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The development of the buckling restrained braces with new end restrains

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ABSTRACT

This paper presents an experimental investigation of buckling restrained braces (BRBs) with new end restraints and casing members (CMs). The component tests for ten BRBs with CMs consisting of concrete-filled steel tube (unbonded), plain concrete, plain concrete wrapped with Fiber-Reinforced Polymer (FRP), reinforced concrete and a built-up section were tested up to a core plate (CP) strain of 2.0%. In unbonded BRBs, an unrestrained part is usually available on the CP. This part may be a candidate for buckling during cyclic excursions. Hence both ends of the BRBs at the unrestrained part of the CP need to be restrained more effectively. The innovations of BRBs in the present study were that additional end restraints were added at the unrestrained part of the CP at both ends, isolation material was employed, and a more economical CM was used. These new end restraints consisted of hollow steel sections and steel plates welded to each other and were attached to the CM. The testing of the improved BRBs indicated that the cyclic performance of the BRBs was satisfactory up to a CP strain of 2.0%. The energy dissipation capacity of the BRBs was found to be significantly dependent on compression strength adjustment factor, β, and strain hardening adjustment factor, ω. Consequently, the improved BRBs with sufficient stiffness to resist out-of-plane buckling at both ends have acceptable cyclic performance according to the test results. Furthermore, the connection details namely slip critical, isolation materials, and their application techniques have also been investigated for the improved BRB design in this study.

1. Introduction

Steel braces are lateral load-carrying members used in structures against the wind and earthquake forces. Steel braces carry lateral forces applied to the braced frame in proportion to their axial rigidity. Since the axial rigidity of the brace members is high, they are the most widely used framing systems in seismic zones. One of the largest challenges in the design of these braces is that their tension and compression capacities are not equal. Black et al. [1] found that when the braces are subjected to large tension forces they yield but they exhibit buckling deformation under compressive forces and their axial load-carrying capacity drops suddenly. This unsymmetrical hysteretic behavior in tension and compression causes unstable seismic performance of the steel braced frames. The axial compression capacity of the brace members can be shifted from unstable to stable if they are prevented from buckling. This fact makes buckling-restrained braces (BRBs) attractive among researchers all over the world. The BRBs consist of a core plate (CP) and casing member (CM), as seen in Fig. 1. Although the CP has negligible compression capacity, its capacity can be increased by using a CM or by restraining its buckling. In this case, the CP may yield in tension or compression or may buckle in high buckling modes. BRBs generally have three parts, namely an unrestrained elastic zone, a restrained elastic zone, and a restrained plastic zone (Fig. 1). The unrestrained elastic zone is designed to provide a connection between the BRB and the gusset plate. This zone is also capable of resisting axial demands without buckling when the restrained plastic zone yields in tension and compression. The restrained elastic zone is a transition part of the CP between elastic and plastic behavior. Although this zone has elastic behavior under tension and compression demands, the CM prevents it from buckling. The restrained plastic zone carries the tension and compression forces elastically and plastically. The CP inside the CM should be separated or isolated from the CP. This can be performed by placing an air gap or using isolation material such as rubber, silicon grease, foam, and so on between the CP and the CM. The air gap or isolation material prevents friction between the CP and the CM and hence the additional axial load capacity may not occur during the application of compression demands. In addition, this air gap or isolation material is also important for the expansion due to the Poisson ratio under compression demands. The expansion of the CP under compression demands creates additional friction between the CP and the CM. In order to determine the gap required between the CP and the CM, Poisson ratios of 0.3 and 0.5 were taken from the study of Uang and Nakashima [2] for the elastic and plastic ranges, respectively.

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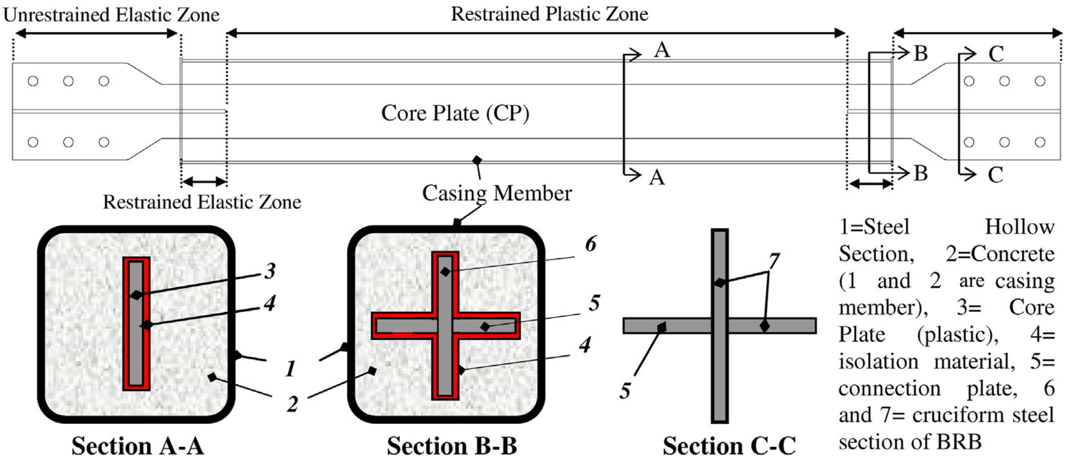

Fig. 1. Details of BRB (adapted from Lopez [40] and Wada et al. [41]).

