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Modified PFI model for SPSWs with moderate and stocky LYP steel infill plates

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Abstract

Steel plate shear walls have been used as a lateral force-resisting system in design of various buildings to resist both wind and earthquake loads. Current practice in the United States and Canada is to use unstiffened slender-web steel plate shear walls, which buckle at very low loads and the resistance of the panel is dominated by tension field action in post-buckling stage. However, the premature buckling of slender plates may pose serviceability problems and also result in reduced structural and seismic performance. Application of low yield point (LYP) steel in shear walls allows the employment of moderate and/or stocky infill plates with low yielding and high buckling capacities, which can result in enhanced buckling stability, serviceability, and energy dissipation capacity of such systems. Hence, it is important to be able to predict and characterize the structural behavior of such stiffening and damping systems via simple approaches. This paper addresses this need by providing a slightly-modified plate-frame interaction model for steel shear walls with moderate and stocky infill plates. The limiting thicknesses corresponding to simultaneous buckling and yielding of moderate infill plates are primarily determined via theoretical and numerical approaches, and the effectiveness of the modified analytical method is evaluated through comparison with both experimental and numerical results. It is demonstrated that the modified plate-frame interaction model is able to properly represent the structural behavior of moderate- and stocky-web steel shear walls, which can be effectively used in design of such systems.

1. Introduction

Steel plate shear walls (SPSWs) have been used as an efficient lateral force-resisting system in new and retrofit construction. By far, the most popular type in North America is the unstiffened slender-web SPSW system, which typically experiences shear buckling at low levels of loading and the lateral loads are mainly resisted through diagonal tension in the web plate (Sabelli and Bruneau 2006). Depending on the design philosophy, the infill plates can be either stiffened or

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unstiffened; however, labor costs in North America indicate that unstiffened panels are preferable (Kulak et al. 2001).

The premature shear buckling of the thin plates in SPSWs usually results in reduced strength, stiffness, and energy dissipation capacity. Although the tension field action is able to provide the post-buckling strength, however if the shear buckling occurred in the early stage, out-of-plane permanent deformation may affect the serviceability of the thin-plate shear wall under small or moderate earthquake (Chen and Jhang 2011). The common practice to improve the buckling stability and to prevent early elastic buckling of infill plates is to increase the web thickness, or to use horizontal and vertical plate stiffeners to force the buckling of the infill plate from a global buckling mode to a localized buckling in the sub-panels (Sabouri-Ghomi et al. 2008). Nonetheless, it is noted that stiffened web plate is not typically as economical as the unstiffened type.

Application of LYP steel, developed by Nippon Steel Corporation in Japan (Yamaguchi et al. 1998), with extremely low yield stress and high elongation capacity is deemed to be a superior alternative compared to using the conventional steel for infill plates. This may not only improve the buckling stability and serviceability, but also considerably enhance the energy absorption capacity of SPSW systems. In addition, with lower yielding strength of the steel plate in SPSW systems, it is easier to design the system to let the shear wall yield prior to that of the surrounding frame and to ensure that the frame would not collapse before the wall reaches its ultimate strength (Chen and Jhang 2006). It is notable that material yielding of the LYP steel infill plates may occur in advance of the geometrical buckling due to low yield stress of this steel material. Hence, accurate assessment of buckling and yielding behavior of LYP steel shear walls can result in effective design of such stiffening and damping systems.

Considering the potential high structural and hysteretic performance of LYP steel shear walls, which have been demonstrated in a number of studies, e.g. Bruneau and Bhagwagar (2002), De Matteis et al. (2003), Tsai and Lin (2005), and Chen and Jhang (2006 and 2011), accurate characterization of behavior of such systems with early yielding and post-yield inelastic buckling characteristics can facilitate the analysis and design of such efficient structural elements. On this basis, this paper provides a slightly-modified version of the well-known plate-frame interaction (PFI) model, originally developed by Sabouri-Ghomi et al. (2005), for predicting the structural behavior of SPSWs with low yielding and high buckling capacities. The effectiveness of the modified analytical model is evaluated by comparing the predicted response with both experimental and numerical results.

