Steel Innovations Conference 2015
Auckland, New Zealand
3-4 September 2015

EARLY FAILURE OF GUSSET PLATES IN BUCKLING RESTRAINED BRACE FRAMES

B. A. Westeneng[1], C.-L. Lee[2], and G. A. MacRae[3]

ABSTRACT

Gusset plates are used to connect buckling restrained braces to the beam-column joint. Current design procedures of gusset plates vary worldwide and in some cases have been proven to not be conservative. Multiple experimental tests have shown that buckling restraint braced frames can fail by sway buckling at the gusset plate before the buckling restrained brace has yielded. The gusset plate is also subject to frame action forces during cyclic loading which are not accounted for in most designs.

This paper compares several design methods used to calculate the buckling capacity of the gusset plate and connection area and determines their assumptions and limitations. It finds that for an experimentally tested frame, all methods are currently not conservative and are unable to accurately predict the buckling capacity of the frame. A finite element model of the frame was developed to determine if the gusset plate buckling failure could be accurately modelled and if frame action forces during cyclic loading reduce the buckling capacity of the gusset plate. By testing the model with and without frame action forces, it was found that under compression, there was no significant difference in buckling capacity. Finally, discussion around future research opportunities has been made to highlight the uncertainty that currently exists in gusset plate design in buckling restrained braced frames.

Introduction

Buckling restrained braced frames (BRBF) are becoming an increasingly popular alternative to traditional braced frames due to the ability of buckling restrained braces (BRB) to undergo yielding and dissipate energy in both tension and compression. BRBs are connected to the beam-column joint through steel gusset plates. The BRB is usually bolted to the gusset plate but can also be welded or pinned. A common failure of BRBF experimental testing is a sway mechanism failure of the gusset plate (Tsai et al. 2004, Chou et al. 2011). The gusset plate buckles out-of-plane, and reduces the BRBFs ability to dissipate energy during an earthquake. This failure mechanism is especially undesirable as it prevents the BRBF from behaving as a low damage solution to seismic forces.

This paper investigates the sway mechanism failure of the gusset plate. It looks at common design methods used on gusset plates and the BRBF to determine if they are able to conservatively predict the buckling capacity of an experimentally tested frame. The assumptions and limitations of each method are discussed to better understand how they predict buckling capacity.

The paper also investigates the effect that frame action forces may have on the buckling capacity of BRBF gusset plates. Frame action forces are the result of the beam-column joint opening and closing during cyclic loading and are not currently considered in most designs. A finite element model was developed and tested with and without frame action forces in order to determine their effect on gusset plate stability.

[1]Postgraduate Student, Civil and Natural Resources Engineering, University of Canterbury, Christchurch, 8041
[2]Lecturer, Civil and Natural Resources Engineering, University of Canterbury, Christchurch, 8041
[3]Associate Professor, Civil and Natural Resources Engineering, University of Canterbury, Christchurch, 8041

Overall, this paper seeks to answer the following questions:

- What methods are available for designers to prevent gusset plate buckling in BRBFs, and what are their assumptions and limitations?
- Which of the methods investigated are accurate and conservative in determining a gusset plate's buckling capacity?
- Can a finite element model be produced to model gusset plate buckling failure?
- Do frame action forces have an effect on a gusset plate's buckling capacity?

Gusset Plate Design Methods

Gusset plates in BRB frames must be designed to prevent buckling from occurring. If a gusset plate buckles, the hysteretic cycle is disrupted and the BRB frame becomes less effective at energy dissipation for the structure during seismic loading. To prevent buckling from occurring, most design methods ensure that the buckling capacity of the gusset plate is larger than the maximum compression capacity of the BRB member. A range of methods used to prevent buckling from occurring are described below.

Thornton Method

The Thornton method considers the Euler buckling capacity of a fixed-fixed equivalent column. The column uses the thickness of the gusset plate, t_g, and the Whitmore effective width, b_e, to develop the sectional area. The Whitmore effective width is shown in Fig. 1 and was initially developed to determine the tensile capacity of the gusset plate (Whitmore 1952). The length of the column, L_{th}, was determined by Thornton (1984) as the maximum of L_1, L_2, and L_3 as shown in Fig. 1. An effective length factor, K, of 0.65 was used. These variables give a gusset plate compression capacity, P_{Th}, as determined in Eq. 1, where E is steel elastic modulus, and r is the radius of gyration.

$$\boldsymbol{P_{Th} = \frac{\pi^2 E}{\left(\frac{KL_{th}}{r}\right)^2} b_e t_g} \qquad \textbf{(1)}$$

Limitations

The Thornton Method does not take into account the effects of plate action and does not consider any reduction in strength from initial imperfections or yielding. Recent experimental testing (Tsai and Hsiao 2008, Chou et al. 2012) has shown a gusset plate can buckle by sway failure, indicating an effective length factor larger than 1 is required and that using K=0.65 is not always conservative. The method only considers the Euler buckling capacity of the gusset plate and does not account for any accidental eccentric loading.

