Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 424

THREE-DIMENSIONAL TESTS OF TWO-STORY, ONE-BAY BY ONE-BAY, STEEL BRACED FRAMES: SPECIMEN DESIGN

Keith Palmer,[1] Taichiro Okazaki,[2] Charles Roeder[3] and Dawn Lehman[3]

ABSTRACT

Concentrically braced frames (CBFs) and buckling-restrained braced frames (BRBFs) are commonly used seismic-load resisting systems. A key design component in CBFs is the bracing connections which must develop the large strength of the brace in tension and accommodate the large rotation associated with brace buckling. Recent tests suggest that the interaction between framing action and brace connections can negatively affect the behavior of SCBFs. Additionally, recent tests indicate that the drift capacity of BRBFs can be rather small in cases when premature yielding of the beams and columns triggers instability of the system. In order to further examine the system behavior of CBFs and BRBFs, large-scale, three-dimensional tests will be conducted at the MAST laboratory at the University of Minnesota. Two specimens will be tested in this program, a CBF specimen with HSS braces, and a BRBF specimen. The specimen design reflects the latest research findings from an ongoing NSF-NEES project. Furthermore, the specimens include unique features such as: some braces framing into the column web; orthogonal brace bents sharing a corner column; a composite concrete slab; near-full scale; and braced bents loaded in the out-of-plane as well as in-plane direction. The 3D specimens will be tested under a bidirectional loading program based on a series of nonlinear time history analyses.

[1]Graduate Research Assistant, Dept. of Civil Engineering, University of Minnesota, Minneapolis, MN 55455

[2]Reasearch Fellow, Hyogo Earthquake Engineering Research Center (E-Defense), Miki, Hyogo, 673-0515 Japan

[3]Professor, Dept. of Civil Engineering, University of Washington, Seattle, WA 98195

Introduction

A large body of research data is available on the design and performance of concentrically braced frames (CBFs). For example, Tremblay et al. (2003) describe a testing program of CBFs with an X-bracing configuration. Chambers and Ernst (2005) present a literature review on gusseted connections under monotonic and cyclic loading. Fahnestock et al. (2006) present a literature review on component tests of buckling-restrained braces (BRBs) under cyclic loading. Many of the earlier tests examined isolated braces and gussets plates but did not necessarily capture the behavior of the overall braced frame. More recent studies by Yoo et al. (2008), Tsai et al. (2006), Mahin et al. (2004), among others, address the effects of the brace connection region on the overall performance of the system.

As a part of an international project funded by the NSF-NEES program, more than 30 full-scale tests have been performed at the University of Washington (UW) to examine the interaction between the brace behavior, brace connection, and framing action. Both CBFs and buckling-restrained braced frames (BRBFs) have been tested. The UW tests suggest that the thick and large gusset plates for CBFs called for by current design provisions can negatively impact the system behavior. By reducing the thickness and size of the gusset plates beyond the limit specified by current provisions, the fatigue life of the buckling brace was extended and fracture at the gusset plate welds was delayed. Larger, thicker gusset plates can stiffen the frame and thereby place more demands on the gusset plate welds, beams, and columns. In contrast to CBFs, BRBFs are generally provided with rigid brace connections that do not deform under compression. The UW tests demonstrated that the rigid brace connection can impose large local demands on the surrounding framing elements and in the BRB itself. All four specimens failed at a cyclic story drift of 0.02 rads due to instability of the BRB. Other components of the NSF-NEES project include a number of two and three-story, full-scale CBF specimens tested at the National Center on Research for Earthquake Engineering of Taiwan (NCREE) and University of California Berkeley (UCB). The tests completed to date suggest that the interaction between framing action and brace connections can negatively affect the behavior of SCBFs and BRBFs.

