BUCKLING-RESTRAINED BRACE STABILITY EVALUATION, EMPIRICAL BASIS AND DESIGN IMPLICATIONS

B. Sitler¹, T. Takeuchi², R. Matsui³ and P.C. Lin¹

ABSTRACT

Buckling-restrained braces (BRBs) are capable of withstanding severe seismic demands without visible damage or requiring replacement. However, stability must be maintained to achieve this performance. While the restrainer design is well established, current guidance to ensure connection stability differs markedly from country to country and the recommended methods produce a wide range of predicted capacities. This is an issue that has been discussed in the commentary to AISC 341 since the 2005 edition, but the specific method of analysis is currently left to the engineer’s judgement. This paper evaluates the accuracy of the stability evaluation methods currently being used by engineers in Japan, New Zealand, Taiwan and the US, based on a test catalogue of 82 specimens, 50% of which experienced out-of-plane connection buckling. This is a global mode characterized by the formation of a hinge just outside of the restrainer, with the gusset subsequently yielding to complete the collapse mechanism. Several recently proposed methods are shown to be conservative, and the critical design variable is identified as the out-of-plane rotational end fixity provided by the gusset and adjacent framing. A three-tier design procedure is proposed, with each tier producing a less conservative design, but at the cost of increased analytical effort.

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Buckling-restrained braces (BRBs) are capable of withstanding severe seismic demands without visible damage or requiring replacement. However, stability must be maintained to achieve this performance. While the restrainer design is well established, current guidance to ensure connection stability differs markedly from country to country and the recommended methods produce a wide range of predicted capacities. This is an issue that has been discussed in the commentary to AISC 341 since the 2005 edition, but the specific method of analysis is currently left to the engineer’s judgement. This paper evaluates the accuracy of the stability evaluation methods currently being used by engineers in Japan, New Zealand, Taiwan and the US, based on a test catalogue of 82 specimens, 50% of which experienced out-of-plane connection buckling. This is a global mode characterized by the formation of a hinge just outside of the restrainer, with the gusset subsequently yielding to complete the collapse mechanism. Several recently proposed methods are shown to be conservative, and the critical design variable is identified as the out-of-plane rotational end fixity provided by the gusset and adjacent framing. A three-tier design procedure is proposed, with each tier producing a less conservative design, but at the cost of increased analytical effort.

Introduction

Buckling-restrained braces (BRBs) rely on global stability to achieve the designated axial yielding mechanism. While it is intuitive to focus on the required strength and stiffness of the restrainer, connection stability tends to govern when attached to gussets in a frame. This is because the restrainer resists negligible axial forces, while the connections are subjected to large compressive overstrength demands. The out-of-plane direction governs due to the inherent flexibility of unstiffened gussets about this axis. Connection buckling is defined by a hinge at the neck (or restrainer end), and is distinct from local gusset buckling, restrainer buckling and bulging (Fig. 1).

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While codes such as AISC 341-16 [1] permit BRB stability to be confirmed from physical tests, it may be difficult to capture real project conditions (frame/web flexibility, out-of-plane drift, etc) and impractical to test all key parameters (gusset topology, neck-to-core size, etc) without being unduly conservative. Contemporary international practice [2,3] has demonstrated that an alternative approach is feasible, where connection stability is confirmed through analytical checks, using methods developed specifically for BRBs.

**Characteristics of BRB stability**

BRBs have several important differences compared to conventional braces, as depicted in Fig. 2. First, (1) the restrainer is axially decoupled, shifting the section with the critical buckling demand-to-capacity ratio to the connections, typically the neck (i.e. core extension immediately outside the restrainer) [2]. While this increases the buckling capacity, (2) BRB compressive overstrength ($\beta \omega N_y$) is much larger than in conventional braces [1] and tension ($\omega N_y$) no longer governs for key aspects of the connection design. A design challenge arises as (3) the neck capacity is linked to the core material and thickness, and the neck must usually fit within the restrainer profile. Economic designs tend to employ large neck axial utilizations ($\beta \omega N_y / N_{ny} = 0.7\sim0.9$), leaving little spare capacity to accommodate geometric imperfections, axial residual stresses and inelasticity. Furthermore, the system stiffness may be compromised by incomplete (4) flexural continuity between the neck and restrainer, which depends primarily on the insert (or overlap) length $L_{in}$ (Fig. 2). While one solution is to increase the neck capacity (say to $N_{ny} > 2.0 \beta \omega N_y$), this may be costly. An alternative strategy is to reduce the buckling $P \delta$ demand by providing rotational end fixity, achieved by adding gusset stiffeners and increasing the adjacent framing rotational stiffness. Finally, (5) local gusset plate buckling rarely governs, as BRB gussets are usually compact and relatively thick.

