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Seismic design and tests of a full-scale one-story one-bay steel frame with a dual-core self-centering brace

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ABSTRACT

Traditional seismic resisting systems in a large earthquake can experience significant damage and residual drifts due to energy dissipation of structural members, which leads to difficult or expensive *repairs*. A steel dual-core self-centering brace (DC-SCB), which utilizes three steel bracing members, two friction devices, and two sets of tensioning elements that are in a parallel arrangement for doubling its axial deformation, has been proposed and validated to provide both the energy dissipation and self-centering properties to seismic resisting systems. A prototype three-story steel dual-core self-centering braced frame (DC-SCBF) was designed, and its full-scale first-story one-bay DC-SCBF was tested to (1) validate the system response, (2) study force distributions in framing members as damage progresses in the DC-SCB, beam or columns, and (3) investigate the repair and replacement characteristics of the frame. The DC-SCBF subassembly specimen showed beam and column yielding at 1% lateral drift, beam local buckling at 1.5% lateral drift and no damage in the brace at 2% lateral drift; the residual drift that was caused by beam yielding or local buckling was 0.3–0.5% after multiple tests. Nonlinear time history analyses were performed on the prototype braced frame to obtain seismic demands under both design and maximum considerable levels of earthquakes.

1. Introduction

A steel braced frame that *relies* on brace members to resist lateral loads and dissipate seismic energy can minimize damage in *other gravity and lateral force resisting elements* in earthquakes. A typical braced frame such as a concentrically braced frame (CBF) or a buckling restrained braced frame (BRBF) is expected to show nonlinear behaviors after moderate interstory drifts of 0.3–0.5%. *In large earthquakes*, these bracing members experience large deformations into the post-buckling or post-yield range. Numerous works have demonstrated satisfactory seismic performance of BRBFs or CBFs [1–10], but these braced frames under earthquakes are prone to lateral residual deformation over the building height due to large energy dissipation in the braces [11]. Applying unbonded post-tensioning (PT) technology to beam-to-column connections to reduce residual drifts of buildings in earthquakes has been demonstrated to be an effective solution [12–14]. Several large-scale tests on steel post-tensioned self-centering (SC) frames also have shown satisfactory SC properties and energy dissipation [15–18]. However, typical slab construction provides restraints to gap *behavior* of PT beam-to-column connections, significantly changing the SC properties of the frame in large deformation [19,20].

Applying PT technology to a single brace is a feasible method to eliminate the restraint of columns or slabs to the frame expansion, as well as the residual drift of structures. Chou et al. [21–23] *developed* a steel dual-core self-centering brace (DC-SCB), which utilizes three conventional steel bracing members, two friction devices and two sets of tensioning elements that are in a parallel arrangement. Three bracing members and two sets of PT elements in the DC-SCB double the axial elongation capacity of the self-centering energy-dissipating (SCED) brace [24] if the same PT elements are used in both braces. The mechanics 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 PT elements. A cross-anchored DC-SCB, which positions the second bracing member as a floating member to simplify the force transfer mechanism and to reduce the work of application of initial PT loads in the original DC-SCB, was also proposed for the seismic resistance [25].

Past work focused on the development and validation of the DC-SCBs that can exhibit a flag-shaped hysteretic response with

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minimal residual deformations. The seismic performance of a steel frame with DC-SCBs has never been studied experimentally; the inelastic responses in the beam, column and brace under multiple tests *require consideration*. The objective of the work was to study the seismic behavior of a dual-core self-centering braced frame (DC-SCBF), which was designed based on the engineering practice for BRBF design. Although the current seismic provisions do not have a design guideline for such a system, the guideline for the BRBF design specified in AISC seismic provisions [26] is adopted because the DC-SCBF generally exhibits similar or smaller peak interstory drifts and residual drifts than the BRBFs based on the same design parameters [23,27]. At medium-to-large drift levels, the beam and column base in both braced frames are expected to develop inelastic behavior or even local buckling.

A prototype three-story steel DC-SCBF was first designed and analyzed; a full-scale one-story one-bay DC-SCBF specimen that represented the prototype first-story braced frame was then tested using multiple loading protocols. The objectives of the test program were to (1) validate the system response of the DC-SCBF, (2) study force distributions in framing members as damage progresses in the DC-SCB, beam or columns, and (3) investigate the repair and replacement characteristics of the braced frame (the same frame, brace and PT elements will be reused in multiple tests). Nonlinear push-over analyses and time history analyses of the prototype DC-SCBF under a suite of 20 earthquake ground motions representative of the design based earthquake (DBE) and maximum considered earthquake (MCE) levels were considered. These seismic demands and displacement histories were adopted for evaluating the performance of the DC-SCBF subassembly specimen in the tests. For comparison purposes, a special moment-resisting frame (SMRF) was similarly designed and analyzed. A comparison between BRBFs and DC-SCBFs subjected to a suit of ground motions can be found elsewhere [23,27].