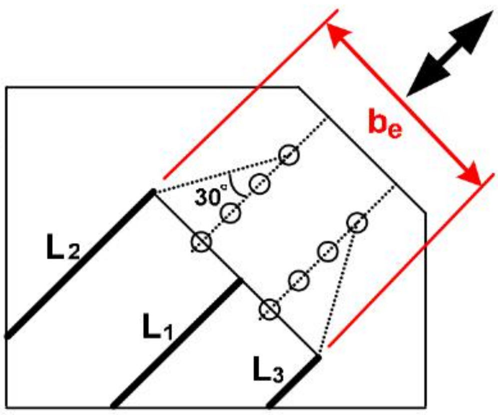


Figure 1.   Gusset plate diagram indicating Whitmore effective width and Thornton Lengths (Tsai et al. 2008)

AISC Method

The AISC Method (AISC, 2005) adopts the concepts used in the Thornton Method and applies the AISC column buckling curve to estimate the ultimate compression capacity of the gusset plate. This accounts for compressive strength, initial imperfections, and accidental eccentric loading. Instead of the maximum length of L_1, L_2, and L_3, it uses the average of the three lengths, L_c (Gross 1990). An effective length factor of 1.2 is used if the gusset plate does not have free edge stiffeners. The gusset plate compression capacity, P_{AI}, is calculated as determined in Eqs. 2, 3, and 4, where F_y is the yield stress.

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

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

$$\lambda_c = \frac{KL_c}{\pi r}\sqrt{\frac{F_y}{E}} \tag{4}$$

Limitations

Recent research has shown in some cases that an effective length factor of 1.2 is not conservative and that 2 is more appropriate (Tsai et al. 2008). Crake and Westeneng (2014) have shown through the use of stability functions that the effective length is dependent on BRB length and in some cases may be larger than 2 for long braces.

Working Point Method (Nakamura Method)

Bruneau et al. (2011) recommends the Nakamura Method to prevent gusset plate buckling and this method is used by American industry. This method was incorrectly referenced to Nakamura (2000) and is believed to have been first considered by Tsai et al. (2002) from design calculations made by Nippon Steel. It will be referred to as the Working Point Method henceforth, due to the method's decision to extend the effective length to the working point of the beam-column joint. This is in contrast to other methods where it is assumed the beam and column are rigid and do not exhibit any rotation once the connection has buckled. This method is a check on the buckling capacity of the connection transition region at the end of the BRB casing. It is based on the theory that both the gusset and the brace end need to hinge to form a mechanism for failure.

It is a simple Euler buckling check where the out-of-plane buckling moment of inertia, I_c, is calculated from the non-yielding segment of the BRB outside the casing. The length, L_b, is considered as twice the length from the end of the BRB casing to the work point of the beam-column joint, as shown in Fig. 2. The effective length factor of 1 is used but if the length is considered as L_b instead of $L_b/2$, then the effective length factor is essentially 2. This would indicate a fixed-free condition exists with the BRB core and casing providing no lateral or rotational restraint. The buckling capacity of the connection can be determined by Eq. 5.

$$\boldsymbol{P_N = \frac{\pi^2 EI_c}{(KL_b)^2}} \tag{5}$$

Limitations

The BRB is assumed to provide no restraint to the connection, by not accounting for any moment transfer capacity the formula may be overly conservative. In reality the BRB will provide some moment restraint, especially where the connection transition region stiffener extends inside the BRB casing by larger than 1.5 times the BRB core plate width. Matsui et al. (2010) has shown that for this condition, moment transfer capacity increases significantly. The formula implies equal section properties along the length, but this is unlikely to be realistic near the beam-column joint and so the increased rigidity is not captured in the formula. Any initial imperfections are not accounted for in this method and no consideration is made for BRB length.

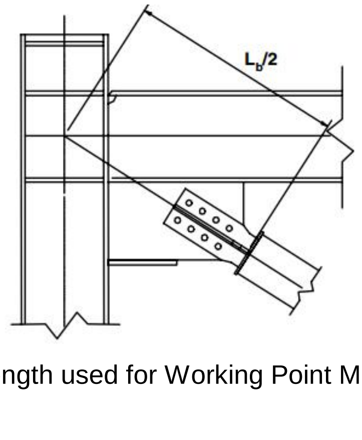


Figure 2. Connection length used for Working Point Method (Tsai et al. 2002)

Koetaka Method

Research by Koetaka et al. (2008) primarily focuses on lateral and rotational stiffness of the beam the gusset plate is attached to. The paper does however offer a method to determine out-of-plane buckling capacity based on the Euler buckling load of the connection area as a whole, including the gusset plate and unrestrained non-yielding segment of the BRB. The method also makes consideration to the BRB length. The beam-column joint is assumed to be rigid in this method and so the length, L_k, is considered from the end of the BRB casing to the beam flange. Out-of-plane buckling of the BRB is determined by Eq. 6 where ξ is the ratio of connection length to BRB length. An effective length factor of 2 is used.

$$P_K = (1-2\xi)\frac{\pi^2 EI_c}{(KL_k)^2} \quad \textbf{(6)}$$

Limitations

The consideration for BRB length is an approximation derived from the first Taylor series of the sine function, the second Taylor series of the cosine function, and approximating $\pi^2/8 = 1$. The method does not consider the work by Matsui et al. (2010) and will be more conservative for BRBs with higher moment transfer capacities. Any initial imperfections are not accounted for in this method and no consideration is made for the varying section properties through the length considered.

