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CYCLIC RESPONSE OF THREE-STORY, FULL-SCALE CONCENTRICALLY BRACED FRAMES

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ABSTRACT

Concentrically braced frames (CBFs) are commonly used seismic resisting systems in building construction. Although prior research has focused on the behavior of the cyclic response of brace frame components, very few studies have simulated the response of multi-story systems. A collaborative project, undertaken by researchers at the University of Washington (UW) and National Taiwan University (NCREE), has developed, tested, and evaluated the performance of both two and three story CBFs. Specifically, the tests were developed to study the impact of brace type (HSS and wide flange braces were tested) and buckling direction (both in-plane and out-of-plane buckling). To design the gusset plate connections, both prior test results and results high-resolution finite element analyses were used. The systems used compact, yielding gusset plates developed at UW at the corner connections and a new compact linear-offset midspan gusset for the connections. The results show that proper design of the gusset plate can lead to total drift ranges exceeding 5%.

Introduction

Performance-based design requires systems that have stiffness and strength to sustain the seismic demands developed during frequent earthquakes and stable cyclic drift and inelastic response to sustain the demands developed during seldom but larger earthquakes. Brace frames meet this dual criteria. Previous research shows that braced frames are inherently stiff and strong and, if properly detailed, can sustain multiple, inelastic drift cycles. Specific performance states for braced frames have been developed and are presented in Table 1 (Roeder et al. 2009). These states were defined

Balanced Design Method

To achieve the latter a balance design method was developed. This method differs from current seismic design methods in that is seeks to meet the performance criteria of the event specified and maximize yielding while preventing failure during the maximum credible even. The balanced design procedure is based on balancing the yield mechanisms and preventing undesirable failure modes. Traditional resistance design, as used by the AISC Seismic Manual and specification,

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use resistance factors (φ) to ensure strength and discourage yielding at the expense of decreasing system ductility. On the other hand, the balanced design procedure encourages yielding in elements whose yielding would improve system ductility and performance. Such yield mechanisms include gusset plate yielding, gusset plate buckling, beam yielding and column yielding. A design controlling the hierarchy of yielding is achieved through the use of balance factors called beta (β) factors. These β factors have similar characteristics to the φ factors, but they are fundamentally different, because β factors are based on achieving ductility and inelastic deformation capacity rather than strength, safety and statistically extreme considerations (Roeder 2002). A β factor is smaller when a given yield mechanisms or failure mode is difficult to predict or has undesirable consequences. On the other hand, β factors should be larger for certain desirable, ductile yield mechanisms or failure modes when the resistance can be accurately predicted and/or the consequences are less severe. Similar to φ factors, β factors should be no larger than 1.0 and both are based on experimental research that can accurately predict the performance of a given response mechanism. Equation (1) demonstrates the use of β factors in balancing the resistances of certain yield mechanisms.

$$\mathrm{R}_{\mathrm{yield\ mean}} = \mathrm{R}_{\mathrm{y}} R_{yield} \le \beta_{yield,1} R_{y1} R_{yield,1} \le \beta_{yield,2} R_{y2} R_{yield,2} \le \beta_{yield,i} R_{yi} R_{yield,i} \tag{1}$$

In this equation, R_y is the ratio of the expected yield stress to the minimum specified yield stress and R_{yield} is the nominal yield resistance of the yield mechanism in question, such as include gusset plate buckling (β = 0.9) or gusset plate (Whitmore) yielding (β = 1),. Along with balancing certain desirable yield mechanisms by satisfying Equation (1); another important aspect of the balanced procedure is to discourage failure in elements whose failure could cause significant, irrecoverable damage and loss of resistance. The undesirable failure modes include block shear, Whitmore fracture, weld tearing and net section fracture of the brace. The following additional balance expression in Equation (2) is used to balance critical failure mode resistances.

$$\mathrm{R}_{\mathrm{yield\ mean}} = \mathrm{R}_{\mathrm{y}} R_{yield} \le \beta_{fail,1} R_{fail,1} \le \beta_{fail,2} R_{fail,2} \le \beta_{fail,i} R_{fail,i} \tag{2}$$

In this equation, R_{fail} is the nominal failure resistance of the failure mechanism in question. Additional information is available in (Roeder et al. 2009).

