BRB System Out-of-Plane Considerations

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ABSTRACT

This paper describes a simple method for BRB system design considering BRB stability and frame out-of-plane deformation effects. The method seeks to prevent yielding in the BRB system except for in the core within the BRB restrainer/casing, and 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. The need to explicitly consider column twist restraint in the design procedure is emphasized.

1 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. While they can provide excellent response, and can be specified to have the desired lateral force capacity which results in an economical structure, a number of concerns have been expressed about the implementation of BRBs into frame systems. In particular, there is concern about the performance about the performance of the systems as the frames move out-of-plane (OOP) during expected frame displacements. There is a need to address this issue if design is to be conducted with confidence.

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

(1) What affects the BRB system performance when subject to OOP frame deformations?

(2) How is it possible to design for this?

2 CONSIDERATIONS

2.1 BRB description and demands

Buckling restrained braces (BRBs) were initially conceived and tested in Japan with initial development in the late 1970s and 1980s (e.g. Takeda et al. 1976 and Fujimoto et al. 1990, who describe tests conducted in 1987). While many variations are possible, they generally consist of a core to which force is applied in tension and compression during earthquake loading as shown in Figures 1 and 2. At the end of the core there is a core connection zone (CCZ) beside which is a core end zone (CEZ) shown in Section A in Figure 1. 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, but not too long or it will reduce the length of core yield zone (CYZ) shown in Section C and the resulting displacement capacity. In the middle of the BRB is a shear key in Section D, to stop the casing sliding along the brace during yielding. Soft material is generally placed at the transition zone allowing it to deform in compression without resistance. Also, gapping material is generally placed around the core, so that as a result of compression, when the core area increased due to Poisson's ratio, and inelastic effects. The casing (or restrainer) limits the CYZ buckling that can occur within the casing. It can be made of a range of materials, including steel and timber, but concrete filled steel tubular sections are most commonly used.

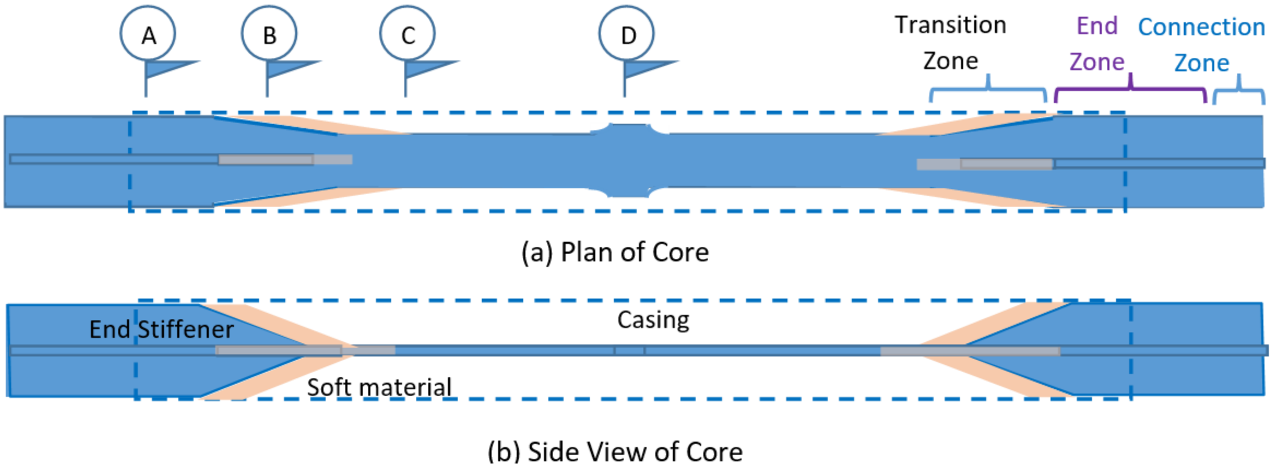

Figure 1. BRB Longitudinal View (Not to Scale)

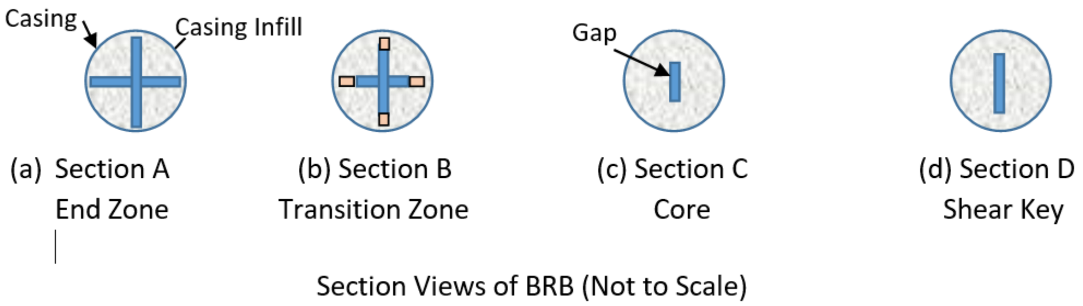

Figure 2. BRB Section Views (Not to Scale)

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).

