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OUT-OF-PLANE BUCKLING BEHAVIOUR OF BRB GUSSET PLATE CONNECTIONS

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Abstract

This paper develops a model of the beam-column joint, gusset plate, connection region and the encased portion of the BRB to determine out-of-plane sway buckling capacity. The model was calibrated and a sensitivity study was undertaken.

The model considered the flexural stiffness of each element in the system. A global stiffness matrix was developed from element stiffness matrices including the gusset plates, connection transition regions, and the BRB. Stability functions were used to consider the effects of axial forces on the members to allow a more accurate stiffness matrix. The stiffness matrix was modified to consider the effects of beam-column joint rotational stiffness and BRB end rotational stiffness. The buckling capacity of the system was found when the axial force applied to the stiffness matrix resulted in the matrix no longer being positive definite.

The model was then used to determine the influence of the individual stiffness elements in the system on the buckling capacity. It was found that for a particular BRB frame, increasing gusset plate stiffness results in the largest improvement of buckling capacity. It was also found that decreasing BRB end rotational stiffness results in the largest decrease in buckling capacity. Because of the non-linear relationship between element stiffness and buckling capacity, it was shown that increasing an element's stiffness can have diminishing returns once the element is sufficiently stiff relative to other elements. This indicates that for some BRB frames, increasing gusset plate stiffness to prevent out-of-plane sway buckling will not increase buckling capacity as high as what is calculated from other gusset plate buckling capacity methods.

Finally, it is shown that using assumptions described in the paper, effective length factors may be considerably greater than unity for diagonal braces, and may be considerably greater than 2.0 for chevron braces.

Keywords: Buckling Restrained Brace, Gusset Plate, Sway Buckling, Effective Length Factor

1. Introduction

Experimental testing of buckling restrained brace (BRB) frames has shown that the gusset plate could fail by out-of-plane sway buckling, despite being designed to code standards [1 - 6]. Currently, gusset plates are designed to only consider local buckling by having an effective length factor of 0.65 [7]. It has been proposed that current design methods are modified to consider sway buckling by increasing the effective length factor to 2 [1, 2]. However, it is suspected that in some cases this is may not be conservative as it does not consider the influence of other frame elements, such as the BRB and the beam-column joint. This paper proposes a design method that considers the stiffness of all BRB frame elements to improve the understanding of BRB frame out-of-plane sway buckling. This paper seeks to answer the following questions:

1. Can a design method that explicitly considers the stiffness of each element be developed to determine buckling capacity?
2. How do individual elements in a BRB frame influence buckling capacity?
3. Is there an appropriate effective length factor that can be used for gusset plate design?

2. Observed Failures

Out-of-plane sway buckling has been observed in a number of experimental tests [1 - 6]. The BRB end forms a plastic hinge due to out-of-plane bending. This leads to instability in the system. Generally, gusset plates have been designed only for local buckling failure and so have insufficient sway buckling capacity. When a plastic hinge forms, the effective length of the gusset plate significantly increases and the gusset plate buckles out-of-plane.

One example of this failure is the Chou et al. frame. Chou et al. [2] experimentally tested a single storey, one bay BRB frame with a diagonal BRB configuration to observe the effects of frame action forces on single and double gusset plates. During the experiment, the top gusset plate buckled out-of-plane at a much lower force than expected, indicating that current design methods may not be conservative in all cases.

During testing, the gusset plate buckled at an axial force of 693 kN in the BRB at an inter-storey drift of 0.63 %. This was lower than the 913 kN maximum compression capacity of the BRB. The failure mechanism, as shown in Fig.1b, clearly indicates that the gusset plate buckled out-of-plane and a hinge formed at the end of the BRB.

