Thin-Walled Structures 132 (2018) 629–641

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Behavior and design considerations of steel plate shear wall with self-centering energy dissipation braces

Longhe Xu[a,*], Jialin Liu[a], Zhongxian Li[b]

[a] School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China
[b] Key Laboratory of Coast Civil Structure Safety of China Ministry of Education, Tianjin University, Tianjin 300072, China

ARTICLE INFO

Keywords:
Steel plate shear wall
Self-centering energy dissipation brace
Hysteretic behavior
Residual deformation
Beam demands

ABSTRACT

An innovative steel plate shear wall with self-centering energy dissipation braces (SPSW-SCEDB) is proposed, and the mechanical behavior is explained. The system has excellent self-centering capability when the remaining restoring force of the braces is greater than or equal to the compressive force of the wall plate. On the basis of capacity design principles, the distribution equations of bending moment, axial force, and shear force along the beam are developed and then verified by cyclic loading analysis. The effects of the SPSW–SCEDB parameters on the bending moment distribution are investigated using an orthogonal experiment and the sequence of plastic hinge appearance in the beam is also analyzed. Results indicate that to satisfy the strength and residual deformation requirements of the system, the initial force of the brace and the thickness of the wall plate should be sufficiently large, and the brace activation force should be controlled to ensure that the plastic hinge in the beam appears before the in-span plastic hinge. The design procedure of the SPSW-SCEDB is presented.

1. Introduction

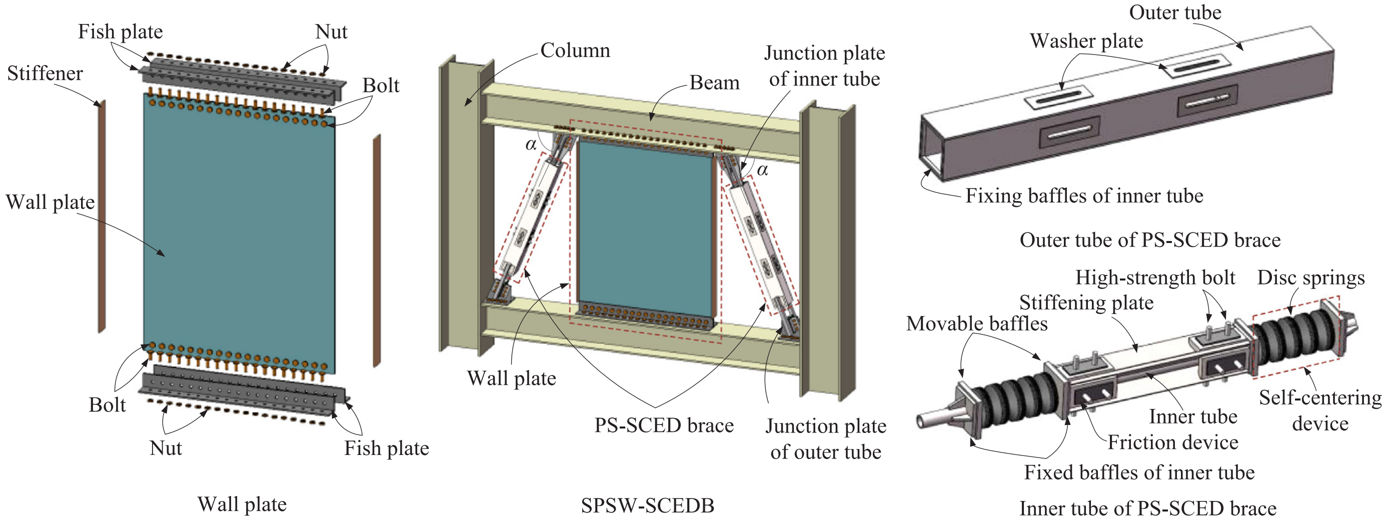
The conventional steel plate shear wall (SPSW) has been widely used as a lateral force-resisting system in a number of buildings to provide primary ductile seismic resistance to serious seismic disasters [1,2]. Until the 1980s, the development of steel plate out-of-plane buckling in the SPSW was prohibited, and heavily stiffened plates were designed [3]. However, the post-buckling tension-field action of the SPSW was found to develop substantial bearing capacity, stiffness, and ductility. Thorburn et al. [4] were the first to propose to use the post-buckling strength of the SPSW. This concept was experimentally verified by Timler et al. [5] and then widely adopted and incorporated into design codes by researchers [6]. Caccese et al. [7] studied the cyclic behaviors of the SPSW with a thin steel plate. The results show that the SPSW with a thin steel plate can effectively resist seismic forces by using the developed post-buckling tension-field action, and the strength increases within a certain range. However, the excellent seismic performances of the conventional SPSW partly benefit from the strength of the boundary columns and beams on the basis of a previous capacity design principle [8]. Plastic hinges in the columns are also developed. With advances in research, optimizing the SPSW system and reducing the requirements for the boundary frame are sought to achieve smaller columns and beams size and effectively ensure structural stability [9]. The premature column failure can be effectively prevented for the SPSW with a beam-connected wall plate (B-SPSW) resulting from the developed tension field acting on the beams only [10]. Ozcelik et al. [11] proposed a mechanics-based analytical model for the B-SPSW to characterize the differences in the developed tension field between the conventional SPSW and the B-SPSW. The partial tension field (PTF) is developed in the B-SPSW and smaller section columns are needed. Several approaches, including those using the perforating wall plate [12], low-yield strength steel [13], and offsetting wall plates at each story [14] to reduce column requirements were also proposed. However, the lateral stiffness and bearing capacity are greatly reduced due to the weakening of the wall plate strength.

