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NEHRP Seismic Design Technical Brief No. 11

Seismic Design of Steel Buckling-Restrained Braced Frames

A Guide for Practicing Engineers

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National Institute of
Standards and Technology
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NEHRP Seismic Design Technical Briefs

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Seismic Design of Steel Buckling-Restrained Braced Frames

A Guide for Practicing Engineers

Prepared for
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By
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Standards and Technology and Director

Contents

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NIST policy is to use the International System of Units (metric units) in all its publications. In this report, however, information is presented in U.S. Customary Units (e.g., inch and pound) because this is the preferred system of units in the U.S. earthquake engineering industry.

Cover photo. Buckling-restrained braced frame under construction.

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1. Introduction

Buckling-Restrained Braced Frames (BRBFs) are one of the newer types of seismic force-resisting systems used in modern building designs. As the two example configurations shown in **Figure 1-1** illustrate, BRBFs resist lateral loads as vertical trusses in which the axes of the members are aligned concentrically at the joints. Although the global geometric configuration of a BRBF is very similar to a conventional Concentrically Braced Frame (CBF), the members, connections, and behavior of BRBFs are distinctly different from those of Ordinary Concentrically Braced Frames (OCBFs) and Special Concentrically Braced Frames (SCBFs). The key difference is the use and behavior of the Buckling-Restrained Brace (BRB) itself.

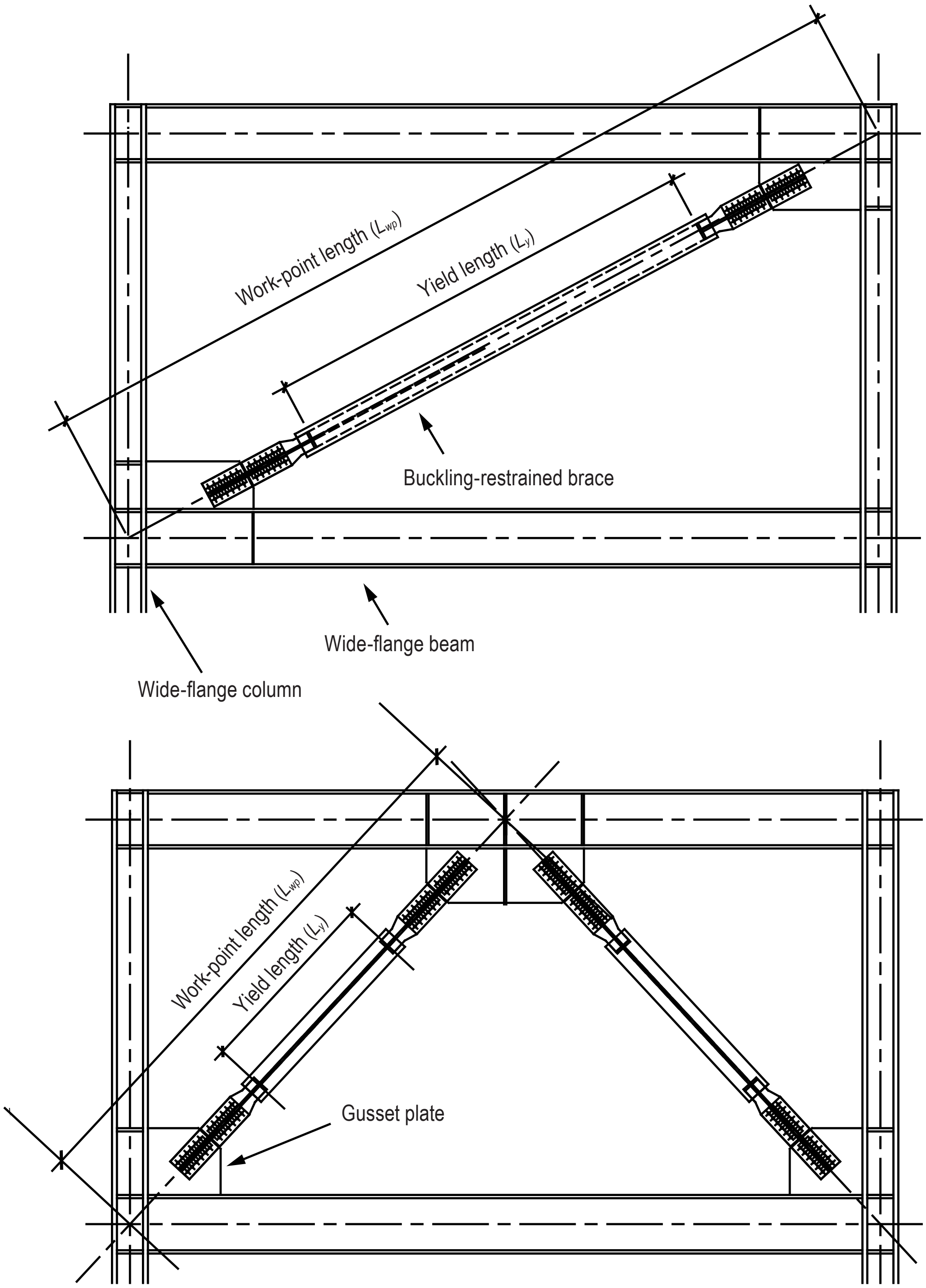


Figure 1-1. Typical BRBF configurations.

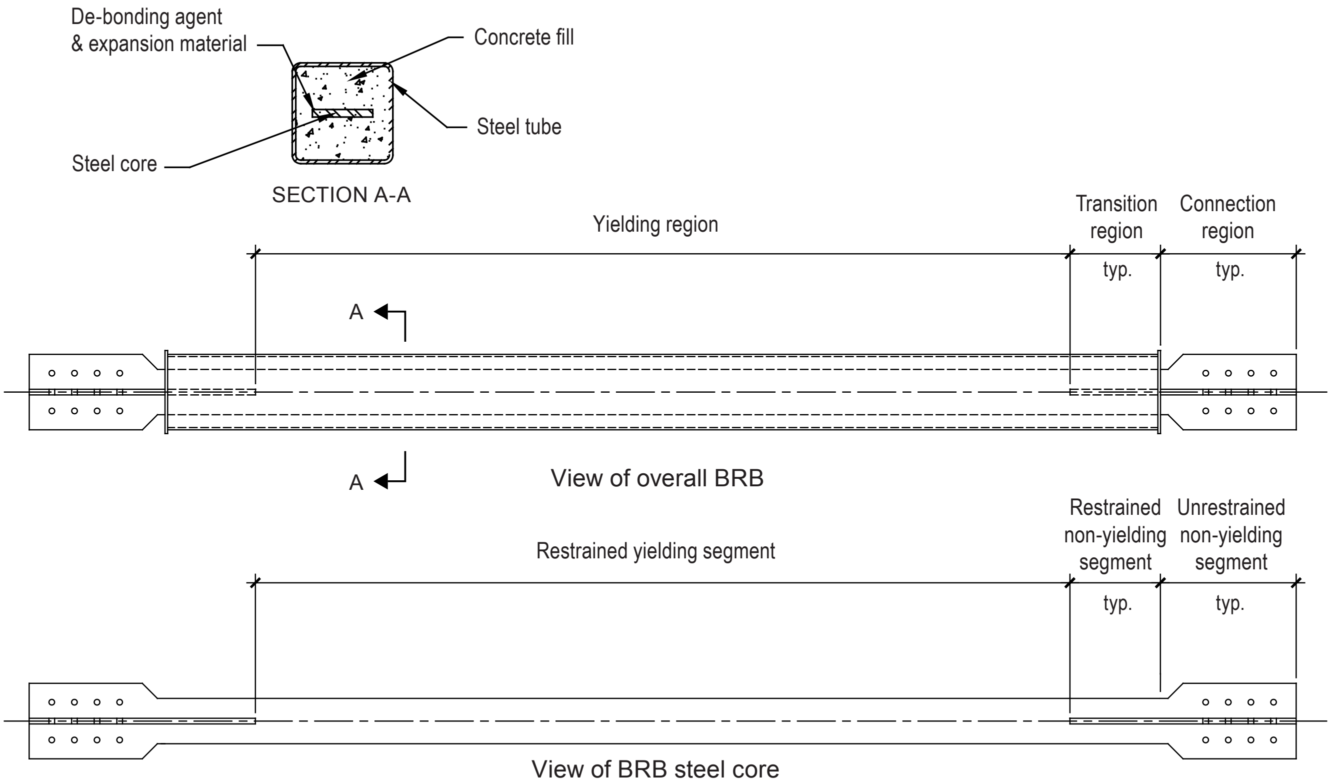


Figure 1-2. Common BRB assembly.

Unlike the standard sections used for braces in OCBFs and SCBFs, the BRB is a fabricated assembly. As shown in **Figure 1-2**, the most common BRBs consist of a steel core-plate (the yielding element, hereafter called the "core") that is surrounded by a steel tube casing filled with grout or concrete. **Figure 1-2** shows a core consisting of a steel plate. Other core cross-sections, such as cruciform or multiple plates can also be used. The core is axially decoupled from the fill and casing by various means that produce a physical isolation or gap. As the name states, the BRB assembly restrains core buckling under compressive loading and achieves a compressive yield strength that is approximately equal to its tensile yield strength. Therefore, the core area can be sized for design-level seismic loads based on the yield stress of the core, F_{ysc}, as opposed to braces in conventional CBFs, which are sized based on the critical buckling stress, F_{cr}, of the section. Buckling braces in OCBFs and SCBFs have significant excess tensile capacity, and the brace buckling behavior leads to degrading cyclic response. In contrast, as shown in **Figure 1-3**, a BRB yields axially in tension and in compression, exhibiting nominally symmetric cyclic response with strain hardening. In BRBFs, the primary source of ductility is the axial yielding of the BRB cores. Unlike BRBFs, CBFs are subject to buckling of the braces and therefore are less ductile. This attribute is reflected in the larger response modification coefficient, R, assigned to BRBFs (R = 8) by ASCE/SEI 7, referred to in this Guide as ASCE 7 (ASCE 2010), as compared to OCBFs (R = 3 1/4) and SCBFs (R = 6). Because the BRBF system is more efficient (having a smaller brace area as a result of the elimination of brace buckling), BRBFs are more flexible than conventional CBFs and may in some cases be governed by drift limits rather than strength requirements. Like nearly every other ductile seismic force-resisting system, the remainder of the frame (beams, columns, and connections) is protected from unintended yielding through special analysis and proportioning provisions, commonly called capacity-based design.

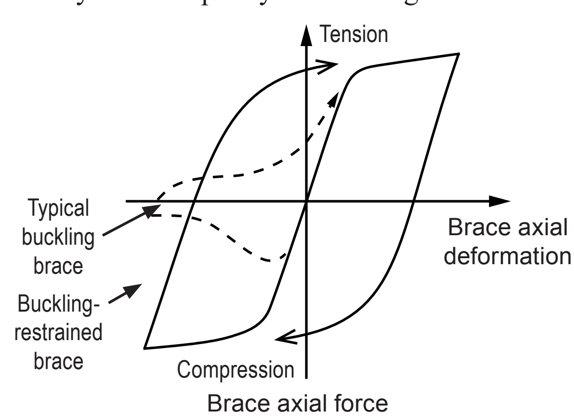


Figure 1-3. Buckling versus buckling-restrained brace behavior.