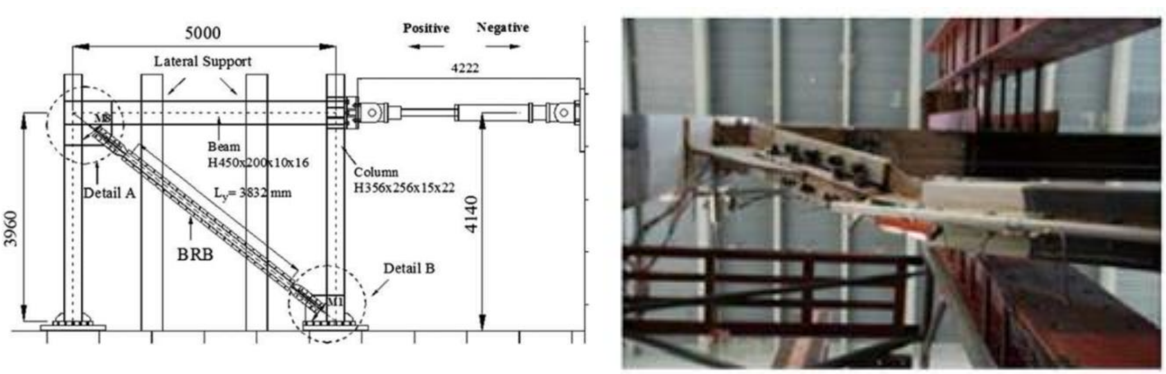


Fig. 1 – a) Chou et al. frame configuration; b) – Chou et al. failure mechanism [2]

3. Design Methods

3.1 Thornton method

Thornton [7] developed a method to determine buckling capacity of a gusset plate that was considered to be a conservative estimation of allowable compressive strength by considering the gusset plate as an effective column strip with the AISC column curve. Eq. (1) to Eq. (3) show the method,

$$\lambda_c = \frac{KL}{\pi r}\sqrt{\frac{F_y}{E}} \tag{1}$$

$$P_{cr} = (0.658)^{\lambda_c{}^2} b_e t_g F_y \qquad \lambda_c \le 1.5 \tag{2}$$

$$P_{cr} = \left(0.877/\lambda_c{}^2\right) b_e t_g F_y \qquad \lambda_c > 1.5 \tag{3}$$

where K = effective length factor; L = Thornton length [7]; r = radius of gyration; F_y = yield stress; E = Young's modulus; b_e = Whitmore width [8]; and t_g = gusset plate thickness

When λ_c is equal to or less than 1.5, Eq. (2) is used to consider inelastic buckling behaviour and residual stress effects. Eq. (3) is used for λ_c greater than 1.5 to consider elastic buckling. Both equations account for various capacity reduction factors including initial imperfections and accidental eccentric loading. These capacity reductions were initially devised considering column members and their applicability to gusset plates has not been fully investigated.

The Thornton length, L, is an approximation of the gusset plate as an equivalent column strip. Thornton proposed that the length should be measured from the centre of the Whitmore width [8] to the beam-column interface parallel to the line of action of the brace [7]. This was considered conservative as it is generally the maximum unsupported length of the gusset plate. Thornton also proposed that a length, L_{ave}, obtained by averaging the lengths L_1, L_2, and L_3, as shown in Fig.2, be used. The average length is most commonly considered [9].

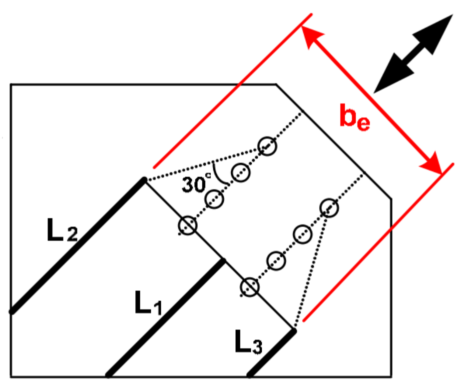


Fig. 2 – Gusset plate diagram indicating Whitmore width and Thornton Lengths [1]

The method has been found conservative in experimental tests by Yam and Cheng [9] and Gross [10]. The Thornton method has been adopted for gusset plate design in BRB frames in most cases [1, 2, 4].

3.2 Design methods where effective length factor is equal to two

Chou et al. [2] recommended the Thornton method is used with the Whitmore width, average Thornton length, AISC column curve, and an effective length factor, K, equal to 2 instead of $K = 0.65$ to prevent out-of-plane sway buckling failure in BRB frames. Using this recommendation, the design capacity of the gusset plate would be 614 kN which conservatively estimates their experimental buckling capacity of 693 kN.

