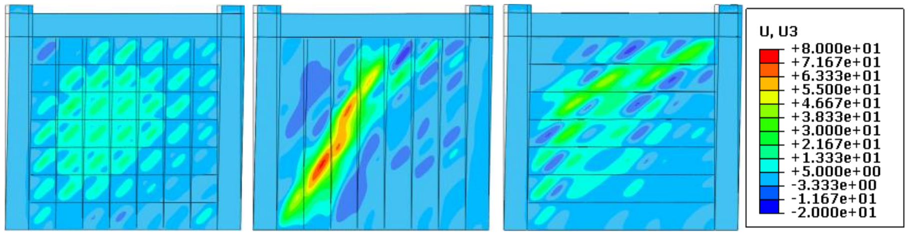
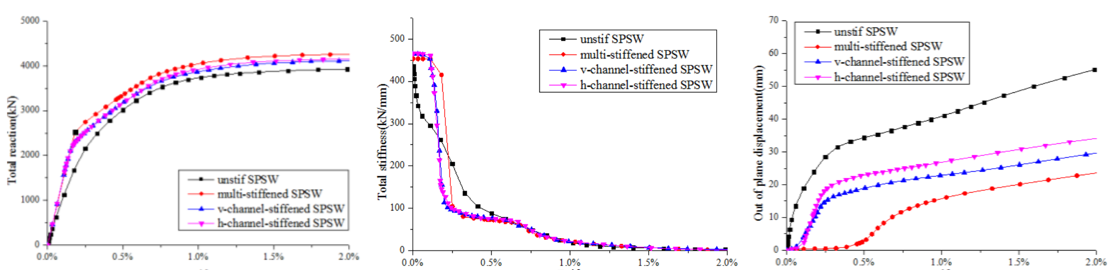


Figure 5: Out-of-plane displacement of M2 & M3 & M4 at ultimate stage

3.3 Analysis of unidirectional channel stiffened SPSW

From the analysis above-mentioned, it can be found that unidirectional stiffened models could show similar performance with multi-stiffened ones if the deformation of stiffener itself can be limited. However, the flat stiffeners have relatively small flexural stiffness and second moment of area, therefore less resistant to global buckling of steel panels. Channel stiffener is considered, for improving the bending and torsion deformation of flat stiffeners in above-mentioned analysis. Channel stiffeners, which have two flanges, therefore two nodal constraints, with high flexural stiffness interacting with the steel panel, and the web with additional lateral stiffness to steel plate, would be more effective to cut the global buckling and resist buckling and tension field into sub-panels. The channel stiffeners also have large torsion rigidity compared with flat open-section stiffeners. In addition, compared with more flat stiffeners, less channel stiffeners would cost less in material and welding procedure. And compared with flat stiffeners, the web of channel stiffeners act as additional resistance to lateral loads, therefore increase the overall lateral stiffness of the system.

From the comparison of these models (see Fig. 6), it is shown that lateral capacity of unidirectional channel stiffened SPSWs are similar to that of unidirectional flat stiffened SPSWs, which is a little below multi-stiffened SPSW, but higher than that of unstiffened SPSW. The initial stiffness is slightly higher than that of multi-stiffened SPSW, but they aren't able to reach material yielding before the geometrical buckle since the larger width of sub-panel. Therefore its decrease of stiffness curve is earlier than that of multi-stiffened SPSW. And the out-of-plane displacement increases after buckling earlier than multi-stiffened one. Compared with flat stiffeners, fewer channel stiffeners could be used to constraint out-of-plane displacement effectively, for its high stiffness of bending and torsion. The difference between the vertical arranged stiffened models and the horizontal arranged ones is similar with the flat stiffened SPSWs.



(a) SPSW reaction (b) Total stiffness (c) Out of plane displacement

Figure 6: Comparison between M1 & M2 & M5 & M6

3.4 Discussion of results of the models without vertical loads

3.4.1 Results of elastic buckling analysis

The elastic buckling load comparison is showed in Table 1. It can be seen that stiffeners could increase the buckling load evidently. Different layout directions of the stiffeners has little influence on the lateral buckling load.