This Guide addresses the seismic design of steel BRBFs in typical building applications within regions of moderate to high seismic hazard, corresponding to Seismic Design Categories (SDC) C through F as defined in ASCE 7. Because current standards address and allow only the use of BRBFs in all-steel frames, composite applications are not addressed in this Guide, but many of the same topics and considerations are applicable. Results from experimental testing and numerical simulations will be used to illustrate the rationale underlying design and detailing provisions.

This Guide is not a complete treatment of the BRBF system or the BRB itself. A number of issues and topics related to BRBFs are not addressed in this document, including the following:

- Specific comparisons of BRBFs to other classes of braced frames, such as Eccentrically Braced Frames (EBFs), OCBFs, and SCBFs. Information on SCBFs is provided in the NEHRP Technical Brief on *Seismic Design of Steel Special Concentrically Braced Frame Systems* (NIST 2013).

- BRBFs used with steel Special Moment-Resisting Frames (SMRFs) as a dual system. Information about steel special moment-resisting frames is provided in the NEHRP Technical Brief on *Seismic Design of Steel Special Moment Frames* (NIST 2009).

- BRBFs used with other systems, for example, as part of outrigger frames in tall buildings.

- BRBs used in non-BRBF conditions or configurations, such as
  - Struts or fuses within a load path, such as along a collector line
  - Buttresses or external bracing
  - Self-centering frame systems
  - Damped assemblies
  - Non-building structures
  - Non-steel frames (“composite” applications)

This Guide refers to the following building codes and standards:

- AISC 341, *Seismic Provisions for Structural Steel Buildings and Commentary*, 2010 edition (AISC 2010a)

- AISC 360, *Specification for Structural Steel Buildings and Commentary*, 2010 edition (AISC 2010b)

- ASCE 7, *Minimum Design Loads for Buildings and Other Structures*, 2010 edition (ASCE 2010)

- IBC, *International Building Code*, 2015 edition (IBC 2015)

Design engineers are responsible for verifying the current building code provisions adopted by the authority having jurisdiction of their project. The Technical Briefs in this NEHRP Series typically are based on the latest available codes and standards, which may not yet have been adopted locally. Discussion with and approval by the building official should occur to verify that a later version of a code or standard not yet adopted locally may be used.

In addition to the code and standards listed above, designers should be aware of other valuable resources for employing BRBFs:

- AISC *Seismic Design Manual* (AISC 2012)

- SEAOC *Structural/Seismic Design Manual* (SEAOC 2013)

- *Seismic Design of Buckling-Restrained Braced Frames* (López and Sabelli 2004)

- *Ductile Design of Steel Structures* (Bruneau et al. 2011)

Use of the 2012 versus 2015 Edition of the IBC

Although the 2015 IBC is listed as the basis for references to the building code in this Guide, the BRBF design requirements under the 2012 IBC match those under the 2015 IBC because both editions of the IBC use the same editions of the applicable reference standards (i.e., ASCE 7-10, AISC 360-10, and AISC 341-10). At the time of production of this Guide, the 2016 editions of AISC 341, AISC 360, and ASCE 7 are nearing completion. Because these documents have not been completed and will not be referenced (and therefore mandated) until the 2018 edition of the IBC, these in-progress standards are not referenced in this Guide.

This Guide was written to provide guidance to practicing structural engineers regarding the use of requirements in applicable codes and standards for the design of BRBF systems. The Guide is also useful to others seeking to understand the basis of, and to correctly implement, the appropriate code provisions related to BRBFs, including building officials, educators, researchers, and students.

In this Guide, the term "design engineer" is used to refer to the person(s) responsible for the design of the entire structural system for a given project. The BRB manufacturers often have an engineer on staff to coordinate with and assist the project's design engineer with different aspects of the BRBF design. When necessary to distinguish between these two engineering roles, this document refers to the BRB manufacturer's staff engineer as the "manufacturer's engineer" or sometimes simply as the "BRB manufacturer."

Section 2 of this Guide provides an overview of the history of the BRBF system and additional detail on BRBs. Section 3 discusses the key principles involved in the design of steel BRBFs. Sections 4 and 5 provide guidance regarding the analysis and design of BRBFs, respectively. Section 6 addresses BRBF coordination topics particularly for the design engineer and the manufacturer's engineer, including detailing and constructability issues. Section 7 provides a summary of forward-looking developments related to the BRBF system.

Use of BRBFs in Regions of Lower Seismicity

This Guide discusses BRBFs particularly for use in areas of moderate to high seismicity (SDC C through F). However, BRBFs are not limited in application solely to those regions and have been used in regions of low seismicity (SDC A and B) and even in wind-governed designs. In most cases, the benefits of using BRBFs are associated with being able to use a larger *R* coefficient to reduce seismic design forces. Although the benefit of reduced seismic design forces may not be as significant in regions of lower seismicity, BRBFs may still be selected as they can provide a more economical overall design of braces, connections, and foundations and to provide better, more reliable performance under lateral loading, for example in structures with very long braces and in structures of high importance.

2. Background of the Buckling-Restrained Braced Frame

2.1 Historical Context of BRB Development

During the past 15 years, BRBFs have been used extensively in the United States as part of the seismic force-resisting system for buildings in regions of high seismicity. The fundamental concept of confining a steel core element so that it can yield in compression as well as in tension was investigated experimentally over 40 years ago in Japan (Xie 2005), with a concrete panel serving as the confining mechanism. Subsequently, a concrete-filled steel tube was used as the confining mechanism, and excellent energy dissipation and ductility were demonstrated experimentally (Watanabe et al. 1988, Watanabe 1992). This BRB configuration first gained wide acceptance in Japan as a supplemental energy dissipation device within a "damage control" design philosophy before being adopted in North America as a primary seismic force-resisting element. Watanabe et al. (1988) and Watanabe (1992) conducted the foundational BRB testing program, which demonstrated the ductility and energy dissipation capability of the brace configuration and illustrated the basic requirement for stiffness of the restraining mechanism. In one of the first studies in North America, Tremblay et al. (1999) tested BRBs in support of a seismic retrofit project in Quebec City, Quebec, Canada. In addition, viable all-steel BRBs have been developed more recently (Tremblay et al. 2006, Wu et al. 2012, and Judd et al. 2015).

BRBs were used extensively in Japan before they gained attention in the United States, however, implementation of BRBs in the United States required significant effort because the U.S. and Japanese design contexts for BRBs are appreciably different. In Japan, BRBs are used as supplemental energy dissipation devices, which are used with moment-resisting frames (Huang et al. 2000, Iwata et al. 2003). BRBs function as hysteretic dampers that control the response of the moment-resisting frames, and the combined system possesses significant stiffness, even after the BRBs yield. Broadly speaking, in Japan, a damage-control design approach is employed (Kasai et al. 1998) to protect the primary seismic force-resisting system (i.e., the moment-resisting frames) with the dampers (i.e., the BRBs). In contrast, the design approach in the United States does not require that BRBFs be used as part of a dual system, and the BRBF system typically has relatively modest overstrength and low post-yield stiffness.

One of the first new construction projects in the United States that employed BRBs was the Plant and Environmental Sciences Building on the campus of the University of California, Davis (Clark et al. 1999, 2000). Soon after, one of the first retrofit projects using BRBs was the Marin County Civic Center Hall of Justice (Shaw and Bouma 2000). Since then, BRBs have been used in numerous buildings in the United States and in limited applications in bridges (Jones 2014) and other structures (Robinson 2012).

Although BRBs were used in the United States as early as 1999, BRBFs were first officially adopted in a model building code in 2005 with their inclusion in ASCE 7-05 (ASCE 2005) and AISC 341-05 (AISC 2005). The adoption process was initiated by a joint task group led by the American Institute of Steel Construction (AISC) and the Structural Engineers Association of California (SEAOC), and this task group developed the document *Recommended Provisions for Buckling-Restrained Braced Frames* (AISC/SEAOC 2001). System parameters from this document were then incorporated in the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* (FEMA 2003), which led to inclusion in ASCE 7-05 and AISC 341-05. Currently, design of BRBFs in the United States is performed within the framework defined by ASCE 7-10 (ASCE 2010) and AISC 341-10 (AISC 2010a).

In Canada, BRBF design provisions were developed within a similar timeframe as in the United States, with BRBFs introduced in the CSA S16 steel design standard in 2009 (CSA 2009) and the Type D (ductile) BRBF system defined in the 2010 edition of the *National Building Code of Canada* (NBCC) (NRC 2010). Although the application context in Canada is like that in the United States where BRBs are used in place of the conventional steel braces in CBFs, differences in U.S. and Canadian code provisions, primarily the design seismic hazard level and the BRBF system parameters, lead to different BRBF member sizes for the same underlying seismicity.

Currently, BRBs are proprietary products in the United States. Although this Guide makes no endorsement of any commercial product, they are currently fabricated by a small number of manufacturers including CoreBrace (www.corebrace.com), Nippon Steel (www.unbondedbrace.com), Star Seismic (www.starseismic.net), and Bluescope Buildings (www.bluescopebuildings.com).

(a) CoreBrace

(b) Nippon Steel

(c) Star Seismic

Figure 2-1. Typical BRBs.

Representative BRBs from three of the manufacturers are shown in **Figure 2-1**. Extensive testing of BRBs from these three manufacturers has been conducted to quantify force-deformation characteristics and to qualify the BRBs for use in the United States (Black et al. 2002, Merritt et al. 2003a and 2003b, Reaveley et al. 2004, Romero et al. 2006, Benzoni and Innamorato 2007, et al.). Although the different BRB manufacturers have unique detailing features in their BRBs, which may influence behavior particularly with respect to BRB-frame interaction, the fundamental BRB force-deformation relationship is similar and is the basis for discussion in this Guide.

In addition to the BRB component tests, several large-scale BRBF tests have demonstrated cyclic performance at the system level for configurations approximately representing U.S. practice (Fahnestock et al. 2007a, Uriz and Mahin 2008, Tsai et al. 2008, Tsai and Hsiao 2008, Palmer et al. 2014). Although these tests generally demonstrated the ductility and energy dissipation capability of BRBFs up to and beyond expected design-level earthquake demands, they also identified potential limitations related to residual drift and localized failures in connections, beams, and columns. Beam-column connection modifications that are capable of mitigating the localized failures have been proposed and experimentally validated (Fahnestock et al. 2007a, Berman and Bruneau 2009, Prinz et al. 2014). However, these modified connections may reduce frame action that provides story stiffness after the BRBs have yielded, and as a result, peak and residual drifts may increase (Fahnestock et al. 2007a, Ariyaratana and Fahnestock 2011). Numerical simulations of BRBF seismic response have established the range of drift and BRB deformation demands that can be expected from code-based designs using the U.S. provisions, including BRBF-SMRF dual systems (Sabelli 2001, Sabelli et al. 2003, Kiggins and Uang 2006, Fahnestock et al. 2007b, Uriz and Mahin 2008, Ariyaratana and Fahnestock 2011, Erochko et al. 2011). Evaluation of BRBFs using the FEMA P-695 methodology (FEMA 2009) demonstrated that the system has acceptable margins against seismic collapse and that the R and Ω_0 values currently used for design are appropriate (NIST 2010a, Chen and Mahin 2012).

