Advances in design requirements for Buckling Restrained Braced frames

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ABSTRACT: Although buckling restrained braces (BRB) have now been a codified system in the US for over five years and have been used in design for much longer, the system is still relatively new in New Zealand. BRB's are now entering their second US code cycle with the AISC Seismic Provisions for Structural Steel Buildings, AISC 341-10, which has introduced significant changes. In addition, several key issues of current research will be discussed that are contributing to the next set of code requirements for 2016. These new changes will be highlighted along with methods to effectively design Buckling Restrained Braced Frames (BRBF) using New Zealand codes. The latest innovative uses for BRBs will also be discussed, including applications to alleviate building pounding concerns when seismic joints are of limited size, many different configurations possible for retrofit construction, ideas for high rise applications, and other unique applications.

1 INTRODUCTION

1.1 Buckling Restrained Brace History

The Buckling Restrained Braced Frame (BRBF) represents the state-of-the-art in braced frame design. A technology introduced in the US in the late 1990's, it has been codified in just over 5 years and has been incorporated into over 500 buildings to date, from 200 ft2 sheds to high rise structures. The system's critical element, the Buckling Restrained Brace (BRB), is a brace that does not buckle and harnesses the inherent ductility of steel to provide stable, predictable dissipation of seismic energy. Although the brace can be used wherever buckling of the brace is undesirable or where higher ductility and energy dissipation is desired (such as bridge, outrigger, or blast designs), they are typically incorporated as part of the BRBF concentrically braced frame system.

The rapid expansion of the use of the BRB in all types of projects has occurred due to the clear cost savings of the overall system and the simplicity of design and erection. Many cost studies have been performed comparing BRBF frames to Eccentrically Braced Frames (EBF) and ductile Concentrically Braced Frames (CBF). The majority of the savings found was due to the smaller, simpler gusset plates, but there were also significant savings on beams, columns, and foundations.

1.2 Anatomy of a BRB

The main characteristic of a BRB is its ability to yield both in compression and tension without buckling. A BRB is able to yield in compression because it is detailed and fabricated such that its two main components perform distinct tasks while remaining de-coupled. The load-resisting component of a BRB, the steel core, is restrained against overall buckling by the stability component or restraining mechanism, the outer casing filled with concrete. See Figure 1. Bonding of the steel core to the concrete is not allowed to ensure that the BRB components remain separate and composite action not allowed to take place. The BRB brace is placed in a concentric braced frame and becomes a buckling-restrained braced frame (BRBF) system. The braces are typically used for structures where seismic activity may be encountered, regardless of whether wind or seismic loads govern the design of the structure.

Studies have shown that BRBFs exhibit robust cyclic performance and possess large ductility capacities. Due to BRBF's outstanding performance, it is given the highest seismic ductility factor; a μ of at least 6. Testing performed on BRBs to date has suggested that BRBs may be capable of withstanding multiple seismic events without failure or loss of strength. Though the construction of the BRB appears to be simple, poor design of a BRB can result in casing buckling, connection failure, and poor BRB performance, so it is important to incorporate only fully tested products manufactured at facilities with personnel who are trained in BRB manufacturing and incorporate rigorous quality procedures.
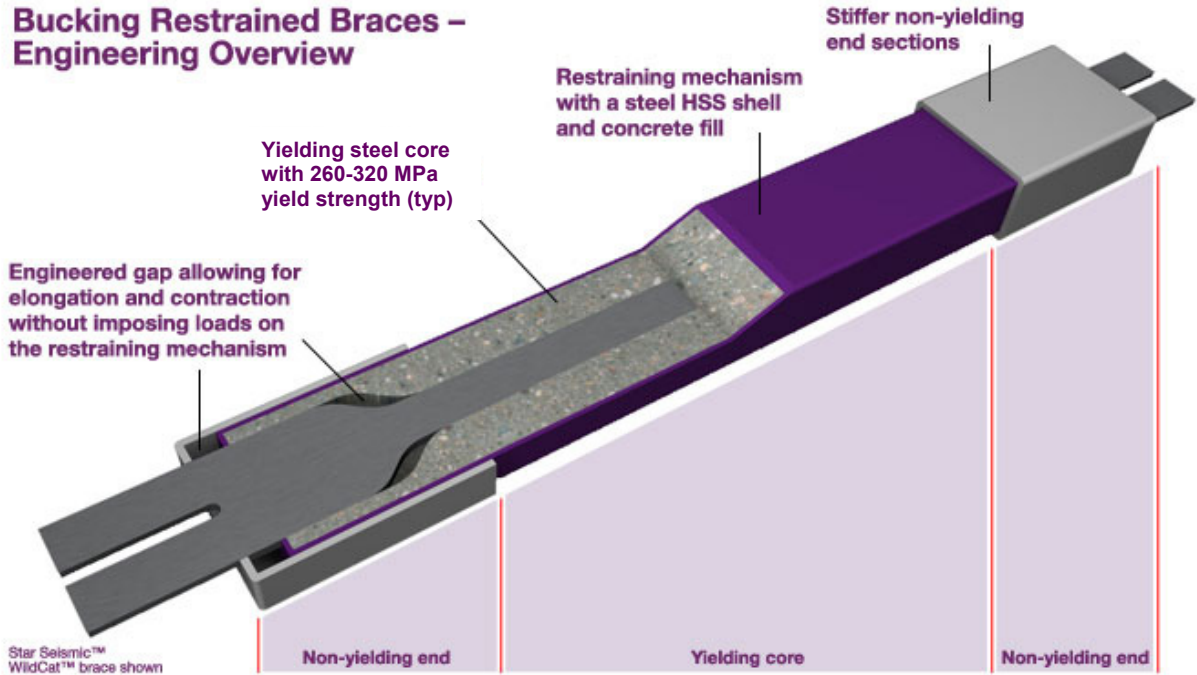

