Bracing for a Solid Education

BY STEVE ANDERSON, P.E., S.E.

How buckling-restrained braced frames became an integral part of one new school.

SIX BUCKLING-RESTRAINED BRACED FRAMES (BRBF) in one new Memphis, Tenn., middle school building are standing by to resist earthquake loads and dissipate energy from activity in the New Madrid seismic zone. Although the zone has not produced a catastrophic quake in nearly 200 years, it has substantial potential to do so. History recorded four magnitude 7.0 or greater events between December 1811 and February 1812.

The new 42,000-sq.-ft, two-story building will be the centerpiece of the school campus. The building's prominence and a strong desire to protect students led the design team to select the BRBF system, which is expected to provide long-term, superior performance.

The new facility includes a gymnasium, a library, a cafeteria, and classroom space. The floor framing—composite beams and girders—supports a lightweight concrete slab on composite metal deck. Light-gage metal trusses and bar joists frame the roof. Steel columns support the two levels on shallow foundations. All six BRBFs have a concentric, single diagonal brace configuration. The 12 braces in this structure are among the first used east of the Mississippi River.

The 2006 edition is the first *International Building Code* to include the BRBF system. Although the system has been available for a decade or more, obtaining building department approval often was difficult in the past because of its absence from adopted codes. BRBFs can be used in all seismic design categories. However, the braces are most advantageous in the more demanding categories (D, E and F) because they provide ductility efficiently and economically.

The brace member itself makes this system unique. It consists of two main parts: the core and its casing. Steel bars form the core and resist the seismic loads. The casing is typically a grout-filled HSS that is axially decoupled from the core and restrains it from buckling when loaded in compression. Ductile compression yielding replaces non-ductile buckling as an energy dissipating mechanism.

Because the effective length of the brace is essentially zero, and buckling is not a consideration, the brace has similar tensile and compressive strengths. Conventional braces tend to be much stronger in tension than compression because they must be sized to prevent buckling. The frame elements surrounding the brace are designed to remain elastic when subjected to the maximum forces that the brace can generate. Because the steel cores of these braces do not contain the excess material normally required to prevent buckling, the frame beams, columns, connections and foundations are designed for much smaller forces. The smaller design forces lead to material and cost savings and more constructible designs. "Design of Buckling-Restrained Braced Frames" (March 2004 *MSC*) and the Steelwise column in the November 2009 *MSC* are good sources for more information about BRBFs.

The Process

Designing, detailing and erecting the structural steel for a building that utilizes the BRBF system is similar to other steel buildings, except the project team has an extra player: the brace supplier. Understanding the new team member's role during the design and construction administration phases helps the process run smoothly.

Unlike more common braces used in regions of high seismicity, bucking-restrained braces are proprietary members and are manufactured by, or specifically for, their supplier. They are not fabricated with the rest of the steel by the fabricator hired by the general contractor. The supplier designs, details and fabricates the braces based on strength and stiffness requirements provided by the Structural Engineer of Record (SER). The brace detailer and the contractor's steel detailer, who details all the steel but the braces, work together while preparing shop drawings so that the members fit together properly in the field.

Design

Traditional modeling and design software can be used to determine base shears, force distributions, and lateral drifts for BRBFs. For this project we used RAM Structural System. Members were added to the software's default property table to represent the buckling-restrained braces. The moment of inertia for the new brace members was assigned a sufficiently large value to preclude buckling. The new members started with a net area of steel core (A_{sc}) equal to 1 sq. in. The largest A_{sc} used was 10 sq. in.·, corresponding to a brace force of about 380 kips.

Early in the design process, the structural model is used to determine approximate brace forces and their required stiffness. This information, along with the basic frame geometries, is provided to the supplier. The supplier's brace designer requires this preliminary design information to size the casings and compute stiffness modification and overstrength factors. The casing sizes are useful for coordinating wall thicknesses, door locations, etc., with the architect. The stiffness modification factor indicates approximately how many times stiffer the real braces will be compared to the modeled braces.

