BUCKLING-RESTRAINED BRACED FRAMES

Rafael Sabelli, S.E.
Walter P Moore
Oakland, California

Rafael Sabelli is Director of Seismic Design at Walter P Moore. He is a member of the AISC Task Committee on the Seismic Provisions for Structural Steel Buildings, the ASCE 7 Seismic subcommittee, and the NCSEA Seismic Code Advisory Committee. He is the coauthor of AISC Design Guide 20: Steel Plate Shear Walls, as well as the author of numerous research papers on conventional and buckling-restrained braced frames. Rafael was the 2000 NEHRP Professional Fellow in Earthquake Hazard Reduction, and is the Past Chair of the Seismology Committee of the Structural Engineers Association of California.

Walterio López S.E.
Rutherford & Chekene
San Francisco, California

Walterio López is a senior associate at Rutherford & Chekene. He has served as project manager for the design of five multi-story buildings using buckling-restrained braced frames (BRBF) as well as numerous other buildings. He participated in the design of a test frame and loading protocol associated with the experimental verification of a BRBF design. He is a coauthor of the guidelines used by structural engineers to design BRBF. He is the author or coauthor of numerous technical papers on behavior and design of BRBF. He serves on two advisory boards for research projects dealing with innovative structural steel systems and is a corresponding member of the AISC Task Committee on the Seismic Provisions for Structural Steel Buildings.

Abstract

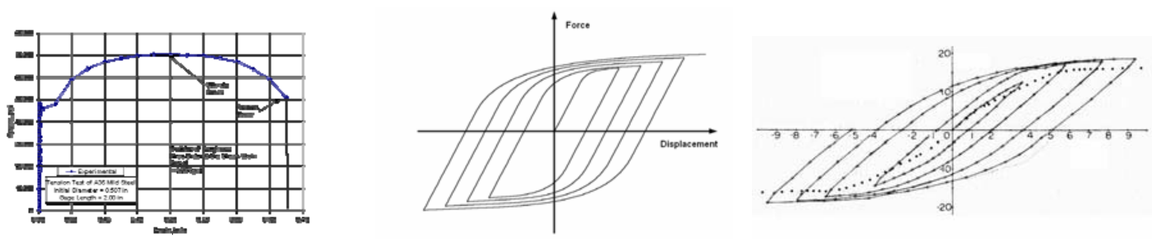
Buckling-restrained Braced Frames (BRBF) are a new and effective Seismic Load Resisting System (SLRS) for engineers designing buildings for ductile seismic performance. The careful design of BRBF provides for a system that can translate the inherent ductility of mild steel into system ductility, thereby controlling the response of the structure to a severe earthquake and presenting an attractive alternative to conventional braced frames. This paper provides a brief treatment of the system, describing its advantages, its development, and current practice.

DESIGN FOR DUCTILITY

Buckling-restrained Braced Frames (BRBF) are a new and effective Seismic Load Resisting System (SLRS) for engineers designing buildings for ductile seismic performance. The careful design of BRBF provides for a system that can translate the inherent ductility of mild steel into system ductility, thereby controlling the response of the structure to a severe earthquake and presenting an attractive alternative to conventional braced frames.

In essence, BRBF represent a direct application of the principles of seismic design of steel systems for ductility. All seismic systems listed in the AISC *Seismic Provisions for Structural Steel Buildings* (“AISC 341;” AISC, 2005) are intended to translate material ductility into some degree of system ductility.

In the ideal case engineers begin with a mild steel material with significant elongation capacity. As a frame of reference, AISC 341 requires an elongation of 20%. This degree of ductility would be excellent in a structure. However, it is not possible to realize this degree of material ductility in every portion of every member, and translating material ductility into adequate system ductility requires careful proportioning of members and systems. Figure 1 shows the stress-strain curve for mild steel (a), an idealized force-displacement hysteretic curve for a ductile member (b), and ductile system behavior (c) (Lee et al., 1993; Tremblay et al., 1999).



(a) (b) (c)

Figure 1

Engineers design members that will exhibit ductility by limiting element slenderness ratios, thereby preventing local buckling. Additionally, instability of the overall member, which would limit its ductility, is typically precluded by somewhat strict member bracing requirements. Engineers ensure that connection failure does not limit member ductility, typically by designing the connections to be stronger than the member. Lastly, systems must be proportioned to prevent excessive concentration of inelastic demands which might exceed the ductility of the member or cause excessive drift in a portion of the building height.