2. Classification of plates and determination of the limiting plate thickness

Material yielding of the steel plates may occur either before or after or even at the same time as geometrical buckling depending on their slenderness and material properties. Hence, steel plates, in general, may be qualitatively and quantitatively classified as slender, moderate, and stocky based on their slenderness parameter as well as geometrical-material bifurcation characteristics (Gheitasi and Alinia 2010). Slender plates undergo early elastic buckling and subsequently yield in the post-buckling stage. Moderate plates, on the other hand, undergo simultaneous buckling and yielding, while stocky plates yield first and then undergo post-yield inelastic buckling. Based on such classification, accurate determination of the limiting plate thickness corresponding to concurrent geometrical-material bifurcation can serve as an effective criterion in efficient design of LYP steel shear wall systems.

The limiting plate thicknesses of the SPSWs ($t_{p\text{-}limit}$ or t_{p-SPSW}) may be determined by assuming clamped support condition. On this basis, the limiting thickness can be obtained using Eq. (1), which is derived by setting the critical shear stress (τ_{cr}) of a rectangular clamped plate, as discussed in Timoshenko and Gere (1961), equal to the plate shear yield stress ($\tau_{yp} = \sigma_{yp} / \sqrt{3}$) determined by considering the von Mises yield criterion.

$$t_{p\text{-}limit}(= t_{p-SPSW}) = b \times \sqrt{\frac{12 \times (1 - v^2) \times \sigma_{yp}}{(8.98 + 5.6 / (a/b)^2) \times \pi^2 \times E \times \sqrt{3}}} \tag{1}$$

In the above equation, E and v are Young's modulus and Poisson's ratio, respectively, and σ_{yp} is the plate yield stress. Moreover, a and b are taken as the respective maximum and minimum values of length and height of the infill plate.

Alternatively, the following linear interpolation equation, i.e. Eq. (2), may also be used for determining the limiting plate thickness, which accounts for the real edge support conditions of infill plates in SPSWs by using the buckling loads of the infill plates as well as considering the simple and clamped support conditions.

$$t_{p\text{-}SPSW} = t_{p-SS} - \frac{(t_{p-SS} - t_{p-Cl}) \times (P_{cr-SPSW} - P_{cr-SS})}{P_{cr-Cl} - P_{cr-SS}} \tag{2}$$

In Eq. (2), t_{p-SS} and t_{p-Cl} are the respective limiting plate thicknesses corresponding to simple and clamped support conditions which are determined by setting $\tau_{cr} = \tau_{yp}$, and also P_{cr-SS} and P_{cr-Cl} are the respective theoretically-determined critical buckling loads for simple and clamped support conditions. $P_{cr-SPSW}$ is the critical buckling load of SPSW model which can be obtained through linear eigen buckling analysis.

The accuracy of predictions of the two aforementioned equations is verified by evaluating the finite element analysis results discussed in the subsequent sections.

3. SPSW models and finite element analysis

Two full-scale and code-designed SPSW models, i.e. SPSW1 and SPSW2, with 3000×3000 mm moderate and stocky LYP steel infill plates are developed and analyzed numerically for the purpose of this study. The limiting thickness of the 3000×3000 mm moderate infill plate, i.e. $t_{p\text{-}limit}$ = 14.0 mm, is determined using Eq. (1). In addition, boundary frame members of SPSW1 and SPSW2 models are designed in accordance with the AISC 341-10 (2010) stiffness and strength requirements. Specifications of the full-scale and code-designed SPSW models are provided in Table 1, in which l, h, and t_p are the length, height, and thickness of the infill plate, respectively.

Table 1: Specifications of the full-scale and code-designed SPSW models

Model	Infill Plate		HBE	VBE	Design Steel Type	
	$l \times h \times t_p$ (mm)	Type	(Beam)	(Column)	Frame	Plate
SPSW1	3000×3000×14.0	Moderate	W14×311	W14×342	ASTM A572 Gr. 50	LYP100
SPSW2	3000×3000×18.7	Stocky	W14×398	W14×426	ASTM A572 Gr. 50	LYP100

Finite element analysis software, ANSYS 11.0 (2007), is utilized in this study to develop and analyze SPSWs under monotonic and cyclic loadings. Boundary frame members as well as infill plates of the steel shear walls are modeled by Shell181 element. This four-node element with six degrees of freedom at each node is suitable for analyzing thin to moderately-thick shell structures and is also well-suited for linear, large rotation, and/or large strain nonlinear applications. The modeling details of a typical full-scale SPSW system with 3000×3000 mm infill plate are illustrated in Fig. 1. As seen in the figure, both columns are fully fixed at their bases and the exterior nodes of the column flange and stiffener elements around the perimeter of the panel zones are restrained against out-of-plane displacement.

