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Effects of stiffeners on steel panel and boundary elements of steel plate shear wall system

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Abstract
Un-stiffened steel plate shear walls, also called special plate shear walls (SPSWs), are getting more and more widely used in North America. The current seismic design code allows the steel wall to buckle under relatively low lateral loads, and relies on yielding of the diagonal tension fields developed in the wall and the associated wall post-buckling strength to provide the required shear strength. In many cases, elastic buckling of the un-stiffened wall plate might be unavoidable, since it is so slender.

In order to avoid wall buckling, many steel plate shear walls in Japan are heavily stiffened so that shear yielding capacity of the wall could be achieved instead of relying on the post-buckling strength from the tension field action. These systems are deemed uneconomical in North America, due to the high labor cost associated with adding stiffeners compared to the limited increase in the wall shear strength. However, there might be other important benefits associated with stiffened steel plate shear walls and a more cost-effectively pattern to add stiffeners. In this paper, linear and nonlinear analyses were conducted on un-stiffened and stiffened steel plate shear walls and performance of the wall panel as well as the boundary members were compared. It turned out that in the stiffened steel plate shear walls, the internal forces induced in the boundary columns were significantly reduced, when the system developed its shear strength, which therefore reduced the required column section for seismic design and the associated costs. In addition, a new type of stiffened steel plate shear wall system was proposed, in which sparsely-spaced channel stiffeners were used instead of closely-spaced plates, thus reducing the number of stiffeners in each bay and the fabrication cost.

1. Introduction
Steel plate shear wall system, which is composed of 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 loads and thus loss part of the capacity and stiffness. In Japan and some European countries, steel plate shear wall are heavily stiffened to postpone or even prevent the elastic buckling. In United States, however, steel plate shear walls are usually un-stiffened due to the high labor cost associated with adding stiffeners, which are called special

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plate shear walls (SPSWs). 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.
In past decades, most of the research work about stiffeners was focused on the stiffener effect on elastic buckling prevention and how the appropriately designed stiffeners postpone the steel panel elastic buckling, but not on the inelastic range or boundary elements. However, in practical design work, engineers do not care much about the elastic buckling stress, since the early elastic buckling does not significantly reduce the ultimate capacity of steel plate shear wall system [2]. On the other hand, engineers care a lot about the resultant forces in boundary elements, since high resultant force would greatly increase the section requirements of boundary beams and columns.

In the past, most of the research on stiffened steel plate shear wall was focused on the effects of stiffeners on prevention and postpone of elastic buckling of the wall panel (Saeid Sabouri-Ghomi at al, 2008; Alinia, 2006; Pavlovcic, 2006; Grondin and Elwi, 1999; Paik and Seo, 2009; Choi et al, 2009), while not much emphasis has been placed on the inelastic behavior of stiffened steel plate shear wall systems. However, elastic buckling of the wall panel is not much of a concern in the current seismic design of SPSWs in U.S., since it will not reduce the ultimate shear capacity very much, which in many cases is considered very high anyway. On the other hand, when the SPSW system is under large shear forces and enter the inelastic region, the anchoring forces required for the successful development of the tension field action in the steel wall panel are usually very large, which in many cases results in large sections of the boundary columns, also called vertical boundary elements (VBEs), and accordingly increase construction costs.

Therefore, it is meaningful to investigate both the elastic behavior and the inelastic behavior of stiffened steel plate shear walls, with emphasis on the behavior of the boundary elements as well as the wall panels. In this paper, elastic and inelastic analysis were conducted on models of the un-stiffened steel plate shear wall as well as the steel plates shear wall with various type of stiffeners, and the results were compared to identify the optimum performance. A new type of stiffened steel plate shear wall system with sparsely-spaced channel stiffeners was proposed based on the analysis results.

2. Analytical work

The nonlinear finite element software ABAQUS is utilized to perform elastic buckling and nonlinear push-over analysis. Elastic buckling analysis is firstly conducted to obtain the buckled shape, based on which initial imperfection is applied to the steel panel in the following nonlinear static push-over analysis.