Not all members of the system are anticipated to provide ductility. Proportioning of systems entails selecting certain members to undergo inelastic deformation while the system as a whole maintains its integrity. Resistance to gravity loads must be maintained, of course, and to prevent excessive drift, so must some resistance to lateral loads. Additionally, systems must be proportioned to prevent excessive concentration of inelastic demands which might exceed the ductility of the member or cause excessive drift in a portion of the building height.

Buckling-restrained braces (BRB) are an excellent means of harnessing material ductility and delivering member ductility. Figure 2 shows a schematic of a BRB. Confinement of the steel core, often achieved by encasing mortar in combination with a steel tube, effectively eliminates local buckling as a design concern. Shaping of the core permits a great portion of the member length to be utilized in providing member ductility while providing connection regions that are sufficiently strong so as to limit their ductility demands. Design procedures for the buckling-restraining mechanism preclude instability of the core, and strong-connection/weak-member design procedures are used for the design of the bracing connections.

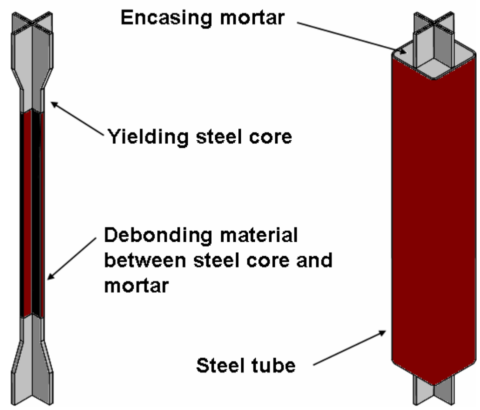


Figure 2

The required strength of framing members also enforces proportioning the system for braces to be the weak link: beams and columns are required to be sized to resist forces corresponding to the expected strength of braces, including factors accounting for strain hardening and other sources of overstrength. Careful designers will also proportion braces over the height of the building to minimize concentrations of drift by performing dynamic analyses and taking advantage of the ability to size braces to within a small percentage of their required strength.

NEED FOR A BETTER BRACE

The introduction of BRBF into the list of standard systems available to designers comes as more attention is being paid to design and performance issues with conventional braced frames (CBF). Examination of recent testing, and reexamination of earlier testing, has led to renewed attention to proper design and detailing of braced frames to overcome potential limitations on their ductility.

Traditional CBF exhibited limited ductility due to a number of nonductile modes: connection failure, brace fracture, and beam failure in V and inverted-V braced frames (Khatib et al., 1988). In addition, even when these modes were not pronounced, CBF tended to exhibit degradation under cyclic loading, a characteristic that can lead to concentrations of drift in a single story.

In order to overcome these inherent limitations design provisions for a more ductile category of braced frames were developed; this system is called a “Special Concentrically Braced Frame,” or SCBF (AISC, 2005) and is intended to provide ductile system performance through a combination of cyclic brace buckling and tensile yielding. The provisions address each of the inherent limitations of CBF, steering the engineer toward designing for the expected yield mechanism of the structure rather than for forces from elastic analysis. There are requirements for minimum design strength of elements based on the maximum brace tension and compression forces, as well as on the maximum difference between the two, which can be considerable when buckling is anticipated.

These requirements lead to significant cost in the design of connections, columns, and, in the case of V and inverted-V (chevron) bracing, beams. Additionally, careful designers recognize other aspects of the design that require consideration of the redistribution of forces after the buckling of one or more braces. Such conditions often lead to high seismic axial forces in members that show none in elastic analyses.

Performance of SCBF is generally limited by the low ductility exhibited by braces subject to cyclic flexural buckling. This buckling requires the formation of plastic hinges in the brace that undergo significant rotation due to the kinematics of the system. Strains at these plastic hinges can be quite large, leading to fracture under predicted demands (Uriz and Mahin, 2004; Kim and Goel, 1992; Tang and Goel, 1989).

From the designer’s point of view BRBF represent a simple and effective solution to many of the problems that affect SCBF. Rather than design for the tremendous differences in brace compression and tension strengths, the Gordian knot is cut by the introduction of a brace that exhibits substantially-symmetrical hysteretic behavior. This is achieved by decoupling the two aspects of resistance to compression: resistance to stress and resistance to instability. A BRB is designed to resist stress in its steel core while an outer sleeve, designed to be isolated from axial stress, provides resistance to buckling of the core. This sleeve effectively reduces the slenderness of the core to zero. Thus the steel core of the buckling-restrained brace can yield in compression in a manner similar to its tension yielding, typically at a similar force level.