2. Design of a prototype three-story DC-SCBF and SMRF

Fig. 1 shows the plan and elevation of the prototype building, which was assumed to be located on stiff soil in Los Angeles, California. The DC-SCBF or SMRF system was designed for providing lateral load resistance in the east–west direction. First, two one-bay DC-SCBFs were considered in design of the braced system; each DC-SCBF was composed of H-shaped steel columns, steel beams and single-diagonal DC-SCBs (Fig. 1(b)). Beam-to-column moment connections were adopted in the DC-SCBF system that would be clarified as a dual system in the US; simple shear connections were used in the rest of the building. For comparison purposes, two one-bay SMRFs were designed to substitute for the DC-SCBFs in resisting earthquake loads (Fig. 1(c)). In both frames, the design dead loads were 5.28 kPa (110 psf) and 4.32 kPa (90 psf) for the floors and the roof while the live loads for the floors and the roof were 2.39 kPa (50 psf). Effective seismic weights for the floors and the roof were 2999 kN and 2445 kN, respectively, resulting in a total seismic weight of the building equal to 8443 kN. The design followed ASCE standard [28] for the SMRF system with a force reduction factor R of 8, an overstrength factor Ω_0 of 3 and a displacement amplification factor C_d of 5.5. The design of the DC-SCBF used a force reduction factor R of 8, an overstrength factor Ω_0 of 2.5 and a displacement amplification factor C_d of 5 (*BRBF values*). The mapped MCE spectral response acceleration at a short period S_S and one second S_1 was 1.5 g and 0.6 g, respectively. For the building located at site class D, the site coefficients F_a and F_v were 1.0 and 1.5, respectively, leading to design spectral response accelerations at a short period and one second of 1.0 g and 0.6 g, respectively. Table 1 lists the structural period T, the seismic response coefficient C_s and the seismic design base shear V_{des} that includes the redundancy factor ρ_y of 1.5 for both frames. A conservative value of ρ_y was used based on two earthquake-resisting frames in one loading direction and the specific ground floor area [28]. The structural period was estimated based on:

$$T_a = C_t h^x \tag{1}$$

where C_t is 0.0724 and 0.0731 for the SMRF and DC-SCBF, respectively; x is 0.8 and 0.75 for the SMRF and DC-SCBF, respectively, and h is the building height. The design base shear of the DC-SCBF is about 1.3 times that of the SMRF because periods used for calculating the design force of both frames are 0.47 and 0.69 s (Table 1), respectively.

Two DC-SCB types were proposed in the past works [22,23,25]; the cross-anchored DC-SCB that consists of three steel box members, inner and outer sets of PT elements, two frictional devices and four end plates was adopted in this study. Fig. 2(a) and (b) shows the dimension of the DC-SCB used in the first floor of the prototype building and the subassembly frame specimen. The three steel box members are designated as the first core, the second core and the outer box; the second core is placed inside two other box 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. Both ends of tendons are anchored to the ends of different bracing members to double the elongation capacity of the brace by the serial deformations of *the* tensioning elements. These tendons are post-tensioned to compress all bracing

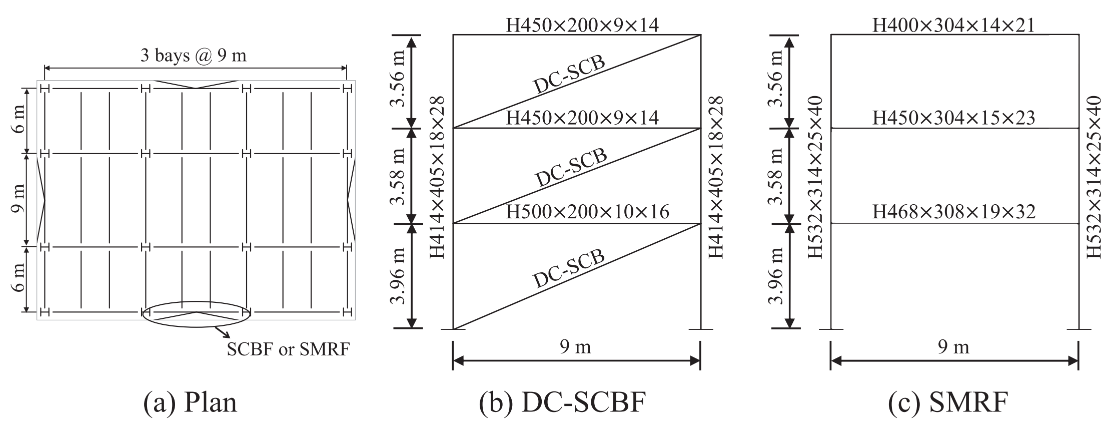

Fig. 1. Plan and elevation of a prototype three-story frame.