Journal of Constructional Steel Research 101 (2014) 19–32

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Development of cross-anchored dual-core self-centering braces for seismic resistance

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ARTICLE INFO

Article history:
Received 6 November 2013
Accepted 29 April 2014
Available online 24 May 2014

Keywords:
Cross-anchored dual-core self-centering brace (SCB)
High-strength steel tendons
Cyclic test
Finite element analysis

ABSTRACT

The steel dual-core self-centering brace (SCB) is an innovative structural member that provides both energy dissipation and re-centering properties to structures, reducing the residual drift of braced structures in earthquakes. The axial deformation capacity of the brace is doubled by using two inner cores and one outer box and by serial axial deformations of two sets of parallel tensioning elements. The original dual-core SCB that used E-glass fiber tendons or T-700 carbon fiber tendons as tensioning elements exhibited good self-centering and energy dissipation up to an interstory drift of 2.5%. The new cross-anchored dual-core SCB halves the work required to apply the initial post-tensioning forces to tendons. The potential use of high-strength steel tendons as tensioning elements is studied herein, and the effects of the number of cycles on the brace behavior, energy dissipation, and durability of the steel tendon-anchorage system are also examined. First, the mechanics and cyclic behavior of the new brace are explained; a 7950 mm-long cross-anchored dual-core SCB is then tested six times. The cross-anchored dual-core SCB exhibits excellent self-centering property up to a drift of 2.5% and a maximum axial load of 1700 kN. No damage to the steel tendons, anchors or bracing members is found after three cyclic loading tests with increasing displacement amplitudes and 60 low-cycle fatigue tests. Finite element analysis further confirms the hysteretic responses and mechanics of the cross-anchored dual-core SCB in the cyclic test.

1. Introduction

A steel-braced frame is a reliable structural system in earthquakes; the braces are designed to dissipate seismic energy such that the beams and columns remain undamaged. Such energy dissipating braces include concentric braces, buckling restrained braces, and many other passive control braces. In an earthquake, the concentrically-braced frame (CBF) causes a large plastic deformation in the gusset connection. The gusset connection must be carefully designed to ensure the high ductility of the CBF [1]. A buckling-restrained braced frame (BRBF) is designed to limit plastic deformations in the brace during earthquakes. A new design accounts for the effects of both the brace action and frame action on the gusset to ensure stable energy dissipation of the BRB [2,3]. Although many studies have demonstrated the satisfactory seismic performance of BRBFs and CBFs [3–8], braces in either BRBFs or CBFs under severe ground motion do not only dissipate seismic energy but also cause residual deformation [9–11].

A post-tensioned (PT) technique, which uses high-strength steel tendons to compress a beam to a column or a column to a footing, has been demonstrated to be effective in eliminating residual deformations of structures in earthquakes [12–16]. However, a slab that is typically used in a building frame limits opening of the gap at the beam-to-column interface, affecting the self-centering (SC) property of the frame [17,18]. Therefore, the use of a single structural member, which exhibits both SC and energy dissipation properties, to eliminate the effects of slab-restraint on the SC performance of structures has been investigated [19–25]. Braces with both SC and energy dissipation properties have been proposed; fiber-reinforced polymer (FRP) tendons or shape-memory alloy bars have been used in these braces as tensioning elements to provide restoring forces to the brace. Christopoulos et al. [19] 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. Miller et al. [20] developed a self-centering buckling-restrained brace (SC-BRB) that uses shape-memory alloy bars to provide restoring forces and a BRB for energy dissipation. Chou and Chen [21,22] proposed a dual-core self-centering brace (SCB) that uses an additional inner core and a second parallel set of PT elements to double the self-centering deformation capacity of the SCED brace. Various types of dual-core SCBs that use the same mechanisms and kinematics

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http://dx.doi.org/10.1016/j.jcsr.2014.04.035
0143-974X/

can be found elsewhere [23,24]. Hysteretic modeling and seismic analysis of steel-braced frames with either BRBs or dual-core SCBs have shown that the SCB frames generally exhibit smaller peak interstory drifts and residual drifts than those of BRBFs [11,25]. These studies confirm that the dual-core SCB performs as predicted by the mechanics and its elongation capacity doubles that of the SCED brace owing to serial deformations of two sets of parallel tensioning elements [21–23]. However, the second set of tensioning elements doubles not only the axial deformation capacity of the brace but also the work required to apply the initial post-tensioning forces to tendons.

This work develops a new cross-anchored dual-core SCB, which uses an intermediate second core to anchor half of the tendons and provide axial force transfer. The intermediate second core is placed inside other bracing members so only half of the tendon anchorages are exposed outside the outer end plates, halving the work required to apply the initial PT forces to the brace. Furthermore, the original dual-core SCB, which uses high-strength steel tendons, did not perform as predicted owing to a loss of the initial tendon forces. The reduction that was caused by a poor tendon-anchorage system at a low initial PT force (16% of the breaking load of the steel tendons) has never been observed in PT connection tests when the initial PT force is 30–40% of the breaking load of the steel tendons [15–18,26]. Therefore, 30% of the steel tendon breaking load is utilized in this work to study whether the high-strength steel tendons can be adopted as tensioning elements in the cross-anchored dual-core SCB.

