Steel Structures Research Update

Advances in Design with Hollow Structural Steel Members

JUDY LIU

INTRODUCTION

Recent advances in design of steel-frame systems with hollow structural steel (HSS) members are highlighted. The featured work includes new and updated design guides that are co-authored by Jeffrey Packer and Jason McCormick. Jeffrey Packer is the Bahen/Tanenbaum Professor of Civil Engineering at the University of Toronto. Dr. Packer has been named a Fellow of the Canadian Academy of Engineering and five other engineering institutes or societies. His accolades include the AISC Special Achievement Award and the American Society of Civil Engineers Shortridge Hardesty Award. Jason McCormick is the Arthur F. Thurnau Associate Professor in the Department of Civil and Environmental Engineering at the University of Michigan. Dr. McCormick's work has been recognized with numerous awards, including the AISC Milek Fellowship, the AISC Early Career Faculty Award, and the National Science Foundation CAREER Award.

Dr. Packer's research interests include static, fatigue, impact, blast, and seismic behavior of HSS members, connections, trusses, and frames. Recent work includes publications on experiments, finite element modeling, parametric studies, and design of welds to branch members in hollow section connections (Tousignant and Packer, 2018). Dr. Packer's experimental, numerical, and analytical research informs the design of HSS for various loading conditions, with a bias toward code/specification-related issues and guidance for practicing engineers (as exemplified in the design guides described in the next section).

Dr. McCormick's research on HSS members and connections ranges from research on steel HSS-based seismic moment frames (Wei and McCormick, 2018; Fadden and McCormick, 2014) to the use of innovative materials (e.g., polymer foam) to control the structural response of HSS members under seismic and wind loads. He has also investigated the cyclic behavior of HSS columns under combined large axial loads and bending moments. Dr. McCormick's research serves to fill gaps in knowledge with regard to HSS behavior, improve design methods, and enhance the performance of systems with HSS members under seismic and wind loads.

Selected studies are featured along with a preview of the new design guides. Research on HSS columns under axial and lateral loads fills knowledge gaps in seismic behavior and design. Foam-filled brace and bending member experiments show improved seismic performance with a light-weight polyurethane fill. Field tests, laboratory experiments, and numerical modeling are used to study behavior and develop design methods for hollow and concrete-filled HSS subject to blast and impact loading. Research on single-sided fillet welds of HSS members leads to improved design recommendations. Improved design procedures are also recommended based on research on HSS connections that are in branch compression, near chord ends, or offset laterally.

DESIGN GUIDES

AISC Design Guide 24, *Hollow Structural Section Connections*, by Packer et al. (2010), was first published a decade ago. A second updated and expanded edition by Packer and McCormick is expected to be published in 2020. Considering that the content of AISC *Specification* Chapter K was significantly reduced in the 2016 edition (AISC, 2016a), this guide will be of immense help to engineers applying AISC *Specification* Chapters J and K to HSS connections. The second edition is planned to be more than 50% longer than the first edition; contains more design examples; and most importantly, adds new chapters on limit states for HSS connections and seismic connections.

Packer and McCormick are also contributors to the next HSS design guide by the Comité International pour le Développement et l'Étude de la Construction Tubulaire (CIDECT) (Zhao et al., 2019). This *Design Guide for Concrete-Filled Hollow Section Columns under Static, Impact, Blast, Seismic and Fire Loading* is the 10th in a series of design guides by CIDECT. Round and rectangular HSS composite columns are covered, with/without rebar, and also concrete-filled double-skin tubes (a tube-in-tube concept where the

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annulus between the tubes is filled with concrete or grout). Design procedures for the five loading conditions are summarized, reviewing the methods in the United States, Europe, Australia, and China. Design examples are given for all loading criteria, including the AISC *Specification* for static loads, the AISC *Seismic Provisions* (AISC, 2016b) for seismic loads, and ASCE 59-11 (ASCE, 2011) for blast.

HSS COLUMNS UNDER AXIAL AND LATERAL LOADS

There is interest in using rectangular and square HSS for columns, but knowledge about their behavior under large axial loads and bending moments is lacking. HSS columns can be effective for multi-axis loading and have lower weak-axis slenderness ratios than comparable-weight W-shapes. To address the knowledge gap and to evaluate current guidelines, validated finite element models were used to study the collapse behavior of HSS columns under combined axial and lateral loading (Sediek et al., 2019).

