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CYCLIC LOADING PERFORMANCE OF FULL-SCALE SPECIAL TRUSS MOMENT FRAME WITH INNOVATIVE DETAILS FOR HIGH SEISMIC ACTIVITY

C. Jiansinlapadamrong[(1)], S. Simasathien[(2)], T. Okazaki[(3)], S-H. Chao[(4)]

[(1)] *Ph.D. Candidate, Department of Civil Engineering, University of Texas at Arlington, chatchai.jiansinlapadamrong@mavs.uta.edu*
[(2)] *Ph.D., Department of Civil Engineering, University of Texas at Arlington, sanputt.siasathien@mavs.uta.edu*
[(3)] *Associate Professor, Graduate School of Engineering, Hokkaido University, tokazaki@eng.hokudai.ac.jp*
[(4)] *Associate Professor, Department of Civil Engineering, University of Texas at Arlington, schao@exchange.uta.edu*

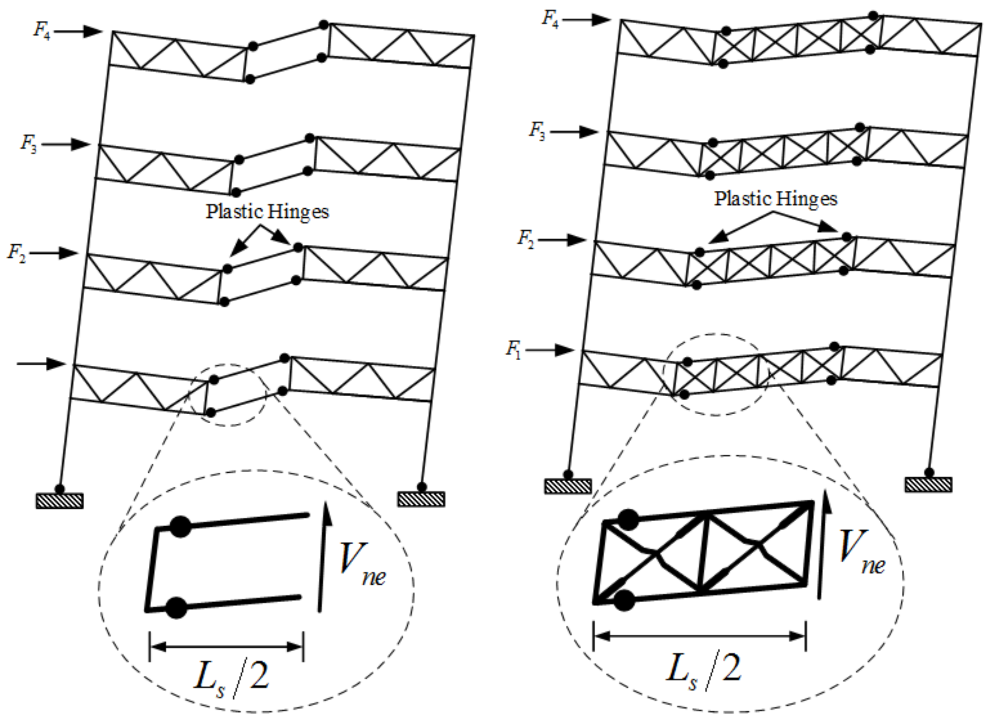
Abstract

Special truss moment frames (STMFs) represent a steel structural framing system which is able to provide long bay width and high lateral stiffness due to the deep truss girders. Moreover, the open webs of the truss girders can accommodate mechanical and electrical ducts which are functionally desirable. When subjected to a strong earthquake, an STMF dissipates energy through a ductile special segment located near the mid-span of the truss girder. This special segment acts like a structural fuse because the chord members and diagonal members in the special segment are designed to behave inelastically, while other members outside of the special segment are designed to remain elastic. Prior experiments and analyses done on STMFs using double-angle sections as truss members led to the current design procedures in the 2010 and 2016 Draft version of the American Institute of Steel Construction's *AISC Seismic Provisions for Structural Steel Buildings*. Due to insufficient capacities of angle sections for buildings under severe earthquakes, there is a strong need for using heavier structural steel sections as STMF members. This paper presents an overview of the test results of a full-scale all-Vierendeel panel STMF enhanced by short buckling-restrained braces (BRBs). The specimens used innovative details to eliminate the lateral-torsional buckling of the chord members, thereby enhancing the rotational capacity of the special segments, as well as incorporated reduced beam section (RBS) of 2C310×30.8 to reduce strength demand of the members outside of the special segment. The test results showed that BRBs could be safely used to enhance both strength and stiffness of the STMF. By using the short BRBs, structural redundancy of STMF increases and when the BRBs are damaged under moderate earthquake, they can easily be replaced. Even after BRBs failed in tension, STMF could still maintain its strength at large story drift because the broken yielding cores reengaged in compression and provided additional resistance.

Keywords: special truss moment frame; buckling-restrained brace; cyclic response; full-scale test; seismic design.