Table 1: Elastic buckling load comparison without vertical load

Model		Lateral load	
		$P_{cr,L}$ (kN)	$P_{cr,L}$/ $P_{cr,L(M1)}$
M1	unstiffened	130.9	1.0
M2	multi-stiffened	4846.0	37.0
M3	vertical-stiffened	1712.5	13.1
M4	horizontal-stiffened	1765.9	13.5
M5	vertical channel-stiffened	1565.2	12.0
M6	horizontal channel-stiffened	1609.2	12.3

3.4.2 Results of inelastic pushover analysis

Define that the state when infill panel reaction reached the 90% $V_{p(T\text{-}mode)}$ as the design capacity state (V_n), since the shear load-carrying mode of infill panel will turn into tension field after buckling. The property at design capacity and ultimate stage (which is 2% drift in this paper) is shown in Table 2.

Table 2: Property at design capacity V_n (V_p=0.9$V_{p(T\text{-}mode)}$) and drift 2.0%

Model	Drift	V_p=0.9$V_{p(T\text{-}mode)}$			drift=2.0%			
		Panel percentage	Out-of-plane disp.		Total reaction		Out-of-plane disp.	
			(mm)	$\frac{D_v - D_{v(M1)}}{D_{v(M1)}}$	(kN)	$\frac{P_u - P_{u(M1)}}{P_{u(M1)}}$	(mm)	$\frac{D_u - D_{u(M1)}}{D_{u(M1)}}$
M1	0.66%	47.0%	36.31	/	3930.9	/	57.5	/
M2	0.23%	59.3%	0.48	-98.7%	4254.5	+8.2%	24.0	-58.3%
M3	0.26%	59.6%	22.31	-38.6%	4153.3	+5.7%	74.2	+29.0%
M4	0.25%	60.4%	24.35	-32.9%	4181.7	+6.4%	46.5	-19.2%
M5	0.28%	60.7%	15.85	-56.4%	4116.7	+4.7%	31.0	-46.0%
M6	0.27%	61.2%	19.17	-47.2%	4149.1	+5.6%	34.5	-40.0%

As shown in Table 2, at the V_n and ultimate stage (which is 2% drift in this paper), the capacities are increased, and the out-of-plane displacements are reduced because of the stiffeners, which means that stiffeners are capable of increasing the capacity and resisting the out-of-plane deflection, and this is especially essential for improving the serviceability. It is also shown in Table 2 that for different arrangement of stiffeners, the effect on increasing lateral capacity are similar. At design capacity V_n, the percentage of the panel reaction and the stiffness are all increased. The larger percentage of panel reaction can improve effectiveness of the infill panel and thus lead to a more economic and reasonable design of SPSWs. As to the out-of-plane deflections, stiffeners decrease them at design capacity from 32% to 98% and at ultimate capacity from 19% to 58%, except that M3 increased the out-of-plane deflections. It is worth to mention that even all stiffener combinations increase the design capacity and ultimate capacity and decrease the out-of-plane deflection, multi-stiffened models does not always show the superiority than channel stiffened models evidently, therefore, from both economical and effective considerations, bi-directional multi-stiffened steel panel is not a good choice compared with unidirectional stiffened steel panel. And, less channel stiffeners is a better choice compared with more plate stiffeners.

4. SPSW models under lateral load with vertical load

In order to satisfy the construction sequence that the infill panel don't need to wait to be installed after the floors are in place since the construction time limit of high-rise buildings in China. The wall system has to undertake part of the gravity loads along with lateral loads. And the system should satisfy the serviceability limit state design requirements and maintain flexibility state at frequent earthquake, therefore, it is essential to study the buckling behavior and the lateral properties of SPSWs with vertical loads. The unstiffened thin plate with large depth-thickness ratio would easily buckled under vertical or lateral load, which couldn't meet the design requirements. So the stiffeners could be used considering vertical load, and the channel stiffeners show more advantages over flat stiffeners according to the previous study in this paper, especially that the flat stiffeners tends to be easier to buckle and experience large deflection, thus lose restriction effect to the panel. Therefore, this part focus on the channel stiffened SPSW behavior under vertical load rather than unidirectional flat stiffened SPSW.

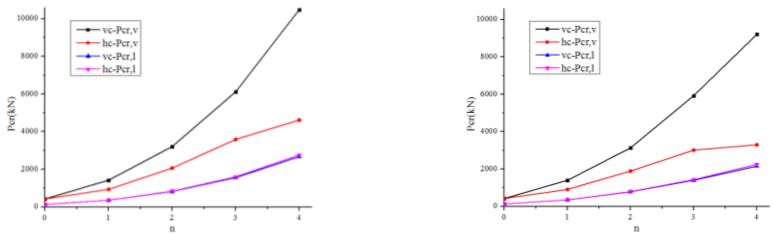
The vertical loads in the construction mainly because of the compression of the boundary columns due to the upper floors are installed gradually, and the vertical loads of the current floor can be avoid through the method that install the infill panel after the current floor is in place. So only the vertical load at the top of column is considered in this study, while the vertical load at the top of infill panel itself is ignored.