Study of BRBs started with component and sub-assemblage tests conducted in Japan by Uang and Nakashima [2], Qiang [3], and Uang et al. [4] and then in Taiwan by Tsai et al. [5] and in the USA by Black et al. [6]. Watanaba et al. [7] tested BRBs with mortar-infilled square and rectangular steel tubes to investigate the global buckling of the brace. Eq. (1) was suggested by Watanaba et al. [7] to prevent global BRB buckling.

$$P_e/P_y > 1.0 \tag{1}$$

where P_y is the yield strength of the CP and P_e is the elastic buckling strength of the CM.

Iwata et al. [8] tested commercially available BRBs in which the CMs were steel tubes filled with mortar and structural steel members with bolt and weld connections. Clark et al. [9] and Black et al. [6] tested BRBs with rectangular and cruciform steel sections. Although the BRBs showed stable cyclic performance, their compression capacities were found to be higher than their tension capacities. Chen et al. [10] tested BRBs with low yield-point steel and a ductile CP. They attempted to prevent friction between the CP and the CM by using silicone grease. Hence the compression capacity of the BRBs was found to be about 1.5 times higher than their tension capacity due to the insufficient gap between the CP and the CM. Instead of a steel tube filled with mortar, a steel pipe filled with a confined non-cohesive material was used as the CM for confined yielding braces similar to BRBs by Higgins and Newell [11]. The CP of the BRBs tested by Young et al. [12] was a steel I-section with a tubular CM without mortar infill. It was found that the thicknesses of the external tube (CM) and the unconstrained part of the core (I section) had a significant effect on the strength and hysteretic behavior of the BRBs. The test results indicated that the BRBs with a thinner tube used as a CM showed global and local buckling. Takeuchi et al. [13] proposed a strategy for the prevention of in-plane local buckling failure of a BRB whose restrainer was composed of a circular or rectangular steel tube infilled with mortar of various thicknesses. The test results indicated that initiation of local buckling failure started later when the mortar thickness increased and that when a circular restraint tube was used, local buckling failure did not occur until the amplitude of the CP plastic strain was 3%, even for large diameter-to-thickness ratios of the tube. They proposed a criterion for the local buckling failure of BRBs that can be modified by the mortar thickness and the restraint tube shape. Eryasar and Topkaya [14] conducted an experimental study of a BRB with a CM consisting of a built-up section. Tsai et al. [15] tested BRBs with steel tubes filled with mortar that were used as a retrofit solution for an existing structure. Tremblay et al. [16] performed sub-assemblage tests on BRBs (the CM was a steel tube filled with mortar) that were used to strengthen a four-story steel frame. Tremblay et al. [17] tested BRBs (the CMs were concrete-filled tubes and hollow steel tubes with a bolt system) to determine the effects of the flexure stress in the BRBs, the influence of the core brace length, the axial rigidity, and the fatigue life. BRBs with concrete-filled tubes in steel frames were tested in the USA by Uriz [18], Lopez et al. [19], and Mazzoloni [20]. Merritte et al. [21] conducted sub-assemblage testing of BRBs using a shake table facility. The shake table imposed both longitudinal and transverse deformations on one end of the BRBs. The test results indicated that the BRBs showed a stable cyclic performance. It was observed from the literature review that most of the BRBs sustained stable cyclic performance in the component and sub-assemblage tests, while the performance of the some BRBs in a steel frame was observed to be unstable. Okazaki et al. [22] and Hikino et al. [23] performed large-scale shake table tests to examine the out-of-plane stability of BRBs. Two planar specimens (single-bay, single-story steel frame, and a pair of BRBs placed in a chevron arrangement) were repeatedly subjected to a near-fault ground motion of increasing magnitude. The specimens were not braced at the brace-to-beam intersection in order to produce a condition where the BRBs were susceptible to out-of-plane instability. Based on the experimental observations and the stability model, a methodology was proposed to evaluate the bracing requirements at the brace-to-beam intersection. Kasai et al. [24,25] conducted three-dimensional shaking table tests for full-scale five-story building specimens with dampers. In tests, four types of dampers (steel, oil, viscous, and viscoelastic) were used. They described such preliminary investigations as well as the blind analysis comparison to be held regarding the performance of the building. Christopulos [26] conducted five steel-braced frame tests by using static testing methods. During these tests, at a drift ratio of 1.5%, local buckling of the BRB occurred. Tsai et al. [27] and Tsai and Hsiao [28] conducted tests on a full-scale three-story three-bay BRB frame by using a pseudo-dynamic testing method. In this experiment, in addition to the damage that occurred at the mid-length of the BRB, buckling was observed at the gusset plate and CP in the vicinity of the casing or connection. Lin et al. [29,30] and Tsai et al. [31] studied the connection between the BRBs and gusset plate experimentally and analytically in order to prevent connection failure. Fahnestock et al. [32] tested a single-bay four-story braced frame by using a hybrid dynamic and quasi-static testing procedure. Sherman and Okazaki [33] conducted an analytical study on BRB braced frames that included columns shared by orthogonal BRBs to examine the bidirectional loading effects. The results suggested that braced frames designed according to the current codes and provisions may not perform as intended. Furthermore, Mazzolani [34], Sarno and Manfredi [35], and Brawn et al. [36] studied the seismic retrofitting of deficient reinforced concrete (RC) frames with BRBs.

As a result, it is clearly seen that the similar BRBs in different studies exhibited different cyclic performance. Hence the end rotations or local buckling can be prevented and the isolation of the CP can be constructed properly, the cyclic performance of the BRBs may be enhanced to an