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Experimental evaluation of large-scale dual-core self-centering braces and sandwiched buckling-restrained braces

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ABSTRACT

This paper presents structural characteristics of large-scale dual-core self-centering braces (DC-SCBs) and sandwiched buckling-restrained braces (SBRBs) in a series of cyclic tests. The DC-SCB has a flag-shaped hysteretic response with high axial stiffness and minimal residual deformation, exhibiting a self-centering mechanism. The SBRB as conventional BRBs has much higher energy dissipation capacity than the DC-SCB, but larger residual deformations are expected for structures equipped with SBRBs. The primary objective of the research was to conduct experimental studies that established a direct comparison basis between DC-SCBs and SBRBs designed with similar axial capacity and length. Three SCBs and SBRBs that were about 7.5 m long and had maximum axial forces from 1500 to 6000 kN were tested to evaluate their cyclic behavior and durability. In general, these tests have shown that the DC-SCB and SBRB exhibit robust cyclic performances with good deformation capacity and durability. The axial elastic and post-elastic stiffnesses of DC-SCB were around two and five times those of SBRB, indicating that the DC-SCB is more effective to resist lateral forces than the SBRB in structures, but the energy dissipation of DC-SCB was around one-third of that of SBRB.

1. Introduction

A steel-braced frame is a reliable structural system for earthquake resistance; the brace is designed to dissipate seismic energy so that beams and columns can be expected to experience low seismic damage. Such steel braces include buckling-restrained braces (BRBs), self-centering braces (SCBs), and many other passive control braces. The BRB is a good seismic-resisting brace because it yields in both tension and compression with abundant energy dissipation [1–8]. The sandwiched buckling-restrained brace (SBRB) proposed by the authors [9] is composed of a ductile steel core, a pair of buckling-restrained member and high-strength bolts. Compared to conventional BRBs that have a steel core inserted into a concrete-filled restrained member, using fully tensioned bolts to sandwich a core plate between a pair of restrained members enables fast assembly. The advantage is the ability to disassemble the brace, which enables replacement of the core plate independently of the restrained members and also provides an opportunity for inspection of the core plate after large earthquakes. Numerous tests have demonstrated satisfactory seismic performances of SBRBs or frames with SBRBs [10,11], but the buckling-restrained braced frame (BRBF) under cyclic loading tests or nonlinear time history analyses is prone to lateral residual deformation [12–14]. The BRB with low post-yield axial stiffness also decreases shear resistance in building structures subjected to large earthquakes.

A post-tensioned (PT) technique, which applies high-strength steel tendons to compress a beam to a column or a column to a footing, eliminates welding of the steel beam to the steel column or cast-in place concrete work in the field. The PT beam-to-column connections have been demonstrated to be effective in eliminating residual deformations of structures in earthquakes [15–18]. However, a slab that is typically constructed in a building frame limits opening of the gap at the beam-to-column interface, affecting the self-centering (SC) property of frames [19,20]. Therefore, a single structural member that can have both SC and energy dissipation properties to eliminate the effects of slab-restraint on the SC performance of frames has been developed in the past few years. Chou et al. [21,22] proposed a novel steel dual-core self-centering brace (DC-SCB), which utilizes three conventional steel bracing member sets, two friction devices, and two sets of tensioning elements that are in a parallel arrangement. Two inner cores and two sets of PT elements in the DC-SCB can double axial elongation capacity of the self-centering energy-dissipating (SCED) brace [23] if the same PT elements are used in both braces. The

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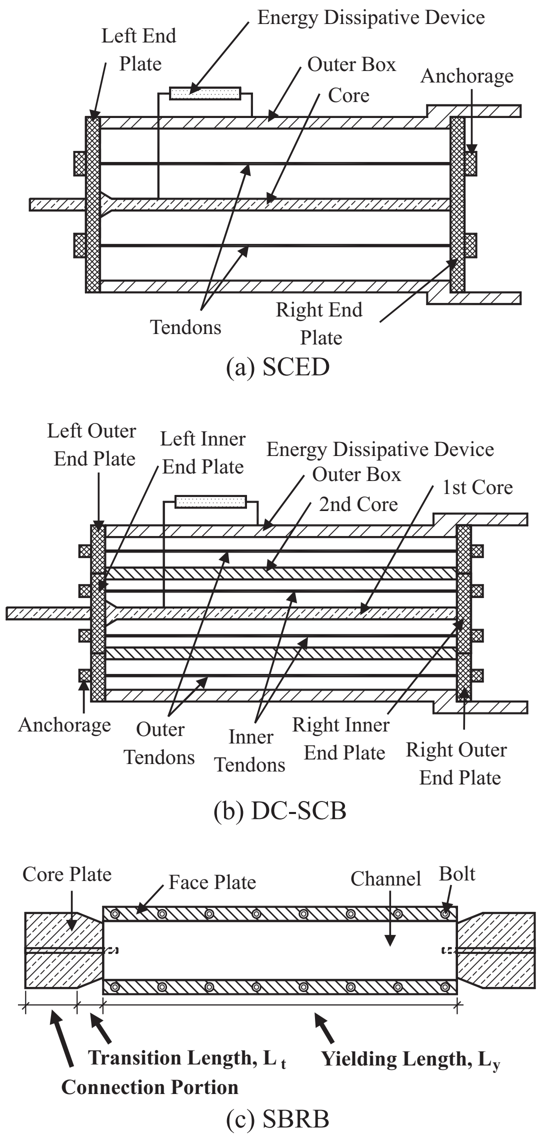