4.1 Elastic buckling analysis

The elastic buckling analysis for M1 SPSW models with 1~4 uniformly vertical or horizontal channel stiffeners under vertical or lateral load is conducted here. In addition to apply channel Ⅰ used in the previous model in this paper, channel Ⅱ with half bending stiffness value of channel Ⅰ is also used to make comparison. It should be noted that vertical load is arranged at column top. The results are showed in Table 3 and Fig. 7.

Table 3: Lateral and vertical elastic buckling load comparison

	n=0 (unstif)	stiffened	n=1		n=2		n=3		n=4	
			P_{cr}	$\frac{P_{cr,II}}{P_{cr,I}}$	P_{cr}	$\frac{P_{cr,II}}{P_{cr,I}}$	P_{cr}	$\frac{P_{cr,II}}{P_{cr,I}}$	P_{cr}	$\frac{P_{cr,II}}{P_{cr,I}}$
$P_{cr,L}$	130.69	vc Ⅰ	357.83	97.7%	818.68	95.4%	1555.9	89.7%	2669.7	80.7%
		vc Ⅱ	349.50		780.95		1395.6		2154.7	
		hc Ⅰ	359.83	97.7%	833.34	95.2%	1600.8	89.3%	2759.6	81.5%
		hc Ⅱ	351.44		793.34		1429.3		2249.2	
$P_{cr,V}$	424.42	vc Ⅰ	1420.3	98.3%	3207.6	97.6%	5459.9	96.9%	10481	87.8%
		vc Ⅱ	1396.6		3132.1		5925.7		9206	
		hc Ⅰ	932.21	97.5%	2061.7	91.7%	3586.2	83.9%	4611.8	71.5%
		hc Ⅱ	908.92		1891		3008.8		3296	



(a) Channel stiffener Ⅰ (b) Channel stiffener Ⅱ

Figure 7: Elastic buckling load of channel stiffened SPSWs with majority of stiffeners increased

From Fig. 7, it can be seen that the properties of SPSW models with channel Ⅰ and Ⅱ is similar. For single-story single-span SPSW with aspect ratio equals 1.0, the shear action plays major role and the bending action is negligible. The SPSW shows almost the same lateral elastic buckling strength with the vertical and horizontal arranged stiffeners of the same number. While it is different for vertical elastic buckling strength that the vertical stiffeners improve the buckling strength more remarkable compared to the horizontal stiffeners. For stiffeners with different bending stiffness, SPSW property imparity increase as the quantity of stiffeners increase (see Table 3). Along with the increasing of the quantity of stiffeners, the subpanel becomes more rigid with smaller depth-thickness ratio, which needs stronger boundary conditions to obtain sufficient anchorage. Thus, channel with smaller bending stiffness may not meet the requirements, so that the effectiveness of stiffeners decreased. In summary, it is suggested to adjust the quantity of vertical stiffeners considering different vertical load for engineering practice. What' more, the stiffener bending stiffness should increase with the decline of subpanel depth-thickness ratio.

In addition to avoid buckling under vertical load during construction period, the SPSW should not buckle at the serviceability limit state (such as wind load) or when frequent earthquake occurs with considering the existing vertical load. So the lateral buckling analysis with different quantity of vertical loads should be studied. The unstiffened and channel stiffened SPSWs (M1, M5, M6) is analyzed here. The results are shown in Fig. 8.

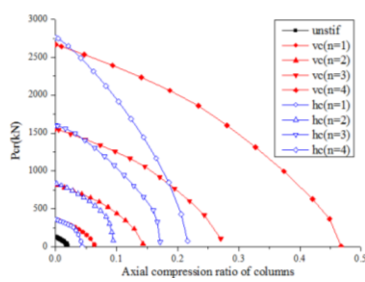


Figure 8: Elastic lateral buckling load considering various quantity of vertical load

