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SEISMIC PERFORMANCE OF CHEVRON BRACED FRAMES WITH YIELDING BEAMS

A. D. Sen[1], C. W. Roeder[2], J. W. Berman[3], D. E. Lehman[4], K. C. Tsai[5], C. H. Li[6], and A. C. Wu[7]

[1] *Doctoral Candidate, University of Washington, adsen@uw.edu*
[2] *Professor, University of Washington, croeder@uw.edu*
[3] *Associate Professor, University of Washington, jwberman@uw.edu*
[4] *Professor, University of Washington, delehman@uw.edu*
[5] *Professor, National Taiwan University, kctsai@ntu.edu.tw*
[6] *Assistant Research Fellow, National Center for Research on Earthquake Engineering, chli@ncree.narl.org.tw*
[7] *Assistant Research Fellow, National Center for Research on Earthquake Engineering, acwu@ncree.narl.org.tw*

Abstract

Steel concentrically braced frames (CBFs) have been used as seismic force resisting systems for many years. In seismically active regions of the US, the chevron configuration was used extensively in older construction but is less common today due to the codification of stringent beam-strength requirements. Today, the AISC *Seismic Provisions* prescribes a post-buckling brace load case for SCBFs which induces large axial-flexural demands that the beam must resist in addition to gravity load effects. These provisions require deep and heavy beam sections which are not economical. An international research collaboration between the University of Washington and the National Center for Research on Earthquake Engineering in Taiwan has examined the use of beams in chevron CBFs that do not meet SCBF requirements and are expected to yield after brace buckling. The research examines the vulnerability of older chevron CBF infrastructure with yielding beams and explores the potential of yielding-beam SCBFs. The results show that brace yielding in tension is prevented due to beam deflection, but frame action mitigates the reduced brace resistance. In addition, yielding-beam frames can achieve drift capacities comparable to SCBF-compliant yielding-brace frames. Consequently, older CBFs with weaker beams may not require beam retrofit and the yielding-beam mechanism shows promise for new construction. This increases the viability for retrofit of older CBFs if the beam can be retained (allowing for focus on more impactful areas) and alleviates economic concerns for chevron SCBFs.

Keywords: steel; braced frames; chevron; nonductile; rehabilitation

1. Introduction and Background

Concentrically braced frames (CBFs) are among the most widely used seismic force resisting systems in steel construction. CBFs develop primary resistance through tension and compression of the braces, and frame action from the beams and columns provides additional resistance. Since brace capacity differs in tension and compression, braces are usually oriented in opposing pairs to provide symmetric lateral resistance. The chevron configuration depicted in Fig. 1 achieves this while accommodating architectural features like windows and doors. Chevron CBFs were commonly deployed before the mid-1990s but are less popular today due to the introduction of stringent capacity-based design requirements for beams with intersecting braces [1].

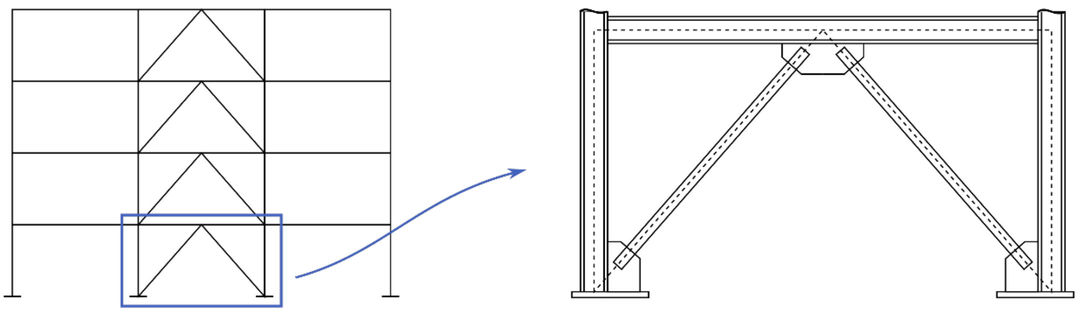


Fig. 1 – Example of chevron CBF

Older chevron CBFs exhibit different inelastic behavior than their modern special CBF (SCBF) [2] counterparts due to their lighter, shallower beams. In large earthquakes, SCBFs are designed to form the plastic mechanism shown in Fig. 2a where the brace yields in tension and buckles in compression with essentially elastic behavior in the surrounding frame. After brace buckling, deterioration of the compressive brace force results in a net downward force on the beam and relatively high axial load. SCBF design avoids yielding of the beam under these combined axial-flexural demands by sizing the beam for prescribed post-buckling brace forces [2]. This post-buckling load case assumes that one brace develops its yield force in tension and the opposing brace force has degraded to 30 percent of its critical buckling load in compression. Consequently, beams in chevron SCBFs must be relatively deep and heavy; this is often not economically or architecturally permissible, which explains their decreased prevalence in new construction.

