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Cyclic experimental and analytical studies of buckling-restrained braces with various gusset connections

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ABSTRACT

Five buckling-restrained braces (BRBs) with various gusset connections, including pinned gusset connection, bolted gusset connection, welded gusset connection, pinned-welded gusset connection as well as pinned-bolted gusset connection, were designed and tested under axial cyclic loading. Typical failure modes for all specimens were summarized and analyzed. The experimental results showed that all specimens exhibited stable hysteretic performance, good ductility and cumulative plastic deformation capacity. In addition, the relationship between the core plate strain demand and the effective factor was adopted to assess whether a BRB deformation satisfied the requirement of at least two times the design story drift. On the basis of Whitmore section and effective length, a formula of equivalent stiffness for a BRB with various gusset plates was suggested and verified by the experimental and numerical results. Furthermore, the finite element (FE) models of BRBs with various gusset connections were established and good consistency between the numerical and test results indicated that the FE modeling could simulate the cyclic behavior of BRB well. The elastic stiffness of gusset plate should be considered in the BRB design, and various gusset connection type and corresponding configurations provided an alternative method for designers to adjust conveniently the equivalent stiffness of brace under the premise of meeting the core plate strain demand.

1. Introduction

Buckling-restrained brace (BRB) generally consists of a core element and a restraining element. The configuration of unbonding layer or air gap is used to eliminate force transfer and accommodate transverse expansion in compression. The existence of the restraining element ensures that the core plate can fully yield in both tension and compression, providing significantly better energy dissipation capacity and ductility than the conventional steel brace. Various types of BRBs were developed and the experimental and analytical results revealed that they exhibited stable hysteretic performance, high ductility and cumulative plastic deformation capacity [1–10]. These favorable attributes have prompted extensive application of BRBs in new and existing frame structures in regions of high seismicity to resist lateral loads and mitigate frame structure damage.

The gusset plate plays a significant connection role in transferring axial force from the BRB to the surrounding frame structure. However, undesirable buckling or failure of the bolted or welded gusset plates occurred on some large scale tests of the buckling-restrained braced frame (BRBF) and limited the BRB to fully yield to dissipate energy. Tsai and Hsiao [11] tested a series of full-scale three-story three-bay BRBFs with bolted gusset plates under pseudo-dynamic simulation. The stiffeners were added when out-of-plane deformation of the first-story gusset plates was observed during Phase 1. Three specimens of BRBFs with welded gusset plates were conducted under cyclic loading by López et al. [12]. The free edge of the gusset plate buckled and the gusset-to-column welds cracked during test. In order to prevent the failure of gusset plates, the stocky pinned gusset plate was used in a 3/5-scale four-story BRBF and was implemented by Fahnestock et al. [13] using a hybrid pseudo-dynamic testing method. Moreover, Wigle et al. [14] studied the effect of various connection configurations, including bolted gusset plate, welded gusset plate and pinned gusset plate, on the global response based on FE analysis. Results showed that the connection configuration influenced local connection demands and global performance.

In order to understand the mechanical behavior of gusset plate and prevent premature buckling or failure, many scholars, such as Kaneko et al. [15], Tsai et al. [16], Chou et al. [17–19] and Khoo et al. [20],

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focused on the opening and closing effect of the beam-column-gusset connection due to frame action; useful guidelines were proposed to design gusset plates to consider the frame action and axial force of the BRB.

The above summaries showed that many scholars focused on the mechanical behavior of BRBs and buckling or failure of gusset plates, whereas few work studied the equivalent stiffness consisting of BRB stiffness, gusset plate stiffness and beam-to-column panel zone stiffness. Chuang et al. [21] introduced an effective stiffness factor to consider the gusset plate stiffness and panel zone stiffness. Judd et al. [22] provided a formula to compute the equivalent stiffness of the BRB with gusset plates, but it didn't present the process of calculating the gusset plate stiffness. During practical BRB design process, the BRB is usually replaced by the truss element with equivalent cross-sectional area and corresponding equivalent stiffness to evaluate the cyclic behavior of the BRB. The panel zone stiffness is assumed as infinitely large and can be negligible in comparison with the equivalent stiffness. However, designers adopt only the BRB stiffness, ignoring the gusset plate stiffness, which might result in overestimation of the BRB stiffness to the structural lateral stiffness. On the other hand, although the core plate strains of most typed BRBs can reach 3% and exhibit good ductility, the length of yielding portion and non-yielding portion varies with different connection types and configurations at the identical length of work point-to-work point. Therefore, it is necessary to check whether the core plate strain capacity of the BRB meets the requirements of the AISC 341-10 [23] that specifies the deformation of BRB shall be at least two times the design story drift. Finally, the numerical analytical results from Jiang et al. [24] showed that smaller width-to-thickness ratio of core plate would reduce the material consumption and the multi-wave contact forces of core plate. Thus, a configuration that could easily reduce the width-to-thickness ratio of core plate was proposed in this paper and described in Section 2.1.

In this study, a total of five BRBs with various types of gusset connections, including pinned gusset connection, bolted gusset connection, welded gusset connection, pinned-welded gusset connection as well as pinned-bolted gusset connection, were studied based on the above problems. Firstly, the failure modes of test specimens were recorded. Subsequently, the hysteretic behavior and the relationship between the core plate strain demand and the effective factor were also analyzed and evaluated to check whether the core plate strain capacity of the BRB satisfied the demand of at least two times the design story drift. The effective factor was described in detail in Section 3.2. Additionally, a formula of equivalent stiffness of the BRB with various gusset plates was suggested based on the Whitmore section and effective length. Finally, the FE modeling of BRBs with various types of gusset connections were established and validated by the experimental results. The experimental and numerical analysis results will be helpful to promote the application of BRBs in frame structure.