Elliptical Design Method and One-Story CBF Tests

An alternate clearance limit that uses an elliptical clearance limit was proposed because of this reduced flexibility. As shown in Figure 1, the ellipse is offset from the beam and column faces a distance Nt_p; where N is the number of plate thicknesses, t_p, that the elliptical line is to be offset from the intersection of the beam and the gusset plate. The ellipse is also defined such that its center is located where the imaginary corners of the gusset plate intersect the centerline of the brace. Finally, the ellipse is defined such that it touches the corner of the brace that is closed to the column. This corner was used because, for sharply inclined braces, the use of this point would lead to the most economical gusset plate size. Through experimental and analytical simulations by Yoo (2006), a value of $8t_p$ was deemed to provide the greatest OOP rotational capability and while permitting the maximum drift range to be achieved.

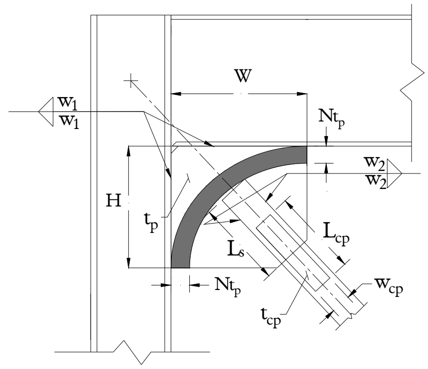


Figure 1 Elliptical Clearance Design Method for Corner Gusset Plates

The elliptical clearance for corner gusset plates has been explored experimentally and analytically though an extensive research program conducted at the University of Washington and funded by a partnership of the National Science Foundation (NSF) and the American Institute for Steel Construction (AISC). The tests were conducted to evaluate current design and to develop a new design methodology to (1) improve the performance of the system by following the balance design method and (2) to develop a more compact gusset plate connection to improve the constructability. Figure 2 shows the gusset plate details and responses of three of the one-story tests. Specimen HSS-5 had thin, rectangular gusset plates with an HSS tube brace, Specimen HSS-23 had thin, rectangular gusset plates with a wide-flange brace and Specimen HSS-28 had thicker, tapered gusset plates with an HSS tubular brace. The results show that Specimens HSS-5 and HSS-23 achieved similar maximum drifts and drift ranges, where Specimen HSS-28 achieved smaller maximum drifts (positive and negative) than the other specimens. Specimen HSS-28 did not meet the balanced design method and therefore did not achieve the desired drift capacity in tension. Additional information can be found in Lehman et al. 2008 and Powell 2009.

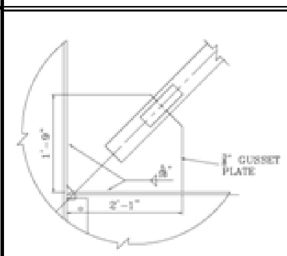
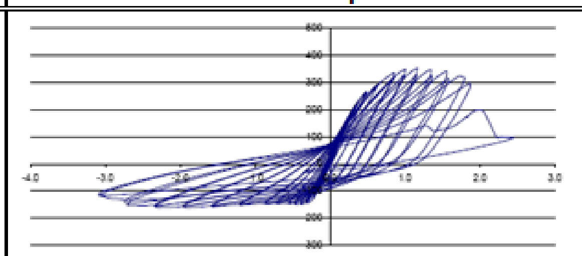
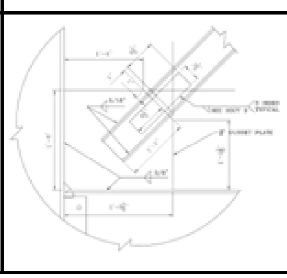
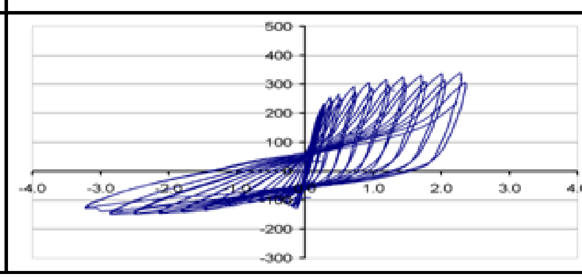
	Corner Gusset Detail	Measured Response
Specimen HSS-5 Rectanguar Gusset		
Specimen HSS-23 Wide-flange Brace		