Takeuchi Method

The Takeuchi Method is used in Japanese industry as an equation that checks for global out-of-plane buckling (Takeuchi et al. 2014). The equation combines and builds on work by Koetaka et al. (2008) and Matsui et al. (2010). It is the most complex method described as it 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. It can also be modified to consider BRBs in chevron frames (Takeuchi et al. 2015). The method considers three separate failure mechanisms as shown in Fig. 3.

The buckling capacity of the system can be determined in Eq. 7 where M^r_p is the minimum moment transfer capacity of the BRB casing or the BRB end connection area, M_0^r is the additional bending moment from out-of-plane story drift, a_r is the initial imperfection at the BRB end, and N^B_{cr} is the buckling capacity of the BRB. N^r_{cr} is the global elastic buckling strength of the connection zone and is calculated similar to the Koetaka Method in Eq. 8 but with consideration of normalised gusset plate rotational stiffness, ξk_{rg}.

$$P_T = \frac{(M_p^r - M_0^r)/ar + N_{cr}^r}{(M_p^r - M_0^r)/a_r N_{cr}^B + 1} \quad \textbf{(7)}$$

$$N_{cr}^r = (1-2\xi)\frac{\pi^2 EI_c}{(K\xi L_0)^2}\cdot\frac{\xi k_{rg}}{\xi k_{rg} + \frac{24}{\pi^2}} \quad \textbf{(8)}$$

Limitations

The formula makes several approximations in order to reduce the number of terms. This includes assuming that the length of the connection is approximately 1/4 of the BRB length. For the Chou and Liu frame used later in this paper, this ratio is 1/5 for a 4 m long BRB. It is likely the formula will become un-conservative for longer BRBs, which are known to extend up to 15 m. The method may also mislead a designer to believe that their frame is safe for gusset plates with very low rotational stiffness. If the gusset plate rotational stiffness is close to zero (causing N^r_{cr} to be approximately zero), the moment capacity of the end connection area may still be sufficiently large to provide the necessary buckling capacity according to Eq. 7. However, a gusset plate with low rotational stiffness is likely to fail under local buckling (i.e. k = 0.65).

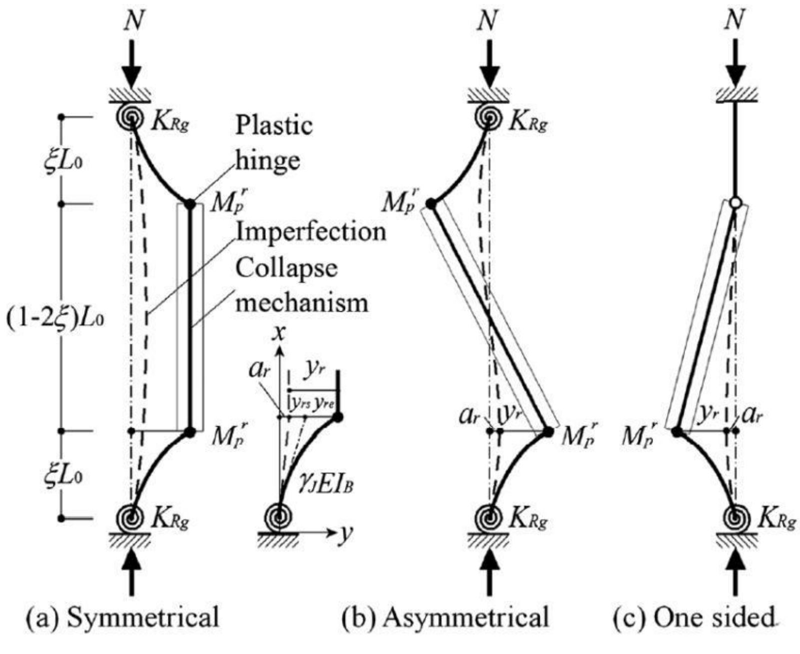


Figure 3. Failure mechanism assumptions for Takeuchi Method (Takeuchi et al. 2014)

Other Methods

Sheng Method

The Sheng Method consists of using a set of design curves developed through finite element analysis (Sheng et al. 2002). The finite element model was analysed for a range of parameters including plate thickness, edge and centreline stiffeners, and different gusset plate shapes. Naghipour et al. (2013) continued work based on the Sheng method specifically for BRB gusset plates. They created design charts with a finite element model calibrated to experimental testing. Chou and Chen (2009) also developed design charts for chevron BRB frames. Due to the limited number of parameters tested, this method is not universally applicable.