Tsai and Hsiao [1] also recommended the Thornton method with $K = 2$, however, the AISC column curve is not applied such that the method follows the Euler buckling curve. For their BRB frame, the design capacity of 842 kN was considered to be in reasonably good agreement with the experimental buckling capacity of 805 kN, although this is not conservative.

Both of these methods are limited in their assumptions. An effective length factor of 2 is equivalent to a column with a fixed end and a free end. The fixed end assumption is not conservative as the beam-column joint is not fully rigid. For Chevron configuration frames, the beam joint has significantly lower rotational stiffness. Assuming a free end at the BRB hinge location may be relatively conservative as some moment transfer capacity will be provided before failure. Westeneng et al. [11] found that the proposed design methods by Tsai and Hsiao [1] and Chou et al. [2] are not always conservative for gusset plates modelled in finite element software with fixed and free end boundary conditions.

3.3 Takeuchi method

Takeuchi and his associates have developed an out-of-plane stability method for BRB frames that considers the whole system to determine if global buckling will occur [5]. The method builds on work by the group [12, 13].

The method is used in Japanese industry as a set of equations that checks for global out-of-plane buckling. They consider strain energy and moment transfer capacities to determine the system axial force limit. It is a complex method that considers initial imperfections, gusset plate rotational stiffness, brace buckling capacity, brace end connection moment capacity, and effects of out-of-plane story drift on the frame. The method also explicitly considers the reduction in capacity for BRBs in chevron configuration frames. Experimental testing has been found to be in good agreement with the method.

4. Proposed Method

It is difficult for a designer to use the Takeuchi method to design a BRB frame without the use of finite element software due to the combined gusset plate and beam-column joint rotational spring. This paper aims to develop an alternative method that uses a stability and stiffness based approach to solve what is a problem of stability. The proposed GP-BRB system stability method uses a global stiffness matrix to determine the critical buckling load of the system.

4.1 Global stiffness matrix

The GP-BRB system stability method considers the stiffness of each element in the BRB frame that can influence the out-of-plane stability of the system. The method modifies the general 4x4 beam element stiffness matrix for each element to consider axial load to account for P-delta effects. The modified 4x4 stiffness matrix is shown inside Eq. (4) which relates the shear forces and bending moments at the end of a beam element to the deflections and rotations at the end of the beam element. Stability functions Eq. (5) to Eq. (9) allow applied axial force to influence the modified stiffness matrix.

$$\begin{Bmatrix} V_a \\ M_a \\ V_b \\ M_b \end{Bmatrix} = \frac{EI}{L}\begin{bmatrix} f/L^2 & g/L & -f/L^2 & g/L \\ g/L & s & -g/L & r \\ -f/L^2 & -g/L & f/L^2 & -g/L \\ g/L & r & -g/L & s \end{bmatrix}\begin{Bmatrix} \Delta_a \\ \theta_a \\ \Delta_b \\ \theta_b \end{Bmatrix} \tag{4}$$

$$\phi = \sqrt{\frac{PL^2}{EI}} \tag{5}$$

$$s = \frac{\phi(\sin\phi - \phi\cos\phi)}{2(1-\cos\phi) - \phi\sin\phi} \tag{6}$$

$$r = \frac{\phi^2 - \phi\sin\phi}{2(1-\cos\phi) - \phi\sin\phi} \tag{7}$$

$$f = 2(s + r) - \phi^2 \tag{8}$$

$$g = s + r \tag{9}$$

where P = applied load, L = length of element, E = Young's modulus, and I = second moment of area.

Beam element stiffness matrices have been developed for the gusset plates, connections, and the BRB. By assembling the stiffness matrices of each beam element in the system, a global stiffness matrix can be assembled.