![Figure 2. Comparison to conventional brace stability](image)

The implication for design is that (1) connections are governed by global stability, and do not achieve the full axial yield strength, (2) end fixity, or lack thereof; has a pronounced effect on stability, and (3) stability is sensitive to a large number of parameters, increasing the uncertainty.

**Current procedures**

**Stability evaluation methods**

While numerous evaluation methods have been proposed, the test data available for validation has increased dramatically over the past decade [4–21]. This paper revisits the empirical basis of these methods, which are summarized in Fig. 3 (refer to original papers for further details).
Representative connection stability evaluation methods considered in this paper include:

**Local gusset buckling** procedures based on the Thornton method [22], but with effective length factors of $k_e=0.65$ [6], 1.2 [21] or 2.0 [7]. This paper uses the centerline length ($L_0$) from the last bolt row or weld (Fig. 3), Whitmore width including the beam web and AISC column curve [22].

**Global elastic buckling** procedures based on the [Rest] restrainer stiffness ($EI_r$) and full end-to-end length ($L_0$), or [Conn] neck stiffness ($\gamma E_\ell$) and cantilever frame workpoint length ($2 \cdot \xi L_0$). The latter is attributed to Nakamura [3,5] and is limited to the neck squash load $N_\theta^0$, following [3]. Alternatively, Koetaka et al. [8], Hikino et al. [12] and Lanning [13] proposed to model the restrainer end as a pin ($K_{rn}=0$ in Fig. 3), referred to as [Post] post-yield elastic buckling methods. This paper models the frame [8,12] and gusset [13] as a combined spring with rotational stiffness $K'_{rg}$ acting at length $\xi' L_0$ (Eq. 1-2), and assumes rigid connections ($\gamma E_\ell=\infty$), following [12,13].

\[
K_{rf} = \left(\frac{\cos^2 \theta + \sin^2 \theta}{K_{rf,zz}} \right)^{-1} \approx \frac{K_{rf,xx}}{\sin^2 \theta} \text{ (if diaphragm slab is present)}
\]

\[
\xi' L_0 = \frac{\left( \frac{\xi'_L L_0}{K_{rg}} \right)^2 + \left( \frac{\xi_{f} L_0}{K_{rf}} \right)^2}{\left( \frac{\xi'_L L_0}{K_{rg}} \right) + \left( \frac{\xi_{f} L_0}{K_{rf}} \right)} \quad K_{rg} = \left( \frac{\xi'_L L_0}{\xi'_L K_{rg}} + \frac{\xi_{f} L_0}{\xi_{f} K_{rf}} \right)^{-1}
\]

**Global inelastic buckling** procedures calculated from the [Ult] ultimate plastic capacity, reduced for the applied axial load, out-of-plane drift and P\&D moments. This paper adopts the lower of two stability limits ($N_{lim1, lim2}$) proposed by Takeuchi et al. [2,16], and for chevron configurations the more onerous connection is adopted at both ends. The initial imperfection $\alpha_r$ includes the rotational slack introduced by the debonding gap (taken as $s_r = 1\text{mm}$ if not specified). A notional load method [NL] proposed by Zaboli and Clifton [23] is also considered, using a simplified estimate of the elastic buckling load $N_\theta^0$ based on the presence, or lack, of gusset stiffeners.

![Figure 3. Stability evaluation methods](image-url)
Test results

Recent tests conducted in China, Ecuador, Iran, Italy, Japan [8–10,12,15–17,19,20], New Zealand, Taiwan [11,14,18], Turkey and the US [13,21] have dramatically increased the quantity and diversity of test data, supplementing well-known tests from the early 2000s [4–7]. Table 1 catalogues a selection of 80 specimens (43 buckled), with representative details shown in Fig. 4.

These specimens represent a wide range of designs encountered in practice, including a variety of adjacent framing, gusset, connection, restrainer and core details. All specimens satisfy conventional BRB design checks [2,3], including restrainer buckling ($\frac{\pi^2 E I}{L_r^2} > 1.5 \beta \omega N_y$), connection axial strength ($N_y ^+,N_y ^- > \beta \omega N_y$), local gusset plate buckling [22] and beam bracing (AISC 341 F4.4a [1]) criteria. Neither global restrainer buckling, bulging, nor local gusset plate buckling along the Thornton length occurred in the catalogued specimens. In-plane drift was included in all tests, while an initial out-of-plane drift was applied in some cases [16,17,19,20].

In-plane drift-induced beam damage caused a loss of end fixity [1,4,6,14,18] in 8 (18%) specimens. Note that the flexural continuity between the neck and restrainer is indicated by the ratio of the insert length ($L_{in}$) and neck breadth ($B_n$), with $L_{in}/B_n > 2.0$ effectively rigid [16].