The un-stiffened steel plate shear wall is built first and composed of an infill steel panel, with the dimensions 84in (height) x 71.7in (width) x 3/16in (thickness), and boundary columns (VBEs) are W12x72 at both sides, as shown in Fig. 1. The stiffened steel plate shear wall is built with the same dimension and stiffeners on one side of the steel panel. Various types and orientations of stiffeners are investigated. Stiffeners are designed to fulfill the minimum required moment of inertia. There is a 1 inch gap at each side of the stiffener to allow the relative deflection between steel panel and stiffeners, and also for the convenience of fabrication. The steel panel, boundary columns, and stiffeners are all modeled using S4R elements, which are the four nodes shell elements with reduced integration.

Figure 1: Un-stiffened steel plate shear wall and stiffened steel plate shear wall

The infill steel panel and stiffeners made of ASTM-A36 structural steel while the boundary columns are made of ASTM-A992 structural steel. The elasto-plastic stress strain relation is used to define the constitutive behavior for both materials with the elastic modulus E=29000 ksi and poison's ratio υ=0.3. The yield stresses are 36 ksi and 50 ksi for A36 and A992 materials respectively and the von-Mises criteria is used to define the yielding of steel panel and columns.

In the elastic buckling analysis, only the steel panel is modeled in order to compare with theoretical results. All four edges of the steel panel are simply supported, and uniformly distributed shear force is applied at the edges of steel panel.

In the nonlinear static push-over analysis, the three-direction translations at the base edge of infill panel and boundary columns are restrained, as well as the rotation to the vertical direction. Considering the floor slabs, the out of plane displacements at the top edges of infill panel and boundary columns are also restrained. A reference point is generated in each model, and it is coupled to the top edges of both infill steel panel and boundary columns. Then, a displacement boundary condition is applied at the reference point, and the system would be pushed until the desired lateral drift, which is 1% drift in this paper.

3. Discussion of results

3.1 Elastic buckling load

The elastic critical buckling loads are generally obtained by three methods, which are the theoretical method, eigenvalue method through elastic buckling analysis and the nonlinear push-over analysis method. In this part, the elastic buckling loads are obtained using all of the three methods, and compared with each other.

Theoretical elastic buckling load

H.G. Allen summarized the equations to calculate the elastic buckling stress for both un-stiffened and stiffened steel panels under uniformly distributed shear loads and simply supported boundary conditions in all edges. To calculate the elastic buckling stress of un-stiffened rectangular plates, the following equations are widely used:

$$\tau_{cr} = \frac{K\pi^2 E}{12(1-\upsilon^2)}(\frac{t}{b})^2$$

where K is the local buckling factor obtained by the following equation, E is the elastic modulus which is 29000ksi for steel, υ is the poison's ratio which equals 0.3, t is the thickness of steel panel, and *b* is the width of steel panel.

For plates with all edges simply supported:

$$K = 5.34 + \frac{4}{\phi^2} \quad \text{For } \phi \geq 1$$

where φ is the ratio between height and width of steel panel, whichever is larger. The elastic critical buckling loads based on the previous equations are shown in Table 1.

Table 1: Comparison of elastic buckling load

	Critical Shear Force (kips)		
	Theoretical	Elastic Buckling Analysis	Nonlinear Push-over Analysis
Un-stiffened	19.19	19.59	19.60
H-stiffened	105.33	108.72	113.56
V-stiffened	133.65	134.75	148.21
Both stiffened	208.47	210.68	203.14

Elastic buckling load by elastic buckling analysis

The critical shear force is also obtained by elastic buckling analysis using ABAQUS for steel panel with only uniformly distributed shear forces on all edges, as stated in section 2. Through elastic buckling analysis, ABAQUS would calculate the eigenvalue for buckling shapes, and the elastic buckling load should be obtained by multiplying eigenvalue and the applied external force. The elastic buckling loads obtained by elastic buckling analysis are also shown in Table 1.

Since the imperfection during fabrication process is non-avoidable, it should be included into the nonlinear push-over analysis. In the present work, the initial imperfection was applied onto the steel panel based on the first buckling mode, and the magnitude was taken as 0.2% of the height of steel panel.