Figure 2 Corner Gusset Details and Measured Responses of Comparison One-Story, One-Bay Braced Frame Specimens.

Two-Story CBF Tests
As part of an effort to improve the understanding of multi-story braced frame response, a series of two- and three-story frames were tested. The two story tests were conducted first and have been reported elsewhere (Clark et al. 2008).

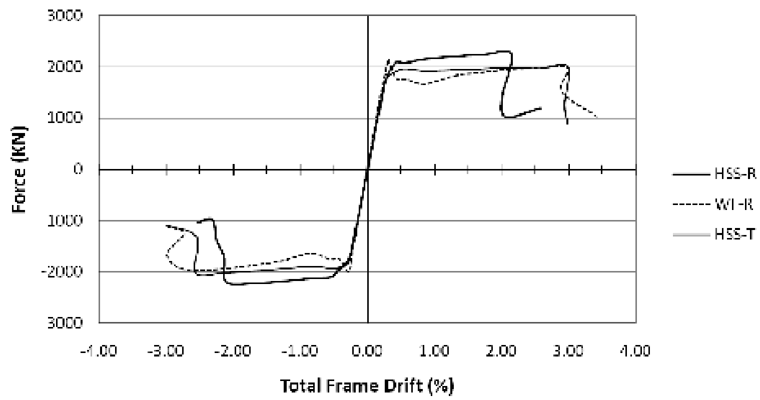


Figure 3 Two-Story Tests: Specimen and Response Envelopes

The two-story tests consisted of a multi-story x-braced frame. The tests varied the type of brace, in that both HSS and wide flange braces were tested, and the type of gusset plate geometry, in that both rectangular and tapered plates were tested. The frame (e.g., beams, columns, and slabs) were reused and only the gusset plates and braces were replaced. Figure 3 shows the response envelopes for the HSS-rectangular (HSS-R), the wide-flange-rectangular (WF-R), and the HSS-tapered (HSS-T) specimens. The results indicated that the HSS and wide-flange sections were both capable of achieving the performance objectives of high initial strength and stiffness with large inelastic drift capacities. The results show some advantages of the wide flanges relative to drift capacity, however this in part is due to the additional frame and slab flexibility resulting from the damage sustain during the HSS-R test (Clark et al. 2008).

One of the most important aspects of the two-story test series was that the specimens represented the first tests of a midspan gusset plate connection, which was largely designed with the aid of structural analysis and design guidelines. As a result, the rectangular midspan gusset had both interior and edge stiffeners, which minimized plate yielding and relied on twisting of the center beam to sustain out-of-plane buckling of the brace. Therefore, further testing of the mid-span gusset with reduced stiffeners to maximize gusset plate yielding was a primary focus of the three-story tests.

Specimen Design

The test specimens simulated a three-story frame and included a multi-story x-brace in Stories one and two and a chevron brace in story three (Figure 4). The specimens were part of a larger

National Science Foundation Project entitled “International Hybrid Simulation of Tomorrow’s Braced Frame Systems” and therefore the specimens were given the acronym TCBF. Since the specimens followed a series of two-story frames, the specimens were designated collectively as 2. For each TCBF2 specimen, only the braces and gusset plates were replaced; each test used the same frame (i.e., beams, columns and slabs). Specifically, the three specimens varied in the type of brace and buckling direction. The three specimens were as follows.