2.2 Fundamentals of BRB Behavior

CBFs with conventional steel braces are used extensively, but their inelastic seismic response is largely dictated by brace buckling, which leads to strength and stiffness degradation of the frame. Although BRBFs are concentric in their configuration, their behavior is significantly distinct from even SCBFs, the most ductile type of conventional CBF with buckling braces.

To address and eliminate the undesirable structural response associated with brace buckling, BRBs are designed so that they can carry compressive axial force without buckling. As discussed above and shown in **Figure 1-2**, this is accomplished by separating the axial load-carrying mechanism from the axial buckling-restraining mechanism (buckling stiffness) of the brace.

A steel core, which can have a variety of cross-sectional shapes, such as flat plate, T-shaped, or cruciform, carries the BRB axial force. The BRB core is manufactured with several distinct regions along its length that enable stable cyclic response. Like a tensile coupon, a BRB core has a yielding region with a reduced area in the center of the length of the BRB. This approach ensures that the inelastic response is restricted to the portion of the BRB that is fully contained within the restraining mechanism. The yielding region must have a constant cross-section so that plastic strain is distributed uniformly along the yielding length. In addition, the yielding length must be selected so that excessive BRB strains do not lead to core fracture. Outside the yielding region, the core cross-sectional area increases in the transition regions. These regions are partially contained within the restraining mechanism but remain elastic even after the yielding region has strain hardened. The connection regions at each end of the BRB are reinforced to prevent localized buckling and to facilitate bolted, welded, or pinned connections to the surrounding beams and columns in the braced frame.

Stiffness to prevent member buckling is typically provided by a concrete-filled tube. This restraining mechanism must be designed with adequate stiffness to prevent both local and global buckling modes (Watanabe et al. 1988, Black et al. 2002, Takeuchi et al. 2010 and 2012, Wu et al. 2014, Tsai et al. 2014). The core is decoupled axially from the restraining mechanism, and a gap is provided between the core and the restraining mechanism to accommodate Poisson expansion of the core in compression as well as axial deformations in both tension and compression so that the restraining mechanism does not carry appreciable axial force at large deformation levels.

BRB yielding in compression as well as tension causes BRBFs to exhibit ductile cyclic behavior with significant energy dissipation. Typical BRB cyclic force-deformation behavior is illustrated in **Figure 2-2**, where the evolution of cyclic behavior and the significant strain hardening response are evident. BRBs exhibit combined isotropic and kinematic hardening, and they are typically slightly stronger in compression than in tension due to Poisson expansion and friction at the interface between the core and the restraining mechanism. Within the AISC *Seismic Provisions*, BRB cyclic behavior including strain hardening is quantified with the compression strength adjustment factor, β, and the strain hardening adjustment factor, ω. These terms are defined and discussed in more detail in the following section.

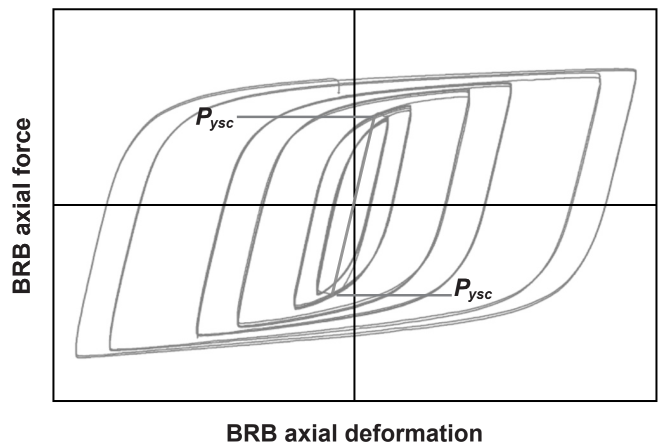


Figure 2-2. Typical BRB force-deformation behavior.

BRBs as Manufactured Items

A BRB is a fabricated assembly, currently available from a small group of manufacturers. BRBs are not prefabricated and stockpiled with specific core plate sizes, casing sizes, or brace lengths. Instead, each BRB is custom-fabricated for each project, although use of BRBs on a project does not require additional time in the construction schedule. For most design-bid-build projects, the design engineer is generally not involved in selecting the manufacturer responsible for fabrication of the BRBs, but rather, specifies critical BRB performance parameters for the fabrication of the BRBs to allow competitive bidding by any manufacturer (see Section 6). For design-build projects, the owner, the general contractor, or even the design team might select the BRB manufacturer. In such cases, the design engineer will have the benefit of working directly with one BRB manufacturer.

3. Principles for Design of BRBFs

BRBFs are proportioned using the fundamental philosophy that is the foundation for all ductile seismic design: the BRBs are the yielding elements, which are sized for a reduced seismic force level and are expected to undergo significant inelastic deformation during a design-level earthquake, while all other elements in the system are capacity-designed so that they remain essentially elastic at the expected strength of the BRBs. In the United States, ASCE 7 provides the overarching seismic design framework within which AISC 341 operates. The ASCE 7 provisions specify essential system-independent criteria, seismic hazard level, redundancy requirements, limitations on analysis methodology, and irregularity conditions. The provisions also specify system-specific design parameters: R, Ω_0, and C_d, and height limits. AISC 341 contains the provisions relating to the design and detailing of the individual members and connections within the BRBF, as well as proportioning requirements to ensure the desired ductile behavior.

The BRBF is the primary seismic force-resisting system and must resist lateral forces and control deformations during a seismic event to maintain the stability of the building. In ASCE 7, the BRBF system is assigned the largest response modification coefficient (R = 8), indicating that the system is expected to withstand large inelastic deformation demands yet maintain life safety and prevent collapse under the most severe seismic ground motion. The anticipated reliability of the structure under seismic loading is given in Table C.1.3.1b of ASCE 7 and is not system-specific but does depend on the Risk Category of the structure.

The three fundamental steps in BRBF design are as follows: (1) the BRBs are sized for ASCE 7 load combinations, where the earthquake loads have been reduced using R; (2) inelastic design-level drift and BRB strain are checked to ensure compliance with ASCE 7 and AISC 341 (or more stringent project-specific requirements); and (3) the adjusted brace strengths (BRB expected capacities accounting for strain hardening and compression overstrength at the expected drift) are determined and used to design beams, columns, and connections so that they remain essentially elastic. The first two steps are quite similar in principle to the process used for other ductile seismic force-resisting systems. However, the coupling among story drift, BRB strain, and strain-hardened BRB force is a unique and critical aspect of BRBF design. The basic BRBF kinematic behavior shown in **Figure 3-1** illustrates that, under the assumption of small changes of angles, BRB axial deformation, Δ_{bx}, equals $\Delta_x \cos(\alpha)$, where Δ_x is the design story drift and α is the BRB angle of inclination with respect to the horizontal. This can be alternately expressed in terms of the brace work-point length, L_{wp}, and the design story drift angle, θ_x or Δ_x/h_{sx}, where h_{sx} is the story height, as $\Delta_{bx} = \theta_x L_{wp} \sin(2\alpha)$. Then, defining the Yield Length Ratio (YLR) as $YLR = L_y/L_{wp}$, where L_y is the length of the yielding region of the BRB steel core with area A_{sc}, and assuming that the beam is rigid and that elastic deformations in the non-yielding region of the BRB steel core are small, the strain in the BRB core, ε_{sc}, can be expressed as:

$$\varepsilon_{sc} = \frac{\theta_x \sin 2\alpha}{2YLR} \qquad \text{(Equation 1)}$$

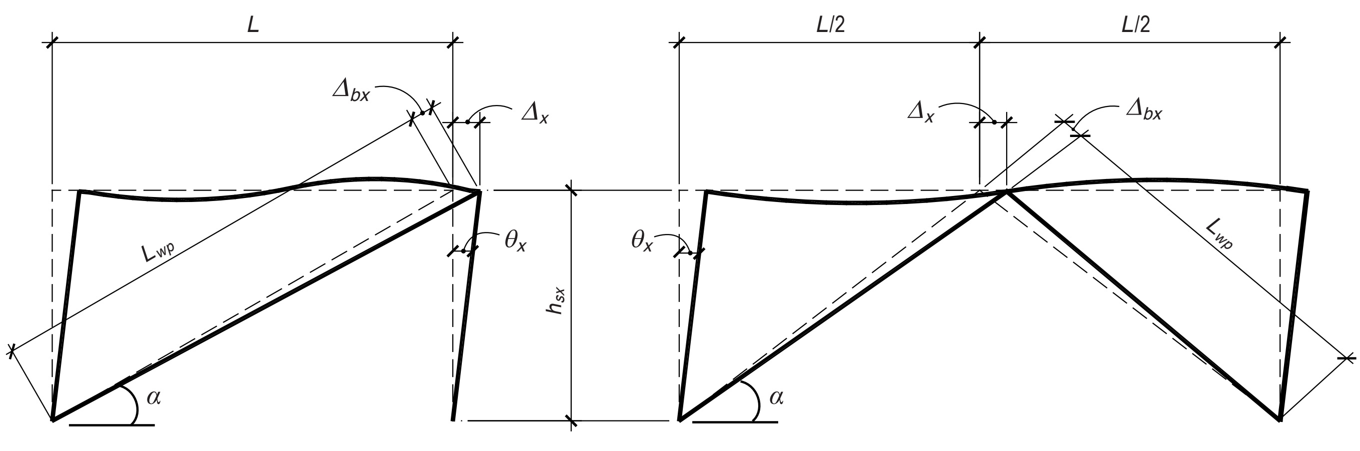


Figure 3-1. Basic BRBF kinematic behavior.

This relatively simple relationship is a useful tool for designers because it allows for rapid estimation of core strain demand and consideration of the effect of varying key parameters, particularly *YLR*. To illustrate the usefulness of Equation 1, consider, for example, a brace with $YLR = 0.5$ and $\alpha = 45$ deg. For such a brace, the equation shows that the BRB core strain is equal to the story drift angle. When evaluated for a 2 percent design story drift ratio and a core with $F_{ysc} = 40$ ksi, the design core strain demand is 14.5 times the yield strain, ε_y. The relationship between design strain demand and yield strain will vary for each brace based on the factors in the equation. This example is not meant to establish a typical relationship between ε_{sc} and ε_y. Futhermore, the inverse relationship between strain and *YLR* in the equation means that for short yield lengths (small *YLR*), large core strains will develop at relatively modest drifts, which should be avoided or could otherwise lead to BRB fracture.

Estimation of core strain demand has two important implications in the design process: (1) core strain demand must be kept below the available strain capacity based on BRB qualification testing to ensure acceptable BRBF performance, and (2) core strain demand is used to calculate the associated strain-hardened core stress that is then used for capacity design of the surrounding frame elements. Both of these issues require representative BRB test data, which are available from the BRB manufacturer, typically in the form of a backbone curve. Core strain calculations should be performed with the racking (global frame "shear" deformation) component of story drift, which is directly related to BRB deformation. In taller frames and in the upper stories of frames with significant overturning effects, column shortening and elongation produce global frame "flexural" deformation, which leads to story drift that does not cause BRB deformation.

