Review of buckling restrained brace design and behaviour

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ABSTRACT: Buckling restrained braces (BRBs) have become a popular alternative to traditional bracing in seismic loading due to their ability to develop full and balanced hysteresis loops resulting in similar tension and compression capacities. However, research internationally for the design and behaviour of BRB compositional elements is still in the infancy stage, with intellectual property rights by commercial providers within America and Asia limiting the available research.

This paper considers the history and development of BRBs (steel-concrete and steel-steel), current design practice, areas for further development and forthcoming research to be carried out that the University of Canterbury. The outcomes of this research which consider the sensitivity in BRB member design aims to equip engineers with an understanding of BRBs but also the ability to design BRBs without the need for testing verification.

1 INTRODUCTION

Buckling restrained braces (BRBs) have become an increasingly popular alternative to traditional bracing in seismic loading. Their ability to develop full and balanced hysteresis loops resulting in similar tension and compression capacities leads to their superiority over traditional bracing in seismic areas (Jones 2011). BRB production has been dominated by commercial suppliers whom design and fabricate BRBs to the engineers desired loading requirements. This has led to intellectual property rights resulting in a lack of understanding of the BRBs compositional elements and their sensitivity in design.

This paper considers the history and development of BRBs including a brief explanation of the key compositional elements and also current international code regulations when designing BRBs. It has been identified that further research into understanding the sensitivity of compositional elements is required. This has resulted not only from a lack of information but also the growing need within New Zealand to design BRBs without undergoing testing verification to uphold the required level of safety. Key questions to be addressed include:

1. What contribution do the concrete restraining medium and outer casing have in the restraining mechanism?
2. How does the transition region affect brace performance and design?
3. How do connections influence design? Do they affect the capacity of the BRB and the surrounding frame?
4. What affect does eccentric loading have on a BRB member?

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2 HISTORY AND DEVELOPMENT

2.1 Conception and early history

BRBs were conceived at the Architectural Institute of Japan in 1973 as a flat steel plate sandwiched between a pair of reinforced concrete panels (Corte 2011). This idea was later expanded in 1976 and published at the Ninth World Conference in Earthquake Engineering in 1988 under the paper "Properties of brace encased in buckling-restraining concrete and steel tube" (Watanabe 1988). This paper details the first tests undertaken resulting in a "buckling-resistant structural member" (Watanabe 1988). These first BRBs comprised of a cross shaped steel core member, enclosed in a concrete filled square steel tube (Figure 1). It was found that the BRBs displayed stable hysteresis if the yielding load applied to the core member was smaller than the buckling load of the steel tube. This finding still holds true today, and the cross-section design has varied little.

Further research of BRBs did not take off until the 1990's (Jones 2011), with commercial development dominating the market, and with it, intellectual property. Commercial markets originated within the United States of America and Japan and are now established also in Europe, Taiwan, North America and Oceania. The first application of BRBs in New Zealand was at the University of Canterbury in the mid 2000's on the Geography and Psychology building. The past decade has seen a rise in academic research in BRB design and behaviour when considered within a system (Jones 2011; Fajfar 2004), however there is a lack of understanding of the BRB member and how its elements interact for design without the need for verification testing.