4.2 BRB end rotational stiffness

The stiffness matrix also explicitly considers the rotational flexibility at the BRB end by assuming the interface between the connection and the BRB end is semi-rigid and governed by a rotational spring. An additional rotational degree of freedom is added to the matrix so that there is a degree of freedom on either side of a hinge. A rotational spring stiffness matrix connecting the two degrees of freedom is developed in Eq. (10). This matches the assumptions made by Takeuchi [5] that full moment transfer isn't available for some BRB designs.

$$\begin{Bmatrix} M_c \\ M_d \end{Bmatrix} = \begin{bmatrix} k_{re} & -k_{re} \\ -k_{re} & k_{re} \end{bmatrix}\begin{Bmatrix} \theta_c \\ \theta_d \end{Bmatrix} \tag{10}$$

where k_{re} = rotational spring stiffness of BRB end hinge

4.3 Beam-Column joint rotational stiffness

The beam-column joint has also been modelled by a rotational spring. The joint is not fully rigid and will have some contribution to reducing the system's stability. This reduction is significant in Chevron braced frames as the attached beam has low rotational stiffness. Chevron configuration frames have contributed to the buckling failure in a number of experimental tests [1, 3, 5, 6].

4.4 Calculation of buckling capacity

A complete diagram showing the available degrees of freedom in the global stiffness matrix for the GP-BRB system has been shown in Fig.3. It can be seen that 12 degrees of freedom have been considered.

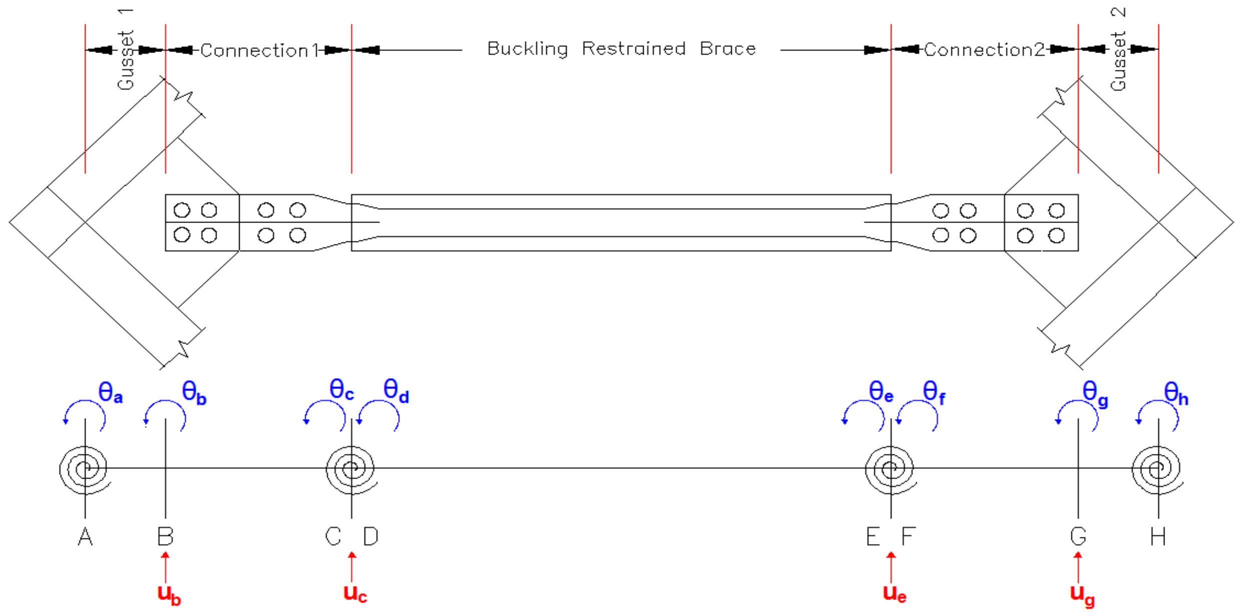


Fig. 3 – Available degrees of freedom and rotational spring locations in the global stiffness matrix

As applied axial force is a variable in the stiffness matrix through Eq. (5), when the global stiffness matrix loses its positive definiteness, the applied axial force is equal to the critical buckling load, P_{cr}. If it is found that the critical buckling load is below the maximum BRB compression capacity, out-of-plane buckling will occur and the system will fail prematurely. A designer could improve the buckling capacity of the system by increasing the stiffness in the system's most flexible elements.