1. Introduction

Special truss moment frames (STMFs) represent a steel structural framing system that dissipates earthquake energy through ductile special segments located near the mid-span of the truss girders. The members outside of the special segment are designed to remain elastic. When an STMF is subjected to lateral forces, the induced shear force in the middle of the truss girder is resisted primarily by the chord members in the special segment as shown in Fig. 1(a). When diagonal members are used in the special segment, their contribution to energy dissipation through yielding and buckling is taken into account in the third term of the expected vertical shear strength of the special segment (V_{ne}) equation, as shown in Eq. (1), according to the American Institute of Steel Construction (AISC) Seismic Provisions (ANSI/AISC 341-10) [1]. The yielding and buckling mechanism of these diagonal elements can be seen in Fig. 1(b).



(a) (b)

Fig. 1 – Energy dissipation mechanism of STMFs

$$V_{ne} = \frac{3.60 R_y M_{nc}}{L_s} + 0.036 EI \frac{L}{L_s^3} + R_y (P_{nt} + 0.3 P_{nc}) \sin\alpha \quad (1)$$

where

- E = modulus of elasticity of a chord member of the special segment
- I = moment of inertia of a chord member of the special segment
- L =length of the truss
- L_s = length of the special segment
- M_{nc} = nominal flexural strength of a chord member of the special segment
- P_{nt} = nominal tensile strength of a diagonal member of the special segment (if any)
- P_{nc} =nominal compressive strength of a diagonal member of the special segment (if any)
- R_y = ratio of the expected yield stress to the specified minimum yield stress
- V_{ne} = expected vertical shear strength of the special segment
- α = angle of diagonal members with the horizontal

Moreover, the seismic behavior of an STMF system was experimentally studied mainly on STMFs using double-angle sections [2, 3]. Recent challenges encountered by engineers are the limitation of available seismically compact angle sections and their limited strengths. In zones of high seismicity, STMFs with large seismic resistant capacity are needed which translates to stronger truss members. As a result, the need to evaluate and explore members stronger than double angles was important to the application of STMFs. In general, STMF chord members in a special segment require plastic rotation capacity of approximately 0.06 rad for a story drift ratio of 0.02 rad [4]. Previous research on double-channel built-up members subject to reverse cyclic bending indicated that once the onset of lateral torsional buckling (LTB) was delayed, the hysteretic behavior of the member became significantly more stable and ductile [5].

Buckling-restrained braces (BRBs) have gained popularity in seismic force resisting systems. The major advantage of BRBs when used as primary lateral force resisting elements in a buckling-restrained braced frame (BRBF) is their nearly equal strength in compression and tension, which eliminates the post-buckling load imbalance inherent in the conventional braced frames found in the special concentric braced frame (SCBF) system. The hysteretic behavior of BRBF is ductile and stable due to the elimination of brace buckling [6]. The advantage of BRBs over conventional braces, and the need for higher STMF capacity in high seismic activity regions was the primary motivation that led to this research. The objectives of this research program are as follows:

1. Investigation of a special detailing for double-channel flexural members with reduced beam section (RBS): The addition of BRBs in the special segment will increase the strength of the special segment and result in heavily reinforced members outside of the special segment. In order to avoid such a condition, a reduced beam section concept used in the wide flange section was implemented in the double-channel sections. The flexural capacity of 2C310 (mm) × 30.8 (kg/m) (US equivalent shape: 2C12 (in.) × 20.7 (lb/ft)) were reduced by 20% by cutting part of the flanges out. Special detailing that prevented LTB in double-channel sections was also used in order to achieve large rotational capacity needed for chord members in the special segment of STMFs.

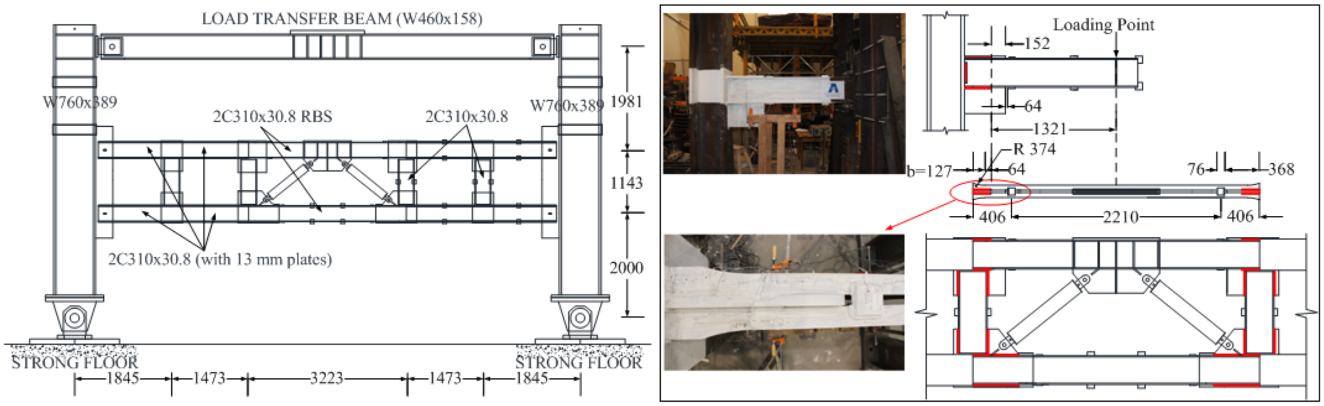
2. Investigation of cyclic response of short buckling-restrained braces: Due to configuration of the full-scale STMF subassemblage, the BRBs that could be incorporated were only 1092.2 mm pin-to-pin in length. Its cyclic behavior was investigated in order to predict its effect on the seismic performance of STMF.

