Specifying Buckling-Restrained Brace Systems

BY KIMBERLEY ROBINSON, S.E.

Using the ductility of steel effectively in concentrically braced frames.

THE TERM BUCKLING-RESTRAINED BRACE (BRB) has become more common in the past few years, appearing in construction magazine articles and conference presentations. The system, the buckling-restrained braced frame (BRBF), has been used more frequently in seismic applications.

The 2008 AISC T.R. Higgins lectureship awardees were honored for their paper on the topic. BRBFs are a codified system covered by both ASCE/SEI 7-05 and ANSI/AISC 341-05. Yet even after so much recent information has appeared on this topic, many engineers still ask: "What is a BRB? Why consider using a BRBF? How do you specify this system?"

Anatomy of a BRB

The main characteristic of a BRB is its ability to yield both in compression and in tension. It is manufactured with two main components that perform distinct tasks while remaining de-coupled. The load-resisting component of a BRB is a steel core restrained against overall buckling by an outer casing filled with concrete, which is the stability component or restraining mechanism. These elements are illustrated in Figure 1. Bonding of the steel core to the concrete is prevented in the manufacturing process to ensure that the BRB components remain separate to prevent composite action that would change the behavior. Otherwise, the BRB would behave like a composite brace, which would still be expected to buckle.

The BRB is placed in a concentrically braced frame, which thus becomes a buckling-restrained braced frame (BRBF) lateral force resisting system. This system typically is used for structures in seismic demand category D, E, or F, regardless of whether wind or seismic loads govern the design of the structure. BRBF systems also have been explored for low seismic applications.

BRBF systems exhibit robust cyclic performance and have large ductility capacity, which is reflected in its seismic response factor R of 8 when the beams in the lateral force resisting frame are moment connected to the columns; R of 7 is applicable when they are not. Testing performed on BRBs to date has suggested that BRBs may even be capable of withstanding multiple seismic events without failure.

Designing and Specifying a BRBF

The design of a BRBF system is straightforward. Engineers typically use the Equivalent Lateral Force procedure provided in ASCE/SEI 7, unless a more rigorous analysis method is selected. The approximation of the structural period T_a should use C_r and x values from Appendix R of ANSI/AISC 341-05, because these values were mistakenly omitted from ASCE/SEI 7-05. A good reference on the methodology of designing with BRBs is *Seismic Design of Buckling-Restrained Braced Frames*, the paper that merited its authors Walterio López and Rafael Sabelli, the 2008 AISC T.R. Higgins lectureship award.

What Should be Included in BRBF Design Drawings?

One of the questions frequently asked on BRBF projects is what information must the structural engineer of record (SER) include in the design drawings to obtain the intended performance. Certain information is necessary to ensure that BRBs can be accurately estimated, priced, detailed, and erected. This includes BRB quantities, sizes, lengths and end connection types. Other information is necessary to ensure that the BRBs provided meet the design intent and are adequate for the seismic response of the structure. This includes design factors and maximum allowable strength adjustment factors. Clearly, it is in the best interest of the SER to communicate design assumptions, acceptance criteria, and interpretation of the requirements of ANSI/AISC 341-05.

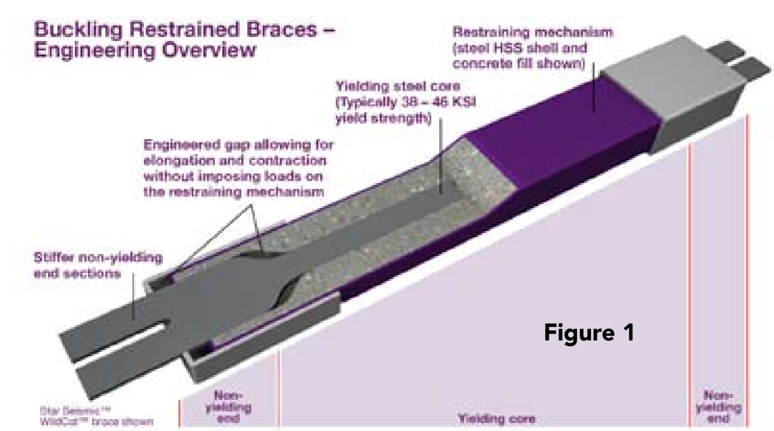

Figure 1

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The following list describes what to include in the design drawings to help make the project a success. Figure 2 provides an example of a BRB Schedule that effectively communicates several of these items.

1. *Seismic design parameters and analysis procedure employed.* Information such as the values of R, C_d, I, and ρ used, and that the analysis was conducted using the equivalent lateral force procedure or nonlinear dynamic analysis, is important in the accurate determination of design brace strains.

2. *Permissible range of steel core yield strength, F_{ysc}.* A range of 38 ksi ≤ F_{ysc} ≤ 46 ksi is generally the accepted practice. However, it is advisable to contact a BRB manufacturer to discuss the recommended range. See Figure 2, note 3.

