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Experimental and theoretical study on a novel dual-functional replaceable stiffening angle steel component

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ABSTRACT

Recently, seismic resilience has become a research frontier in civil engineering. The self-centering steel frame can effectively control structural damage and reduce structural residual deformation, which ensures rapid repair after an earthquake. Therefore, such a structural system has attracted extensive attention from researchers. One of the important research directions on self-centering steel frames is the development of high-performance energy-dissipating components. A new type of dual-functional replaceable stiffening angle steel (SAS) component is proposed here. It can effectively improve the stiffness and strength of beam-column connections and has sufficient energy-dissipating performance and ductility. Seven different energy-dissipating components were tested, including one angle steel component and six SAS components. The strength and deformation capacity of the components were compared based on monotonic loading tests. The SAS component with the highest out-of-plane stability and sufficient strength and initial stiffness was selected and subsequently tested under hysteretic loading to investigate its energy-dissipating performance. The theoretical analysis methods of the initial stiffness and the yield moment provided by the SAS components were proposed and validated by the finite-element (FE) models calibrated using experimental data.

1. Introduction

Owing to their advantages of lightweight, high strength, and excellent ductility, steel structures have been widely used in tall buildings. However, since the 1994 Northridge earthquake, many steel joints have been severely damaged when subjected to earthquakes. Such damages are difficult to repair. Therefore, ways to improve structural seismic resilience have become the focus of many researchers in recent years. The main ways to improve structural resilience include the following: (1) avoiding the damage of key components; (2) using replaceable or easy-repair energy-dissipating components; and (3) reducing the residual deformation after an earthquake. Based on these approaches, many resilient structural systems have been proposed [1–6]. Among them, self-centering steel frames [7–15] can well meet structural resilience requirements, and consequently they are widely studied.

One of the key issues in the development of self-centering steel frames is the improvement of the performance of energy-dissipating components. Four types of energy-dissipating devices are commonly used in a self-centering steel frame: (a) energy-dissipating bar, (b) friction devices, (c) angle steels, and (d) shape memory alloy rods. For example, Christopoulos et al. [16] proposed a post-tensioned energy-dissipating connection with energy-dissipating bars, which can undergo large deformations with energy-dissipating characteristics while retaining the beam and column undamaged and without residual drift. The above energy-dissipating components exhibit remarkable energy-dissipating performance. However, it is inconvenient to replace them. Vasdravellis et al. [17,18] adapted web hourglass-shaped pin devices in a self-centering beam-to-column connection as a reliable method for increasing the energy-dissipating capacity of structures under seismic loading. The above work has shown that replacing the web hourglass pins is straightforward and does not require welding. Additionally, the web hourglass pins have remarkable energy-dissipating performances. Flange friction devices [13,14] and web friction devices [19,20] were used in self-centering frames to dissipate seismic energy. The test results reveal that the energy-dissipating performance of the friction devices is satisfactory. However, the friction coefficient of the friction devices are likely to change after long-term static pressure, and this will

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influence the seismic-energy-dissipating performance. Angle steels, which are convenient to replace and capable of dissipating seismic energy, were widely used to connect the beams and columns in self-centering steel frames. For example, Garlock et al. [21,22] experimentally investigated the behavior of angles in a bolted angle beam-to-column connection and discussed the influence of the design parameters on the seismic response of post-tensioned steel moment resisting frame systems; Deng et al. [23] tested and simulated full-scale self-centering beam-to-column connection, and the result revealed that this type of connection exhibits a reasonably resilient performance with only a straightforward replacement of the angles. Moradi and Alam [24] developed detailed three-dimensional finite-element (FE) models of steel beam-column connections with post-tensioned strands and validated these models with respect to the results of prior experiments on interior post-tensioned connections with top-and-seat angles; furthermore, the performance of these models under cyclic loading was analyzed. Moradi et al. [25,26] identified the parameters that significantly influence the lateral load-drift response and seismic response of steel post-tensioned connections, through FE analysis. López-Barraza et al. [27] and Shiravand and Mahboubi [28] used post-tensioned steel moment resisting frames with semi-rigid connections to regulate the hysteretic energy demands, reduce the maximum inter-story drift, eliminate structural damage, and minimize residual drifts. The results of the above studies on semi-rigid connection demonstrated that this type of connection when adopted in self-centering steel frames exhibits a reasonably resilient performance. The disadvantage of this type of semi-rigid connection is that it exhibits lower stiffness and strength compared to traditional bolt-welded connections or full-welded connections. Wolski et al. [29] adopted angle steel in conjunction with bottom flange friction device as beam-to-column connection. The test results indicate that this type of energy-dissipating device can provide reliable energy dissipation. In addition, the connection remains damage-free under the design earthquake. Wang et al. [30,31] used shape memory alloy rods or a combination of shape memory alloy rods and angle steels, as beam-column connections. Shape memory alloys can effectively improve the energy-dissipating performance and self-centering capability of beam-to-column connections. However, the shape memory alloy is expensive, which hinders its popularization and application. Therefore, this study attempted to develop a new type of energy-dissipating device, which can be adopted in self-centering steel frames with convenient reparability and higher economic benefit and can simultaneously guarantee adequate stiffness, strength, and energy-dissipating performance.