Finite element models of rectangular HSS columns were validated against experiments of HSS beams undergoing cyclic bending up to rotations of 8% (Fadden and McCormick, 2012) for use in a parametric study. Comparisons of the computational model and the physical test results show good agreement in the cyclic responses, including moment capacity, strength degradation, and local buckling (Figure 1). The ASTM A500 Grade B HSS columns investigated in this study represented a range of local and global slenderness ratios. Global slenderness ratios, L/r, ranged from 60.7 to 80.1. In the absence of a highly ductile limit for HSS webs under combined compression and flexure, the limit for built-up box sections was used. The axial compressive load was constant in the analysis; one of two lateral displacement histories was then applied. The first loading history was the symmetric cyclic (SC) loading with increasing displacements specified in the AISC *Seismic Provisions*. The second loading protocol was a cyclic ratcheting (CR) drift history developed by Wu et al. (2018) to simulate more realistic first-story column displacements (Sediek at al., 2019).

The HSS columns were evaluated using the critical constant axial load ratio (CCALR), the maximum axial load ratio for which the column is able to reach 4% drift for both loading protocols without axial failure. The analysis results revealed effects of element width-to-thickness ratios, axial load levels, and loading protocols. The results also suggested potential revisions to current design specifications. Increasing the axial load level reduced the ductility of the HSS columns. The same HSS column that reached 6% drift with an initial axial load level of $0.2P_y$, or 20% of the nominal yield strength of the column, failed at 4% drift under an axial load level of $0.4P_y$. Of the loading protocols, the SC load history was more severe; CCALR values were typically lower for the SC protocol than for the CR loading protocol. The CCALR was not sensitive to the global slenderness ratio but decreased by 46% when the web width-to-thickness ratio, h/t, increased from 10.4 to 24.6. Results indicated that columns that qualified as highly ductile for h/t but were subjected to axial load levels higher than $0.7P_y$ were unable to sustain the loading to 4% drift. On the other hand, an HSS column that was not highly ductile for the flange width-to-thickness ratio, b/t, was able to reach to 4% drift under a

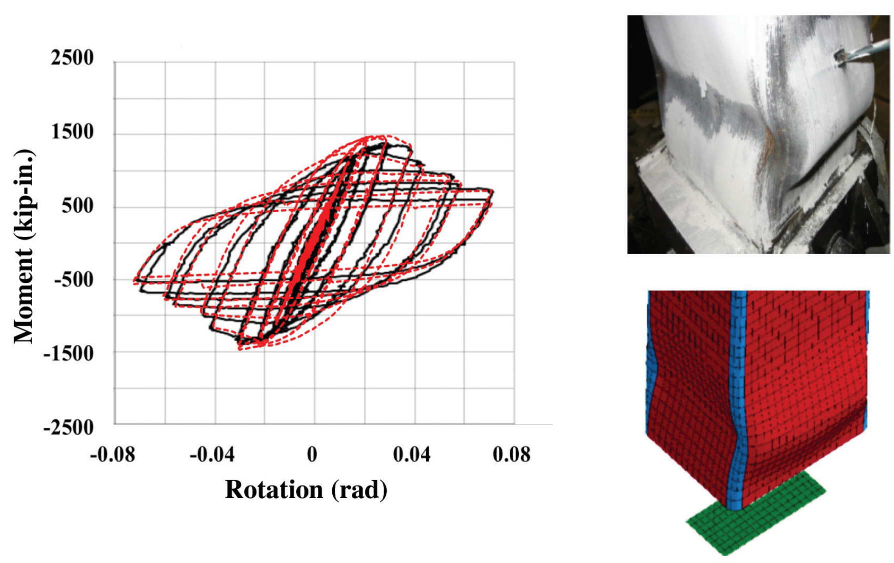


Fig. 1. FE model of HSS beam validated with results from Fadden and McCormick (2012).

typical gravity load of $0.25P_y$. Some revisions to the highly ductile limits for HSS columns should be considered.

FOAM-FILLED BRACES AND BENDING MEMBERS

A pourable, expanding, closed-cell polyurethane foam is explored as an alternative fill in hollow structural section (HSS) braces and beams. The foam is lightweight and commonly used in insulation, for flotation, and in impact protection in automobiles. Starting as a two-equal-part liquid mixture, the foam expands into a rigid solid with approximately four times its liquid volume. The foam fill is used to delay local buckling and increase energy dissipation in the HSS braces and beams while limiting increases in strength that could influence a capacity-based design approach. Furthermore, the foam's advantages over concrete fill include lower mass for seismic demands and ability to be used as an in-situ retrofit strategy.

Foam-Filled Braces

Filling HSS braces with foam provides a lightweight method to limit local buckling and improve fracture life. Under cyclic inelastic loading, HSS braces yield in tension and buckle in compression. The braces can exhibit local buckling followed by premature fracture. A study has been undertaken to evaluate the effectiveness of a polyurethane foam fill in improving the seismic performance of round HSS braces. Another research objective was to explore whether diameter-to-thickness, D/t, limits can be less stringent for filled steel braces in seismic design (Ammons et al., 2018).

