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Developing an all-steel buckling controlled brace

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ABSTRACT

The development of all-steel tube-in-tube buckling controlled brace (TinT-BCB) is presented. The efficiency of the TinT-BCBs is evaluated experimentally and numerically. The cyclic behavior and fracture life of TinT-BCBs was first investigated through physical testing, followed by FE-based simulations revealing the inherent correlation between fracture and peak cyclic strain in load-bearing braces. The cyclic strain in plastic zones was recorded up to 0.02 strain range during the cyclic tests, enabling the study to use the recorded strain in verifying the FE simulation models. The strain response of plastic zones was captured by the FE simulation up to fracture in conventional large-size braces. The paper concludes that (1) the TinT-BCB, developed based on the buckling-controlling concept, has demonstrated stable and symmetrical cyclic response, with global and local buckling controlled up to 0.035–0.04 story drift ratio; (2) the TinT-BCB is proven to be effective in elongating cyclic fracture life of conventional CBF from 2% SDR to 3.5–4% SDR by adding simple buckling controller. The cost for adding the buckling controller is low in comparison with the substantially increased lateral strength and energy dissipation capacity; and (3) the efficiency of the TinT-BCB in improving overall cyclic behavior in general and elongating fracture life of braces in particular is attributed to its ability in controlling highly concentrated strain in plastic zones of conventional braces. By spreading the concentrated strain demand throughout the entire length, the buckling controller is shown to reduce excessive peak strains in conventional braces by 7–8 times.

1. Introduction

Concentrically braced frames (CBFs) are extensively used in earthquake-resistant design of steel buildings. Early experimental data on testing of conventional braces indicated that the majority of the tested conventional braces were composed of double-angles, double-channels, WT- and W-shapes [1–4], which generally possess longer fracture life, on the order of 50% [5] to 85% [6], compared to tubular braces. However, braces in braced frame steel construction today are often comprised of cold-formed tubular steel bracings (circular or rectangular) for their economy with regard to low material cost and less labor-intensive connections. Hence, it might not be the most rational way to justify the anticipated ductility of special CBFs based on the tested brace specimens predominantly made of double-angles [3] and W-shapes [2,4] and to establish a design procedure accordingly.

Recent studies on testing of conventional tubular brace specimens consistently pointed out the premature fracture in braces [5–10]. The experimental data reported in [5,6,7,9] are summarized in Table 1. It appears that the maximum ductility capacity among these braces was no more than 10.0 with many in the range of 6.0 to 8.0, which is substantially less than those from the small-size brace specimens with various types of sections [1,8,11,12,13]. The brace ductility of 10.0 is equivalent to a story drift ratio of 0.02 in a typical CBF. A number of studies on the seismic response of CBFs indicated that the seismic story drift demands are often in the range of 0.03 and 0.04 for the design earthquake [14–16]. Recent studies on popular two-story X-braced frames by Shen et al. [17] and Shen et al. [18] revealed that the ductility demand in braces might exceed 20.0 for collapse-prevention level of ground motions in a two-story X-braced frame designed based on the current seismic design provisions [19].

Attempts to addressing buckling-induced fractures have resulted in various types of all-steel buckling-restrained brace (BRB). The advantage of having numerous possibilities to enhance the performance resulted in unnecessarily complex [20–23] all-steel BRB designs with closely spaced bolted or welded attachments [24] as well as sections built up by combining multiple structural shapes. A comprehensive state-of-the-art review can be found in [25], in which Shen et al. introduced a new concept of two-phase buckling-controlling mechanism, and a simple system named tube-in-tube buckling-controlled brace (TinT-BCB), as shown in Fig. 1. The TinT-BCB consists of a load bearing member (the inside tube) and an outer tube (the buckling-controller) that controls the global and local buckling of the main brace by providing a continuous lateral support. Note that the gap between the tubes is to allow the inside tube to slide freely so that the outer tube does not contribute to the axial load-carrying tube. The model-based numerical study carried out by Shen et al. [25] has identified three main parameters, gap between the tubes, the relative outer tube thickness and the coefficient of friction. The

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Table 1
Peak brace ductilities of the recently tested tubular braces.

Item	Test ID	Brace member l(mm × mm × mm)	b/t or D/t	KL/r	Peak brace ductility (μ)[a]	Reference
1	S85-14	HSS100 × 100 × 6	13.7	85	10.0	Han et al. (2007) [9]
2	HSS1-1	HSS102 × 102 × 6.4	14.2	77	8.9	Fell et al. (2009) [6]
3	3B	HSS127 × 127 × 8.0	15.0	65	6.0	Shaback et al. (2003) [7]
4	2B	HSS152 × 152 × 9.5	12.1	52	7.0	
5	RHS19	HSS254 × 254 × 15	14.2	60	8.0	Tremblay et al. (2008) [5]
6	RHS2	HSS254 × 254 × 15	14.2	40	6.0	
7	CHS2	HSS273 × 9.5	30.8	62	10.0	
8	CHS1	HSS273 × 9.5	30.8	42	8.5	

[a] The given ductility ratios are estimated from the published plots.

authors [25] concluded that TinT-BCBs have high potential to be used in engineering practice and are able to significantly improve the performance of braced frames efficiently and economically.