The modeled braces typically have centerline-to-centerline lengths and constant cross sections. The real braces will be shorter due to the connections and panel zones; increasing their stiffness. The overstrength factor accounts for higher than specified yield strengths, strain hardening, and lab testing results to indicate how many times stronger the braces may be relative to their axial strength, $P_{ysc} = F_{ysc} A_{sc}$. The overstrength factor multiplied by the axial strength results in the Adjusted Brace Strength. Depending on the brace sizes and frame geometries, the stiffness modification and overstrength factors may differ for each brace.

The information obtained from the brace supplier is incorporated into the structural model to study the effect of the stiffness modification factor(s) on story drifts and lateral force distributions. If the brace forces change significantly, it may be necessary to provide them to the supplier again to confirm the initial modification factors. When determining the required stiffnesses it is important to remember that the code allows the importance factor, I, and redundancy factor, ρ, to be divided out of the drift level seismic forces. Also, if the computed fundamental period of the structure is higher than the approximate fundamental period, T_a, a higher period may be used for determining the drift level forces. The ultimate, axial brace forces, P_u, provided to the brace supplier should include I and ρ as required by the code. Figure 1 shows a typical brace elevation indicating P_u and the required brace stiffness.

The beams, columns, and brace connections in the frame are designed to resist forces calculated based on the Adjusted Brace Strengths. Load combinations were created in RAM to accomplish this for the beam and column design forces. The connec-

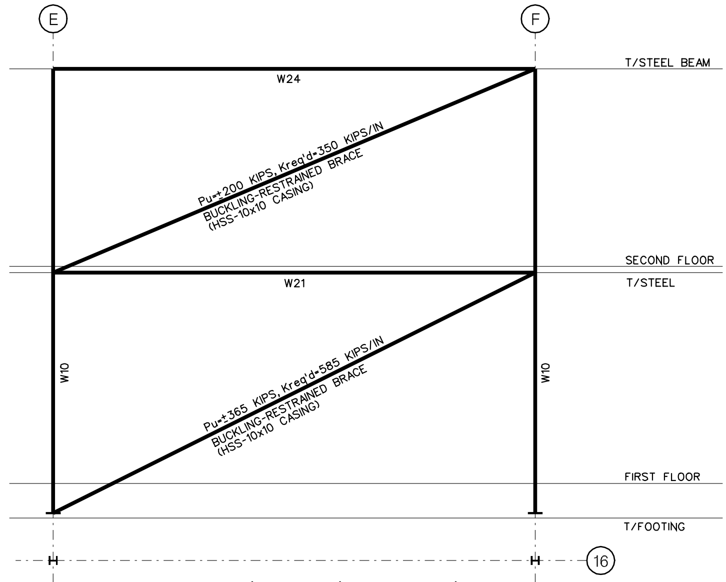

Fig. 1- Typical Brace Elevation With Required Brace Stiffness

All photos bySteve Anderson

The gray HSS10x10 casing of the brace provides the restraint to prevent the inner, more slender element from buckling.

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tion design may be performed by the SER or by the brace supplier. The supplier designed the connections for this facility.

Construction Administration

The submittal from the supplier for this project included a shop drawing for each brace, a lab report from qualifying cyclic tests, a production and quality assurance manual, a signed and sealed calculation packet for the casing and connection designs, and a connection schedule.

AISC *Seismic Provisions for Structural Steel Buildings* (ANSI/AISC 341-05) requires that the brace designs be based on test results from qualifying cyclic tests. Appendix T describes the procedures for qualifying testing, including test reporting requirements and acceptance criteria. The report submitted by the supplier should be in accordance with Appendix T and indicate that the tested braces conform to the acceptance criteria. Appendix T also requires that a manufacturing quality control and quality assurance plan be included with the test reporting. This document specifies, among other things, the materials and manufacturing procedures necessary to ensure that project braces are produced in a manner consistent with the test-qualified braces.

