TEST OF A FULL-SCALE TWO-STORY STEEL X-BRBF: STRONG-AXIS INSTABILITY OF BUCKLING RESTRAINED BRACE ASSOCIATED WITH OUT-OF-PLANE BENDING OF GUSSET CONNECTIONS

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ABSTRACT: This paper presents tests and finite element analyses of a two-story, buckling-restrained braced frame (BRBF) with X-bracing configuration, called X-BRBF. The BRB used in this work is composed of a core plate sandwiched by a pair of the restraining member with bolts, called a sandwiched buckling restrained brace (SBRB). The weak-axis of the SBRB core that had a rectangular plate was positioned transverse to the dual-gusset plate connection and in-plane movement of the frame. The objectives of the frame test were to evaluate: (1) the seismic performance of SBRBs with a small width-to-thickness ratio of the core plate (i.e. 3), (2) the effects of free-edge stiffeners on the gusset and BRB stability, and (3) the BRB stability associated with the lateral torsional buckling (LTB) of the beam. The two-story X-BRBF subassembly had two test phases: all gusset connections had free-edge stiffeners in Phase 1 test, and free-edge stiffeners were removed from half of gusset connections in Phase 2 test. The X-BRBF in Phase 1 test exhibited good performance up to a second-floor drift of 1.6%, but in Phase 2 test the second-floor SBRB caused by LTB of the beam showed asymmetric instability about its strong-axis of the core plate at 1.6% second-floor drift. The other SBRB with no LTB of the beam showed one-side instability about its strong-axis at 2% second-floor drift (about 2.5% interstory drift). However, the strength degradation of the X-BRBF subassembly was not observed in the strong-axis instability of SBRBs, indicating an acceptable orientation of BRBs for eliminating a typical weak-axis buckling of BRBs together with out-of-plane bending of gusset plates. The strong-axis instability of SBRBs could be evaluated by using the BRB stability concept together with the measured out-of-plane deformation of gusset plates in Phase 2 test.

KEYWORDS: SBRB, Frame Test, Strong-Axis Instability.

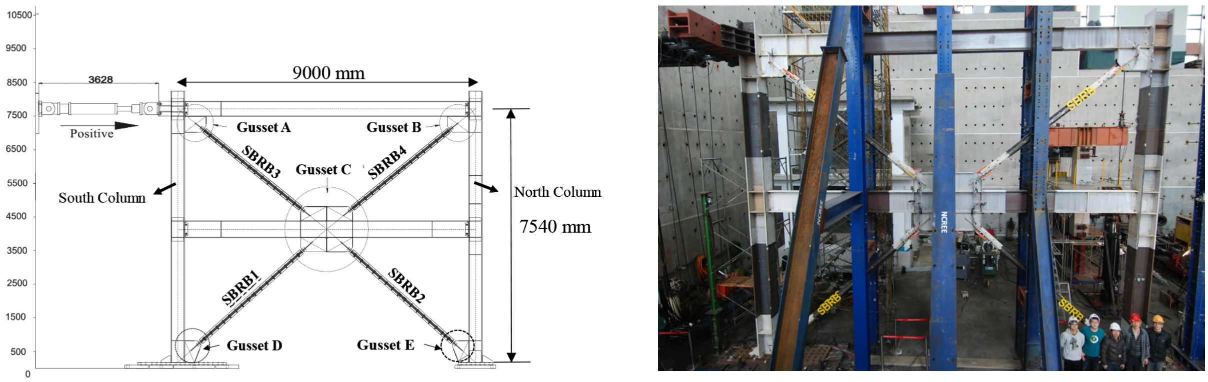
1. INTRODUCTION

A SBRB with two identical restraining members is formed by welding a steel channel to a flat plate (face plate). Unlike conventional BRBs that have a steel core embedded in the concrete-filled restraining members, the SBRB has a core plate between a pair of restraining members using high strength A490 bolts. This enables inspection after earthquakes by removing restraining members from the core plate. A SBRB is capable of sustaining stable hysteretic responses up to a core axial strain of 3% in the component and frame tests [1, 2, 3, 4, 5]. This work was aimed to study the stability of SBRBs with different gusset connections in a two-story steel frame.