As can be seen from Equation 1, story drift, BRB core strain, and *YLR* are interrelated, and BRB strength is also connected to these parameters through strain hardening. Per AISC 341, a BRB must be designed and detailed (and also validated by prior testing) to accommodate expected deformation, which can also be expressed as core strain, ε_{sc}, where expected deformation corresponds to a story drift of 2 percent or twice the design story drift, whichever is larger. This expected deformation (or core strain) is then used to determine β and ω from a qualification test data backbone curve. **Figure 3-2** shows representative BRB cyclic test data, along with the associated backbone curve. At expected

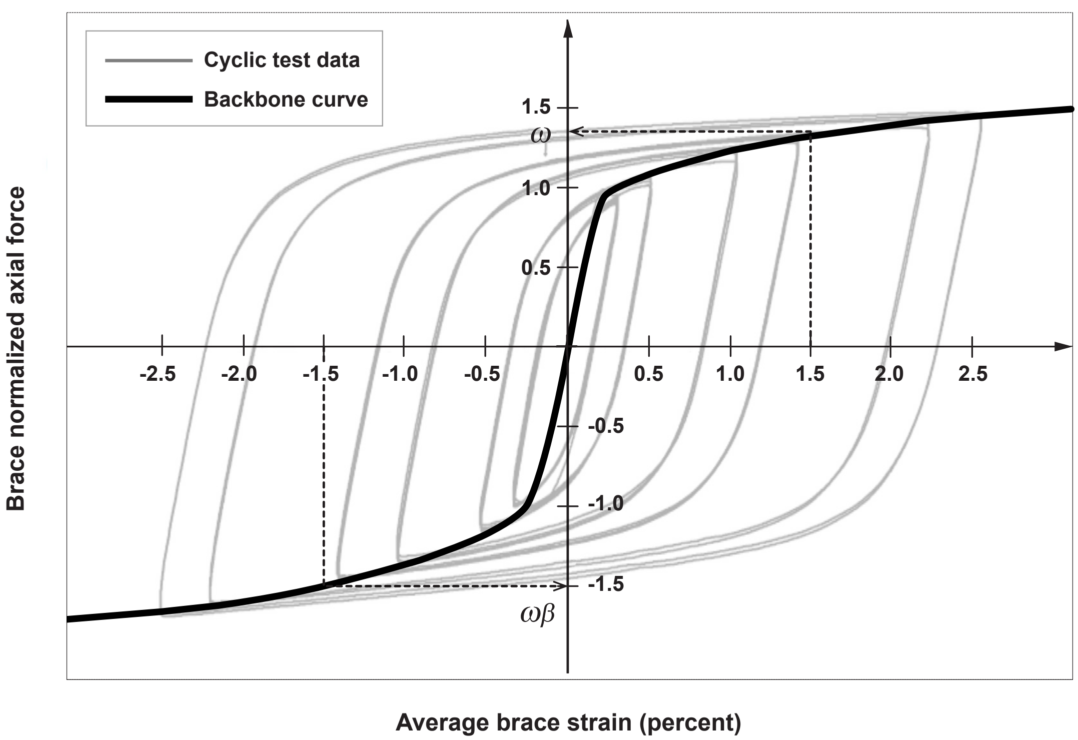


Figure 3-2. Conceptual BRB cyclic test data and backbone curve.

strain (deformation), the strain hardening adjustment factor, ω, is the ratio of the maximum tension force to the measured tensile yield force. Similarly, at expected strain, the compression strength adjustment factor, β, is the ratio of the maximum compression force to the maximum tension force. Stated differently, and as illustrated in **Figure 3-2**, the product $\omega\beta$ is equal to the ratio of the maximum compression force to the measured tensile yield force. These adjustment factors are then used as part of the capacity design process for proportioning the BRBF beams, columns, and connections so that they remain essentially elastic and so that the inelastic response is limited to the BRBs. The BRB adjustment factors vary based on manufacturer, *YLR*, and other detailing features, but ranges of typical values are 1.3 to 1.5 for ω and 1.05 to 1.15 for β. In addition to backbone data available directly from a particular manufacturer, Saxey and Daniels (2014) have reviewed data from numerous tests by CoreBrace, Nippon Steel, and Star Seismic and have statistically developed equations for design engineers to use to estimate values of ω and β.

4. Guidance for Analysis of BRBFs

ASCE 7 defines the analysis procedures, modeling criteria, and other requirements that must be followed when analyzing the effects of seismic loading on a given structure. For the analysis procedures in particular, ASCE 7 provides three different options, and ASCE 7 Table 12.6-1 lists the permitted analysis procedures for different combinations of parameters, such as SDC, risk category, type of construction, height, and presence or absence of irregularities. The three analysis options are (1) Equivalent Lateral Force (ELF) procedure per ASCE 7 §12.8; (2) Modal Response Spectrum Analysis (MRSA) procedure per ASCE 7 §12.9; and (3) Seismic Response History procedure per ASCE 7 Chapter 16, which contains both linear and nonlinear procedures. The ELF procedure and MRSA procedure are most commonly applied to BRBF structures and are the focus of this discussion.

4.1 Elastic Analysis

The ELF and MRSA procedures are both elastic analysis procedures that are based on seismic forces reduced by the response modification coefficient, R, in accordance with ASCE 7. For certain elements beyond the BRBF system (such as collectors), ASCE 7 and the IBC require design for amplified seismic loads by multiplying the elastic results by the overstrength factor, Ω_0. Similarly, to determine the BRBF design displacements, the elastic analysis deflection results are amplified to approximate inelastic response in accordance with ASCE 7 by multiplying them by the deflection amplification factor, C_d. The appropriate values of R, Ω_0, and C_d applicable to the BRBF system when using either the ELF or the MRSA procedures are found in ASCE 7 Table 12.2-1.

Although the ELF procedure is the simplest to implement, ASCE 7 Table 12.6-1 does place limitations on its use. However, there are no limits on the use of the MRSA procedure. Furthermore, with the capabilities of today's commercial structural analysis software platforms, the MRSA procedure may often require little additional time and effort over the ELF procedure. For BRBF systems, especially in taller buildings, the MRSA procedure will typically provide more economical frame designs than the simpler ELF procedure. When the ELF procedure is used, the BRBF system is assigned $C_t = 0.03$ in ASCE 7 for calculating the approximate fundamental period of the structure, distinct from the value of 0.02 assigned to conventional CBF systems (considered as "All other structural systems" in ASCE 7 Table 12.8-2). The difference between the values reflects that fact that the BRBF system generally is more flexible and thus would have a larger natural period than CBFs.

Like other CBFs, BRBFs are typically modeled with columns that are continuous over the frame height and with the idealizations that columns have pinned bases and that beams and braces have pinned end connections. Although beam end connections do have the potential for significant moment transfer, particularly when gusset plates are present to connect the BRBs to the column-beam joints, the portion of story shear resisted by these mechanisms is generally small in the elastic range. When elastic analysis is used to determine the fundamental period and the forces and deformations in the BRBF members, it is reasonable to neglect frame behavior.

An important analysis consideration for the BRBF system is modeling of the BRB elastic stiffness. As shown in **Figure 1-2**, the BRB is a nonprismatic member that has three primary regions that each must be considered to accurately determine its actual stiffness: yielding core region, transition region, and connection region. The analysis model needs to account for the actual BRB stiffness, which is commonly accomplished with a stiffness modification factor, KF, that is multiplied by the core area, A_{sc}. When applied, KF will result in the elastic stiffness of the modeled prismatic truss element matching the elastic stiffness of the actual nonprismatic BRB element. The BRB stiffness modification factors vary depending on the *YLR* and several other factors related to BRB geometry, end connection detail, and even manufacturer. Different types of BRBs will have different stiffness modification factors, and multiple KF values may be needed for the BRBs in a building. A reasonable range of KF is between 1.3 and 1.7. As described in Section 6 of this Guide, close coordination with the BRB manufacturer is needed to help the design engineer understand the actual BRB stiffness and determine the appropriate stiffness modification factor(s) to use in analysis and design. BRB manufacturers provide convenient designs aids for accurately estimating the KF values for a given project. In addition, directly modeling the BRB core as a nonprismatic member is a viable alternative for capturing the correct BRB elastic stiffness.

A tolerance on the KF value(s) needs to be specified to effectively account for maximum BRB forces that are based on expected deformations of the BRBs, deformations which in turn are based on the *KF* value(s) used. The AISC *Seismic Design Manual* (AISC 2012) provides the following guidance on the issue:

> Designers should not perform bounding analyses or otherwise place undue emphasis on the effects of variability [of elastic stiffness and yield strength] beyond accounting for maximum brace forces in the design of connections, beams and columns. Such variability in stiffness is routinely (and justly) neglected in the seismic design of many systems and is minimal in the context of the use of elastic methods to represent inelastic response.

The main point of the AISC *Seismic Design Manual* guidance is that the design engineer need not perform endless iterative parametric studies considering numerous permutations seeking to determine a precise acceptable tolerance for the *KF* value(s). Instead, the design engineer is encouraged to consider and understand the general sensitivity of the modeling results to variations in BRB stiffness and arrive at a reasonable tolerance. Current practice commonly allows for approximately +/- 10 percent tolerance in BRB stiffness accounting for variation in *KF* values and A_{sc}. The design engineer needs to determine an acceptable tolerance for the *KF* value(s) based on the specific conditions of the given project.

Understanding Tolerance on BRB Stiffness

When determining an acceptable tolerance for *KF* values, the design engineer should consider the effect of variations of BRB stiffness on global building response rather than on local response. If all of the actual BRBs have greater stiffness than used in the analysis, the building will have a shorter fundamental period and the design engineer needs to consider whether this results in an increased design base shear and higher BRB design forces. If all of the actual BRBs have less stiffness than used in the analysis, the building will have a longer fundamental period and will be more flexible. In this case, the design engineer needs to consider whether this results in a decreased design base shear and/or results in increased lateral story drifts.

4.2 Inelastic Analysis

Although not commonly used in typical BRBF designs, Nonlinear Response History Analysis (NRHA) is a valuable inelastic analysis tool for performance-based projects, when increased economy is desired, or when unusual and/or irregular configurations need to be justified. Whereas the ELF and MRSA procedures use elastic analysis to estimate inelastic response, the NRHA procedure directly considers inelasticity and second-order effects in the analysis and therefore provides a more accurate assessment of story drift, BRB strains, and forces and moments in beams, columms, and connections. The benefits of using NRHA include the following:

- Observing and mitigating undesirable concentrations of drift in a single story or a limited number of stories.
- Allowing greater flexibility to use system configurations that are not permissible when elastic analysis methods are employed.
- Directly quantifying story drift and BRB strain demands, which will typically be smaller than the estimates of strain made by amplifying elastic analysis results. Smaller BRB strain demands result in less strain hardening and reduction of BRB forces that are used in designing beams, columns, and connections.
- Assessing BRB cumulative ductility demand directly. Although BRBs have large cumulative ductility capacity and are expected to be capable of sustaining multiple large earthquakes without fracture (Fahnestock et al. 2003), some special scenarios may require direct consideration of cumulative ductility demand.