Global system stiffness can be increased by 1) increasing the BRB end rotational spring stiffness, k_{re} by increasing the non-yielding segment embedment length, or 2) increasing gusset plate flexural stiffness, by either increasing the gusset plate thickness or adding free-edge stiffeners. It is beneficial to BRB behaviour to have a small non-yielding segment embedment length so that there is as large of a yielding segment length as possible to minimise low cycle fatigue [14]. By increasing the non-yielding segment length, the yielding segment length could decrease significantly. Therefore, it is likely that the better solution is to increase gusset plate stiffness.

4.5 Comparison to Takeuchi method

There are a number of differences and similarities between the proposed method and the Takeuchi method. The GP-BRB system stability method uses a stiffness based approach to calculate buckling capacity instead of the strain energy approach used by the Takeuchi method. The Takeuchi method also assumes a buckling mode shape, whereas the proposed method requires no buckling mode shape assumption. This is significant as because the mode shape is assumed, the Takeuchi method will be an upper bound solution. The two methods also consider the BRB system in slightly different ways and these have been shown in Fig.4.

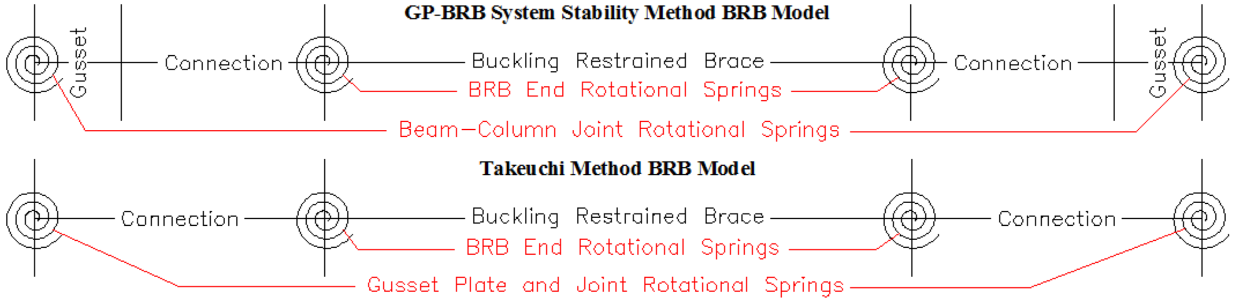


Fig. 4 – Comparison between GP-BRB system stability method and Takeuchi method system models

The GP-BRB system stability method considers the gusset plate as a beam element instead of a combined rotational spring. The rotational stiffness of the combined gusset plate and joint rotational spring is difficult for a designer to determine without finite element software. The flexural stiffness of the gusset plate is usually significantly less than the connection stiffness so it may be inappropriate to assume the connection length includes the gusset plate length. The Takeuchi method considers initial imperfections in the BRB and gusset plate, whereas this is not accounted for in the GP-BRB system stability method.

5. Calibration

5.1 Experimental frames

Of the experimental frames that have experienced failure [1 – 6], most are unsuitable to compare them to the GP-BRB system stability method. This is a result of insufficient information being available to correctly model them. The Christopulos frame [4] can be modelled, however, its failure due to both out-of-plane sway buckling and frame action effects cannot be used to verify the GP-BRB system stability method.