- TCBF2-HSS used square hollow structural section (HSS) braces with gusset plates oriented to promote out-of-plane brace buckling. The corner gusset plate connection used the elliptical clearance method (Lehman et al. 2008). The mid-span gusset used an 8-t linear offset with midline stiffeners
- TCBF2-WF used wide flange (WF) braces with the braces and gusset plates oriented to promote out-of-plane brace buckling. The corner gusset plate connection used the elliptical clearance method (Lehman et al. 2008). The mid-span gusset used an 8-t linear offset with midline stiffeners.
- TCBF2-IP used square HSS braces with knife plates oriented to promote in-plane buckling. The connections were different than the prior two specimens in that the braces were connected to a knife plate which was then connected to a corner gusset plate. The knife plate was designed using a linear offset to promote rotation of the knife plate at the end of the brace, and the gusset plate was designed to remain elastic.

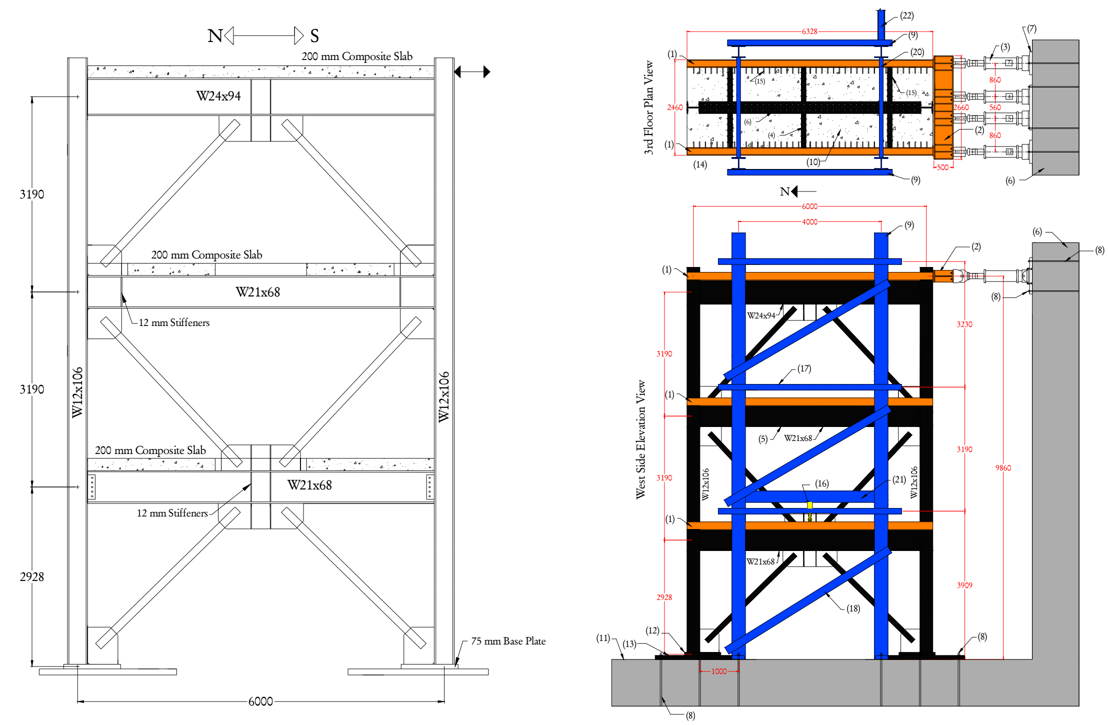


Figure 4 TCBF2 Test Frame and Setup (TCBF2-1 shown)

The specimens were designed using both the balanced design procedure for the corner gusset plates and associated welds and nonlinear analysis for the mid-span gusset plates. Specifically, the corner gusset plates were designed by balancing following yield mechanisms: Whitmore yielding and fracture, block shear, net-section fracture and gusset plate buckling. Figure 5 shows the corner and mid-span gusset connections and the knife-plate detail for Specimen TCBF2-IP. The corner connections used the elliptical clearance and were designed to balance Whitmore yielding. The mid-span gusset connection used a linear offset method, in which an offset of six (6) times the thickness of the plate (t_p) was used. In Specimen TCBF2-IP, tensile yielding and in=-plane rotation was expected in the knife plate (as opposed to the gusset plate for the other specimens); a linear offset of $2t_p$ was used.