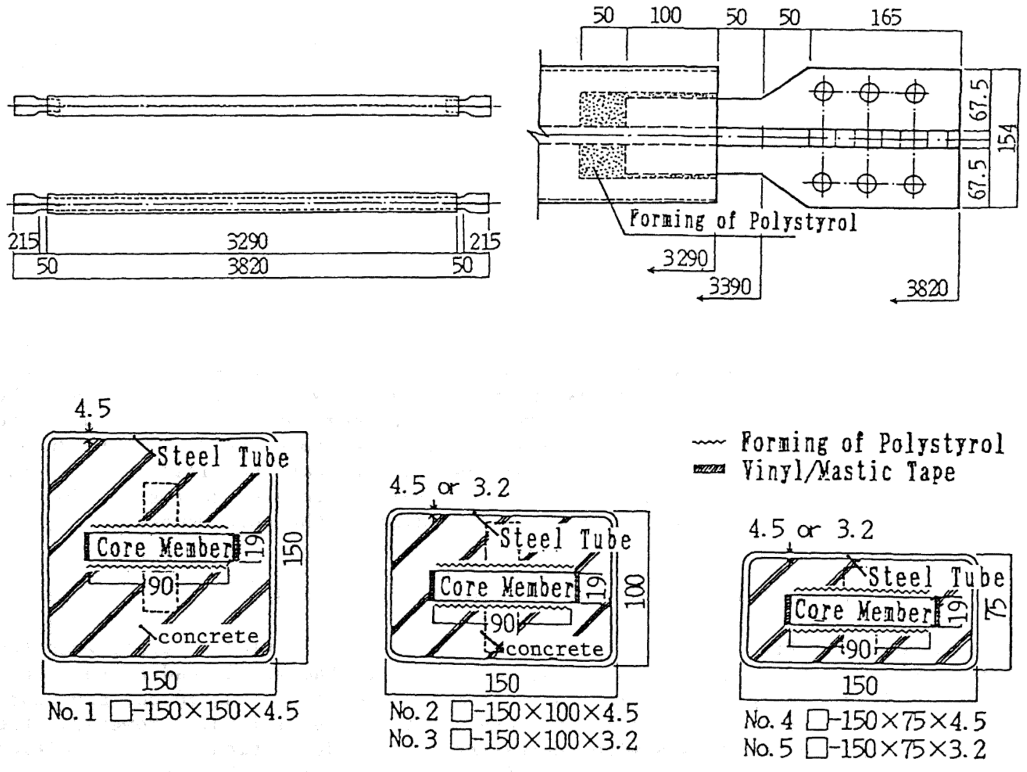

Figure 1. Cross-section of first BRB specimens (Watanabe 1988)

2.2 Compositional element development

BRBs are typically defined by five elements (Figure 2), a restrained yielding core, a restrained non-yielding region, a stiffened non-yielding region, an unbonding agent/expansion material and an outer casing. The restrained yielding core is typically flat plate or cruciform in shape and can range in composition from steel, aluminium to stainless steel (Figure 3) (Narasimha 2007; Smelser 2003;

Fanucci 2004; Tsai 2012). The core is designed for full plastic cross-section capacity (Corte 2011), with the yield capacity in tension assumed to be equal or greater in compression (Corte 2011; Jones 2011; Watanabe 1988). The restrained non-yielding region is typically referred to as the transition region and is the region in which the core increases in cross sectional area (Fussell 2010). There is a gap present between the increasing core area and surrounding restraining medium to prevent bearing (Fussell 2010).

