No Buckling Under Pressure

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A unified design approach to buckling-restrained braced frame design.

THE BUCKLING-RESTRAINED BRACED FRAME (BRBF) has come a long way since its introduction to the U.S. market in the late 1990s.

It was codified as a lateral-force-resisting system when it was included in ASCE 7-05 and AISC 341-05 and has been incorporated in more than 450 U.S. buildings to date, with many more projects around the globe. The system's critical element, the buckling-restrained brace (BRB), harnesses the inherent ductility of steel to provide stable and predictable dissipation of seismic energy without reliance on a global brace-buckling mechanism employed in other concentrically braced frame systems. Although BRBs can be used wherever higher ductility and energy dissipation is desired (such as bridge, outrigger or blast designs), they are typically incorporated as part of the BRBF system.

Necessary Coordination

The typical approach to designing BRB projects involves coordination between the engineer of record and one or more of the BRB manufacturers. This coordination has generally been necessary because designing with BRBs is highly dependent on various characteristics of the brace itself, which often differ between the manufacturers or even between braces with different connection types provided by an individual manufacturer. It is essential that design engineers incorporate appropriate BRB attributes into their design to ensure that a BRB manufacturer can make a brace that meets the specified design criteria. Doing this after the fact often leads to redesign that could have been avoided.

The flowchart ("Typical BRB Design Process Flowchart," on page 53) shows the typical design process for a BRBF project, demonstrating the flow of information back and forth between the design engineer and the BRB manufacturer. Domestic brace manufacturers typically do not charge for this service. Though the input from the brace manufacturer may include a variety of important contributions to the design, there are three critical design items that must always be considered: brace stiffness, brace overstrength factors and verification of testing coverage for the proposed braces.

Brace stiffness and modeling. For an ordinary or special concentrically braced frame, brace stiffness is determined using the simple equation:

$$K_{\text{model}} = \frac{AE}{L_{wp\text{–}wp}}$$

where A and E are functions of the brace cross section, and $L_{wp\text{-}wp}$ is the workpoint-to-workpoint distance along the axis of the brace between beam and column centerlines. The determination of brace stiffness is automatically done as part of most structural design software packages. However, BRBs are non-prismatic, with regions of different stiffness along the length of the brace. Brace strength is controlled by the area of the brace yielding core, but the use of the yielding core area in the structural model over the entire workpoint-to-workpoint length without any adjustment will not correctly capture the effective stiffness of the brace. This effective stiffness is usually captured in the model through the use of a stiffness modification factor (KF). The effective brace stiffness is then represented by the equation:

$$K_{\text{model}} = \frac{KF\,(A_{sc})E}{L_{wp\text{–}wp}}$$

where A_{sc} is the yielding steel core area. Effective brace stiffness (in units of k/in.) can also be obtained directly from the manufacturer.

The effective brace stiffness is unique to each brace manufacturer's design, although it may be similar between manufacturers. It is also dependent on brace capacity, bay geometry and connection details. Additionally, BRB manufacturers can control the effective stiffness of their braces within certain limits. In the typical process, the design engineer will assume an initial value for this factor for early estimation of required brace capacity and preliminary sizes of beams and columns. This preliminary design information is then sent to a brace manufacturer for early coordination to verify initial assumptions or to obtain recommended stiffness factors for the braces. If brace capacities, frame geometry or beam or column sizes are adjusted as the design process continues, final stiffness values should be confirmed with the manufacturer prior to finalizing design.

Brace overstrength factors. For the BRBF system, the brace is designated as the ductile "fuse" element, and all other parts of the frame and connections are designed to remain elastic. As the BRB engages in a seismic event, the steel core yields and then strain hardens. This process requires the beams, columns and connections to be designed for the higher forces present in the strain-hardened braces. The relationship between the strain-hardened force and the initial brace yield force is represented by the factor ω in tension, and $\beta\omega$ in compression. These factors are determined based on analysis of the testing required by AISC 341. Brace overstrength factors also vary by brace manufacturer and even by brace connection type.

Verification of testing coverage. Many qualification tests have been performed to date by all domestic BRB manufacturers covering a wide range of configurations that would be encountered in most projects. BRB manufacturers provide input when proposed braces are outside the range of qualification testing by recommending ways for the project to be reconfigured to alleviate the concerned braces. They also provide language for the project specifications requiring additional testing, or, as allowed by the code, provide analysis demonstrating that the larger brace has stress distributions and magnitudes of internal strains consistent with or less severe than the tested assemblies, which then allows for extrapolation beyond the tested limits.

Unified Design Process

As BRBs have become more common, some design engineers have sought an alternative to the typical design approach described above. Although coordinating with a manufacturer will nearly always lead to a more economical design, an alternative approach has been suggested in order to provide benefits to design engineers, including:

- improving the initial estimates of stiffness and overstrength enabling designers to conduct analysis with greater confidence
- maintaining confidentiality of discrete projects
- allowing design to a general set of parameters that can be achieved by all manufacturers within enlarged tolerances

In response, BRB manufacturers have collaborated with design engineers to develop a unified design methodology to allow design engineers to do more without the direct input from a BRB manufacturer. This procedure was presented at the 2012 NASCC: The Steel Conference and is available for viewing on the AISC website at **www.aisc.org/uploadedcontent/2012NASCCSessions/N38**. Key components of the unified design methodology include relationships that can be used


Courtesy of Star Seismic

Pin-connected BRBs.