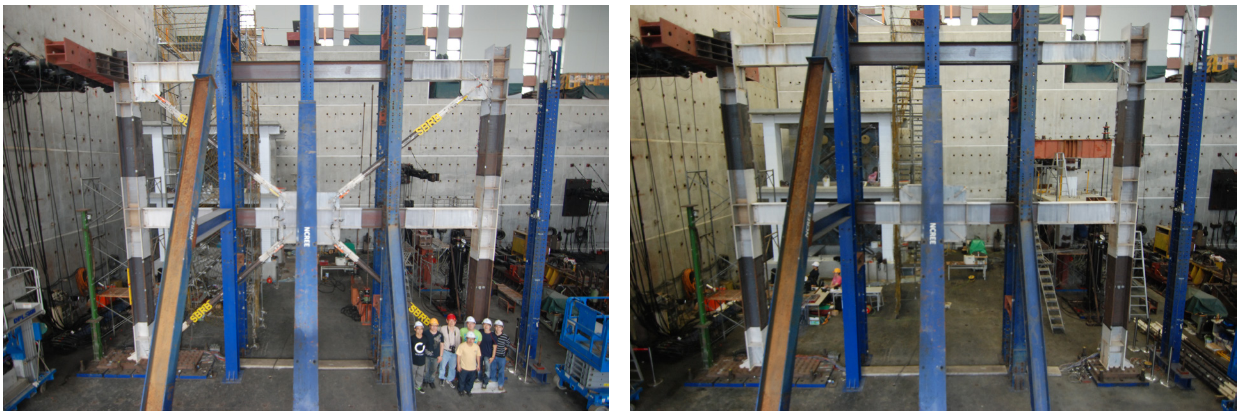
2. X-BRBF SUBASSEMBLY TEST

Tests of a full-scale two-story X-BRBF with a span of 9 m and height of 7.54 m (Figure 1(a)), were conducted at the National Center for Research Earthquake Engineering (NCREE), Taiwan. The entire test program consisted of two testing phases. In phase 1 test, a two-story X-BRBF subassembly that had SBRB and a dual gusset configuration with free-edge stiffeners in all gusset connections was subjected to a prescribed loading protocol from *AISC Seismic Provisions* (2016) [6] to 1.6% second floor drift (Figure 1(b)). In phase 2 test, half of free-edge stiffeners of gusset plate connections were removed from gusset configuration (Figure 1(c)) and then tested using the same loading protocol to 2% second floor drift. The moment resisting frame (MRF) was tested up to 1.2% second floor drift after removing all SBRBs and gusset plates to investigate the MRF behaviour (Figure 1(d)).

A large number of instruments included strain gauges, string pots, dial gauges, and rosettes, linear variable differential transformers (LVDTs), dial gauges were used to determine the test specimen behavior. Over 250 channels of instruments were used in each test. The strain gauges were placed on the columns, beam to estimate the internal forces