Figure 1. Anatomy of a BRB

2 TYPICAL BRB DESIGN PROCESS

The design approach of applications using BRB's typically incorporates the coordination of a BRB manufacturer. This is because some of the factors needed for design with BRB's are dependent on the design of the brace itself and may differ from manufacturer to manufacturer and even from brace connection type provided by an individual manufacturer. It is essential for the design engineer to incorporate design attributes of a BRB brace into their design for a brace that is possible to manufacture. Otherwise, an uncomfortable discussion awaits the design team during the bidding process or after the project has been awarded, when redesign to achievable brace design parameters may be necessary.

Figure 2 shows the typical design process for a BRBF project, demonstrating the flow of information back and forth between the design engineer and the BRB manufacturer. Most brace manufacturers do not charge for this service, nor do they need to be under contract or obligation to provide it. Though the input from the brace manufacturer may include a variety of important contributions to the design, there are three critical design items that are contributed by the BRB manufacturer: brace stiffnesses, brace overstrength factors, and verification of testing coverage for the proposed project braces.

2.1 Building Design Factors

In the United States, the Buckling Restrained Braced Frame system (BRBF) is given the highest Response Modification Coefficient (R factor) possible. The use of R=8 is reserved for only the most ductile systems, and this factor is shared with only a few other systems, such as the Special Moment

Frame and the Eccentrically Braced Frame. This R factor is used without hesitation or restriction unless the system is combined with another system that requires a lower R factor by code. Ductility demands in excess of 15 are regularly encountered during testing, with some tests exceeding 25, so the braces can have exceedingly ductile performance. R is roughly equivalent to μ/S_p, giving a rough $\mu=5.6$ when other variations between code approaches are ignored. However, the US design climate and codes do not have the emphasis on immediate occupancy/low damage solutions that currently exists in New Zealand. Therefore, the designer should select a μ value to provide both the high performance in the Ultimate earthquake as well as the lower damage in the Service earthquake. To date, this has been a μ not exceeding 6.0 and often taken as 4.0.

2.2 Brace Stiffness and Modelling

For an Ordinary or Special Concentric Braced Frame, brace stiffness is tied to the brace area and is determined using the simple equation below.

$$K_{\text{model}} = \frac{AE}{L_{wp-wp}} \qquad\qquad (1)$$

Where L_{wp-wp} is the workpoint-to-workpoint distance along the axis of the brace, A is the area of the brace, and E is the Modulus of Elasticity. This analysis is automatically done as part of most structural design software packages. However, a buckling restrained brace is non-prismatic and consists of the yielding core segment, with the minimum cross-sectional area of the brace, and the outer portions of the brace that are designed to stay elastic and therefore include a greater cross-sectional area. Brace strength is controlled by brace core area, but the use of this core area in the structural model without any adjustment will not correctly capture the stiffness of the brace. This stiffness is usually captured in the model through the use of a stiffness modification factor (KF). The modelled brace stiffness would then be represented by the equation below.

$$K_{\text{model}} = \frac{KF(A_{sc})E}{L_{wp-wp}} \qquad\qquad (2)$$

Where A_{sc} is the steel core area of the buckling restrained brace.

The modelled brace stiffness can also be represented as a spring with a defined stiffness K_{model}.