3. Pushover analysis of STMF with BRBs in special segment: Pushover analysis on STMF with BRBs was performed using nonlinear models of double-channel RBS and single BRB. The member forces obtained from the analysis were then used to design members outside of the special segment of the full-scale STMF subassemblage.

4. Full-scale test of STMF subassemblage with BRBs in the special segment: A full-scale test of STMF with BRBs was conducted at the Multi-Axial Subassemblage Testing (MAST) Laboratory at the University of Minnesota, one of the former Network for Earthquake Engineering Simulation (NEES) facilities to evaluate the performance of the new STMF configuration.

2. Double-Channel RBS Component Test

A full-scale STMF consisting of truss members using 2C310 × 30.8 with two BRBs oriented in a chevron pattern in the special segment is shown in Fig. 2(a). Flanges of the chord members in the special segment were cut in order to reduce their flexural capacity by 20%. This ratio was determined so the chord members outside of the special segment did not have to be over-reinforced. The chord members were reinforced with 13 mm thick plates to prevent them from yielding (Fig. 2(a)). The component test of the 2C310 × 30.8 RBS was conducted in order to investigate its cyclic behavior. The specimen represented half of the chord member in the special segment as shown in Fig. 2(b). The two key features used at the connection were an extended weld-free gusset plate and horizontal stitches. The weld length between the gusset plate and the channels was 279.4 mm, while the weld-free length was 152.4 mm. The first pair of stitches was horizontal and welded at 25.4 mm distance from the end of the gusset plate.



(a) (b)

Fig. 2 – (a) Subassemblage test of full-scale STMF with BRBs and (b) specimen as a representation of the chord member in the special segment

2.1 Loading Sequence

Prior to the test of 2C310 × 30.8 with RBS, a series of cyclic loading tests of double-channel built-up sections was carried out. These members represented the chord members in the special segment of a full-scale STMF without BRBs [7]. The loading protocol of the tests followed the AISC loading protocol [1] for beam-to-column moment connections which is designated by numbers of cycles vs. frame story drift ratio. In order to conform to the standard, a nonlinear pushover analysis of a prototype STMF was carried out to obtain the relationship between story drift ratio and plastic rotation of the chord member in the special segment. A monotonic test of a double-channel specimen, 2C310 × 30.8, was conducted to acquire member rotation at first yield. The total member rotations were then determined and converted to the needed vertical displacements corresponding to the story drift ratio used in the component test. Due to the limitation of the hydraulic actuator's stroke, the specimens could only be pushed to story drift ratio of 2.75%. Since this limited maximum story drift ratio was less than the AISC requirement at story drift ratio of 3%, two cycles of 2.38%, which was the midpoint between 2% and 2.75%, were added for stringency. In the component test of 2C310 × 30.8 with RBS, the same story drift ratio versus member rotation relationship was used and the loading sequence is shown in Fig. 3.

2.2 Test Result

It can be seen in Fig. 4(a) that the specimen was able to maintain ductile and stable hysteretic behavior up to approximately 2.5% story drift ratio. The first fracture initiated at the end of the weld between the bottom flange of the channel and the gusset plate at 1% story drift ratio, while a slight bulging was observed at the 1.5% story drift ratio. Its strength gradually dropped starting at the 2% story drift ratio (or 0.054 rad member rotation). The combination of crack propagation and bulging with flange and web local buckling contributed to the subsequent slight loss of strength. The last cycles of loading were limited by the maximum actuator stroke of 125 mm which was equivalent to 0.09 rad member rotation. Before reaching the first positive cycle of this displacement, the top horizontal stitch hit the gusset plate. Hence the strength picked up slightly in the hysteresis loop shown in Fig. 4(a). The specimen maintained a strength about 80% of the peak moment capacity for a full cycle of this drift level until the bottom stitch fractured half way through the second loading cycle (Fig. 4(b)). Both innovative features employed here proved to prevent lateral torsional buckling and effectively enhanced the rotational capacity of the double-channel RBS.