The confining element, the sleeve of the buckling-restrained brace, also benefits from this decoupling. Because it is not subject to high axial stress, inelastic buckling is not a design consideration, and the compression strength can be determined from Euler buckling. Figure 3 shows two curves of theoretical compression strength plotted against member slenderness: the typical column curve, which includes material limitations (inelastic buckling and squashing) is shown solid; the Euler curve is shown dashed.

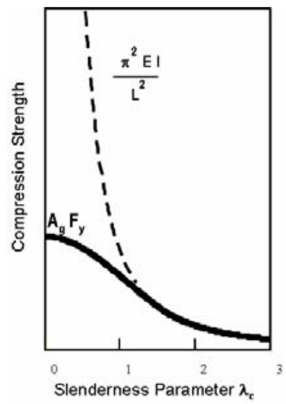


Figure 3

It is interesting to note that in certain combinations the decoupled core and sleeve can have significantly greater compression strength than if they were to act compositely (Sridhara, 1990). The confining element does not contribute to the axial stiffness of the BRB and the steel core size is chosen based on stress requirements only. As a result, braces in BRBF tend to be significantly more flexible than braces in SCBF.

It is not possible to eliminate all stress in the sleeve under compression. Also, due to Poisson's effect, the steel core area at yield in compression is somewhat larger than the area yielding in tension. For these two reasons BRB have a compression strength somewhat higher than their tension strength. The difference is typically less than 10% (Merritt et al., 2003a, 2003b, and 2003c).

The balanced hysteretic behavior that results is very stable. Yielding in both tension and compression can be distributed over a significant percentage of the brace length (typically on the order of 50-70%). The steel core is shaped to provide a yielding length of reduced area, and larger regions at each end for connections that remain nominally elastic under the maximum forces from the yielded core. This shaping also permits a high degree of control over the strength provided by the brace. Hysteretic behavior in tension and compression is very similar, and a substantial amount of energy is dissipated (Watanabe et al., 1988). Figure 4 shows a typical hysteretic plot for a BRB (Tremblay et al., 1999).

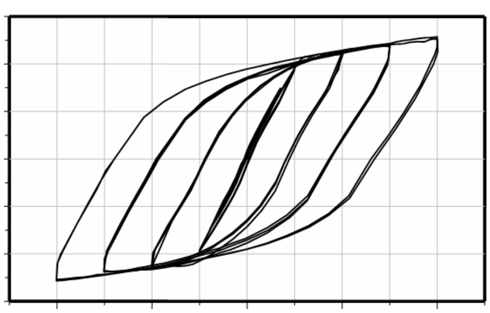


Figure 4

With such distributed inelastic strain demands, long fracture life is the norm for BRB (Merritt et al., 2003a, 2003b, and 2003c). Such cyclic axial strain without degradation due to instability also results in significant strain hardening (Watanabe et al., 1988; Tremblay et al., 1999).

Design of concentrically braced frames employing buckling-restrained braced frames can be significantly simpler than design of SCBF. The small difference between tension and compression BRB strengths results in inelastic force distributions more closely aligned with elastic ones. Inelastic axial and flexural demands on beams in V and inverted-V frames are modest or negligible, and for this reason alone tonnage can be reduced. Because BRB can be sized more precisely than conventional braces selected from a list of available sections, unnecessary system overstrength can be reduced, and connection design forces tend to be closer to BRB required strengths.

A BETTER BRACE

Use of buckling-restrained steel compression members dates back several decades. Such members found application in India as minimum-weight compression members (Sridhara, 1990; Kalyanaraman, et al., 1994). In Japan, BRB were developed as hysteretic dampers for seismic resistance (Iwata et al., 2000; Wada and Huang, 1999). Typical applications followed a design methodology in which a substantial proportion of the seismic resistance was provided by a welded steel moment frame; the hysteretic damping provided by BRB served to reduce response and permit a lighter frame to be used, but it was not considered to be the SLRS.

The devices developed for such use in Japan were put to use in the US as the SLRS (Clark et al., 1999). As such, the system has been treated with a combination of techniques used for other braced frame systems: truss-type analysis as is typically done for concentrically braced frames (both Special Concentrically Braced frames and Eccentrically Braced Frames), and estimation of a longer fundamental period and use of capacity-design procedures for framing members similar to the procedures utilized for Eccentrically Braced Frames.