Foam-Filled Brace Test Specimens, Loading, and Test Set-Up

Four 62-in. brace specimens were tested to investigate the effectiveness of the foam fill and the potential to relax the D/t limits for seismic design with foam-filled braces. The two unfilled brace (UB) specimens and two filled brace (FB) specimens used cold-formed circular sections of Japanese STK400 steel. The steel had specified minimum yield stress and tensile strength of 34 ksi and 58 ksi, respectively. The specimens with the 3.51-in.-diameter round HSS satisfied the highly ductile limits from the AISC *Seismic Provisions*, while the 4.50-in.-diameter round HSS qualified as moderately ductile. The UB and FB specimens were designated by their diameter and thickness in millimeters—for example, UB11445 and FB11445 for the moderately ductile, 4.5 mm thick, 114-mm-diameter round HSS.

The test specimens were placed in a four-pin frame and subjected to quasi-static cyclic loading at increasing displacements. The specimens were oriented at 45°, and pin connections at each end allowed for buckling in the plane of the frame (Figure 2). The loading history consisted of two cycles each of displacements ranging from 0.1 to 4% story drift. Cycles then continued at 4% drift until brace fracture occurred.

Foam-Filled Brace Test Results

The cyclic inelastic behavior of the filled and unfilled brace specimens was similar until local buckling and fracture. The elastic stiffnesses and yield strengths of the filled braces were comparable (within 3%) to those of the unfilled braces. Yielding and global buckling was followed by the initial

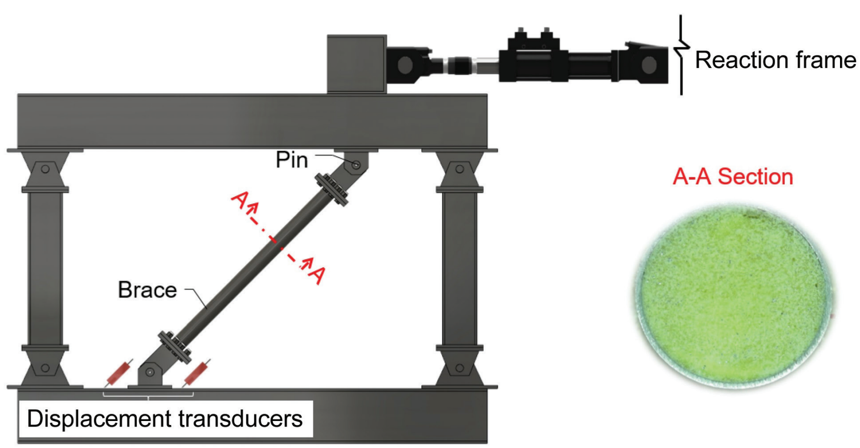


Fig. 2. Test set-up for unfilled and filled brace specimens.

formation of a plastic hinge at mid-length. The first instance of global buckling for Specimen FB11445 was delayed to the first 0.75% compressive cycle, compared to the first 0.5% cycle for Specimen UB11445. Local buckling was therefore also delayed. In both foam-filled braces, the local buckling and strength degradation were less severe than for the unfilled specimens. Figure 3 visually compares the plastic hinge regions in Specimens UB11445 and FB11445. Figure 4 confirms the lower strains at brace mid-length for FB11445. Meanwhile, with the foam fill, both sizes of braces were able to undergo an additional cycle of loading before fracture, and the cumulative energy dissipation increased by approximately 25%. Further testing is ongoing at the University of Michigan with round HSS that have D/t ratios beyond the moderately ductile requirement.

Foam-Filled Bending Members

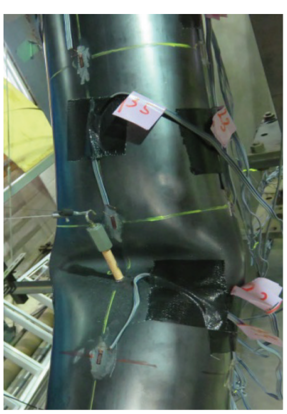
Foam fill provides similar benefits for HSS bending members. The use of HSS beams in seismic applications may be limited by width-to-thickness and depth-to-thickness limits. Full-scale tests on empty and foam-filled HSS beams were conducted to evaluate the benefits of the foam fill, including the potential to inhibit local buckling in their plastic hinge region (Carreras et al., 2018).

Foam-Filled Bending Member Test Specimens, Loading, and Test Set-Up

The testing program was designed for evaluation of overall moment-rotation behavior, degradation of moment capacity, local buckling, and energy dissipation. The 60.5-in. beams were tested as vertical cantilevers with a fixed support at the base and lateral load applied at the top (Figure 5), following the loading protocol for qualifying connections (AISC, 2016b). The full-scale specimens were fabricated with U.S. cold-formed ASTM A500 Gr. B/C steel. The six section sizes allowed evaluation of different width-thickness and depth-thickness ratios in addition to the behavior of empty and filled HSS beams. One of the HSS satisfied the highly ductile limits from the AISC *Seismic Provisions*; four sections met the moderately ductile limit for the flange, and one was outside the moderately ductile limit. The foam fill was placed at the fixed-end connection to a depth of 1.5 times the theoretical plastic hinge length of the HSS.