5.1.1 Christopulos frame

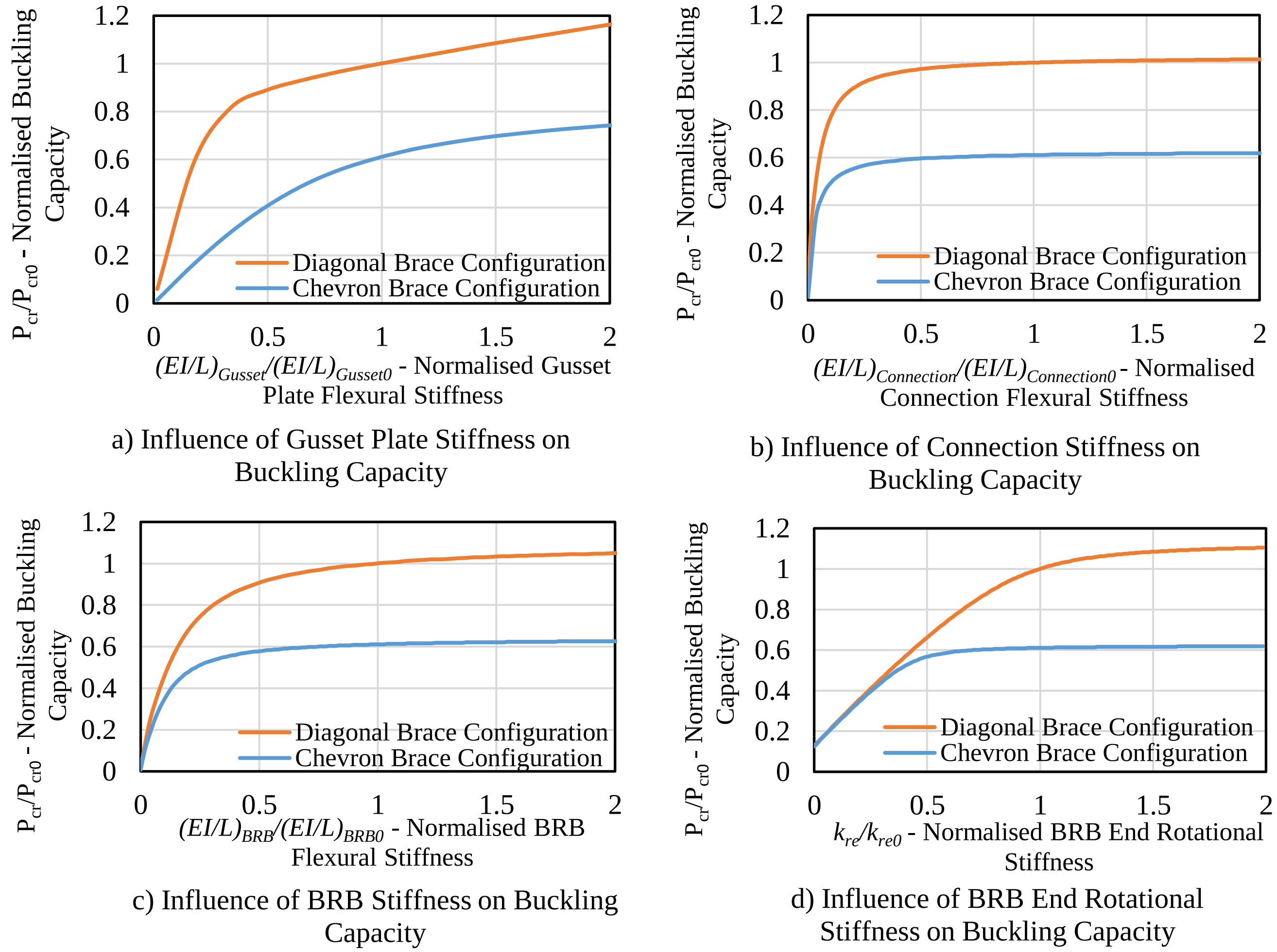
The Christopulos frame experienced out-of-plane sway buckling failure after the welds connecting the gusset plate to beam-column joint degraded during cyclic loading. Frame action effects caused additional stresses on the gusset plate welds which eventually failed in some tests. For one test, the BRB frame was able to sustain loads of about 1500 kN before degradation of the welds occurred. Using the GP-BRB system stability method, a parametric study was undertaken considering a range of input variables such as using different methods to calculate BRB and Gusset plate stiffness (this resulted in 864 input combinations). From this study, the maximum buckling capacity was 1423 kN and the minimum buckling capacity was 327 kN. It can be said that the GP-BRB system stability method conservatively predicts a buckling capacity, for the least conservative combination of inputs, lower than the sustained load when the beam-column joint has not degraded. After degradation, the tested BRB failed at approximately 500 kN. In relation to the global stiffness matrix, it could be said that the beam-column rotational spring was constantly reducing as the welds degraded until the system became unstable during the experimental test. As this rotational stiffness value has not been observed it is not possible to use the test to validate the proposed method and determine which input variable combination is most valid.

5.2 Upcoming Experimental Testing

Given the difficulties of using the current data available to validate the proposed method, upcoming experimental testing of BRB frames at the University of Canterbury will be undertaken in the near future. This testing will help determine whether the GP-BRB system stability method will conservatively predict buckling failure for a number of BRB frames. It is the intention that this validation can ensure a model is available to designers to quickly develop more stable BRB frames.