Elastic buckling load by nonlinear analysis

The nonlinear push-over analysis is also performed to obtain the elastic buckling load. During the lateral loading procedure, the principle tensile and compressive stress will develop, and the infill steel panel experiences elastic deformation under relatively low lateral load. With the increase of loading, when the principle compressive stress exceeds the critical stress, the infill steel panel buckles elastically. When elastic buckling occurs, the maximum out of plane deflection of steel panel increases suddenly, and this would be the criterion to define the elastic buckling during nonlinear push-over analysis. In Fig. 2, the maximum out of plane displacement of steel panel is plotted against the lateral drift. It is obvious that stiffeners postpone the elastic buckling of steel panel, therefore increase the elastic buckling load. However, diffenent stiffener configurations are with various effectiveness. Steel panels with stiffeners in both directions increase the elastic buckling loads the most, while channel stiffeners also restrict the out of plane deflection the most after elastic buckling. The base shear force corresponding to elastic buckling points are also shown in Table 1.

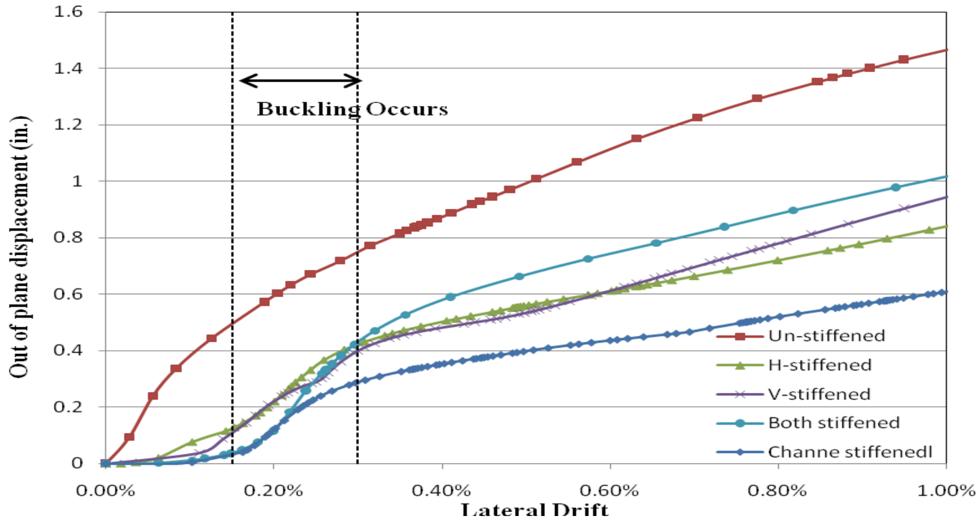

Figure 2: Out of plane deflection with respect to lateral drift

3.2 Lateral Resisting from Nonlinear pushover

After elastic buckling, steel plates behave geometrically nonlinear and the system experiences an obvious loss of stiffness (Fig. 3). Due to the development of diagonal tension field, infill plates can carry additional loading and post-buckling deformations continuously until localized yield points occur within the plate. After that, the yielding areas spread onto the whole panel, until the steel panel reaches its design capacity V_n, diagonal yield zones are formed, and frame members yield gradually and finally reach the ultimate lateral deflection. During this procedure, stiffeners are expected to restrict the local buckling into sub-panels between stiffeners from forming the global buckling, and postpone the spreading of yield zone onto the whole panel, therefore both increasing the design capacity and ultimate capacity of steel plate shear wall systems.

As shown in Table 2 and 3, at the V_n and ultimate stage, 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 serviceability. It is also shown in Table 2 and 3 that for different stiffener combinations, the effect on increasing the design capacity and ultimate capacity are similar, with the increasing rates on design capacity ranging from 13% to 21%, and on the ultimate capacity ranging from 10% to 15%. As to the out of plane deflections, stiffeners decrease them at design capacity from 55% to 61% and at ultimate capacity from 23% to 43%. It is worth to mention that even all stiffener combinations increase the design capacity and ultimate capacity and decrease the out of plane deflection, both stiffened steel panel does not always increase capacity and decrease the out of plane deflection the most, therefore, from both economical and effective considerations, bi-directional stiffened steel panel is not a good choice compared with uni-directional stiffened steel panel.