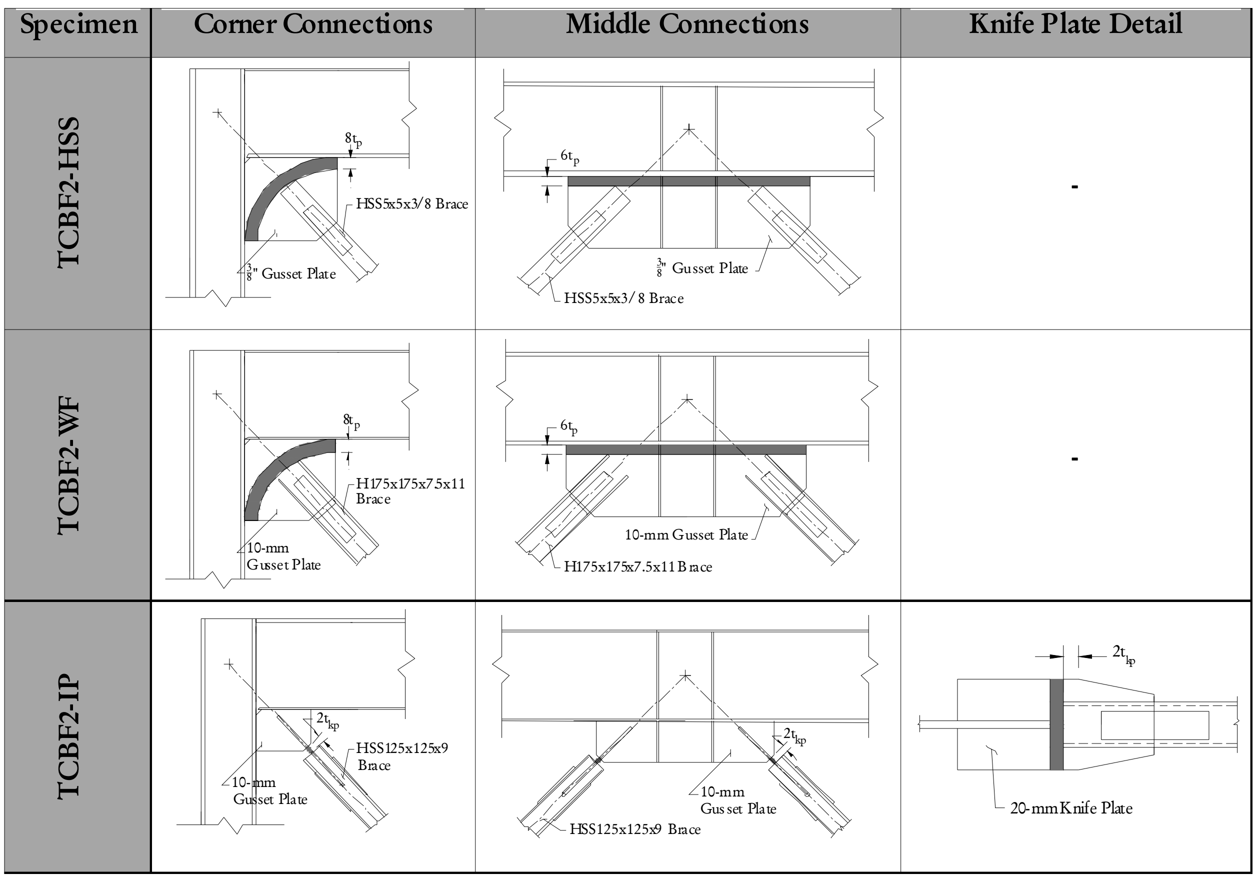


Figure 5 Gusset Plate Details for TCBF2 Tests

Another deviation from conventional AISC was the size of the beam at the third story. The AISC Seismic Manual requires beams intersected by braces to sustain the unbalanced vertical forces from simultaneous tensile yield and post buckling force in the intersecting braces with a 70% reduction to the nominal buckling force to account for the loss of load carrying capacity in the compression brace after substantial buckling or plastic hinging has occurred. Few tests results have supported or contradicted this requirement. Using the required strength from the AISC Specification check indicated that the combined axial and moment loads exceeded the capacity of the W 28x94 by 23%. However, the capacity check using the additional flexural capacity from the composite slab resulted in a section that was adequate. The results were verified by FEM analyses.

Test Setup

The specimens were subjected to cyclic lateral loading. Axial load was not applied. Figure 4 shows a schematic test set-up, including an elevation and plan (from the top of the specimen). The lateral load was applied to the top story of the specimen only, using four 100-ton actuators. The actuators were anchored to the strong wall and attached to a transfer beam that was attached to the slab though shear studs, which transferred from the edge beams to the slab. From the slab, the load was transferred to the test frame through a double row of shear studs on the third story beam and the single row of shear studs on the support beams. Any out-of-plate (OOP) movement of the frame was resisted by the blue OOP restraint frame which consisted of OOP verticals, OOP horizontals and OOP lacing. The OOP frame was not directly connected to the test frame; instead it rested on it with a series of roller guides, as shown in the plan view. The OOP frames on both the east and west side of the specimen were connected through a