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Buckling Restrained Braces - Issues and Solutions

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ABSTRACT

This paper describes some design issues relating to buckling restrained braced frames (BRBFs) including: (i) BRB system capacity under both axial compression and out-of-plane (OOP) frame deformations, (ii) BRB demand estimation, (iii) brace inertial effects, (iv) gusset plate (GP) weld strength, (v) frame element requirements near the gusset plate, (vi) frame ratchetting considerations, (vii) frame demands, (viii) load paths into the frame, and (ix) BRB quality control.

Methods to address these issues are proposed. As part of this, a simple method for BRB system design considering BRB stability and frame out-of-plane deformation effects is described. The method seeks to prevent yielding in the BRB system except for within the core inside the BRB restrainer/casing. It uses standard equations with which engineers are familiar. The method discourages brace/gusset plate regions which are too flexible (where instability may occur as a result of axial force), or which are too stiff (where yielding may occur due to out-of-plane frame deformations thereby compromising the performance in later in-plane deformation cycles).

INTRODUCTION

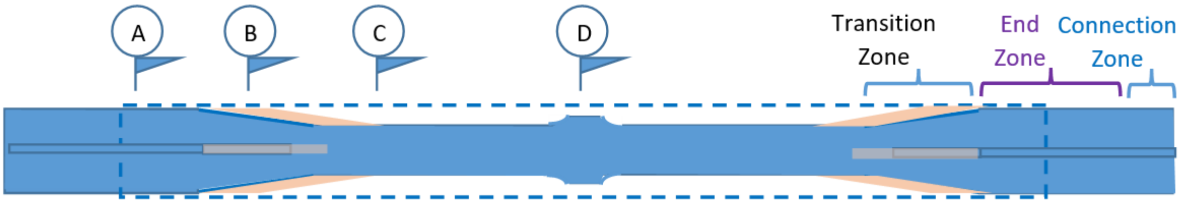
In order for structures to behave well under earthquake excitation, economical new methods and systems are continually being investigated. One approach is the application of buckling restrained braces (BRBs) in building frames. These have become popular over recent years and are now implemented in structures in seismic regions around the world. The braces themselves may be specified to have a lateral force capacity matching the expected force demand. This can result in an economical structure. Also, the seismic response may be good. However, number of concerns have been expressed about the design and detailing of BRB structures. There is a need to address these issues if design is to be conducted with confidence.

This paper addresses this need for BRBs by seeking answers to the following questions:

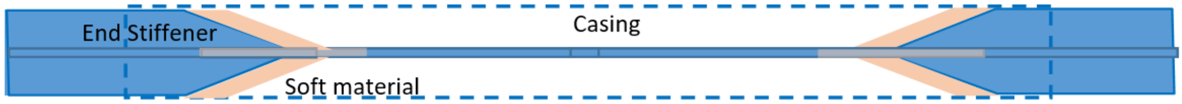
1. (1) What are the issues?
2. (2) How may they be addressed?

1 BRB DESCRIPTION AND DEMANDS

Buckling restrained braces (BRBs) were initially conceived and tested in Japan. Early development was in the late 1970s and 1980s according to Takeda et al. (1976) and Fujimoto et al. (1990). They generally consist of a core which is subject to tension and compression forces during earthquake shaking. The central part of the core, the core yield zone (CYZ), placed within a casing (or restrainer), is expected to undergo axial inelastic strain demands and dissipate the energy from the earthquake. The casing restrains CYZ buckling during compressive loading. While many variations of BRB design are possible, one of the most common forms uses concrete-filled steel tubes for the restrainer as shown in Figures 1 and 2. At the ends of the BRB brace, there is are core connection zones (CCZs) which are attached to the structural frame. Beside this is the core end zone (CEZ) shown in Section A which moves in an out of the casing during CYZ inelastic deformations. Next is the Core Transition Zone (CTZ) shown in Section B, where the core section changes. It should be long enough to prevent stability issues at the casing end and stress concentration issues within the core, but not too long or it will reduce the length of the core yield zone (CYZ), which is shown in Section C, and the resulting displacement capacity. In the middle of the BRB is a shear key (Section D), placed to stop the casing sliding along the brace during yielding. Soft material is generally placed beside the transition zone the core deform in compression without resistance. Also, gapping material (not shown) is generally placed around the core, to prevent binding of the core in compression, due to Poisson's ratio, and inelastic effects.

