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Design of Buckling-Restrained Braced Frames

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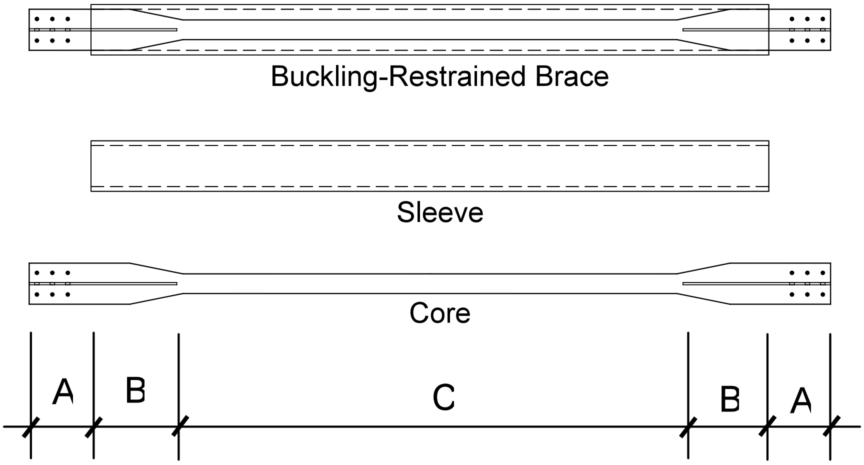
Buckling-restrained bracing elements offer designers a way to add even more seismic energy dissipation capacity to braced-frame systems.

The Buckling-Restrained Braced Frame (BRBF) is a relatively new type of concentrically braced frame system. BRBF use the ductility of steel more effectively than conventional braced frames, such as Special Concentrically Braced Frames (SCBF) or Ordinary Concentrically Braced Frames (OCBF), which depend on brace buckling for their ductility. Buckling-restrained braces have been used extensively in Japan as hysteretic dampers within moment-resisting frames. These braces were introduced to U.S. design practice in 1999, and their use has been mostly as a building's primary seismic-load resisting system.

The Need for a Better CBF

The concentrically braced frame (CBF) is one of the most efficient lateral-load resisting systems. However, CBFs are known to be prone to many non-ductile modes of behavior when subjected to large ductility demands. Such modes include connection failure, member fracture, and severe loss of strength and stiffness due to beam ductility from unbalanced tension and compression strengths. Traditionally, CBFs have been treated as high-strength, low-ductility systems. In recent years, building-code provisions explicitly have recognized methods of preventing or forestalling undesirable modes through proper design, proportioning and detailing of concentrically braced frames to create a more ductile system. A new category, "Special Concentrically Braced Frames," was introduced, incorporating many of the recommendations resulting from testing at the University of Michigan.

In frames designed according to SCBF requirements, the primary source of the frame's ductility is axial inelasticity of the braces, in both tension and compression. While tension yielding of braces can be considered a fairly ductile ele-



Schematic diagram of buckling-restrained brace.

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Buckling-restrained brace gusset connection.

ment behavior, compression buckling results in dramatic degradation of brace capacity and stiffness, and the associated plastic hinge formation in the brace is responsible for eventual brace fracture. Buckling of braces represents a severe limitation to their ductility and the performance of the system.

Additionally, the imbalance between compression capacity and tension capacity, significant in the elastic system and dramatic after buckling, can lead to undesirable system response. Frames with single diagonals are prone to accumulate inelastic drift in the direction in which the brace is loaded in compression. V and inverted-V braced frames are subject to loss of stiffness as beams are called upon to resist the unbalanced forces resulting from the difference between the capacity of the brace in tension and the (possibly degraded) capacity of the brace in compression. For multistory SCBF, the stiffness and strength degradation of a brace in compression will result in subsequent concentrations of inelastic drift at that level. For all SCBF, the degradation of the braces increases the susceptibility to extreme response; fracture of braces can result in very low confidence levels of adequate performance.

