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Behavior of semi-supported steel shear walls: Experimental and numerical simulations

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ABSTRACT

This paper presents an experimental and numerical study of semi-supported steel plate shear walls which are connected to frame beams and a pair of secondary columns. As the infill plates are not connected to the frame primary columns, the large stresses due to tension field, causing the formation of plastic hinges in the primary columns, are avoided. In order to intensively investigate the structural mechanism of this new type of shear walls, eight specimens were tested under reversed cyclic lateral load. The effects of four perforation diameters as well as two slenderness ratios of infill plates on the seismic behavior of SSSWs were studied experimentally and numerically. All the specimens exhibited satisfactory cyclic inelastic and energy dissipation, thereby indicating an alternative to traditional steel shear walls. Based on the test results, the strength, stiffness, ductility factor and energy absorption characteristics of the specimens were substantially reduced in specimens with openings. Maximum strength reduction, stiffness loss and ductility deterioration in the perforated specimens were 42%, 61%, and 33%, respectively. Deteriorating pinched hysteresis was observed due to the occurrence of cyclic out-of-plane buckling and tension field action. In addition to the test program, complex elastoplastic FE models of the eight specimens were developed to investigate in detail the cyclic behavior of semi-supported steel plate shear walls. Excellent agreement was observed between the experimental and numerical results.

1. Introduction

Steel plate shear walls (SPSWs) are a robust and economical lateral force resisting system in seismic regions. A SPSW consists of a steel frame, which can have either flexible or rigid beam-to-column connections, with slender web plates connected to the surrounding steel frame. Commonly the steel plates are slender and unstiffened, providing negligible compressive resistance prior to buckling in shear [1,2]. Similar to tension field action in plate girders, the infill plates provide significant post-buckling resistance by developing diagonal tension fields. The boundary elements anchor the diagonal tension field, enabling the web plate to yield. The web plate yielding mechanisms dissipates a significant amount of energy and provides excellent ductility. Generally, the web plates of unstiffened SPSWs were connected to their surrounding frames either by welds or bolts. In SPSWs, tension field action applies large stresses on surrounding elements which may lead to early failure of the column. To alleviate this problem, some attempts including use of light-gauge, cold-formed steel panels and low-yield steel were recently addressed by Bruneau et al. [3] and Vian et al. [2], respectively. Xue and Lu [4] suggested an additional mean of reducing demand on framing adjacent to an SPSW, including the connection of the infill panel to only the beams in a moment frame. Driver et al. [5] proposed the idea of separation of SPSWs from the moment resisting frame by inclusion of secondary columns. Moharrami et al. [6] conducted some experimental studies on this new type of SPSWs entitled semi supported steel shear walls (SSSWs), and concluded that tension field action in the plate can be developed as the traditional type of SPSWs, provided a pair of secondary columns carrying no gravity loads are used to restrain the vertical ends of infill plate. Guo et al. [7] investigated the influence of stiffeners on the hysteretic behavior of two steel plate shear wall connected to frame beams only. The experimental results showed that the energy dissipation capacity of specimens with stiffeners was larger than that of the specimens without stiffeners. Meanwhile, analytical results showed that the free edges deformed with evident out-of-plane deformation and should be constrained by stiffeners to meet the design requirements. Jahanpour et al. [8] proposed a new method for evaluating the

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ultimate shear capacity of a given SSSW especially when it undergoes bending moments. Jahanpour et al. [9] also investigated experimentally the interaction between the wall plate and the surrounding frame for typical SSSW systems in which the wall-frame has a bending-dominant behavior. Kurata et al. [10] presented a rehabilitation technique that utilizes a semi-supported thin steel plate as a supplemental shear wall system for small, low rise steel structures. The system employs supplemental elements as tension-only elements to speed up the construction work and to enforce strict capacity design principles. Jahanpour and Moharrami [11] studied the behavior of secondary columns in semi-supported steel shear walls. They proposed an algorithm to develop shear capacity of SSSWs showing relatively good conformity with the result of finite element analysis. Clayton et al. [12] investigated the impact of using beam-only-connected web plates on self-centering steel plate shear wall design and seismic performance. Expressions for determining beam demands for purposes of design were developed.