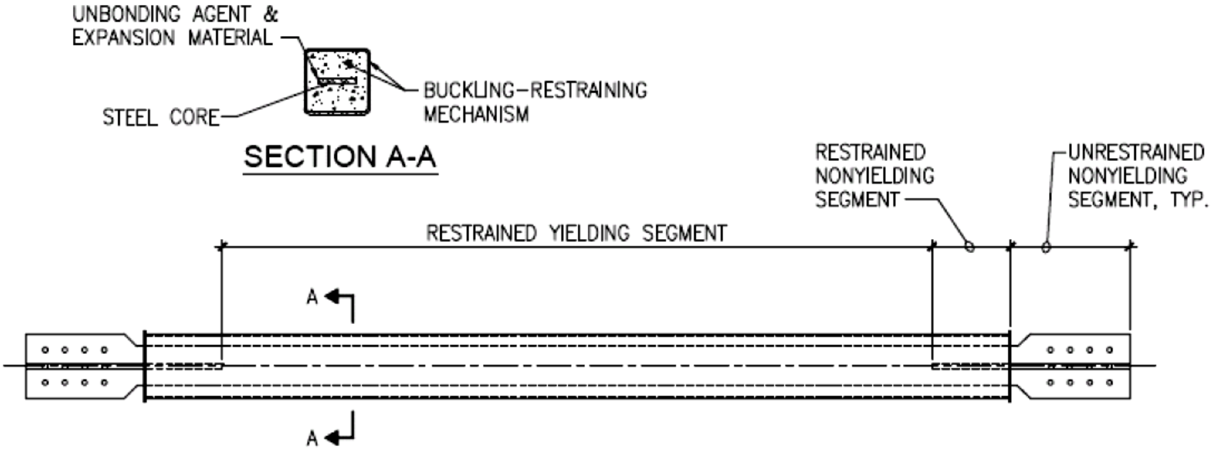

Figure 2. Typical steel-concrete BRB cross-section with elements (Fussell 2010)

The stiffened non-yielding region or unrestrained non-yielding segment is not encased by the restraining medium and outer casing. This region is where the connection to the structural frame occurs, and is typically stiffened to prevent local buckling (Fussell 2010). The relationship between the stiffened non-yielding and the transition region is important. The transition region prevents buckling stresses from being transferred to the connections, and the stiffened non-yielding region prevents local buckling stresses from influencing the yielding core (Jones 2011).

The expansion material and outer casing are commonly referred to as the restraining element which is unbonded to the core (containing the yielding, non-yielding and stiffened region). The unbonded term originated from the 1970’s research in which a shock absorbing material was used to avoid adhesion and allow transverse expansion of the core (Corte 2011). The unbonding between the core and restraining element allows the core to deform and yield without a high level of additional stresses being introduced into the restraining element (Jones 2011). This also allows the core to develop equal tension and compression capacities through full lateral restraint along the member length (Jones 2011).

Early development of BRBs consisted of a void separating the steel core from the restraining element; this resulted in local buckling as a result of plastic strain concentrations affecting the hysteresis performance (Corte 2011) and hence similar compression and tension capacities. It is common to use a material such as Teflon or lubricant as the unbonding material, which is sufficiently soft for transverse expansion of the core to occur (Corte 2011). Layers commonly vary from 0.15mm to 2mm and it has been found that the compression strength can be up to 35% greater than that of tensile by using different unbonding materials (Corte 2011). For steel-steel BRBs, where the restraining element is composed solely of steel, a void is commonly used varying between 0.7mm and 3.5mm, however these braces are highly susceptible to local core buckling as a result of the void (Corte 2011).

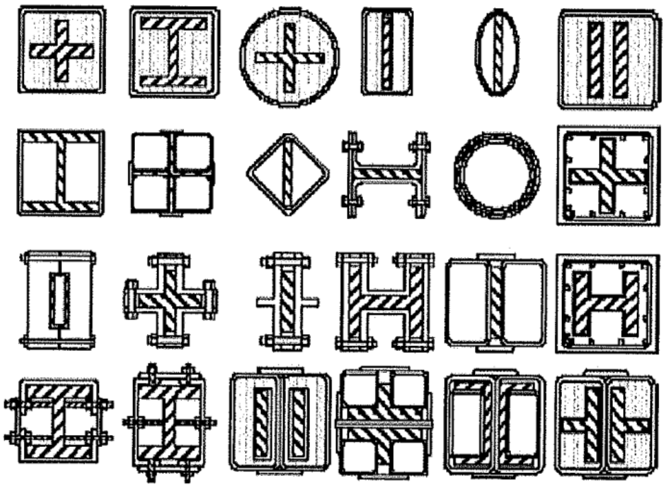

Figure 3. Common steel-concrete and steel-steel BRB cross-sections (Corte 2011)

The outer casing is typically a steel hollow section. The steel casing must poses adequate stiffness to maintain the steel core in axial configuration (Corte 2011). With a reduction in casing thickness, it has been found there is an increase in strain, affecting the brace performance and capacity (Corte 2011). For steel-steel BRBs, the casing is the restraining element and can be composed of multiple steel sections depending on the core cross-section.