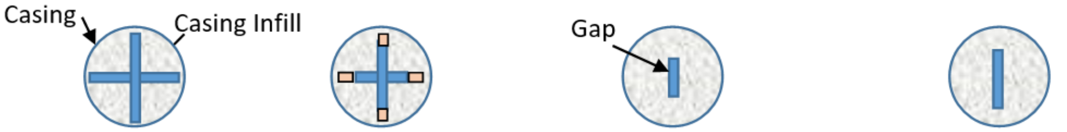


(a) Plan of Core



(b) Side View of Core

Figure 1. BRB Longitudinal View (Not to Scale)



(a) Section A End Zone

(b) Section B Transition Zone

(c) Section C Core

(d) Section D Shear Key

Figure 2. BRB Section Views of BRB (Not to Scale)

Many studies have been conducted around the world to understand the behaviour of BRB frames and many have been summarized by Takeuchi and Wada (2017).

2 BRB System Issues

2.1 BRB system capacity with axial compression and out-of-plane (OOP) frame action

BRBs are part of a building system. Their performance under the multi-directional earthquake shaking to which the structure is subjected, depends demands as well as the details of the BRB itself, the connections, and the neighbouring elements.

The acceptability of a BRB used in design is generally based on the demonstrated brace test performance experimental testing of the BRB itself (or a scaled version of it). Sometimes in-plane tests of the BRB as part of a frame may also be conducted. Specific cyclic testing requirements are given in the USA, Japan, and mainland China. There are no specific BRB system design provisions in current NZ standards. BRBs implemented in NZ are required to comply with the NZ Building Code (NZBC) as “Alternative Solutions”. AISC341-16 F4 (2016) provisions, test protocols and performance criteria, are commonly used for BRB frames in NZ and around the world.

Since the standard acceptability tests do not consider BRB frame out-of-plane (OOP) deformations, there are concerns that the earthquake performance will not be satisfactory. Frame OOP deformations affect the frame differently depending on the boundary conditions (MacRae, 2021). Also, in traditional BRB frames with gusset plates connecting to the beams and columns, the connections at the end of a BRB should be: (i) stiff/strong enough that they are stable under expected applied compression forces and not buckle, and (ii) flexible enough that they do not yield due to OOP frame deformations in combination with axial forces as this may compromise the subsequent system performance. Because an end-connection stiffness that is either too high, or too low, is not desirable, an end-connection stiffness in the “sweet spot”, satisfying both of the criteria above, is required.

2.2 BRB demand estimation

The BRB axial force capacity is generally used as a demand for the design other BRB frame elements as part of the capacity design process. This strength is often estimated based on the results of experimental testing. Cui has recently shown that BRB peak axial strength increased by 30% above the in-plane strength (MacRae et al. 2021). This was explained as being because the transition zone digs into the casing. It is not currently considered in BRB design.

2.3 Brace Inertia Forces

As braces, become longer, brace inertial forces may be significant. Tsai and Wu (2022) describe the testing of a 1/3 scale brace with 6.9m between work points (indicating 20.7m for the prototype) planned for an actual structure. Braces at long as 46m extending over several stories have also been proposed.

2.4 Gusset plate (GP) weld strength

Some standards require the GP weld to be designed for the expected force from the brace. In other cases the weld demand is enhanced by an empirical distribution factor obtained from in-plane considerations only. This may not be sufficient if the plate also undergoes demands from significant OOP action. If weld fracture is not desired, these likely effects should be considered.

2.5 Frame element requirements near the gusset plate

Often large gusset plates connect to the beams and columns. For the expected demands on these plates to be realized, sufficient strength is required in the beams and column webs to ensure that the BRB, rather than the surrounding frame sustains the inelastic deformation.

2.6 Frame ratchetting

Because BRBs often exhibit a low amount of post-yield hardening, their hysteresis loop may be similar to elastoplastic. This can result in seismic ratchetting, where the frame yields primarily in one direction in an earthquake, causing large permanent displacements and possible collapse.

