Thin-Walled Structures 97 (2015) 53–62

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

# Behavior of stiffened and unstiffened steel plate shear walls considering joint properties

Hong-Chao Guo [a,b,*], Ji-Ping Hao [c], Yun-He Liu [a,b]

[a] State Key Laboratory Base of Eco-hydraulic Engineering in Arid Area, Xi′an University of Technology, No.5 Jinhua Road, Xi′an 710048, PR China
[b] Department of Civil Engineering and Architecture, Xi′an University of Technology, No.5 Jinhua Road, Xi′an 710048, PR China
[c] Department of Civil Engineering, Xi′an University of Architecture and Technology, No.13 Yanta Road, Xi′an 710055, PR China

ARTICLE INFO

*Article history:*
Received 23 April 2015
Received in revised form
24 August 2015
Accepted 7 September 2015
Available online 22 September 2015

*Keywords:*
Shear wall
Stiffener
Semi-rigid
Energy dissipation
Spring element

ABSTRACT

Steel plate shear wall (SPSW) systems have dual characteristics, the frame and infill wall action. The connection flexibility of frame joint not only changes the force and moment distribution, but also increases the lateral displacement and weakens the overall stability in SPSW structure. This paper presents the influence of hinged, rigid and semi-rigid connection joints on the behavior of SPSW structures. The bearing capacity, energy dissipation mechanism, failure mode, stress and deformation development process of the semi-rigid composite frame with steel plate shear walls under different stiffener forms were studied using experimental tests and finite element analysis. It was observed that with stiffeners the specimen yield load increased about 20% on the elastic stage, the ultimate bearing capacity of the diagonal stiffener was about 5% larger than the cross stiffener on the plastic stage, but the overall failure modes were basically the same. Additionally, the quantitative indications of the effect of joint stiffness on load carrying capacity were presented.



## 1. Introduction

Steel plate shear wall (SPSW) is composed of a frame and infill steel plate. With the advantages of high elastic stiffness, stable hysteretic behavior, high energy dissipation capacity and ductility, it is an economic and efficient lateral force resisting structure system in tall buildings [1,2]. In the past two decades, several experimental studies have been carried out on the thin steel plate shear walls by Caccese et al. [3], Driver et al. [4] and Lubell et al. [5]. Thorburn et al. [6] and Timler et al. [7] presented a strip model for the analysis of thin steel plate shear walls. Hitaka and Matsui [8] studied the performances of slits in steel shear walls. Roberts and Sabouri-Ghomi [9–11] introduced the Plate-Frame interaction theory for predicting the linear and nonlinear behavior of different steel plate shear walls. The effects of holes in the infill plate of unstiffened SPSWs were investigated by Vian and Bruneau [12]. Nateghi and Alavi [13,14] evaluated the seismic performance of a diagonally stiffened steel shear wall with a central opening in comparison with the un-stiffened and diagonally stiffened solid-plate shear walls. Design rules of the thin steel plate shear wall are also specified in the design specifications, such as AISC [15] and CSA [16].

In recent years, some researchers were interested in studying SPSW system because its dual characteristics regarding the frame and infill wall action which may be well treated as two subsystems, the shear capacity of an infill wall is affected by the rigidity of its surrounding frame members [17]. With regard to the interaction effect between the infill plates and frame members, Alinia and Dastfan [18,19] analyzed the nonlinear response of SPSW dual systems under lateral loading.

Indeed, on one hand, the mechanical properties of thin steel plate shear wall itself have been relatively clear. On the other hand, the load carrying capacity and stiffness of the steel frame does not only depend on the member section, but also related to the joint forms. Therefore, the objective of this research is to study the effect of frame joint forms on the behavior of steel plate shear wall structures with or without stiffeners. For this purpose, three experimental tests of steel plate shear walls with cross, diagonal stiffeners and without stiffeners were conducted. Additionally, the influences of hinged, rigid and semi-rigid connections on the SPSW structure bearing capacity were compared using finite element analysis.

* Correspondence to: State Key Laboratory Base of Eco-hydraulic Engineering in Arid Area, Xi′an University of Technology, Xi′an 710048, China.
Tel.: +86 13227009454.
*E-mail address:* ghc-1209@163.com (H.-C. Guo).

http://dx.doi.org/10.1016/j.tws.2015.09.005
0263-8231/

## 2. Experimental test

### 2.1. Experimental design

For studying the effect of the joints stiffness and stiffeners form on the seismic performance of SPSW structure, three one-third scaled two-story single-bay experimental specimens with around 1.35 m width and 2.75 m height of SPSW were prepared and tested under cyclic loading in the Structure and Seismic Laboratory, Xi′an University of Architecture and Technology University. The 4 mm thick infill steel plates were welded at the edges to the surrounding beam and column elements using 8 mm thickness fish-plate connections, as shown in Fig. 1. By setting reasonable stiffeners can decrease height thickness ratio of panel, delay the buckling of the thin steel plate shear wall, improve buckling loads and initial stiffener of the thin steel plate shear wall. To prevent the premature buckling of stiffener, the two parameters such as the width-thickness ratio of stiffener $\lambda$ and stiffness ratio of stiffener to panel $\eta$ can be considered in design, and the formula is shown in Eqs. (1) and (2). Thus, the final section of the stiffener adopted is $-40$ mm $\times$ 4 mm, the stiffness ratio of stiffener to panel with cross stiffener is 18.85, and diagonal stiffener is 25.61. The width-thickness ratio of stiffener is 10.