The stiffness factor or modelled brace stiffness is unique to each brace manufacturers' design, although it may be similar between manufacturers. It is also dependent on brace capacity, bay geometry and connection details. The design engineer will need to assume an initial value for this factor for early estimation of required brace capacity and preliminary beam, and column sizes and send this information to a brace manufacturer for early coordination to obtain the recommended stiffness factors for the braces. If brace capacities are adjusted, final values should also be confirmed with the manufacturer prior to finalizing contract documents.
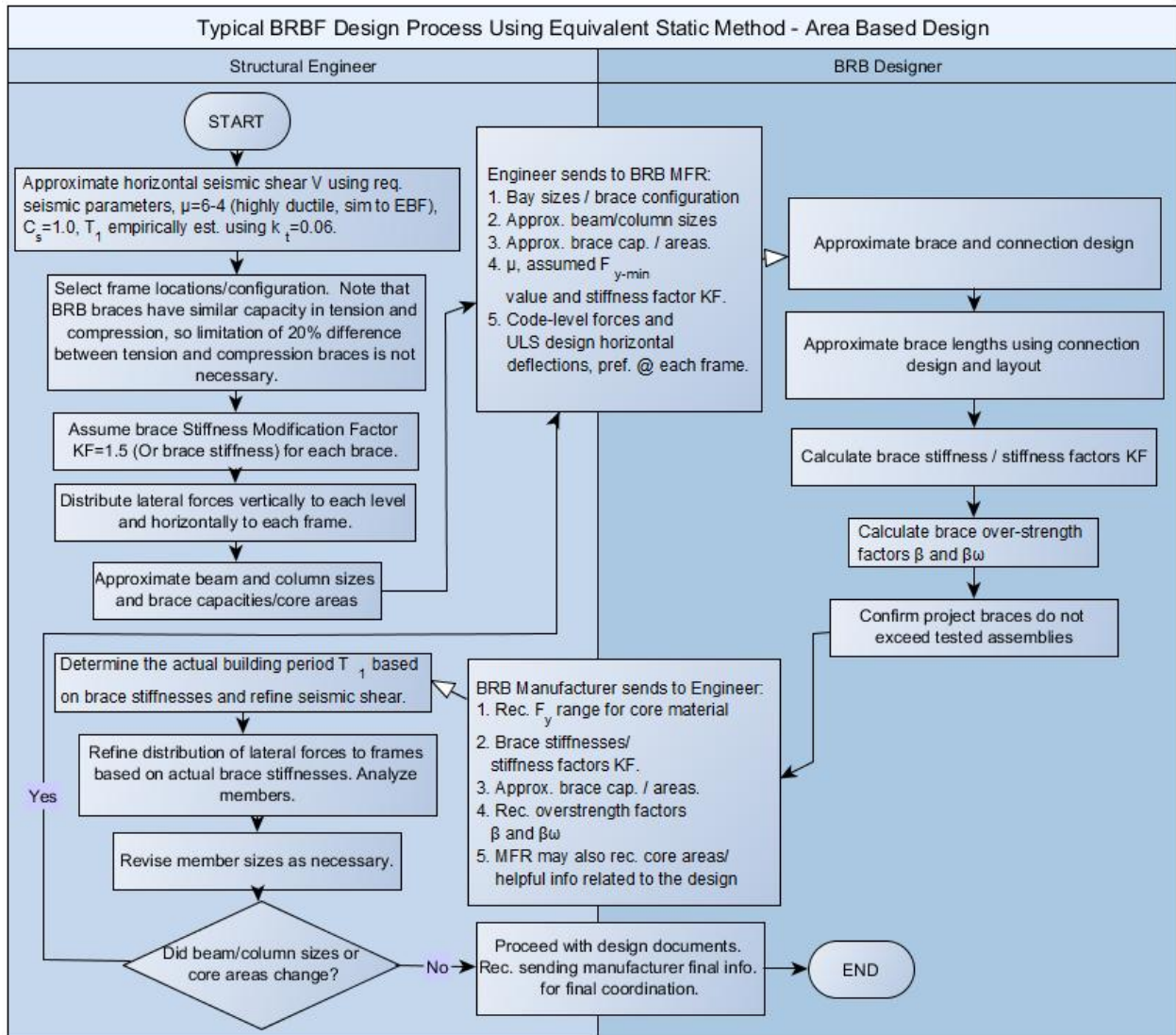
Figure 2. Typical BRB design process

