

Seismic Design and Behavior of Concentrically Braced Steel Frames

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Concentrically braced steel frames (CBFs) are a practical and economical structural system for many applications. Diagonal braces employ gusset plate connections and are very efficient elements for developing stiffness and resistance to wind and earthquake induced lateral loads. For wind loading, braced frames are normally designed to provide adequate elastic strength and stiffness to resist the force demands and to assure occupant comfort due to building movements and vibrations. In seismic design, there is a trend towards engineering systems to meet specific performance objectives. In current codes, there is an implied multi-level, performance criteria. For small, frequent earthquakes, the structure is designed to remain elastic and provide adequate strength and stiffness to assure serviceability during and after the earthquake. For large, infrequent seismic events, significant inelastic deformation of the structure is required. For CBFs, the inelastic deformation consists of tensile yielding and post-buckling inelastic deformation of the brace. This inelastic behavior is extremely important to the overall seismic performance of the system, but is not well understood by structural engineers.

The AISC *Seismic Design Provisions* (AISC 2005) employ detailing requirements for Special Concentrically Braced Frames (SCBFs) as a method of achieving the latter seismic design

requirements. The SCBF design requirements were initially developed in the early 1990s, and the evolution of these design requirements continues with improvements in the understanding of the CBF system resulting from previous and current research efforts. Current AISC seismic design provisions (2005) for SCBF provisions focus on:

- Assuring that the system has the required lateral resistance needed to assure good seismic performance.
- Adapting the performance to the wide variety of possible brace types and bracing configurations.
- Controlling the local and global slenderness of the brace to provide adequate post-buckling inelastic deformation of the brace during extreme earthquakes. Local slenderness limits depend on the brace cross section, because some cross sections are more susceptible to fracture at smaller post-buckling inelastic and tensile yield deformations than others.
- Assuring that gusset plate connections used to join the brace to other frame members permit the end rotation of the brace needed for brace buckling, while developing tensile and compressive resistance greater than the maximum expected capacities of the brace.
- Sizing the other structural members to assure that primary yielding and buckling occurs in the brace.

Over the years, there have been changes in the SCBF design requirements in response to the improved understanding of CBF behavior, and there is continuing, ongoing research to better understand the seismic behavior of this important structural system. Recent research suggests that advancements in the design of SCBF systems are needed, and work is underway to develop and evaluate proposed advancements. Several clear observations, which may be made from some of this recent work, are presented in the sections that follow.

CBFs Do Not Behave as Trusses

One important observation is that, although the initial design of CBFs is normally achieved by analyzing the braced frame as a truss, braced frames do not behave as trusses. The brace and gusset plate connection are designed under the hypothesis that the brace is a member with pure axial load. This is a very simple and appropriate approximation for initial design. However, recent research suggests that latter design phases should incorporate the actual properties to evaluate that actual behavior.

Historically, research into the response of braced frame systems has focused on the seismic behavior of individual elements such as braces and gusset plates, but recent research has focused to provide a more integrated picture of the behavior of CBFs. This recent research has shown that significant inelastic deformation occurs within the beams and columns of braced frames, in addition to the buckling of the brace. *Figure 1* shows significant yielding of the beam and column occur due to large bending moments induced into these elements through the gusset plate connection. Although the frame may be designed assuming truss behavior, the large gusset plate connections effectively create a stiff, moment-resisting connection rather than a pin. This flexural stiffness induces large bending moments in the beams and columns. These moments effectively increase the resistance of the frame over that expected from the frame analyzed as a pure truss, but the moments also introduce unexpected yield and failure modes in the CBF and complicate the current understanding of braced frame behavior.



Figure 1: Extensive Yielding in Beam and Column.

Brace Buckling



Figure 2a: Out-of-Plane Deformation.

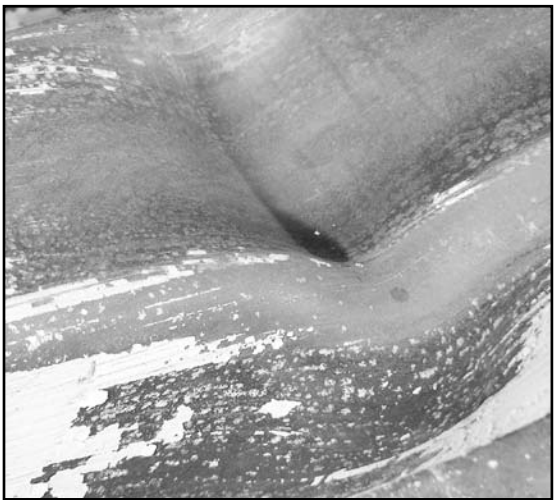


Figure 2b: Local Deformation of HSS Tubes.