2.7 Frame design

While capacity design is conducted to obtain the member sizes, the moments considered may be small and do not govern the design. If no moment capacity is provided in the columns, a storey mechanism may occur. There is no clear guidance as to how to prevent such a mechanism in current standards.

2.8 Load paths into the seismic frame

It is essential that there are clear and robust load paths for all forces resulting from the shaking. In many software packages, engineers may use the “rigid diaphragm assumption”. Also, in some cases, rigorous design of the diaphragm for the horizontal inertia, transfer, compatibility, bearing and other forces, is not performed. Also, since the floor slab cannot always transfer compression force directly into the steel column because, due to displacement compatibility, the column generally moves away from the slab at that location, horizontal forces must travel through a more indirect load path. This is through the slab, shears studs, beam, beam-end connection into the columns. Such considerations are not common in design but are essential to obtain a high likelihood of desirable performance through the structure.

2.9 BRB quality control

The strength and deformation capacity of BRBs is totally dependent on the BRB manfacture quality. Tests of some imported braces, and of some made in NZ, have indicated poor performance (MacRae et al. 2021) with high or low strength, or unstable response. Also, deformation capacities have been lower than expected.

3 BRB System Solutions

3.1 BRB system capacity assessment with axial compression and OOP frame action

(a) Plastic mechanism approach

A number of approaches are available to determine member compressive strength considering material nonlinearity, out-of-straightness, and other effects. Takeuchi and Wada (2017) method uses a plastic mechanism approach. This approach i) gives results sensitive to the initial deformation assumed, δ_o, (ii) does not explicitly consider residual stresses effects which may be significant (Bažant and Cedolin, 2010), (iii) uses the symbols and concepts are not simple or easy for engineers to understand, and (iv) has little discussion on the importance of beam column joint flexibility, (v) does not keep the system outside the BRB casing elastic, and (vi) the is no axial compressive force enhancement for out-of-plane effects. The approach has been simplified by Zaboli et al. (2021) where a notional force is applied. The approach, which has has been applied by Saxey (2023), (i) is iterative, (ii) uses an effective length factor for the gusset plate (GP), k_{gp}, of 0.7 even though the failure mode is known to be sway (indicating that k_{gp} should be unity or greater), and (iii) most of the issues from Takeuchi and Wada (2007) remain.

(b) Column Curve Approach

An alternative approach is proposed to address the disadvantages of the methods above (MacRae et al. 2022). The column curve approach has the following advantages. It (i) is direct (and not iterative), (ii) uses simple equations and symbols commonly used by (and familiar to) engineers, (iii) it considers the whole system stability, (iv) it does not require the computation of effective length factor, (v) residual stresses and out-of-straightness are considered directly from the column design curve so an arbitrary notional load or initial deformation is not required, and (vi) it aims to prevent inelastic action occurring outside the CYZ. This approach is advocated in this paper. The design check is conducted in 2 stages:

(i) Preventing elastic buckling under axial force

This is achieved by considering that the maximum in-plane axial force, C_{max}^{*}, is significantly less than the system elastic buckling force, P_e, as shown in Equation 1 (MacRae et al., 2021). This equation, from NZ3404 (2007), considers the case that the brace maximum compressive axial strength, C^{*}_{max}, may be significantly greater than that expected, there may be significant uncertainty in the analysis, and the consequences of this failure mode.

$$C_{max}^{*} < 0.285\, P_e \tag{1}$$

The system elastic buckling force, P_e, is dependent on the properties of all elements in the BRB system load path as described by Westeneng et al. (2015). As a result, design guides considering only the gusset plate (GP) properties are inadequate. BRB elements and rotational flexibilities are shown in Figure 3 at the:

(i) beam-column joints, considering joint rotations θ_A and θ_H,
(ii) casing ends, with relative rotations θ_{CD} and θ_{EF}, which has been studied by Takeuchi et al. (2009), and
(iii) connection ends with rotations θ_B and θ_G.