The objective of this work is to verify the cyclic behavior of the new cross-anchored dual-core SCB, which uses high-strength steel tendons as tensioning elements to maintain its self-centering properties and to prevent premature failure of the FRP tendons [21,22] when the brace is overloaded beyond the design limit. After the mechanics and hysteretic responses of the cross-anchored dual-core SCB are introduced, the results of cyclic tests of several steel tendon-anchorage elements and one friction device are presented. A 7950 mm-long cross-anchored dual-core SCB, which uses ASTM A572 Gr. 50 steel bracing members and ASTM A416 Grade 270 steel tendons, is tested six times to evaluate its cyclic performance. Finite element analysis is then used to verify the mechanics of the cross-anchored dual-core SCB.

2. Mechanics of a cross-anchored dual-core SCB

Fig. 1 shows the cross-anchored dual-core SCB, which consists of three steel bracing members, two sets of PT element, energy dissipation devices, and end plates. The three steel bracing members are designated as the first core, the second core, and the outer box; the second core is placed inside the two other bracing members. 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 first core. The outer tendons are anchored to the left inner end plate and the right outer end plate; the inner tendons are anchored to the left outer end plate and the right inner end plate (Fig. 2(a)). Both ends of tendons are anchored to the ends of different bracing members to double the elongation capacity of the SCB by the serial deformations of two sets of parallel tensioning elements [27]. These tendons are post-tensioned to compress the bracing members against the end plates and are elongated to provide self-centering when the brace deforms axially. The inner end plate always bears against the second core so the outer end plate does

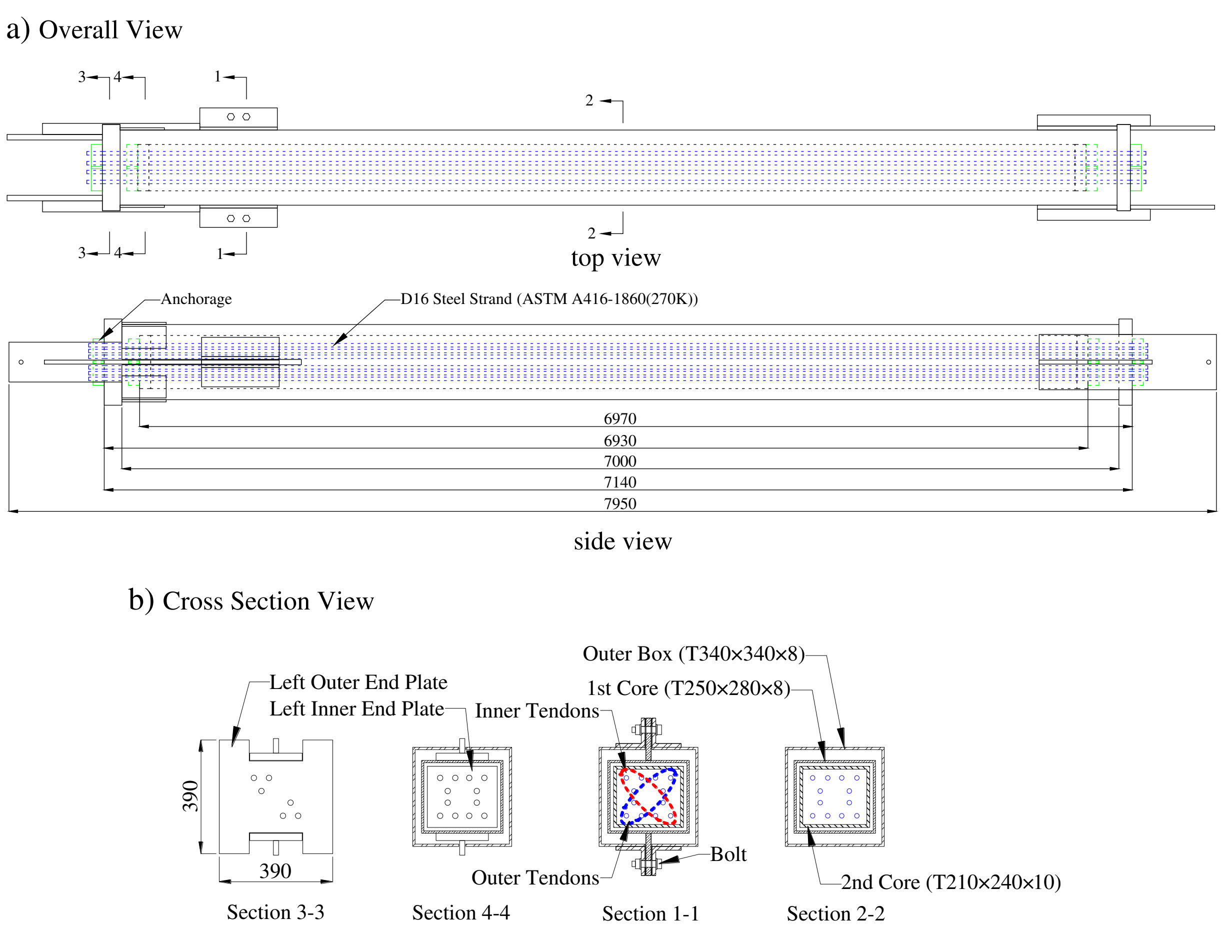

Fig. 1. A proposed cross-anchored dual-core SCB (unit: mm). (a) Overall view. (b) Cross section view.