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Shaking table test of buckling-restrained steel plate shear walls

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ABSTRACT

A shaking table test of a 1:3 scale semi-rigid steel frame with buckling-restrained steel plate shear wall was conducted herein to study the seismic performance of this type of structure. The model was designed as ordinary steel plate shear walls, but with buckling-restrained. Its members consisted of non-simplified sections. The descriptions of the test specimen, instruments, set-up procedures were also presented. The dynamic characteristics, acceleration, displacement, and shear force were analysed. The maximum inter-storey drift angle in elastic-plastic was 1/68. The lateral stiffness drop was only 12% when completely loaded. The test model did not collapse under rare earthquakes. The results showed that the seismic behaviour was adequate for survival in large seismic excitations, and the design methods of the members and the semi-rigid connections were reasonable.

1. Introduction

Steel plate shear walls (SPSWs) have been widely used in several buildings around the world in the past few decades [1–2] because of their high initial elastic stiffness, stable bearing capacity, high-energy dissipation capacity, superior ductility and stable hysteretic performance. The primary system of a steel plate shear wall structure is usually composed of a steel frame and steel plate shear walls. The wall plates are often bolted or welded with the surrounding frame, and the joints of the beam-column are rigid or semi-rigid hinges. For a seismic design, the steel plate shear walls are generally designed as a highly efficient structural system for resisting lateral forces [3–4].

The design basics of a steel frame with steel plate shear walls were established based on a series of analytical and experimental studies by Thorburn et al., Kulak et al., Tromposch et al. and Elgaaly et al. [5–8]. The researchers investigated the post-buckling performance of the steel plate shear wall, their results demonstrated that the out-of-plane shear buckling of the steel plate does not mean structural damage. Several researchers also conducted experimental investigations on the seismic behaviour of the steel plate shear walls.

Caccese et al., Elgaal, and Sabouri et al. [9–11] performed studies on stiffened and non-stiffened steel plate shear walls. The results showed that local and overall buckling occurred earlier in the non-stiffened steel walls than in stiffened ones when subjected to seismic loads. In other words, the non-stiffened steel wall was almost buckled when loading started. Driver et al. [12] and Lubell et al. [13] conducted cyclic tests. Chen et al. [14] examined the inelastic shear buckling behaviour of a low-yield point (LYP) steel plate. In another study [15], finite element models and test specimens of a large-scale, four-storey steel plate shear walls were represented by a series of tension strips. The abovementioned research results indicated the constant greater sound and out-of-plane deformation under repeated loads, which lessened the users' comfort level. All of which affected the popularisation and application of the structure in a certain extent. Therefore, the capacity of this type of structure to resist earthquake action should be deeply studied.

Studies on the semi-rigid connection of steel plate shear walls have also been conducted. Naderl et al. [16] conducted shaking table tests on the beam-column connections that could be flexible, semi-rigid or rigid. The results indicated that a well-proportioned semi-rigid connection can effectively contribute to the nonlinear behaviour of the structure, thereby providing additional global structural ductility. H.-C. Guo et al. [17] presented a semi-rigid composite frame with steel plate shear walls under different stiffener forms. The results showed that the ultimate bearing capacity was approximately 5% larger than the cross stiffener (the two stiffeners are perpendicular to each other) on the plastic stage.

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These previous studies were mostly loaded by monotonic or cyclic, quasi-static loading. The results of the dynamic loading tests were relatively lacking, although information on the structure behaviour under dynamic loading was necessary. Few results concerning the dynamic performance of the steel plate shear walls were presented. Rezai et al. [18] conducted shaking table tests on semi-rigid frame unstiffened steel plate wall models on two four-storey single span with 1:4 scale. The results illustrated that the tension belt appeared earlier in the wall, which affected its performance to some extent. Dowden et al. [19] performed shaking table tests on self-centering steel plate shear walls. Shamim et al. [20] described the dynamic shaking table tests of steel-sheathed, cold-formed, steel-framed shear walls. Determining which limit state or what section or floor controls the performance of the structure under seismic action is difficult because of the intense optimisation of the geometry for steel plate shear walls. Therefore, it is interesting to further experimentally investigate the dynamic characteristics and dynamic behaviours of buckling-restrained steel plate shear walls.