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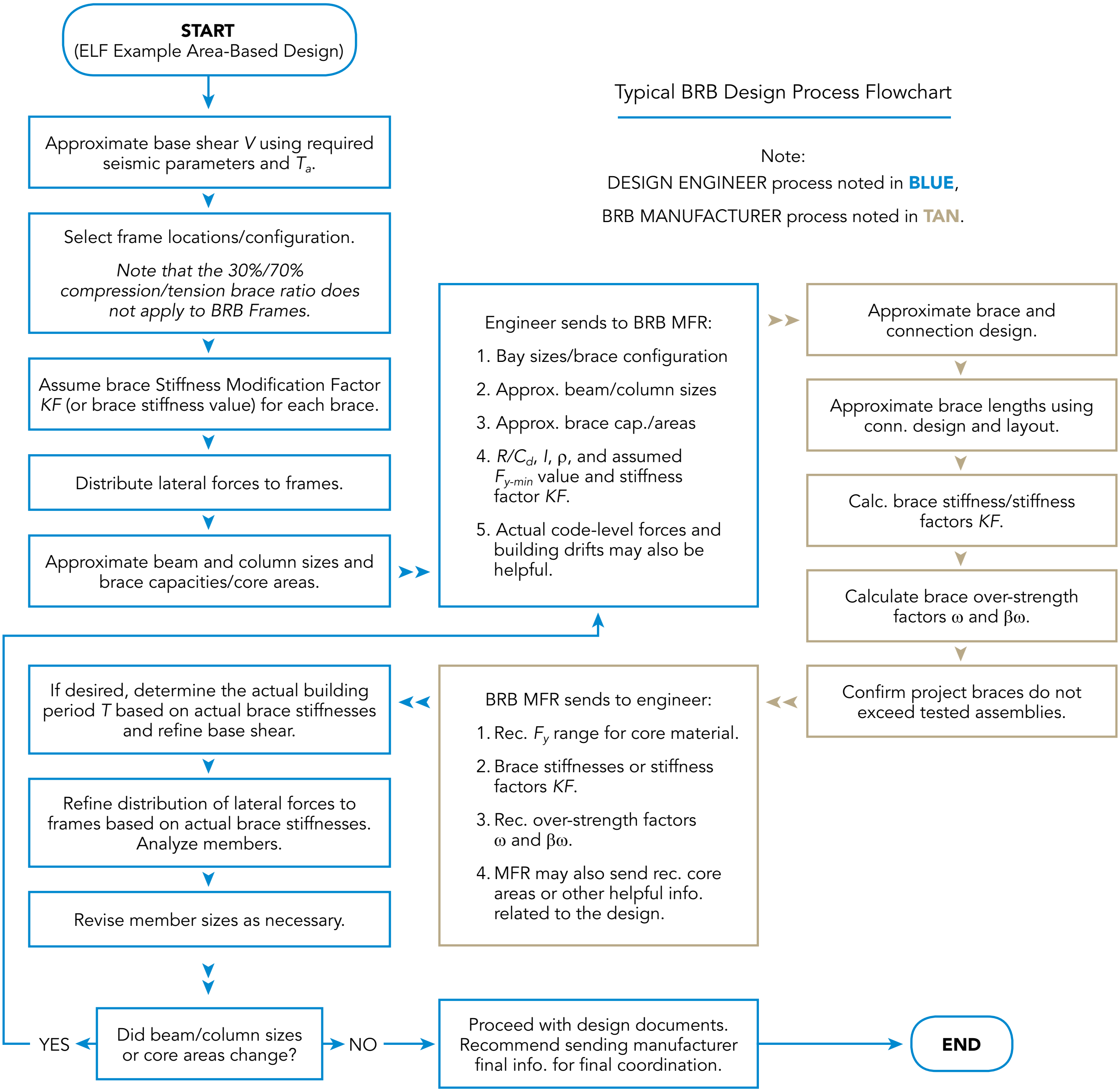
to estimate critical factors such as effective BRB stiffness and overstrength factors relative to common combinations of variables like brace strength, frame geometry and connection type. While any generalized design process will inherently contain some conservatism compared to use of specific parameters, the goal was to balance and limit the level of conservatism with the benefits of the approach listed above.

In order for the design engineer to estimate brace properties without the input of a BRB manufacturer, the steps outlined in tan in the flowchart must be adopted by the design engineer. The unified approach provides tools and equations allowing the design engineer to step through the process of estimating the properties of the braces incorporated in a BRBF frame.

This process demonstrates reasonable correlation with the estimation of effective brace stiffness and the estimation of overstrength factors using AISC 341-05. However, AISC 341-10 includes a new

Architecturally exposed, bolted-end BRBs.

Courtesy of CoreBrace



requirement stating that in addition to the requirement that brace overstrength factors be determined from 2 times the design story drift, these factors must also take into account a minimum drift of the structure of 2%. Since most BRBF structures are not controlled by drift, this revision has greatly affected the overstrength factors in ways that are not necessarily predictable. In its current form, the unified design methodology does not include a process to estimate these values, given this new requirement. The BRB manufacturers will continue to work closely with those involved in the development of the code to address the concerns related to the new 2% minimum drift criterion. In the meantime, engineers are encouraged to coordinate overstrength factors with the manufacturers if AISC 341-10 is required for the project.

Whichever method an engineer decides to use for the design of a BRBF project, it is recommended that a manufacturer be consulted to review the BRB design prior to finalizing the project design and contract documents in order to verify that there are no concerns. Doing so can save potential headaches that might otherwise arise in the construction phase. MSC

*This article is a summary of the 2012 NASCC: The Steel Conference session "Unified Design Approach to Buckling Restrained Braced Frame Design." To view a PowerPoint presentation of this session, with audio, visit **www.aisc.org/uploadedcontent/2012NASCCSessions/N38**.*