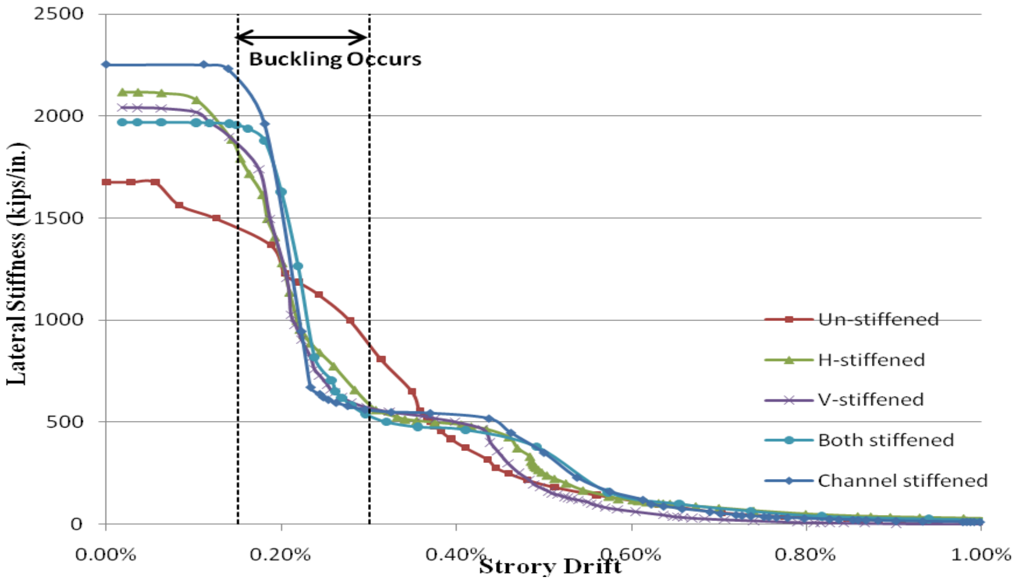

Figure 3: Lateral stiffness with respect to lateral drift

As shown in Table 2 and 3, at the V_n and ultimate stage, 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 serviceability. It is also shown in Fig. 4 that for different stiffener combinations, the effect on increasing the design capacity and ultimate capacity are similar, with the increasing rates on design capacity ranging from 13% to 21%, and on the ultimate capacity ranging from 10% to 15%. As to the out of plane deflections, stiffeners decrease them at design capacity from 55% to 61% and at ultimate capacity from 23% to 43%. It is worth to mention that even all stiffener combinations increase the design capacity and ultimate capacity and decrease the out of plane deflection, both stiffened steel panel does not always increase capacity and decrease the out of plane deflection the most, therefore, from both economical and effective considerations, bi-directional stiffened steel panel is not a good choice compared with uni-directional stiffened steel panel.

Table 2: Steel panel property at design capacity V_n

	Un-stiffened Wall	Wall and Horizontal Stiffener	Wall and Vertical Stiffener	Wall and Both Stiffener	Wall and Channel Stiffener
Force (kips)	195.6	221.7	227.6	237.5	228.7
Stiffness (k/in.)	667	1015	1022	1079	1111
Lateral Drift (%)	0.349	0.260	0.265	0.262	0.245
O.O.P Disp.(in)	0.8154	0.3662	0.3214	0.3324	0.2258

Table 3. Steel panel property at ultimate capacity (1.0% drift)

	Un-stiffened Wall	Wall and Horizontal Stiffener	Wall and Vertical Stiffener	Wall and Both Stiffener	Wall and Channel Stiffener
Force (kips)	233.3	268.6	257.1	269.1	263.1
Stiffness (k/in.)	N.A	N.A	N.A	N.A	N.A
Lateral Drift (%)	1.010	1.030	1.016	1.062	1.010
O.O.P Disp.(in)	1.4740	0.8433	0.9570	1.1297	0.6135