Subsequent research on the seismic behaviour of the structure system is needed for a deeper and comprehensive understanding. In this study, a shaking table experiment was conducted on a 1:3 scale model of a four-storey semi-rigid space frame with buckling-restrained steel plate shear walls. The main objectives of the experiment were as follows: (1) evaluate the effectiveness of the steel plate wall for low-rise frame structures when subjected to severe seismic loads and the effectiveness of the buckling restraint on both sides of the steel plate shear wall; (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 summarised in Section 3. The test results were discussed in Section 4, mainly concentrating on the dynamic characteristics, structural displacement, and shearing force responses.

2. Experimental program

2.1. Test model design

A one-third scale model was designed in accordance with the *Code for Seismic Design of Buildings* (GB 50011-2010) [21] and the *Technical Specification for Steel Structure of Tall Buildings* (JGJ 99-2015) considering the limited size and capacity of the shaking table and the effects of the similitude law [22]. The materials used for the test model were identical to those of the prototype structure, thereby indicating that the scaling factor of the elastic modulus was $S_E = 1$. The scaling factor of the acceleration was assumed to be $S_a = 1.6$. Table 1 shows the similarity relationships.

Table 1
Similarity coefficient of the test model.

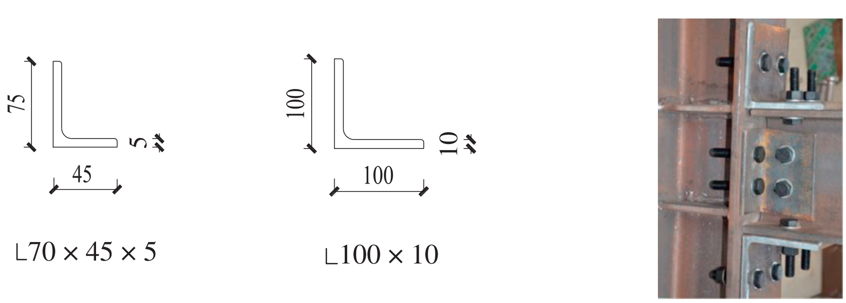
Physical quantity	Dimensions	Ratio of similitude
Length	L	$S_L = 1/3$
Young's modulus	FL^{-2}	$S_E = 1$
Stress	FL^{-2}	$S_\sigma = 1$
Mass	FT^2L^{-1}	$S_m = 1/14.4$
Time	T	$S_T = 0.4564$
Poisson ratio	1	$\nu = 1$
Acceleration	LT^{-2}	$S_a = 1.6$

The test model was a space frame structure consisting 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. Each floor had a height of 1.2 m.

The buckling-restrained steel plate shear walls were placed along the height of each floor in the middle frame of the structure. The wall plates were connected to the surrounding frames through 18 high-strength bolts M12 (the thread diameter is 12 mm) on each fishplate. Lateral bracings were set according the Y-direction of the test model. The two ends of the brace were welded at the top and bottom flanges along the diagonal of the upper and lower beams, respectively. The beam-column joint forming a semi-rigid connection was bolted with double-web and double-flange angle steel. Fig. 1 shows the details of the semi-rigid connection.

The column–base connections were made as rigid as possible. The test model was placed on a rigid beam base firmly attached to the shaking table surface with high-strength bolts. The total height and mass of the model were approximately 5.30 m and 18.50 t, respectively. Fig. 2 shows the detailed dimensions and the plan layout of the test model.

The figures show the test model on the shaking table, plan layout, and arrangement of the steel plate shear wall members. The reinforced concrete floor slab was 80 mm thick. Artificial counter weights were applied in the form of reinforced concrete blocks on each storey to accurately simulate the weight distribution of the prototype structure. The weight of the counter from the first to the third floor was 4.20 t, and the top floor's was 2.30 t (Fig. 2(a)). The test model was symmetrical along the north–south direction of the shaking table. The east--west direction was the direction of the table motion (Fig. 2(b)).



(a) Specification of theangle steel (b) Semi-rigid connection

Fig. 1. Details of the semi-rigid connection.