In order to further examine the system behavior of CBFs and BRBFs, large-scale, three-dimensional tests will be conducted at the MAST laboratory at the University of Minnesota. As described in a later section, the specimen design reflects the latest research findings from the NSF-NEES project. The primary objectives of the MAST tests are summarized in the following:

- To examine the large-displacement, bidirectional loading behavior of CBFs and BRBFs. Such testing has not been conducted previously with realistic brace boundary conditions.

The P-Delta effects produced by out-of-plane drifts can have detrimental effects, particularly for BRBFs. Because BRBFs are provided with stiff bracing connections, out-of-plane drift, which is not explicitly addressed in typical design procedures, may cause hinges to form at the relatively flexible portion of the bracing connection or inside the BRB itself. This can then lead to premature failure of the system and reduced drift capacity.

- To examine whether the latest design and detailing rules for CBFs and BRBFs, developed based on the parallel studies at UW, UCB and NCREE, are applicable to a 3D frame subjected to bidirectional loading.
- To examine the behavior of corner columns shared by orthogonal braces, and which are hence directly subjected to bidirectional loading effects. The braces sharing the column may influence each other. Although shared columns are encountered in braced frames and in many seismic-load resisting systems, little research information is available on their behavior and design requirements.
- To examine the behavior of CBFs arranged with the brace connecting into the web of the column. Such brace connections are bound to occur at the shared column. However, there is limited experimental data on the performance of braces connecting to the column web.
- To examine the effects of composite concrete slabs on the behavior of CBFs. Although some of the previous NCREE tests included a composite slab, those specimens were planar, and hence, were not adequate to fully examine the composite slab effects.

Test Specimen Design

Two specimens will be tested in this research program. Both specimens will be nearly full-scale, one-bay by one-bay, two-story frames with braces in two orthogonal bays framing into a corner to share the column. HSS braces will be used in the CBF specimen while proprietary BRBs will be used in the BRBF specimen. The bay widths are 16 feet 6 inches, which is 50 to 80 percent of typical building bays. The story heights are 10 feet 5 inches, which is 70 to 90 percent of typical building story heights. The member sizes represent the upper stories in a mid to high-rise building or the lower stories of a low-rise building.

Figs. 1(a) and (b) show the second and third floor plan, respectively, of both test specimens. The braced frames occur along grid lines A and 1 as indicated by the dashed lines near the girder lines. Note that column A-1 is shared by two orthogonal braced bents. Also note that the braced frames along grid 1 frame into the web of the shared column. The second floor deck consists of a 2-in. ribbed metal deck topped by 3.25 in. of normal weight concrete for a total depth of 5.25 inches, as typically seen in steel buildings. The third floor slab will transfer the load from the loading beam (termed the crosshead, shown in Fig. 3) into the test specimen, and as such, required a 10 in.-thick, 6 ksi formed concrete slab.