While many methods are available to design BRBs, their acceptance for use in practice is generally determined based on demonstrated brace test performance. Test protocols and performance criteria commonly used around the world generally follow the American Institute of Steel Construction (AISC) criteria. While there are a number of requirements, the main ones are that the brace is required to be tested to a displacement equal to twice that expected during a design level earthquake, $2\Delta_{bm}$, following a specific displacement protocol (AISC, 2016), and the cumulative plastic ductility (CPD) must be greater than 200. However, most braces are tested individually without the beams, columns, or gusset plates, and brace bending effects from in-plane or out-of-plane (OOP) frame displacements, are not considered (MacRae, 2021).

A number of concerns have been expressed about the implementation of BRBs into frame systems for a number of reasons. These relate to: BRB demands; maximum BRB force; BRB system capacity (considering the gusset plate (GP) configuration, unstiffened GP design considerations, system elastic design considerations considering stability under axial force, axial strength, and demands considering axial compression and out-of-plane (OOP) frame deformations, and verification of not yielding considering axial compression and OOP deformations); GP weld strength; required beam and column web strengths; frame elements near gusset plate; brace inertial effects; frame ratchetting considerations; frame demands; load paths into the frame; and BRB quality control (MacRae et al. 2021). Many of these issues remain unresolved but are discussed elsewhere. This paper discusses only the design of the BRB-GP system design from frames with unstiffened gusset plates. BRBs with pins at the ends are discussed elsewhere (MacRae et al. 2021).

2.2 BRB System Capacity

2.2.1 BRB System Strength Considerations

BRB strength is commonly obtained based on testing and analysis. Specific requirements for this testing 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 are commonly used for BRB frames in NZ.

The compressive force that can be carried by the BRB as part of the system, assuming it is elastic, depends on all the elements of the system, considering the boundary conditions. GPs should be: (i) stiff/strong enough that they are stable under expected applied compression forces, and (ii) flexible enough that they do not yield, or cause yielding of nearby elements, due to OOP frame deformations in combination with axial forces. A GP stiffness that is too high, or too low, is not desirable. Instead, GP stiffness in the "sweet spot" satisfying both of the criteria above, is required. The following describes how the BRB system with the GPs, may be assessed.

2.2.2 BRB System Elastic Compressive Strength, P_e

The system strength, P_e, is dependent on the properties of all elements in the BRB system as described by Westeneng et al. (2015). As a result, design guides considering only the properties of the GP are inadequate. The axial strength is related to the properties of all elements of the system along the load path. Figure 3 shows the BRB elements and rotational flexibilities 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 lateral movement of a joint may affect the buckling strength, such as in some chevron BRBs, this should also be considered in computing P_e.

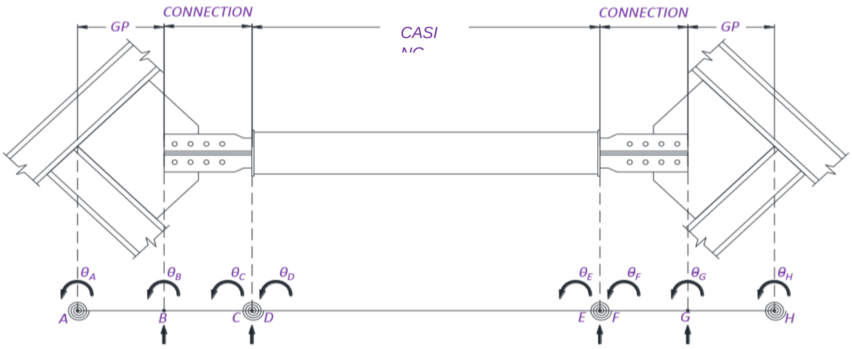

Figure 3. BRB System Sub-elements and Rotational DOFs (Westeneng, 2017)

Beam column joint flexibility, decreasing P_e, may occur when either (i) the members framing into the joint use simple (e.g. bolted web side plate) connections, and/or are fully plastic due to bending (so there is no lateral stiffness), and/or (ii) 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 then be obtained easily using readily available software.

In addition, it has been recommended that Equation 1 be satisfied (MacRae et al., 2021) to consider the case when the brace maximum compressive axial strength, C^*_{max}, is significantly greater than that expected.

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

2.2.3 BRB Design Considering Axial Compression and OOP displacements

2.2.3.1 Plastic mechanism approach

To determine member compressive strength considering material nonlinearity, out-of-straightness, and other effects, a number of approaches are available. Takeuchi and Wada (2017), and Zaboli et al. (2021) use a plastic mechanism approach. Issues with this approach include the sensitivity to the initial deformation, δ_o, assumed, no explicit consideration of residual stress effects which may be significant (Bažant and Cedolin, 2010), almost no discussion on the importance of beam column joint flexibility, and the fact that before formation of a full *plastic mechanism*, significant yielding at one hinge location may occur compromising the performance.