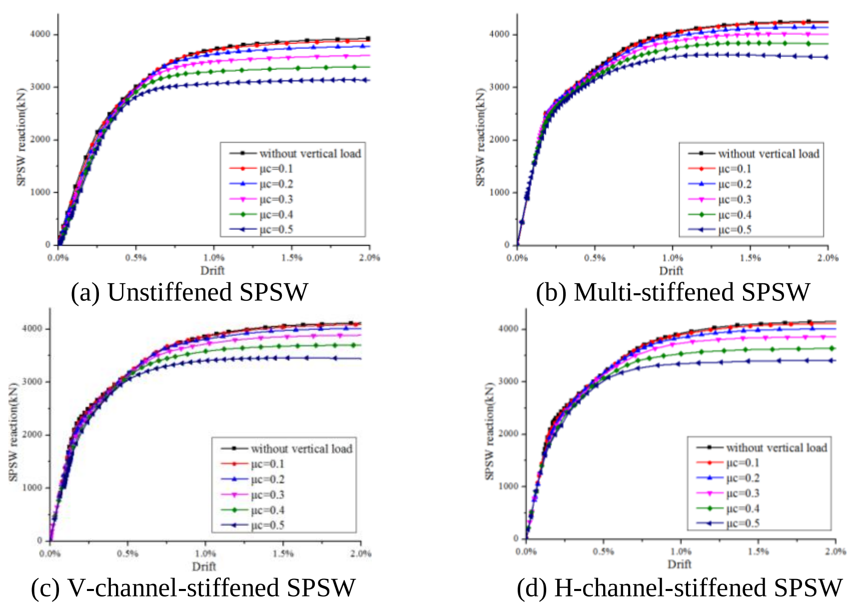
From Fig. 8, it can be seen that the lateral buckling strength for SPSW models with the same quantity of stiffeners almost equals without the vertical load, while the buckling strength for horizontal arranged stiffened SPSW is a little higher than vertical arranged stiffened SPSW. Nevertheless, the decline speed for horizontal arranged stiffened SPSW is apparently larger than vertical arranged stiffened SPSW as the vertical load increase, for instance the buckling strength for horizontal arranged stiffened SPSW with four stiffeners is smaller than vertical arranged stiffened SPSW with three stiffeners.

So vertical arranged stiffened SPSW has larger buckling strength compared to horizontal arranged stiffened SPSW with the same quantity of stiffeners. In other words, vertical arranged stiffened SPSW shows good buckling stability under vertical-lateral load. And the quantity of vertical stiffeners should be arranged according to the vertical load and the needed buckling load.

4.2 Inelastic Pushover analysis

According to the analysis under the lateral load without the vertical load in the previous study, the occur of buckling will affect the load-carrying mode of the inner panel, which has a little effect on bearing capacity and mainly impacts stiffness and out-of-plane displacement. The inelastic pushover analyses of M1, M2, M6 and M7 under vertical load is conducted here. The quantity of vertical loads is measured through the axial compression ratio of columns, and it varies from 0 to 0.5. And the same analysis is also conducted on pure frame with the same geometric parameter for comparison.

The lateral load-drift curves is shown in Fig. 9. The lateral strength for the different SPSW declines at almost the same level as axial compression ratio improves. Compared to the stiffened SPSWs, the initial stiffness of the unstiffened SPSW exhibits apparent decline. The three kinds of stiffened models all keep a relatively high initial stiffness, the curves when the drift is not so large are almost overlapped, but the decline occurs earlier as the axial compression ratio increases. Meanwhile, the remarkable turning point in the curve of stiffened models fade away with the increase of the axial compression ratio, in other way, the decline of the stiffness becomes more homogeneous. The reason is that with the increase of the axial compression ratio, the elastic buckling gradually turn into inelastic buckling. It means that the material nonlinearity and the geometrical nonlinearity exhibit together.



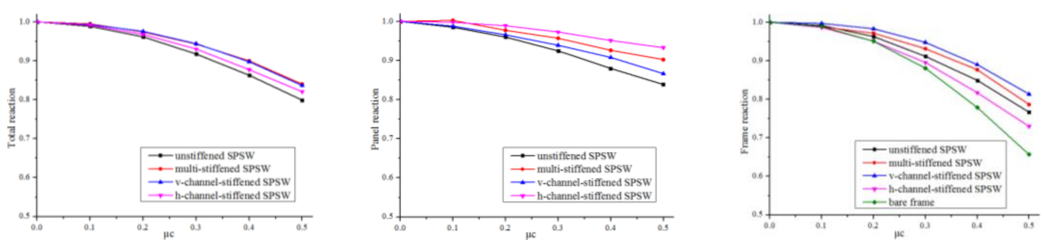
(a) Unstiffened SPSW (b) Multi-stiffened SPSW