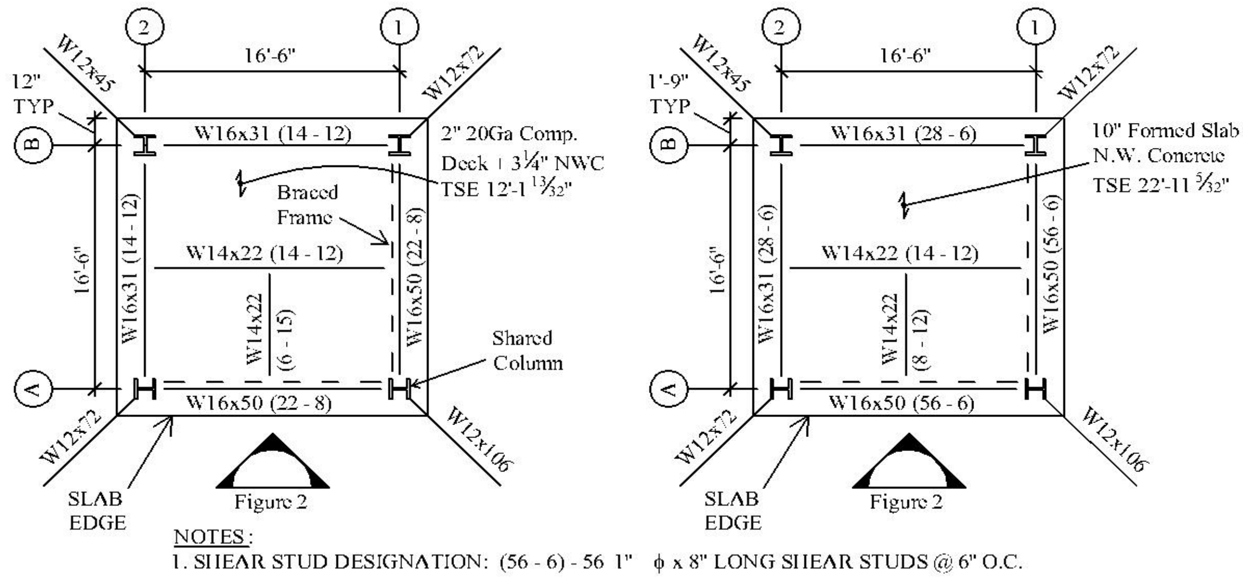

Figure 1. Test specimen floor plans: (a) second floor; (b) third floor plan

Elevations of the CBF and BRBF specimens are shown separately in Fig. 2. The beam-to-column connections in the braced bays are welded flange–welded web (WFWW) connections with demand-critical welds, while those in the other two bays (not shown in Fig. 2) are simple shear connections. The CBF specimen places A500B HSS3x3x1/4 braces in an X-configuration. The BRBF specimen places BRBs in a single-diagonal configuration. The specified steel core yield strength of the BRB is 46 ksi, and the target adjusted brace force is 220 kips. Fig. 3 shows a 3D schematic of the test setup showing the strong walls, strong floor, crosshead, and the BRBF specimen. The four actuators connecting the crosshead to the strong walls and four actuators connecting the crosshead to the strong floor are not shown in the figure.

Three-story and six-story prototype BRBF buildings were designed to check whether the specimen member sizes are reasonable. Nonlinear time-history analyses were performed on these prototype buildings, from which a cyclic loading program for the bidirectional loading test was developed. This prototype building is a slight modification of the building studied by Sabelli (2007). The specimen is roughly 0.8-scale of this prototype building. Four BRBFs are placed in a single-diagonal arrangement in each loading direction at the four corners of the floor plan. As in the test specimen, the corner columns of the prototype building are shared by BRBFs in orthogonal directions.

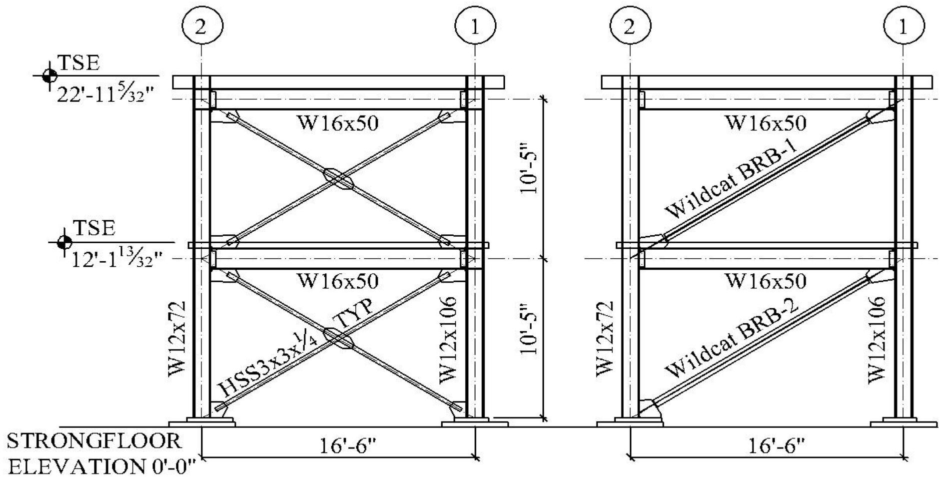

Figure 2. Specimen Elevations: (a) CBF with HSS braces; and (b) BRBF.