3. *Permissible variability in BRB required strength.* There are two options for complying with the BRB strength requirements in AISC 341. Option 1 involves maintaining a constant steel core area (A_{sc}) and allowing F_{ysc} (and P_{ysc}) to vary as stated above. Option 2 involves allowing F_{ysc} to vary and compensating by adjusting A_{sc} such that P_{ysc} remains constant. Option 2 results in lower BRB overstrength but also results in a wider variation of BRB stiffnesses. BRBs with identical specified strengths may have stiffnesses that vary by as much as 15 to 20%. If not controlled, this may result in a different load distribution than what was assumed in the design phase, which can lead to unintentional soft stories or torsional behavior. See the table in Figure 2 and schedule note 2.

4. *Permissible variability in BRB stiffness.* Specify either a minimum stiffness or both a minimum and a maximum stiffness. This can be given as a stiffness modification factor (KF) in the drawings, or as a K_{eff} value. Whatever approach is taken to present the stiffness, the SER should provide guidance on how the BRB manufacturer should use the information given. See Figure 2, note 4 for one possible method.

5. *Definition of methodology for determining BRB strains.* Calculated BRB strains should be smaller than those associated with successfully-tested braces. As a result, the BRB manufacturer determines BRB strains to verify code compliance and should be required to document submit proof of this compliance (see Figure 2, note 1). The most common methods used to determine brace deformations are noted below, but there are certainly other ways that this information can be conveyed. See Figure 2, note 5.

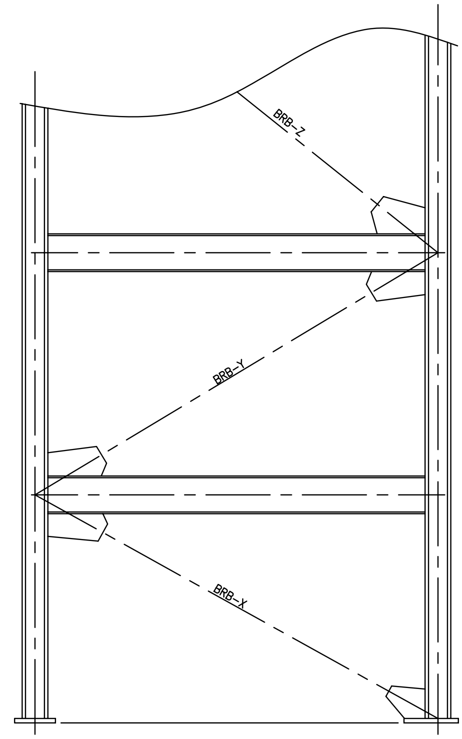
a) Use the relationship: $\Delta_{bservice}=P_{service}/K_{eff}$. $P_{service}$ can either be obtained from the SER during the design process or approximated by the BRB manufacturer if the importance and redundancy factors are shown in the design drawings.

b) The BRB manufacturer can calculate Δ_{bm} from building drifts. It is important to note that compliance with code drift limits is the responsibility of the SER and that the BRB manufacturer is only a user of the building drift data. The SER has control of and responsibility for the structural analysis model including accurate modeling of feasible BRB stiffnesses.

6. *Maximum permissible BRB strength adjustment factors.* Frame beams, frame columns, and BRBF connections are checked using BRB-dependent strength adjustment factors ω, β, and ωβ. These factors can be obtained from BRB manufacturers early in the design of the structure. To guard against imposed forces that are greater than those assumed during design, maximum permissible values for β and ωβ factors should be shown in the design drawings. See Figure 2, note 6.

7. *BRB connection details (even in skeleton format) that include work-point location and beam/column connection configuration.* If requested by the SER, BRB manufacturers will design and detail the connection of the brace to the gusset plate and may design and detail the entire gusset plate connection. To accomplish that, a minimum level of information on the design drawings is required. Connection limit states that include gravity and drag loads remain the responsibility of the engineer providing connection design for the structure.

Figure 2– Braced Frame BF-1



Braced Frame	Brace Type	P_u (kips)	A_{sc}	Stiffness Modification Factor (KF)
BF-1	BRB-X		X	
	BRB-Y		Y	
	BRB-Z		Z	

BRB Schedule Notes

1. Buckling restrained braces are to be tested per the provisions of AISC 341-05. Supplier to submit proof of each brace's compliance with the qualified load and strain ranges.

2. P_u given is the governing code level force in the brace, using LRFD force levels $P_u \leq 0.9\, A_{sc}\, F_{y\,min}$.

3. F_{ysc} is the actual yield stress of the steel core as determined by a coupon test. 38 ksi ≤ F_{ysc} ≤ 46 ksi. Charpy testing required when thickness of the core material exceeds 2 in.

4. Brace stiffness K_{eff} to be $KF \times (A_{sc}E\,/L)$ ±10%, where the values for Stiffness Modification Factor (KF) and A_{sc} are taken from the table and L is the workpoint–workpoint length of the brace.

5. Brace strains to be calculated as $P_{service}$ / K_{eff}, where $P_{service} = P_u/\rho I$ (ρ = code redundancy factor and I = code importance factor).