2.3 Brace Overstrength Factors

For the BRBF system, the brace is designated as the "fuse" element and all other parts of the frame and connections are designed to remain elastic. As the BRB brace engages in a seismic event, the steel core is designed to yield and then to strain harden. This process will require the beams, columns, and connections to be designed for these higher, strain-hardened brace forces. The increase in the brace force in tension is represented by the factor ω, while the increase in compression is represented by the factor βω. Using the AISC341 (US) test interpretation methods, factors can be determined from the results by use of a "backbone curve" drawn through the resulting peak values of the test data. Again, these factors vary by brace manufacturers and even by brace connection type. The engineer need not calculate these, as they can be provided by the manufacturer. These values are determined from the expected elongations in the braces. These may be determined by the BRB designer from the engineer's drift analysis or simply through use of the design factors used by the design engineer. Following the drift analysis, the engineer may provide the BRB manufacturer with work-point to work-point elongations at each frame based on the final governing drift profiles of the frame. If these profiles include possible inelastic mechanisms, indicate this to the BRB manufacturer. Elongations determined directly from the amplified elastic deflections may require an additional factor of 2 to be

applied to the brace strains, while elongations determined from possible mechanisms or those determined from inelastic analysis should not require this factor. Note that the use of inelastic drift alone to determine brace elongations may be overly conservative, since there are many contributors to drift from all the members of the frame (column elongation/shortening, beam distortion, etc) and the commonly used formulas to calculate brace elongation from drift assumes all the members in the frame besides the braces are infinitely rigid.

3 INNOVATIVE USES FOR BRBS

BRBs have been used on many types of structures as part of a standard BRBF Frame. They are enjoying widespread usage in building structures such as office buildings, hospitals, retail, car parks, multi-story residential, schools, religious, stadiums and arenas, as well as non-building and industrial structures. However, many projects use the Buckling Restrained Brace in unique ways that differ from the standard BRBF concentrically braced frame. The braces have been used in or proposed for a variety of applications, including bridges, civil structures, horizontal diaphragm elements, highrise outrigger frames, externally anchored braces, wind towers and many other unique applications. The following projects show a sampling of some of the most innovative applications.

Figure 3. Hazeldean Car Park, Christchurch, NZ

3.1 Alleviate Building Pounding/Shear

Often in retrofit construction, two buildings are located in close proximity and the pair of buildings may be expected to pound into one another and/or displace in such a manner that may potentially damage the piping or other equipment running between the two structures. The Veteran's Administration Nursing Tower retrofit was such a project. Pairs of BRBs were employed to address these concerns and provide a shock absorber between the two structures to limit the damage that may be encountered. Refer to Figure 4. The two beams shown each belong to a separate structures, separated by an expansion joint but free to move independently from one another. Brace B-34 was added spanning between the two buildings to address pounding between the two buildings. Brace B-35 was also connected to each building, but was added to address shearing displacements between the two buildings. The analysis for the structural incorporated non-linear time history analysis and verified that the incorporation of the BRBs alleviated the concerns of the design team regarding damaging interaction between the two structures.
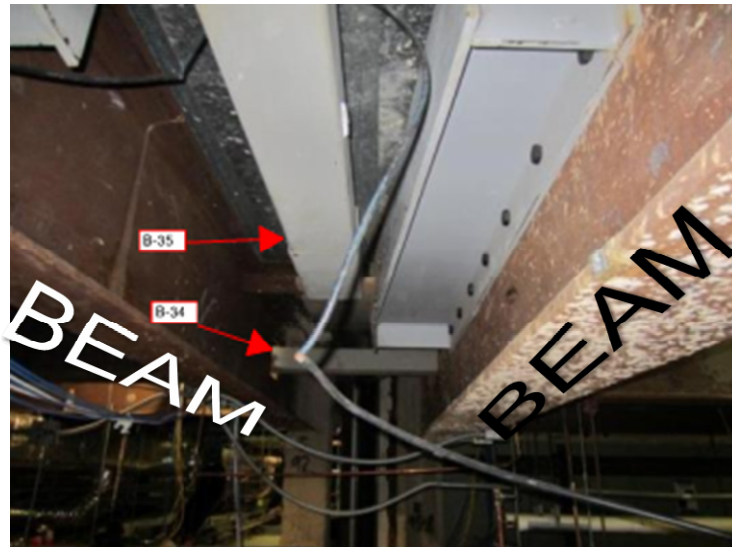
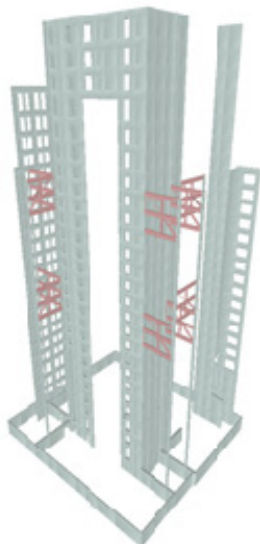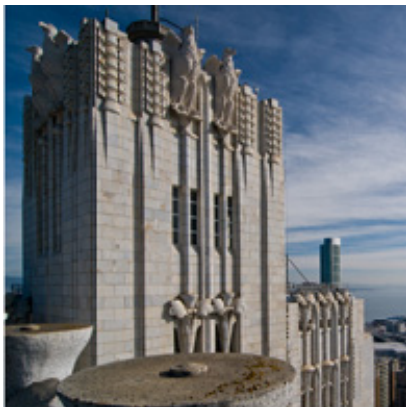**Figure 4. VA Medieal Service Center, Seattle, WA**