series of diagonal and horizontal lacing members. The OOP frame also ensured that the test frame behaved planer and that the only motion was in the direction of the applied actuator forces. The specimens were subjected to a lateral drift history consisting of monotonically increasing drift cycles until significant loss of lateral load.

Experimental Observations and Measured Response

Performance assessment of structural systems requires accurate prediction of yielding, cracking, buckling and other important damage and failure modes. To that end, these states were carefully noted during testing for all the braced frame components including the braces, gusset plates, beams, columns and slabs. However, detailed discussion of these observations is not possible within this paper. Further description of the yielding and other damage is available in Lumpkin 2010. Here, only the primary performance states are presented.

Specimen TCBF2-HSS

Specimen TCBF2-HSS achieved negative and positive drifts of -1.74% to 2.08%, respectively, with a total drift range of 3.82%. Figure 6 shows the total force-drift response. The measured responses for each story, which are as follows: 1st Story: -2.20% to 2.18% → 4.38% drift range, 2nd Story: -2.15% to 2.17% → 4.32% drift range, and 3rd Story: -1.06% to 1.07% → 2.13% drift range. The following provides a brief overview of the yielding, buckling and component failure modes that were observed during the initial (to 0.5% drift), moderate (0.5% to 1.49% drift) and final drift (to -1.74% and 2.08% drift) ranges. When beneficial, photographs showing the state of yielding or other damage in the brace, gusset, or framing components are included.

- Initial Drift Range: Brace buckling was initiated at the 0.35% drift level in each story, and visible brace buckling occurred during the 0.52% drift cycles in the first and third story braces (Figure 7). Initial yielding was also observed in the second story beam adjacent to the midpan gusset.