2. Test program

2.1. Test specimens

The specimen BRB-GP3 with welded gusset connection was designed following the guidelines of the AISC 341-10 [23] as the diagonal brace and installed in a steel frame with 2.50×10^3 mm span length and 2.10×10^3 mm story height with scale of 1:2 from engineering practice. In order to investigate the equivalent stiffness of the BRBs with various gusset connections in a same frame, pinned gusset connection, bolted gusset connection, pinned-welded gusset connection as well as pinned-bolted gusset connection were designed on the basis of specimen BRB-GP3 with welded gusset plates. The dimension and detail description of the test specimens were presented in Figs. 1–3 and Table 1. The total length of all specimens was same as 3.04×10^3 mm while the dimension of BRBs and gusset plates of the five specimens were not identical because of various connection type and configuration.

The BRB studied in this paper was composed of a core element and a restraining element. A flat core element with a cross-section of 25×41 mm was used for all specimens to provide the same force demand to surrounding frame members. In general, the deformation capacity of a BRB was affected by the length of yielding portion. The objective of this paper was to examine the deformation capacity of a BRB with different yielding length, such as 1.70×10^3 mm, 7.60×10^2 mm, 1.30×10^3 mm, 1.50×10^3 mm and 1.20×10^3 mm for five specimens and illustrated in Table 1 and Fig. 1. It was expected that the deformation capacity of specimen BRB-GP2 with the shortest yielding length of 7.60×10^2 mm among all specimens might not satisfy two times the design story drift. Meanwhile, the configuration of abrupt variation of the cross-section in a transition part was designed to form weak part and check whether the specimen failure concentrated at this position (Fig. 1).

The restraining steel tube infilled with fine aggregate concrete was used as the restraining element. Four steel plates were welded together to form a restraining steel tube with size of $120 \times 120 \times 8$ mm based on Watanabe et al. [1]:

$$P_{e,sc}/P_y \geqslant 1.5;\ P_{e,sc} = \pi^2 EI_{sc}/L_{sc}^2 \tag{1}$$

where P_y is the yield strength of the core plate; $P_{e,sc}$ is the elastic buckling strength of the restraining steel tube without considering the contribution of concrete bending stiffness; E is the Young's modulus; I_{sc} and L_{sc} are the moment of inertia and the length of the restraining steel tube (Table 1), respectively. The yield strength of the core plate is $P_y = A_y f_y$, where A_y and f_y are the cross-sectional area and yield stress of the core plate, respectively, and f_y can be obtained from the coupon test. In this study, the restraining members of all specimens were designed following Eq. (1) to prevent global buckling failure. In addition, the stopper w as welded at the mid core to prevent the restraining element from slipping. A 2 mm-thick silicone rubber sheet was provided as a unbonding material between the core element and the restraining element to accommodate transverse expansion of the core plate and also to minimize the frictional effect. Unlike some proposed BRBs that the core plates were usually extended from the restraining elements as part of the non-yielding portion, a configuration that the flexible stiffeners were welded to the end of core plate to form a non-yielding portion of the BRB was used in five specimens (Fig. 1). There are two advantages for the alternative configuration. The first is that smaller width-to-thickness ratio of core plate could easily be achieved to reduce material consumption of restraining element and the multi-wave contact forces of core plate [24]. The second is that the thinner thickness of non-yielding portion of the BRB could be used by higher strength steel and conveniently match with the dimension of gusset plate.

The bolted and welded gusset plates in the specimens were designed to satisfy Eqs. (2) and (3) to avoid failure of gusset plate as result of yielding in tension and buckling in compression [23,25,26].

$$\phi P_{y,gp} = \phi b_e t_{gp} f_{y,gp} \geqslant P_{max}/\beta \tag{2}$$

$$\phi P_{cr,gp} = \phi(0.658)^{\lambda_c^2} b_e t_{gp} f_{y,gp} (\lambda_c \leqslant 1.5) \phi P_{cr,gp} = \phi(0.877/\lambda_c^2) b_e t_{gp} f_{y,gp} (\lambda_c \leqslant 1.5) \geqslant P_{max} \tag{3}$$

where $\lambda_c = \frac{KD_w}{\pi r}\sqrt{\frac{f_{y,gp}}{E}}$, $D_w = \frac{L_{l1}(L_{u1}) + L_{l2}(L_{u2}) + L_{l3}(L_{u3})}{3}$, $r = \frac{t_{gp}}{\sqrt{12}}$ and $\phi = 0.9$. $P_{y,gp}$ and $P_{cr,gp}$ are the yield strength and the buckling strength of the gusset plate, respectively. $f_{y,gp}$ and t_{gp} are the yield stress and thickness of the gusset plate, respectively. P_{max} is the maximum strength of the BRB that is computed from $P_{max} = \omega\beta P_y = 501.79$ kN, in which 1.5 is used for the strain hardening adjustment factor (ω) in accordance with JGJ99-2015 [28] and 1.15 is selected for the compression strength adjustment factor (β) based on Ref. [21]. The parameter of b_e is the Whitmore section [25] where the stress is distributed along a 30° from the line connecting the first bolt hole to the last bolt hole (Figs. 1 and 4). The effective length (D_w) is the average length of L_{l1}, L_{l2} and L_{l3} for