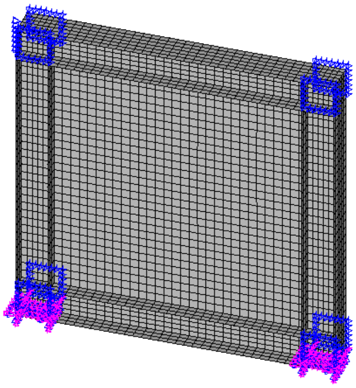


Figure 1: Typical SPSW model

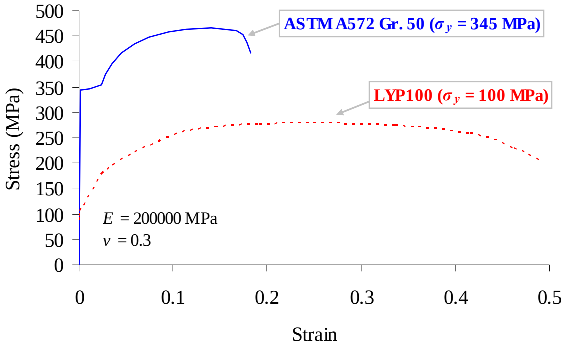
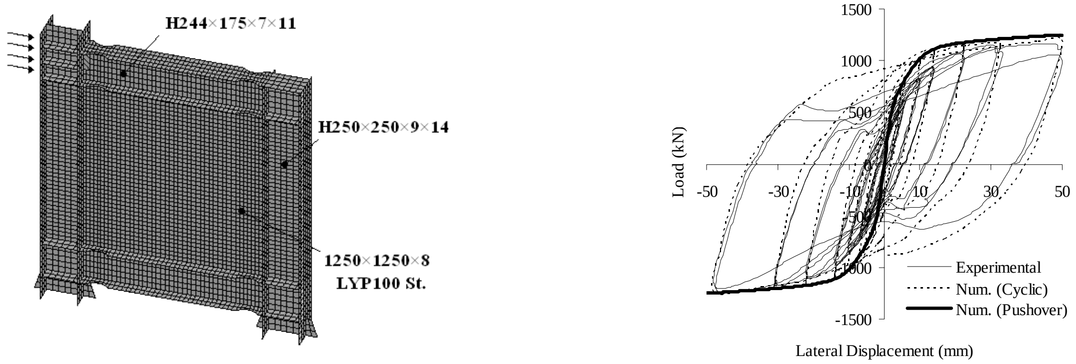


Figure 2: Material properties of full-scale SPSW models

The material properties of the boundary frame members as well as infill plates of the full-scale SPSW models are given in Fig. 2. ASTM A572 Gr. 50 steel with 345 MPa yield stress is selected for the boundary frame, and LYP100 steel with respective 100 MPa yield stress is selected for the infill plate. In addition, von Mises yield criterion is used for material yielding, and isotropic and kinematic hardening rules are incorporated in the respective nonlinear pushover and cyclic analyses.

In order to account for initial imperfections, very small out-of-plane deformations proportional to the lowest eigen-mode shape of elastic buckling are introduced to the SPSW models. Also, as shown in Fig. 1, in-plane lateral load is applied to the beam-column connection in a displacement-controlled and incremental manner, and both geometrical and material nonlinearities are considered in the finite element analyses.

Numerical modeling of SPSWs is validated by considering the experimental data and results of specimen no. 1 tested by Chen and Jhang (2006) which represents LYP steel shear walls with stocky infill plates. The comparison details and results are illustrated in Fig. 3. From Fig. 3(b), it is evident that the agreement between the numerical and experimental results is quite satisfactory.