Dowswell Method

The Dowswell Method is similar to the AISC Method but accounts for variable stress dispersion across the gusset plate, suggesting a wider width than that determined by Whitmore is used (Dowswell 2013). The effective length factor is variable based on the effective width and ranges from 0.35 to 0.5 for corner gusset plates. Through comparison to 91 experimental gusset plate tests, a column curve 0.75 x the AISC curve is recommended to cover all cases. The method does not consider gusset plates that buckle by sway failure.

New Zealand Standards

There are currently no specific requirements for BRB frame design in New Zealand. Many consultants base their designs on the AISC specification for structural steel buildings (AISC, 2005). BRB manufacturers also give advice and aid in the design process. Some principles from NZS3404 may be applicable to gusset plate design and they are described below.

NZS3404 Clause 6.7.2 requires any member, and its connections, in the restraining system used to brace compression members to laterally resist an applied load equal to 2.5% of the maximum axial compression force (Standards New Zealand 2007). Clifton has suggested that this can be applied to gusset plate design (MacRae and Clifton 2015). A force of 2.5% of the maximum BRB axial compressive force is applied laterally to the gusset plate at the end of the gusset plate, generating an out-of-plane moment that the gusset plate must resist.

NZS3404 Section 4.9, Frame Buckling Analysis, is applied to ensure in-plane frame buckling does not occur (Standards New Zealand 2007). An elastic buckling load factor, λ_c, is used to account for any unknowns and must be equal to or larger than 3.5. It is calculated in Eq. 9 where N^* is the design axial force and N_{omb} is the member buckling load. Clifton has also suggested this can be applied to gusset plate design (MacRae and Clifton 2015). Eq. 9 can be rewritten as Eq. 10 where N^* is the axial force on the gusset plate and is equal to the maximum BRB axial compressive force and N_{gusset} is equal to the buckling capacity of the gusset plate.

$$\lambda_c = \frac{N_{oms}}{N^*} \quad \textbf{(9)}$$

$$N^* \leq 0.29\, N_{gusset} \quad \textbf{(10)}$$

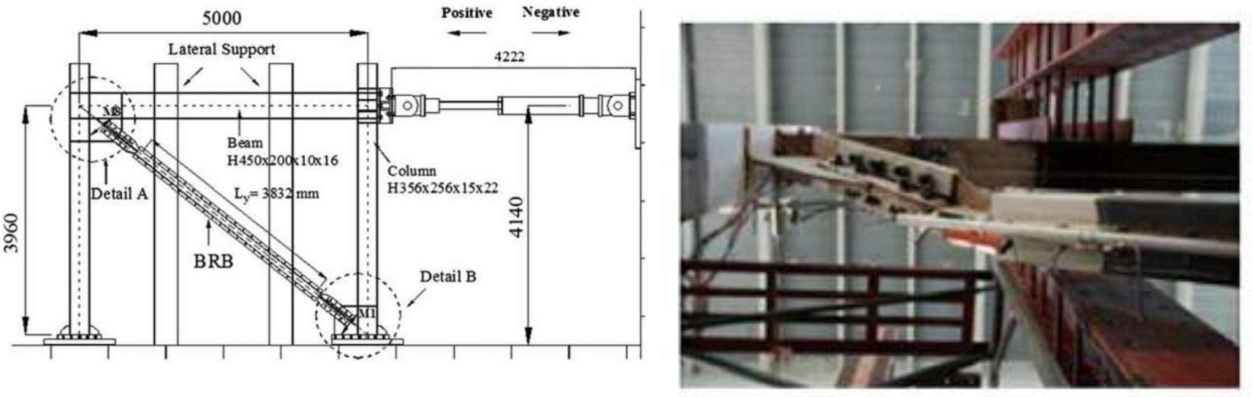
Chou and Liu BRB Frame

Chou et al. (2012) experimentally tested a one storey, one bay BRB frame with a single BRB 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. This particular experiment has been chosen by this paper to compare design methods due to the following factors:

- The BRB is singular and not in chevron configuration and so is not dependent on beam stiffness
- The gusset plate buckled after the BRB core plate began yielding
- The frame is suitably documented, allowing a finite element model to be developed

The dimensions of the model are shown in Fig. 4a. The BRB used was unique with two C channels bolted around the core plate to allow easy inspection of the core after testing. Both the core plate and gusset plate are 14 mm thick and were bolted together through splice plates. The BRB was expected to yield at 611 kN and would theoretically not buckle until 1812 kN.