Advantages of a BRB

By contrast, buckling-restrained braces (BRBs) do not exhibit any unfavorable behavior characteristics of conventional braces. Buckling-restrained braces have full, balanced hysteretic behavior, with compression yielding similar to tension-yielding behavior. They achieve this through the decoupling of the stress-resisting and flexural-buckling-resisting aspects of compression strength. A shaped steel core resists axial stresses. A sleeve, which can be of steel, concrete, composite, or other construction, provides the core with buckling resistance. Because the steel core is restrained from buckling, it develops almost uniform axial strains across the section. The plastic hinges associated with buckling do not form in properly designed and detailed BRBs. This also permits BRBs to be designed to develop very high compression strength. Because there is no reduction in the available material strength due to instability, the effective length of the core can be considered zero.

For some commonly used BRBs, the core is divided into three zones: the yielding zone, a reduced section within the zone of lateral restraint provided by the sleeve; transition zones (of larger area than the yielding zone and similarly restrained) on either side of that yielding zone; and connection zones that extend past the sleeve and connect to the frame, typically by means of gusset plates.

In order to accommodate axial yielding of the steel core, and to prevent instability of the sleeve, the detailing of BRB end connections must be able to transmit forces to the core without permitting significant stress to develop in the sleeve. The end connections also must be designed to preclude modes of overall brace instability; therefore, they are designed to have greater yield strength than the core within the sleeve so that yielding is confined to a limited length of the core. Because the length of the yielding zone changes when the BRB is subject to inelastic deformation, the ends of the sleeve are detailed so that the larger area of the core does not bear on it under expected deformations.

By confining inelastic behavior to axial yielding of the steel core, the brace can achieve great ductility. The ductility of the steel material is realized over the majority of the brace length. Thus the hysteretic performance of these braces is similar to that of the material of the steel core. Braces with core materials that have significant strain hardening also will exhibit strain hardening.

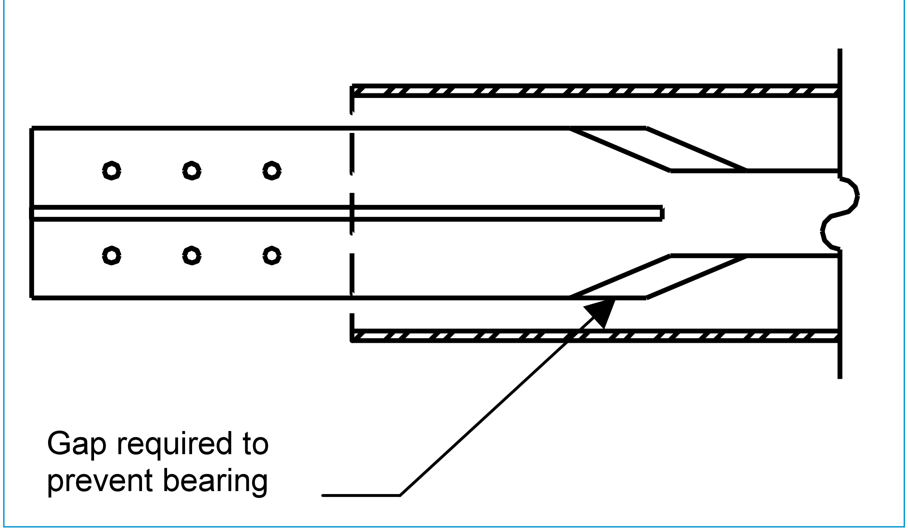
Because the strains are not concentrated in a limited region such as a plastic hinge, the braces can dissipate large amounts of energy. Testing has established the braces' low-cycle fatigue life; this capacity is well in excess of demands established from nonlinear dynamic analysis.

Such analyses also show that using braces with this type of hysteretic behavior can lead to systems with very good performance. Drifts are expected to be significantly lower than for SCBF, due largely to two aspects of BRBF behavior. First, inelastic demands are distributed over multiple stories due to the ability to provide near uniform brace demand-to-capacity ratios. Second, BRBs are not subject to fracture under the demands imposed by the considered earthquakes when they are designed according to current U.S. practice. BRBF response to seismic loading provides a much higher confidence level in adequate performance than does the behavior of SCBF.