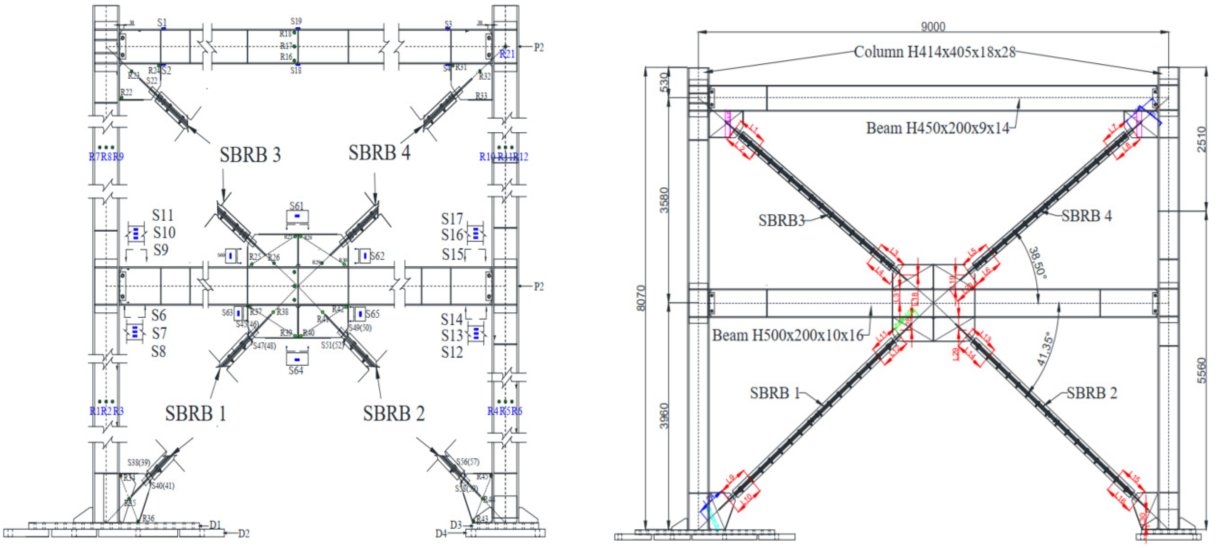


(a) Test set up (b) Phase 1 test (1.6% second floor drift)



(c) Phase 2 test (2% second floor drift) (d) MRF test (1.2% second floor drift)

Figure 1. Tests of a two-story X-BRBF subassembly specimen.



a) Strain guages location b) LVDT layout of frame test

Figure 2. Strain gagues and LVDT location of two story frame X_BRBF

and moment in the system, and estimate when the member yield occurred, as shown in Figure 2(a). The rosettes were attached to the gusset plate to measure the strain. Additionally, a large number of cameras were used to capture during the test. Three string pots were measured the lateral displcament of the frame at the first and second story, respectively. Additionally, three string pots were used to measure the slip and uplift at the base and slip between the crosshead and floor slab.

Four linear variable differential transformers (LVDTs) were installed on both ends of the BRB to measure the axial displacement and several displacement transducers were positioned transverse to the gusset plate and pi gauges to measure the out-of-plane deformation and axial displacement of the gusset plates as shown in Figure 2(b)).

3. TEST OBSERVATION

The X-BRBF specimen performed well up to the second-floor drift of 1.6%, without buckling of SBRBs or gusset plates. By watching through the acrylic, no yielding was found on both ends of the core plate. All gusset plates with free-edge stiffeners did not show yielding in the test. The yielding of the specimen was observed only on the second-floor beam flange near the south column (Figure 2(a)) and north column (Figure 2(b)) at 1.6 % second-floor drift. Although beam yielding was observed, no lateral movement or buckling of the beam was visible on the second-floor. The observation showed that the core orientation of SBRBs with the weak-axis transverse to the in-plane movement of the frame is effective to improve the sudden strength drop of BRBs with weak-axis buckling.

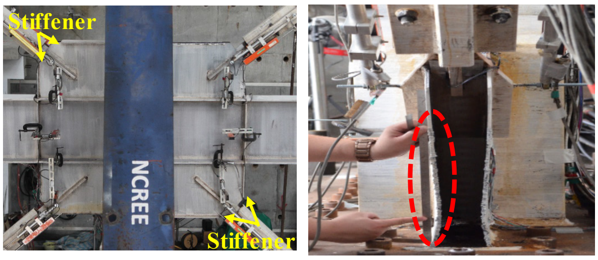
Beam Yielding (South Column side)

Beam Yielding (North Column side)

Figure 3. Observed performance in Phase 1 test (1.6% second_floor drift).

After completing the Phase 1 test, all free-edge stiffeners were removed from Gusset B and D, and half of the free-edge stiffeners from Gussets C (Figure 1(a)) were removed. The specimen was tested again using the same loading protocol as in Phase 1 test, but up to the second-floor drift of 2%. The lateral-torsional buckling (LTB) of the second-floor beam was clearly seen between the south column and the adjacent lateral support at the second-floor drift of 2%. The out-of-plane movement of the beam top flange was 5 mm (Figure 3(a)). Gusset C did not show yielding or buckling at the 2% second-floor drift (Figure 3(b)), but Gusset D at the column base without free-edge stiffeners exhibited out-of-plane buckling and web crippling (Figure 4(c)) when the SBRB1 was in tension, so-called the frame action buckling.