Foam-Filled Bending Member Test Results

The foam fill was beneficial in limiting local buckling and reducing the degree of moment degradation. Comparisons of the empty and filled beams showed comparable moment capacity, initial stiffness and unloading stiffness. All specimens did experience local buckling and strength degradation. However, even at 0.06 radian, there was restraint of the local buckling in the filled specimen (Figure 6), and the degradation in moment was less severe. Degradation at the first positive 0.04-rad cycle ranged from 4.8% to 5.1% for the filled beams as compared to 7.8% to 23.9% for the empty beams. The degradation was the most severe for the empty HSS beam with the largest flange width-to-thickness ratio, b/t, of 31.3. The web flange-to-thickness ratio, h/t, had a lesser effect but did contribute to the moment degradation. This effect was evidenced by the two specimens with the same b/t and moment degradation of 10.5% for an h/t of 39.9 as compared to 7.8% for an h/t of 31.3. As a result, the influence of the foam fill is most significant for members with larger element slenderness ratios. Meanwhile, the increase in energy dissipation due to the foam fill ranged from 21.1% to 34.2%. One reason for the increased energy dissipation is the reduction in local buckling. Another reason is the crushing of the foam and dissipation of energy once local buckling does occur.



(a) empty braces

(b) filled braces

Fig. 3. Local buckling.

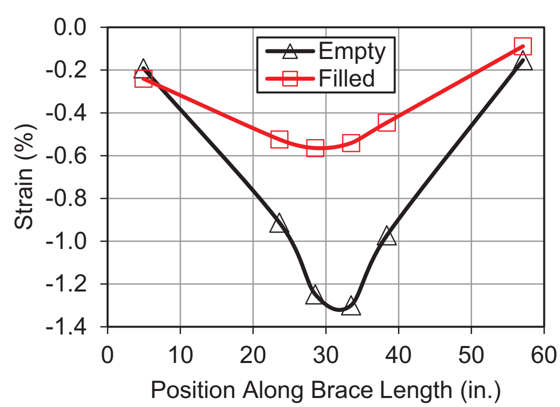
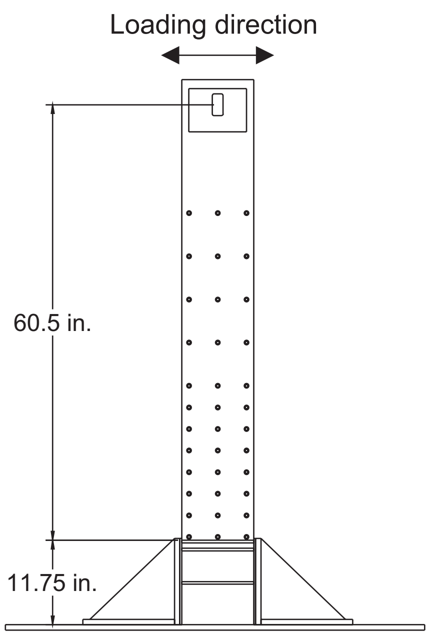


Fig. 4. Comparison of strain over brace length for empty and filled braces.

Conclusions and Future Work on Foam-Filled Braces and Bending Members

From the tests on the foam-filled braces, the foam delayed the local buckling and improved the energy dissipation. The effect of the lightweight foam fill on the elastic stiffness and yield strength was negligible. As such, the foam need not be considered in determination of loads, drift, or nominal capacity. The initial test results suggested that current element slenderness limits could be less stringent for foam-filled braces. Additional tests and detailed finite element studies for a broader inventory of braces are being conducted for development of revised element slenderness limits.

The results for the HSS beams filled with the polyurethane-based foam were similar. The filled HSS beams exhibited less moment capacity degradation and dissipated more energy. The foam fill helped to inhibit local buckling in the member. As with the foam-filled braces, the results for the HSS beam tests suggested that the use of the foam fill could result in a "relaxation of current slenderness requirements." (Carreras et al., 2018). A large-scale parametric study is being conducted to quantify the potential slenderness limits for foam-filled beams.



(a) test set-up drawing

(b) test of specimen

Fig. 5. Bending member testing.

(a) unfilled

(b) filled HSS beams

Fig. 6. Local buckling.

BLAST RESPONSE OF STEEL AND COMPOSITE MEMBERS

Interest in research on the effects of blast loading on structural and other elements has led to the creation of the Centre for Resilience of Critical Infrastructure (CRCI) at the University of Toronto. The work emphasizes short-duration, impulsive loading and includes experimentation and numerical modeling of the behavior of the components under blast and impact. Structural elements and materials studied include architectural and blast-resistant glazing, steel HSS and wide-flange shapes, concrete-filled tubes, energy-dissipating steel connectors, historic masonry façades, and neo-classical columns. "Ongoing research in this area will continue to help develop design methods and best-practice approaches" for blast and impact loading on buildings (Seica et al., 2019). The work on the steel HSS and concrete-filled tubes, including concrete-filled double-skin HSS, will be briefly highlighted.