(a) Specimen no. 1 FE model

(b) Experimental vs. numerical results

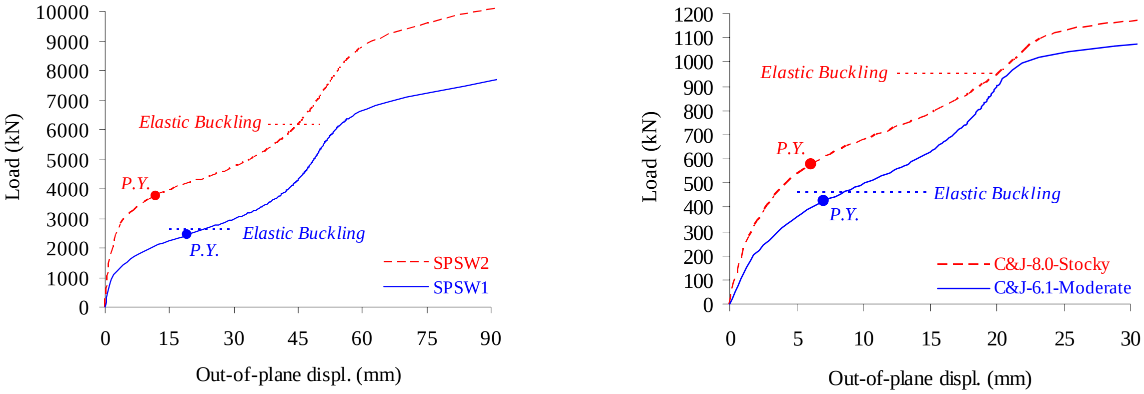
Figure 3: SPSW finite element model validation with Chen and Jhang (2006)’s test results

Numerical results from finite element analysis of specimen no. 1, with moderate and stocky infill plates are also considered in this study. It should be noted that the limiting plate thickness in this case, i.e. $t_{p\text{-}limit} = 6.1$ mm, is determined using Eq. (2). The specifications of the two numerical models of the small-scale experimental specimen are given in Fig. 3(a) and Table 2.

Table 2: Specifications of numerical models of the tested SPSW specimen

Model	Test	Infill Plate	
		$l \times h \times t_p$ (mm)	Type
C&J-6.1-Moderate	Chen and Jhang (2006)	1250×1250×6.1	Moderate
C&J-8.0-Stocky		1250×1250×8.0	Stocky

In order to verify the accuracy of predictions of Eqs. (1) and (2), linear and nonlinear finite element analyses are performed to evaluate the buckling and yielding behavior of the four SPSW models listed in Tables 1 and 2, the results of which are shown in Fig. 4. As it is seen in the figure, geometrical buckling and material yielding occur almost simultaneously in SPSW1 and C&J-6.1-Moderate models with moderate infill plates, while SPSW2 and C&J-8.0-Stocky models with stocky infill plates undergo material yielding prior to geometrical buckling. This indicates that Eqs. (1) and (2) provide reliable predictions for the limiting thickness, given the plate is under shear loading.



(a) SPSW1 and SPSW2

(b) C&J-6.1-Moderate and C&J-8.0-Stocky

Figure 4: Buckling and yielding behavior of the SPSW models (*P.Y.: Plate first yield*)

4. Lateral load-displacement relationships

The PFI model was introduced by Sabouri-Ghomi et al. (2005) and it was demonstrated that this modeling technique is able to predict the behavior of different SPSW configurations with thin or thick infill plates, and with or without stiffeners and openings. This simple analytical method provides the designers with a powerful tool to efficiently design the SPSW systems by evaluating the individual properties of the plate and frame components and their interaction as well as contribution to the overall performance of the panel. This section presents a slightly-modified version of the PFI model for predicting the response of SPSW systems with moderate and stocky infill plates.

The steel shear wall panel consists of the infill plate and boundary frame components. As shown in Fig. 5, in this method the shear load-displacement diagrams of the infill plate and surrounding frame are obtained separately, and by superimposing these two diagrams, that of the steel shear wall panel is obtained consequently.

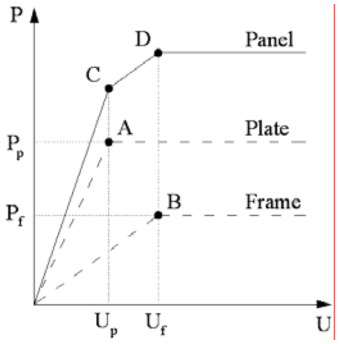


Figure 5: Shear load-displacement diagrams of frame, plate, and panel

As demonstrated by Gheitasi and Alinia (2010), moderate plates reach their ultimate strength immediately after geometrical-material bifurcation and neither possess post-buckling nor post-yield reserves, while stocky plates exhibit some post-yield capacity prior to failure due to plastic buckling. This indicates that stability and resistance of such plates are highly influenced by material bifurcation. Accordingly, it is assumed that the limit state of moderate and stocky infill plates under shear loading is reached when the shear stress acting on the plate attains the shear yield stress, i.e. $\tau_{yp} = \sigma_{yp} / \sqrt{3}$. Point A in Fig. 5 corresponds to the plate material bifurcation limit. The shear yield strength (P_p) and the corresponding lateral displacement (U_p) of the plate may be obtained from