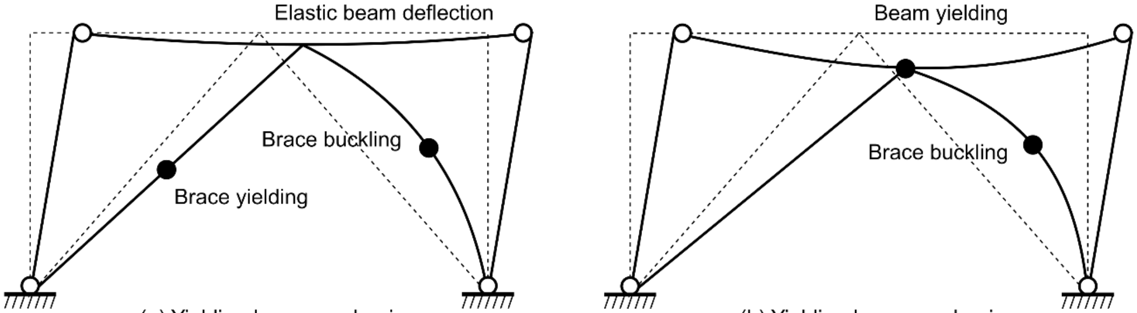


Fig. 2 – Chevron CBF plastic mechanisms

Beams in chevron CBFs designed prior to the 1994 *Uniform Building Code* (UBC) [1] were only designed for gravity loads and therefore are typically deficient with respect to the assumed post-buckling brace forces. These older chevron CBFs develop the plastic mechanism in Fig. 2b in which the brace buckles and the beam yields; inelastic deformation in the beam precludes full yielding of the brace in tension. This behavior has been discouraged largely because the reduced brace force in tension accelerates lateral resistance degradation in the brace pair and the unbalanced brace forces induce inelastic beam deflections [3]. However, the resistance developed through frame action is often understated and beam deflection may be acceptable in a performance-based seismic design approach.

Chevron CBFs with yielding beams were studied as part of a larger research program investigating the seismic rehabilitation of nonductile CBFs (NCBFs) [4]. NCBFs were designed prior to the adoption of capacity-based design principles in the 1988 UBC [5] and other special requirements which ensure ductility, including chevron beam strength requirements [2]. In an infrastructure review of 12 NCBFs in the US, 8 had chevron bracing and each of these had beams with axial-flexural interaction demand-to-capacity ratios (DCRs) greater than 1 based on the assumed unbalanced load from the *Seismic Provisions* [2, 6]. The NCBFs reviewed also had widespread brace and connection deficiencies with respect to SCBF capacity, geometric, and material requirements. Many NCBFs are expected to be retrofitted to improve their seismic performance, but retrofitting to mitigate the yielding-beam mechanism would likely be invasive, costly, and time consuming. Therefore, a thorough understanding of the yielding-beam response is critical.

This paper presents experimental research that evaluated CBFs exhibiting the yielding-beam plastic mechanism. The research suggests that beam yielding is not necessarily detrimental to system response and supports relaxed beam-strength requirements.

2. Experimental Setup and Specimen Design

To study the yielding-beam mechanism's impact on NCBFs, retrofitted NCBFs, and potentially new construction, a series of four (4) tests were conducted at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. The experimental setup is shown in Fig. 3. The specimens were two-story chevron-configuration CBFs loaded at the top story under a fully reversed cyclic loading protocol with increasing amplitude. Since the second-story beam was required to transfer the actuator load into the frame, a fully composite W24×94 was used with fully restrained welded-web-welded-flange (WWWF) beam-to-column connections. This second-story beam was compliant with the SCBF requirements, so the focus of the study was the first-story, which had a W16×45 beam. Preliminary nonlinear analysis showed that the strength and stiffness of the second-story beam had a reasonably small effect on the first-story response, validating the use of the fully composite W24×94 second-story beam [7].