In this work, a new type of dual-functional replaceable stiffening angle steel (SAS) component (comprising an angle steel and two rib stiffeners) was proposed. It can be adopted as the beam-column connections in self-centering steel frames. Rib stiffeners formed by cold bending, combined with angle steels can improve the strength and initial stiffness of beam-to-column connections in comparison with angle steel connections. Additionally, the energy dissipation of the beam-to-column connections can be increased by tensile and compressive deformation of rib stiffeners caused by the rotation at the beam-column interface. Moreover, the SAS component is connected with the beam and column through bolts and can be replaced rapidly after an earthquake. Therefore, the proposed SAS components can promote the structural seismic resilience. The connection between the proposed SAS components and floor slab is not considered in this work, which will be implemented in the future. In this work, seven different energy-dissipating components are examined, including one angle steel component and six SAS components. The strength and deformation performance of each component were compared based on a monotonic loading test. The SAS component with the highest out-of-plane stability and sufficient strength and initial stiffness was selected. Subsequently, the hysteretic test was carried out to investigate the energy-dissipating performance. Theoretical models of the initial stiffness and the yield moment provided by SAS components are proposed, and they were validated by FE models calibrated using experimental data.

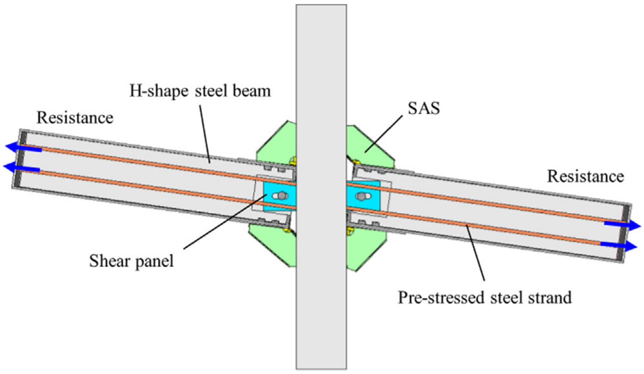

Fig. 1. Principle of SAS in self-centering steel frames.

2. Principle of dual-functional replaceable SAS components

The construction of the self-centering steel joint discussed in this work is shown in Fig. 1. The SAS components have two functions: to resist the bending moment and to dissipate seismic energy. Meanwhile, the shear panels can resist the shear force, and the pre-stressed steel strands can provide self-centering capacity after earthquakes. A number of researchers have studied this type of self-centering steel joint [26–31] and verified that the energy-dissipating component is the key to ensuring energy-dissipating performance, and the convenient reparability of the energy-dissipating devices is the key to ensuring seismic resilience. Therefore, to improve the performance of the traditional angle steel connection, a new type of dual-functional replaceable SAS component is proposed in this work, as shown in Fig. 2, in which SAS-IN refers to the rib stiffener installed inside the angle steel, while SAS-OUT refers to the rib stiffener installed outside the angle steel. By combining the angle steels with the rib stiffeners, the strength and energy-dissipating performance are improved. Additionally, the rib stiffeners are manufactured through cold forming to avoid the negative effect due to welding and other thermal processing, which may reduce the deformation and energy-dissipating performance.

3. Experimental program

3.1. Design of specimens and material properties

The specimens were designed based on the prototype of the web-bolted flange-welded beam-column composite joints of a high-rise building [32]. The prototype beam-column joints were designed following the Code for Seismic Design of Buildings (GB 50011-2010) [33], in which the specified limitation of nonlinear story drift is 0.02 rad and seismic performance is defined as the state wherein the structure can be repaired after the design basis earthquakes, whose 50-y probability of exceedance is 10%. The specimens were designed according to the yield strength specified in the design code [33]. In order to balance the energy dissipation and self-centering performance of the connection, the yield moment provided by the energy-dissipating device SAS was designed to be half of the yield moment provided by the web-bolted and flange-welded connection or the welded connection, which was the target performance for the preliminary exploration. The objective of this test was to investigate the contribution of the SAS component to the seismic performance of the angle steel bolted beam-column connection. Therefore, the pretension strand was not included in the specimens. The replicability of the SAS components is also investigated in this test. An additional objective of these tests was to verify whether replaceable energy-dissipating components can attain the required plastic rotation without significant damage and strength deterioration and thus achieve