$$P_p = \tau_{yp} \times l t_p \tag{3}$$

and

$$U_p = \left(\frac{\tau_{yp}}{G} \right) \times h + \frac{P_p \times h^3}{3EI_p} \tag{4}$$

in which, G is the elastic shear modulus of the plate steel material and I_p is the moment of inertia of the infill plate. As noted, both shear and bending deformations are considered for determining U_p in Eq. (4), since the global deformation of a SPSW system is a combination of shear and bending deformations. On the other hand, the shear load-displacement diagram of a frame may be reasonably defined by assuming that the beam-column connections are fixed and the beams behave as rigid elements. Accordingly, the ultimate shear strength (P_f) and the corresponding lateral displacement (U_f) of the frame, defining point B in Fig. 5, may be determined by

$$P_f = \frac{4 \times M_{pc}}{h_s} \tag{5}$$

and

$$U_f = \frac{M_{pc} \times h_s^2}{6EI_c} \tag{6}$$

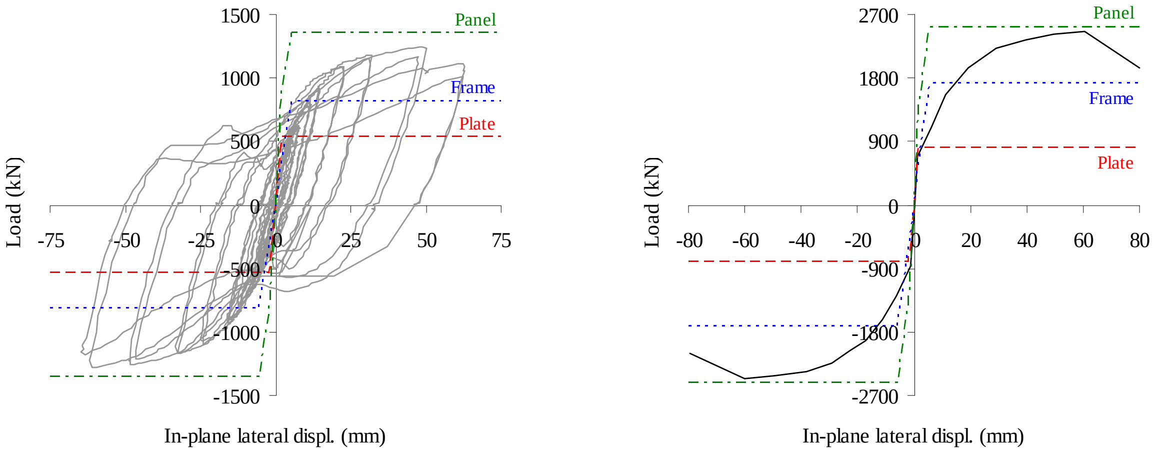
where, M_{pc} and I_c are the plastic moment and moment of inertia of the column, respectively.

It is noted that the behaviors of the steel plate and frame are assumed to be elastic-perfectly plastic, so material hardening effects are ignored in this method. In accordance with Sabouri-Ghomi et al. (2005)'s recommendation, $U_f > U_p$ requirement has to be satisfied, since this will ensure that the plate dissipates more energy than the frame, and also the plate complies with the capacity design method that targets the plate to fail as the fuse of the system. Moreover, boundary frame members have to be strong and stiff enough to be able to sustain the boundary forces associated with the tension field and also to prevent the occurrence of any type of instability.

5. Effectiveness of the modified PFI model

The accuracy and performance of the modified PFI model are evaluated by comparing the predicted response with experimental as well as numerical results.