6. Sensitivity Study

The GP-BRB system stability method can determine how adjusting the stiffness of each component affects the buckling capacity of a typical BRB frame. This information can be used to optimise BRB frame design by determining which frame elements have the most influence on buckling capacity.



a) Influence of Gusset Plate Stiffness on Buckling Capacity

b) Influence of Connection Stiffness on Buckling Capacity

c) Influence of BRB Stiffness on Buckling Capacity

d) Influence of BRB End Rotational Stiffness on Buckling Capacity

Fig. 5 – Influence of individual element stiffness on BRB frame out-of-plane sway buckling capacity

In the above graphs in Fig.5, the GP-BRB system stability method was used to determine the influence of each individual element stiffness on the global buckling capacity. The results were normalised by considering the Chou et al. BRB frame and assuming a BRB end rotational stiffness. For this particular frame, it can be seen that increasing gusset plate stiffness will result in the largest increase in global buckling capacity for a diagonal brace configuration frame. However, decreasing BRB end rotational stiffness will result in the largest decrease in buckling capacity.

Each graph indicates that there is a point in which increasing the stiffness of an individual element has diminishing returns in increasing buckling capacity. For some of the elements such as the connection and the BRB, this point has been clearly passed for this frame, indicating that these elements are substantially stiffer than the other elements.

For Chevron brace configuration frames, it was conservatively assumed that one beam-column joint rotational spring would have zero rotational stiffness, indicating a beam joint with lower rotational stiffness behaving as a perfect pin. This resulted in the chevron frame having 60% of the diagonal brace configuration frame buckling capacity. The influence of individual frame elements differs slightly from the diagonal frame, notably BRB end rotational stiffness has less of an individual effect on buckling capacity, whereas gusset plate stiffness has a larger effect.

In all cases, it can be seen that when one individual element has substantially lower flexural or rotational stiffness, the buckling capacity of the BRB frame is significantly reduced. It is, therefore, essential that a designer ensures that all elements are sufficiently stiff.

7. Effective Length Factor Effects

Using the Thornton method, the effective length factor of a gusset plate is 0.65 based on a theoretical minimum of 0.5 and accounting for the end conditions not being fully rigid. By rearranging Eq. (1) and Eq. (3), an equivalent effective length factor can be determined as shown in Eq. (11). Inelastic buckling has not been considered as it is unlikely the gusset plate will yield at this low capacity.

$$K_{equiv} = \sqrt{\frac{0.877\pi^2 E b_e t_g r^2}{L^2 P_{cr}}} \tag{11}$$

where K_{equiv} = Equivalent effective length factor; P_{cr} = Buckling capacity found by GP-BRB system stability method.

Fig.6 considers the equivalent effective length factor for a range of gusset plate flexural stiffness. In this case, it was assumed there is full moment transfer at the BRB ends and the beam-column joints are fully rigid. These assumptions were made to resemble those made in the Thornton method to allow comparison between the methods. It can be seen in Fig.7 that the minimum equivalent effective length factor must be greater than 1. This indicates that the Thornton method is theoretically non-conservative. It has been shown that the Thornton method is conservative for gusset plates tested with boundary conditions corresponding to an effective length of 1 [9] but the ends of those gusset plates tested are likely to be more rigid than gusset plates in a BRB frame. The figure also shows that for chevron configuration BRB frames, if the beam joint is conservatively assumed to be a pin, then the theoretical minimum effective length factor is greater than 2. These findings match a study by Crake et al. [15], which considered only the gusset plate and the BRB.

Note that as gusset plate stiffness increases, the equivalent effective length factor increases. From Fig.5 a) we can see that for gusset plates with high flexural stiffness, when flexural stiffness increases, buckling capacity increases at a slower rate. In Eq. (11), an increase in flexural stiffness (note $b_e t_g r^2$ is equal to gusset plate moment of inertia, I), which results in a smaller increase in buckling capacity, will ultimately result in a larger effective length factor. As it shown that the equivalent effective length factor can be larger than 2, the GP-BRB system stability method will often calculate a buckling capacity lower than the recommendations made by Tsai and Hsiao [1] and Chou et al. [2]. This indicates that the methods proposed by Tsai and Hsiao and Chou et al. may not always be conservative for all BRB frames.

