**Experimental study on out-of-plane stability of buckling-restrained braces**

**DOI 10.37153/2686-7974-2019-16-1163-1171**

An-Chien WU[[1]](#footnote-1), Li-Wei CHEN[[2]](#footnote-2), Keh-Chyuan TSAI[[3]](#footnote-3)

**ABSTRACT**

Buckling-restrained braces (BRB) have been widely used as cost-effective energy dissipaters in seismic designs of steel buildings. However, several issues of out-of-plane (OOP) instability have been observed in previous research. The stability evaluation method commonly used in seismic design practice applies three limit states to check the stability of the steel casing, connections, and gussets separately. Nevertheless, they appear to be over-simplified, by adopting unreasonable end conditions and neglecting coupling effects among them. This study adapts an advanced stability assessment procedure and proposes a new stability model that considers the flexural deformation of the restrainer, gusset rotations, and the aforementioned coupling effects. To verify the effectiveness of the proposed model, four full-scale BRB specimens each 5.8 m long with a 988-kN nominal yielding strength, varying restrainer stiffness, gusset thickness, and with/without edge stiffeners or OOP end drift are tested. Test results show a 9% drop in buckling strength due to a 57-mm OOP end drift, highlighting the significant impact from the OOP end drift. The proposed model exhibits an improvement in the buckling strength of over 80% with a 24% enlargement in the restrainer diameter, indicating the critical effects of the restrainer’s flexural stiffness.

*Keywords: buckling restrained brace; out-of-plane buckling; cyclic loading test; gusset rotation; out-of-frame plane drift*

**1. INTRODUCTION**

Buckling-restrained braces (BRB) have been widely recognized as cost-effective energy dissipaters for seismic-designed buildings around the world in the past few decades. Studies have confirmed that buckling-restrained braced frames (BRBF) possess high stiffness, strength, and seismic resilience. However, issues of BRB out-of-plane (OOP) instability, mitigating the aforementioned benefits, have been documented (Tsai et al. 2008, Tsai and Hsiao 2008, Wu et al. 2016). As a result, the stability of BRBs has become a critical issue in BRBF design and applications. Several studies have been conducted recently to establish stability criteria for BRBs in order to ensure stable performance. Matsui et al. (2010) highlighted the importance of the rotational strength, or the moment transfer capacity, at the restrainer end that dramatically affects the overall stability of BRBs. A series of procedures were proposed to calculate both the rotational stiffness and strength for rectangular and circular restrainers. Zhao et al. (2014) proposed a practical method to measure the in-plane stability of pin-connected BRBs based on a moment amplification factor. Zaboli et al. (2017) adopted the notional load yielding line method and proposed a simplified method to determine the minimum size of gusset plates required to achieve overall OOP stability for both BRBFs and concentrically braced frames. Takeuchi et al. (2013, 2014, 2016) proposed an advanced stability model based on the observation in which the overall instability is triggered by plastic hinges formed during compressive loading. Meanwhile, it considers initial imperfection, OOP end drift, flexural connection and rigid restrainer.

The stability evaluation method commonly used in practice (Chuang et al. 2015) applies three limit states to separately check the stability of the steel casing, connections, and gussets for welded buckling restrained braces (Tsai et al. 2014). Wu et al. (2016) investigated the implementation of BRBs in a new reinforced-concrete frame (BRB-RCF). A series of pseudo-dynamic and cyclic tests on a full-scale two-story BRB-RCF were conducted at National Center for Research on Earthquake Engineering (NCREE) in 2015. It should be noted that the two BRB specimens were designed by applying the above three independent limit states, which are considered neither to incorporate the coupling effects among themselves nor to apply a reasonable assumption on end conditions. After the four hybrid tests, one of the BRBs buckled with severe OOP deformation along the restrainer and with gusset failure during the first 4.5% inter-story drift ratio (IDR) in the subsequent cyclic loading tests (Figures 1(a) and (b)). Recently, Tsai et al. (2017) investigated the possible buckling mode and proposed an evaluation procedure. This procedure was extended from Takeuchi’s approach (2013, 2014, 2016) but with consideration of flexural restrainer and gusset rotations. This buckling mode was applied in a performance analysis of the abovementioned two BRBs installed in the BRB-RCF specimen. Good consistency with the test results was documented.

