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Seismic design of buckling-restrained brace welded end connection considering frame action effects: Theoretical, numerical and practical approaches

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ABSTRACT

The negative effect of in-plane frame action on the performance of buckling-restrained brace (BRB) end connections was confirmed experimentally in the authors' prior work. The triggering moment induced by rigid-body rotation of BRB ends, and the amplified moment resulting from bending and semi-rigid effects of the connections, were found to be responsible for premature in-plane buckling of the BRB end connections. These effects, however, have not yet been incorporated into the current design procedure. This study aims to further discuss the amplified moment from theoretical, numerical and practical perspectives. As a companion research, the frame action effects of non-moment braced frame and their influences on the cruciform BRB end section using full penetration groove weld connection to the gusset plate are discussed. An analytical model is first proposed for derivation of the BRB end moments considering the concerned frame action effects. Theoretical analysis is conducted to highlight the key parameters affecting the amplified moment factor, an index for evaluating the contribution of the amplified moment. To avoid direct prediction of the complex semi-rigid effects between BRB end and gusset plate, an equivalent rigidity concept is proposed to combine the contributions of both flexural and rotational rigidities of the entire connection. Simple formulae for estimation of the equivalent rigidity and the effective length factor of the connection are determined by finite element analysis. The theoretical BRB end moments using such an equivalent approach are validated experimentally and numerically. A practical approach to simply estimation of the amplified moment factor is also presented. Seismic design procedure for the BRB welded end connection considering the concerned effects are summarized finally.

1. Introduction

Buckling-restrained braces (BRBs), viewed as high performance metallic yielding dampers with ductile, full, and stable hysteretic behavior [1–12], have been widely implemented into seismic-prone areas to mitigate structural damage. Generally, axial yielding of a BRB (Fig. 1(a)) is only allowed within the plastic zone, while the end zones projected from the casing are required to remain elastic to ensure stability of the connections. In actual applications, the BRB-to-gusset connection by full penetration groove weld (Fig. 1(a)) is quite popular, with the advantage of higher strength and easier construction than the traditional bolted and pinned end connections. Another type of welded end-slot connection for BRBs was also proposed recently [13] and has gained wide acceptance in Taiwan. With such a welded (bolted) BRB end, rigid-body rotation (see θ_t and θ_b in Fig. 1(b)) between the end zone and the plastic zone would be inevitable under the impact of in-plane frame action effects (see H and R in Fig. 1(b)). Previous subassemblage [14–16] and frame tests [17] showed that such rotational demands could be comparable to the inter-story drift angle of buckling-restrained braced frames (BRBFs), making the BRBs and their connections more susceptible to unexpected failure than the pure axial loading condition.

Saeki et al. [18] conducted component tests of the BRBs with cruciform bolted end connections. The BRB was assumed as a continuous elastic flexural member to estimate the in-plane frame-induced secondary moments on the BRB ends. The BRB specimens were placed vertically with fixed bottom ends, while an equivalent

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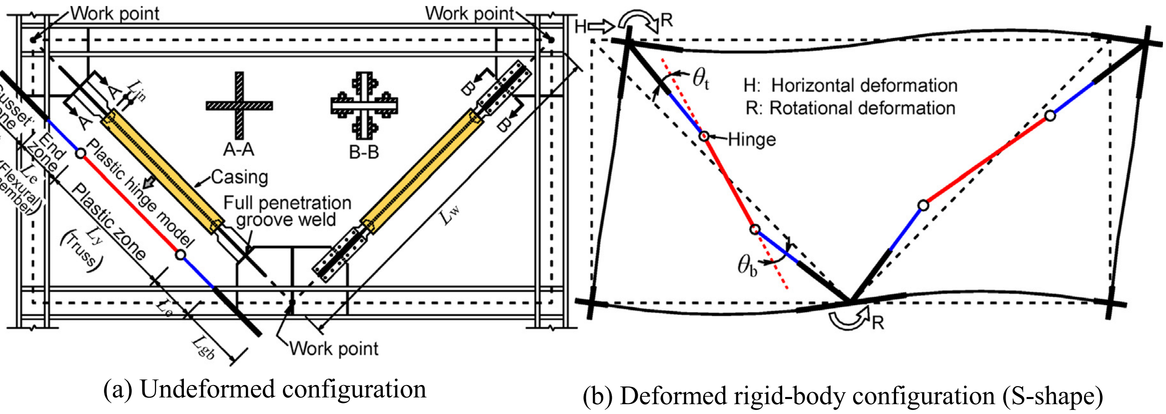

Fig. 1. BRB end rotation induced by a typical frame action effect.