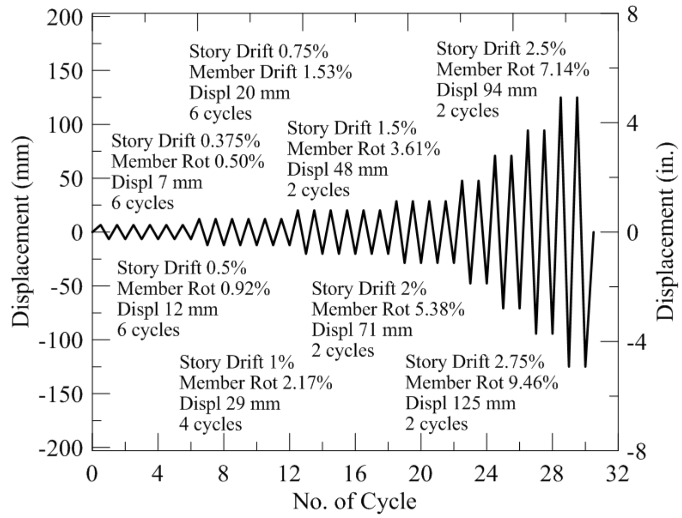
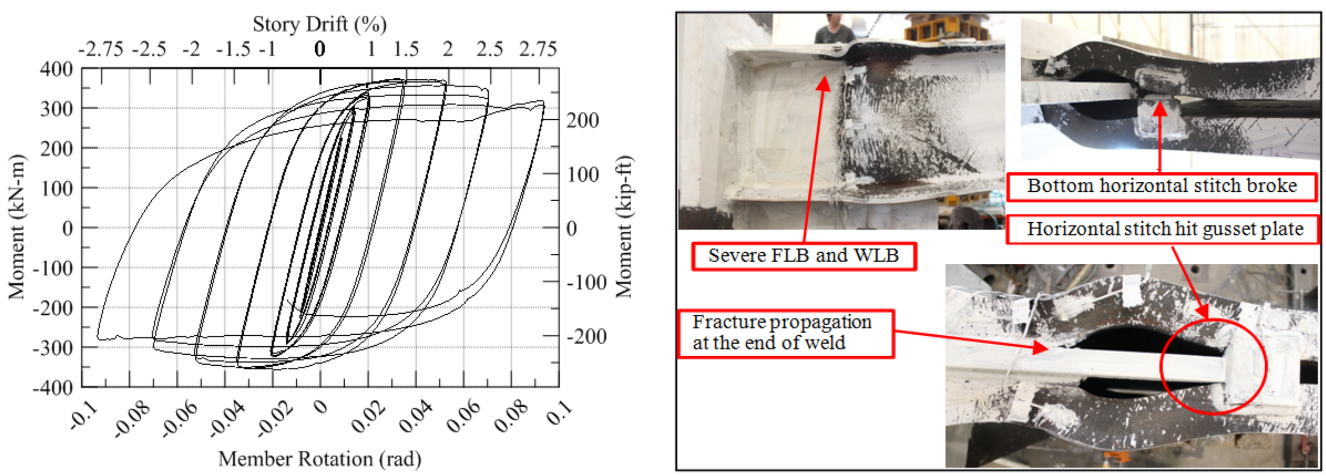


Fig. 3 – Loading sequence for 2C310 × 30.8 RBS



(a) (b)

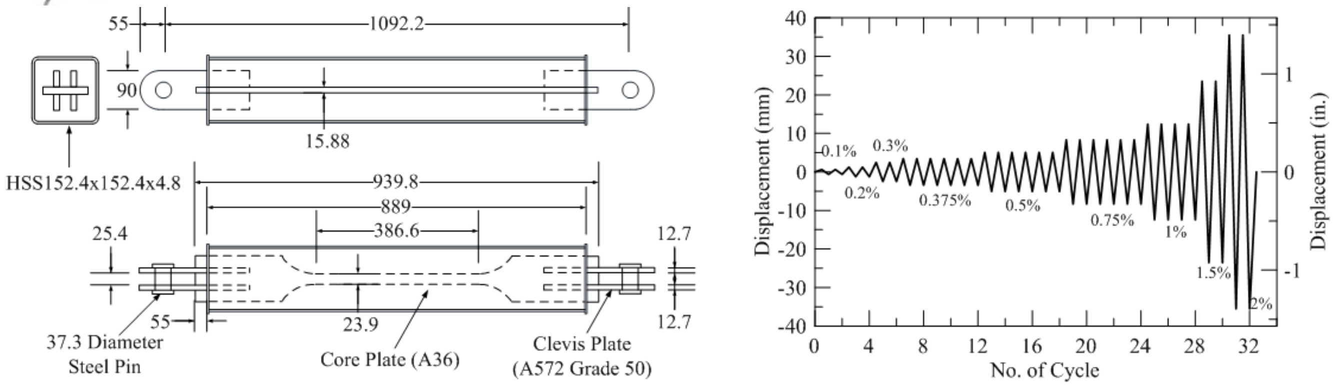
Fig. 4 – 2C310 × 30.8 RBS component test results

3. Isolated Buckling-Restrained Brace Test

A pair of short buckling-restrained braces (BRBs) as shown in Fig. 5(a) was used in the full-scale STMF specimen. Their behavior was first examined through isolated axial testing in order to formulate the basic modeling parameters as well as to precisely analyze and understand behavior of the STMF with BRBs. The yield strength and dimensions of the BRB were the only given properties by the manufacturer. The strain-hardening ratio was estimated to be 1.75 and the ratio between compressive strength and tensile strength was estimated to be 1.1. With the given information and dimensions, the properties of the steel core are shown in Table 1.