Even though few experimental studies were performed on SSSWs, further research on the systems' behavior investigating their merits in seismic applications in terms of stiffness, ductility and cumulative hysteretic energy dissipation capacity is needed. In an attempt to provide some quantitative data for this purpose, this paper describes and compares the results from cyclic testing of eight SSSWs considering the effects of four perforation diameters, as well as two slenderness ratios of infill plates on the seismic behavior of these systems. In addition, numerical finite element analysis using ABAQUS [13] software was conducted to investigate the behavior of this kind of steel shear wall and provide useful information for design.

2. Experimental study

The experimental study was conducted on 1:6 scaled single-story SSSW specimens in the thin-walled structure research laboratory of Urmia University. It should be noted that seismic performance of the steel shear walls is often studied using small-scale models because of constraints on economics, time, and laboratory space. The test results of small-scale models do not necessarily represent the behavior of full-scale structure. Therefore, in order to employ the model test results to predict the behavior of full-scale structures, the scale effect should be studied. The non-dimensional response of the specimens, e.g. the normalized shear strength versus drift index, is scale independent and that fully describes the behavior of a SSSW. However, the comparisons between same-scale studied models conducted in the current study do not need scale effect. The specimens were established on a rigid platform resting on a strong floor. The reaction frame braced to reduce the in plane deformations, was employed for applying the lateral loads on the specimens. A lateral restrain system was used to prevent out of plane deformations of the testing frame (Fig. 1). Each test was performed under fully reversed cyclic quasi-static loading in compliance with SAC test protocol [14]. The loading history consists of stepwise increasing deformation cycles as illustrated in Table 1. The deformation parameter used to control the loading history is the interstory drift ratio, defined as interstory displacement divided by story height. The horizontal loads were applied on the specimens up to drift ratio of 5% by means of an actuator with 100 kN capacity. A schematic view of the test set-up was shown in Fig. 2.

2.1. SSSWS specimens

Eight specimens with different parameters were fabricated and tested. The primary parameters were the infill plate thickness ratio and circular opening ratio. The circular hole on the infill plate was cut with CNC machine. All the specimens were 1:6 scale models of the prototype structure with hinge type connections at four corners. The frames measured 620 mm wide and high between horizontal boundary elements (HBEs) and vertical boundary elements (VBEs) centerlines, while the depth and width of the infill plates were equal to 500 and 460 mm, respectively. The boundary elements of the frame were similar and consisted of standard profile

Table 1
Loading protocol based on SAC [14].

Load step	Drift ratio	Number of cycle
1	0.00375	6
2	0.005	6
3	0.0075	6
4	0.01	4
5	0.015	2
6	0.02	2
7	0.03	2
8	0.04	2
9	0.05	2

Continue with increments in of 0.01, and perform two cycles at each step.

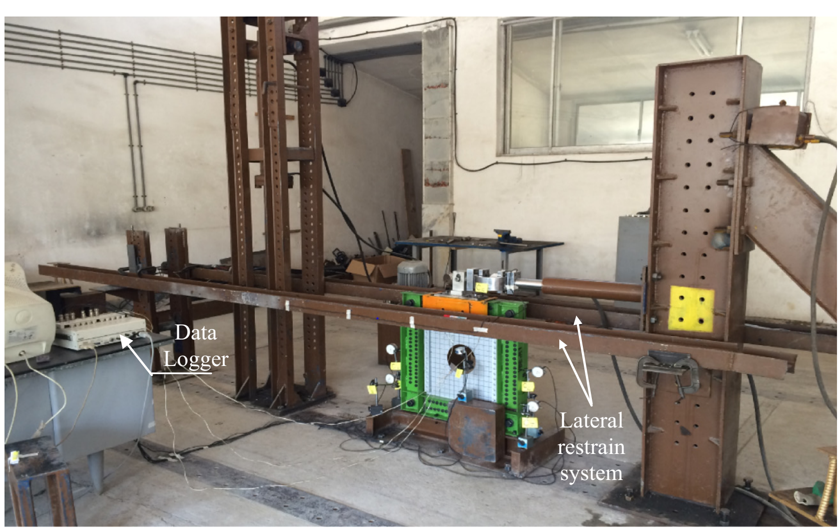

Fig. 1. Lateral restraint system of the SSSW specimens in the laboratory.