$$\lambda = \frac{h_S}{t_s} \tag{1}$$

here, $h_s$ is the width of stiffener, $t_s$ is the thickness of stiffener.

$$\eta = \frac{EI_S}{D(h\sin a + L\cos a)} \tag{2}$$

where $I_s$ is the moments of inertia of stiffener which is relative to the infill plate middle surface, $D$ is the cylindrical stiffness of panel, $\alpha$ is inclined to the diagonal stiffener and vertical angle, $h$ and $L$ are the infill plate height and width.

Where only panels are used in the specimen without stiffener is named as HAP, panels with cross stiffener is named as HAC, and panels with diagonal stiffener is named as HAX. For considering the effect of the joints stiffness, all beam-to-column connections were constructed as semi-rigid joints by using top and seat angles and double web angles, as shown in Fig. 2. The details of the specimen are shown in Fig. 1 and member sections are listed in Table. 1. To determine the material properties of the steel (Chinese Q235 steel), six tension test coupons were prepared and tested according to the “Metallic materials tensile testing at ambient temperature [20]” (GB/T228.1-2010) and “Steel and steel products-Location and preparation of test pieces for mechanical testing [21]” (GB/T 2975-1998), A summary of the tests results are presented in Table 2.

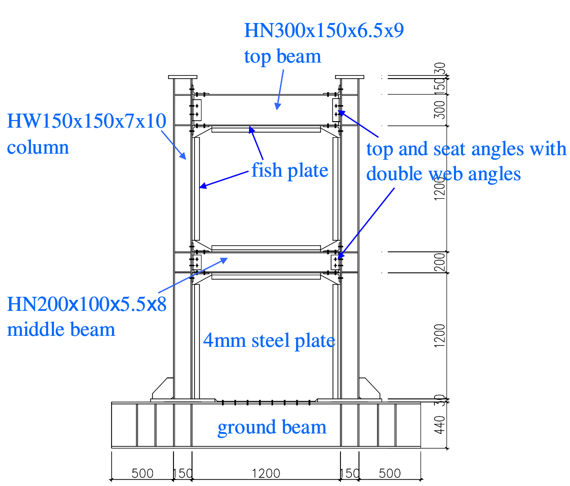


**Fig. 1.** Design of specimen.

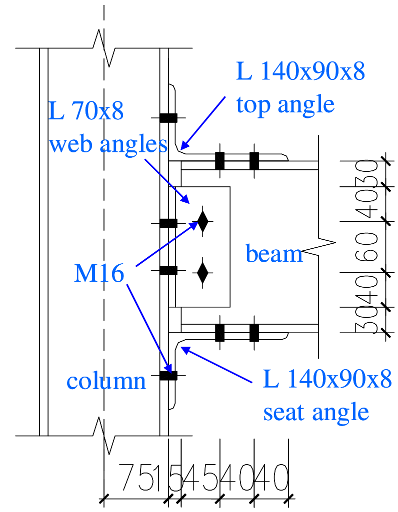


**Fig. 2.** Details of the semi-rigid connection.

### 2.2. Testing and instrumentation

After assembling the SPSW structures, the specimen was fixed on the rigid base of the laboratory with two ground beams. Two lateral bracings were placed to prevent out-of-plane movement of the specimen. Vertical loads were applied by two 2000 kN synchronized hydraulic jacks and horizontal loads were provided by the 1000 kN MTS actuator. The vertical jacks were applied to exert axial pressure to steel columns, at the end of the jacks were set up pulleys to ensure synchronous motion with specimens along the horizontal direction. Through the voltage stabilizer, vertical load of the top of columns could automatically compensate and remain constant. The loading device is shown in Fig. 3. Several triaxial and uniaxial strain-gauges were installed on the steel plate and columns.

According to “Specification of Testing Methods for Earthquake Resistant Building [22]” (JGJ101-96), force and displacement combination control of loading were used. Before the specimen yielded, loading increment control to 100 kN increments of one grade and single cycle at each level was applied. After the specimen yielded, displacement increment control and three cycles at each level were applied until the destruction of the sample.

## 3. Numerical analysis

### 3.1. Finite element models

Finite element models of the specimens were generated to predict behavior of the specimens in the testing. The finite element study was used to determine locations of the maximum stresses and strains in the elements for strain-gauges arrangement. The modeling was performed using the general-purpose nonlinear finite element ANSYS software, its recent editions are suited for the solution of nonlinear engineering problems such as SPSW. The steel plate and frame were meshed with shell181 element, the semi-rigid joint was simulated using Combin39 spring element. The bilinear kinematical material model was used for steel to consider the Bauschinger effect of the steel material under cyclic loading. Von Mises yield criterion was used, and the material properties are shown in Table 2.