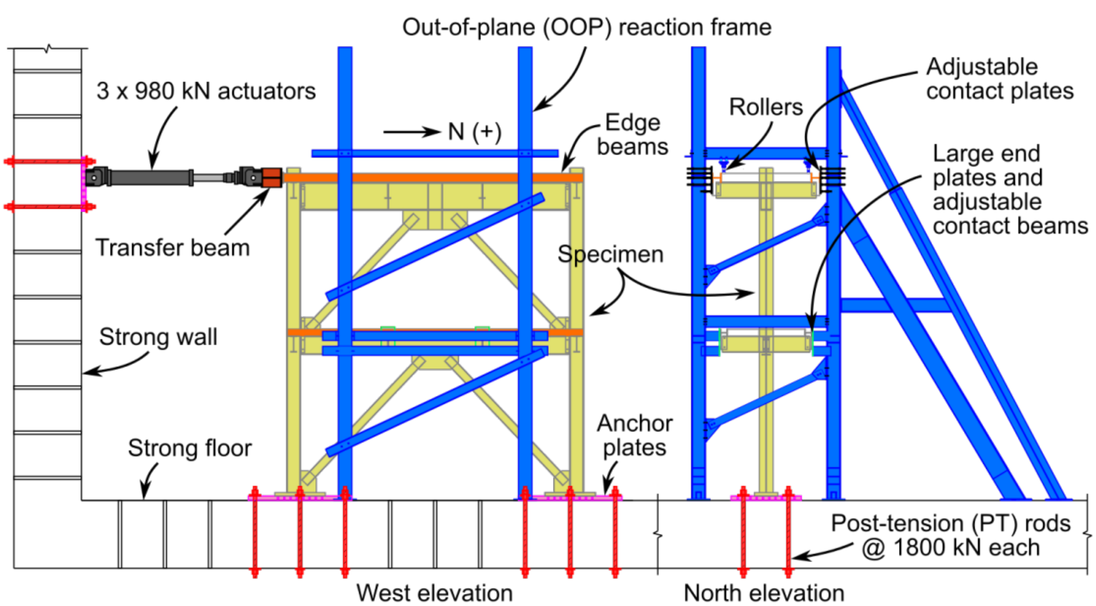
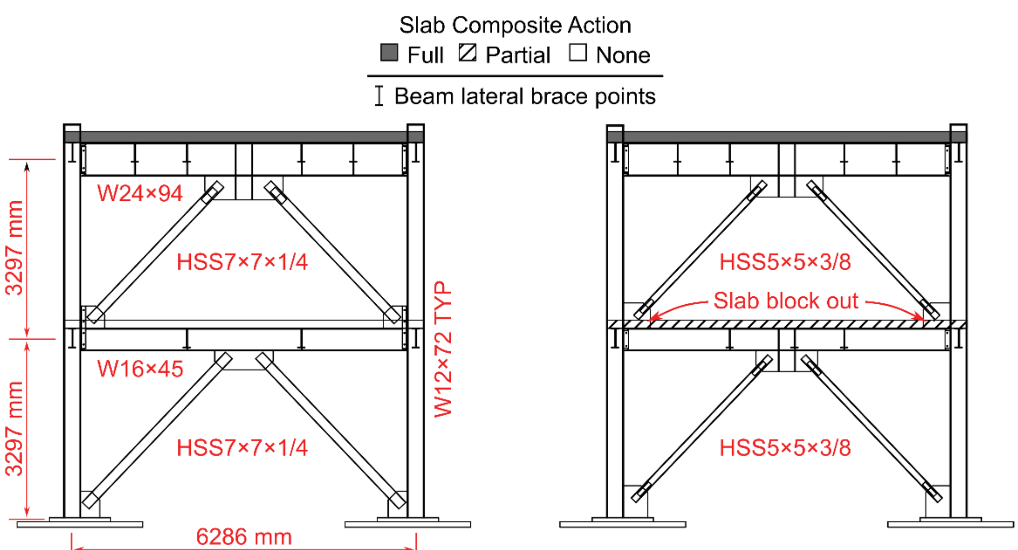


Fig. 3 – Experimental setup

This paper examines two (2) of the specimens tested at NCREE, which are shown in Fig. 4. The beam and column sections used were consistent between specimens but connection type and composite action varied. The W12×72 columns were welded to the base plates with CJP welds meeting demand critical requirements. The gusset-plate connection details for each are shown in Fig. 5. Table 1 shows salient DCRs for these specimens with resistance factors applied [8]. Note that the horizontal and vertical gusset-plate welds were evaluated here using the uniform force method [9].

The DCRs in Table 1 are classified as yield mechanisms, failure modes, or geometric limits. Yield mechanisms are typically beneficial and can enhance deformation capacity if balanced with the brace capacity. Failure modes are detrimental and must be suppressed because they lead to premature and/or sudden loss of resistance, and geometric limits help delay these limit states.