The SPSW develops satisfactory seismic performances through yielding of steel and results in significant residual deformations, structural damage to a certain degree, and economic losses [15]. With structural safety and economic costs considered, the self-centering steel plate shear wall (SC–SPSW) was proposed. Clayton et al. [16] proposed a SC-SPSW that used the wall plate to dissipate energy and the post-tension (PT) moment rocking connection for the system to return to its original position; they then presented a design process for the SC-SPSW. Dowden et al. [17] provided insights into the distribution formulations for the beam requirements of the SC-SPSW and integrated moment, axial force, and shear force into the design procedure. The experiment results show that the SC-SPSW has high strength and good self-centering capability, but the energy capability need to be improved [18].

---

[*] Corresponding author.
E-mail address: lhxu@bjtu.edu.cn (L. Xu).

https://doi.org/10.1016/j.tws.2018.09.024



Wall plate

SPSW-SCEDB

Outer tube of PS-SCED brace

Inner tube of PS-SCED brace

Fig. 1. Schematic diagram of the SPSW-SCEDB system.

This study proposes an innovative lateral force-resistance system, SPSW-SCEDB system, which is mainly used in frame-shear wall structure, frame-core tube structure, and other high-rise building structures. The recoverable function not only is characterized by the self-centering capability, but also the wall plate is designed as a replaceable energy dissipation element using bolt connections for facilitating structural repair. Meanwhile, the SPSW-SCEDB system has satisfactory seismic performance with sufficient strength, good ductility and energy dissipation capability. A fundamental understanding of the SPSW-SCEDB system behavior is illustrated and the formulas for calculating the bending moment, axial force and shear force distributions are developed. The effects of the SPSW-SCEDB parameters on the bending moment distribution along the beam are evaluated using the orthogonal experimental method, and the sequence of plastic hinge appearance in the beam is also analyzed. The design procedure of the SPSW-SCEDB system is presented.

2. Configuration and hysteretic behavior of SPSW-SCEDB system

Fig. 1 shows the configuration of the SPSW-SCEDB, where a wall plate as a replaceable energy dissipation element with stiffeners is bolted with beams through the fish plates and separated from the frame columns. 2 inclined PS-SCED braces are symmetrically mounted on both sides of the wall plate. The PS-SCED brace consists of the inner tube, outer tube, friction, and self-centering devices [19,20]. The inner tube and outer tube of the PS-SCED brace are respectively connected to the upper beam and the lower beam through the junction plates.

When the SPSW-SCEDB is subjected to the lateral force, the mechanical behaviors of the PS-SCED brace are illustrated in Fig. 2. It is observed that whether the brace is in tension or in compression, the combination disc springs of the self-centering devices are compressed by the movable baffles, which are pushed by the fixed baffles, to consistently provide the restoring force for the brace. The inner and outer tubes of the brace return to their initial positions to further restore the SPSW-SCEDB.

The hysteretic response of the SPSW-SCEDB can be obtained by superposition of the hysteresis curves of the wall plate and the braces because of the parallel connection between them. Fig. 3 shows the idealized hysteretic curves of the wall plate, PS-SCED brace, and SPSW-SCEDB. As shown in Fig. 3(c), the SPSW-SCEDB exhibits a similar flag-shaped hysteretic response with large lateral stiffness, high bearing capacity, good energy dissipation, and self-centering capabilities. To clearly demonstrate the hysteretic behaviors of the SPSW-SCEDB, the hysteretic curve is divided into 6 different stages in the positive and negative directions according to changes in stiffness. The stages in tension are described as below, and similar stages can be obtained when the system is in compression.

From Point O to Point A, the SPSW-SCEDB shows a large initial stiffness k_1^{S} provided by the elastic stiffness of the wall plate $k_{\mathrm{y}}^{\mathrm{P}}$ and the lateral initial stiffness k_1^{B} of the PS-SCED braces:

$$k_1^{\mathrm{S}} = k_{\mathrm{y}}^{\mathrm{P}} + 2k_1^{\mathrm{B}}\cos\alpha \tag{1}$$

where α is the angle between the braces and the beam. As the applied force exceeds Point A, the wall plate exhibits plasticity and shows a plateau with no stiffness. The stiffness of the AB stage k_2^{S} is only provided by the lateral initial stiffness of the 2 PS-SCED braces.

$$k_2^{\mathrm{S}} = 2k_1^{\mathrm{B}}\cos\alpha \tag{2}$$

Point B indicates that the activation force of the PS-SCED brace $V_{\mathrm{a}}^{\mathrm{B}}$ is

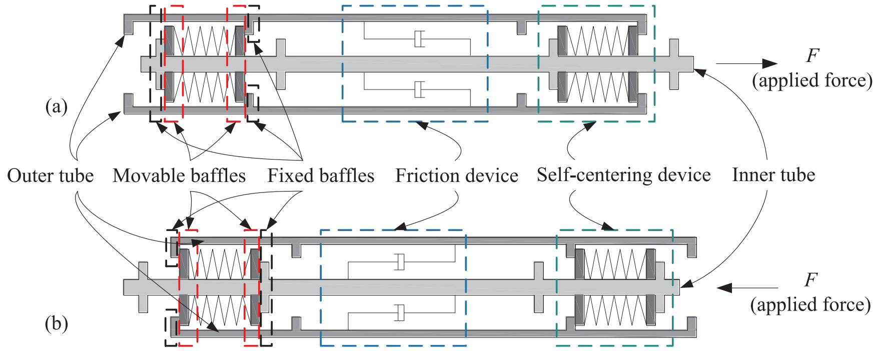


Fig. 2. Mechanical behaviors of PS-SCED brace (a) in tension and (b) in compression.