Design and Detailing of the Gusset Plate Connection is Important

Current AISC provisions require that gusset plates and the interface welded connections be designed to develop the expected maximum resistances of the brace in tension and compression, which engineers may interpret as greater connection resistance provides improved behavior. Concurrently, AISC *Seismic Design Provisions* require that the connections be designed to permit end rotation to accommodate brace buckling. These two requirements are inconsistent. Large out-of-plane deformations of the brace are required to achieve larger inelastic story drift as illustrated by the photo of *Figure 2a* (page 38), and so brace end rotations may be quite large. Current design methods normally use a $2t$ linear clearance from the intersection line of the gusset plate to achieve the end rotation capacity. Unfortunately, this method leads

to very large gussets as shown in *Figure 3a* (page 38), and the larger dimensions also lead to thicker plates. These combine to create a rotationally stiff joint, which limits the rotation of the connection and leads to the extensive frame yielding illustrated in *Figure 1* (page 37).

Recent research (Lehman et al. 2008) has developed and evaluated a new elliptical clearance model, as shown in *Figure 3b*. The model permits smaller, thinner and more compact gusset plates. Both gusset plates in *Figures 3a* and *3b* were tested under inelastic cyclic deformation and with nominally identical braces. *Figures 4a* and *4c* compare the system response of frames designed using the $2t$ -linear and $8t$ -elliptical clearance expressions. The CBF with the more compact, thinner gusset plate, achieved by the elliptical clearance requirement and illustrated in *Figures 3b* and *4c*, provided significantly greater ductility and inelastic deformation capacity of the system.

Recent research has evaluated a full range of plate thicknesses, offsets, and weld sizes and types for the gusset plate connections (Lehman et al. 2008). In all cases, an HSS $5 \times 5 \times \frac{3}{8}$ brace was used. Although previous research results have indicated that HSS sections may not achieve the expected drift demands of a braced frame system (e.g., Fell et al. 2006), the research results shown in *Figure 4* indicate that simple modifications in the gusset plate geometry and weld size have a profound impact on the system drift range capacity. For example, *Figures 4b* and *4c* indicate that a change in plate thickness from $\frac{7}{8}$ to $\frac{3}{8}$ inches increases that drift range by

more than 50%. Using the proposed elliptical clearance with the plate designed to yield after brace yielding assures the maximum ductility and deformation capacity of the CBF system. This research shows that gusset plates should be designed with enough stiffness and resistance to develop the expected maximum resistance of the attached brace, but additional connection stiffness and capacity may reduce the inelastic deformation capacity of the CBF system. Additionally, the weld used to attach the gusset plate to the beam and column must have strength that is sufficient to develop the ultimate strength of the gusset plate. A weld designed to simply resist the strength of the brace will result in weld fracture (Lehman et al. 2008).

Multi-story Systems Require Special Consideration

Inelastic story drift demand results in large buckling deformation in the brace, as shown in *Figure 2a*. Post buckling deformation results in the non-symmetric force deflection behavior for CBFs, as shown in the force-drift response graphs of *Figure 4*. These figures show the variation in the measured response for different gusset plate connection details for a single braced bay with a diagonal brace. The braced bay includes the gusset connections and beam and column members. In all cases the resistance of the brace is greater in tension than in compression, and thus the braced bay is clearly stronger in one direction than in the other. Furthermore, the response shows little evidence of strain hardening and the resistance may deteriorate at increased inelastic deformation, because of the $P-\Delta$ moments associated with post-buckling deformation and the localization of inelastic deformation of the buckled brace as shown in *Figure 2b*.