These rotational flexibilities reduce the system elastic compressive buckling strength, P_e. For frames where the possibility of joint lateral movement may affect the buckling strength, such as in some chevron BRBs, this should also be considered in computing P_e (MacRae et al. 2021).

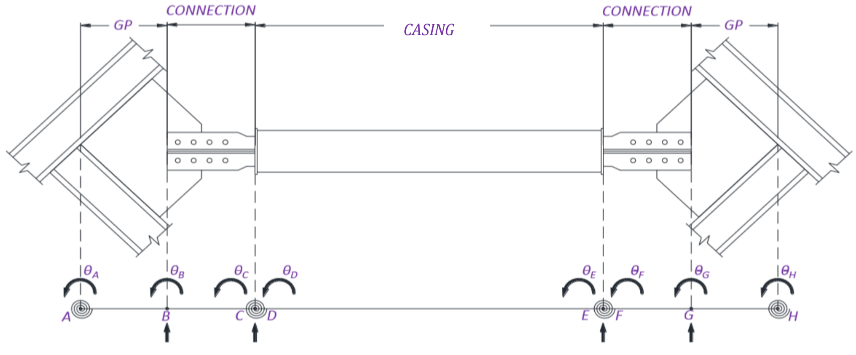


Figure 3. BRB System Sub-elements and Rotational DOFs (Westeneng, 2017)

Beam-column joint flexibility, decreasing P_e, may occur when:

(i) members framing into the joint use simple (e.g. bolted web side plate) connections,

(ii) these members are fully plastic due to bending (so there is no lateral stiffness), and/or

(iii) the slab does not provide significant column twist restraint either because it does not exist near the column, or is separated from the column (for example to reduce beam overstrength effects into the column) (MacRae et al., 2021). The flexural stiffnesses at the casing ends, $k_{\theta CD} = M_{CD}/\theta_{CD}$ and $k_{\theta EF} = M_{EF}/\theta_{EF}$ at the critical (usually maximum) elongation may be obtained experimentally. Discussions of this are given by Takeuchi et al. (2009) and MacRae et al. (2021).

The value of P_e can be obtained easily using proper second order analysis (Lu et al. 2009) and readily available free software, such as MASTAN2 (McGuire et al., 2015), or commercial software. Also, specialized software is available, such as that by Vazquez-Colunga, (2021) which computes the gusset plate properties. The most critical (i.e. lowest) P_e occurs at the maximum brace elongation.

(ii) Preventing yield under axial force and OOP frame deformations

The simple moment axial force interaction relationship in Equation 2, which is similar to that in NZS3404 (1997) Section 8.3, can be used to discourage flexural yield within BRB system which may compromise the performance of the BRB after several cycles of loading. It should be checked at every cross-section, *i*. Here $\phi = 0.90$, C^*_{max} is the maximum axial force that can occur in the brace considering OOP deformation, P_n is the inelastic axial strength of a column, M_{yi} is the yield flexural strength at section *i*, and M^*_i is moment demand at the section, *i*. If Equation 2 is satisfied then, apart from core yield within the casing, additional yielding of the BRB system is unlikely due to brace axial force and frame out-of-plane moment.

$$\frac{C^*_{max}}{\phi P_{ni}} + \frac{M^*_i}{\phi M_{yi}} < 1.0 \tag{2}$$

The inelastic axial strength of a column, P_{ni}, with $k_f = 1$ can be found using the slenderness parameter, λ_{ni}, according to NZS3404 (1997) Clause 6.3.4b and AS/NZS2327 (2020) Clause 4.1.3.4, as per Equation 3. If US column curves are used then $\lambda_i = kl/(\pi r_i).\sqrt{(F_{yi}/E)} = \sqrt{(P_{yi}/P_e)}$. Members with multiple cross-sections along the length (such as BRBs, with the different regions as shown in Figure 1), have one elastic buckling force, P_e, for the whole system. However, P_{yi} is different for each cross-section, *i*. Therefore, in Equation 2, for each cross-section, *i*, $P_{yi} = F_{yi}A_i$ for calculating λ_{ni}, and $P_{ni} = F_{ni}A_i$. This method converges to the Euler buckling load of a uniform cross-section member. P_{ni} may be computed assuming the NZS3404 column curves with $\alpha_b = 0.5$.

$$\lambda_{ni} = kl/r_i.\sqrt{(F_{yi}/250\text{MPa})} = 90.\sqrt{(P_{yi}/P_e)} \tag{3}$$

BRB moments, M^*_i, from OOP deformations at each section, *i*, may be found directly from second order analysis. The result is generally similar to that from first order analysis since the member is often double curvature. Critical moments will occur at the shortest BRB length. This OOP deformation is $2\Delta_{bm}$ (AISC, 2016).