2.2.3.2 Column Curve Approach

The value of P_n may also be computed using relevant column curves which consider residual stresses, out of straightness, etc. This approach is advocated in this paper. Advantages of using column curves directly are that they are familiar to engineers, yielding outside the confined core is prevented, BRB system flexibility effects can be considered, and the design approach is conceptually clear.

Methods to obtain P_e, which is needed to compute P_n, include (a) specialized software, such as that by Vazquez-Colunga (2020), or (b) general frame software conducting full second order analysis which gives the buckling force. Commercial software, and free software such as MASTAN2 (McGuire et al., 2015), is available. Methods to compute the gusset plate properties may be obtained using simple concepts (e.g. Vazquez-Colunga 2020). The most critical (i.e. lowest) P_e occur when the brace deformation is the maximum in elongation, because the member will be longer.

The inelastic axial strength of a column, P_n, with $k_f = 1$ can be found using the slenderness parameter, λ_n, according to NZS3404 (1997) Clause 6.3.4b and AS/NZS2327 (2020) Clause 4.1.3.4 as:

$$\lambda_n = kl/r.\sqrt{(F_y/250\text{MPa})} = 90.\sqrt{(P_y/P_e)} \tag{2}$$

Members with multiple cross-sections along the length (such as BRBs, with the different regions as shown in Figure 1), have an elastic buckling load, P_e, for the whole system. However, P_y is different for each cross-section, i. Therefore, in Equation 2, for each cross-section, i, $P_{yi} = F_yA_i$ 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} can be computed assuming the NZS3404 column curves with $\alpha_b = 0.5$.

BRB moments from OOP deformation at each section, i, the location of interest, M^*_i, may be estimated (i) directly from second order analysis, or (ii) from first order analysis, where the *first order moment* M^*_1 is magnified according to Equation 3 from NZS3404 (1997) Section 4.4.3, and C_{max}^* is the maximum compressive brace force. The most critical moments will occur at the estimated OOP frame deformation, when the brace deformation causes the shortest BRB length. This deformation should be taken as twice that expected during a design level event.

$$M^* = \frac{M_1^*}{\left(1-\frac{C_{max}^*}{P_e}\right)} \tag{3}$$

The simple moment axial force interaction relationship in Equation 4, 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 ϕ = 0.90 and M_{yi} is the yield flexural strength at section *i*, and M^*_i is moment demand at the section, *i*. If Equation 4 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.

$$\frac{C^*_{max}}{\phi P_{ni}} + \frac{M^*_i}{\phi M_{yi}} < 1.0 \quad (4)$$

If this equation is not satisfied at the location of the gusset plate, which is the usual case, increasing the size of the gusset plate may not provide significant benefit. 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. A better method may be to minimise the BRB system OOP drifts, and therefore minimise M^*_i. This may be performed by: (i) minimizing the BRBF frame interstorey drift, or (ii) reducing the flexural demands at the BRB system ends. In the upper stories of the structure, these demands may not be large even if there are significant frame drifts because the frame drifts in successive stories are often similar, as the columns like to remain straight. The peak BRB system drifts are therefore most likely significant in the structure bottom storey (Hogan and Lin, 2020). Mitigating the BRBF drifts in the first storey, may be achieved by allowing the basement beam/foundation top to rotate, or by providing a pin at the end of the BRB.

3 CONCLUSIONS

This paper briefly describes the behaviour of, and provides simple design recommendations for, Buckling Restrained Braced Frames (BRBFs) considering stability under axial force and frame out of plane deformations in order to prevent yielding apart from within the casing. It is shown that:

i) the BRB system performance is sensitive to the boundary conditions, as well as the elements of the system. Also, gusset plates which are too stiff, or too flexible, can cause undesirable system behaviour.

ii) a simple approach is proposed which discourages gusset plate yield, so that the large inelastic displacement demands are concentrated in the restrained core, and that the performance of the BRB is not compromised by OOP deformations.

4 ACKNOWLEDGEMENTS

The authors wish to thank the MBIE Natural Hazards Research Programme Research Objective 4 (New Buildings) for sponsoring the third author and the University of Canterbury for providing support for the fourth author. Support of the NZ Heavy Engineering Educational Research Fund and the Department of Civil and Natural Resources Engineering at the University of Canterbury for work conducted by both the third and fourth authors is appreciated. The third author is also grateful to funding from National Council of Science and Technology of Mexico (CONACyT). The sponsorship above was part of the catalyst for the ideas produced in this paper. The opinions expressed in this paper are those of the authors alone.

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