Table 1 – Material properties of BRB steel core

F_y MPa (ksi)	Length mm (in.)	Area mm^2 (in.^{2})	F_{ut} kN (kips)	F_{uc} kN (kips)
293 (42.5)	386.6 (15.22)	379.4 (0.588)	194.6 (43.75)	213.5 (48.0)



(a) (b)

Fig. 5 – Buckling-restrained brace (BRB) (a) dimensions (in mm) and (b) loading sequence

3.1 Loading Protocol

A pushover analysis of the full-scale STMF with the short BRBs was carried out by the software program PERFORM-3D. The inelastic model of the chord members, obtained from the double-channel RBS component test, as well as the model of the short BRB, were incorporated. From the pushover analysis, the relationship between the STMF's story drift ratio versus the axial extension and contraction of the BRB was found. At the same story drift ratio, the extension and contraction were not the same due to a slight difference in tensile and compressive strengths. Therefore, the average absolute values between the two were used in the loading protocol for both positive and negative cycles. The loading protocol was developed (Fig. 5(b)) by employing the loading sequence for beam-to-column moment connections from AISC 341-10 [1] with some additional elastic and inelastic cycles (at 0.1%, 0.2% and 0.3% story drift ratios).

3.2 Test Result

Fig. 6 shows the test setup of the isolated BRB test, which was comprised of anchor blocks at each end, a hydraulic actuator, axial link and link brace, and the BRB specimen. Due to the very short core area embedded inside the much longer concrete-filled case of the BRB, it was impossible to measure the deformation of the yielding core alone. Thus, the deformation of the BRB was measured across a gauge length of 1003 mm. Fig. 7 shows that the BRB exhibited a stable hysteretic behavior up to 1.5% story drift ratio. The steel core of the BRB fractured when it was loaded to the positive 2nd cycle of the 1.5% story drift ratio. The BRB achieved a cumulative inelastic axial deformation of more than 200 times the yield deformation required by AISC 341-10 [1].