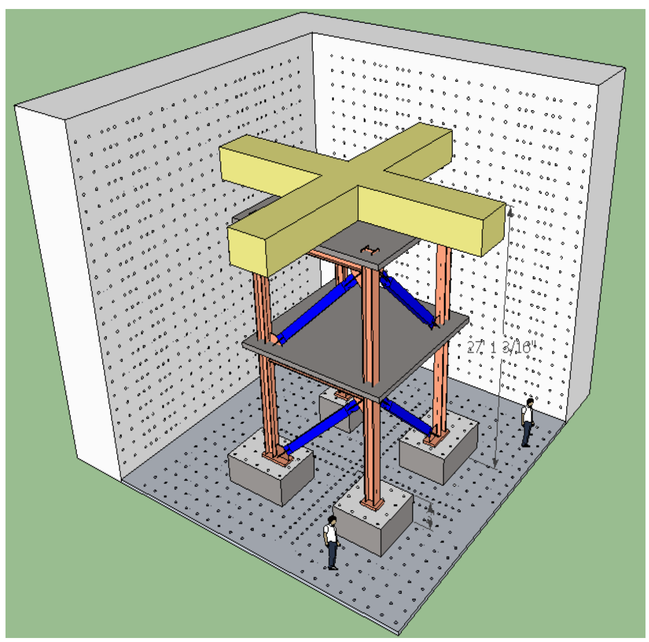

Figure 3. Schematic of BRBF specimen placed in MAST setup

Gusset Plate Design

Buckling Brace Frame

The AISC Seismic Provisions (AISC 2005b) require the bracing connection in special-

CBFs to develop the tensile strength of the brace while accommodating the rotation associated with out-of-plane brace buckling. As shown in Fig. 4(a), accommodation of the rotational capacity is generally accomplished through a linear clearance model, whereby the brace is terminated a distance $2t_p$ before the line of restraint, where t_p is the thickness of the gusset plate. This requirement can result in large buckling lengths of the gusset plate, and consequently, lead to heavy and overly stiff connections that have a detrimental effect on the behavior of the system (Roeder and Lehman 2009).

Based on over 30 one-bay, one-story planar CBF tests, a new clearance model has been developed by Roeder et al. (2005). When combined with the so-called balanced design procedure, the new clearance model illustrated in Fig. 4(b), called the elliptical clearance model, results in thinner and smaller gusset plates. Interestingly, CBF specimens provided with the thinner and smaller gusset plates demonstrated improved behavior over CBFs provided with code-compliant, thicker and larger gusset plates.

The balanced design methodology proposed by Roeder et al. (2005) applies to the following limit states:

1. Yielding on the Whitmore section ($\beta = 1.0$)
   - $R_y F_y A_{g,brace} \leq \beta R_y F_y(\text{Whitmore width})t_g$
2. Whitmore net section fracture ($\beta = 0.85$)
   - $R_y F_y A_{g,brace} \leq \beta F_u(\text{Whitmore width})t_g$
3. Block shear rupture ($\beta = 0.85$)
   - $R_y F_y A_{g,brace} \leq \beta R_n = \beta(0.6 F_u A_{nv} + U_{bs} F_u A_{nt})$
4. Gusset plate welds to beams, columns and baseplates ($\beta = 0.65$)
   - $R_y F_y t_g \leq 1.5\beta(0.6F_{EXX})t_{eff}$ where $t_{eff} = \dfrac{\sqrt{2}}{2}\dfrac{D}{16}$
5. Brace net section fracture ($\beta = 0.9$)
   - $R_y F_y A_{g,brace} \leq \beta R_n = \beta U(R_{tbrace} F_{ubrace} A_{nbrace} + R_{tplate} F_{uplate} A_{plate})$

The above design equations replace the resistance factor, ϕ, in LRFD design with the balance factors, β, that are calibrated to test results. The balance factors are somewhat larger than the corresponding resistance factor, and thereby encourage limited yielding of the gusset plate to achieve ductile behavior of the bracing connection. The remaining limit states may be addressed by the AISC Main Specification (AISC 2005a).