The calculation packet contains detailed calculations for the casings and braced frame connections. Because of the smaller design forces associated with the BRBF system, the gusset plate sizes are very reasonable. Recent code provisions for other braced systems have resulted in some enormous gusset plates, sometimes occupying the majority of a braced panel. The BRBF's smaller connections are more economical and constructible and are a significant benefit of the system. Figure 2 compares gusset plates from a BRBF and an ordinary concentrically braced frame. The connections are from similarly sized buildings in Memphis.

The connection schedule summarizes the information determined by the calculations. It provides the information necessary to completely detail the brace connections. The same schedule is provided to the structural steel detailer. It is very important for the SER to closely scrutinize the structural steel shop drawings to be sure that the brace supplier's connection design has been correctly interpreted by the steel detailer.

Lessons Learned

Brace-to-gusset connections may be welded, bolted or pinned. This structure had welded connections. The contractor chose to place the slab-on-grade prior to completing the welds. That increased the difficulty of welding at the foundation level, although the welds would have been difficult even without the slab interference. A bolted or pinned connection would have provided better connection quality and faster erection.

The final size of the column base plates in the frame is unknown until the BRBF supplier completes the gusset design. The lower gusset plate typically is welded to the column and the base plate, and its size frequently dictates a larger base plate than would otherwise be required. It is important to note this to the contractor if the plan is to place the slab-on-grade before erecting the steel because the final plate size is needed to coordinate block-outs in the slab-on-grade. Left uncoordinated, the base plates will require field modification or placed concrete will require removal.

The *Seismic Provisions* define the steel core and the elements that connect the steel core to the frame as *protected zones*. Welds, bolts, screws and shot-in attachments are prohibited within these zones. When a brace is hidden in a metal stud wall, as is commonly the case, the wall must be framed around the brace connections. Also, fasteners attaching runner tracks to the brace casing will be very short. This is because they may not penetrate the grout inside of the brace and must stop within the casing wall. Fasteners were 0.25 in. long for this structure. These conditions are not typical. Communicating them to the contractor will avoid field delays.

Conclusions

The BRBF is a promising system for seismic resistance. Now that the system is codified, an increase in its use is likely. With proper communication between team members throughout the project, the frames are straightforward to design, detail and erect. The brace's efficient use of steel leads to material and cost savings. The braces have performed well in the laboratory. Unfortunately, the first real tests will coincide with a natural disaster. What does the future hold for the BRBF system? Stay tuned. MSC

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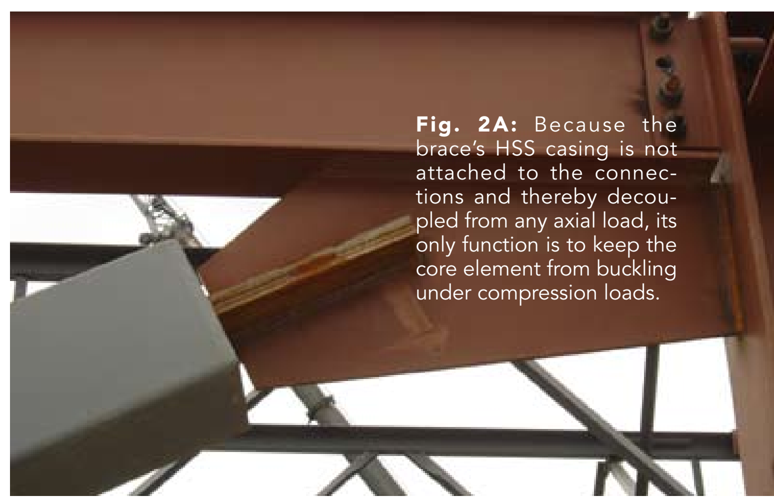

Fig. 2A: Because the brace's HSS casing is not attached to the connections and thereby decoupled from any axial load, its only function is to keep the core element from buckling under compression loads.

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Fig. 2B: During an earthquake, conventional braces typically generate larger maximum forces than buckling-restrained braces, so their connections are much larger.