Chen et al. (2018) further analyzed the buckling mode described in Tsai’s study (2017) and refined the stability model, in which the effects of the initial imperfection along the restrainer and the OOP end drift on the overall stability were investigated using finite-element model (FEM) analysis. In addition, a method was developed to compute the gussets’ rotational stiffness and strength using FEM analysis. In order to verify the effectiveness of the proposed stability model, four full-scale welded BRB specimens each 5.8 m long with a 988-kN nominal yield strength, varying restrainer stiffness, gusset thickness, and with/without edge stiffeners or OOP end drift were tested using the multi-axial testing system (MATS) at NCREE. It is demonstrated that the proposed model can accurately predict the failure modes and buckling strengths of the BRB specimens.

|  |  |
| --- | --- |
| (a) | (b) |

Figure 1. (a) Buckling of the first-story BRB and (b) the plastic hinge formed at the upper gusset.

|  |
| --- |
|  |

Figure 2. Schematic of the simplified model.

**2. STABILITY ASSESSMENT**

Takeuchi et al. (2013, 2014) proposed an advanced stability model where the BRB assembly is simplified into four rotational springs and three members in series (Figure 2). The model is based on the observation in which the global OOP buckling of BRBs is triggered by plastic hinges occurring at the restrainer ends (point A) and/or gussets (rotational points), as shown in Figure 3(a). However, the precise location of the rotational point is not clearly defined in any of Takeuchi et al.’s publications. The stability concept is illustrated in Figure 3(b), where the two strength versus OOP deformation relationships are constructed from the following equations:

Elastic buckling path (EBP):  and (1)

Ultimate strength path (USP):  (2)

The EBP given in Equation 1 represents the equilibrium state between the BRB axial force and the overall OOP deformation. Here, *ar* denotes the total initial imperfection contributed from the restrainer imperfection, the load eccentricity, and the clearance between the restrainer and the core; *yr* denotes the deformation developed from the second-order effect; represents the elastic buckling strength computed from the aforementioned model of four rotational springs and three members in series. The USP given in Equation 2 presents the typical equation form for the asymmetrical buckling mode resulting from plastic hinges forming at the restrainer ends only, as illustrated in Figure 4. Here, denotes the rotational strength of the restrainer end and represents the additional bending moment demand caused by the OOP end drift. The intersection point between the EBP and USP is defined as the stability limit, *P*lim:

 (3)

OOP stability is guaranteed as long as the stability limit is higher than the maximum possible compressive strength, *P*max, developed from BRBs.

|  |  |
| --- | --- |
| (a) | (b) |

Figure 3. (a) Definition of the restrainer end zone and (b) stability concept and limit.

In Takeuchi’s theory (2013, 2014, 2016), the buckling mode is based on the assumption in which the restrainer would behave as a rigid body, while the connection zones defined in Figure 2 would bend. Nevertheless, according to the geometrical characteristics of the welded BRB, where the restrainer length, or the steel casing length, is much longer than that of the connections, the bending flexibility of the restrainer could be relatively significant compared with that of the connections. Thus, it appears appropriate to treat the connection zones, instead of the restrainer, as rigid bodies when it comes to investigating the buckling modes. In addition, according to the recommendations from Takeuchi et al., the buckling mode is dominated by either an “asymmetrical mode” or a “one-sided mode”. However, the asymmetrical mode is usually regarded as the second buckling mode, which has a higher buckling strength than a symmetrical mode or the first buckling mode. Test results for the BRB-RCF specimens (Wu et al. 2016) showed that the first-story BRB buckled in a symmetrical mode with gusset rotations, while the restrainer ends and the connections remained undamaged, as illustrated in Figures 1(a) and (b). However, the buckling modes suggested by Takeuchi et al. only cover cases where either the restrainer ends fail or the restrainer ends and gussets fail simultaneously, as shown in Figure 4. Thus, this study proposes a new stability model that considers restrainer flexibility and a symmetrical buckling mode induced by the gusset rotations. The details of the proposed model can be found in (Chen et al. 2018).