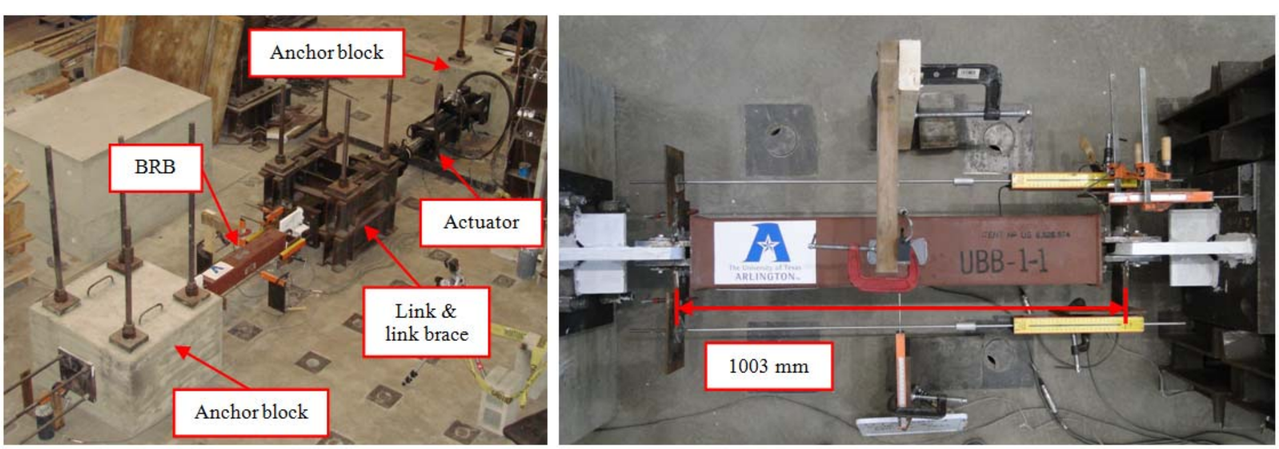


Fig. 6 – Isolated BRB test setup

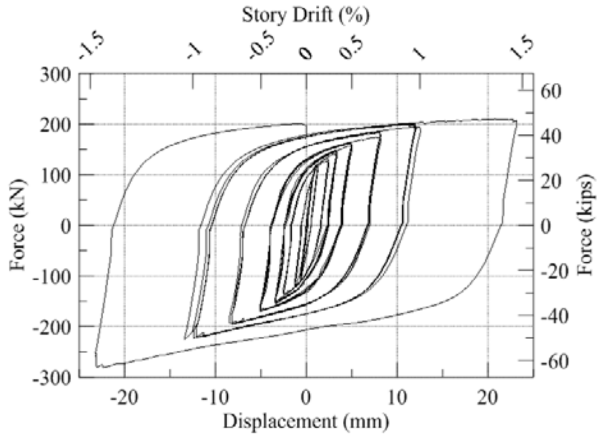


Fig. 7 – Axial force versus displacement relationship of BRB

4. Full-Scale All-Vierendeel Panel STMF with BRBs Subassemblage Test

The design procedures of the full-scale all-Vierendeel panel STMF with BRBs started with a nonlinear pushover analysis of the subassemblage. The nonlinear properties of the RBS chord members as well as the BRBs, acquired from the component tests, were incorporated into a PERFORM-3D model. The design of members outside of the special segments, including truss members, columns, and connections, was based on the capacity design approach such that those members remained elastic when the RBS chord members in the special segment, and the BRBs reached their ultimate capacities.

4.1 Specimen and Special Features

The chord members of the full-scale STMF specimen were made of double-channel sections (2C310 × 30.8 RBS). The chord members outside of the special segment were made of 2C310 × 30.8 with 25.4 mm thick and 330 mm deep cover plates welded to the flanges on both sides of the built-up members. These cover plates were needed in order for the chord members outside of the special segment to remain elastic when the special segment reached its ultimate strength. The vertical members were made of 2C310 × 30.8. The special features of this specimen are (Fig. 8):

- Diagonals were all removed. An all-Vierendeel panel STMF was functionally preferred for mechanical and electrical ductwork.
- Innovative detailing near the plastic hinge utilized extended center gusset plate and horizontal stitches thereby preventing LTB (lateral-torsional bracing) and enhancing rotational capacity of 2C310 × 30.8 RBS up to 0.09 rad member rotation.
- BRBs in chevron pattern were incorporated in the special segment to increase strength and stiffness of the STMF.
- For comparison purposes, the left vertical member outside of the special segment was not welded to the chord members while the right vertical member outside of the special segment was. Previous research showed that welding vertical members to the flanges of horizontal flexural member near plastic hinge could lead to early fracture of the flexural member [7].
- For comparison purposes, the corners of the lower gusset plates, connecting to the BRBs, were sharp on the left connection versus smooth on the right connection. According to a finite element analysis, the sharp corner posted higher stress concentration than the smooth corner.

4.2 Test Setup

Fig. 9 shows the full-scale STMF and the test setup at the University of Minnesota’s Multi-Axial Subassemblage Testing (MAST) Laboratory, a former member of the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES). The lateral force applied by a crosshead was transferred to STMF through a load transferred beam. Stability bracing of the truss was provided, as required by AISC 341-10 through the truss bracing system [1]. However, it was located slightly outside of the special segment so that it would not obstruct the movement of the specimens when local buckling initiated at the plastic hinges at large story drift ratios. Stability bracing of truss-to-column connection was also provided as per AISC 341-10 around both columns [1].

4.3 Loading Protocol

The full-scale STMF was cyclically loaded according to the AISC 341-10 loading sequence for beam-to-column moment connection [1]. Graphical representation of the loading history is shown in Fig. 10(a).

4.4 Test Result

The hysteretic behavior is shown in Fig. 10(b). It can be seen that the specimen remained elastic up to approximately 0.5% story drift ratio. The peak lateral strength of 1,334 kN (300 kips) was reached on the negative cycle at 1.5% story drift ratio as expected because the short isolated BRB achieved its maximum capacity at this story drift level according to the isolated BRB test. Stiffness and strength of the STMF slightly dropped during the second cycle of the 1.5% story drift ratio. According to the short BRB component test and pushover analysis, the BRB cores fractured due to tension force at the 1.5% story drift ratio. At the 2% story drift ratio, pinching in the hysteresis loop occurred due to the loss of stiffness caused by fracture of the BRB cores. While pushing the STMF toward 2% story drift ratio, while the tension BRB had lost its tensile strength due to the fractured core, the broken core of the compression BRB reengaged; hence, the strength started to pick up again. This created unbalanced forces at the center of the special segment. Moreover, because lateral bracing system was near the lower two gusset plates, the brace-to-vertical member connection had higher out-of-plane stiffness than the brace-to-chord member connection at the middle of top chord of the special segment. The brace-to-chord member connection started to rotate out of plane during the second cycle of the 1.5% story drift ratio. Figs. 11(a) and (b) show out-of-plane coordinate (z-direction) at the center of the chord members measured on both the top and bottom flanges of the top and bottom chords by using a Krypton imaging system. It can be seen that the bottom chord exhibited much less out-of-plane movement than the top chord member. The same behavior continued at 3% story drift ratio during which the strength peaked in the positive cycle at 1,303 kN (293 kips). By 4% story drift ratio, twisting of the top chord was too large, and the bottom chord was completely broken at the right flexural plastic hinges (Fig. 12) causing a quick degradation in stiffness and strength. The test was terminated after the first cycle of the 4% story drift ratio. Fig. 12 shows that plastic hinges occurred within the special segment. Flexural hinges formed at the ends of the chord members while shear hinge formed in the vertical members at the end of the special segment. Even though slight yielding occurred at members outside of the special segment as indicated by strain gauge readings, the yielding level was very minor and did not affect the performance of the STMF.

