Journal of Constructional Steel Research 145 (2018) 128–136

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Shaking-table test of a novel buckling-restrained multi-stiffened low-yield-point steel plate shear wall

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ARTICLE INFO

Article history:
Received 18 October 2017
Received in revised form 10 February 2018
Accepted 14 February 2018
Available online xxxx

Keywords:
Steel plate shear wall
Buckling-restrained
Low-yield-point steel
Shaking-table test
Seismic behavior

ABSTRACT

We proposed a novel buckling-restrained multi-stiffened low-yield-point steel plate shear wall (BR-LYP-SPSW). To study the seismic behavior of BR-LYP-SPSW, a 1:3 scale model shaking-table test was conducted. The increase in the peak ground acceleration decreased the natural frequency and acceleration dynamic magnification factor and increased the damping ratio. The advantage of the sandwiched LYP infill plate is the higher order buckling formed at the LYP infill plate, which played an important role in "the first line of defense." The maximum inter-storey drifts during frequent and rare earthquakes were 1/694 and 1/88, respectively, which met the demands of the seismic design code of buildings.

1. Introduction

For stable hysteretic characteristics, high plastic energy-absorption capacity, and enhanced stiffness, strength, and ductility, steel plate shear wall (SPSW) systems have drawn the attention of many engineers in the past three decades. However, if shear buckling occurs in the early stage, out-of-plane permanent deformation may affect the serviceability of a thin-plate shear wall under a small or moderate earthquake. One method of preventing shear buckling and increasing the energy dissipation capacity is to use stiffening devices for the plate wall, and the other method is to use low-yield-point (LYP) steel plates with extremely low-yield strength and with high ductility and elongation properties.

Since the buckling-restrained SPSW (BRSPSW) was originally proposed by Zhao and Astaneh-Asl [1], various types of BRSPSWs with different configurations have been proposed to reduce the stiffness demand of vertical boundary elements (VBEs), and they actually showed high performance in terms of ductility, initial stiffness, shear resistance, and energy absorption [2–7]. These results can be achieved by adding steel stiffeners, which is the current practice in Japan. The structural stability and performance of the plates are characterized by geometrical buckling and material yielding, which are two independent phenomena that may interact with each other [8]. LYP steel plates may actually undergo early material yielding, followed by inelastic geometrical buckling with economical plate thickness. Such efficient lateral force-resisting and energy-dissipating elements have been demonstrated to be quite advantageous based on their superior characteristics and performance [9,10].

Set against this background, a novel buckling-restrained multi-stiffened LYPSPSW (BR-LYP-SPSW) is proposed in this paper to prevent shear buckling and increase the energy-dissipation capacity of SPSWs, as shown in Fig. 1. The proposed BR-LYP-SPSW is composed of horizontal boundary elements (HBEs), VBEs, LYP infill steel plates (LYPISPs), steel multi-stiffened grids (SMSGs), four-angle-connections (FACs), fish plates (FPs), covering plates (CPs), circular steel tubes (CSTs), and bolts. Fig. 1 shows that the HBEs and VBEs are first connected to the FACs. Secondly, the FPs are welded to the HBEs and VBEs using fillet weld. Thirdly, the LYPISPs are sandwiched between bilateral SMSGs by the CPs, CSTs, and bolts and are connected to the FPs using bolts. The SMSGs are not connected to any HBE and VBE to prevent it from being involved in resisting the horizontal and vertical loads from the HBEs and VBEs. The SMSGs are designed to restrain lateral low-order buckling modes of the LYPISPs, so that they will only buckle in high-order modes. We must note that the bolt holes on the LYPISPs are generally oversized for precise installation. Hence, lateral buckling of the steel plate would not be prevented by the bolts. In other words, the bolts are not considered as lateral restraints in the high-order buckling modes of

Abbreviations: SPSW, steel plate shear wall; BRSPSW, buckling-restrained SPSW; VBEs, vertical boundary elements; BR-LYP-SPSW, novel buckling-restrained multi-stiffened LYP SPSW; LYPISPs, LYP infill steel plates; HBEs, horizontal boundary elements; SMSGs, steel multi-stiffened grids; FACs, four-angle-connections; FPs, fish plates; CPs, covering plates; CSTs, circular steel tubes; PGA, peak ground acceleration; HDTs, horizontal displacement transducers.

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https://doi.org/10.1016/j.jcsr.2018.02.009
0143-974X/

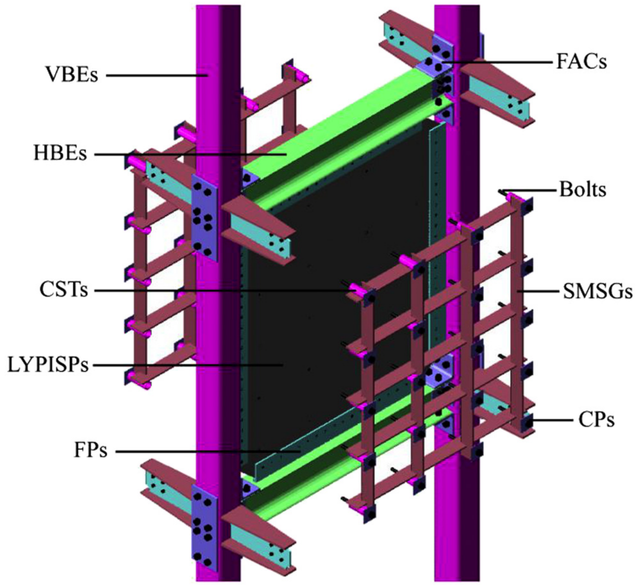

Fig. 1. BR-LYP-SPSW.

the steel plate. The cyclic loading experiments show that this lateral system (BR-LYP-SPSW) exhibits in-plane flexure-shear failure. The failure mechanism is yielding and local buckling until tearing of the infill plate, then plastic hinges shaping at beam ends and column base of the perimeter frame. The specimen exhibits stable bearing capacity and good plastic deformation capacity, associated with considerable overall initial lateral stiffness during the experiment. The application of multi-stiffeners reaches the objective of buckling-restrained and improves mechanical behavior of steel plate, resulted in full hysteretic loops and energy dissipation capacity of specimens. The additional effect of the VBEs was significantly reduced. The other advantages of this system are its light weight, convenient manufacturing, and easy installation and disassembly [11].

