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Numerical investigation of seismic behavior of short-core all-steel buckling restrained braces

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ABSTRACT

Conventional buckling restrained braces used in concentrically braced frames are expected to yield in both tension and compression without significant degradation of capacity under severe seismic ground motions. On the other hand, a new short core buckling restrained brace system could be introduced as an alternative for a conventional full core BRB. In a short core BRB (SCBRB), the core element is built shorter than usual. Therefore, for a given story drift, the core accepts bigger axial strains compared to a conventional (full core) BRB. A short core BRB seems to be easily fabricated, inspected, and replaced after a severe earthquake. The purpose of this study is to show how this type of buckling restrained braces is feasible. Reducing the core length in a buckling restrained brace may result in a shorter encasing member, decrease in frictional forces acting at the core and buckling restraining mechanism interface, and, as a consequence, reduction of the compression strength adjustment factor in the brace. This paper numerically investigates the seismic behavior of short core buckling restrained braced frames. The minimum core length of BRB is determined by considering the low cycle fatigue life of the core plate and the maximum anticipated strain demand under standard loading protocol. Nonlinear time history analyses were also performed on four and ten story prototype buildings equipped with full core (conventional BRBs) and short core BRBs and the story drifts were compared. The results showed that the SCBRB system is partially able to reduce the story and residual story drifts in the braced frames. In addition, SCBRBs sustain large plastic deformations without crossing the low cycle fatigue life borders or instability of the encasing system. However, the economic and practical aspects of using SCBRB seem to be more distinct in comparison to its mechanical characteristics.

1. Introduction

Conventional steel braces used in concentrically braced frames are expected to yield in tension and buckle in compression under severe seismic ground motions. This inelastic response under cyclic loading reversals is characterized by significant degradation of the brace compression resistance and stiffness, permanent brace deformation, and, eventually, local buckling and fracture at plastic hinge locations. The system thus exhibits limited ductility and energy dissipation capability. In addition, capacity design provisions require that brace connections as well as beams, columns and foundations be designed to develop the expected tensile yield strength of the braces. As bracing members are typically designed for compression, this requirement results in design forces much larger than those associated with prescribed seismic loads and, thereby, significant additional costs.

Buckling restrained brace (BRB) typically includes a steel core element which is encased in a steel tube filled with concrete or mortar such that buckling of the brace under compression is prevented. An unbonding agent such as PTFE strip or butyl rubber film may be provided to minimize friction between the concrete and the core element. Thus, the entire axial load is assumed to be resisted by the core and the outer steel tube only provides flexural stiffness to prevent overall buckling of the brace. The core element typically has a dog bone shape with longitudinal stiffeners added at the ends such that the projections extending at both ends of the encasing tube remain elastic and do not locally buckle. Under severe earthquake loading, the core segment is expected to yield in tension and compression and undergo large plastic excursions with stable hysteretic behavior. The balanced hysteretic response provides suitable brace behavior under extreme seismic loads. Generally, a BRB is comprised of three components, namely, a yielding core, buckling restraining system, and a separating gap or unbonding material at the interface. Large body of knowledge exists on

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conventional BRBs' performance in the literature. Black et al. [1] performed component testing of BRBs and modeled a hysteretic curve to compare the test results and found that the hysteretic curve of a BRB is stable, symmetrical, and ample. Inoue et al. introduced buckling restrained braces as hysteretic dampers to enhance the seismic response of building structures [2]. Numerous researchers have conducted experiments and numerical analyses on BRBs for incorporation into seismic force resisting systems. Qiang investigated the use of BRBs for practical applications for buildings in Asia [3]. Clark et al. suggested a design procedure for buildings incorporating BRBs [4]. Sabelli et al. reported seismic demands on BRBs through a seismic response analysis of BRB frames [5], and Fahnestock et al. conducted a numerical analysis and pseudo-dynamic experiments of large-scale BRB frames in the US [6]. Previous studies have demonstrated the potential of manufacturing BRB systems made entirely of steel, called all-steel BRBs [7]. In a common all-steel BRB, the steel inner core is sandwiched by a buckling restraining system made entirely of steel components, thus avoiding the costs of the mortar needed in conventional BRBs. This eliminates the fabrication steps associated with pouring and curing the mortar or concrete, significantly reducing manufacturing time and costs. The hysteretic behavior of all-steel BRBs was experimentally investigated by Tremblay et al. [7] and the potential of the proposed steel BRB system for adequate ductile seismic response was demonstrated. Observations and test results clearly indicated the necessity to control local core buckling response to minimize frictional response between the core and the buckling restraining mechanism (BRM) and develop uniform strain demand in the brace core [7]. An experimental study on the hysteretic behavior of all-steel BRBs was also conducted by Eryasar et al. [8]. Test results revealed that providing a direct contact between the core and the encasing is adequate for stable hysteresis at high strains. Continuously welded and snug-tight bolted attachments for encasing were found to be detrimental. Tack welding the core to the encasing was found to be a considerable option for preventing slipping of the encasing and a set of design recommendations was presented based on the experimental findings [8]. A significant amount of research work has been performed in Japan and U.S. and elsewhere in Asia over the last few decades for the development of BRBs. A detailed report of findings is summarized in an excellent report by Uang [9]. In the United States, design recommendations have been incorporated into AISC Seismic Provisions for Structural Steel Buildings [10]. This provision requires qualifying cyclic tests to be performed on a sub-assemblage and a uniaxial test specimen. More interesting numerical investigations have been conducted by Korzekwa et al. [11] to survey the behavior of the core plate in all-steel BRBs, which indicated a complex interaction developed between the brace core and the encasing.