(c) V-channel-stiffened SPSW (d) H-channel-stiffened SPSW

Figure 9: Lateral load-drift curves of different SPSWs considering the vertical load

The shear strength variation trend as the axial compression ratio increases is shown in Fig. 10. The structure systemic bearing capacity uniformly declines as axial compression ratio increase in Fig. 10(a). The decline amplitude of SPSW in descending order is unstiffened SPSW, horizontal channel stiffened SPSW, vertical channel stiffened SPSW and multi-stiffened SPSW at the same axial compression ratio. It can be noted that the panel strength curve variation trend (see Fig. 10(b)) is not the same with the structure systemic strength. The decline amplitude of SPSWs varies greater, with the descending order is unstiffened SPSW, vertical channel stiffened SPSW, multi-stiffened SPSW, and horizontal channel stiffened SPSW. The decline amplitude of frame shear capacity strength showed in Fig. 10(c) is large, with the decline value of all models is larger than 20% at 0.5 axial compression ratio. For the positive effect of infill panel on the frame, the decline amplitude for pure frame is largest among all the model, with the shear strength declines 35% at 0.5 axial compression ratio.

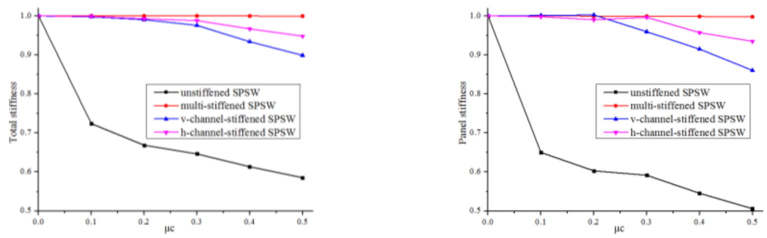
Comparing the three figures in Fig. 10, the systemic strength of vertical channel stiffened SPSW is better than horizontal channel stiffened SPSW, for the vertical channel stiffened infill panel bears more vertical load and impaction of vertical load on the SPSW frame is smaller. The infill panel with horizontal channel stiffeners isn't badly affected by the vertical load but the large part of vertical load decrease the strength of SPSW frame evidently. Taken these together, the systemic strength of horizontal channel stiffened SPSW is not as well as vertical channel stiffened one. Due to the stiffeners are more easily to deform for multi stiffened SPSW, the strength of multi-stiffened SPSW doesn't show more advantages compared with vertical channel stiffened SPSW with consideration of vertical load. As for unstiffened SPSW, the systemic shear strength decline is the largest for the large vertical load impaction on inner panel and frame.



(a) SPSW reaction (b) Infill panel reaction (c) Frame reaction

Figure 10: Influence of vertical load on the lateral strength of different models

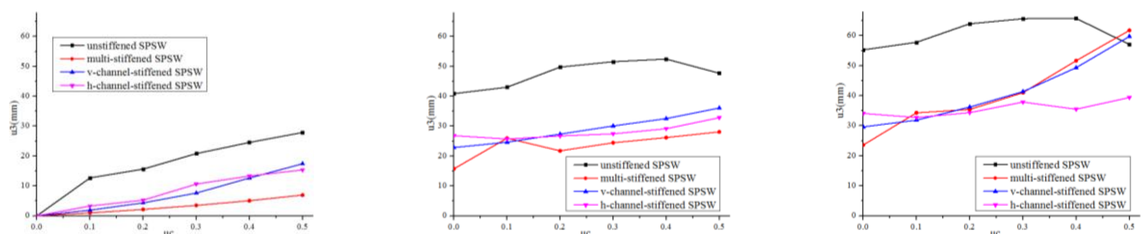
From initial stiffness curves in Fig. 11, it can be seen that the total initial stiffness curve variation trend is similar to the infill panel initial stiffness curve and the vertical load impaction on inner panel initial stiffness is slightly larger than that of the system. Compared to unstiffened SPSW, vertical load impaction on stiffened SPSW stiffness is much smaller. The initial stiffness decline amplitude for system and panel of unstiffened SPSW are separately 27% and 35% at 0.1 axial compression ratio, while the initial stiffness decline amplitude of stiffened SPSW is smaller than 1%, significantly lower than that of unstiffened SPSW; the initial stiffness of multi stiffened SPSW declines little as the axial compression grows and it can be noted that the decline amplitude is smaller than 1% at 0.5 axial compression ratio. Compared to horizontal channel SPSW, vertical channel SPSW decline amplitude is larger, and the decrease degree for infill panel is slightly larger than that of the system. The infill panel for vertical channel SPSW bears more vertical load than horizontal channel SPSW, thus the initial stiffness of vertical channel SPSW declines more. And when it comes to the frame columns, the horizontal channel stiffeners supply larger side compression stiffness than that of vertical stiffeners. The horizontal channel SPSW has some advantages over vertical channel SPSW under vertical load in terms of initial stiffness.