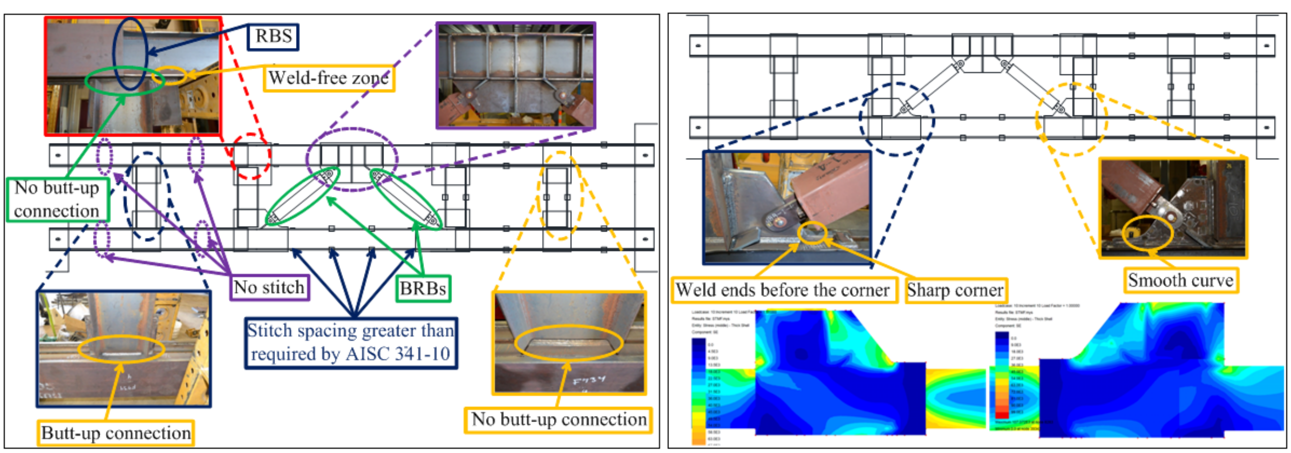
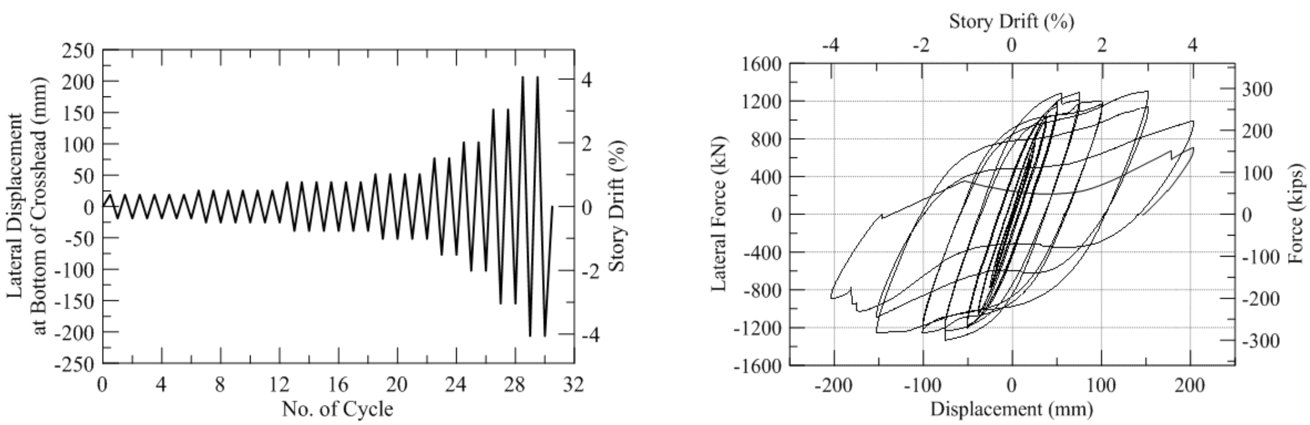