Hollow and Concrete-Filled HSS under Blast and Impact Loading

Field blast testing, laboratory testing, and numerical modeling of hollow and concrete-filled rectangular HSS has been conducted with the goal of developing blast design procedures. The field blast testing was conducted on 16 square HSS members, half of the specimens filled with a cementitious grout. HSS with 4.72-in. outside dimensions and 0.197-in. or 0.315-in. thickness were used. Duplicate pairs of the 10.7-ft span, simply supported, vertical flexural members were covered by steel cladding. The specimens were subjected to TNT explosive charges up to 2,200 lb. Pressures, displacements, and strains were measured. Figure 7 shows HSS specimens before and after the field blast test. Laboratory tests included material property static tests, "post-test 'autopsies' … on the concrete-filled RHS to evaluate the composite action and to measure the average bond stress," split Hopkinson pressure bar (SHPB) tests to evaluate high-strain-rate behavior of the HSS material, and Charpy V-notch tests to evaluate notch toughness of the HSS (Seica et al., 2019). Numerical modeling included comparisons of single-degree-of-freedom (SDOF) analysis and finite element (FE) analysis using LS-DYNA, displaying the blast response modeling capabilities of the FE analysis (Figure 8). Related work includes Ritchie et al. (2017a, 2017b, 2018a, 2018b) for far-field air-blast loading (characterized by member global failure) and Grisaro et al. (2019) for close-in blast loading (characterized by member local or cross-section failure).

Concrete-Filled Double-Skin HSS under Blast and Impact Loading

Concrete-filled, double-skin steel tubes (CFDST) were also studied. In these CFDST, an outer square HSS had 4.72-in. outside dimensions and 0.236 in. thickness. For the inner tube, a square HSS of 2.36- or 3.15-in. outside dimensions and 0.118-in. thickness was used, as illustrated in Figure 9. After field blast tests, sections cut from the centers of the

(a) HSS test specimens in concrete reaction structure

(b) HSS members after field test, with displacement transducers, illustrating global failure of members due to far-field air-blast

Fig. 7. HSS test specimens before and after field blast test.

test specimens showed no noticeable damage for the CFDST with the smaller inner tube (2.36 in.), but crushing of the cementitious grout and local buckling of the inner tube was observed for the specimen with the 3.15-in. HSS. In the laboratory, four-point bending tests were conducted to inform the numerical modeling. SDOF and FE analyses were again conducted. The FE analysis was able to represent the blast response with higher accuracy than the SDOF analysis.

WELDING OF HSS

Experimental and numerical research on fillet welds to round and rectangular HSS members (which are inherently single-sided), joined to rigid (plate) landing surfaces, has led to clarification of the application of the directional strength-increase factor (which accounts for direction of loading relative to the weld axis) for single-sided fillet welds (Packer et al., 2016; Tousignant and Packer, 2017b, 2019). Thus, for fillet welds to square and rectangular—but not round—HSS branches, it has been proposed that the directional strength-increase factor be disallowed in the 2022 edition of AISC *Specification* Chapter J for branch elements in tension, which tend to cause opening of the fillet weld at the root.

Other research on round-to-round HSS weld-critical connections, where the weld is joined to a flexible (HSS) landing surface, has led to design recommendations for weld effective lengths in such connections. The weld around the perimeter of a round HSS can have a highly nonuniform stress and be prone to weld "unzipping," but no specifications exist currently for weld effective length (e.g., in AISC *Specification* Section K5). Experimental and numerical research on welds in round-to-round HSS connections has addressed questions about the weld behavior (Tousignant and Packer, 2017a, 2018). Synthesis of the results has produced weld effective length recommendations for round HSS cross-, T-, and Y-connections (Tousignant and Packer, 2019). For fillet welds in such connections these recommendations are shown to provide adequate structural reliability in conjunction with the use of the directional strength-increase factor.