Table 1. Dimensions and strengths of specimen.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **ID** | ***Bc***  (mm) | ***tc***  (mm) | ***Bj***  (mm) | ***Dj***  (mm) | ***Rr***  (mm) | ***tr***  (mm) | ***tg***  (mm) | ***Lc***  (mm) | ***Lt***  (mm) | ***Lj***  (mm) | ***Lsc***  (mm) | ***LBRB***  (mm) | ***Lwp***  (mm) |
| G18 | 103 | 16 | 162 | 172 | 216.3 | 7 | 18 | 4530 | 70 | 1270.5 | 5210 | 5760 | 7211 |
| G16 | 216.3 | 16 |
| G18\_LC | 267.4 | 18 |
| G16\_ES | 216.3 | 16 |

Table 2. The calculated stability results for the BRB casing, connection region, and gusset using the existing methods.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Limit state | DCR | G18 | G16 | G18\_LC | G16\_ES |
| BRB steel casing flexural buckling | (DCR-4) | 0.97 | 0.97 | 0.58 | 0.97 |
| BRB connection region compression buckling | (DCR-2) | 0.90 | 0.90 | 0.90 | 0.90 |
| Gusset plate compression buckling [*K*=0.65]\* | (DCR-6) | 0.83 | 1.05 | 0.83 | (1.05) |
| [*K*=2.0]\* |  | (1.10) | (1.34) | (1.10) | 1.34 |

\*The *K* value in the parentheses indicates the effective length factor applied in computing the gusset’s compressive capacity. It is 0.65 for the case with gusset edge stiffeners and 2.0 for the case without the stiffeners.

|  |
| --- |
|  |

Figure 4. The possible buckling modes proposed by Takeuchi et al.

**3. EXPERIMENTAL PROGRAM**

***3.1 Specimen Design***

The specimens were designed to reflect a typical BRBF with a beam bay width of 6000 mm and a story height of 4000 mm. The beam depth is 500 mm and the column width is 550 mm. These four specimens were constructed using CNS SN490B steel (nominal yielding strength *σcy* = 325 MPa) with the same core cross-sectional properties and longitudinal dimensions. Thus, the four specimens have the same design yield strength. The detailed dimensions are illustrated in Figure 5 and given in Table 1. The specimens were denoted such that the first three alphanumeric letters indicate the thickness of the gusset. The label ‘LC’ denotes a larger restrainer, while ‘ES’ denotes the gusset stiffeners. The maximum possible compressive strength, *P*max, was estimated to be 1772 kN from the nominal yielding strength and the suggested adjustment factors for SN490B steel. These factors include the material over-strength (1.2), strain hardening (1.3), and compression strength adjustment (1.15) factors. The specimens were fabricated using 16-mm- or 18-mm-thick gussets (G16 or G18). In order to understand the restrainer’s flexural effects, one of the BRBs’ restrainers was made from a larger casing (G18\_LC) 267 mm in diameter. One of the BRB specimens (G16\_ES) was equipped with 10-mm-thick stiffeners along the long sides of its gussets to investigate the effects of the gusset stiffener. The detailed designs were based on existing procedures (Chuang et al. 2015), in which the stability demand-to-capacity ratio (DCR) of the steel casing, connections, and gussets were checked separately. The BRB’s compressive force demand of 1772 kN was applied in computing these DCRs.

|  |
| --- |
|  |

Figure 5. Detailed dimensions of the specimens.

The evaluation results are given in Table 2. These calculations did not consider the strength reduction factor. Specimens with a 216.3 mm restrainer (G18, G16, G16\_ES) all have a rather critical DCR value of 0.97 in the steel casing flexural buckling check (DCR-4). In contrast, G18\_LC, which equipped with a 267.4 mm restrainer, has a quite low DCR value of 0.58. G18\_LC was supposed to be designed with a restrainer of which the diameter is in between 216.3 mm and 267.4 mm, possibly with a DCR-4 of about 0.8 so that there would be a more striking comparison to justify the effectiveness of this method. However, the restrainer selection depended on whether the manufacturer had the steel casing with needed size in stock. Therefore, it was actually an expediency to make such restrainer layouts. It is noted that an effective length factor (*K*) of 0.65 is adopted in calculating the gusset’s compression buckling strength (DCR-6) when the edge stiffeners are detailed. On the other hand, a value of *K* = 2.0 is applied for the case without them. The DCRs for the four specimens calculated using the *K* values described above are marked in red and in parentheses in Table 2. However, the evaluation results of using both the *K* values on all four specimens are also listed in Table 2 for comparison purposes. G16 has a DCR of 1.34 in the gusset compression buckling check, indicating an unsafe design, while G18, G18\_LC, and G16\_ES have smaller DCRs, but still greater than 1.0. To sum up, based on these limit state evaluation results, the four specimens were designed to have various levels of gusset buckling potential.