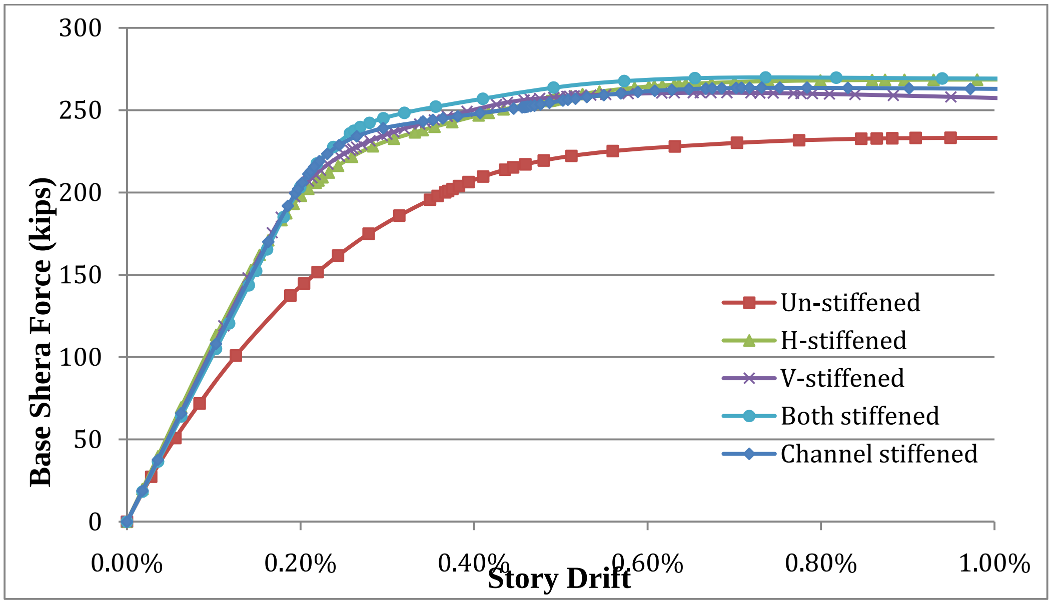

Figure 4: Base shear force on steel panel with respect to story drift

3.3 Effect of channel stiffeners

Stiffeners are effective in reducing out of plane displacement and increase the lateral stiffness; this is mainly because the stiffeners with adequate flexural stiffness could prevent the global buckling of steel plate, and force the local buckling into sub-panels. However, the flat stiffeners have relatively small flexural stiffness and second moment of area, therefore less resistant to global buckling of steel panels. 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. In addition, compared with both directional stiffeners, channel stiffeners would cost less in welding procedure. Therefore, in this paper, the channel stiffeners, with the section MC8x20, are analyzed and compared with other stiffener types to see the effectiveness in resisting global buckling, out of plane displacement and in increasing lateral stiffness and reducing resultant force in boundary columns.

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. In Fig. 3, the lateral stiffness of steel plate shear wall system with channel stiffeners is compared with that of un-stiffened and both stiffened steel plate shear wall systems. Channel stiffener increases lateral stiffness by around 30% compared with un-stiffened steel panel, and also more than the both stiffened case.

In addition to the lateral stiffness, channel stiffeners also increase the ultimate capacity of the steel panels the similar amount compared with other stiffener types, as also shown in Fig. 4. As to the out of plane deflection, it is obvious in Fig. 2 that at the same lateral drift, channel stiffened steel panel has the least out of plane deflection, which means that the channel stiffened steel panel buckles after bi-directional stiffened case. Besides, after buckling, the out of plane deflection in both stiffened steel panel increase suddenly, while the deflection in channel stiffened steel panel keeps the least compared with all other models.

3.4 Behavior of boundary columns in nonlinear pushover

During lateral loading procedure, bending moments, axial, and shear forces are generated along the boundary columns (VBEs), which are criteria for practical design work. In previous research work, researchers are mainly focused on the stiffener effects on steel panel or steel plate shear wall systems, seldom of research is related to the effects on VBEs. However, in current steel plate shear wall designs, boundary columns are usually with large sections because of large resultant forces. For instance, in un-stiffened steel plate shear walls, the obvious tension field action is formed across the whole panel, resulting in large tensile forces at diagonal corners. Furthermore, large axial and shear forces and bending moments are formed at the boundary columns. Therefore, the effective reduction of resultant forces on boundary columns would allow engineers to design the VBEs using smaller sections. Stiffeners with enough flexural moment of inertia are to divide the whole steel plate into sub-panels, cut the diagonal tension field across the whole panel, and are finally expected to reduce the resulting forces in VBEs. However, the different stiffener types also have different influence on VBEs.