For accurate inelastic analysis, the following are recommended:

- Nonlinear truss or frame elements should be used to model BRBs. BRBs have relatively simple cyclic response: elastic-plastic with strain hardening and no strength or stiffness degradation for well-detailed configurations. This response can be represented with reasonable accuracy using commercial structural analysis platforms. BRB cyclic test data should be used as the basis for the numerical model, with particular attention given to modeling strain hardening in the BRB so that the cyclic response matches representative BRB experimental data. Calibration of hardening parameters to cyclic experimental data is critical because calibration to a backbone curve will not provide a reasonable model. Commercial structural analysis platforms used in design offices contain a variety of options for modeling steel hardening behavior, so a careful assessment of the BRB modeling approach is required to ensure reasonable response over the full range of behavior. For example, when kinematic hardening is used to model inelastic BRB behavior, the model will harden continuously and may ascribe unrealistically large force levels to BRBs at large deformations if an inappropriate post-yield stiffness is used. This overestimation of BRB hardening can lead to unnecessarily large connection design forces but can also lead to unrealistic BRB strength and stiffness that may cause understated drift demands and overly optimistic collapse capacity.

- Nonlinear frame elements should be used to model beams and columns. In particular, inelastic column behavior will be important when significant differences in story drifts develop between adjacent stories. Although beams and columns in BRBFs are designed to remain nominally elastic, actual inelastic seismic demands will not match the force distribution(s) used in design, and yielding may occur outside the BRBs in the surrounding frame.
- Connections should accurately represent the actual conditions in the BRBF, with consideration for the relatively high stiffness provided at beam-column connections with gusset plates. In cases where drift concentrates in a single story, the frame action provided by columns and attached beams will be significant and should be captured in the model. The high stiffness of the beam-column connections with gusset plates means that nonlinear column panel zone behavior is unlikely, and panel zone regions may be modeled with rigid offsets.
- Although not unique to BRBFs, the global destabilizing effects of the gravity system must be included in the model. These effects can be captured by including gravity columns, which carry the tributary seismic mass for the modeled BRBF, in parallel with the BRBF. Thus, as lateral displacement occurs during the analysis, P-Delta effects will amplify demands on the BRBF.

Design engineers considering the NRHA procedure should consult relevant literature for guidance on modeling procedures, including the NEHRP Seismic Design Technical Brief *Nonlinear Structural Analysis for Seismic Design* (NIST 2010b). Several references that discuss NRHA of BRBFs in more detail include: Sabelli et al. (2003), Tremblay and Poncet (2004), Fahnestock et al. (2003, 2006, 2007b), Uriz and Mahin (2008), and Jones and Zareian (2013). In addition, rigorous development of site-specific ground motions and external peer review of the design are critical steps when using the NRHA procedure.

Nonlinear Static Analysis

In addition to these three analysis procedures defined in ASCE 7, nonlinear static analysis can also be a valuable tool in the BRBF design process. Nonlinear static analysis is discussed extensively in ASCE/SEI 41 (ASCE 2014), and although ASCE/SEI 41 was written as a guide for seismic retrofit projects, it is commonly used as a guide when employing nonlinear static analysis to assess new building design. The nonlinear static analysis procedure should follow the same inelastic analysis guidelines provided for the Nonlinear Response History Analysis (NRHA) procedure. The nonlinear static analysis procedure is simpler than the NRHA procedure because it uses monotonic static loading and does not require design ground motion development and time-stepping integration of the governing equations of motion. However, by considering only a few lateral load patterns, the nonlinear static procedure still provides significant insight into the inelastic response of the BRBF system. For example, the nonlinear static procedure can identify distribution of inelastic demand over the height of the frame, expose potential story mechanisms, provide demands for use in capacity design of the frame, and allow for comparison with nonlinear response of other seismic force-resisting systems.

BRBFs in Retrofit Applications

Although the focus of this Guide is on the design of new buildings, BRBFs can also be effectively implemented in retrofit applications, particularly because the stiffness and strength can often be tuned to the needs of the given existing building. Depending on the governing code or other regulations in the jurisdiction of the given retrofit project, BRBFs in a retrofit may still need to be designed using the ASCE 7 and AISC 341 provisions for new construction. In other cases, as when nonlinear analysis is used, ASCE/SEI 41 provisions might be allowed. ASCE/SEI 41-13 is the first version to contain modeling parameters and acceptance criteria for BRBFs. Prior to this version, design engineers developed project-specific parameters and criteria with the assistance of the project peer reviewer, using appropriate project-specific data from a BRB manufacturer. Even with general parameters and criteria now given in ASCE/SEI 41-13, design engineers should engage with a peer reviewer to determine if those parameters and criteria are appropriate for the particular project.

5. Guidance for Design of BRBFs

As discussed, proper application of the BRBF provisions in AISC 341 should result in a design in which the earthquake-induced inelastic deformations are largely borne by the BRBs while all other elements of the seismic force-resisting system remain nominally elastic at the load effects associated with yielded and strain-hardened BRBs (the "adjusted brace strength"). Because step-by-step design of BRBFs has been covered in other publications (López and Sabelli 2004, AISC 2012), this Guide only provides additional background and guidance regarding the current state of the practice. Section 5 presents a basic design procedure and other items for consideration specifically by the design engineer, whereas Section 6 provides discussion of design topics related to coordination between the design engineer and the BRB manufacturer.

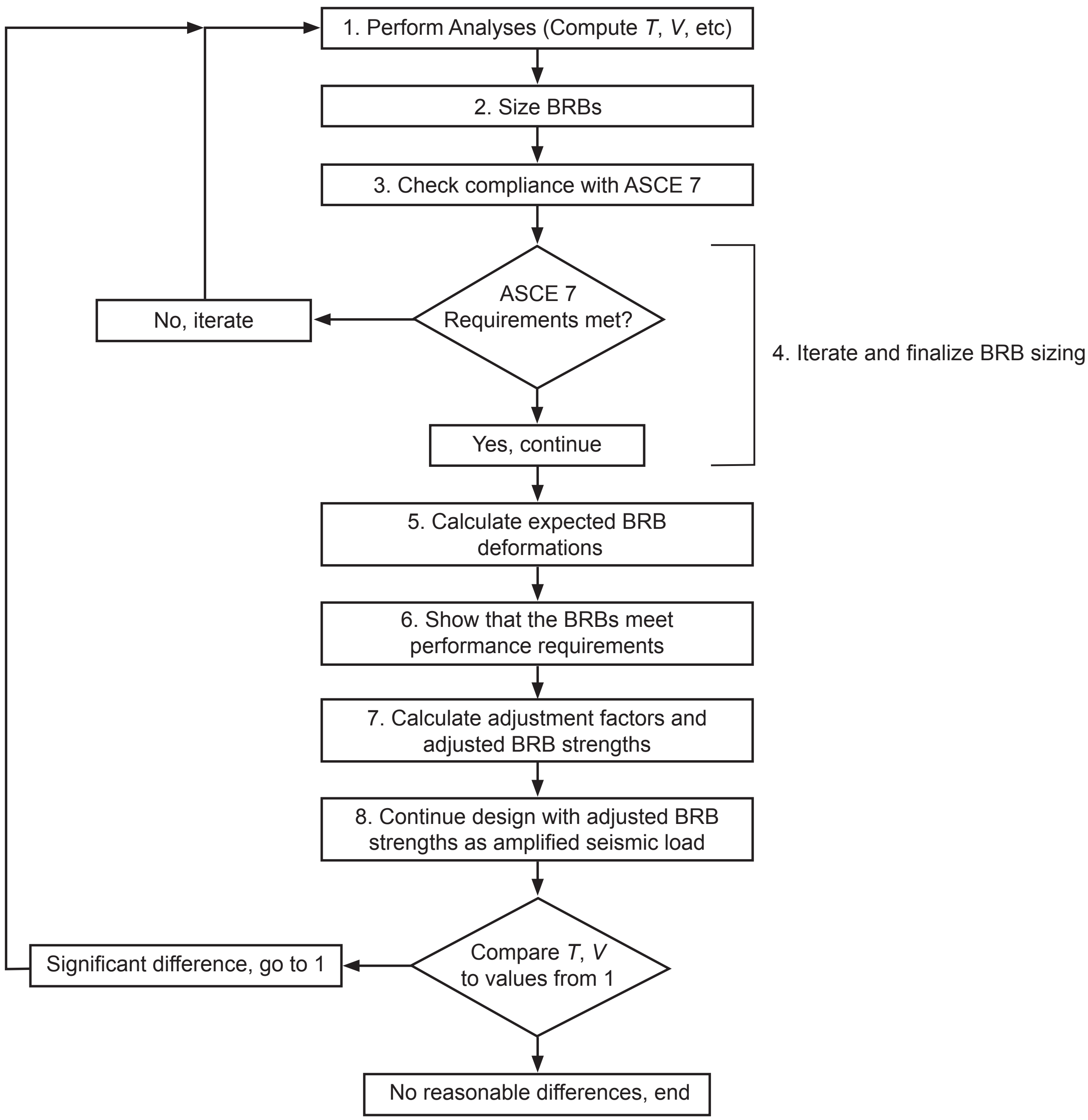


Figure 5-1. Flowchart for design of BRBFs.

5.1 Basic Design Procedure

Figure 5-1 presents the basic design procedure for BRBFs. BRBF design is analogous to design of other high ductility "fuse-based" structural systems in that the design process can be simplified into three basic concepts: (1) design the ductile yielding elements (the fuses) for a reduced seismic force, (2) check the inelastic deformation of the ductile elements against acceptable limits, and (3) design the remainder of the system for the expected capacity of the ductile elements. For example, the primary concepts for EBF design are: (1) the link beams (the fuses) are proportioned for demands from loads reduced by the *R* coefficient; (2) inelastic deformations, concentrated within the link beams, are checked to meet acceptable limits; (3) using a capacity-based design approach, the link beam strengths are used to proportion the connections, braces, beam outside the link, columns, and column bases. Likewise for BRBFs, the fundamental design concepts are: (1) the BRBs (the fuses) are proportioned for demands from loads reduced by the *R* coefficient; (2) inelastic deformations, concentrated within the yielding core of the BRB, are checked to meet acceptable limits; (3) using a capacity-based design approach, the connections, frame beams, frame columns, and column bases are designed for the adjusted BRB strengths.

The following steps diagrammed in **Figure 5-1** summarize the process required by the integrated requirements of ASCE 7 and AISC 341:

1. *Perform analyses*. Build an analysis model that is consistent with the guidelines defined in Section 4 of this Guide. In order to properly model the BRBs, a preliminary value for *KF* will need to be selected with input from the BRB manufacturer or other resources as discussed. Likewise, values of ω and β will need to be estimated as discussed in Section 3 in order to determine initial sizing of the BRBF beams and columns. The values of *KF*, ω, and β will be validated later and not need to be overly precise for the initial analysis.

2. *Size BRBs*. From the required strengths obtained from the analysis model, size each BRB such that its design strength exceeds the calculated required strength. Core plates are generally fabricated from ASTM A36 steel and BRBs sizes should be based on an F_{ysc} in the range of of 38-46 ksi. In general, it is best not to unnecessarily oversize BRBs, both for economy and performance. This is usually achieved by increasing core plate areas in 1/4 square inch to 1/2 square inch increments for smaller BRBs and in 1 square inch to 2 square inch increments for larger BRBs. The number of sizes used for a given project is a balance between demand capacity ratio efficiency and economy of repetition at the judgement of the design engineer. At this stage, BRB connections should be preliminarily considered in terms of basic type, size, or both, since they will affect BRB stiffness and strength adjustment factors.