Under the AISC Method, the gusset plate was expected to have a buckling capacity of 1152 kN using an effective length factor of 1.2. This was larger than the 913 kN maximum compression capacity of the BRB and so it was expected that the gusset plate would not fail under buckling. During testing, the gusset plate buckled at an axial force of 693 kN in the BRB at an inter-storey drift of 0.63%. The failure mechanism as shown in Fig. 4b clearly indicates that the gusset plate buckled out-of-plane and a hinge formed at the end of the BRB, this is similar to other gusset plate failures (Tsai et al. 2002, Takeuchi 2014).



Figures 4a. Chou and Liu frame dimensions and Figure 4b. Failure mechanism (Chou et al. 2012)

Comparison of Design Methods

To determine the merit of the design methods outlined in this paper, they have been compared to the Chou and Liu frame in Table 1.

Table 1. Comparison of buckling capacity design methods for Chou and Liu frame

	Experiment Result	**Thornton Method (K=0.65)**	**Thornton Method (K=2)**	**AISC Method (K=1.2)**	**AISC Method (K=2)***	**Working Point Method**	**Koetaka Method**	**Takeuchi Method**	**Finite Element Model**
Buckling Capacity	693 kN	8677 kN	917 kN	1152 kN	759 kN	3479 kN	4128 kN	930 kN	622 kN

* In Chou and Liu (2012) this method is calculated as 614 kN, Chou et al. (2012) calculated a capacity of 759 kN, the author of this paper has separately calculated 750 kN based on the information available.

It can be seen that all current methods are not conservative for the Chou and Liu frame. This holds true even with a suggested effective length factor of 2 for methods that consider just the gusset plate. Methods that consider the connection transition area and the BRB system as a whole also overestimate the buckling capacity despite consideration of more variables.

The Working Point Method operates on the assumption that the BRB provides no restraint to the connection indicating the method should be reasonably conservative. However the method predicted a buckling capacity 5 times larger than the experiment.

It is worth noting that for many tested gusset plates, the AISC method is overly conservative. Dowswell (2009) assessed 59 experimental specimens and 56 finite element models to determine the most appropriate effective length factor. For non-compact corner gusset plates, using K=1 was conservative for 11 of 12 gusset plates with some buckling at up to 8 times their calculated capacity. As such, a more conservative approach in gusset plate design may result in a number of uneconomic designs.

Finite Element Modelling of Chou and Liu Frame

A finite element model of the Chou and Liu frame was developed in Abaqus FEA (Dassault Systems, 2005) as a representation of the full experiment. The model uses shell S4R elements for the beam, columns, gusset plates and connections as shown in Fig. 6. Shell elements were chosen to form the model instead of solid elements. This was due to their faster computational time and their suitability for accurately modelling thin plate members. All members were tied together and fixed boundary conditions were established at the base of the model. An initial imperfection was added to the model based on the first buckling mode due to the tendency of shell elements to remain in plane. This corresponded to 1/1000 of the BRB length and was within manufacturing tolerances.

In order to fully model the BRB separate concrete, steel core, and steel tube sections would be required. Contact modelling between the concrete and the steel core would also be required in order to simulate the unbonding layer. This would increase computational time significantly. Instead, the BRB was modelled as a wire with defined sectional properties. Using a generalised section to captures the yielding properties of the inner core plate and the inertial properties of the concrete and steel casing was not sufficient. This is because ABAQUS limits the generalised section integration calculations to before the analysis and as such the wire was unable to yield. To resolve this limitation, two wires were used in the same plane, one with the section properties of the inner core plate and the other considering the outer casing and concrete. The two wires were then coupled together along their lengths and fixed in all degrees of freedom except axially. This allowed the BRB member to yield while preventing out-of-plane buckling. Only the yielding segment of the BRB was modelled a wire couple.

The model was displaced laterally at the right beam-column joint until buckling occurred. Static general analysis was used and non-linear geometry was considered to allow large rotations and the stiffness matrix to update throughout the model simulation. Axial section forces in the BRB were measured to determine the buckling capacity of the gusset plate. Through equilibrium, this gave a good indication of the forces inside the gusset plate that transferred to the BRB and is consistent with the experimental test methodology (Chou and Liu 2012).

The model was found to buckle at an axial load of 622 kN. This is lower than the experimental value of 693 kN but was expected as the model does not consider the resistance of the outer casing and concrete on the non-yielding segment inside the casing of the BRB as shown in Fig. 7. This choice was made to more accurately model the connection transition region’s failure mechanism. It would not be captured if the BRB wire was inclusive of the non-yielding segment due to rigidity of the outer casing and concrete wire.