Specimen NCBF simulated NCBF construction with locally slender HSS7×7×1/4 braces on both stories. The first-story beam had a 150-mm slab but no shear connectors; its axial-flexural interaction DCR was 2.8, indicating the yielding-beam mechanism would likely develop. All connections except the second-story midspan gusset plate (Fig. 5a) had DCRs representing those computed from the infrastructure review [6] and their welds were formed with AWS E71T-7 electrode which does not meet demand critical minimum toughness requirements [2]. It is also noted that the first-story slab was not blocked out around the second-story corner gusset plates. Table 1 shows that the brace-to-gusset weld DCR was especially high, which is a major concern since these are failure modes. The gusset-plate Whitmore yielding [10] DCR exceeded 1, but this is less concerning because it is a yielding mechanism.



(a) Specimen NCBF and typical dimensions and beam and column sizes

(b) Specimen SCBF

Fig. 4 – Specimen overviews

Table 1 – Salient experimental specimen demand-to-capacity ratios

Classification	Criterion	Specimen NCBF		Specimen SCBF	
		1F	2F	1F	2F
Yielding mechanisms	Whitmore yielding	1.1	1.0	0.8	0.8
	Beam axial-flexural interaction	2.8	0.5	1.6	0.5
Failure modes	Brace-to-gusset weld fracture	1.3	1.3	0.8	0.8
	Gusset block shear rupture	1.0	1.0	0.9	0.9
	Gusset-to-frame horizontal weld fracture	0.9	0.7	0.5	0.4
	Gusset-to-frame vertical weld fracture	1.0	1.5	0.5	0.4
Geometric limits	Brace local slenderness	2.3	2.3	0.9	0.9

Note: All ratios consider measured material properties and AISC resistance factors (ϕ) [6].

Specimen SCBF had HSS5×5×3/8 braces and simulated new construction with the exception of the first-story beam strength (DCR of 1.6). The first-story slab was partially composite (about 30% composite based on the axial capacity of the beam) with WWWF connections like the second-story beam. The connections were designed using the balanced design procedure (BDP), which is a design methodology that improves the deformation capacity of SCBFs by establishing clear yield and failure hierarchies [11]. The BDP also encourages the use of an $8t_p$ elliptical clearance [12] and a $6t_p$ vertical clearance at corner and midspan connections, respectively, to accommodate end rotation of the brace. These recommendations were heeded as shown in Figs. 5e through 5h, and the first-story slab was also blocked out around the second-story corner gusset plates to allow out-of-plane deformation. Welds on Specimen SCBF were formed with AWS E71T-1 electrode, which satisfies demand critical weld requirements [2].