In the US, BRB are typically procured as performance-specified items. Engineers specify some of the design parameters such as steel core areas, yield strengths, overall lengths, acceptable end connections, and define tolerances with which fabricators are to meet those parameters. In order to arrive at cost-efficient designs, engineers are encouraged to specify some but not all of the design parameters. The steel fabricator supplying the BRB for a project has the responsibility of designing the BRB to meet the performance criteria specified by the Engineer of Record and hires a separate engineer to validate a BRB design through calculations and submittal of previously tested braces. In the US, there are three manufacturers who have supplied BRB in projects and their names can be found in López and Sabelli (2004). Other, unpatented brace designs have been tested and can be considered for future use (Tremblay et al., 1999; Tsai and Lin, 2003).

Truss analysis is adequate for determining the seismic axial forces on braces (as well as on framing members). However, it is important for engineers to understand that braces essentially shed their gravity forces at the onset of yielding, and thus at relatively small drifts. Thus it is prudent to size the surrounding frame to resist the full gravity load (for all load combinations, not just seismic) without the participation of braces. Otherwise, the reliability of the structure to withstand gravity loads might be compromised by relatively small seismic demands, even ones in which no residual drift is visible. Assigning all gravity forces to the surrounding frame and designing braces for seismic forces is correct for the seismic resistance as well; otherwise the design of braces will include unnecessary overstrength which could interfere with the desired frame yield mechanism in which braces at all levels share the ductility demands and lead to concentrations of story drift in levels with a higher ratio of seismic demand to gravity demand.

In the code BRBF have been incorporated into the 2005 edition of AISC 341 (AISC 2005), the 2005 ASCE *Minimum Design Loads for Buildings and Other Structures* ("ASCE 7," ASCE, 2005), and the 2006 International Building Code. Previous editions of these standards did not include the system. BRBF were introduced into US building codes based on the earlier recommended provisions in FEMA 450 (FEMA, 2004), which in turn were based on work by the Structural Engineers Association of California (Sabelli and Aiken, 2003). These current building-code provisions have only begun to be used, and subsequent revision is likely as both unnecessary conservatism and unwarranted permissiveness become clear through use.

The presence of this system in the building code permits engineers to design this system in a manner similar to that in which other CBF have traditionally been designed. Design forces can typically be derived from a generic response spectrum considering the fundamental period of the structure and Response Modification Coefficient (*R*) based on the system's ductility, overstrength, historical performance, and other relevant information (Uang, 1991). BRBF are given R values of 7 or 8, depending on whether beam-to-column connections within the frame are non moment resisting (R=7) or moment resisting (R=8).

Use of either variation on the system is predicated on successful brace and subassemblage testing, including anticipated brace-end rotations (AISC, 2005). Such testing is required to impose deformations beyond those indicated by conventional building-code analytical methods.

Because BRB are more flexible than conventional braces for the reasons stated previously, BRBF tend to have a substantially longer period than SCBF. In some cases of buildings of moderate height (4-7 stories), the difference in period comparing SCBF to BRBF, combined with the difference in Response Modification Coefficients (R=6 for SCBF and R=8 for BRBF) can result in a the BRBF design base shear being as low as 50% of that of the SCBF (Treat and Sabelli, 2007). Figure 5 shows the design spectra for SCBF and BRBF, as well as the design base shears associated with the approximate periods for each system.

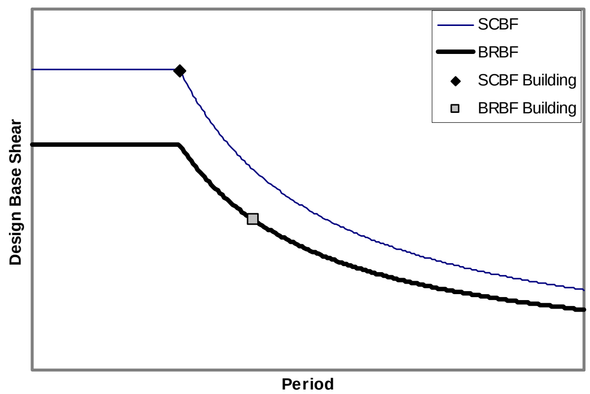


Figure 5

Forces associated with the design base shear are used to determine BRB required strengths and to check drift. These forces are not adequate for the design of the frame surrounding the BRB. Because BRB are subject to significant inelastic demands, BRB forces associated with the design ground motion are higher than their nominal strength. As a result, the frame surrounding the BRB (which is assumed to remain nominally elastic) should be designed for those BRB forces higher than nominal. The BRB forces in question are derived from the braces' nominal strength amplified by the strain-hardening adjustment factor ω, the compression overstrength adjustment factor β, and the material overstrength factor R_y, where appropriate. Frame member forces are calculated assuming all braces are at their adjusted strength level; whether this force is tensile or compressive is determined considering a plastic mechanism for the frame, typically corresponding to the fundamental mode. Step-by-step examples of an application of the above procedure are found in López and Sabelli (2004). In complex configurations or where the other modes dominate (e.g., tall buildings), this simplified procedure may be too conservative. Another method which is intended to better predict brace ductility demand, and thus surrounding frame required strengths, through nonlinear dynamic analyses is discussed below.