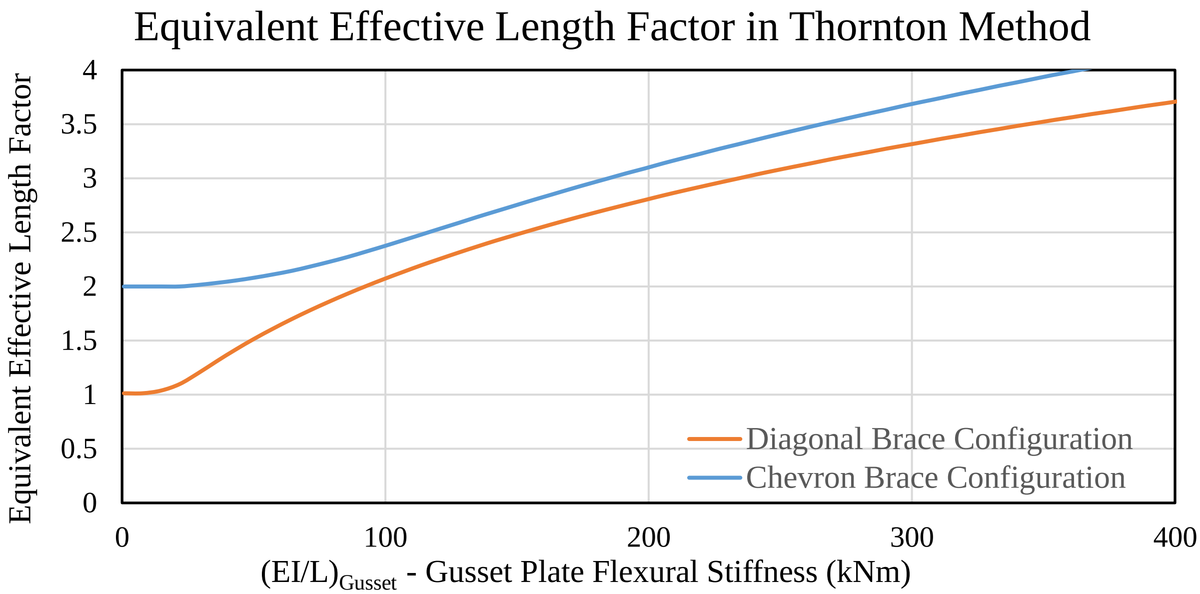


Fig. 6 – Equivalent effective length factors for a range of gusset plate stiffness

8. Conclusions

A new design method to prevent gusset plate buckling in BRB frames subject to in-plane loading and loading where frame action is not significant has been proposed. By developing a global stiffness matrix to find buckling capacity, all elements in the BRB system are considered. Buckling capacity can be determined by finding when the global stiffness matrix is no longer positive definite. For a typical BRB frame, a number of conclusions have been made. It was found that increasing any individual element stiffness will increase buckling capacity, however, this will have diminishing returns. If any element is significantly more flexible than the other elements, the buckling capacity of the system is significantly reduced. It is, therefore, essential that all elements are sufficiently stiff when considering BRB frames subject to in-plane loading. It was also found that increasing gusset plate stiffness was the most effective way to increase buckling capacity, but this increase is non-linear.

The questions considered by this paper have been answered:

1. A method, called the GP-BRB system stability method, was developed to consider effects of the whole system, and not just the stiffness of the gusset plate, on the overall axial strength. It does not require explicit definition of the buckling mode shape.
2. Parametric studies indicated that increasing the stiffness of one component of the system has a significant effect on the buckling strength over a limited range only. System considerations are needed to assess the total strength and benefit of any stiffening.
3. By determining an equivalent effective length factor, it is shown that for BRB frames, the effective length should be at least 1 for the Thornton method and that this effective length can be larger than 2. The effective length factor for a specific situation can be computed using the method described. Alternatively, the in-plane axial strength of the structure may be obtained using the method described.

9. Acknowledgements

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