In the present work, the bending moments, axial and shear forces on boundary columns are studied and compared with respect to the height of column, and the comparison for left and right columns are depicted in Fig. 5 and Fig. 6.

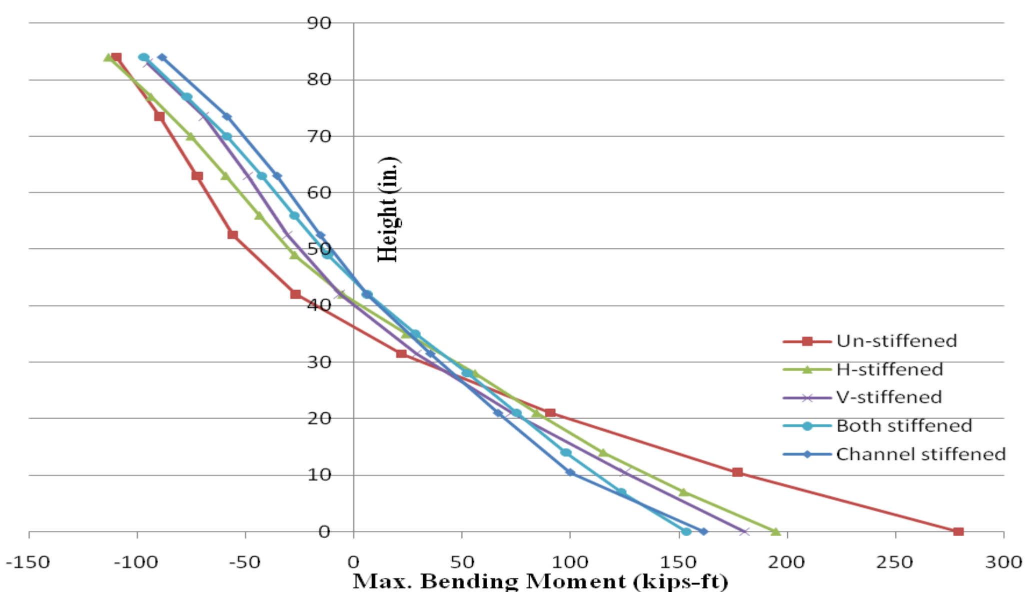

Figure 5: Maximum bending moments on left column at design capacity

For the un-stiffened steel panel at design capacity V_n, in left VBE, the maximum moments occur at the column base, which is evidence that the diagonal tension field action generates a large tensile force across the whole panel, and the force is transferred onto the left anchor, therefore the large bending moments are induced. On the other hand, on right VBE, the diagonal tensile forces are applied at the top of columns; therefore the maximum bending moments happen at the top of right columns. However, in stiffened steel panels, the stiffeners would force the buckling into sub-panels and the tension field would not occur on the whole panel, but restricted into sub-panels. Therefore, instead of the tension field action in the whole panel with large tensile forces, tension field in stiffened panels would occur in sub-panels, with smaller tensile forces, and furthermore would reduce the resultant forces in boundary columns.