The strain-hardening adjustment factor ω and the compression overstrength adjustment factor β are calculated from the testing of braces of the same type and similar size to those in the design. These tests are required to demonstrate that the brace design can function adequately when subject to significant inelastic strains. AISC 341 limits the extrapolation of results of tested BRB to validate BRB proposed for a building design.

Drifts for BRBF must be calculated for two reasons: first, to establish that the system complies with code requirements limiting the expected drift; and second, to establish the deformation demands expected of the braces so that they may be appropriately designed and detailed.

Drifts calculated using design base shears and an amplified elastic analysis tend to be underpredicted by the Displacement Amplification Coefficients (C_d) that are less than the Response Modification Coefficient (R) (Uang and Maarouf, 1994). This is true for all systems and is generally acknowledged by engineers. Additionally, the elastic and inelastic distributions of deformation demand are quite different, with the post-elastic deformations being largely in the yielding elements. Thus elastic methods with the code Displacement Amplification Coefficient will significantly underpredict the deformation demand on a buckling-restrained brace. To a degree these two inaccuracies are addressed by the application of an additional factor of 2.0 placed on the computed brace deformation, Δ_{bm}. A BRB ductility demand calculated using elastic, force-based methods and the requirements of AISC 341 will produce an upper bound value of $10\Delta_{by}$. As a comparison, the results of nonlinear dynamic analyses show that the range of mean of maximum BRB ductility demands for 10%/50-year ground motions is 9-11(Fahnestock et al., 2006; Sabelli et al., 2003). At first glance, one could assume that maximum BRB ductility demands are reasonably computed by elastic, forced-based methods. However, results of analytical studies using 2%/50-year ground motions (Fahnestock et al., 2006; Sabelli et al., 2003) show that the range of mean of the maximum BRB ductility demands is 17-19. One can clearly see that, as currently written, AISC 341 provisions cannot predict expected BRB ductility demands for ground motions with a probability of exceedance other than 10%/50-year. As a result, engineers are advised to include in their performance specifications language that requires that BRB be manufactured with lengthening and shortening abilities to safely accommodate cyclic ductility demands of 17-19. It follows that BRB manufacturers should be strongly encouraged to conduct any new testing to ductility demands in the range of 17-19. While BRB ductility demands are underestimated for 2%/50-year ground motions, adjusted BRB strengths are not underestimated as demonstrated by Fahnestock et al., (2006). Other analytical studies showing that adjusted BRB strengths computed from elastic, force-base methods are not underestimated when compared to results of nonlinear dynamic analyses are those of López and Sabelli (2004), and López and Nakayama (2006).

As an alternative to building-code elastic analyses, designers may prefer to use nonlinear analysis in their designs. Such nonlinear analysis may be static ("pushover" analysis) or dynamic (utilizing a series of scaled ground motion time-history records). In the former case, a target displacement is selected, typically using methods from FEMA 356 (FEMA, 2000); BRB axial deformation demands, frame member forces, and connection rotation demands are evaluated at that displacement and compared to tabulated capacities. In the case of nonlinear dynamic analysis, the evaluations are typically made at an average of the maximum force or displacement conditions for each record; cumulative brace ductility could also be evaluated, but this is typically very far from being a controlling parameter.

BRB force-displacement behavior used in nonlinear analyses can be derived from the results of the tests used to qualify the BRB in the building design. While FEMA 356 has data on other elements of the SLRS, some of FEMA's recommended values are based on limited testing and are very conservative, especially for columns. Designers using nonlinear analyses may need to consider results of more recent testing and alternate sources of data to establish more accurate estimates of the BRBF deformation capacity.