The research providing the basis for the new recommendations included 12 large-scale laboratory tests on round-to-round HSS connections (Tousignant and Packer, 2017a). The A500 Grade B/C specimens had HSS10.75×0.500 or HSS16.00×0.500 chord members and branches at 60° or 90° with 0.25 to 0.47 branch-to-chord width ratios. Quasi-static axial tension forces were applied to the ends of the branches [Figure 10(a)], causing brittle fractures in all fillet welds [as shown for a 90° connection in Figure 10(b)]. Measured strain distributions around the welds, a numerical parametric study (Tousignant and Packer, 2018), and a

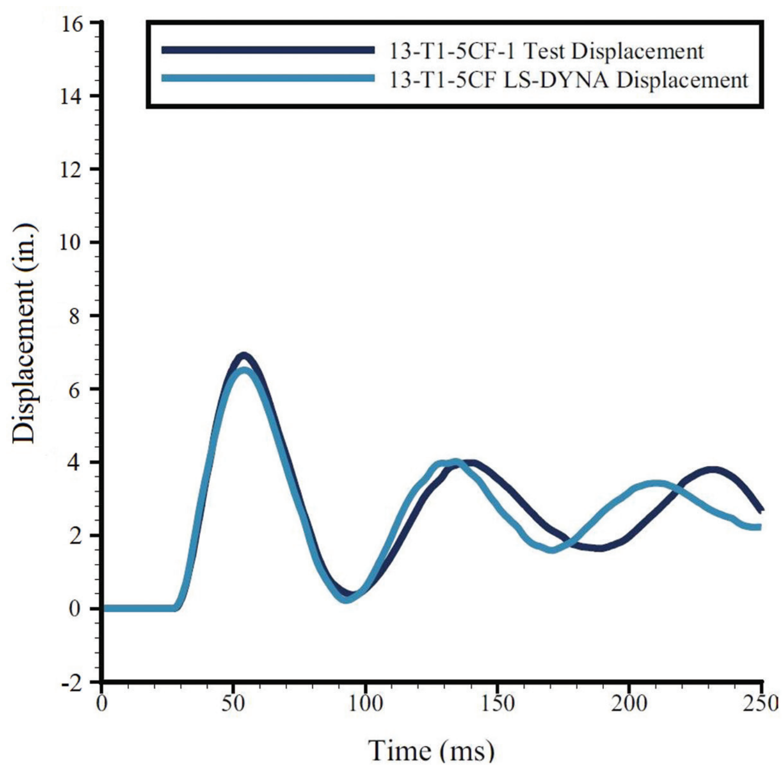


Fig. 8. Mid-span displacement vs. time (measured vs. predicted by LS-DYNA).

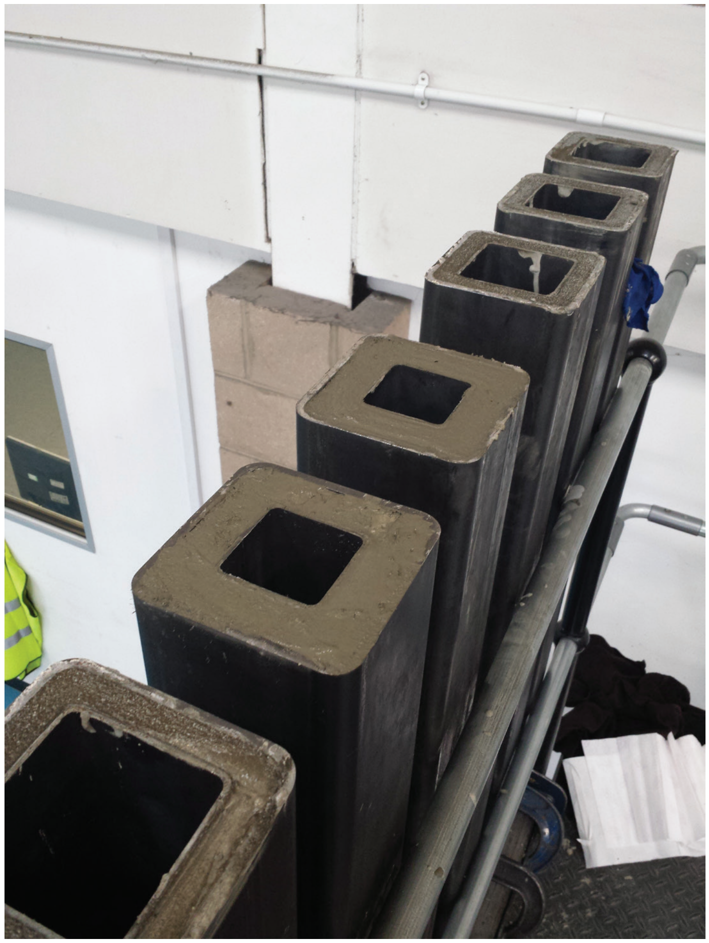
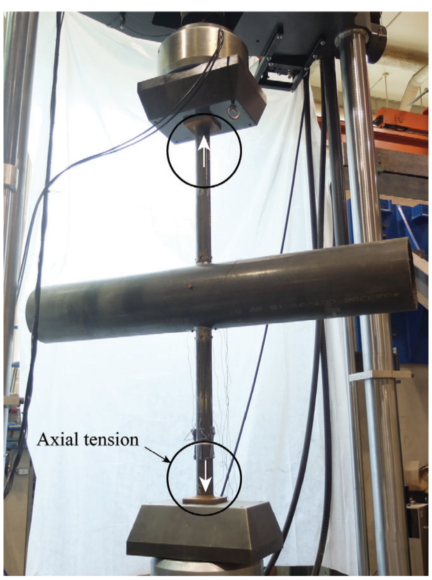
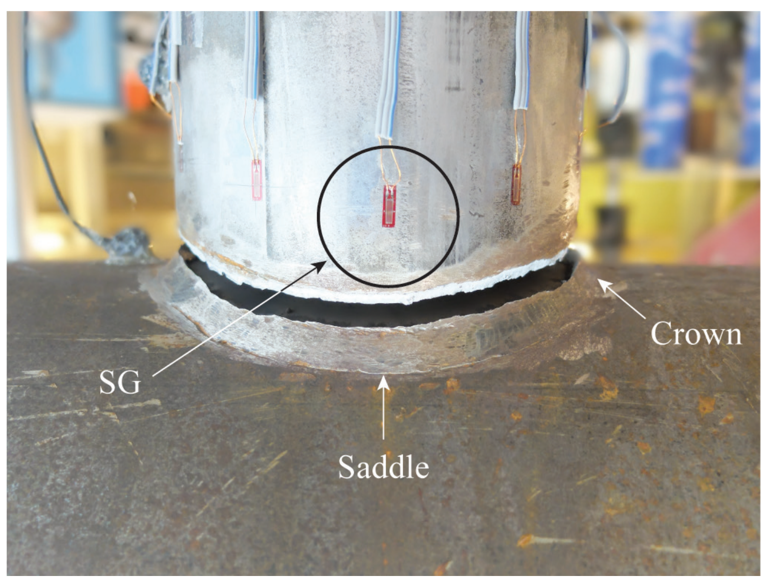