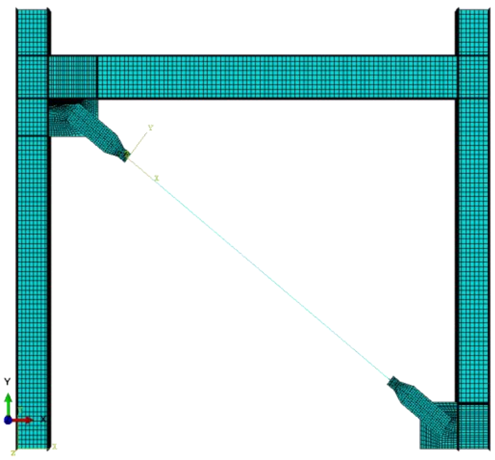


Figure 6. Meshed finite element model of Chou and Liu frame

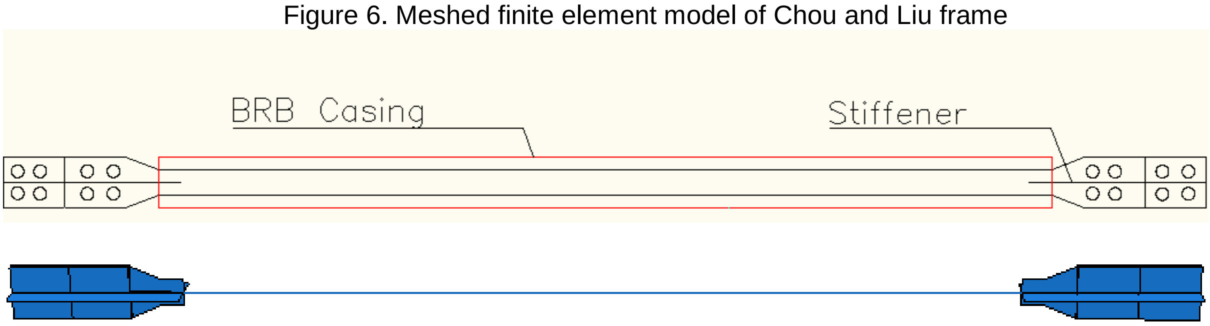


Figure 7. BRB model comparison

Frame Action Forces and Buckling Capacity

Frame action forces are the result of the beam-column joint opening and closing when the frame undergoes cyclic loading (See Fig. 8). When the BRB is in compression, the beam-column joint is opening. This results in additional tension forces on the gusset plate. This has resulted in several experimental tests exhibiting weld fracture at the gusset plate interfaces to the beam and column (Chou et al. 2012, Lin et al. 2013).

Similarly, when the BRB is in tension, the beam-column joint closes and additional compression forces are on the gusset plate. Local flange buckling has been observed on the beam and column as a result of this compression (Jia et al. 2013). Mahin et al. (2004) has experimentally proven a possibility of a gusset plate buckling while the BRB frame is in tension as a result of frame action pinching. This effect is not currently designed for but could be prevented through the addition of gusset plate stiffeners.

Research has not been undertaken to quantify the effects of frame action forces on the buckling capacity of gusset plates. There is lack of understanding as to why the gusset plate fails at forces much lower than expected, even when considering sway failure by k=2. To quantify if frame action has any effect on gusset plate compressive buckling, the finite element model of the Chou and Liu frame was displaced until buckling occurred with and without frame action.

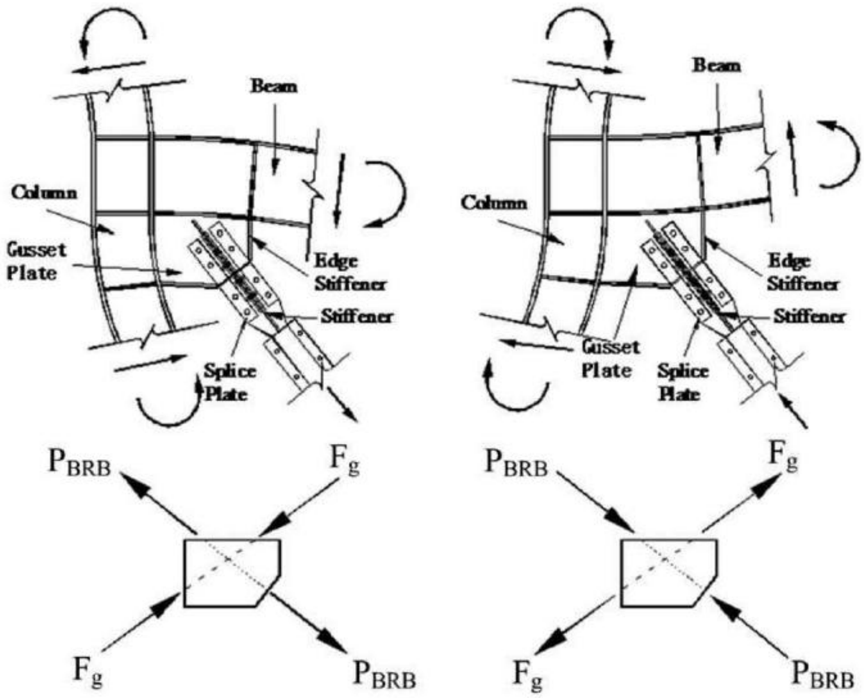


Figure 8. Frame action forces acting on the gusset plate (Chou et al. 2012)

Reduced Model with Frame Action Forces Removed

In order to prevent the beam-column joint from opening and closing, a reduced model was developed (See Fig. 9). This was achieved by removing the right column and bottom gusset plate from the model and replacing the beam to right column connection with a pin. The left column was also pinned at the base. Instead of the right end of the beam being displaced to cause compression in the BRB, the BRB member itself was displaced to the left at the bottom gusset end. This method is similar to that of Lin et al. (2013) and was verified by observing that no beam-column joint rotation occurred.