The experimental results obtained from tests performed by Chen and Jhang (2006) and Tsai and Lin (2005) are primarily considered to demonstrate the effectiveness of the analytical method. The first test specimen, i.e. specimen no. 2 in Chen and Jhang (2006), is an unstiffened steel shear wall with stocky LYP steel infill plate, whose details are similar to those illustrated in Fig. 3(a) with the exception of an extension of 15 cm steel plate added to the bottom of the boundary beam. The second specimen, i.e. specimen 3T in Tsai and Lin (2005), is a stiffened LYP steel shear wall with 3.0 mm thick and stocky sub-panels. Fig. 6 shows the comparison between experimental and analytical results.



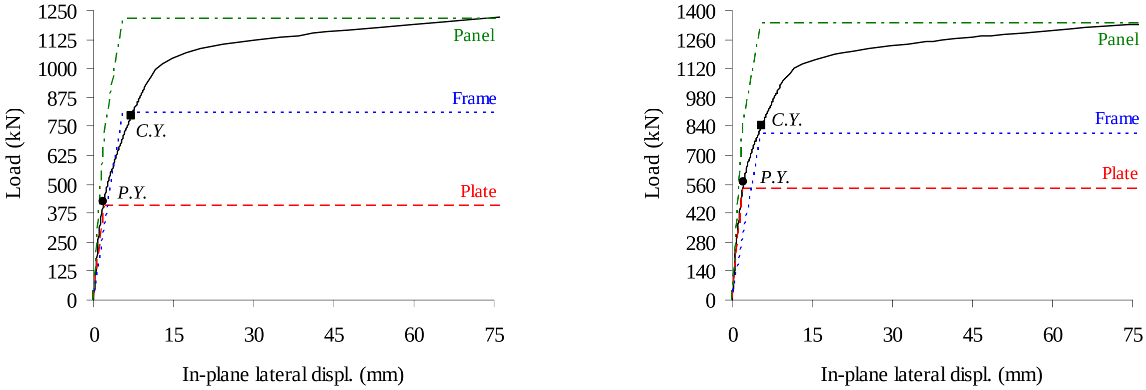
(a) Chen and Jhang (2006) - specimen no. 2

(b) Tsai and Lin (2005) - specimen 3T

Figure 6: Comparison of the modified PFI model predictions with experimental results

As it is seen in Fig. 6(a), the ultimate strength of the first test specimen is closely predicted by the modified PFI model; however, the initial stiffness is overestimated by this model. Fig. 6(b), on the other hand, shows that the analytical model closely predicts both initial stiffness and ultimate strength from the envelope of the cyclic response of the test specimen 3T. It should be noted that the stiffness performance of the test specimens is largely influenced by the material nonlinearities, particularly those of the LYP steel material, which are present in both elastic and inelastic ranges and are not considered in the analytical model. Nevertheless, the agreement between experimental and analytical results is found to be by and large satisfactory in both cases.

Numerical results are also considered in here for detailed evaluation of accuracy of the modified PFI model predictions. Analytical results are initially compared with the numerical results from finite element analysis of experimental and small-scale C&J-6.1-Moderate and C&J-8.0-Stocky SPSW models, and comparison results are given in Fig. 7.