3. *Check compliance with ASCE 7 requirements*. After sizing BRBs, perform checks of all ASCE 7 global requirements such as story drift ratios, global stability, and irregularity. Satisfying these requirements may involve several iterations of BRB sizing, frame placement, or frame configuration. For the same bay geometry and brace configuration, a BRBF will have a lower lateral stiffness than an SCBF, and thus BRBF designs may be governed by limits on global lateral displacements, relative story drift ratios, and torsional irregularity. Therefore, drift and displacement should be considered earlier in the design process for a BRBF than for an OCBF or SCBF design.

4. *Iterate and finalize BRB sizing*. Iterate through steps 2 and 3 as necessary until resizing of BRBs is no longer needed. Coordination with the BRB manufacturer is important to validate the values selected for *KF*, ω, and β to this point in the process. Upon closing the iteration, the strength portion of BRB sizing is complete.

5. *Calculate expected BRB deformations*. Section 3 of this Guide provides a discussion of one method to determine expected BRB deformations given that certain parameters of the brace are known (particularly *YLR*). Step-by-step procedures for calculating the expected BRB deformations are also in AISC (2012) and López and Sabelli (2004). The latter reference is based on the requirements from AISC 341-05, and the check on expected BRB deformations has been modified in AISC 341-10. Per AISC 341-10 §F4.2, the expected brace deformations are those corresponding to the larger of 2 percent of the story height or two times the design story drift (where the design story drift is C_d times the elastic drift as given in ASCE 7).

6. *Show that the BRBs meet performance requirements*. The design engineer now has enough information to define two of the required BRB parameters: BRB size and BRB deformations. A BRB with a specific end connection can now be selected from the various types offered by the different manufacturers. To demonstrate compliance with AISC 341, the selected BRB must have been successfully tested to the expected BRB deformations for a similar size for each BRB used on the project, within the similarity requirements specified in AISC 341 §K3. Both strength and deformation requirements must be met for the tests of a BRB type to have demonstrated conformance. This assures that the BRBs selected for the project are similar in size and deformation capability to BRBs that have successfully demonstrated cyclic deformations under appropriate test conditions.

   There are at least two potential solutions for cases where the selected BRB cannot satisfy the requirements of AISC 341 §K3: (1) portions of the seismic force-resisting system can be redesigned by adding more frames, changing the frame layout or adjusting BRB sizes, (2) project-specific BRB testing can be done to qualify BRBs for the expected deformations. When calculating BRB deformations, consideration of beam, column, and gusset plate sizes are critical because they affect the BRB yield length, which should be maximized.

7. *Calculate adjustment factors and adjusted BRB strengths*. After a BRB with a specific end connection is chosen, the strain hardening adjustment factor and compression strength adjustment factor are determined using the BRB backbone curve provided by the BRB manufacturer, as illustrated in **Figure 3-2**. These adjustment factors are used to calculate the adjusted BRB strengths. The design engineer should examine the backbone curve received, ensuring that it corresponds to qualifying tests and that it is applicable to project conditions.

8. *Continue design with adjusted brace strengths as amplified seismic load*. The adjusted brace strengths in tension and in compression computed in Step 7 are used as the amplified seismic load in the applicable load combinations for the design of the remaining components of the frame, such as the frame beams, frame columns, brace connections, and column bases. Because the adjusted brace strength in compression is β times greater than the adjusted brace strength in tension, two different sets of adjusted strengths apply for design of BRBF elements, depending on the BRB orientation and load direction. Per AISC 341, connection designs must account for the effects of 1.1 times the adjusted brace strength in compression. Additionally, the BRBF beam and column members must comply with the prescriptive detailing requirements of AISC 341. These detailing requirements apply to all systems listed in AISC 341 and are not specific to BRBFs. Once the required strengths are computed for the appropriate load combinations, perform calculations and generate details to ensure that all other elements of the seismic force-resisting system have design strengths, ϕR_n, greater than the calculated required strengths, R_u. Final connection design may also affect the BRB stiffness (the final core length and resulting stiffness modification factor) and strength adjustment factors. Thus, iteration may be required.

Design of BRBFs for Out-of-Plane Loading

The weight of a BRB along its length is comparable to that of a heavy W section, and in certain conditions, a BRB's size or length is large enough that its out-of-plane inertial seismic force is substantial. In most building applications, a structural diaphragm is present and can be detailed to provide out-of-plane stability to BRBF beams and columns at brace-beam and brace-beam-column intersections. Where such a diaphragm is not present, the BRBF beams and columns must be designed to have adequate stiffness, strength, and stability to resist the out-of-plane seismic forces from the BRBs.

5.2 Frame Layout and Configuration Considerations

When designing BRBFs, the design engineer is called upon to coordinate with the architect and others regarding the location and configuration of BRBFs. This type of coordination is routine for any structural system. Because BRBs can be easily economized by design engineers to efficiently provide strength to match demand, the sizing of BRBs during the earliest stages of design can often indicate that fewer BRBs are required compared to conventional CBFs. However, the economic benefits of fewer braces need to be considered alongside the negative effects of less redundancy, higher design forces for collectors and foundation elements, and possibly higher story drifts and therefore higher strength adjustment

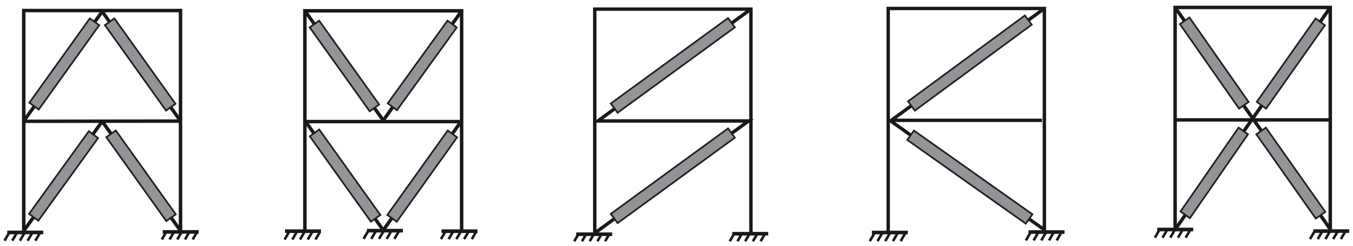


Figure 5-2. Examples of BRBF configurations.

factors. Furthermore, care should be taken in distributing frames in plan to minimize the negative effects of torsional response.

In terms of frame configuration and BRB orientations, greater latitude is given to BRBFs compared to other CBFs because BRBFs mitigate the consequences of brace buckling. **Figure 5-2** shows examples of BRBF configurations. In multistory buildings, stacked inverted-V (chevron) and V configurations of BRBFs are common. The beam in a stacked inverted-V and in a V configuration needs to be sized for the unbalanced loading. However, the difference in axial forces between BRB tension and compression, when yielded and strain-hardened, does not generate unbalanced vertical loads as large as if the system were an SCBF. The adjusted compressive brace strength of a BRB is larger than (or at least equal to) its tensile adjusted brace strength. Therefore, the beam in an inverted-V frame configuration has an unbalanced vertical load counteracting gravity loads. Generally, multistory X configurations, **Figure 5-2(e)**, are preferred because they offer advantages by minimizing both unbalanced vertical loading and axial loads to the frame beams and by providing opportunity to better distribute yielding across multiple stories. Single diagonals in the same direction along the same line are permitted by the code for BRBFs. In multistory applications, arranging single diagonals in a zig-zag configuration minimizes axial loads in frame beams.

5.3 Preventing Story Mechanisms

Compared to conventional CBF designs, BRBFs have lower initial stiffness and reduced post-yield stiffness and therefore may be more susceptible to the formation of story mechanisms. Although the possible formation of a story mechanism is not unique to BRBFs, story strengths are more easily "tuned" in BRBFs than in other seismic force-resisting systems because the design engineer has the ability to carefully choose the steel core area that is needed and to minimize system overstrength. When sizing BRBs along the height of a frame, it is desirable to increase the size of the BRBs from smallest at the roof to largest at the base, at least maintaining similar demand-to-capacity ratios, to achieve distribution of the yielding in multiple stories. Although not a specific code requirement, good seismic design philosophy would lead a design engineer to continually increase the story strength from the roof to the base. Consider, for example, the case where two adjacent stories have the same story strength. As expected, the lower story has a larger shear demand than the upper story. Because both stories have the same story strength, the lower story will undergo more ductility demand than the upper story. More importantly, not paying attention to the vertical distribution of BRB sizing may result in the creation of a weak story where an upper story is adjacent to a taller lower story or where an upper story with inverted-V or V configurations is adjacent to a lower story with single diagonals. Furthermore, the use of a back-up frame (beam-column moment connections) and a dual system, or both, will enhance the resistance to the formation of a story mechanism.

5.4 Connection Considerations

For BRBFs, there are three types of connections within the frame to consider: (1) connection of the BRB to the gusset plate, (2) connection of the beam to column (including gusset plates), and (3) connection of the column to base plate.

AISC 341 requires BRBF gusset plates to be designed for 1.1 times the adjusted brace strength in compression. BRBF gusset plates are not intended to develop a hinge zone the way SCBF gusset plates are detailed to develop. In SCBFs, gusset plate hinging is part of the brace buckling mechanism, but in BRBFs, the design objective is to limit the inelastic deformation to the BRB cores. General principles for design of gusset plates are discussed in AISC *Design Guide 29* (Muir and Thornton 2015). As noted by Muir and Thornton, additional nonnegligible frame action demands develop in braced frames when the story drifts become large. As a result, the design and detailing of the BRBF beam-column connection needs to be adequate for the expected demands (Lin et al. 2015).

Column bases need to be designed for the maximum axial compressive and axial tensile loads to which the column will be subjected, including the effect of BRBs attached directly to column bases. Per AISC 341 §F4.3, these loads are determined assuming that the forces in all BRBs correspond to their adjusted brace strengths in tension and compression to ensure a complete load path from the top of the BRBF to the foundation. Included in the definition of column bases are the column-to-base welds, the base plate, and the anchor rods. Although not explicitly required by codes, the concrete foundation receiving the anchor rods and providing bearing support to the base plate should also have a design strength greater than the required axial strength of the column base. If the foundation were to be designed to a lower strength, although allowed by code, it would imply that the foundation would have to undergo inelastic deformations, which would not align with the AISC 341 intent that inelastic deformations occur primarily in the BRBs. If the best practice approach of designing the foundations for the strength of the column bases is adopted, reinforcing bars in those foundations need not comply with ductile detailing requirements, because inelastic deformations are not anticipated.

6. BRBF Design and Fabrication Coordination

As a performance-specified item, BRBFs are characterized by special considerations that are unique to its design compared to other seismic force-resisting systems. During the design phase, there are certain performance decisions made by the design engineer regarding material strength, ductility demand, casing size, and other items that need to be communicated to and coordinated with the BRB manufacturer to ensure that the fabricated product will meet the design intent for the BRBF. In addition, it is becoming more common in the United States for BRB manufacturers to provide design assistance that extends beyond the out-to-out dimensions of the BRBs. Therefore, construction documents need to communicate not only BRB performance requirements but also the design scope, if any, delegated by the design engineer to the BRB manufacturer's engineer. Only the project Engineer of Record (EOR) can delegate scope as the licensed professional responsible for sealing the contract documents. For some projects, the EOR and the design engineer may be the same person, although in most cases the design engineer is under the responsible charge of the EOR. The discussion that follows emulates Section 3 of the *Code of Standard Practice for Steel Buildings and Bridges* (AISC 2010c) and is supplementary to the requirements of AISC 341 §A4.1 and §A4.2.