2.3 Academic research and research needs

The effect BRBs have on a structural system has been increasingly researched throughout the last ten years. However, due to BRBs being governed by story drift rather than capacity, testing has been limited to drift ratios, in place of full system capacity tests. Research has predominantly been analytical, with full scale tests carried out in Japan and the first in America at the University of California, Berkeley in 2002 (Fajfar 2004; Mahin 2004). The 2008-08 PEER report (Fajfar 2004) outlined previous research and the need for an understanding of fatigue life in BRBs which has been neglected in previous research.

The response of the system (frame, connections etc.) when BRBs are used has not widely been investigated (Fajfar 2004). It has been found that BRB system performance may be lower than the isolated BRB member as a result of in-plane and out-of-plane rotational demands imposed on the system by the connections (particularly gusset plates) (Corte 2011). Pinned connections have been suggested as a method of improving the seismic performance of BRB systems. However, greater flexural stiffness and/or adequate restraints to the transition segments and core projections are recommended (Corte 2011). Connections have been the main focus of recent research, especially when considering gusset plate design (Tsai 2004). Connection design with respect to load transfer has not been adequately addressed to understand the BRB-system behaviour (Fajfar 2004). Additional issues such as the reduction in column and beam sizes as a result of the BRBs high capacity have not been addressed in research to date (Fajfar 2004).

Within New Zealand, the first BRB research was conducted at the University of Auckland by the present author (Jones 2011), considering BRB design for low rise buildings in developing countries and the use of non-conventional materials (bamboo and expandable polyurethane foam). Following this (Wijanto 2012) explored design of BRBs based on concentric brace design, providing two in plane proof tests up to 250kN within the BRB with bolts not fully tensioned. These tests did not evaluate the suitability and sensitivity of the concentrically braced based BRB design outside of the two proof tests.

Although BRB research and development has come a long way since their initial implementation in the 1990’s, little information is still available on the restraining mechanism and how BRBs affect the overall structural system.

3 CURRENT DESIGN PRACTICE

The presence of BRBs in design guidelines is relatively new. The first recommendations were published in 2001 by The Structural Engineers Association of Northern California (SEAONC) who produced testing provisions, in which the BRB had to achieve at least two successful cyclic tests in two sub assemblage forms (SEAONC 2001). These provisions also introduced guidance on designing the steel axial core and also expressions for the strain hardening adjustment factor (ω), which accounts for material overstrength and strain hardening of the core, and the compression strength adjustment factor (β), which accounts for the difference in tension and compression capacities (SEAONC 2001).

These recommendations were adopted by the National Earthquake Hazard Reduction Program (NEHRP) in 2003 (FEMA 450) (NEHRP 2003) and have served as the only BRB design guidance for engineers. In 2010 these provisions were adopted in Section F4 and K3 of ANSI/AISC 341-10 “Seismic Provisions for Structural Steel Buildings” (AISC 2010) and are now code regulated within the United States of America.

Within the Eurocodes, no BRB design regulations are found. Commercial suppliers are complying with Eurocode 8, Part 1, “Design of structures for earthquake resistance” (BSI 2004) Section 4.3.3.4.2.1, seismic no-collapse through non-linear static (pushover) or non-linear dynamic (time-history, response history) analysis (S.S.E 2010) for design. European Standard EN 15129, “Anti-seismic devices” (ESC 2010) includes the use of BRB among its displacement dependent devices; however no guidance or referral to design guidelines is cited.

As a result, the only method of quantifying the design of BRBs is through experimental testing, with guidance on BRB member design only available for the yielding segment of the BRB core. Within New Zealand, in-house BRBs are being designed and implemented into new and retrofit structures without undergoing verification testing, resulting in unknown level of safety and uncertain behaviour under seismic loading.