Fig. 9. CFDST test specimens under fabrication.



(a) test set-up



(b) weld fracture in a 90° cross section

Fig. 10. Round-to-round HSS testing.

reliability analysis were considered in the development of the new design recommendations presented to AISC (Tousignant and Packer, 2019).

The recommendation for weld effective length in a round-to-round HSS cross-, T-, or Y-connection is a function of the branch-to-chord member angle, θ; the branch-to-chord diameter ratio, D_b/D; and the chord wall slenderness, D/t. As shown in Figure 11, the effective length, l_e, considers two arcs around the saddle regions of the weld. Additional details and a design example can be found in Tousignant and Packer (2019).

STATIC STRENGTH OF HSS CONNECTIONS

Several issues are currently being explored for statically loaded rectangular HSS-to-HSS connections. The first involves connections where the branch is near an open chord end. As may be expected, the connection strength is reduced for a small "end distance," so there is a minimum distance from an open chord end in order to achieve full connection capacity. A requirement for this minimum end distance, l_{end}, was incorporated in AISC *Specification* Table K3.2A (AISC, 2016a) based on the work of Fan and Packer (2017). This end distance was based only on a flexural yield-line mechanism in the chord connecting face, which presumes a chord plastification limit state, so research is currently in progress to generate an end distance requirement that applies to all potential limit states.

Another recent study has evaluated the case of loading across the full width of a rectangular HSS in compression, engaging both webs. Possible limit states include web local yielding, web local crippling, and web compression buckling. However, the AISC *Specification* (AISC, 2016a) is based on the behavior of I-shaped sections with a single web. Extensive experimental and numerical research has revealed that for matched-width rectangular HSS cross-connections with a chord sidewall slenderness (H/t) up to 50, web local yielding will govern if the bearing length is $\leq 0.25H$ (where H is the chord depth), web local crippling will not control, and web compression buckling will govern if the bearing length $>0.25H$ (Kuhn et al., 2019). Wei and Packer (2019) have shown that the web compression buckling failure load is well-predicted by treating each HSS sidewall as a fixed-ended column and designing in accordance with AISC *Specification* Chapter E.

A third topic currently under study deals with rectangular HSS-to-HSS connections in which the branch is laterally offset to be flush with one sidewall of the chord. This is sometimes done in practice for ease of attaching cladding to the side of an HSS truss or frame. All HSS connection design recommendations, however, internationally, only cater to the case of a branch (or branches) aligned with the centerline of the chord. Laboratory experiments (Figure 12) and numerical studies—to expand the connection geometric database and consider different loading situations—are currently under way. Under branch axial compression, the connection capacity is determined by a combination of buckling of one chord sidewall and chord face plastification. The aim of this study is to derive design recommendations for HSS connections with laterally offset branches based on the existing set of limit states (and design equations) pertaining to connections with coincident branch and chord centerlines.