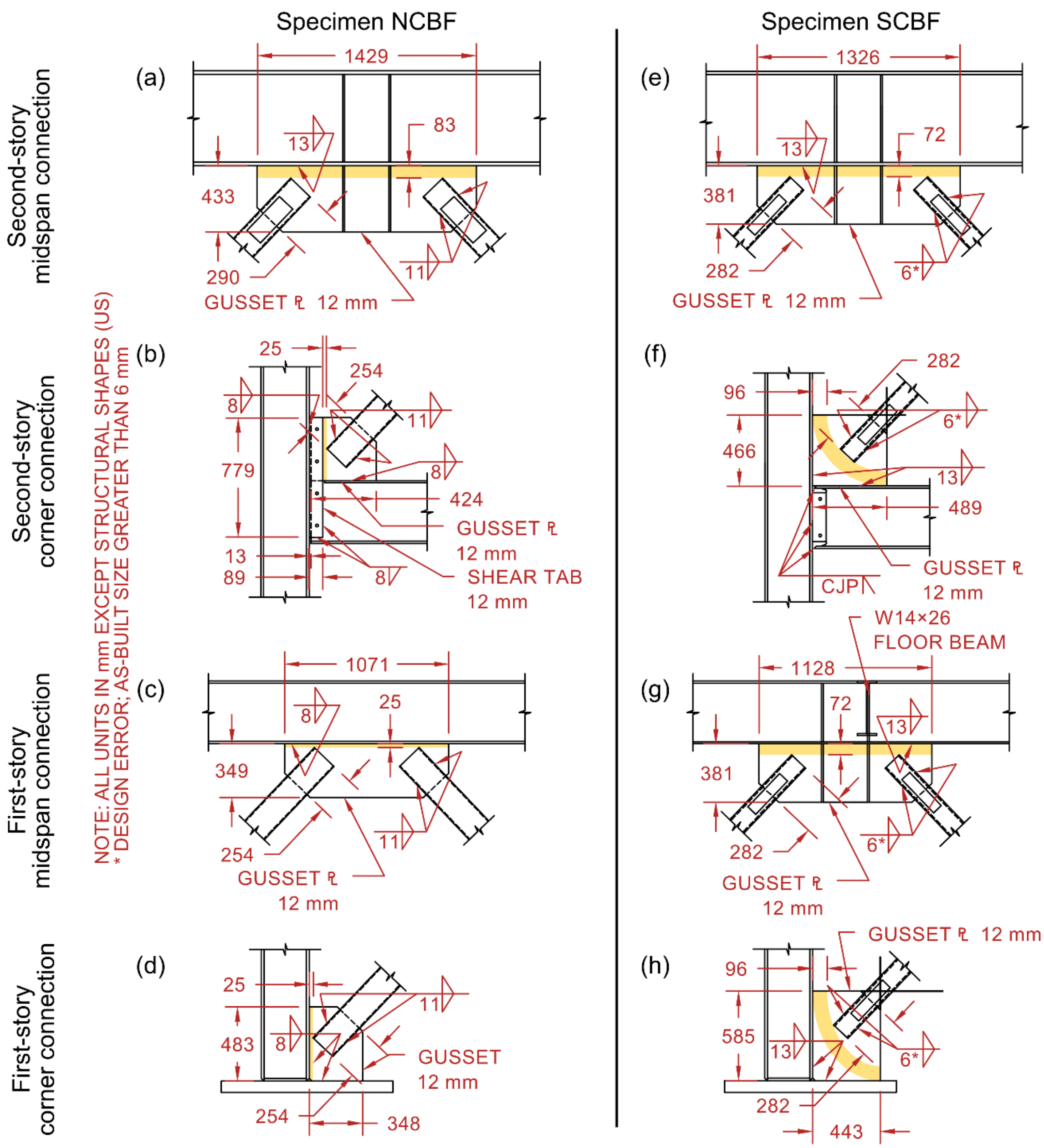


Fig. 5 – Specimen connection details

3. Experimental Observations

Figure 6 shows the hysteretic behavior of Specimens NCBF and SCBF. In these plots, force is normalized by the predicted story shear at initial brace buckling, $V_{bb,n}$, which considers the critical buckling load of the brace and the frame resistance at the corresponding deformation. The subscript n corresponds to the story of interest. In the following discussion, lateral deformation capacity is discussed in terms of drift range, or the total maximum deformation of the frame in both directions of loading.