Reduced Model with Frame Action Forces

The model with frame action forces included is similar to the above model but the left column base is not pinned, the BRB bottom gusset end acts as a pin out-of-plane only, and the model is displaced at the right end of the beam. This model was compared to the full finite element model to ensure that the changes did not have a drastic effect on the model's ability to resemble the experimental data.

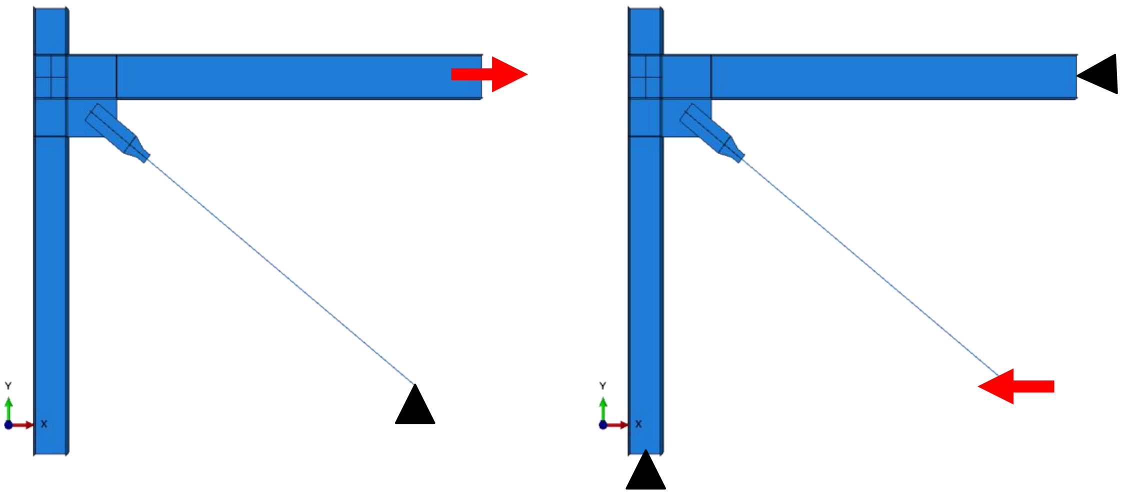


Figure 9. Boundary and loading conditions of frame action (left) and without frame action (right) models

Results

It can be observed in Table 2 that the reduced model behaves almost identically to the full frame model and is a good representation of the Chou and Liu frame. As such it is now reasonable to compare it to the reduced model without frame action.

Table 2. Comparison of finite element models to determine frame action forces

	Full Frame Model	**Reduced Model with Frame Action**	**Reduced Model without Frame Action**
Buckling Capacity	622 kN	624 kN	631 kN

The reduced model without frame action has a higher buckling capacity by 2%. This indicates frame action may reduce the buckling capacity of a gusset plate. The amount that this capacity has reduced can be considered negligible. It can be said that for the Chou and Liu frame, frame action forces do not need to be considered to determine a gusset plate's buckling capacity.

Research Opportunities

Further research is required to determine a suitable method for preventing buckling of gusset plates in BRBFs. Focus will be placed on determining an effective length that can allow a conservative estimate of a gusset plate's buckling capacity. It is likely that the effective length factor will not be a fixed value and instead dependent on the length of the BRB. It is also clear that the connection transition region plays a role in the stability of the BRB frame and more work on the relationship between gusset plate stiffness and connection transition region stiffness is required to develop accurate and conservative design methods.

Frame action forces have so far not been shown to have a substantial effect on a gusset plate's buckling capacity. However, it is theorised that the transition between the tension phase and the compression phase may result in the gusset plate buckling unexpectedly. This is because the gusset plate will still remain unstable from being pinched in the tension phase as well as being axially compressed. As highlighted earlier, gusset plate buckling under tension also requires further investigation.

Free edge stiffeners have been suggested and implemented as a solution to early buckling failure in BRB frames (Tsai et al. 2008) Testing of stiffened gusset plates has shown a significant increase in gusset plate capacity, preventing sway buckling (Crake and Westeneng 2014, Tsai et al. 2008). Stiffeners also have the added benefit of reducing weld fracture and beam and column flange buckling from frame action forces. However, they are currently designed empirically, based on experiments and finite element models, so there is the opportunity to determine analytically how they affect gusset plate behaviour. There are also concerns that a stiffened gusset plate can stiffen the beam-column joint undesirably and this effect has not yet been investigated.