3.2 High Rise Retrofit

In 1925, when it was completed, the Pacific Telephone and Telegraph Company structure at 140 New Montgomery was San Francisco, California's tallest structure at 413 feet (125.9 m). The moment connections used in the original design were not adequate to achieve the performance objectives for the project. They did not have adequate stiffness to limit the drifts to an acceptable level given the brittle terra cotta façade. They also lacked the ductility needed for the performance desired. A new lateral system was needed to stiffen up the structure and protect the existing elements from excessive deformation and damage. The design team added a combination of BRBs and new shear walls. BRBs (shown below in red in Figure 5) were incorporated into "outrigger" truss systems. The BRBs provide both the strength and the stiffness needed to tie the new wall segments together, greatly enhancing the overall stiffness of the system. Unlike ordinary bracing, a BRB does not buckle and will limit the load that could be transferred to the rest of the structure, greatly reducing the forces that the rest of the structure would need to be designed for.

3.3 Civil Structure

Casad Dam is a concrete gravity arch dam built in the 1950's that includes an integral intake tower located on the upstream face at the center of the dam. The intake tower was not adequate to support the anticipated seismic demands, where the peak ground acceleration was increased due to the proximity of the Seattle fault and new research into the magnitude of potential events. A retrofit scheme was needed for the intake tower that would have minimal impact on the normal operation of the dam, would have minimal underwater work, and could be done with minimal expense.

Figure 5: High Rise Retrofit, 140 New Montgomery

Figure 6. Casad Dam, Bremerton, WA, US

The design team at Hatch Associates Consultants, Inc. in Seattle, WA investigated several options and found that bracing the tower back to the dam best met their key objectives for the retrofit, rather than strengthening the tower at its base. However, the arch dam required protection by limiting the brace forces. Viscous dampers and buckling restrained braces were considered and, after detailed simulations, stainless steel buckling restrained braces with a yielding steel core were selected (see Figure 6).

The project successfully met diverse functional objectives that included preventing tower collapse under a maximum credible earthquake with a 0.78g peak ground acceleration, meeting low maintenance requirements while providing high reliability, and ensuring that there were no environmental or water quality impacts.

The projects listed above provide only a small sampling of unique uses for buckling restrained braces. As the brace usage expands, functions requiring symmetrical capacity between tension and compression, calibrated stiffness of elements, limiting of force transfer through an element, the incorporation of ductility and energy absorption and other features of the brace will continue to be found. The applications found truly demonstrate the abundant creativity of the engineering designers using the technology.

Figure 7. Data Centre Retrofit Utilizing Existing Gusset Plates

REFERENCES

American Institute of Steel Construction. 2010. *Specification for Structural Steel Buildings*, (ANSI/AISC 360-10), American Institute of Steel Construction, Chicago, IL.

American Institute of Steel Construction. 2010. *Seismic Provisions for Structural Steel Buildings*, (ANSI/AISC 341-10), American Institute of Steel Construction, Chicago, IL.

American Society of Civil Engineers 2010. ASCE/SEI 7–10: Minimum design loads for buildings and other structures. Virginia: American Society of Civil Engineers

Robinson, K.R., Kersting, R.A., Saxey, B. November, 2012. No Buckling Under Pressure: A Unified Design Approach to Buckling-Restrained Braced Frame Design. *Modern Steel Construction*.

NZS 1170.5 2004. Earthquake actions –Wellington: New Zealand. Standards New Zealand.

NZS 3101 2006. Concrete structures standard. Wellington: Standards New Zealand.

Robinson, K.R., August, 2012. Brace Yourself! Novel Uses for the Buckling Restrained Brace. *Structure Magazine*, 8-10.