The enhanced ductility of BRB compared to conventional braces has led to renewed attention to configuration and proportioning issues in the design of concentrically braced frames. Specifically, designers and researchers have sought ways to convert the member ductility into system ductility by avoiding concentrations of ductility demands in a minority of the building stories. Methods for enhancing structural ductility range from the basic to the elaborate. At the former end is more precise brace proportioning using building dynamic characteristics (Uang and Nakashima, 2003). Through this proportioning, the propensity toward drift concentration is reduced, perhaps to the point where column continuity is sufficient to ensure adequate distribution of inelastic demands throughout the building height.

Beyond this, the use of dual systems in which a largely elastic moment frame prevents excessive ductility demands at any level has been shown to improve the performance of BRBF (Uang and Kiggins, 2003). The demands on such frames can be reduced by proper proportioning of braces.

Tremblay (2003) has studied alternative configurations in which an elastic truss, rather than column continuity or a moment frame, resist any tendency toward drift concentration. In one variation, a vertical truss of conventional steel members links the BRB, providing multiple inelastic load paths so that the BRB, linked in series for elastic forces, can be considered to work in parallel in the inelastic range; see Figure 6.

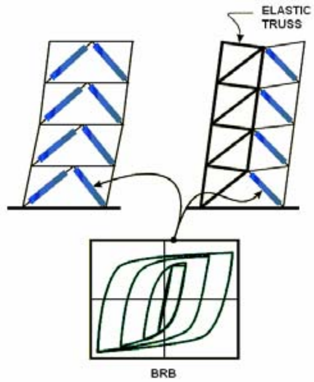


Figure 6

Tremblay (Tremblay et al., 2004) has also studied a variation of the previously-described concept in which a vertical truss of conventional steel members imposes overturning forces on a pair of BRB; see Figure 7. The truss is designed to remain elastic, resisting all higher-mode demands and ensuring that inelastic demands only occur in the fundamental mode. BRB are designed to provide adequate ductility in this mode. While consideration of gravity forces is not necessary for the seismic design of these braces, it is important that braces not be subject to cyclic inelastic demands due to live load as this could exhaust their inelastic strain capacity prior to an earthquake.

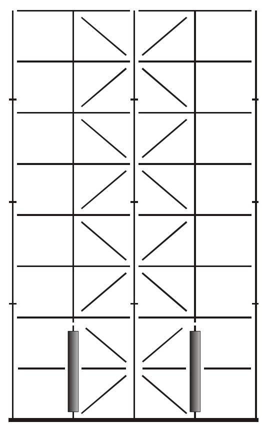


Figure 7

THE DETAILS

The design and detailing of gusset plate connections is one of the more delicate aspects for engineers employing this system. Gusseted beam-to-column connections tend to be very rigid, and highly restrained conditions are some times unavoidable. While this is true for virtually all braced frame systems, the high ductility of buckling-restrained braces leads to situations where the brace deformation ductility can exceed that of connections. Testing has shown this (Lin et al., 2005; López et al., 2002).

While much testing has focused on the behavior of the brace, a number of full frame tests have been performed (Fahnestock et al., 2006; López et al., 2002; Tsai et al., 2006). These provide some information on details that are effective in providing the necessary rotation capacity to accommodate the expected interstory drifts. These tests indicate that the stability and cumulative inelastic rotation capacity of bracing connections may pose a significantly lower limit than cumulative axial ductility of BRB. Tsai reported two gusset instabilities in a full-scale test that included several types of braces (Figure 8a); these were corrected with stabilizing plates and testing continued (Figure 8b).

(a) (b)

Figure 8

Tests included connections that are effectively fully restrained, as well as connections that are effectively pinned; see Figure 9 (Fahnestock et al., 2006). While both approaches appear to be feasible, pinned connections similar to those tested successfully may be the easiest for designers to use. Limiting connection rotation demand by limiting interstory drift may be necessary where the performance of a connection at larger drifts is questionable.

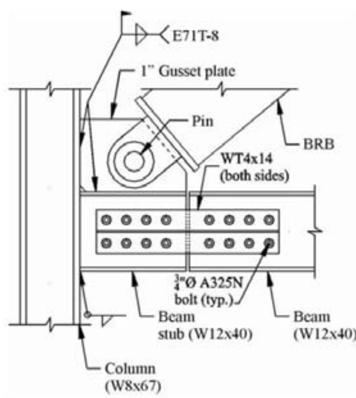


Figure 9

CONCLUSION

Buckling-restrained braced frames allow engineers to utilize the material ductility of steel and translate it into system ductility. As BRBF are afforded adequate system ductility, acceptable behavior to design ground motions has been observed analytically and experimentally. BRBF design procedures can be considered simpler than those corresponding to other concentrically braced frames and, depending on building and site characteristics, this can result in more cost-efficient designs. The simplicity of BRBF notwithstanding, designers need to understand the underlying assumptions found in AISC 341. Engineers designing BRBF should be aware of the limitations that elastic procedures have in predicting BRB ductility demands, consider expected ductility demands in the writing of BRB performance specifications, account for adjusted brace strengths in the design of the surrounding frame, and follow best-practices in the design of gusset connections.