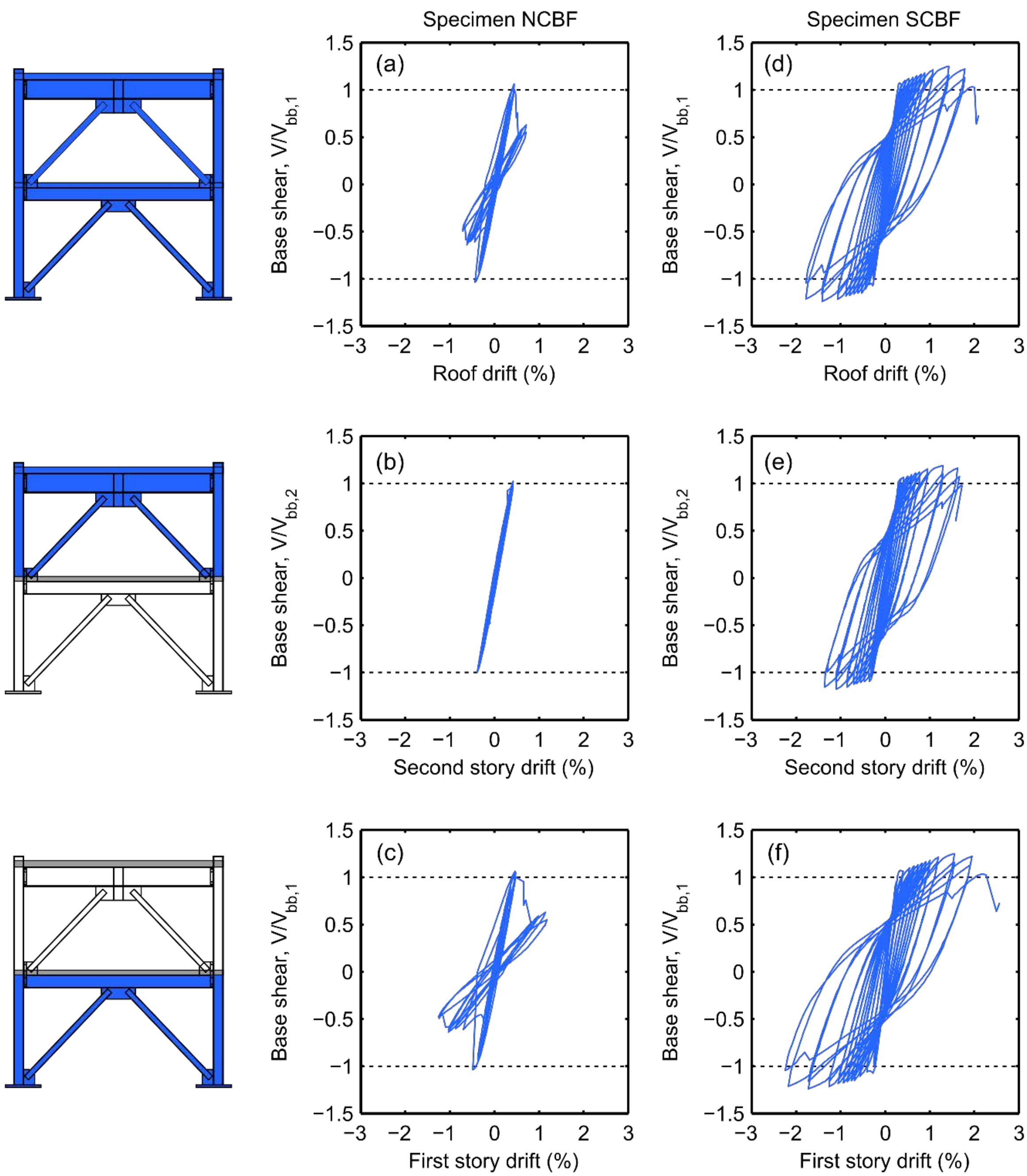


Fig. 6 – Test specimen hysteretic response

Specimen NCBF exhibited highly nonductile behavior at its first-story (see Fig. 6c). Rapid strength and stiffness deterioration resulted in the concentration of damage on the first-story. Up to a first-story drift range of

0.7%, both stories were essentially elastic. The south first-story brace buckled out-of-plane at a first-story drift range of 1.0% and a plastic hinge at the brace midspan developed during this event (see Fig. 7a). The severe local deformation of the brace resulted in high strength degradation in compression and led to fracture in tension at 1.2% first-story drift range, as is common for locally slender tubular braces [13]. This drift-range capacity is exceptionally low compared to SCBFs, which are expected to achieve a story drift range of about 5% prior to brace fracture.

Brace fracture resulted in a sharp decrease in lateral resistance, but the frame still maintained significant resistance. The north first-story brace did not buckle or yield because the beam yielded in flexure and limited brace deformation. As such, the first-story behaved much like an eccentrically braced frame (EBF) with a long link. To accommodate the beam end rotations, the weld between the south shear plate and beam web cracked slightly; yielding in the beam web was also noted in this region as shown in Fig. 7b. The EBF-type behavior was sustained up to a first-story drift range of 2.2% when the north first-story brace-to-gusset connection fractured (see Fig. 7c). This can be attributed to the excessive gusset-to-beam weld DCR (1.3). Frame action could still be developed in the beams and columns, but the test was ended at this point.

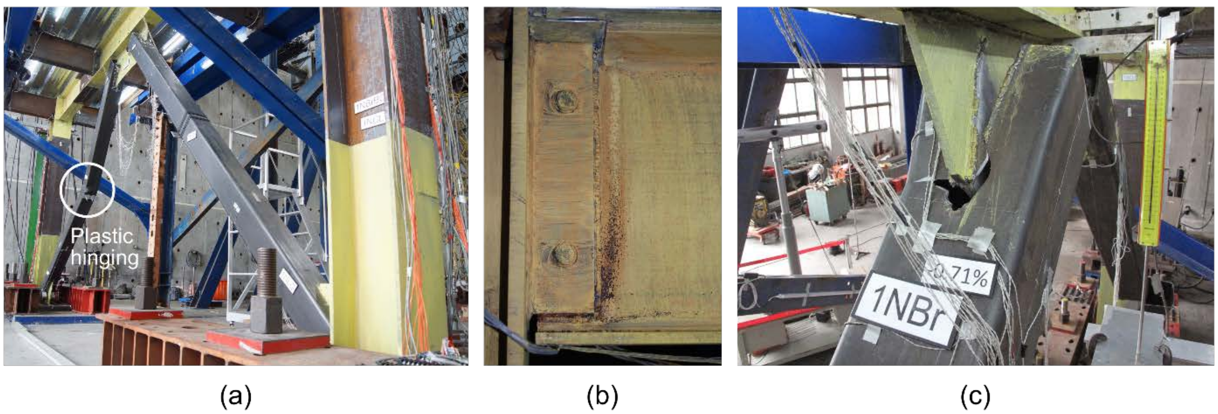


Fig. 7 – Specimen NCBF (a) first-story brace buckling and plastic hinging, (b) yielding and weld cracking near first-story beam end, and (c) first-story brace-to-gusset connection fracture