BRB manufacturers and practicing engineers have collaborated to give design engineers guidance regarding how to effectively specify and coordinate BRB design and detailing parameters (Robinson and Black 2011; Robinson et. al. 2012). A BRB cannot be fabricated with zero tolerances from specified values, and the design engineer should also want to allow for differences between manufacturers or BRB types. Therefore the design engineer is strongly encouraged to contact at least one BRB manufacturer to understand the level of tolerance needed for BRB stiffness and strength parameters for the design of a given project. To quantify the performance of a BRB, it is reasonable to expect that design documents would define the nine items described below for each BRB, including acknowledgment of the tolerances acceptable to maintain the design intent. (See also **Figure 6-1**).

1. The required area of the steel core, A_{sc}, and any allowable tolerances in meeting such value.

2. The required yield stress of the steel core, F_{ysc}, to be validated by coupon testing of the actual material to be used by the BRB manufacturer, and any allowable tolerances in meeting such value.

3. The BRB required axial strength; further specify whether it represents a Load and Resistance Factor Design (LRFD) or an Allowable Stress Design (ASD) value.

4. The stiffness modification factor(s), *KF*, used in the analyses and any allowable tolerances in meeting such value(s).

5. The expected BRB deformations to which BRBs are to be designed and for which the BRB supplier is to demonstrate compliance with the testing requirements of AISC 341 §K3.

6. The maximum permissible strain-hardening adjustment factor, ω, and the BRB deformation at which the factor is to be calculated (see item 5).

7. The maximum permissible compression strength adjustment factor, β, and the BRB deformation at which the factor is to be calculated (see item 5).

8. The type of BRB end connection(s) allowed. If a specific end-connection or configuration is not allowed because of aesthetic or performance issues, such restriction should be noted.

9. The maximum permissible casing size and the casing shape agreed upon between the design engineer and project design team. If there are no requirements on casing size and shape, documents should so state, because there is a potential for more economical designs if the BRB manufacturer is allowed to execute its casing design unencumbered by constraints.

Items 1 through 3 of the preceding list are interrelated when sizing BRBs, for which there are two methods commonly used by design engineers. The first method is characterized by keeping A_{sc} fixed while allowing F_{ysc} to vary within permissible tolerances. Since A_{sc} does not vary, A_{sc} must be sized for the lowest F_{ysc} allowed within the specified tolerances. This first method allows for more

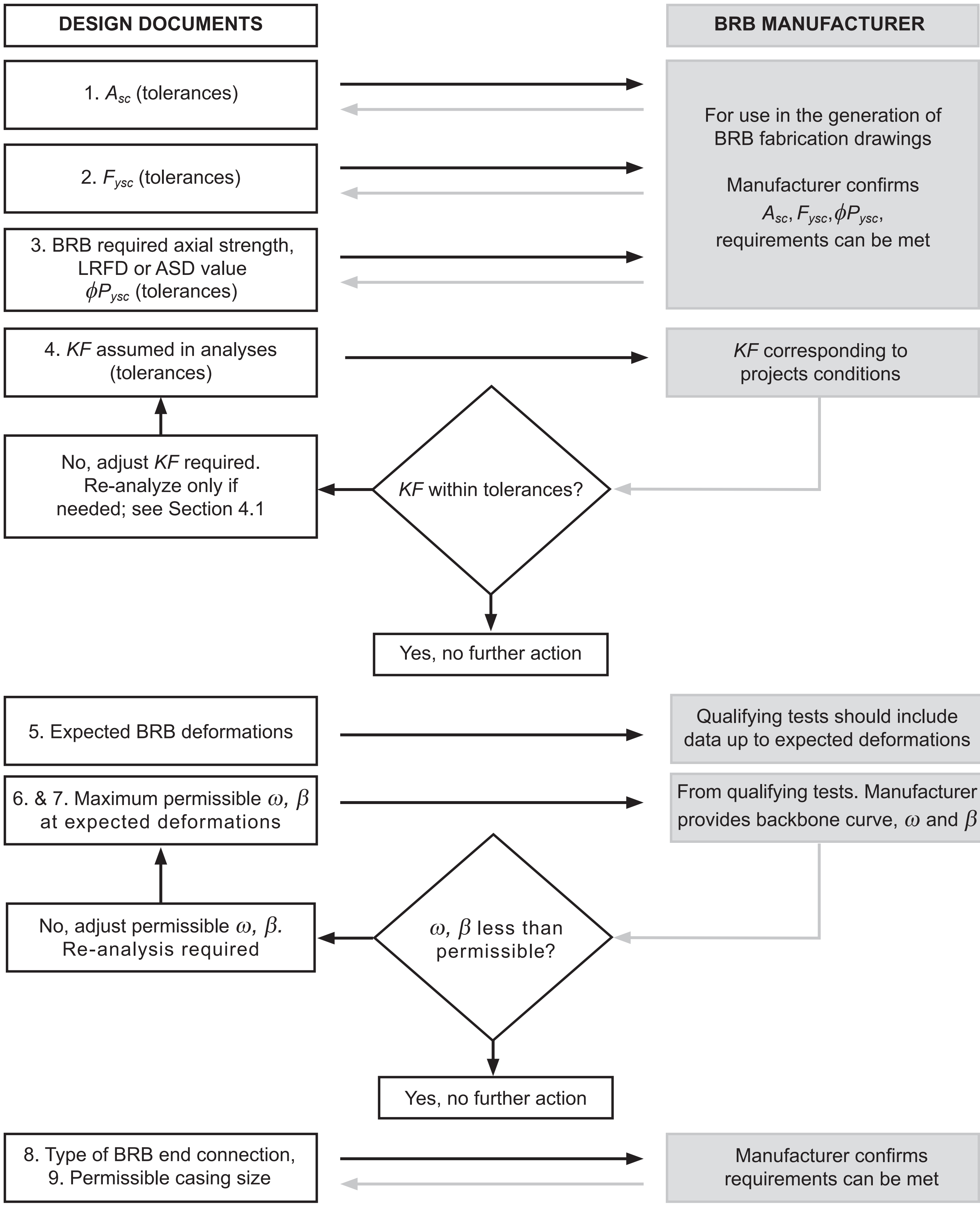


Figure 6-1. Flowchart for design and fabrication coordination (with arrows indicating the direction of the flow of information from the design engineer to and from the BRB manufacturer.)

control of the calculated interstory drifts but may result in larger forces for all other members of the seismic force-resisting system, because the maximum F_{ysc} allowed is applied to a fixed A_{sc} as part of the BRB expected strength calculation. The second method is characterized by minimizing overdesign in the brace design axial strength, ϕP_{ysc}. The BRB manufacturer is allowed to adjust A_{sc} as F_{ysc} varies within tolerances, based on coupon testing of the actual core plate material, such that ϕP_{ysc} is as close to P_u as possible. The axial forces in all other members of the seismic force-resisting system are potentially smaller than those corresponding to the first method. However, the design engineer needs to establish reasonable limits on the variability of A_{sc} to avoid having to recheck base shear and drift calculations after receipt of BRB shop drawings with the final A_{sc} values. A hybrid of these two methods has been successfully implemented by design engineers with prior BRBF experience working in close collaboration with the BRB manufacturer to maintain minimum stiffness and strength, minimize BRB overstrength, and still allow for efficient detailing and fabrication practices.

While conducting analyses, the design engineer needs to use appropriate values of the BRB stiffness modification factors, *KF*, in the analysis model. These factors are manufacturer-specific and depend on BRB sizes, lengths, configuration (single diagonal vs. chevron), *YLR*, end-connection type, and other parameters. The stiffness factors used in the analyses need to be representative of what can be furnished by any BRB manufacturer, and the design engineer should coordinate with the BRB manufacturer on the appropriate values to use. Acceptable tolerances must be considered and specified. Refer to Section 4.1 above for guidance regarding acceptable tolerance on BRB elastic stiffness.

The expected BRB deformation is one of the most important performance parameters to define. Such deformation is the minimum deformation to which BRBs must have been subjected in qualifying tests. At such deformation, the values of ω and β are determined and are to be used for design of all other elements of the seismic force-resisting system. The design engineer needs to clearly define this deformation value in the design documents such that there is no ambiguity as to what kind of performance is expected of the BRBs on the project. At this deformation, qualifying tests should show stable hysteretic loops, and the observed behavior of the BRB should show no sign of buckling, binding, instability, or other detrimental characteristics.

BRB Connection Design and Coordination

In parts of the western United States, it is common practice for the Engineer of Record (EOR) to fully develop the design and details for the connections associated with the seismic force-resisting system. In the case of BRBFs, that would imply that connection components such as gusset plates, welds, and bolts would be shown on the EOR's design drawings. On some projects, BRB manufacturers have helped the EOR by providing the design for the gusset connections. Authorities having jurisdiction over the issuance of building permits for BRBF projects generally have not had any objection to engineers other than the EOR designing the gusset connections. As long as the gusset design is performed under the responsible charge of the EOR, who also complies with all ethical, code of conduct, and licensing regulations of the jurisdiction in which he/she practices, the codes do not mandate that the gusset designer needs to be an employee of the EOR.

Although there is general agreement that the gusset connections can be designed by the BRB manufacturer as long as the EOR maintains overall responsibility, there is no agreement as to when such designs should appear in the contract documents. Jurisdictions seem to be split in allowing the design of the gusset connections to be a deferred approval item. This Guide recommends that gusset connection detailing appear in the drawings prior to securing a building permit and not be a deferred approval item. Arguments for the gusset connection design to be a deferred approval item appear to be about competitiveness in the marketplace. One argument against a deferred approval of the gusset connection design is that *KF*, BRB strains, and BRB adjustment factors are affected by the length of the gussets. A second argument against a deferred approval of the gusset connection design is that BRBF behavior is affected by the length of the gussets. The seismic response of a frame beam or frame column may change from a flexure-governed response to a shear-governed response depending on the interaction between story heights, bay lengths, and gusset lengths. A third argument against a deferred approval of the gusset connection is that frame beams and columns could be subject to revision once the design of the connection is finalized and the design engineer reviews the applicable requirements of AISC 360 §J10. If the gusset design is not known until after the building permit is granted, assurances need to be in place that adequate values of *KF* were used, BRB strains are within qualified ranges, beams and columns have been designed to adequate force levels, and the response of beams and columns is aligned with the response assumed in the analysis. For these reasons, it is considered preferred practice to include the detailing of the gusset connections in the contract documents prior to obtaining a building permit.

The remaining important parameters in the coordination between design engineer and BRB manufacturer are the BRB end connection type, casing shape, and maximum allowed casing size. The BRB end connection type is sometimes specified or limited based on aesthetic reasons when the BRBs are exposed. Sometimes the connection type is dictated by performance requirements. A pin-ended BRB is preferred by some design engineers at steep-angle conditions to avoid large flexural demands at expected interstory drift ratios. The casing shape and maximum casing size are often chosen to satisfy the building's space planning and functional needs. The design engineer must coordinate casing shape and size to validate that the basis of design can be furnished by the BRB manufacturer.