![Figure 4. Schematic of test setups](image-url)
Comparison to test data

Key variables

A large number of structural properties potentially influence the connection buckling capacity, compared in Fig. 5 as normalized parameters against the peak experimental load ($\gamma_{max}$ or $N_{cr}$).

The out-of-plane rotational stiffness of the adjacent framing ($K_{Rf}$), gusset ($K_{Rg}$) and restrainer end ($K_{Rr}$) was calculated analytically [24] and normalized against the connection stiffness ($\gamma EI_{r}$) and length ($\xi L_{0}$), denoted as $K_{Rf}$, $K_{Rg}$, $K_{Rg}'$ and $K_{Rr}$ (where $K_{R} = K_{R} \cdot \xi L_{0} / \gamma EI_{r}$). Almost all buckled specimens either had rotationally flexible adjacent framing ($K_{Rf} < 0.5$) or lacked full-depth gusset stiffeners ($K_{Rg} < 0.5$), indicating that end fixity plays a crucial role. The others had negligible restrainer end flexural continuity ($K_{Rr} < 0.5$). Neither the connection stiffness ($\gamma$) nor length ($\xi$) ratio had a clear effect, and 6 (14%) with short connections ($\xi \leq 0.15$) buckled. 14 specimens (33%) with significant restrainer end flexural continuity ($K_{Rr} \geq 3.0$) buckled, indicating that even BRBs with collars or long insert lengths could be at risk.

Buckling occurred for a wide range of gusset-to-core (1.1<$N_{gy}/N_{y}$<7.0) and neck-to-core strength ratios (1.0<$N_{ny}/N_{y}$<3.5), and in 16 (37%) cases both $N_{gy}^B$ and $N_{ny}^B$ were greater than twice the core yield strength (i.e. designed for $\beta_{0} \geq 2$). The inelastic buckling stress ($\sigma_{cr} = N_{cr}/A$) was calculated from the smaller of the gusset or neck area, and slenderness ($\lambda = \pi \sqrt{EA/\gamma_{cr}}$) from the best-estimate elastic buckling load $N_{Bcr}^B$, following [16]. Almost all specimens fall in the imperfection-sensitive inelastic buckling range (20 < $\lambda$ < 120). While best fit by the SSRC group 3 curve [25], this would also predict most (27, 70%) stable specimens to be inadequate.

Figure 5. Correlation of buckling load to key variables
Accuracy of evaluation methods

As the local gusset buckling capacity was sufficient for all 43 buckled specimens, using $k_e = 0.65$ was always unconservative, predicting on average twice the observed buckling load (Fig. 6). However, increasing the effective length factor to $k_e = 2.0$ is also unconservative for 90% of the buckled specimens. Similar results are obtained for the subset of specimens most similar to conventional braces with unstiffened gussets, clevis connections [7,11,13,14,21] and large restrainer end continuity ($\kappa_{Rr} > 3$). It appears that BRB connection buckling is not solely related to the gusset properties, and that simply picking a longer effective length factor may be unconservative. Therefore, it is recommended that local gusset stability be checked following Muir and Thornton [22], but other methods be used to evaluate BRB connection stability.

Both the restrainer [Rest] and connection [Conn] elastic buckling load estimates overestimate the connection buckling load by a large margin, with few exceptions. This is consistent with Fig. 5, which indicates that almost all specimens in the test catalogue fall in the imperfection sensitive inelastic buckling range, buckling at $0.3 \sim 1.0 N_{cr}^B$ (on average, $0.7 N_{cr}^B$).

However, a conservative estimate is usually obtained from the post-yield elastic buckling load [Post], where the yielded neck is modelled as a pin. Note that this is not conservative when the end fixity is large ($K_{Rg} \rightarrow \infty$), and the restrainer end lacks flexural continuity ($K_{Rr}=0$). Nevertheless, this is a good first estimate as long as at least some restrainer end continuity is provided ($\kappa_{Rr} \geq 0.5$).
Both inelastic buckling methods ([Ult] and [NL]) require iteration to determine the safety factor (as opposed to pass/fail), as they use plastic NM interaction equations. These were reasonably accurate considering the diversity of BRB specimens in the test catalogue. On average the predicted buckling loads were $0.97N_{cr}^{exp}$ [Ult] and $1.24N_{cr}^{exp}$ [NL], but with 27% and 70% standard deviations, respectively. The discrepancy is primarily attributed to the different elastic buckling load $N_{cr}^B$ calculations. Similar results are produced when excluding specimens with exceptionally flexible restrainer end continuity ($K_{Rr} < 0.5$), adjacent framing ($K_{Rf} < 0.5$), and/or connections ($\gamma < 0.5$). Both appear to target the mean, rather than characteristic, strength.