The purpose of the present study is to examine the efficiency of the TinT-BCBs with and without enhanced gusset plate connections in terms of hysteretic response and fracture life of braces by experimental and numerical simulations. For this purpose, a set of TinT-BCB specimens were first tested under cyclic loading. Subsequently, the strain demands on the BCBs and conventional braces are evaluated through the strain readings obtained from the experiment and finite-element-method (FEM) based simulations in order to quantify the level of enhancement supplied by the TinT-BCBs.

2. Experimental study

A set of Tube-in-Tube type all-steel BCB (TinT-BCB) specimens with different design parameters were tested at the structural laboratory of Iowa State University to investigate hysteretic behavior of the TinT-BCBs under cyclic loading. The primary objective of the experimental study is to evaluate the influential parameters that have substantial impact on the cyclic behavior and the fracture life of TinT-BCBs. These key parameters have been identified by various experimental studies [20,21,26], and a comprehensive parametric study [25]. They are as follows:

(1) The initial gap between the main brace and the buckling controller (BC).
(2) The relative stiffness of the buckling controller.
(3) The friction between the main brace and the buckling controller surfaces.
(4) Connection type.

Table 2 summarizes the main brace and outer tube sections, the gap amplitude, the outer tube thickness and gusset plate design of the tested specimens. As can be seen from Table 2, in order to characterize the impact of the selected parameters as well as the connection design, the same main brace (load-bearing tube) size was employed for all specimens. The main brace section was selected considering the available loading capacity of the test equipment as well as the slenderness and width-to-thickness ratio of the inside tube. Each specimen has its own characteristics to reveal how the design parameters would affect hysteretic response of the developed BCBs:

- Specimen TinT#1 is specifically designed to emphasize the significance of proper connection design and its potential effects on the overall cyclic response. For this purpose, the gusset plates were designed based on the requirements for conventional ductile (special) braced frames. Besides, TinT#1 has a relatively large gap amplitude and moderate buckling-controller (BC) stiffness, an ideal specimen to act as a control for the other two specimens.
- Specimen TinT#2 was designed to be identical with the first specimen in terms of the gap amplitude and the BC stiffness while the gusset plates were reinforced with vertical stiffener plates to minimize end rotations.
- Specimen TinT#3 was designed to represent the targeted case (with small gap and stiff outer tube) in order to indicate the sensitivity of the controlling design parameters. Therefore, the thickness of the outer tube was increased from that in the first two specimens and the gap amplitude was adjusted to a small but practical value.

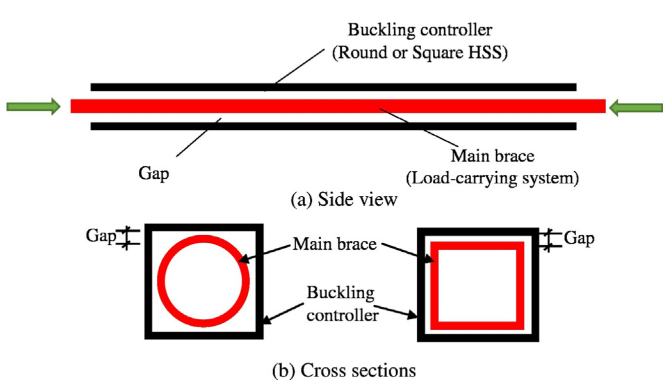

Fig. 1. Scheme of tube-in-Tube BCBs.

2.1. Design and fabrication of the tested TinT-BCB specimens

TinT-BCB specimens were shop fabricated using round and square hollow sections with gusset assemblies at ends. Side and section views of the first specimen (TinT#1) are shown in Fig. 2. The first test specimen consists of a round HSS1.900 × 0.125, eight 6″ × 1/2″ × 3/16″ net section reinforcing plates, a square HSS2 1/2 × 2 1/2 × 1/8 section and 3/8″ thick gusset plates. The total length of the main brace, the outer tube and the entire assembly are 42″, 37.25″ and 50″, respectively. The locations of the reinforcing plates were determined based on the geometry of the cross section. The gap between the two tubes was 0.175″ (Fig. 2).

Design of TinT#2 and TinT#3 were identical to each other except for their outer tube sizes. Specimen TinT#2 was composed of a circular HSS1.900 × 0.125, eight 41/2″×1/2″×1/8″ net section reinforcing plates, a square HSS 2 1/2 × 2 1/2 × 1/8 and two gusset assemblies. The main brace was encased in a square HSS 2 1/2 × 2 1/2 × 1/4 outer tube in Specimen TinT#3 while the gusset assembly design and the main brace size of the specimen were identical to those of TinT#2. The total length of the main brace, the outer tube and the entire assembly were 42″, 37.25″ and 51.50″, respectively, for both TinT#2 and TinT#3. Shop drawings of TinT#2 and TinT#3 are given in Fig. 3.

Fig. 4 demonstrates the scheme of a chevron type TinT-BCB frame with stiffeners. A special attention was paid to represent the actual boundary conditions at brace ends of TinT#2 and TinT#3 specimens.