(a) SPSW stiffness (b) Infill panel stiffness

Figure 11: Influence of vertical load on the initial stiffness of different models

From Fig. 12, it can be seen that the out-of-plane displacement for unstiffened SPSW is larger than that of the other three kinds of stiffened SPSW under the vertical load. The restriction of out-of-plane displacement of multi-stiffened SPSW is the most effective and effectiveness of vertical and horizontal channel stiffened SPSW is similar, which has almost the same out-of-plane displacement. For lateral load analysis with vertical load, the advantage of multi-stiffened SPSW would fade away as lateral displacement increases. This phenomenon occurs due to material yielding of the stiffener itself as the vertical load and lateral load becomes large. Because of the larger load percent withstood by the vertical channel SPSW, the restraint effectiveness of vertical arranged channel is smaller than that of horizontal arranged channel, which can be noted that the vertical arranged channel occurs material yielding with large out-of-plane deformation.



(a) O.o.p disp.(after vertical load) (b) O.o.p disp.(drift=1%) (c) O.o.p disp.(drift=2%)

Figure 12: Influence of vertical load on the out-of-plane displacement of different models

5. Conclusions

Application of unstiffened thin SPSWs is limited due to the early buckling in China, and application of stiffeners has been shown in a number of studies to improve the behavior of unstiffened SPSWs. However, for efficient design and prevalent use of stiffened systems, further research work is still required to balance between structural demands and economical considerations. And due to the construction requirements, the SPSWs would bear some vertical loads, which was barely considered in existing research. On this basis, the elastic and inelastic behavior of single-bay and single-story framed steel plate shear walls with unstiffened and stiffened thin infill plates with and without vertical loads were studied to investigate the efficiency of the stiffeners. The findings obtained in the present study are summarized as follows.

(1) The load-carrying mode of infill panel of SPSWs has classified to shear load-carrying mode and tension field load-carrying mode. The slender infill panels like unstiffened thin SPSW is occupied in the tension field load-carrying mode, while the stocky one like heavily stiffened SPSW is occupied in the shear load-carrying mode. These two modes has only a little effect on the ultimate lateral strength, but evident influence on the stiffness and out-of-plane displacement.

(2) Unstiffened and stiffened models with normal frames are all behaved reasonably even though local buckling of the unstiffened panel occurred at the early loading stage. The failure of these SPSWs occurred at the column base after the panel's full yielding.

(3) When the normal-framed SPSWs reach their design shear capacity V_n, the stiffeners increase the lateral stiffness of the system, and reduce the out-of-plane displacement, which improves serviceability of the system greatly. And the stiffeners also increase the percentage of panel reaction which increase the effectiveness of infill steel panel in this system thus lead to a more economic and reasonable design of SPSWs.

(4) Less channel stiffeners which has higher stiffness of bending and torsion compared with more flat stiffeners can constraint the infill panel more effectively. And the flat stiffeners themselves are easy to deflect especially considering the vertical loads. And compared with bidirectional flat stiffeners, less unidirectional channel stiffeners not only can receive outstanding performance but also can lead to convenient and economic construction. So the channel stiffened SPSWs was recommend to be used in engineering practice.

(5) The channel stiffeners can effectively increase the effectiveness of infill steel panel in the SPSW system significantly. Another important advantage is that the stiffeners decrease the out-of-plane displacement obviously.

(6) When considering the vertical load, the vertical arranged stiffened SPSW shows better buckling stability than that the horizontal stiffened SPSW. The quantity of vertical stiffeners in the design should be arranged according to the vertical load and the needed buckling load, and the vertical load should be smaller than half of the vertical buckling strength $P_{cr,V}$.

(7) Although the vertical arranged stiffened SPSW shows better buckling stability, but due to bearing more vertical loads, the stiffener's requirements are higher than horizontal stiffeners, this shouldn't be ignored in the design.

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