![Figure 8. Accuracy of inelastic buckling methods](image)

**Three-tier design procedure**

**Tier 1: Prescriptive detailing**

All of the catalogued instances of out-of-plane connection buckling featured flexible adjacent framing (low $K_{Rf}$), gussets (low $K_{Rg}$) or restrainer ends (low $K_{Rr}$). Instability is unlikely when the normalized stiffness $K_{Rf}, K_{Rg}, K_{Rr} \geq 1.0$ (where $K_{R} = K_{R} \cdot \gamma EI / \xi L_0$) and the connections have at least 50% of the restrainer stiffness ($\gamma \geq 0.5$). In this case, no further calculation should be required. Example details satisfying these provisions are listed below and illustrated in Fig. 9:

- Adjacent framing, $K_{Rf} \geq 1.0$: diaphragm slab and transverse beam at beam/column connections, or fixed-end transverse beam at all beam connections
- Gusset, $K_{Rg} \geq 1.0$: full-depth gusset stiffeners, with matching web stiffeners
- Restrainer end, $K_{Rr} \geq 1.0$: insert or overlap ratio of $L_{inl}/B_n \geq 2.0$, or equivalent reinforcement

![Figure 9. Prescriptive detailing](image)
**Tier 2: Evaluate gusset stiffness $K_{Rg}$ and elastic buckling load**

If a more flexible gusset or adjacent framing configuration is desired, stability may be checked using a conservative estimate of the elastic buckling load with the critical restrainer end hinge modelled as a pin, following [8,12,13]. The combined spring given by Eq. 1-2 may be applied, and connections must be reasonably stiff ($\gamma \geq 0.5$) if assumed rigid in the analysis. This method requires that at least partial restrainer end continuity be provided ($\kappa_{Rr} \geq 0.5$: $L_{in}/B_n > 1.0$).

**Tier 3: Evaluate full brace stiffness and elasto-plastic buckling load**

If stability is still not satisfied, or more efficient design is desired, a detailed elasto-plastic buckling analysis may be conducted following Takeuchi et al. [16], Zaboli and Clifton [23], or an equivalent method, using a suitable strength reduction factor. If numerical nonlinear buckling analysis is used, symmetric and anti-symmetric modes, adjacent frame stiffness, restrainer end continuity and rotational slack introduced by the debonding gap [16] must be considered.

The proposed three tier procedure results in progressively increasing economy, but at the cost of greater analytical effort. Conservative details to ensure stability are identified by the prescriptive Tier 1 stage, and subsequently relaxed upon further detailed analysis. Note that the objective is to increase the system stiffness and neck axial capacity. A common solution used in Taiwan and Japan to increase stiffness is to adopt full-depth gusset stiffeners and rotationally stiff adjacent framing, details that performed well during the 2011 Tohoku earthquake.

**Conclusions**

Tests conducted over the past decade have only recently provided sufficient data to clearly identify the risk posed by BRB connection instability. While BRBs can and do perform well under severe seismic demands, care must be taken to explicitly consider the connection inelastic buckling mode. This paper has found several widely-used stability evaluation methods to be unconservative.

- A diverse test catalogue was assembled, consisting of 39 stable and 43 buckled specimens, all of which comply with conventional BRB design criteria. None experienced restrainer or local gusset buckling, and beam damage due to in-plane drift was rarely a factor (18% of buckled specimens), indicating that large drifts are not a necessary condition for connection instability.
- Counter-intuitively, 40% of the buckled specimens had full flexural continuity between the neck and restrainer, and 37% had neck strengths of twice the core yield strength (i.e. $\beta_0 \geq 2$). It may be insufficient to simply increase the restrainer end continuity and strengthen the neck. Providing full-depth gusset stiffeners with rotationally stiff framing is an effective solution.
- It is insufficient to solely check local gusset plate stability, or even global elastic buckling, as inelastic buckling initiated by neck yielding typically governs. Even when using the Thornton method with $k_e = 2.0$, 90% of the buckled specimens were predicted to be stable.
- Recently developed residual elastic methods that model the restrainer end as a pin [8,12,13], and full brace elasto-plastic [16,23] methods appear conservative and suitable for design.
- A three tier design method is proposed: (1) prescriptive detailing (full-depth edge stiffeners, $L_{in}/B_n \geq 2.0$, and fixed end transverse framing), (2) elastic check with calculated gusset/framing stiffness, but pinned restrainer ends, (3) elasto-plastic analysis with restrainer end continuity.


