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Seismic performance of all-steel buckling-controlled braces with various cross-sections

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ABSTRACT

An all-steel buckling-controlled brace (BCB) with two different configurations is studied and its behavior is compared with the conventional braces in terms of energy dissipation and ductility capacities. A parametric study was first conducted on an ensemble of all-steel BCBs in a general purpose finite-element (FE) software in order to study the influential parameters of these braces. The select types of BCBs were then experimentally investigated. Finally, seismic performance of buckling-controlled braced frames (BCBFs) was compared with that of special concentrically braced frames (SCBFs) as well as that of buckling-restrained braced frames (BRBFs). The study concludes that (1) the BCB with round-in-square tube section has stable hysteretic behavior either when thickness ratio of the outer tube to inner tube is greater than one or when an enhanced gusset plate is employed. Furthermore, due to much increased compressive strength in square in round BCBs, it is necessary to utilize an enhanced gusset plate in order to achieve ductile behavior; (2) BCBs have a stable and symmetrical hysteretic behavior in tension and compression with little post-yielding strength decrease or increase, avoiding the significant unbalanced force on the brace-intersected beams in SCBFs and BRBFs; (3) BCBFs are capable of sustaining larger story drift ratio response without considerable strength loss in comparison with SCBFs; (4) Inelastic deformation demand distributes throughout the height of BCBF floors, preventing the occurrence of weak story often observed in SCBFs.

1. Introduction

Hollow Structural Sections (HSS) are the most popular shapes utilized in Special Concentrically Braced Frames (SCBFs) construction for their large compression strength-to-weight ratio and simplicity in construction. However, recently observed premature fracture of HSS braces and its potentially hazardous impact on the collapse prevention objective of SCBFs have challenged researchers to find effective and practical solutions to reducing the seismic hazard.

A SCBF is expected to dissipate the major portion of the seismic energy input through buckling and yielding of its braces, which would undergo large ductility demands, on the order of 10 to 25 [1,2], when subjected to severe earthquake ground motions. Several evaluations on seismic demands in ductile CBFs [3–5] indicated that mean peak interstory drift demands on CBFs may reach nearly 4% [6] and up to 5.7% [3] for ground motions with 10% and 2% probability of exceedence (P.E.) in 50 years, respectively. Recent experimental studies [7–13], on the other hand, showed that a few cycles with relatively large plastic amplitudes lead to local buckling-induced fracture in HSS braces, which may in turn precipitate torsional irregularities and inelastic deformations (or even fracture) in columns [7] due to framing action subsequent to brace fracture. Moreover, experimental studies on isolated steel brace specimens demonstrated that brace fracture is likely to occur prior to attaining a peak brace ductility of 6 [11,13] to 10 [13,14], which correspond to an equivalent inter-story drift angle of 0.015 to 0.025. This high discrepancy between the anticipated ductility capacity of ductile CBFs and the seismic demand on the structure may be attributable to the early experimental data obtained from testing of small-size conventional braces made of double angles [15–17], double channels [16], W- and WT-shapes [16,18], which usually possess longer fracture life than tubular braces.

Further, conventional buckling braces exhibit unstable and unsymmetrical inelastic cyclic behavior due to the strength degradation following brace buckling. This abrupt change in compressive strength not only imposes large unbalanced brace forces [19] on brace-intersected girders and columns in braced bays, but also significantly amplifies the possibility of weak story formation [6] in conventional CBFs. Although recent advances in the seismic design provisions (i.e. AISC 341 [20] and Eurocode 8 (EC8) [21]) resulted in more stringent design requirements for ductile CBFs with the purpose of enhancing their relatively less ductile and redundant behavior, researchers addressed the issues associated with the non-dissipative structural member design, which are designed to remain elastic, such as girders [1,22] and columns [23,24] in ductile CBFs. For instance, Brandonisio et al. (2012) proposed an approach alternative to the one stipulated in EC8. In the proposed design procedure, the authors

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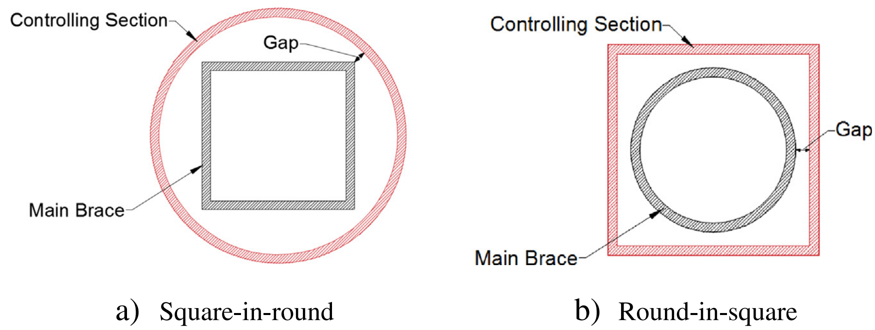

