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Seismic performance of concentrically braced frames with and without brace buckling

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ABSTRACT

This paper presents an analytical study on seismic performance of special concentrically braced frames (SCBFs) with and without brace buckling. It demonstrates that the collapse prevention goal needs attention in modern buildings using SCBFs as main seismic-force-resisting systems, and an simple and low-cost solution is possible to achieve this goal. Typical 6-story buildings using two-story X-braced frames with strong and weak braced-intersected beams and inverted V braced frames with and without brace buckling were subjected to a set of 15 earthquake ground motions, and resulting seismic responses were discussed in terms of seismic strength and deformation demands on braces, beams and columns. The study finds that the braces in SCBFs often fracture prior to 2% story drift ratio response, particularly in the popular two-story X-braced frames with weak beams, mainly due to premature yielding of the beams. The buckling-controlled braced frames (BCBFs) are shown to be a cost-effective system to improve the seismic performance of SCBFs. The analysis indicates that the buckling-controlled braces may substantially reduce story drift response, eliminate weak beam yielding, and prevent braces from fracturing.

1. Introduction

1.1. Assumptions in seismic design of SCBF

The intention for seismic design of a ductile (special) concentrically braced frame (SCBF) is to make use of global buckling of braces as a viable energy-dissipation mechanism while columns and beams in braced bays are intended to remain elastic. In order to realize this intention, the design has been based on these two basic assumptions: (1) the braces shall not fracture under expected seismic deformation demand; and (2) the beams, columns, and gusset plates/connections in braced bays shall have little inelastic deformation. The concept behind these assumptions is consistent with the principles employed in all traditional earthquake-resistant systems, but ensuring no fracture in braces and elastic beams and columns has been facing serious challenges since more and more actual-size braces suffered fractures during laboratory tests. Large ductility demand on braces may have been mutually influenced by inelastic deformation in beams and columns. As shown in the literature survey later in this paper, there has been the situation in SCBFs that two basic assumptions and reality are at odd for some time, at least since 1990s, but little has been known about how the situation is created.

1.2. Ductility capacity and demand of braces

Recent tests, since 2000, on increasingly larger size braces with the hollow structural section (HSS) indicate that the braces with HSS 4×4 sections fractured under less than ductility of 10 and 0.03 story drift ratio (SDR) response [1,2], and the braces with the full-size sections between HSS6 $\times$ 6 and HSS 12 $\times$ 12 fractured consistently under 5–10 ductility and 0.02 SDR [2–4]. In other words, most of the HSS braces used in existing buildings would have their fracture life substantially shorter than what is expected for collapse-prevention performance [5–7]. A closer look at other recent tests on HSS braces [8–11,12] indicates that the brace ductility prior to fracture was marginally higher in small-size HSS braces, but still consistently less than 0.04 SDR in all tested specimens. In particular, a set of HSS braces with various sizes but the same b/t ratio, tested by different researcher groups as cited earlier, provide us with the strongest evidence yet that the fracture

Abbreviations: BCB, buckling-controlled brace; BRB, buckling-restrained brace; BCBF, buckling-controlled brace frame; BRBF, buckling-restrained brace frame; HSS, hollow structural section; SCBF, special concentrically braced frame; SDR, story drift ratio; TinT-BCB, tube-in-tube buckling-restrained brace; TSXBF, two-story X brace frame.

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life of an HSS brace is closely related to its size, and the larger size HSS has shorter fracture life. The braces with HSS101 × 101 × 6.4 (b/t = 14.2) were observed initial fracture at about 0.03 SDR [7,11]. With the sizes increased to HSS152 × 152 × 9.5 (b/t = 14.2), the initial fracture occurred around 0.02 SDR [1]. A full-size HSS254 × 254 × 16 (b/t = 14.2) suffered complete fracture at 0.015 SDR [4]. Note that HSS254 × 254 × 16 is about an average size used in multi-story SCBF buildings; and, any square HSS with b/t ratio less than 16 would be considered as seismically compact section (AISC 341-05 [13]) and has been used extensively in seismic design of steel buildings in high seismicity area prior to 2010. In other words, commonly used HSS braces in steel buildings following AISC 341-05 or its earlier editions would suffer fracture under less than 0.02 SDR response. The significant deficit of the actual fracture life (<SDR = 0.02) over the expected seismic drift demand (in the order of 0.04 SDR) is of concern for achieving collapse prevention objective for SCBF buildings. A historic review on the braces tested in 1970s and 1980s [14–16] indicates that all possible structural shapes (angles, channels, tubes, and wide-flange) were used, and were relatively small in size in comparison with the sizes used in current practice. Most specimens, particularly those with double-angle and wide-flange sections, were able to sustain consistently 3.5% or larger SDR deformation without fracture. Among the tested small tubes, the large majority of them reached 3–4% SDR; a small percentage of them showed as large as 5–6% SDR; only a few specimens failed with smaller than 2% SDR. As a system having 3–4% SDR capacity shown by large majority of tests, the SCBF was considered a ductile seismic system up to today's standard. In engineered building structures, however, many different brace sections (such as double-angle and wide-flange sections) that were tested in 1970s and 1980s have gradually phased out of practice and the tube section (HSS) has become almost exclusively the section of braces in seismic SCBFs since 1990s. Furthermore, the tube sections used in the CBFs built in last two decades are often 3 – 4 times heavier than the tubes tested in 1970s and 1980s, and are apparently much more vulnerable to premature fracture.