Both the shortest and longest brace extension/shortening cases should be considered separately. This is because the critical brace length for flexural yield, given as the maximum moment term in Equation 2, occurs for a specified OOP drift when the brace is shortest because M^* is greatest. The critical stability term, given as the axial force term in the equation, is greatest when the brace is at maximum extension, because P_{ni} is lowest.

In regular frames the left hand side of Equation 2 is most likely to exceed unity in the bottom story of a frame especially if there is a stiff foundation due to large OOP moment demands. In the upper stories, moment demands may not be large because the drifts in adjacent stories may be similar allowing columns to remain straight (Hogan and Lin, 2020).

If Equation 2 is not satisfied at the location of the gusset plate (GP), increasing the GP size may not help. This is because while the capacities, ϕP_{ni} and ϕM_{yi} are increased, the moment demand, M^*_i, for the same drift is also increased. Other ways to satisfy Equation 2 by minimising M^*_i involve (i) limiting BRB system OOP interstorey drifts, (ii) by placing pins at the BRB ends (MacRae et al., 2021), or (iii) providing foundation beam rotational flexibility for first storey BRBs.

Examples of the use of this approach have been provided by Dorrance et al (2023) and Simpson et al. (2023).

3.2 BRB demand estimation

Since the BRB force capacity can increase considering OOP deformations, C^*_{max} should be multiplied by 1.3 before it is used in Equation 2.

3.3 Brace Inertia Forces

In many cases these may be small, but provisions from “Parts and Components” in the loadings standard can be used to increase the moment demands along the BRB length.

3.4 Gusset plate (GP) weld strength

Welding should be conducted to carry the full strength of the gusset plate (rather than the force in the brace). In this way, weld fracture is not expected.

3.5 Frame element requirements near the gusset plate

Beam and column web doubler plates, with sufficient welds, may be required to carry the full GP strength. This will ensure that significant inelastic deformations are not expected in the beam column members.

3.6 Frame ratchetting

Methods to estimate ratchetting displacements are given by MacRae et al. (2023). Frame peak and residual displacements may be minimised by providing the structure with stiffness and strength, and providing significant continuous column stiffness over the height of multistorey structures (MacRae, 2011).

3.7 Frame design

To minimise the possibility of a soft storey, the continuous columns should be provided with sufficient stiffness and strength (Sherborne et al. 2022).

3.8 Load paths into the seismic frame

The full load path for horizontal forces resulting from seismic action transferring from the slab, through the shear studs, into the floor beams, through the connections, into the seismic frame and down to the ground should be explicitly considered. Elements on the load path should be designed to resist these anticipated forces. Methods to do this, relating to the design of the slab and neighbouring elements, have been developed by Alizadeh et al. (2017).

3.9 BRB quality control

It is essential that a BRB be purchased from a manufacturer who has demonstrated satisfactory brace behaviour, and who will guarantee it under the strong earthquake shaking.

CONCLUSIONS

This paper briefly describes some design and detailing issues related to the performance of buckling restrained braced frames (BRBFs). Some possible solutions are also described. It is shown that:

i) Issues with the following may compromise BRB frame performance: (i) BRB system capacity under both axial compression and out-of-plane (OOP) frame deformations, (ii) BRB demand estimation, (iii) brace inertial effects, (iv) gusset plate (GP) weld strength, (v) frame element requirements near the gusset plate, (vi) frame ratchetting considerations, (vii) frame demands, (viii) load paths into the frame, and (ix) BRB quality control.

ii) Possible solutions to the issues above are proposed. As part of this, a simple method for BRB system design considering BRB stability and frame out-of-plane deformation effects is described.

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