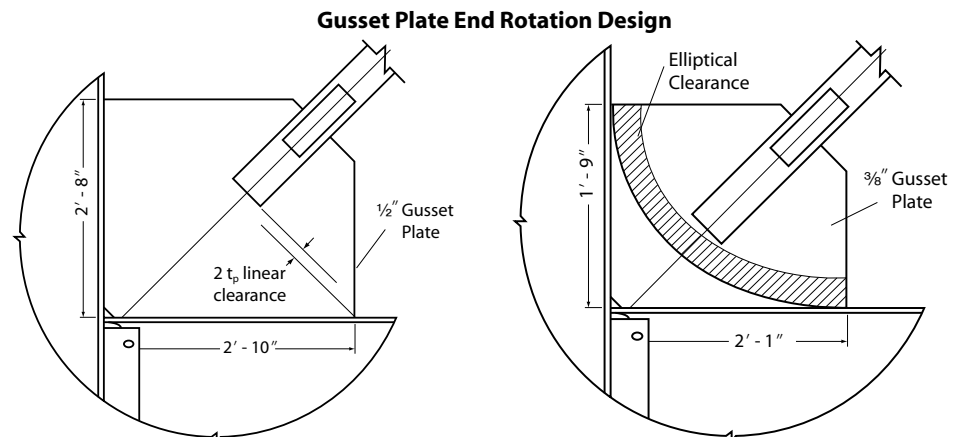


Figure 3a: $2t$ Clearance.

Figure 3b: Proposed Elliptical Clearance.

Range in Inelastic for Deformation Behavior of a CBF System

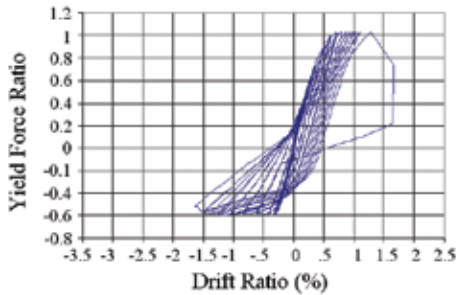


Figure 4a: AISC Reference Specimen.

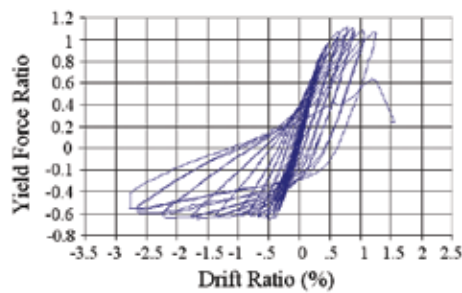


Figure 4b: Elliptical Clearance with Thick (7/8 inch) Plate.

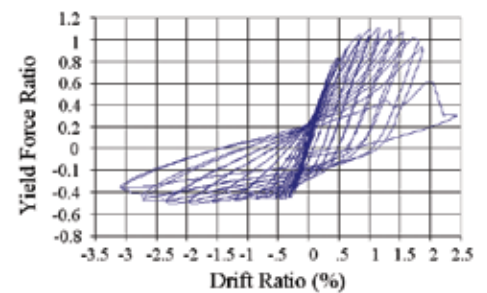


Figure 4c: Elliptical Clearance with Thin (3/8 inch) Plate.

As a result of these observations, design provisions require that braces be used in balanced pairs to assure that the structure is not significantly weaker in one direction than the other at all deformation levels.

However, there is an additional consequence of this behavior. Once buckling has occurred in a single story of a multi-story CBF, the inelastic deformation typically concentrates into that story. CBFs are a stiff structural system, and initial yielding and buckling are expected to occur at a story drift of approximately 0.35%. If inelastic deformation is approximately evenly distributed over the height of the structure, a relatively modest maximum inelastic deformation can be expected in any given story. However, concentration of inelastic deformation requires a large deformation for that story to achieve the expected roof drift demands. This response raises uncertainty about the seismic design demands that are currently used as the ability to distribute yielding over the height of the structure is an ongoing concern.

Not all Braces are Created Equal

The local deformation caused by cyclic brace buckling and illustrated in *Figure 2b* has additional consequences. Brace fracture is the preferred failure mode expected of CBFs during extreme seismic loading. As illustrated in *Figure 2b*, brace fracture initiates in the region where large local strains accumulate due to local deformation associated with brace buckling and tensile yield. Some brace cross sections suffer more severe local strains during brace buckling, and may experience braced fracture at smaller story drift. Seismic design provisions attempt to address these issues by providing local slenderness limits for various brace cross sections. However, future changes in these limits and the brace cross sections permitted for seismic design should be expected. As shown in *Figure 4*, additional system capacity is afforded by properly detailing the gusset plates and the associated welds to maximize the system drift range capacity.

Closing Comments

This is a brief discussion of the seismic design and performance of CBFs. CBFs are a very economical and practical structural system. However, their seismic performance is more complex than, and not as well understood as, other commonly used structural systems. A large, integrated, international research program, with researchers from the U.S., Canada, Taiwan and Japan, is in progress to improve the understanding of CBFs and to develop seismic design procedures that will result in economical design and optimal seismic performance. CBFs are expected to continue to be a viable system for resisting seismic loads, but future changes in the design methods are expected and will improve the performance and predictability of these systems. ■

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