Analytical studies of the response of BRBF also have been used to estimate the maximum ductility demands on BRBs. BRBs must be designed and detailed to accommodate inelastic deformations without permitting undesirable modes of behavior, such as overall instability of the brace or bearing of the non-yielding zones of the core on the sleeve.

Design of BRBF

Buckling-restrained braced frames (BRBF) are designed using an equivalent lateral force method. As in the design procedure for other concentrically braced frame types, a reduced seismic load is applied to a linear elastic model to determine the frame's required strength and stiffness. For common building types, this system tends to be governed by strength. For BRBF with braces proportioned according to this method, the difference between the elastic- and inelastic-deformation modes is much less dramatic than for SCBF. Because of this, an inelastic (nonlinear) analysis typically is not required, although such an analysis can give a much better estimation of brace ductility demands.



Brace end detail.

Typically, frames are modeled using software or by hand, as seismic loads are resisted by axial forces in the frame and bracing members. (Frames with slight eccentricities at the connections have not been used extensively, although they are permitted; flexural forces resulting from such a condition must be addressed.) It should be noted that beam-column connections are closer to a "Type 1" (fully-restrained) condition than a "Type 2" (pinned) condition. Therefore, it is appropriate to consider the flexural forces resulting from this restraint for both member and connection design. Designers must demonstrate Type 2 connections to accommodate rotations. This applies to all braced frames with gusseted connections.

Explicit modeling of the gusset plate is not necessary for typical design. However, modeling it as a rigid offset is helpful: It facilitates estimation of brace connection rotations necessary to establish the adequacy of a tested brace design; and it is useful in modeling the true brace stiffness, since only the yielding segment of the brace contributes significantly to its flexibility.

Designers have created more sophisticated models of gusset plates for higher performance. Finite-element models explore the rotational capacity of gusseted connections in order to demonstrate adequate performance of the frame at significant ductility. The performance of these connections requires more research.

Braces with sufficient ductility (both maximum and cumulative) to withstand the demands of seismic loading are required for the analysis to be valid. To ensure this degree of ductility, brace designs are based on successful tests, which exhibit full, stable, hysteretic behavior with only moderate compression overstrength while demonstrating the required ductility and dissipating a specified amount of energy.

Once BRBs have been designed for adequate strength, other frame members can be designed using capacity-design principles. The forces corresponding to the maximum expected forces that the braces can develop for their expected deformations are used as the required strengths of beams, columns, and bracing connections.

These maximum expected brace forces can be significantly higher than the brace design force due to oversizing of the brace for stiffness, use of a resistance factor, brace-compression overstrength, and, most significantly, strain hardening of the brace at large deformations and under repeated cyclic inelastic loading. These last two contributions are determined from the results of BRB tests used to qualify the braces used in the construction.

The design of BRBF is not governed by any building code, but recommended provisions are available. A joint AISC/SEAOC (Structural Engineers Association of California) task group developed recommendations, with the intention of including them in the 2005 edition of the AISC Seismic Provisions for Structural Steel Buildings. These BRBF design provisions (the Recommended Provisions) are also under review for inclusion in the 2003 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures. The provisions contain requirements corresponding to the design procedures described above; they also contain detailed testing requirements for establishing the adequacy of BRBs. The Recommended Provisions will be published in AISC's *Engineering Journal* this year.

Researchers and manufacturers have developed several BRB brace types commercially available in the United States. The brace connections to the gussets can be a fixed- or pin-end type. Braces can have a single steel core, or multiple cores in single- or multiple-joined sleeves. Cores can be a single plate, a rod, a reduced shape, or a built-up section; core orientation also can be varied. Sleeves can be bare steel, concrete, or a combination of the two. Several methods of preventing stress transfer to the sleeve also have been developed. Since use of any BRB is predicated on successful testing, all BRB types are admissible.