Mirtaheri et al. [12] conducted experimental test on short core BRBs to investigate their overall responses. In those studies, FEMA 450 [13] loading protocol for BRBs was applied to estimate the minimum core lengths of the BRB member. The test results showed that the shorter the BRB, the higher the energy absorption capacity. The response of the specimens was strictly dependent upon the material being used in core, since high amount of hardening may have pronounced influence on the hysteretic behavior of the BRBs and enhances the amount of strength and energy dissipation. Using material with considerable work hardening such as stainless steel material in the BRB core may be an appropriate alternative for ordinary carbon steel. Hoveidae et al. conducted finite element analysis on global buckling behavior of all-steel BRBs [14]. The local buckling behavior of core plat in bucking restrained braces was also investigated by the aforementioned researchers [15].

Low-cycle fatigue testing of extruded aluminium alloy buckling-restrained braces was conducted by Wang et al. [16]. Moreover, a new modular buckling restrained brace was proposed and tested by Piedrafita et al. [17]. A finite element analysis study of all-steel buckling restrained braces was conducted by Aniello et al. [18] to address the interaction between the core and encasing in all-steel BRBs. Those studies included the effect of bolt spacing and also the gap between core and encasing on local buckling behavior of BRBs. In addition, cyclic full scale tests on all-steel dismountable BRBs applied to an existing damaged reinforced concrete building were conducted by Corte et al. [19] and Aniello et al. [20]. Moreover, the effectiveness of special only-steel BRBs and also eccentric braces to enhance the seismic resistance of an existing RC building was tested by Mazzolani et al. [21]. The results showed the distinct ability of all-steel BRBs to increase the lateral resistance and stiffness of RC frames and produce a stable hysteretic behavior and good ductility in the braced frame.

The study on SCBRBs in this paper consists of two parts, determining the minimum core length and nonlinear time history analysis to compare the seismic demands in full core and short core BRBs.

2. Concept of short core BRB (SCBRB)

A BRB can be classified as a hysteretic damper, since it is expected to yield in tension and compression and sustain large plastic deformations without any significant degradation of capacity. SCBRB in which the core length is reduced can be deemed as an alternative for a full-core BRB since it seems to be easily fabricated, inspected, and replaced after a severe earthquake. Reducing the core length in a BRB may result in the design of a short restraining member, decrease in frictional forces between the BRM interface, and reduction of the compression strength adjustment factor, subsequently. However, a larger strain hardening adjustment factor may be developed in a short core BRB since the core plate is expected to experience large plastic strains in comparison to a full core typical BRB.

In a seismic yielding device such a BRB, the strength and stiffness for the whole brace member is ensured by the strength and the stiffness of the yielding part. Therefore, the overall stiffness and strength of the brace and subsequently the braced frame are much lower beyond the yielding load of the brace. However, this cannot be deemed as a shortcoming of these systems because the material property of constructional steel dictates having a low stiffness after yielding of material.

This study investigates the feasibility of a new bracing type. The SCBRB system proposed is comprised of a short steel core restrained laterally by coreless structural HSS members which is expected to remain elastic because of its larger cross sectional area in comparison to the core plate. The pre-yield stiffness of the SCBRB is expected to be significantly larger because of the serial summation of stiffness of the core and the coreless member. In addition, by considering the steel hardening properties, the post-yield stiffness of the whole member is also expected to partly increase because of the over-strength of steel material and the redistribution of the axial force demand in the brace components. Therefore, the post-yield stiffness of the entire SCBRB might be partly assured by the coreless segment. In addition, the coreless segment should be strong enough to inhibit overall buckling of the brace. The capability of SCBRB system to decrease the story drifts of the braced frame is one of the main goals to be investigated in this study. As expected in a conventional BRB, during a seismic ground motion, the core plate in a SCBRB acts like a fuse and yields in both tension and compression. The encasing part may be fabricated by extending the coreless segment over the core plate. However, it can be an independent part as well. Different details can be suggested for a SCBRB. Fig. 1 illustrates a proposed configuration of SCBRB. In the proposed detail shown in Fig. 1, a continuous structural HSS member is used as the coreless segment and also the encasing. The core plate is inserted inside the slotted HSS member. The core encasing system is the extension of the coreless segment over the core. The core plate is connected to the HSS member using standard bolted connection at the enlarged zone of the core. The enlarged zone of the core plate is expected to remain elastic. The face plates are welded to the HSS member throughout the core to form the encasing system. Filler plates are provided between two upper and lower parts of face plates to cover the clearance between the core segments and face plates in both sides. A bolted connection is used to