|  |
| --- |
|  |

Figure 6. Test setup.

***3.2 Test Setup and Instrumentation***

Figure 6 illustrates the test setup, where the positive X-direction is toward the south (the platen side), and the positive Y-direction is toward the east. This coordinate system was applied for both the loading protocol and the instrumentation. Two gusset connectors were fabricated to provide end boundary conditions for the gussets, and to simulate the gusset–beam and gusset–column interfaces. It should be noted that both the in-plane and OOP rotation of the beam–column joint is neglected in this study. Thus, the gusset connectors were stiffened to be sufficiently rigid without rotation. Model analysis using Abaqus confirmed that the difference in the computed gusset rotational stiffness between the perfectly rigid gusset edges and the existing condition was less than 4%.

In order to recover the OOP deformations of the specimens, an optical measuring system (OMS), which comprise a controller, a camera and several markers, was used. An array of OMS markers was placed along the BRB member and gussets. The markers emitted optical signal which was subsequently captured by the camera. As a result, the instant three-dimensional coordinates of each marker were computed and recorded. Four displacement transducers were arranged at the restrainer ends (two on each side) to measure the BRB’s axial deformations. An array of uniaxial strain gauges was attached at the head of the overlap portion between the joint segment and the gusset to recover the axial force and the bending moment if necessary.

|  |
| --- |
|  |

Figure 7. Loading protocol.

***3.3 Test Procedure***

The specimens were tested by applying cyclically increasing displacements. The loading protocol comprised the standard and fatigue cyclic loading tests, as illustrated in Figure 7. The standard loading cycles followed the recommendations of AISC 341-16 (2016) for BRBs, where the first two cycles consider the yielding displacement of the BRB specimen. Then, the loading proceeds with an increasing IDR ranging from 1% to 4% for two cycles at each level. In order to trigger the instability of the specimens, two additional cycles with a 5% IDR were adopted following the last cycle of 4% IDR if necessary. Once the specimen went through the abovementioned loading cycles without failure, the fatigue cyclic loading test with constant displacements of 3% IDR was repeated until failure occurred.

***3.4 Test results***

G18, G16, and G16\_ES buckled with plastic hinges forming at the gussets and significant flexural deformation developing along their restrainers, as shown in Figures 8-10. G18\_LC exhibited a stable performance throughout the loading cycles without any observable damage. Fatigue failure did occur at the 16th cycle in the subsequent fatigue test. The BRB force vs. axial deformation relationships are given in Figure 11 for all specimens.

|  |  |
| --- | --- |
| (a) | (b) |

Figure 8. (a) The folding line at the southern gusset and (b) the buckling shape of G18.

|  |  |
| --- | --- |
| (a) | (b) |

Figure 9. (a) The folding line at the southern gusset and (b) the buckling shape of G16.

|  |  |
| --- | --- |
| (a) | (b) |

Figure 10. (a) The folding line at the southern gusset and (b) the buckling shape of G16\_ES.

|  |
| --- |
|  |

Figure 11. Hysteresis loops of the specimens.

*3.4.1 Specimen G18*

G18 buckled at the first cycle of 5% IDR and the axial strength dropped drastically after reaching 2118 kN. The maximum tensile strength was 1728 kN at the peak of 5% IDR. The compressive strength adjustment factor, *β*, was computed to be 1.17 from the second cycle of 4% IDR. The cumulative plastic deformation (CPD) had reached 252 by the time it buckled. An OOP end drift of 7.3 mm was measured by the OMS. From the axial force vs. axial deformation relationships, it can be seen that the axial stiffness rose slightly during compression in the 4% IDR cycles, and even went higher during the 5% IDR cycle. This kind of phenomenon was also observed in the other specimens, which should be caused by the effects of severe high-mode buckling developed along the core. Figure 8(a) shows the folding line developed on the gussets when the global instability occurred. The overlap portion between the gusset and the joint segment formed a rigid zone, which pushed the folding line inward to the gussets, causing a curved folding line. The distance between the end of the BRB member and the folding line is approximately twice the gusset thickness.