(a) Beam LTB (2 % second-floor drift)

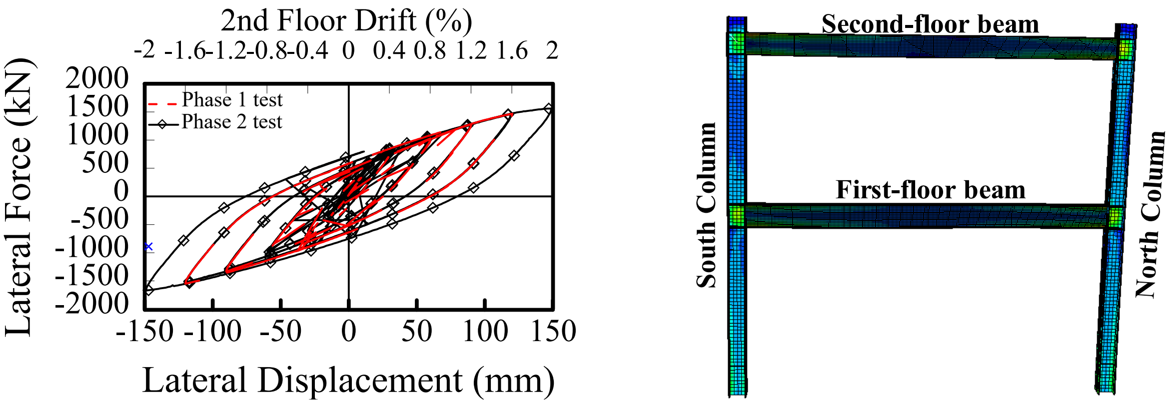


(b) Gusset C (c) Gusset D

Figure 4. Observed Performance in Phase 2 test.

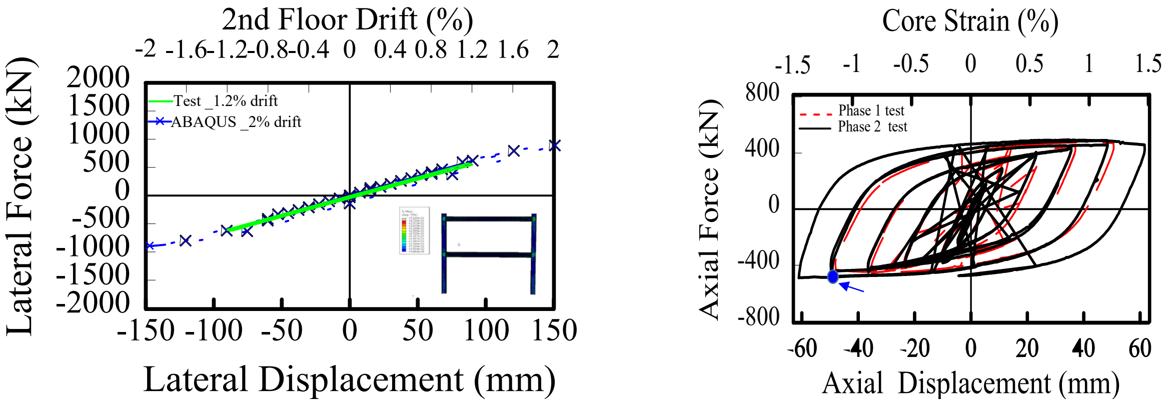
4. TEST RESULTS

Figure 5(a) shows the lateral force versus lateral displacement of the X-BRBF specimen in Phase 1 and Phase 2 tests. Two phase tests showed similar cyclic responses except the last cycle of 2%. The finite element analysis program ABAQUS [7] was used to correlate the response of MRF up to 2% second floor drift as shown in Figure 5(b). The beams, columns and gusset plates were modelled by the eight node solid elements (C3D8R). The mesh size of 50 mm was used for steel beams, columns and gusset plates. The column base was fixed, and the out-of-plane movement of the beam was constrained at the location of the lateral supports. Since in Phase 2 test, the severe lateral-torsional buckling (LTB) of the second-floor beam (Figure 4(a)) was observed at 1.6% second floor drift, therefore the MRF was tested up to 1.2% second floor drift as shown in Figure 1(d)) in order to preventing the lateral buckling (LTB) of beam in this phase. Figure 5(c) shows MRF response from the finite element analysis is almost linearly up to 1.2% second floor drift. Figure 5(d) shows the axial force versus axial displacement of SBRB3 in Phase 1 and Phase 2 tests, which was obtained by subtracting the lateral force of the X-BRBF from that of the MRF. When these SBRBs buckled about the strong-axis of the core plate. Although both SBRBs showed buckling about the strong-axis of the core, the hysteretic loops were still stable with no sign of strength degradation.