7. Future Developments

7.1 Enhanced Seismic Stability and Residual Drift Control

As currently used, BRBFs exhibit good ductility and energy dissipation capability. Additional enhancements are possible through modifications in BRB and system configuration. BRBFs may concentrate drift in one story because BRB yielding in a given story can cause the stiffness of that story to drop, perhaps significantly. This drift concentration is undesirable because it could lead to global instability caused by P-Delta effects, or it could cause potentially problematic residual drift. There are currently no specific U.S. provisions to address this concern. However, Canadian design provisions for BRBFs, which are otherwise similar to U.S. provisions, have an additional column design requirement. CSA S16 (CSA 2014) requires BRBF columns to be designed to resist axial forces from analysis using expected BRB capacity plus minimum additional bending moments induced by nonuniform drifts developing in adjacent stories. These moments are approximated as 20 percent of the column plastic moment strength.

Beyond the basic BRBF design provisions, several options have been proposed for preventing concentration of drift in a single story. A hybrid BRB has been studied, which uses different grades of steel in the BRB core (Atlayan 2013, Atlayan and Charney 2014). This modification is intended to provide a wider region of controlled yielding in the BRBs so that positive global stiffness is maintained up to higher drift levels. Similarly, positive global stiffness can be maintained by using a dual system that provides secondary stiffness–after the BRBs have yielded–with parallel special moment-resisting frames (Kiggins and Uang 2006, Ariyaratana and Fahnestock 2011). This BRBF-SMRF configuration, which is shown schematically in **Figure 7-1(a)**, is included as an option in ASCE 7 and places the two components of the dual system in parallel. As shown in **Figure 7-1(b)**, another type of BRBF dual system has also been proposed. This dual system configuration uses an elastic truss spine with BRBs (Tremblay 2003, Tremblay and Merzouq 2004a and 2004b). The elastic truss that spans over the height of the building causes BRB yielding to occur over multiple stories and prevents concentration of drift in one story.

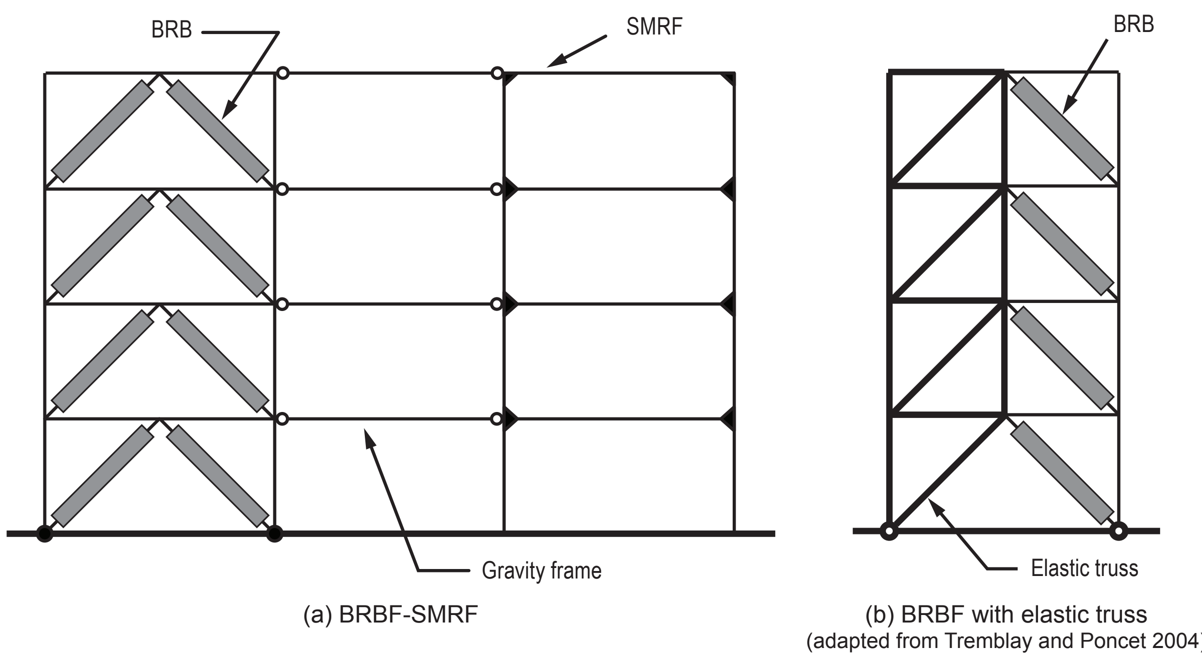


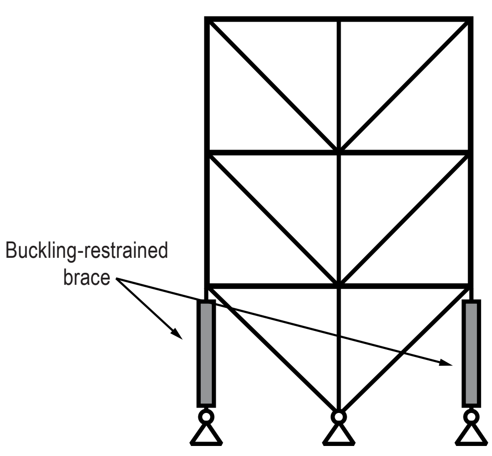
Figure 7-1. Schematic BRBF dual system configurations.

7.2 Novel BRB Configurations

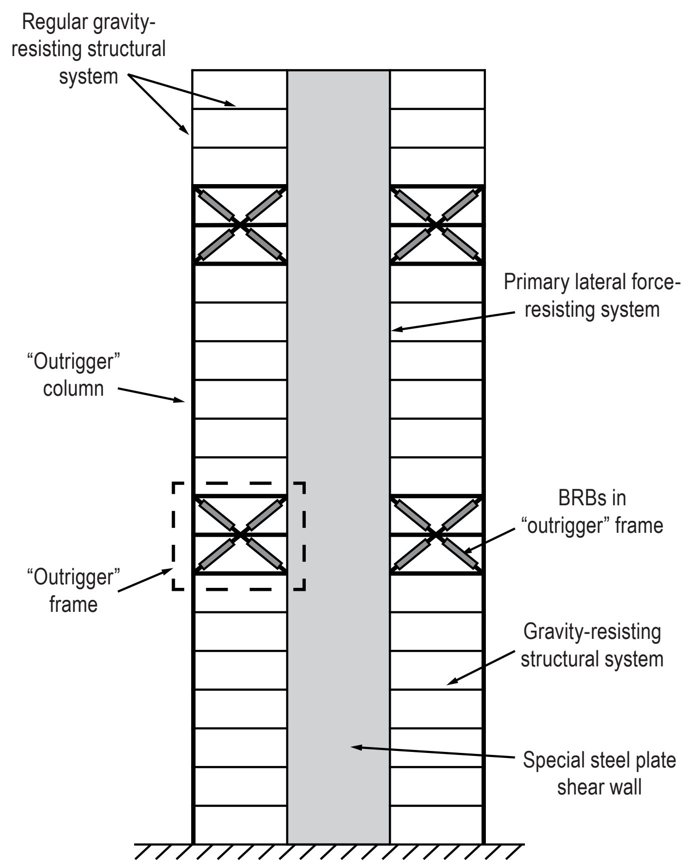
In addition to the dual system configurations presented above, BRBs may be used in other novel configurations that have not been incorporated into current design provisions. One class of application strategically positions BRBs in locations and orientations that leverage global flexural building deformations to produce axial BRB deformations. **Figure 7-2a** illustrates a configuration where BRBs are used in place of columns at the base of a taller braced frame. In this case, the braced frame uses conventional steel braces in the remainder of the frame and focuses the inelastic response and energy dissipation at the base of the frame in the BRBs. Similarly, **Figure 7-2b** illustrates a configuration where BRBs are used as energy dissipating outriggers in a tall building system. In this case, the primary seismic force-resisting system is a steel special plate shear wall, and the BRBs are used for supplementary energy dissipation. There is a wide range of related opportunities for incorporating BRBs as supplementary energy dissipation devices, including the approach employed in Japan where BRBs are metallic yielding dampers used within moment-resisting frames, BRB fuses are used as horizontal diaphragm collectors, and diagonal BRB struts are placed outside a building as a retrofit solution for a deficient seismic force-resisting system.

7.3 Performance-based Seismic Design

Although performance-based seismic design is a broader topic than BRBFs, it is of particular relevance to BRBFs because they are one of the more straightforward seismic force-resisting systems to model for nonlinear analysis procedures commonly used for performance-based design and because they can be tailored for different performance objectives at different seismic hazard levels. As performance-based seismic design becomes more common, the application for BRBFs is expected to grow, particularly for taller structures and buildings of high importance or in need of high performance. The enhancements and novel applications discussed in the previous sections provide additional system configurations that expand the range of options for consideration in the performance-based design process. In addition, these enhancements relate to system parameters and response quantities, such as post-yield stiffness and residual drift, which are not directly considered in the current code-based design framework. Performance-based seismic design provides more flexibility to the design engineer in proportioning a seismic force-resisting system. BRBFs employed in a hybrid or dual configuration or BRBs employed in more novel arrangements as fuses with other systems can be adapted through choice of a variety of parameters to achieve desired performance objectives.



(a) Interior vertically-oriented BRBs at base of frame
(Bruneau et al. 2011)



(b) Exterior outrigger BRBs

Figure 7-2. Novel BRB configurations.

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9. Notations and Abbreviations

A_{sc}	cross-sectional area of the yielding segment of steel core
C_d	deflection amplification factor as given in ASCE 7
F_{cr}	critical stress
F_{ysc}	specified minimum yield stress of the steel core or actual yield stress of the steel core as determined from a coupon test
h_{sx}	story height
KF	stiffness modification factor
L_{wp}	brace work-point length
L_y	length of the yielding segment of steel core
P_u	required axial strength
P_{ysc}	axial yield strength of steel core
R	response modification coefficient as given in ASCE 7
T	fundamental period of the structure
V	design base shear
YLR	yield length ratio
α	brace angle of inclination with respect to the horizontal
β	compression strength adjustment factor
ϕ	strength reduction factor
Δ_x	design story drift
Δ_{bx}	BRB deformation
ε_{sc}	core strain
ε_y	yield strain
θ_x	design story drift angle
Ω_0	overstrength factor as given in ASCE 7
ω	strain hardening adjustment factor

AISC	American Institute of Steel Construction
ASCE	American Society of Civil Engineers
ASD	Allowable Strength Design
ATC	Applied Technology Council
BRB	Buckling-Restrained Brace
BRBF	Buckling-Restrained Braced Frame
CBF	Concentrically Braced Frame
CUREE	Consortium of Universities for Research in Earthquake Engineering
EBF	Eccentric Braced Frame
ELF	Equivalent Lateral Force
EOR	Engineer of Record
IBC	International Building Code
LRFD	Load and Resistance Factor Design
MRSA	Modal Response Spectrum Analysis
NRHA	Nonlinear Response History Analysis
NIST	National Institute of Standards and Technology
NEHRP	National Earthquake Hazards Reduction Program
OCBF	Ordinary Concentrically Braced Frame
SCBF	Special Concentrically Braced Frame
SMRF	Special Moment-Resisting Frame
SDC	Seismic Design Category
SEAOC	Structural Engineers Association of California

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