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Structural performance of unstiffened low yield point steel plate shear walls

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ABSTRACT

Employment of low-yield stress steel plates in shear wall systems has been demonstrated in a number of studies to be a promising alternative for improving the buckling stability, energy absorption capacity, and serviceability of these lateral force-resisting systems, in which material yielding of infill plates may occur either before or after or even at the same time as geometrical buckling. Accordingly, based on their slenderness parameter as well as buckling and yielding behavior, infill plates in steel shear wall systems may be divided into slender, moderate, and stocky categories with respective early buckling, concurrent buckling and yielding, and early yielding characteristics. Such a classification enables the accurate evaluation of buckling and yielding behavior of low yield point steel plate shear walls, which can consequently result in efficient structural and economical design of these lateral force-resisting as well as energy dissipating systems. On this basis, this paper assesses the structural behavior as well as plate–frame interaction characteristics of unstiffened low yield point steel plate shear wall systems via finite element and analytical approaches. Following the experimental validation of the numerical modeling, advantages of use of low yield point steel as compared to the conventional steel are demonstrated. Subsequently, the structural performances of code-designed shear walls with slender, moderate, and stocky low yield point steel infill plates are evaluated comparatively. Finally, the effectiveness of a modified plate–frame interaction (PFI) model in predicting the response of steel shear wall systems with moderate and stocky infill plates is demonstrated.

1. Introduction

Steel plate shear walls (SPSWs) have been frequently used in the United States, Japan, and Canada over the past three decades or so. Considerable amount of theoretical and experimental research has been conducted in Canada, Iran, Japan, Taiwan, the United Kingdom, and the United States on their structural behavior and analytical modeling as a lateral force-resisting system in design of low-, medium-, and high-rise buildings against seismic and wind loads. The advantages of using SPSWs as the lateral force-resisting system in buildings include stable hysteretic characteristics, high plastic energy absorption capacity, and enhanced stiffness, strength, and ductility [18].

SPSWs have been used with two different design philosophies as well as detailing strategies. One approach employs heavily-stiffened SPSWs to ensure that the wall panel achieves its full plastic strength prior to out-of-plane buckling. Thus, the stiffened wall panels can resist large lateral forces and dissipate earthquake-induced energy. Such systems are current practice in Japan, where high-fabrication cost is tolerated in order to guarantee high seismic and structural performance. North American practice, on the other hand, is to use thin unstiffened steel wall plates, which exhibit nonlinear behavior at relatively small story drifts as they buckle out of plane [8]. The elastic shear buckling of the thin plate in SPSW usually results in reduced stiffness, strength, 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 [6]. Even though the infill plates can be either stiffened or unstiffened depending on the design philosophy, labor costs in North America indicate that unstiffened panels are preferable [11].

Buckling stability, energy dissipation capacity, and serviceability of SPSW systems can be improved by either increasing the web-plate thickness or using horizontal and vertical stiffeners. Nevertheless, this may not result in economical design of shear walls with conventional steel infill plates. Application of low yield point (LYP) steel with extremely low yield stress and high elongation capacity, developed by the Nippon Steel Corporation in Japan [23], nowadays provides the possibility to design relatively economical SPSW systems with high structural and seismic performance.

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Table 1
Specifications of code-designed SPSW models.

Model	Infill plate		HBE (Beam)	VBE (Column)	Design steel type	
	$l \times h \times t_p$ (mm)	Type			Frame	Plate
SPSW1	2000 × 3000 × 10.6	Moderate	W14 × 120	W14 × 311	ASTM A572 Gr. 50	LYP100
SPSW2	3000 × 3000 × 4.7	Slender	W14 × 120	W14 × 132	ASTM A572 Gr. 50	ASTM A36, LYP100
SPSW3	3000 × 3000 × 9.3	Slender	W14 × 233	W14 × 257	ASTM A572 Gr. 50	LYP100
SPSW4	3000 × 3000 × 14.0	Moderate	W14 × 311	W14 × 342	ASTM A572 Gr. 50	LYP100
SPSW5	3000 × 3000 × 18.7	Stocky	W14 × 398	W14 × 426	ASTM A572 Gr. 50	LYP100
SPSW6	4500 × 3000 × 15.8	Moderate	W30 × 391	W14 × 370	ASTM A572 Gr. 50	LYP100

Nakashima and his associates [15,16] reported an experimental study demonstrating the superior hysteretic behavior of shear panels made of LYP steel, and on this basis proposed simple analytical models to simulate the hysteretic behavior of LYP steel shear panels. The hysteresis curve, low-cycle fatigue, and hysteresis energy properties of LYP steels under high strain were also studied by [19], and the superb mechanical properties of LYP steel compared to those of conventional steel were demonstrated in this study. The advantages of application of LYP steel in SPSW systems have been partially demonstrated through some experimental studies, e.g. [22,21,5,6], and numerical investigations, e.g. [4,7,12,14], and the research is still underway in this regard.