The recent seismic design specifications [17,18] include certain provisions to address the issues related to ductility and redundancy in SCBFs, resulting in marginally improved performance but probably higher cost. Some researchers have devoted efforts to design methodologies to improve the seismic performance of SCBF, lower the cost, or the both. may improve its seismic performance. Brandonisio et al. [19] suggested to modify overstrength factor and slenderness limitations specified by EC8 [18] to reduce the overall structural weight and possibly obtain a more uniform plastic deformation distribution along with a desirable overall non-linear behavior. Shen et al. [6,7] pointed out the stronger brace-intersected beams in two-story braced frames would reduce possibility of brace fracture substantially. Tremblay and Robert [20], Bosco et al. [21] and Marino [22] have studied seismic behavior of columns in braced frames, proposed methods in how to deal with the columns in the buildings with SCBF. It is believed that these analytical studies on seismic behavior and proposed design modifications have high potential to improve seismic performance of SCBF after cyclic behavior and ductility capacity of braces are improved. In engineering practice, some structural engineers have chosen to use wide-flange sections instead of HSS as brace members in conventional SCBFs to address the premature fracture vulnerability in HSS sections since the wide-flange section was shown less vulnerable to fracture than HSS [14–16].

1.3. Buckling-restrained and buckling-controlled braces

Brace buckling results in excessive deformation, leading to the premature fracture in a SCBF. The attempt to prevent the buckling of steel brace was found as early as 1970s [23], and has resulted in many forms of buckling restraining mechanisms, all of which share the same simple concept of providing nearly continuous lateral support to the brace along its length. The brace with any form of buckling restraining mechanism has called buckling-restrained brace (BRB), and the frame using BRB is named buckling-restrained brace frame (BRBF). The most popular BRB in current practice consists of load-bearing steel core embedded in mortar inside a steel tube. The mortar together with the steel tube provides a continuous lateral support to the steel core throughout its length. The steel core is coated with un-bonding material to minimize the friction between the core and surrounding mortar so that the participation of the restraining mechanism in resisting axial force might be limited. The braced frames with the un-bonding BRB have been tested [24], and used for seismic design and retrofit in buildings and bridges [25–28]. Two major concerns with this type of BRB: (1) its compressive strength is significantly higher than its tensile strength under large inelastic deformation; and (2) little information is available with regard to the deformation inside the brace after a major earthquake.

Instead of using mortar-filled tube as buckling restrainer, all-steel buckling restraining mechanisms were also studied for over two decades [29–36]. The all-steel buckling-restrained brace (BRB) employs only steel parts for both load-bearing and buckling-restraining functions. Most common all-steel BRBs [29–34] consist of a steel plate as load-bearing core sandwiched between two back-to-back channels or the alike that are bolted or welded together along the length. The experimental studies have demonstrated that the all-steel BRBs with the sandwiched plate are sensitive to the gap and friction between the plate and the buckling restrainers, prone to low-cycle fatigue induced fracture. Also, the sandwiched-plate all-steel BRBs seem to be labor-extensive due to its unnecessarily complex design. All-steel BRB with cruciform-shaped four angles (back-to-back) as load-bearing core encased in a square tube made of two large-sized angles welded together as buckling restrainer was studied in [35–37]. The global buckling of the brace was postponed, but not restrained under design earthquake. Substantial local buckling was observed during cyclic loading tests. In summary, the all-steel BRBs with sandwiched plate or angles appear to be much more complicated than the simple goal that it intends to achieve: restraining the buckling, with some of studied all-steel braces, though named as BRB, actually under design load.

With substantial advancements in existing BRB systems, there exist a number of challenges, including (a) large unbalance in tension and compression (mortar-filled tube BRB), (2) low-cycle fatigue induced fracture (all-steel BRB with sandwiched plate or angles), and (c) high cost (all BRBs). Recently, Shen et al. [38] introduced a two-phase buckling-controlling concept with an attempt to address these challenges. The equal tension and compression and fracture prevention can be achieved by completely controlling any buckling in the first phase, up to the design story drift ratio (typically for life safety design goal), and partially controlling buckling deformation in the second phase with large inelastic deformation (for collapse prevention objective). The brace with the two-phase buckling controlling concept was named as buckling-controlled brace (BCB) [38]. A simple all-steel BCB system, made of hollow structural sections (HSSs) that are widely available in the market, was developed using this concept [38]. The system consists of a steel tube encased in another tube as buckling restrainer, named tube-in-tube buckling-restrained brace (TinT-BCB), The experimental and associated analytical studies demonstrated that the TinT-BCB has a stable and tension-compression symmetrical hysteresis behavior over 2% story drift ratio, and global and local buckling may occur prior to fracture on the order of 3% story drift ratio.