4 AREAS FOR DEVELOPMENT

With the rise in in-house BRB design without experimental testing verification, key areas within the BRB member and member-frame interaction have been identified as requiring additional investigation, which is planned in forthcoming research at the University of Canterbury.

4.1 Restraining mechanism

4.1.1 *Unbonding layer*

The unbonding layer is one of the key defining elements in the BRB. Without it, high levels of stresses are transferred from the yielding core and also significant composite action between the yielding core and restraining mechanism is possible. If composite action forms, the yielding core and restraining mechanism act as a single unit. As the yielding core is no longer laterally restrained along its full length, a reduction in compression capacity occurs and pre-mature buckling results. It has been found that even with unbonding layers; binding of the concrete restraining medium to the yielding core is possible in fabrication, resulting in localised areas of composite action and a reduction in yielding length. Great care must be taken such that the unbonding layer does not move or be drastically altered in cross-sectional area in the fabrication process. Significant research (Tsai 2004) has been undertaken as to which unbonding materials are suitable for use in BRBs.

4.1.2 *Restraining medium*

For steel-concrete BRBs a concrete restraining medium is present between the yielding core and the outer casing. Little information is available on the composition and volume of this medium, typically due to intellectual property and a lack of available research. It has been indicated by commercial suppliers that the aggregate-cement mixture is very important in the restraining of the yielding core, to what degree is unknown. It is proposed that the concrete restraining medium be investigated numerically and experimentally with respect to varying stiffness, addressing its contribution to the restraining mechanism of the outer casing and restraining medium.

The stiffness of concrete is a function of the modulus of elasticity, which is non-linear. Based on Section 5.2.3, NZS 3101 (SNZ 2006);

$$E'_c = 3320\sqrt{f'_c} + 6900 \qquad (1)$$

where E_c' = concrete modulus of elasticity (MPa); and f_c' = specific concrete strength (MPa).

It is expected that with the increase in concrete stiffness, there is an increase in compression capacity and the ability to restrain the steel core through bearing. There will be a cross-over point where the concrete stiffness is too little to support the yielding core from buckling, and where the concrete stiffness is sufficient in buckling support. This cross-over will be dependent on the volume, composition and stiffness of the concrete and also the cross-sectional area and capacity of both the steel core and outer casing.

With an increase in concrete stiffness, the chance of fracture from radial pressures exerted from the steel core increases. This results from the build up of surface pressure between the yielding core and the concrete restraining it. It is possible these pressures could result in a localised surface fracture between the yielding core and the concrete medium, reducing the restraining mediums' strength.

4.1.3 *Outer casing*

It was proposed in (Watanabe 1988), that the Euler critical buckling load of the outer casing should be greater than 1.5 times the core yield load. This rule has been adopted in general design however an understanding of how the outer casing contributes to the restraining mechanism in steel-concrete BRBs and to what degree has not been investigated. The outer casing for steel-steel BRBs is the primary restraining mechanism, currently there is no available design information for this type of BRB. It is proposed that the contribution of the outer casing with respect to the restraining mechanism be investigated when considering steel-concrete BRBs and a development of guidelines for design of the outer casing when considering steel-steel BRBs.

For steel-concrete and steel-steel BRBs it is expected that a stiff outer casing will provide sufficient restraint to prevent global buckling; however whether this contributes to an increase in brace capacity is unknown. For steel-concrete BRBs with a less stiff outer casing, it is possible that the brace will prematurely buckle if the outer casing cannot support the concrete restraining medium, this relationship would be dependent on the concrete compression and bending strength and the bending strength of the outer casing. There may also be an increase in localised bearing stress on the outer casing. This could result in pre-mature buckling, failure or a reduction in brace capacity as the outer casing is both contributing to restraining of the yielding core but also confinement stresses of the concrete restraining medium.