*3.4.2 Specimen G16*

G16 buckled during the first 3% IDR loading cycle with an initial end drift of 57.4 mm caused by experimental misalignment. The buckling strength was 1721 kN, while the maximum tensile strength was 1607 kN. The *β* value was 1.11, calculated from the second cycle of 2% IDR. By the time it buckled, the CPD had reached over 80. After buckling, G16 was stretched first and compressed again. It can be seen that the BRB member somehow behaved like a conventional buckling brace and completely lost its stability even through it had been re-stretched. The axial force vs. axial deformation relationships are illustrated in the plot designated “G16\_After buckling” in Figure 11. Figure 9(a) shows the folding line developed on the gusset. Again, the distance between the end of the BRB member and the center of the folding line was twice the gusset thickness.

*3.4.3 Specimen G18\_LC*

G18\_LC exhibited stable hysteresis behavior throughout the standard cyclic loading test without any observable instability or damage. Subsequently, a fatigue cyclic loading test with a constant amplitude of 3% IDR proceeded. The core fatigue fracture did occur at the sixteenth cycle of the fatigue test. The total CPD reached over 674 at the end of the tests. The maximum tensile strength and the maximum compressive strength developed at the second cycle of 5% IDR were 1747 kN and 2178 kN, respectively. The corresponding *β* value was 1.25. A large end drift of 72.2 mm was measured at the initial state and was attributed to experimental misalignment.

*3.4.4 Specimen G16\_ES*

Concerning the unintentional OOP end drift measured from the abovementioned tests, G16\_ES was carefully calibrated without any drift in the first place using the OMS. G16\_ES performed stably throughout the prescribed standard loading cycles without any observable damage. Thus, it was further subjected to an OOP end drift of 1/100 L0 (57.1 mm) and loaded from the 3% IDR cycle to investigate the effects of end drift on the overall stability. Eventually, G16\_ES buckled at the first cycle of 5% IDR with a buckling strength of 1942 kN. The maximum tensile strength was 1680 kN. The *β* value was 1.16, as calculated from the second cycle of 4% IDR with the end drift. The CPD reached 491. Figure 10(a) shows the folding line developed on the gusset. It can be found that the edge stiffener welded along the long side of the gusset had impeded the development of the folding line near the gusset’s free edges, causing a more curved folding line. The axial force vs. axial deformation relationships with no end drift and with end drift, designated as “G16\_ES(I)” and “G16\_ES(II)”, respectively, are given in Figure 11.

**4. Conclusions**

Existing methods do not consider either the coupling effects of the gussets’ and the restrainer’s buckling, or the effects of the restrainer’s flexural deformation. Therefore, these methods may lead to incorrect predictions of the buckling mode and strength. The proposed model considers both the aforementioned coupling effects and the restrainer’s flexural deformation. It is able to provide a more reliable design for BRBs and gusset connections compared to that given by existing methods.

Three specimens buckled with severe out-of-plane (OOP) deformations of the restrainer and plastic hinges forming at the gussets. The restrainer’s flexural stiffness plays a critical role with respect to the overall BRB stability. The full contribution of the infilled mortar can be applied when calculating the equivalent area and effective flexural stiffness of the restrainer. The test results for G16, G16\_ES(II), and G18 confirmed that the improvement in the overall stability is limited when attaching only one gusset stiffener or using slightly thicker gussets. Doubling the gusset’s rotational stiffness and strength from G16 to G16\_ES(II) improves the buckling strength by only 13%. The test results for G16\_ES(I) and G16\_ES(II) confirmed that a large OOP end drift can trigger severe OOP deformation and subsequent buckling. An end drift of 1/100 L0 in G16\_ES(II) reduced the buckling strength by at least 9%, indicating that the OOP end drift is a crucial factor affecting the overall stability.