Due to the low yield stress of LYP steel, material yielding in LYP steel shear walls may occur before geometrical buckling. Hence, accurate evaluation of buckling and yielding interaction and behavior of SPSWs can enable the efficient structural and economical design of these systems. Accordingly, infill plates in SPSWs may be qualitatively and quantitatively classified as slender, moderate, and stocky based on their slenderness parameter as well as geometrical–material bifurcation characteristics [9]. 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 this classification, accurate determination of the limiting plate thickness corresponding to concurrent geometrical–material bifurcation can serve as an effective tool in the design of LYP steel shear wall systems with enhanced energy dissipation capacity.

In this paper, the structural performance of code-designed and unstiffened LYP steel shear wall systems is examined primarily through finite element analysis. The advantages of using LYP steel material in SPSW systems as compared to the conventional steel material are demonstrated through comparison studies. In addition, the performance of the SPSW models with slender, moderate, and stocky LYP steel infill plates under monotonic and cyclic loads is investigated as well. Lastly, the effectiveness of a modified plate–frame interaction model, originally developed by [18], in predicting the response of steel shear wall systems with moderate and stocky infill plates is evaluated through comparison with some experimental as well as experimentally-verified numerical results.

2. Design and specifications of SPSW models

Six single-story, single-bay, and full-scale steel shear walls with 2000 × 3000, 3000 × 3000, and 4500 × 3000 mm infill plates of various slenderness ratios and steel material are designed in accordance with the AISC 341-10 [1] seismic provisions for the purpose of this study. Specifications of the 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. Highlighted rows in the table indicate SPSWs with moderate infill plates.

SPSWs are designed according to capacity-design principles, in which boundary elements are designed to permit the web plates to develop significant diagonal tension. In fact, horizontal and vertical boundary elements, i.e. HBEs (beams) and VBEs (columns), are designed to elastically resist development of the full expected yield strength of the infill plate. This will ensure that the infill plate can yield in tension prior to plastic hinging of the boundary elements [17]. As it is seen in the table, ASTM A572 Gr. 50 steel with 345 MPa yield stress is selected for the boundary frame, and LYP 100 and ASTM A36 steel with respective 100 and 250 MPa yield stresses are selected for the infill plates.

In order to design the boundary frame members in SPSWs, corresponding infill plate thicknesses are initially determined. The limiting

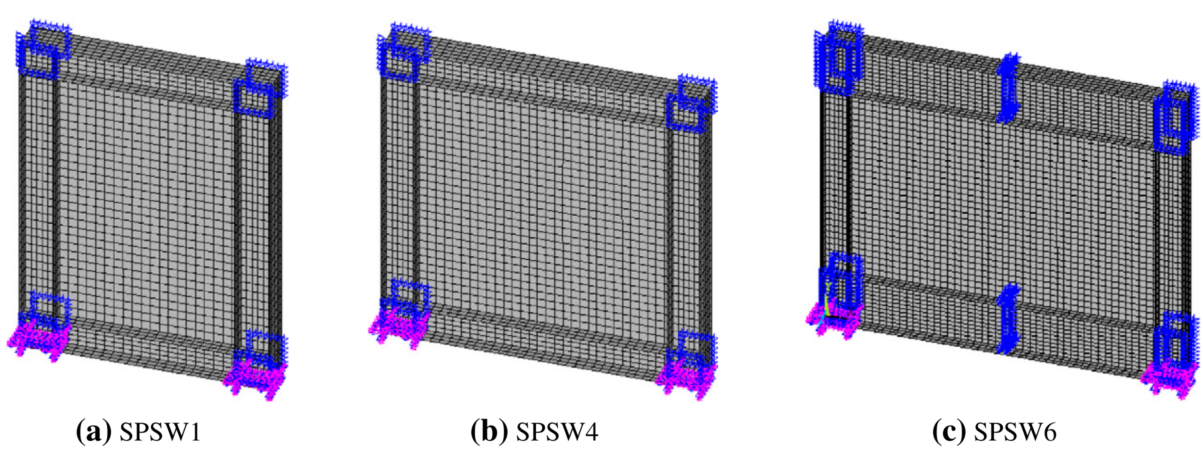

Fig. 1. Finite element models. (a) SPSW1. (b) SPSW4. (c) SPSW6.