The shaking-table test can be used to input measured and artificial seismic waves, and the whole earthquake process can be reproduced. It is the most direct method to study the seismic response and failure mechanism of structures in the laboratory. However, the present seismic studies of SPSWs mainly concentrate on quasi-static test except for the shaking-table test of two single-span four-storey SPSW specimens carried out by Rezai [12]. In the present work, a shaking-table test of a four-storey 1:3 scaled model was carried out to study the seismic behavior of this novel BR-LYP-SPSW. The main objectives of the experiment were as follows: (1) evaluate the effectiveness of the buckling-restrained multi-stiffened low-yield-point steel plate shear wall when subjected to severe seismic loads; (2) investigate the dynamic characteristics of the test model; and (3) test the rationality of the test model design. The experimental program was described in detail in Section 2, which covered the similarity relationship, model design, material properties, instrumentation, and testing protocol. The main experimental observations were summarized in Section 3. The test results were discussed in Section 4, mainly concentrating on the dynamic characteristics, acceleration response, storey displacement response, and inter-storey drift response.

2. Experimental program

2.1. Design and specifications of the SPSW models

In accordance with the AISC 341-10 seismic provisions [13], a three-storey single-bay and 1:3 scale steel shear walls were designed for the purpose of this study. The dead load for the floors and roofs were 4 kN/m^2. The floor live load, roof live load, and snow load used were 2, 0.5, and 0.25 kN/m^2, respectively. Three levels of seismic hazard with 63.2%, 10%, and 2% probabilities of exceedance in 50 years were classified as frequent, moderate, and rare earthquakes, respectively. The designs were characterized by a peak ground acceleration (PGA) of 0.200 g with a 10% probability of exceedance in 50 years. The material of the models used in the test was identical to that of the prototype structure, indicating that the scaling factor of the elastic modulus was $S_E = 1$. In addition, the scaling factor of the acceleration was considered as $S_a = 1.6$, and the remaining similarity relationships are listed in Table 1.

The size of the MTS shaking table is 4.1 m × 4.1 m with a maximum capacity of up to 200 kN and an operating frequency range of 0.1–50 Hz. The shaking table can simulate a maximum horizontal ground acceleration of 1.5 g and a maximum vertical ground acceleration of 1.0 g. Considering the limited size and capacity of the MTS shaking table, a one-third scale model was adopted in this test, as shown in Fig. 2. The test model consisted of four storeys and three one-span frames. The steel plate walls were installed along the full height in each floor of the middle frame. The span of the direction, where the wall was located (*x* direction), and the direction vertical to the wall (*y* direction) were 1.2 m and 1.5 m, respectively. The first- and second-storey heights were all 1350 mm, and the third- and fourth-storey heights were all 1050 mm (Fig. 2).

In the test model, the VBE (column) member was a square steel tube, and the HBE (beam) was an H section. The specifications of the model are listed in Table 2. The girder in the *y* direction and the square steel-tube column were connected to a semi-rigid double-top and seat-angle steel, as shown in Fig. 3. The SMSGs were composed of mutually embedded and orthogonal 6-mm steel strips. In the junction of every strip, 34-mm-diameter circular steel tubes with thickness of 4 mm and length of 60 mm were welded to the strips to allow M12 bolts to go through and be fixed to the CPs, which consisted of the ribbed grid buckling-restrained steel wall system, as shown in Fig. 4. Due to unwelded connections between low-yield-point steel plate shear wall and the steel ribs, its stiffness should be enlarged. In addition, 6-mm-thick, 60 mm × 60 mm square steel tube members were used as braces to ensure longitudinal stiffness (*x* direction) of the test model. Table 2 indicates that Q235 steel with a 235-MPa yield stress was selected for the boundary frame, and LYP 135 steel with a 135-MPa yield stress was selected for the infill plates. The summary of the material properties according to the tensile coupon test results is listed in Table 3.

The representative value of the gravitational load in each floor of the prototype structure was calculated in accordance with Chinese seismic code GB50011-2010 [14]. According to the ratio of similarity determined from Table 1, the weight in each floor in the test model can be calculated, and the total weight of the test model was 200.28 kN, as listed in Table 4.

Table 1
Principal similarity coefficients of the structural model.

Physical parameters	Symbol	Dimensions	Ratio of similarity
Length	l	$[L]$	0.3333
Acceleration	a	$[LT^{-2}]$	1.6
Elastic modulus	E	$[FL^{-2}]$	1
Strain	σ	$[FL^{-2}]$	1
Stress	ε	–	1
Density	ρ	$[FT^2L^{-4}]$	1.8750
Mass	m	$[FT^2L^{-1}]$	0.0694
Frequency	f	$[T^{-1}]$	2.1909
Velocity	v	$[LT^{-1}]$	0.7303
Time/natural period	t	$[T]$	0.4564