REFERENCES

AISC. *AISC 341: Seismic Provisions for Structural Steel Buildings*, American Institute of Steel Construction, Chicago, Illinois, 2005.

ASCE. *ASCE-7: Minimum Design Loads for Buildings and Other Structures,* American Society of Civil Engineers, New York, 2005.

Clark, P., Aiken, I., Kasai, K., Ko, E., and Kimura, I. "Design procedures for buildings incorporating hysteretic damping devices," in *Proceedings of the 68th Annual Convention*, Structural Engineers Association of California, Sacramento, 1999, pp. 355-371.

Fahnestock, L.A., Sause, R., and Ricles, J.M., *Analytical and Large-Scale Experimental Studies of Earthquake-Resistant Buckling-Restrained Braced Frame Systems*. Report ATLSS 06-01, Engineering Research Center for Advanced Technology for Large Structural Systems, Lehigh University, Bethlehem, PA, 2006.

FEMA. *Prestandard and Commentary for the Seismic Rehabilitation of Buildings*, prepared by the Building Seismic Safety Council for the Federal Emergency Management Agency, Washington, D.C. (FEMA Publication No. 356), 2000.

FEMA. *2003 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures Part1: Provisions*, prepared by the Building Seismic Safety Council for the Federal Emergency Management Agency, Washington, D.C. (FEMA Publication No. 450) 2004.

Iwata, M., Kato, T. and Wada, A. "Buckling-Restrained Braces as Hysteretic Dampers," In Mazzolani & Tremblay (eds), *Behavior of Steel Structures in Seismic Areas*, STESSA 2000, Proc. International Conference, Montreal, 21-24 August, Rotterdam: Balkema, 2000.

Kalyanaraman, V., Sridhara, B.N., Mahadevan, K. "Sleeved Column System," *Proceedings of the SSRC Task Group Meetings and Task Force Sessions*, Lehigh University, Bethlehem, PA, 1994.

Khatib, I.F., Mahin, S.A., and Pister, K.S. *Seismic Behavior of Concentrically Braced Steel Frames*. Report UCB/EERC-88/01, Earthquake Eng. Research Center, University of California, Berkeley, California, 1988.

Kim, H. and Goel, S., *Seismic evaluation and upgrading of braced frame structures for potential local failures*, UMCEE 92-24, Dept. of Civil Engineering and Environmental Engineering, Univ. of Michigan, Ann Arbor, 1992.

Lee, G.C., Chang, K.C. and Siguira, "Experimental Basis of Material Consitutive Laws of Structural Steel Under Cyclic and Non Proportional Loading," *Stability and Ductility of Steel Structures Under Cyclic Loading.* Fukumoto, Y., and Lee, G.C., ed.s. CRC Press, 1992.

Lin, M.L., Tsai, K.C., Hsiao, P.C., and Tsai, C.Y. "Compressive Behavior of Buckling-Restrained Brace Gusset Connections" *First International Conference on Advances in Experimental Structural Engineering* AESE 2005, July 19-21, 2005, Nagoya, Japan.

López, W.A., and Sabelli, R. *Seismic Design of Buckling-Restrained Braced Frames*, Steel TIPS Publication, Structural Steel Educational Council, Moraga, CA, 2004.

López, W.A., Gwie, D.S., Saunders, C.M., and Lauck, T.W. "Lessons learned from large-scale tests of unbonded braced frame subassemblages," in *Proceedings of the 71st Annual Convention*, pp. 171-183, Structural Engineers Association of California, Sacramento, 2002.

López, W.A., and Nakayama, Y. "Behavior of Buckling-Restrained Braced Frames Subject to Near-Field Ground Motions," in *Proceedings of the 75th Annual Convention*, Structural Engineers Association of California, Sacramento, 2006.

Merritt, S., Uang, C.M., and Benzoni, G. "Subassemblage testing of CoreBrace buckling-restrained braces," in *Report No. TR-2003/01*, University of California, San Diego, La Jolla, 2003a.