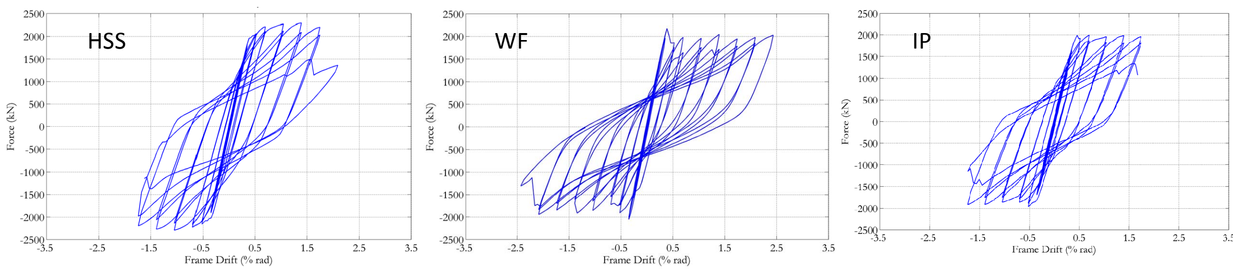
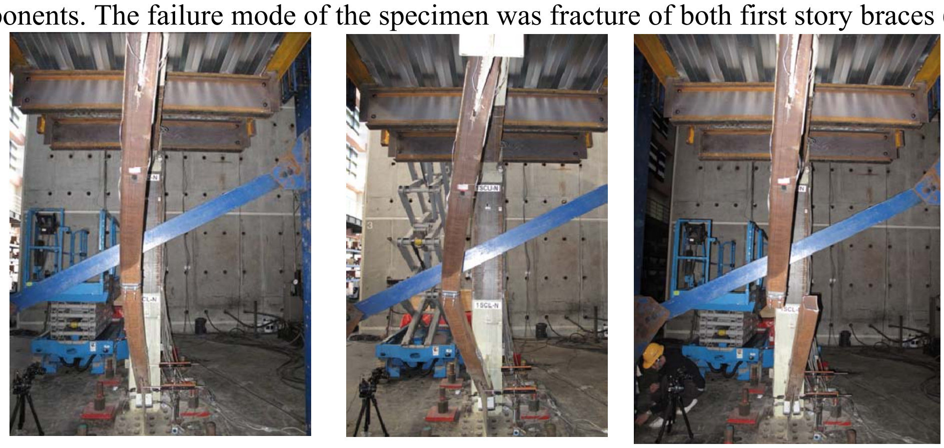
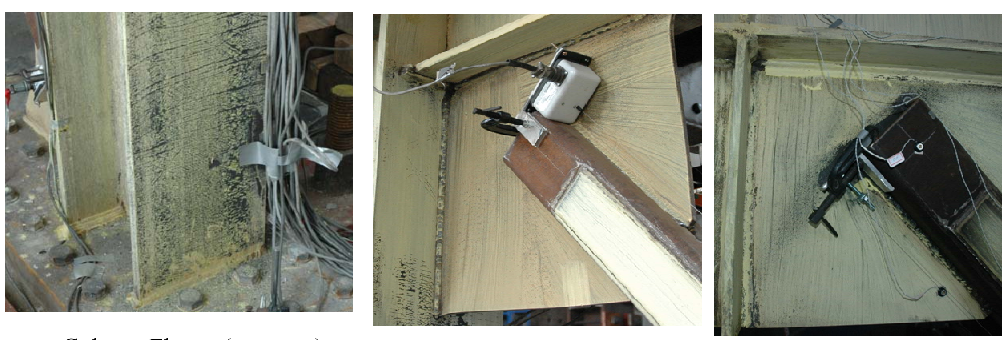


Figure 6 Measured Responses of TCBF2 Specimens (Total Drift)

- Moderate Drift Range: Yielding increased in the midspan at the first story; at a drift in the first story of 1.0%, a small crack was noted at the end of the brace. In addition to increase in brace buckling as shown in Figure 7 (the OOP displacement in the first and second story braces reached twice the brace depth), yielding in the base columns progressed up the height and in the web.
- Final Drift Range: Increased drift demands in the final drift range lead to increased yielding in the gusset plates, column bases, and beams. Figure 7 shows the extent of yielding in these components. The failure mode of the specimen was fracture of both first story braces (Figure 7).



First Story Brace -0.52% First Story Brace -1.39% Complete Fracture +2.08%



Column Flange (post test) Second-Story Gusset (post-test) Mid-Span Gusset (post-test)

Figure 7 Observed Response of Specimen TCBF2-HSS Components

Specimen TCBF2-WF

Specimen TCBF2-WF achieved negative and positive drifts of -2.43% to 2.43%, respectively with a total drift range of 4.86%. Figure 8 shows the total force-drift response. The measured responses for each story, which are as follows: 1st Story: -2.57% to 2.64% → 5.21% drift range, 2nd Story: -2.51% to 3.05% → 5.56% drift range, and 3rd Story: -1.37% to 1.62% → 2.99% drift range.