4.2 **Transition region**

The transition region has been seldom considered in BRB research to date. (Mirtaheri 2011) carried out experimental testing on four BRB specimens, optimising their transition lengths with respect to FEMA-450 and the Coffin-Manson relationship for fatigue. It was recommended that further research is required to determine empirical formulas for the transition length relationship within BRBs as results from the experimental testing were dependent on the specimens' compositional materials and the amount of hardening which occurred, influencing hysteresis behaviour.

It is proposed in the forthcoming research to investigate the influence the transition length has within design and overall brace performance. BRBs are composed of three lengths, the yielding length, transition length and the non-yielding unrestrained (connection) length. Through adjusting one of these lengths, it influences not only the behaviour of the adjacent lengths but also the overall brace stiffness. The sensitivity of this adjustment such to optimise the length of the BRB to sustain high levels of energy dissipation and fatigue will be of interest in this investigation.

As the yielding length decreases, so does the susceptibility to local and global buckling and with it an increase in energy dissipation. However, the shorter this length, the greater plastic deformation and hysteresis energy will be exhibited on the yielding length. With an accumulation of plastic deformation, the susceptibility to low cycle fatigue increases and so does the brace susceptibility to local buckling in higher modes and a reduction in brace capacity.

The non-yielding lengths of the transition length and connection length are typically stiffened or have an increase in cross-sectional area to prevent plastic deformation and/or high strains from being transferred from the yielding core to the frame member, and vice versa. The balance between the three lengths, their cross-sectional areas, compositional materials and interaction with the restraining mechanism will be considered through both numerical modelling and experimental testing.

4.3 **Connections**

Common connection types of bolted, welded and pinned have not been extensively researched when considering their use with BRBs; instead research has been focused on the gusset plate interaction in the BRB frame. The proposed research will consider bolted and pinned connection design with respect to current New Zealand practice in conjunction with a BRB in a steel frame. The interaction between the BRB-connection and frame-connection will be of key interest. Pinned connections are preferred in design due to their ability to provide load transfer within the system without introducing any additional connection strains. However pinned connections are known for tight installation tolerances and in some cases imperfect load transfer, resulting in additional strains unaccounted for in design.

Bolted connections are favoured due to their simplicity in installation and greater tolerance ranges. Additional rotational loads are imposed on the system and allowances for this must be made in the surrounding frame elements, increasing member sizes and overall cost. The forthcoming research will investigate experimentally the effect both pinned and bolted connections have, design considerations and how they interact with adjacent elements. The effect the connection has on the BRB capacity will be of key interest, with monitoring of load transfer and the development of any additional strains within the unrestrained non-yielding region and the restrained non-yielding region. The interaction between the connection and the frame will also be considered and whether the current design practice is suitable for BRB frame design.

4.4 **Eccentric loading**

BRBs are restricted to use in concentrically braced frames, however eccentric loading can occur due to poor installation or permanent deformation post event. The proposed research will consider the effects of eccentric loading of a BRB member. This will be carried out through axial loading of the member, adjusting the load eccentrically from the central core to the restraining mechanism. The sensitivity of this loading and behaviour when the load is transferred through the restraining medium will be investigated. It is expected that there will be a cross over point of stability, this stability-instability relationship to the core cross-sectional area and brace design will be evaluated.

5 **CONCLUSIONS**

BRBs have become a common form of bracing in seismic areas, however their lack of design provisions without the need for experimental verification have lead to untested and unverified BRBs being installed in New Zealand structures. The proposed research at the University of Canterbury aims to equip engineers with an understanding of the sensitivity of BRB design elements for both common forms (steel-concrete and steel-steel). This research considers a range of BRB compositional elements including the restraining mechanism and its contribution in preventing local and global buckling, the transition region and how this affects load transfer throughout the yielding regions and connections, frame and connections designed to the current New Zealand standard, how these behave and if there is any reduction in brace capacity as a result of connection type, and the effect eccentric loading has on a BRB member. This research will provide the ability to design BRBs without the need for experimental verification and confidence in the BRB level of safety.

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