6. Maximum ωβ not to exceed X.XX. Maximum β not to exceed X.XX.

Lessons Learned From BRBF Projects

Although the process of designing and specifying BRBFs is generally straightforward, all parties can benefit from heeding the lessons of past projects to avoid re-learning those lessons at further expense. With that in mind, two recommendations are presented below.

1. Clearly state the force level for any forces given in the design drawings. Problems with design or pricing of BRB projects have been encountered because the force level given in the documents was ambiguous. Sometimes this force level is stated as a P_u value, or the actual load taken from the model and perhaps rounded up to make fewer brace types. The value may be a P_{ysc} force level, or the actual force level at which the engineer requires the brace to yield (which must be greater than or equal to P_u/ϕ). P_u or P_{ysc} may be obtained using either ASD or LRFD design. It is recommended that the design drawings include both the design approach used (ASD vs. LRFD) and an equation showing the manufacturer how it is intended that the loads given are to be used. For example, see Figure 2, note 2.
2. During the design phase, verify with the BRB manufacturer that BRB stiffnesses specified are feasible. Occasionally, the engineer specifies a BRB stiffness that cannot be accomplished at the required BRB strength. Sometimes the steel core area specified results in a BRB stiffness that is much higher or much lower than what is specified in the design drawings. The lack of understanding of what is achievable in terms of stiffness has resulted in the SER having to redo analyses with more accurate BRB stiffness values. See additional discussion in the sidebar "Accounting for BRB Stiffness."

Although BRBF design and specification is not complex, there are always things to learn with any new structural system. On a regular basis BRB manufacturers work with engineers who are unfamiliar with BRBF design. BRB manufacturers are eager to assist in any way possible to make the process easier for the design professional.

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Accounting for BRB Stiffness

In the modeling of any structural system, simplifying assumptions are made that will yield results that are considered close enough to predicting the actual performance of a structure. Connections that are semi-rigid may be considered stiff enough to be treated as rigid; brace lengths are considered to extend from work-point to work-point; panel zone flexibility may be accounted for in an approximate way; etc. With a buckling-restrained brace (BRB) project, it is possible to arrive at very accurate modeling parameters that closely reflect the linear-elastic (or post-elastic) behavior of a structure. It is also possible to model a structure in such a manner that the actual behavior varies significantly from what was assumed during the modeling process (see Figure 3). The ability to correctly model the stiffness of the BRBs usually depends on the communication between the structural engineer of record (SER) and the BRB manufacturer during the modeling process.

When modeling the BRB elements in structural analysis software, the stiffness of the braces used in the frame should be taken into account. Overall brace stiffness is determined by analyzing the two stiffer end segments that are "non-yielding" and the less stiff center yielding core segment (see Figure 1, previous page). The steel core area (A_{sc}) can be selected based on the brace load using the equation: $A_{sc} \geq P_u/(\phi F_{ysc\text{-}min})$. However, if A_{sc} is input into the analysis software with the typical modulus of elasticity of steel, E = 29,000 ksi, building drifts will be overestimated by the model, and the seismic forces will potentially be underestimated.

Modeling programs use either an input spring stiffness K or the stiffness equation $K=AE/L$. If the brace is modeled using an area of steel and modulus of elasticity (as is usually done), engineers working on BRB projects usually incorporate the stiffness of the braces and connections by providing either a larger steel area than the steel core area or a higher modulus of elasticity than 29,000 ksi. The factor that is used to increase either A_{sc} or E is sometimes referred to as a stiffness modification factor, *KF*. This factor is determined based on bay geometry, connection size, brace type and length of the yielding core. Figure 4 demonstrates how this factor can vary from frame to frame and brace type to brace type (note that two different brace types are shown). Generally, the brace stiffness will be expected to vary slightly from the model and only a few *KF* factors will be used to simplify the modeling process.

It is not expected that the SER determine what the *KF* factors or the brace stiffness *K* should be. This is even discouraged. All brace manufacturers currently producing in the United States provide this service free of charge and engineers are encouraged to contact them to discuss their models. Some building officials even require this coordination to take place prior to approving the structure for permit.

Figure 3

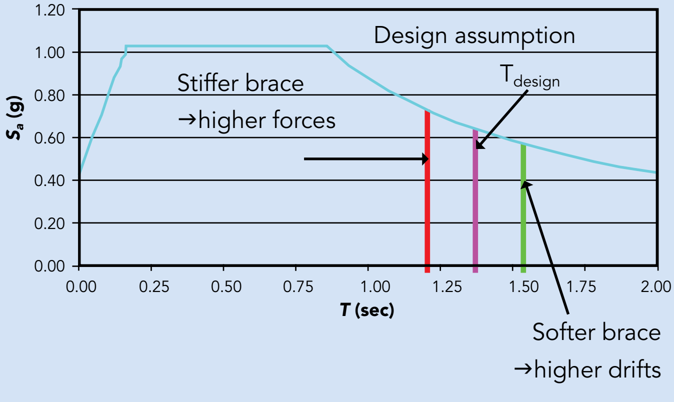

Figure 4