Fig. 1. Scheme of TinT-BCBs.

modified the overstrength factor and slenderness limitations given by EC8 to reduce the overall structural weight and to obtain a more uniform plastic deformation distribution along with a satisfactory overall non-linear behavior [23]. Likewise, Bosco et al. (2014) studied the seismic response of columns in 4- and 8-story CBFs with diagonal braces by means of non-linear dynamic analyses using five sets of ground motions with 10%, 5%, 4%, 3% and 2% P.E. in 50 years. Their results indicated that both gravity columns and the columns in braced bays designed according to EC8 experienced yielding (or buckling) before diagonal braces attained their assumed ductility limits [25]. Shen et al. (2014, 2015) studied ductile CBFs with popular two-story X-bracing configuration, which is a combination of inverted V- and V-type bracing configurations in alternating stories. It is known that two-story X-bracing system usually leads to light brace-intersected beams due to the fact that axial forces in the braces cancel out each other when first-mode mechanism is assumed. However, their numerical results indicated that this assumption is valid for rare situations and might not be applicable to all structures [1,22]. They concluded that the unbalanced brace forces would induce substantial demands on the brace-intersected girders designed based on the first-mode assumption stipulated in the current Seismic Provisions [20].

Efforts to mitigate seismic hazards in CBFs resulted in numerous all-steel buckling restrained braces (BRBs) [26–29] to date. Although all-steel BRBs have been increasingly attracting more attention from researchers, the extreme complexity [26,27] in the all-steel BRB configurations are among the drawbacks of these braces, which make the engineering society hesitant to employ these braces in an actual CBF construction as an effective substitute for conventional steel braces. With the purpose of avoiding such complexity, instead of using combination of filler plates, channels and HSS along with bolted or welded attachments as a buckling restraining mechanism, Shen et al. (2016) introduced a simple and promising buckling control concept without compromising the intended performance goals and practicality [2]. As illustrated in Fig. 1, Tube-in-Tube buckling-controlled braces (TinT-BCBs) consist of a load bearing tube (main brace), which is responsible for lateral resistance to the seismic forces, encased in another tube (controlling section) made of circular or rectangular HSS that controls the global and local buckling of the main brace by providing a continuous lateral support along the brace length. Note that the gap between the tubes is to limit the contribution of the outer tube to the axial load-carrying system. The FEM-based numerical study performed by Shen et al. (2016) has discussed the influential parameters, which are the gap between the tubes, the relative outer tube thickness and the coefficient of friction, using built-up HSS with square-in-square bracing configuration so as to establish a conceptual foundation for cyclic behavior of TinT-BCBs [2]. Their study implied that TinT-BCBs are promising in terms of economy and overcoming the aforementioned issues related to seismic performance of ductile braced frames [2].

The purpose of the present study is to evaluate the relative effectiveness of TinT-BCBs with Round-in-Square and Square-in-Round configurations with an emphasis on applicability of the developed TinT-BCBs composed of HSS that can be employed in an actual CBF construction. The results are evaluated in terms of hysteretic response of bracings and global response of braced frames with and without buckling-controller by means of testing and Finite Element (FE) simulations. For this purpose, first, the behavior of a set of isolated TinT-BCBs with round-in-square and square-in-round configurations has been compared through FE simulations under uniaxial and cyclic loading. Subsequently, two round-in-square type BCB specimens have been tested in order to validate the observation carried out in the model-based study. Finally, seismic response of the braced frames that incorporate conventional braces and TinT-BCBs are compared with regard to seismic demands on structure, braces and girders.

Table 1
Properties of simulation cases.

Name[a]	Main Brace (in × in)	Length (in)	Controlling Section (in × in)	Friction Coefficient	Gap (in)	Thickness ratio
SR	Square HSS6 × 6 × 3/8	113.63	Conventional Buckling Brace			
SR1A			HSS10 × 0.625	30%	0.1765	1.67
SR1B			HSS10 × 0.625	10%	0.1765	1.67
SR2A			HSS9.625 × 0.5	30%	0.105	1.33
SR2B			HSS9.625 × 0.5	10%	0.105	1.33
RS	Round HSS7.5 × 0.375	113.63	Conventional Buckling Brace			
RS1A			HSS8 × 8 × 1/4	30%	0.017	0.67
RS1B			HSS8 × 8 × 1/4	10%	0.017	0.67
RS2A			HSS8 × 8 × 1/8	30%	0.134	0.33
RS2B			HSS8 × 8 × 1/8	10%	0.134	0.33
RS3A			HSS8 × 8 × 3/16	30%	0.076	0.5
RS3B			HSS8 × 8 × 3/16	10%	0.076	0.5
RS4A			HSS9 × 9 × 5/8	30%	0.169	1.67
RS4B			HSS9 × 9 × 5/8	10%	0.169	1.67

[a] SR: Square-in-round tube. RS: Round-in-square tube.