eccentricity of 20 mm, 30 mm, 50 mm, and 80 mm was applied, respectively, onto the top ends of four of the specimens to simulate the secondary moments. Test results showed that the BRBs performed well within the elastic stage only, and plastic hinge formed at the neck of the projected end zone shortly after compressive yielding of the core members. This behavior led to premature buckling of the entire BRB end connections that failed to develop full hysteresis of the BRBs. Uemura et al. [19] conducted subassemblage tests to simulate more realistic frame action effects on the chevron BRBs with cruciform welded end connections. A very limited insert length of the end zone (see L_{in} in Fig. 1(a)) was provided to ignore the moment transfer from the connections to the casing, the same as the plastic hinge model specified in the stability design provisions of Japan for steel structures [19]. The bottom gusset connections of the specimens were fixed onto the strong floor while both horizontal and rotational deformations were imposed onto the top gusset connections through a pin-ended rocking column. Test results showed that plastic hinge formed at the BRB-to-gusset section that caused in-plane buckling of the entire connection prior to 2% drift. However, the connections all satisfied the required axial strength capacity considering the maximum BRB compressive force. The two studies [18,19] highlighted the negative effect of frame-induced secondary moments on the in-plane BRB end connection performance.

On the other hand, many frame tests [21–28] also demonstrated the negative frame action effects on the BRB corner gusset connections. It was found that the seismic shear forces of the beam and the column would cause the beam-column-gusset joint opening or closing under repeated loading. Such behavior would introduce diagonal strut force at the gusset-to-beam and gusset-to-column interfaces [22–26], making the corner gusset connections more susceptible to fracture at the gusset tip, or out-of-plane buckling when the BRBs were still in tension [21,23]. To improve the seismic performance of BRBFs under severe earthquakes, the formulae considering the frame action force in design of the corner gusset connections were proposed [22,24–26]. Some new corner gusset configurations to minimize the frame action effects were also reported [29–32].

The above summary indicates that the in-plane interaction between the BRBs and their surrounding framing members impacted negatively on the seismic performance of BRBFs. However, most of these researches focused on the corner gusset connection performance only, and very few of them examined the structural behavior of BRB welded/bolted end connections. Therefore, this topic has been one of the most concerned issues of the first authors' prior researches [14,33–37]. One effective way to eliminate the frame-induced moments is to use pinned connections on the BRB ends [33,35]. However, a minimum insert length of the end zone is generally required to stabilize the projected pinned connections. Cyclic tests on the pin-connected BRBs [33,35] showed that significant BRB end rotation, ranging from 2% to 3% radius, could still be observed due to the presence of gap between the inserted end zone and the casing. Similar to the previous observation on the bolted/welded BRB ends [18,19], premature buckling of the projected pinned connections [33] or even global buckling of the casing [35] were observed in the tests, although the required design check were all satisfied. These studies imply that the BRB end rotation, no matter caused by the frame action [18,19] (for welded/bolted end) or the gap [33,35] (for pinned end), is the major source of secondary moments on the BRB end connections. For the former case, the rotation of BRB ends are only governed by frame action effects, but the key factors affecting such rotational demands still remain unclear. This motivated the first author to move forward and discuss the interaction between frame action and BRB welded end connection behavior in the prior companion research [14]. The deformations of non-moment-resisting braced frame using flexible beam-column connections were examined in such a prior study. Theoretical analysis and large-scale subassemblage tests showed that two types of rotational/flexural deformations (see Fig. 2) could be observed with the variation of BRB geometry (inclined angle, end zone length, etc.), bracing configurations (single diagonal, chevron, etc.), and the story where the BRB locates. The BRB end moments governed by the S-shape deformation (see Fig. 2(a)) could be twice of those controlled by the C-shape for the BRBs having the inclined angle of 45°. Additionally, the end moment could be separated into two parts, i.e. the triggering moment induced by the rigid-body rotation of BRB (see e_{tr} and M_{tr} in Fig. 2), and the amplified moment (see the amplified moment factor A_m in Fig. 2) due to additional bending of the end zone and semi-rigid behavior of the BRB-to-gusset section (represented by rotational spring). Test results showed that the total end moment could be twice of the yield moment of the cruciform BRB end, although the cross-sectional area of the end zone was enlarged to be 2.3 times the plastic zone (rectangular section). The corresponding amplified moment factor could be up to 1.5, which cannot be ignored in design. Although the triggering moment could be easily determined from rigid-body motion analysis, the combined influences of the semi-rigid and bending effects of the entire BRB end connections, and their interaction with the rotational configurations of BRBs, were highlighted as the key issues for future researches on the amplified moment [14].