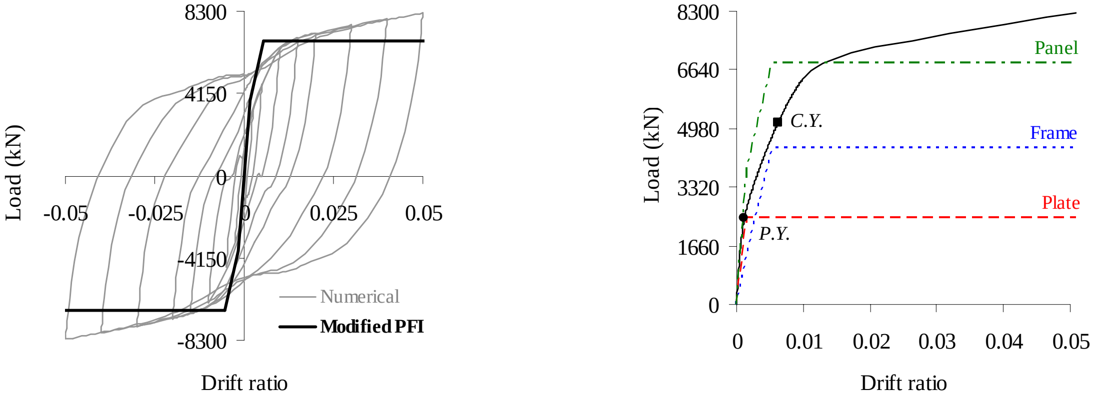
(a) C&J-6.1-Moderate

(b) C&J-8.0-Stocky

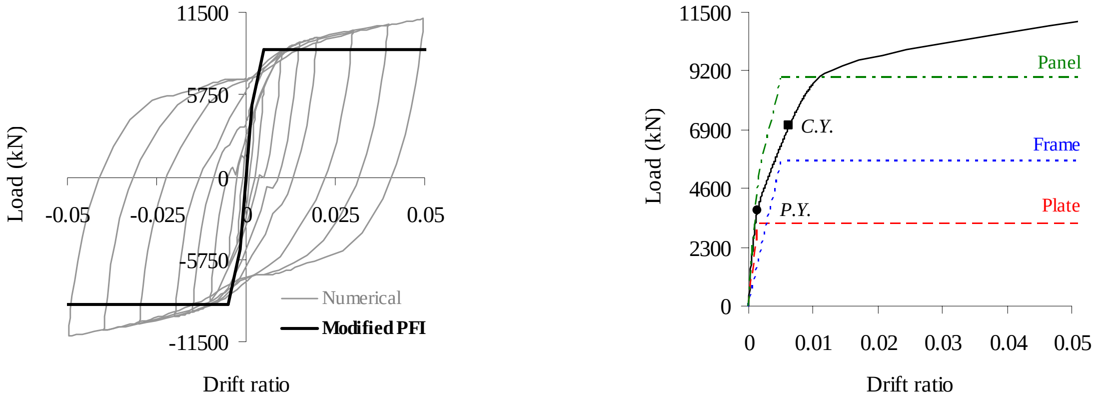
Figure 7: Comparison of the modified PFI model predictions with numerical results of Chen and Jhang (2006)'s specimen no. 1 model

From Figs. 7(a) and (b), it is found that the modified PFI model is able to effectively predict the overall behavior of the SPSW models. Consistent with the two cases, predictions of the initial stiffness, plate first yield displacement, and ultimate strength of the panel are satisfactory.

In addition, Fig. 8 shows the comparison between finite element results of code-designed and full-scale SPSW1 and SPSW2 models and the predicted response by the modified PFI model.



(a) SPSW1



(b) SPSW2

Figure 8: Comparison of the modified PFI model predictions with numerical results of code-designed and full-scale SPSW1 and SPSW2 models

As it is seen in Figs. 8(a) and (b), the modified PFI model has successfully captured the overall performance of SPSW1 and SPSW2 models. A closer look at the results reveals that the initial stiffness and plate first yield displacement of the two models are closely predicted by the analytical model, while the ultimate capacity is underestimated in both cases.

Based on the findings of this study, it is concluded that the PFI model is in general a powerful tool which can be effectively used to predict the behavior and performance of the LYP steel shear walls, and also facilitate the design of such efficient lateral force-resisting and energy dissipating systems. However, further experimental and parametric studies are still needed for improving the accuracy and performance of the modified PFI model.

6. Conclusions

Using LYP steel for infill plates of shear wall systems has been demonstrated to be an efficient alternative for improving the lateral resistance and damping characteristics of new and existing structures. The enhanced buckling stability, serviceability, and energy absorption capacity of such lateral force-resisting and energy dissipating systems are provided in the light of use of LYP steel. However, further research is required to characterize the behavior and performance of such systems and also to address the structural and economical considerations in their design and applications.

Considering the merits of application of LYP steel shear wall systems with relatively low yielding and high buckling capacities, it is important to be able to predict the behavior of such systems via non-laboratory theoretical approaches with less complexity and sufficient accuracy. PFI method is a simple and effective analytical technique which is able to facilitate the analysis and design of SPSW systems without introducing much complexity.

A slightly-modified version of the original PFI model was developed in this paper to predict the response of LYP steel shear wall systems with moderate and stocky infill plates. Evaluation of effectiveness of the modified PFI model was performed by comparing the predicted responses with both experimental and numerical results. It was demonstrated that the analytical PFI model has an overall acceptable performance and is capable of predicting various behavioral characteristics such as initial stiffness, plate first yield displacement, and ultimate capacity of the considered SPSW systems. However, the accuracy of the analytical predictions can be improved by considering further congruent experimental and parametric investigations in the future.

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