Specimen SCBF had behavior characteristic of an SCBF despite clearly developing the yielding-beam plastic mechanism at its first story. Unlike Specimen NCBF, inelastic deformation was not concentrated in one story (see Figs. 6e and 6f). The first-story braces buckled first at a first-story drift range of 0.6% (see Fig. 8a), but the story shear increased with respect to drift due to supplemental frame resistance. This allowed the second-story braces to buckle at a second-story drift range of 0.6% and develop a yielding-brace plastic mechanism.

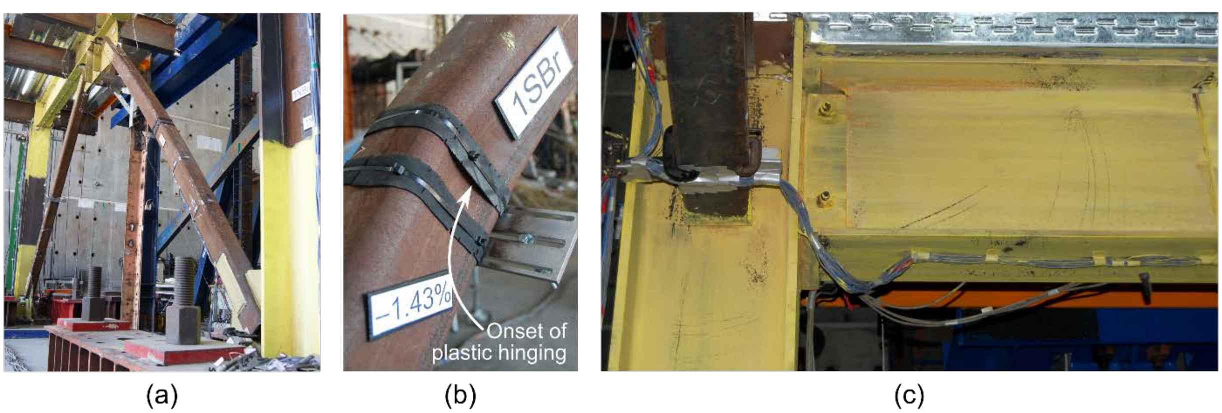


Fig. 8 – Specimen SCBF (a) first-story brace buckling, (b) onset of first-story brace plastic hinging, and (c) yielding near first-story beam end

Since the connections were designed using the BDP, premature failure modes were effectively suppressed. The first-story braces developed midspan plastic hinges as depicted in Fig. 8b at a first-story drift range of 2.4%; one second-story brace also developed a plastic hinge at a second-story drift range of 3.1%. The first-story braces fractured at 4.5% first-story drift range, and the frame was not loaded further. The second-story braces did not fracture and were not deformed beyond a second-story drift range of 3.1%. Figure 8c shows the extent of yielding in the first-story beam by the end of the test; whitewash flaking is seen in the flanges and web, but there was no significant local deformation.

4. Retrofit and the Yielding-Beam Mechanism

As expected, the two specimens exhibited very different responses. Specimen NCBF had nonductile behavior due to severe deficiencies in the brace and its connections. Although the first-story beam strength was deficient by factor of 2.8, it did not negatively impact performance. This result is not obvious since the beam DCR was higher than any others (see Table 1), which suggests it is the most critical deficiency. In fact, the relatively low beam strength may have been beneficial because this limited demand on the north first-story brace which eventually sustained brace-to-gusset connection fracture. This behavior underscores the important distinction between yield mechanisms and failure modes. In retrofit, failure modes and geometric limits with excessive DCRs present more concern and should be higher priorities in design.

Specimen SCBF had inelastic deformation on both stories and engaged both the yielding-beam and yielding-brace plastic mechanisms. Figure 9 shows story-shear envelopes for both stories of Specimen SCBF. The total story shear and the contribution from the braces alone are shown, and therefore the filled areas between these curves shows the contribution of frame action. There was marginal difference in total story shear with respect to drift between the two mechanisms, and this finding counters traditional notions of yielding-beam mechanism behavior. Although the brace forces were limited due to beam yielding in flexure, the frame provided a greater proportion of the lateral resistance than in the yielding-brace case.