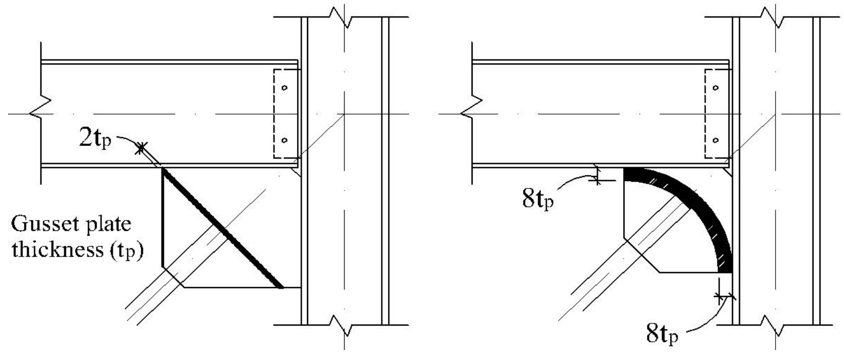

Figure 4. Current and proposed clearance models: (a) AISC $2t_p$ clearance and (b) $8t_p$ elliptical clearance model

The method combining the elliptical clearance model and balance methodology was used to design the gusset plate connections in the CBF specimen. An example is shown in Fig. 5(a). The fillet welds connecting the gusset plate to the beams and columns are sized to resist the strength of the gusset plate (item 4 of the balanced design methodology) and not the force components that result from the Uniform Force Method (UFM). The buckling length of the gusset plate was computed as the average of three isolated lengths measured parallel to the brace axis: from the center and two edge points of the Whitmore width. An effective length factor K = 0.65 was used, as suggested by Roeder and Lehman (2009).