- Initial Drift Range: Initial brace buckling was measured at 0.35% drift and observed at 0.52% in the first and second story braces. Gusset plate rotation accompanied brace buckling and yielding was observed in the first story corner and mid-span gusset plates.
- Moderate Drift Range: During this drift range, buckling in the first and second story braces increase, thereby increasing the yielding and hinging in the corner and mid-span gusset plates. Yielding at the column bases also initiated during this drift range. Finally, at a drift of 1.4%, buckling was initiated in the third story braces. The initiation of buckling can be observed in the total drift ration in that it results in a sharp but temporary decrease in the lateral force. It is noted that at the end of this drift range, the out of plane movement of the gusset plates was more significant than the prior, TCBF2-HSS, specimen.
- Final Drift Range: Increased drift demands in the final drift range lead to increased yielding in the gusset plates; yielding of the framing elements was more limited than TCBF2-HSS. Yielding was also noted at the net-section reinforcement in the brace at 2.43% drift (Figure 8). The failure mode of the specimen was complete fracture of one of the second story braces. Figure 8 shows the brace just prior to fracture.

Yielding at Brace Net-Section (-2.43%) Brace Distortion Prior Buckling (2.43%) Midspan Gusset (post-test)

Figure 8 Specimen TCBF2-WF: Yielding States for Braced Frame Components

Specimen TCBF2-IP

Specimen TCBF2-WF achieved drift range of 3.48% with the first story drift range of 3.99%, second story range of 4.56% and a third story drift range of 1.99% (Figure 6). The response of the specimen was different than the prior two, in that in-plane buckling was the desirable response mode.

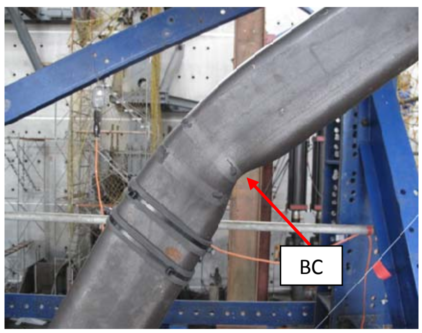
- Initial Drift Range: Initial brace buckling was observed at 0.52% in the first and second story braces. Knife-plate rotation accompanied brace buckling and yielding was observed in the 2-t_p region of the knife plates adjacent to the buckled braces. (Figure 9)
- Moderate Drift Range: During this drift range, buckling in the first and second story braces increased, thereby increasing the yielding and hinging in knife plates beyond the 2t_p region, suggesting that this offset might be too limited to achieve the rotation

demands. At a drift of 1%, buckling was initiated in the third story braces, in-plane buckling in one and out-of-plane in the other.

- Final Drift Range: The final drift range was the first in which column yielding was noted (1.74%). Brace fracture occurred in the second story braces at 1.74% drift. Small tears were noted in the metal of the knife plate adjacent to the gusset plate (Figure 9).

Brace Buckling (+0.52%)

Yielding in Knife Plate (+0.52%)



Brace Cupping (+1.74%)

Tears in Mid-Span Knife Plate (+1.74%)

Figure 10 Specimen TCBF2-IP: Yielding and Damage States

Summary and Conclusions

The three-story specimens demonstrated that multi-story buckling and yielding can be achieved with concentrically braced frame systems. The specimens drift capacities were maximized by careful attention to sizing the gusset plate and balancing the relative strengths of the braced frame components. Prior tests have indicated that both HSS and wide-flange braces can achieve drifts ranges above 4%. This test indicates that the drift capacity of the HSS frame was slightly smaller, however the drift capacity of the wide-flange brace specimen was also smaller than the prior tests. Finally, although in-plan buckling has promise for performace, it did not achieve the drift capacities of the other specimens.

References

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