SUMMARY AND FUTURE WORK

Recent advances in design of HSS members and connections have been highlighted. Research on HSS columns under axial and lateral loads has contributed knowledge about seismic behavior and revealed a need for revisions to the highly ductile limits for HSS columns. In foam-filled brace and

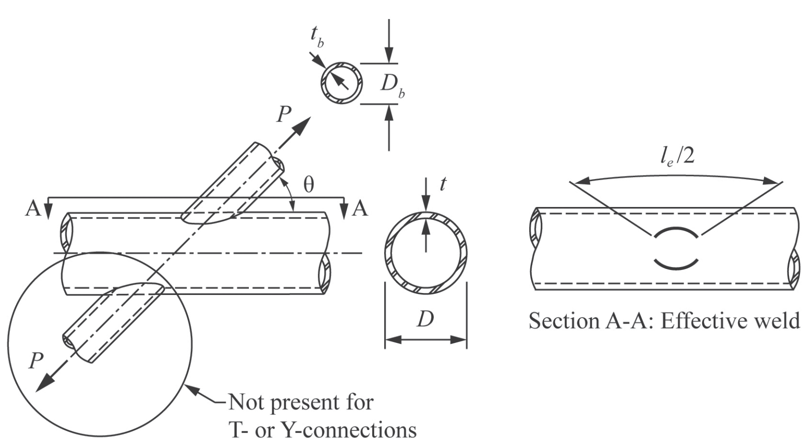


Fig. 11. Weld effective length for round-to-round cross, T-, and Y-connections.

bending member experiments, the lightweight polyurethane foam improved seismic performance by delaying local buckling, reducing strength degradation, and increasing energy dissipation. The database is being expanded with additional tests and detailed finite element studies on a broader inventory of braces for development of revised element slenderness limits. A large-scale parametric study, under way, is exploring potential slenderness limits for foam-filled beams. Design methods for hollow and concrete-filled HSS subject to blast and impact loading are being informed by field tests, laboratory experiments, and numerical modeling. Finally, a substantial amount of research on HSS connections has resulted in improved design procedures for single-sided fillet welds to HSS members, connections in compression, connections near chord ends, and connections that are offset laterally.

ACKNOWLEDGMENTS

Special thanks to Jason McCormick and Jeffrey Packer for all of the materials, coordination, edits, and other feedback and contributions. The work of their numerous research assistants is also appreciated.

The researchers would like to acknowledge their sponsors: the Explora Foundation; the Natural Sciences and Engineering Research Council of Canada (NSERC); the Steel Structures Education Foundation (SSEF)/Canadian Institute of Steel Construction (CISC); the American Institute of Steel Construction (AISC); the Thornton Tomasetti Foundation; the Lyon Sachs Research Fund; Atlas Tube; Walters Inc.; the National Science Foundation (CMMI–1334272, CMMI–1350605); U.S. NSF East Asia and Pacific Summer Institutes (EAPSI) Fellowship and Japan Society for the Promotion of Science (JSPS) Award No. 1713850; the University of Michigan; and the U.S. Department of Commerce, National Institute of Standards and Technology. Any findings, recommendations, or other material within are those of the researchers and do not necessarily reflect the views of the sponsors.

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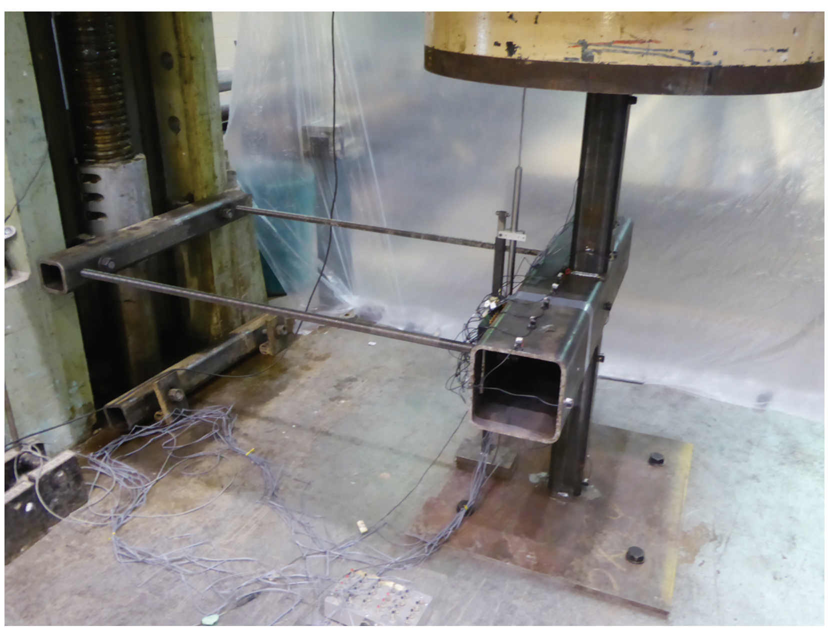

Fig. 12. Test set-up for rectangular HSS cross-connections with laterally offset branches.

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