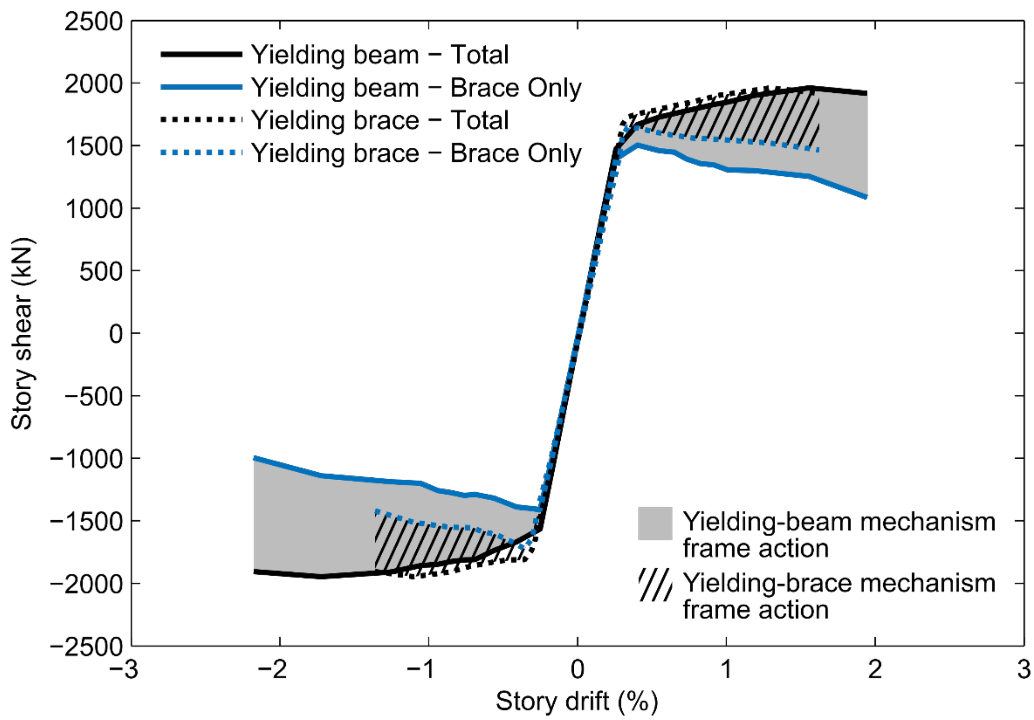


Fig. 9 – Specimen SCBF story shear envelopes

The yielding-beam mechanism necessarily induces beam deflections but, in Specimen SCBF, these did not exceed 1% of the beam's length during loading (L/100) and amounted to just 0.4% (L/250) residual deflection.

These are large deflections relative to typical serviceability limits for gravity loads, but the beam in Specimen SCBF was subjected to severe cyclic loading which would only be expected in large earthquakes. This level of deformation may be justified for many buildings, but further study is needed to understand the practical implications of weaker beams.

5. Conclusions

Current SCBF requirements encourage a plastic mechanism which consists of brace yielding and brace buckling. In chevron-configuration SCBFs, this necessitates deep, heavy beams to resist the post-buckling brace forces and develop brace yielding. NCBFs were built prior to these provisions and have considerably weaker beams. Therefore, NCBFs are expected to develop a plastic mechanism in which the brace buckles and the beam yields in flexure. Historically, the yielding-beam mechanism has been considered to have poor seismic performance, and this motivated an experimental research program at the NCREE laboratory in Taiwan [4]. The research examined specimens with braces and connections with both nonductile (NCBF) or ductile (retrofitted NCBF or SCBF) characteristics.

The experimental results showed that in the context of other severe component deficiencies, the beam presented far less of a vulnerability. Brace local slenderness and brace-to-gusset weld deficiencies drove the nonductile response of Specimen NCBF which had a beam axial-flexural interaction DCR of 2.8. Further, the yielding-beam mechanism did not hinder the seismic performance of Specimen SCBF, which had a beam DCR of 1.6 and SCBF-compliant braces and connections. The hysteretic response and deformation capacity of the system was comparable to those with yielding braces [11].

The performance of Specimen SCBF demonstrates the viability of the yielding-beam mechanism for both retrofitted NCBFs and new construction. Ongoing research is being conducted to explore these possibilities. A numerical study is investigating the impact of local NCBF deficiencies and partial retrofit schemes on system seismic performance, and chevron CBFs with yielding-beams comprise an important subset of these analyses. In additional, an experimental program at the University of Washington is being conducted to enable the design of more economical chevron SCBFs.

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