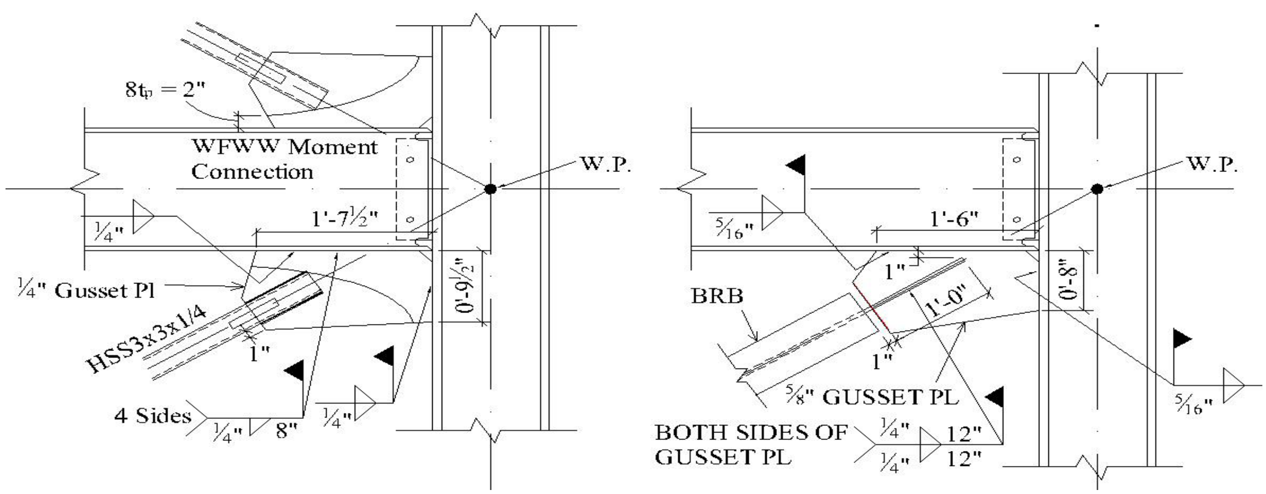

Figure 5. Typical gusset plate connections: (a) buckling brace frame; (b) BRBF

Buckling-Restrained Braced Frame

Because BRBs are generally not expected to deform out-of-plane, the clearance model for CBFs does not apply to BRBFs. Engineers generally avoid a design that encourages yielding of the gusset plate. Therefore, the gusset plates in the BRBF specimen were designed according to the current standards instead of the balanced design approach. A typical gusset plate connection based on this approach is shown in Fig. 5(b).

Test Plan

The test specimen will be subjected to bi-directional cyclic loading through the crosshead attached to the third floor slab (see Fig. 3). The crosshead will supply lateral loads in displacement control, restrain torsional motion about the vertical axis, and introduce no overturning moment on the specimen. The bidirectional loading will be controlled according to a predetermined protocol based on nonlinear time history analyses of the prototype building described earlier. In each lateral direction, the loading protocol is consistent with the sequence defined by the ATC-24 protocol and the AISC Seismic Provisions (AISC 2005b) for prequalification testing of BRBFs. Instruments will be placed to measure the bidirectional story drifts, torsional motion of the floor diaphragms, shear forces and moments in each column, elongation of each brace, out-of-plane brace deformation of the braces and gusset plates, panel zone deformation, beam rotation, column rotation near the bases, and yielding in the beams.

Expected Frame Behavior

The CBF specimen will be tested first. It is expected that brace fracture will occur in the upper story of the braced bent that frames into the web of the shared column since this bent is less stiff due to the weak axis bending of the shared column. Therefore, a larger percentage of the frame shear will be resisted by the braces in this bent. Based on the UW, NCREE and UCB tests, this is expected to occur at a story drift between ±2 and 3 percent. Gusset plate yielding and tearing of the welds connecting the gusset plates to the beams and columns is also expected. Additionally, local yielding of the beams and columns in the connection region will occur at these drift levels.

Based on previous BRBF tests at UW, NCREE and UCB, the BRBF specimen may reach drift ratios similar to the buckling brace of ±2 to 3 percent. Failure in the UW and UCB BRBF tests has occurred due to beam fracture at the gusset, or out-of-plane movement of the beam causing a plastic hinge to form in the BRB just outside of the casing. The out-of-plane loading that this frame will be subjected to may exacerbate this behavior and cause a plastic hinge to form in the BRB at a lower drift level than previously observed.

Conclusions

Large-scale, three-dimensional tests will be conducted at the MAST laboratory at the University of Minnesota to study the system behavior of CBFs and BRBFs. The two specimens will be a two-story, one bay-by-one bay frame with braces placed in two of the four bents. The first specimen will use HSS braces in an X-configuration while the second will use BRBs in a single-diagonal configuration. The brace connections of the CBF specimen will adopt the elliptical clearance model (Fig. 4(b)) and balanced design approach proposed by Roeder et al. (2005). The brace connections of the BRBF were designed according to the uniform force method. The main objectives of these tests are to examine the following: (1) the potentially detrimental effect of out-of-plane drift; (2) the proposed gusset plate design rules applied to a more realistic condition; (3) the performance of bracing connections connecting into the web of a column; (4) the effect of composite concrete slabs; and (5) the behavior of columns shared by braces in orthogonal bents. Additionally, the tests will provide invaluable data to validate analytical models and ultimately improve the design of CBFs and BRBFs.

Acknowledgements

This research project is funded by the National Science Foundation through Grant CMS-619161, "NEESR-SG: International Hybrid Simulation of Tomorrow's Braced Frame Systems." Dr. Joy Pauschke is the Program Officer for this grant. Support has also been provided by the American Institute of Steel Construction under the direction of Mr. Tom Schlafly.

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