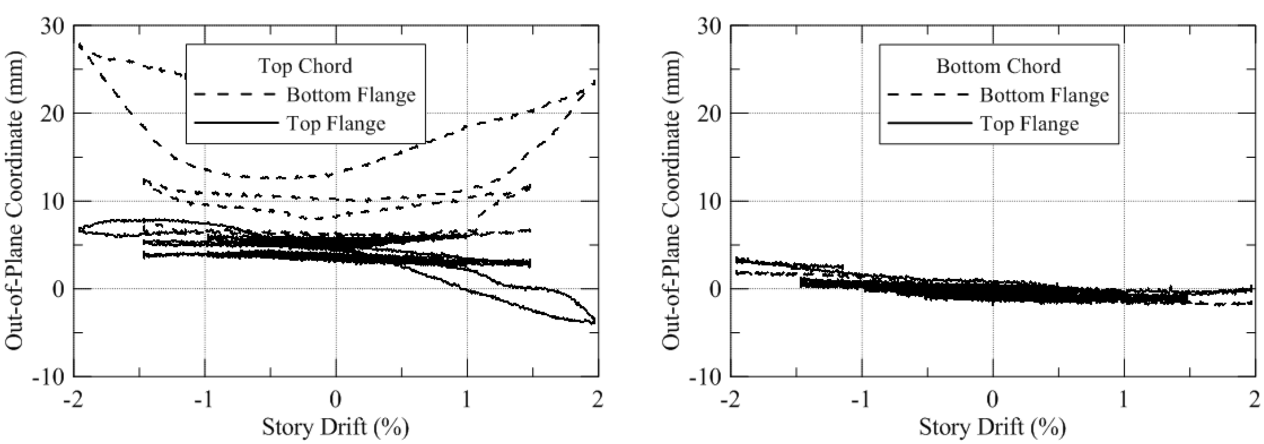
Fig. 8 – Special details of full-scale STMF with BRBs

Fig. 9 – Full-scale STMF with BRBs subassemblage



(a) (b)

Fig. 10 – (a) Loading sequence for full-scale STMF with BRBs subassemblage and (b) hysteretic behavior of full-scale STMF with BRBs subassemblage



(a) (b)

Fig. 11 – Out-of-plane coordinate of near center of the special segment of (a) top chord and (b) bottom chord

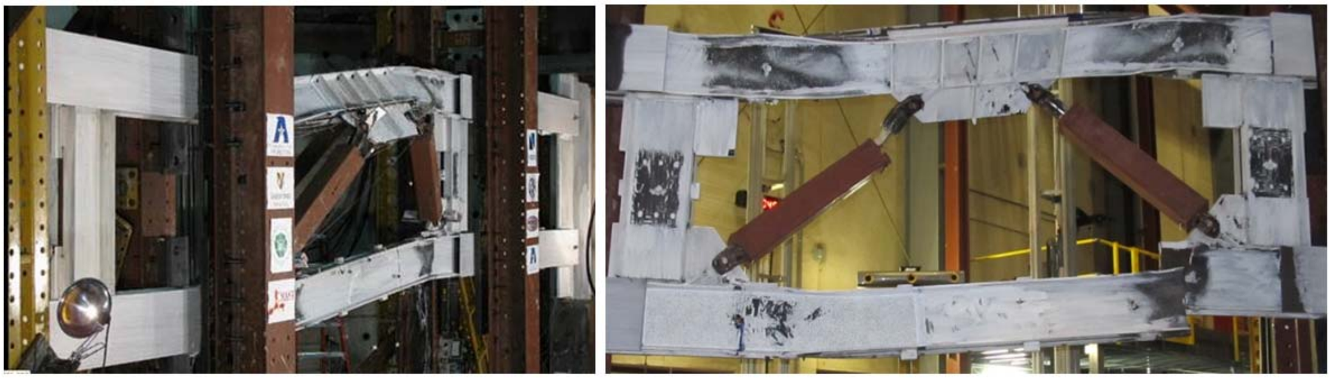


Fig. 12 – Full-scale STMF with BRBs subassemblage at the end of the test

5. Conclusions

This paper presents an overview test results of an innovative all-Vierendeel panel STMF with BRBs. The specimen members were made of double-channel chord members with special detailing designed to enhance the performance of STMFs under seismic events. The following conclusions can be drawn from the results of this study:

1. Reduced beam section (RBS) can be used in a double-channel built-up section as a chord member in a special truss moment frame to alleviate strength demand of members outside of the special segment.
2. The extended center gusset plate and horizontal stitch detailing can prevent lateral torsional buckling, which in turn enhances rotational capacity of double-channel built-up sections.
3. Short buckling-restrained braces can be used to increase strength and stiffness of special truss moment frames. At large lateral displacements, the broken cores of the BRBs could reengage in compression. As a result, the STMF regained strength and reached 3% story drift with only a slight loss of strength.
4. Structural redundancy of the special truss moment frame can be increased when buckling-restrained braces are designed to yield first. Although BRBs might be damaged in a moderate earthquake, they can be easily replaced.
5. The all-Vierendeel panel special truss moment frame provides high lateral resistance and performs well under large displacement reversals and can be used to accommodate mechanical and electrical ductwork.
6. The ends of the vertical members do not need to be welded to the chord members. This simplifies the connection details.
7. The gusset plates used in this experiment all either remained elastic or only slightly yielded. Gusset plate buckling or yielding was not a limit state.

6. Acknowledgements

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