BRBF can have braces in many configurations. Because there is no strength or stiffness degradation permitted in the braces, and because the tension and compression strengths are almost equal, the single-diagonal configuration is permitted without any penalty. The single-diagonal configuration is also an effective way to take advantage of the high strengths possible for BRBs. K-bracing is not permitted.

The chevron (V or inverted-V) configuration is also popular for BRBF, as it maintains some openness for the frame. Because of the balance between brace tension and compression strength, the beam is required to resist only modest loads; a deflection limit also is imposed to prevent excessive vertical beam displacement.

Other configurations of BRBF are possible. BRBs can be combined with conventional braces as long as designers confine the ductility demands to the BRBs.

Testing

Because the design of buckling-restrained braced frames is predicated on the excellent hysteretic behavior of the braces, to assure that performance, the Recommended Provisions mandates testing the braces.

Testing is intended to verify that the buckling-restrained brace employed can function as intended, providing adequate maximum and cumulative ductility capacity, including any required rotational deformations. Testing also evaluates the quality-control methods used in the production of braces, and establishes overstrength factors for design.

Although the Recommended Provisions address the hysteretic behavior of the braces, the testing requirements are directed to assure that certain failure modes do not limit the performance of the brace and the system. These include global modes, like overall brace instability, and local modes, like bearing or binding of the connection, which would prevent the steel core from yielding at the anticipated force level.

Specification

Buckling-restrained braces typically are manufactured rather than built—a specialty manufacturer, rather than a contractor or steel fabricator makes them. Specifications should address the furnishing of the braces, including associated brace-design calculations and quality-control procedures, and the documentation of successful tests that qualify the furnished braces for use in the project.

When BRBF were introduced into U.S. practice, there was only one manufacturer on the market. Today there are enough manufacturers to permit competitive bidding, so there is no need to specify a sole source or to provide an alternative structural system for competitive bidding.

As mentioned, the testing requirements are delegated to the brace manufacturer. Manufacturers have developed many tests, and for most projects, they can provide braces without project-specific testing.

There is a great deal of proprietary knowledge in the design and manufacture of buckling-restrained braces, so designers and manufacturers should establish a relationship that assures the designer that braces are being designed and assembled competently, and assures the manufacturer that trade secrets are not being revealed. It is in the designer's interest to require that manufacturers document their design and quality-control methodology, and follow it in the production of the prototype braces (a requirement of the Recommended Provisions). Manufacturers should require that such information not be shared.

Performance Considerations

The Recommended Provisions are intended to help create buckling-restrained braced frame structures capable of performing at least as well as other systems in a seismic event; building codes characterize this performance as providing life safety. Although it is recognized that BRBF can be designed to provide superior seismic performance, this is beyond the scope of the provisions.

In the development of the provisions, additional design requirements were considered and not included because they would be radically more stringent than other systems' requirements and were not necessary to assure the basic seismic objective required by building codes. Such considerations are appropriate when higher performance goals are desired:

- Analysis of the post-elastic deformation modes and the potential concentration of ductility demands in a limited number of stories.
- Exploration of the rotation capacity of the gusseted beam-column connection.
- Exploration of the residual drift and post-earthquake utility of the structure.
- Consideration of building drift orthogonal to the braced frame and its effect on the stability of the brace and gussets.

Conclusion

Buckling-restrained braces use the inherent ductility of steel to provide system ductility by preventing extreme concentrations of inelastic strain. Frames using these braces can be designed as an effective and efficient seismic-load-resisting system. Using the Recommended Provisions developed by AISC and SEAOC, engineers can design a system with performance that is more than adequate for building-code requirements. Some specialty manufacturers have developed braces that meet the needs of designers, and have amassed a body of test data to satisfy testing requirements for many projects. Where a performance better than the life-safety requirement of building codes is desired, additional analysis and design considerations are appropriate. ★

This paper has been edited for space considerations. To learn more about blast-resistant design, read the complete text online at ***www.modernsteel.com*** *or in the 2004 NASCC Proceedings.*