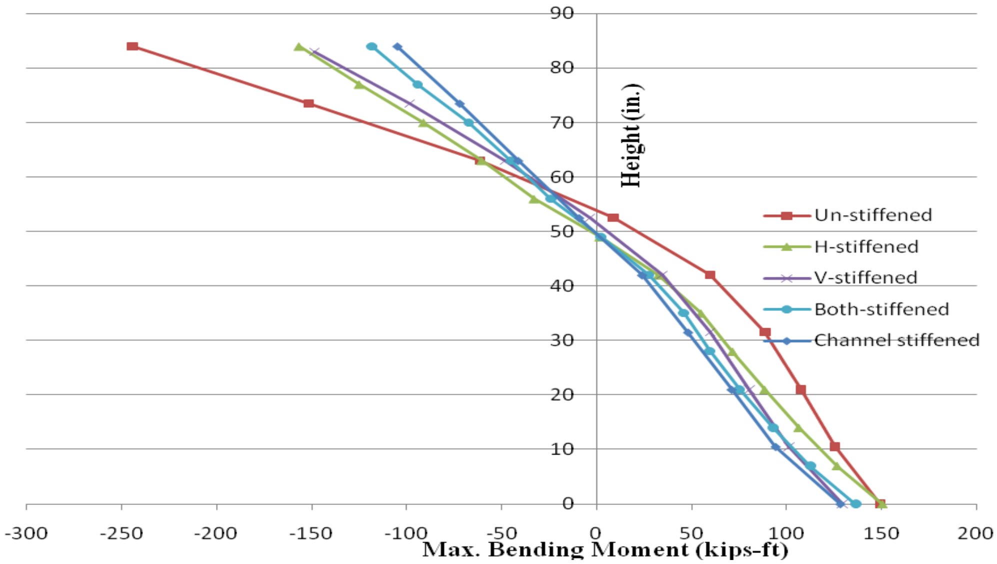

Figure 6: Maximum bending moments on right column at design capacity

In Table 4, the influence of stiffener types on maximum bending moments in VBEs is compared. In this table, it is obvious that the magnitudes that stiffeners reduce the bending moment in columns are different. Both stiffened and channel stiffened steel panels reduce the maximum bending moments for around 50% in both columns. However, both directional stiffeners are not economical as discussed before. Channel stiffeners, on the other hand, have two flanges welded to steel panel, therefore two nodal constraints. Because of the two nodal constraints, the steel panel parts between channel flanges would have less buckling happened compared with other areas, and has small but more tension fields compared with un-stiffened steel panels. Since the tension field zone acting on VBEs are with smaller value, the resultant forces are expected to be smaller than in un-stiffened panels.

Table 4: Bending moments comparison in columns at design capacity V_n

	Left column		Right column	
	Max. Moment (k-ft)	% Diff. with Un-stiffened	Max. Moment (k-ft)	% Diff. with Un-stiffened
Un-stiffened	279	0%	244	0%
H-stiffened	194	-30%	156	-36%
V-stiffened	180	-35%	149	-39%
Both stiffened	154	-45%	118	-52%
Channel stiffened	145	-48%	128	-48%

In design practice, the bending moments and axial forces would act together in VBEs, and the interaction of these two values would define the acceptable scope of column sections. In Table 5, the maximum axial forces are compared, and used to draw the P-M interaction curve together with the maximum bending moments shown in Table 4. The stiffener effects on axial forces in VBEs are different with the effects on bending moments, with the axial forces in left columns increased and in right columns decreased.

Table 5: Axial forces comparison in columns at design capacity 1.0% drift

	Left column		Right column	
	Max. Axial Force (kips)	% Diff. with Un-stiffened	Max. Axial Force (kips)	% Diff. with Un-stiffened
Un-stiffened	305	0%	447	0%
H-stiffened	310	2%	380	-15%
V-stiffened	335	10%	370	-17%
Both stiffened	381	25%	396	-11%
Channel stiffened	376	23%	380	-15%

The P-M interaction curves are drew here in Figs. 7 and 8 to show the design practice. The P-M values are taken from Tables 4 and 5, and compared with the column section W12x72. This section is capable to resist all resultant forces for both un-stiffened and stiffened models. However, with the using of stiffeners, the resultant forces in left columns are reduced and a smaller section, which is W12x58, would be enough to resist the resultant forces in left columns.