Merritt, S., Uang, C.M., and Benzoni, G. "Subassemblage testing of Star Seismic buckling-restrained braces," in *Report No. TR-2003/04*, University of California, San Diego, La Jolla, 2003b.

Merritt, S., Uang, C.M., and Benzoni, G. "Uniaxial testing of Associated Bracing buckling-restrained braces," in *Report No. TR-2003/05*, University of California, San Diego, La Jolla, 2003c.

Sabelli, R., and Aiken, I. “Development of Building Code for Provisions for Buckling-Restrained Braced Frames,” *Behavior of Steel Structures in Seismically Active Areas*, STESSA Conference, Naples, Italy, 2003.

Sabelli, R., Mahin, S.A. and Chang, C., “Seismic Demands on Steel Braced-Frame Buildings with Buckling-Restrained Braces,” *Engineering Structures*, 2003.

Sridhara, B.N. “Sleeved Column-As a Basic Compression Member,” *4th International Conference of Steel Structures and Space Frames*, Singapore, 1990,

Tang, X., and Goel S. C., “Brace Fractures and Analysis of Phase I Structures,” *Journal of Structural Engineering* 115 (8), 1960-1976. 1989.

Treat, K., and Sabelli, R. “New Systems in the AISC Seismic Provisions,” *North American Steel Construction Conference Proceedings*, American Institute of Steel Construction, Inc., Chicago, 2007.

Tremblay, R. “Achieving a Stable Inelastic Seismic Response for Concentrically Braced Steel Frames. “*Engineering Journal*, AISC, 40, 2, 111-129, 2003.

Tremblay, R., Ben Ftima, M., and Sabelli, R. “An Innovative Bracing Configuration for Improved Seismic Response.” *Proc. of the Recent Advances and New Trends in Structural Design Colloquium* Timisoara, Romania, 2004.

Tremblay, R., Degrange, G. and Blouin, J. “Seismic Rehabilitation of a Four Storey Building with a Stiffened Bracing system,” *Proc. 8th Canadian Conference on Earthquake Engineering*, Canadian Association for Earthquake Engineering, Vancouver, B.C., 549-554, 1999.

Tsai, K. C., Lin, M. L., Tsai, C. Y., Hsiao, P. C., and Chen, C. H. Bi-Directional Sub-Structural Pseudo-Dynamic Testing of a Full-Scale 2-Story BRBF Part 3: Compressive Behavior of Gusset Plates, *Proceedings of the 8th National Conference on Earthquake Engineering*, San Francisco, 2006.

Tsai, K.C. and Lin, S.L, “A Study of All Metal and Detachable Buckling Restrained Braces,” Center for Earthquake Engineering Research, National Taiwan University, Report No. CEER/R92-08, 2003.

Uang, C.M. “Establishing R (or R_w) and C_d Factors for Building Seismic Provisions.” *Journal of Structural Engineering.* 117(1), 19-28, 1991.

Uang, C.M. and Maarouf, A. “Deflection Amplification Factor for Seismic Design Provisions.” *Journal of Structural Engineering.* 120(8), 2423-2436, 1994.

Uang, C.M., and Kiggins, S. “Reducing Residual Drift of Buckling-Restrained Braced Frames As A Dual System,” in *Proceedings of International Workshop on Steel and Concrete Composite Construction (IWSCCC-2003*), pp.189-198, Report No. NCREE-03-026, National Center for Research on Earthquake Engineering, Taipei, 2003.

Uang, C.M., and Nakashima, M. “Steel Buckling-Restrained Frames,” in *Earthquake Engineering: Recent Advances and Applications*, Chapter 16, Y. Bozorgnia and V.V. Bertero, eds, CRC Press, 2003.

Uriz, P., and Mahin, S. “Seismic Performance Assessment of Concentrically Braced Steel Frames.” *Proceedings of the 13th World Conference on Earthquake Engineering*, 2004.

Wada, A. and Huang, Y., “Damage-Controlled Structures in Japan”, PEER-1999/10, *U.S.-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures*, 13 September 1999, Maui, Hawaii, Berkeley: Pacific Earthquake Engineering Research Center, University of California, Dec. 1999, pages 279-289.

Watanabe, A., Hitomi Y., Saeki, E., Wada, A., and Fujimoto, M. “Properties of Brace Encased in Buckling-Restraining Concrete and Steel Tube,” *Proceedings of Ninth World Conference on Earthquake Engineering*, Vol. IV, pp. 719-724, Japan Association for Earthquake Disaster Prevention, Tokyo-Kyoto, Japan, 1988.