Fig. 1. Brace components.

mechanism and kinematics of the DC-SCB have been verified successfully from brace tests by using either fiber-reinforced polymer (FRP) tendons or high-strength steel tendons as the PT elements [22,24]. Hysteretic modeling and seismic analyses of steel-braced frames with either BRBs or DC-SCBs have shown that SCBFs generally exhibit smaller peak interstory drifts and residual drifts than those of BRBFs [13,14].

The objective of this work was to evaluate the cyclic behaviors of DC-SCBs and SBRBs, which were designed to develop similar axial loads at a target drift. The initial elastic stiffness, post-elastic stiffness, residual deformation, energy dissipation and durability of the SBRB and DC-SCB could be directly compared in a series of cyclic tests. Prior to this work, the maximum axial capacity of the DC-SCB and SBRB that were ever tested had axial loads of around 2000 kN. For DC-SCBs and SBRBs to be useful in a wide range of building structures, practical, constructible DC-SCB and SBRB designs of high axial capacity must be available. To this end, a high-capacity DC-SCB and SBRB with maximum axial strength of 6000 kN was designed, built and tested. A total of six 7.5 m-long specimens were fabricated and tested at the National Center for Research on Earthquake Engineering (NCREE), Taiwan; each specimen was subjected to six phase tests to evaluate their seismic behavior, durability and failure modes.

The development and prior tests of the DC-SCBs and SBRBs have demonstrated that it is possible to design both braces to develop high axial loads. Therefore, the first part of this paper describes briefly the mechanism and kinematics of the DC-SCB and SBRB. The second part of this paper presents test results of six 7.5 m-long braces, which focus on their axial stiffness, residual deformation, durability and energy dissipation. The study is essential for the application of DC-SCBs and SBRBs in bracing frame systems because it highlights structural characteristics of both braces in details that can be used in seismic design.

2. Dual-core self-centering brace and sandwiched buckling-restrained brace

2.1. DC-SCB

Christopoulos et al. [23] presented a self-centering energy-dissipating (SCED) brace that uses two steel bracing members for compression, friction devices for energy dissipation, and one set of FRP tensioning elements to provide the SC property (Fig. 1(a)). When the initial PT force and the force required to activate the friction device are exceeded, the outer box and the inner core begin to move (Fig. 2(a)). The relative displacement δ between the outer box and the inner core, which is also the deformation of tensioning elements, results in an axial displacement of the brace, δ.

Chou and Chen [21,22] proposed a dual-core self-centering brace (DC-SCB) that uses two inner cores and two sets of PT elements to double the self-centering deformation capacity of the SCED brace (Fig. 1(b)). Two inner end plates are placed on each end of the second core, and two outer end plates are placed on each end of the outer box and the second core. All bracing members, end plates, and tendons in the DC-SCB are arranged so that a relative motion induced between these bracing members causes serial elongation of the inner and outer tendons to achieve the desired brace elongation or shortening. When the initial PT force and the force required to activate the friction device are surpassed, the outer box and the first core begin to move with respect to the second core. The relative displacement δ between the outer box and second core and between the first core and second core results in an axial displacement of the brace, 2δ (Fig. 2(b)), which doubles the elongation of the outer and inner tendon sets, δ. Fig. 3(a) shows a typical cyclic response of the DC-SCB or the SCED, which is attributed to the bi-linear elastic behavior of PT elements with bracing members and the rigid plastic behavior of frictional energy dissipative devices.

The initial PT force applies compressive forces $P_{1c,in}$, $P_{2c,in}$ and $P_{ob,in}$ to each bracing member. The tensile activation force of a DC-SCB at which the bracing members begin to move is

$$F_{dt} = P_{dt} + P_f = \frac{nT_{in}}{2} + P_f \tag{1}$$

where T_{in} is the initial PT force in each tendon, n is the total number of tendons, and P_f is the frictional resistance of the energy dissipative device. Considering the friction device, the axial deformation δ_{dt} corresponding to the activation force is

$$\delta_{dt} = 2\delta_{in} + \delta_{2c} = \frac{2P_f}{K_{ob}} + \frac{nT_{in}/2}{K_{2c}} + \frac{nT_{in}}{K_{1c} + K_{2c} + K_{ob}} \tag{2}$$

where δ_{in} is the initial shortening of the bracing member, δ_{2c} is the axial deformation of the second core resulting from the initial force of $P_{2c,in}$ to $nT_{in}/2$, K_{1c}, K_{2c}, and K_{ob} are the axial stiffnesses of the first core, second core, and outer box, respectively. The elastic stiffness of the brace is $K_{m,it} (= F_{dt}/\delta_{dt})$. When the brace load reaches the tensile activation force, the post-elastic stiffness of the brace, $K_{m,pt}$,