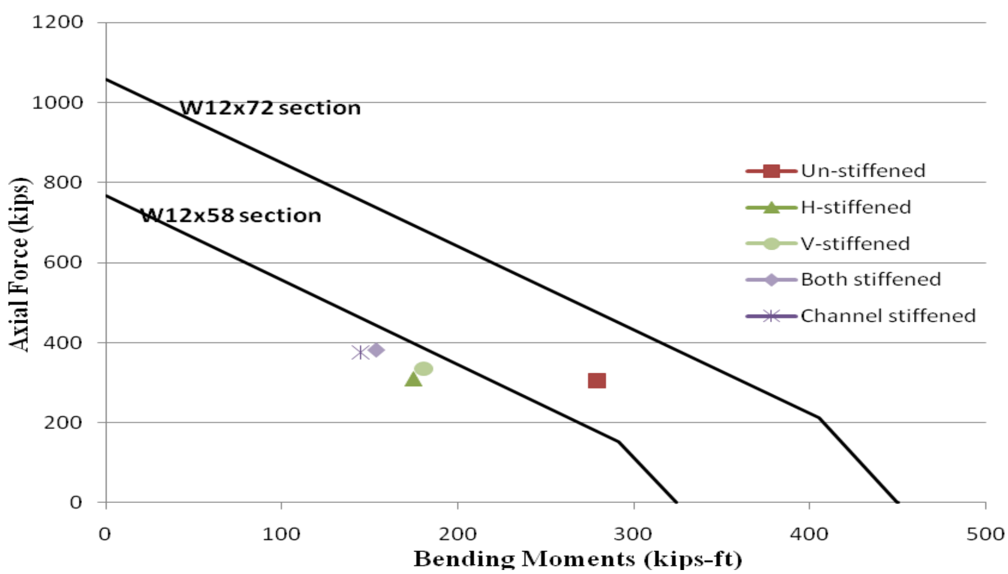

Figure 7: P-M interaction of left column at design capacity Vn

The same condition happens in the right column as shown in Fig. 8, in which the W12x72 column section must be used to resist forces in un-stiffened steel plate shear wall, while the smaller section, W12x58 section, could be used for all the stiffened steel plate shear walls.

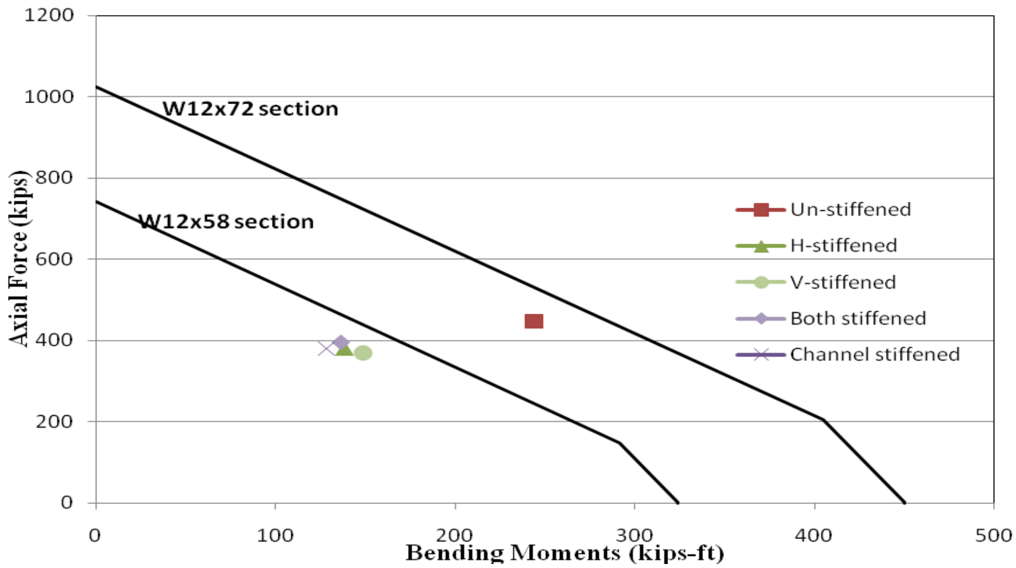

Figure 8: P-M interaction of right column at design capacity V_n

4. Conclusions

(1) When the systems reach their design shear capacity Vn, all stiffeners increase the lateral stiffness of the system by the maximum value of 28%, and reduce the out of plane displacement by the maximum of 61%, which improves serviceability of the system greatly.

(2) The ultimate shear capacity of stiffened steel plate shear walls is increased by as much as 15% compared with un-stiffened steel plate shear wall.

(3) A new type of channel stiffener is introduced in this paper, which provides two lines of nodal constraints instead of only one, and therefore restrains buckling of the steel wall panel more effectively with less materials and welding work.

(4) The usage of stiffeners could successfully force the tension field to develop inside the sub-panels instead of across the whole panel, and reduce the resultant forces on VBEs. Channel stiffeners and plate stiffeners in both directions are the two most effective ways in reducing resultant forces on VBEs, while channel stiffeners are more economical.

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