Conclusions

This paper was able to answer all questions proposed, allowing the following conclusions to be made:

- A range of methods are available to determine gusset plate buckling capacity, all of which make a number of assumptions and have limitations.
- For the frame investigated, it was found that no method could conservatively estimate the buckling capacity
- A finite element model was able to accurately model gusset plate buckling failure
- For the frame investigated, frame action forces do not significantly affect buckling capacity

References

Astaneh-Asl, A. Seismic behavior and design of gusset plates. Structural Steel Educational Council.

American Institute of Steel Construction (AISC). 2005. Specification for structural steel buildings. ANSI/AISC 360–05.

Bruneau, M., Uang, C. M., and Sabelli, S. R. 2011. *Ductile design of steel structures*. McGraw Hill Professional.

Chou, C. C., and Chen, P. J. 2009. Compressive behavior of central gusset plate connections for a buckling-restrained braced frame. *Journal of Constructional Steel Research*, 65(5), 1138-1148.

Chou, C. C., and Liu, J. H. 2012. Frame and brace action forces on steel corner gusset plate connections in buckling-restrained braced frames. *Earthquake Spectra*, *28*(2), 531-551.

Chou, C. C., Liu, J. H., and Pham, D. H. 2012. Steel buckling-restrained braced frames with single and dual corner gusset connections: seismic tests and analyses. *Earthquake Engineering & Structural Dynamics*, *41*(7), 1137-1156.

Crake, M., Westeneng, B., Lee, C-L., MacRae, G. A., and Jones, A. 2014. Effects of Stiffened Gusset Plate Connection on Buckling Restrained Brace Frames. *Civil and Natural Resources Engineering Research Conference*

Dassault Systems. 2005. Abaqus FEA. (Version 6.12)

Dowswell, B. 2006. Effective Length Factors for Gusset Plate Buckling. *Engineering Journal - American Institute Of Steel Construction*, *43*(2), 91.

Dowswell, B. 2013. Gusset Plate Stability Using Variable Stress Trajectories. *Structures Congress 2014.* 2629-2639

Gross, J. L. 1990. Experimental study of gusseted connections. *Engineering Journal*, *27*(3), 89-97.

Jia, M., Lu, D., Guo, L., and Sun, L. 2014. Experimental research and cyclic behavior of buckling-restrained braced composite frame. *Journal of Constructional Steel Research*, *95*, 90-105.

Koetaka, Y., Kinoshita, T., Inoue, K., and Iitani, K. 2008. Criteria of buckling-restrained braces to prevent out-of-plane buckling. *The 14th World Conference on Earthquake Engineering,* 12-1.

Lin. P-C., Tsai, K. C., Wu. A-C., and Chuang. M-C. 2013. Seismic design and test of buckling-restrained brace connections. *10th international conference urban earthquake engineering*

MacRae, G. A., and Clifton, C. 2015 Research on Seismic Performance of Steel Structures. *Steel Innovations 2015 Conference.*

Mahin, S., Uriz, P., Aiken, I., Field, C., and Ko, E. 2004. Seismic performance of buckling restrained braced frame systems. *13th World Conference on Earthquake Engineering*.

Matsui, R., Takeuchi, T., Nishimoto, K., Takahashi S., and Ohyama, T. 2010. Effective buckling length of buckling restrained braces considering rotational stiffness at restrainer ends. *7th International Conference on Urban Earthquake Engineering & 5th International Conference on Earthquake Engineering Proceedings*, 1049–1058

Naghipour, M., Abdollahzadeh, G., and Shokri, M. 2013. Analysis and Design Procedure of Corner Gusset Plate Connection in BRBFs. *Iranica Journal of Energy and Environment*, *4*, 271-282.

Nakamura, H., Takeuchi, T., Maeda, Y., Nakata, Y., Sasaki, T., Iwata, M., and Wada, A. Fatigue Properties of Practical-Scale Unbonded Braces. *Nippon Steel Technical Report*. 82.

Sheng, N., Yam, C. H., and Iu, V. P. 2002. Analytical investigation and the design of the compressive strength of steel gusset plate connections. *Journal of Constructional Steel Research*, *58*(11), 1473- 1493.

Standards New Zealand. 2007. NZS 3404-1997 + Amendment 2-2007, *Steel Structures Standard.* Wellington

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

Takeuchi, T., Matsui, R., and Mihara, S. 2015. Out-of-plane Stability Assessment of Buckling-restrained Braces with Chevron Configurations. *Proceedings of STESSA 2015*.

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

Tsai, K.C., Hwang, U.C., Weng, C.S., Shirai, T., and Nakamura, H. 2002, Experimental tests of large scale buckling restrained braces and frames. Proceedings, *Passive Control Symposium*. December, Tokyo Institute of Technology, Tokyo, Japan.

Thornton, W. A. 1984. Bracing connections for heavy construction. *Engineering Journal (AISC)*, 21 (3), 139-148.

Whitmore, R. E. 1952. Experimental investigation of stresses in gusset plates. *Engineering Experiment Station*, 16.