**5. RefereNCES**

American Institute of Steel Construction (2016) Seismic Provisions for Structural Steel Buildings (AISC 341-16). AISC, Chicago, Illinois.

Chen L.W., Tsai K.C., Tsai C.Y., Wu A.C. (2018) Evaluating out-of-plane stability for welded BRBs considering flexural restrainer and gusset rotations. *Journal of Constructional Steel Research*, in review.

Chuang M.C., Tsai K.C., Lin P.C., Wu A.C. (2015) Critical limit states in seismic buckling-restrained brace and connection design. *Earthquake Engineering & Structural Dynamics*, 44(10): 1559-1579.

Matsui R., Takeuchi T., Nishimoto K., Takahashi S., Ohyama T. Effective buckling length of buckling-restrained brace considering rotational stiffness at restrainer ends. *Proceedings of the 7th International Conference on Urban Earthquake Engineering & the 5th International Conference on Earthquake Engineering Proceedings*, 2010, Tokyo, Japan.

Takeuchi T., Ozaki H., Matsui R., Sutcu F. (2013) Out-of-plane stability assessment of buckling restrained braces including moment transfer capacity at restrainer-end. *Journal of Structural and Construction Engineering*, 78:1621-1630. (in Japanese)

Takeuchi T., Ozaki H., Matsui R., Sutcu F. (2014) Out-of-plane stability of buckling-restrained brace including moment transfer capacity. *Earthquake Engineering & Structural Dynamics*, 43(6): 851-869.

Takeuchi T., Ozaki H., Matsui R., Sutcu F. (2016) Out-of-plane stability assessment of buckling-restrained brace including connections with chevron configuration. *Earthquake Engineering & Structural Dynamics*, 45(12): 1895-1917.

Tsai C.Y., Tsai K.C., Chen L.W., Wu A.C. (2018) Seismic performance analysis of BRBs and gussets in a full-scale 2-story BRB-RCF Specimen, *Earthquake Engineering and Structural Dynamics*, 47(12): 2366-2389.

Tsai K.C., Hsiao P.C., Wang K.C., Weng Y.T., Lin M.L., Lin K.C., Chen C.H., Lai J.C., Lin S.L. (2008) Pseudo-dynamic tests of a full-scale CFT/BRB frame -Part I: Specimen design, experiment and analysis. *Earthquake Engineering & Structural Dynamics*, 37:1081-1098.

Tsai K.C., Hsiao P.C. (2008) Pseudo-dynamic tests of a full-scale CFT/BRB frame -Part II: Seismic performance of buckling restrained braces and connections. *Earthquake Engineering & Structural Dynamics*, 37:1099-1115.

Tsai K.C., Wu A.C., Wei C.Y., Lin P.C., Chuang M.C., Yu Y.J. (2014) Welded end-slot connection and debonding layers for buckling restrained braces. *Earthquake Engineering & Structural Dynamics*, 43:1785-1807.

Wu A.C., Tsai K.C., Yang H.H., Huang J.L., Li C.Y., Wang K.J., Khoo H.H. (2016) Hybrid experimental performance of a full-scale two-story buckling-restrained braced RC frame. *Earthquake Engineering & Structural Dynamics*, 46(8): 1223-1244.

Zaboli B., Clifton C., Cowie K. Out-of-plane stability of gusset plates using a simplified notional load yield line method. *Proceedings of the NZSEE Annual Technical Conference and the 15th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures*, 2017, Wellington, New Zealand.

Zhao J., Wu B., Ou J. (2014) A practical and unified global stability design method of buckling-restrained brace: discussion on pinned connections. *Journal of Constructional Steel Research*, 95: 106-115.

1. Associate researcher, National Center for Research on Earthquake Engineering, Taipei, Taiwan, acwu@ncree.narl.org.tw [↑](#footnote-ref-1)
2. Research assistant, Department of Civil Engineering, National Taiwan University, Taipei, Taiwan, r04521250@ntu.edu.tw [↑](#footnote-ref-2)
3. Professor, Department of Civil Engineering, National Taiwan University, Taipei, Taiwan, kctsai@ntu.edu.tw [↑](#footnote-ref-3)