(a) X_BRBF response

(b) Finite Element Model (MRF)



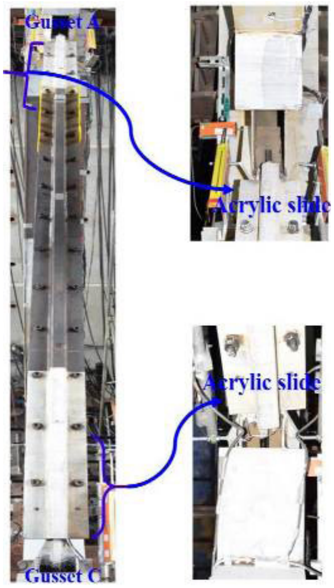
(c) MRF Response

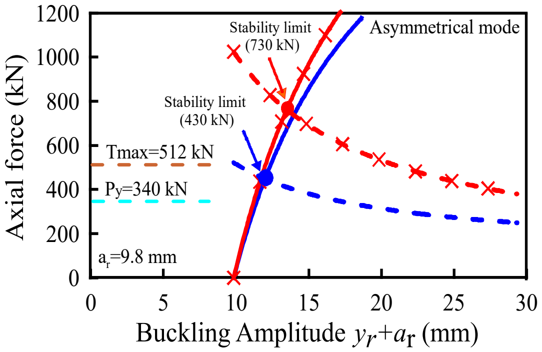
(d) SBRB3 response

Figure 5. Test Results

5. STABILITY OF SANDWICHED BUCKLING -RESTRAINED BRACED

When free-edge stiffeners were removed from gusset connections of the framed specimen in Phase 2 test, the SBRB experienced buckling about the strong-axis of the core plate, which was not observed in previous component tests [1, 2, 3, 4, 5]. At the last peak of 1.6% drift, the Gusset C started to bend in the opposite direction to Gusset A deformation due to the beam LTB. The out-of-plane movement caused the acrylic plates, positioned on both ends of the restraining members, slide in different directions, indicating asymmetrical buckling about the strong-axis of SBRB3 (Figure 6(a)). Since all gusset plates at the second floor remained elastic under frame testing at 2% second-floor drift, so that the buckling failure modes were examined by stability limit axial force from Eq. (1) in [8]:





(a) Asymmetric buckling of SBRB3

(b) Stability limit of SBRB3

Figure 6. SBRB buckling observations

$$N_{\lim} = \frac{(M_p^r - M_0^r)/\mathrm{a}_r + N_{cr}^r}{(M_p^r - M_0^r)/(\mathrm{a}_r\, N_{cr}^B) + 1} \qquad (1)$$

Figure 6(b) shows that the stability limit axial force calculated based on Eq. (1). The value of $N_{\lim}$ for the SBRB3 about the strong-axis are lower than those about the weak-axis. The stability limit for the strong axis buckling of SBRB3 (=430 kN) are close to the buckling forces obtained from the Phase 2 test (Figure 4(c). Moreover, the stability limit predicted for the weak axis buckling of SBRB3 (=730 kN) is much higher than that of the maximum axial load of SBRB ($T_{\max}$ = 512 kN), indicating that the weak axis buckling of SBRB associated with in-plane deformation of gusset plate is not possible to occur.

6. CONCLUSIONS

The SBRB in the two-story X-BRBF subassembly presents stable hysteretic response in two test phases. At 1.6% second floor drift, the SBRB3 showed asymmetrical buckling about its strong-axis of the core due to lateral-torsional buckling (LTB) of the second-floor beam. The buckling force of SBRB could be estimated based on the stability concept of Takeuchi et al. (2014) [8] together with a measured out-of-plane deformation. Not that the strength degradation of the X-BRBF subassembly or SBRB itself was not observed in the strong-axis instability of SBRBs, indicating an acceptable orientation of BRBs for eliminating typical weak-axis buckling of BRBs with sudden strength decrease.

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