ENHANCEMENT OF STEEL TUBE BRACE BEHAVIOR UNDER CYCLIC LOADS

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The performance of steel braced frame systems under earthquake loads can be severely compromised due to local buckling of the braces and damage associated with plastic deformations. To mitigate these shortcomings, a lightweight, pourable and expanding polyurethane foam is employed within the voids of circular hollow section (CHS) braces. An experimental investigation is undertaken that shows the ability of the foam fill to delay the initiation and reduce the severity of local buckling in CHS braces under large cyclic loads, leading to a prolonged fracture life and greater energy dissipation. The resulting data is used to calibrate and validate finite element (FE) models of empty and foam-filled CHS braces. The FE models are then used to conduct a parametric study that considers a variety of brace diameter-to-thickness (*D/t*) and slenderness (*KL/r*) ratios. Results from the parametric study are used to assess the effectiveness of the foam fill, particularly as it relates to being able to select a wider range of brace geometries. The results suggest that the foam fill is most effective in braces with larger *D/t* ratios, and less stringent *D/t* limits are necessary when considering the inclusion of foam within the voids of CHS braces.

Keywords: Circular hollow sections, Seismic, Braces, Local buckling, Polyurethane foam.

1 Introduction

Steel braces are commonly employed in buildings located in regions of high seismicity due to their ability to efficiently resist earthquake forces and limit story drifts. During severe ground shaking the diagonal braces are expected to dissipate seismic input energy and provide lateral drift capacity through cycles of yielding in tension and buckling in compression. However, the behavior of conventional steel braces is characterized by asymmetric behavior in tension and compression with substantial degradation of compressive strength occurring after buckling as a result of residual deformations and the Baushinger effect (Tremblay, 2002). The degradation of the compressive strength results in unstable energy dissipation, which can compromise the ability of surrounding frame members to respond elastically, leading to costly permanent damage associated with inelastic behavior. Furthermore, when subjected to inelastic cyclic loads conventional hollow structural section (HSS) braces have been shown to be susceptible to severe local buckling at their mid-length, ultimately leading to early fracture and reduced ductility (Fell et al. 2009).

To mitigate the foregoing deficiencies, a lightweight, high energy dissipating polyurethane foam is introduced into the voids of CHS braces. The ability of concrete fill to reduce the severity of local buckling and improve the overall performance of rectangular hollow section (RHS) braces under representative seismic loads is well documented (Liu and Goel 1988, Broderick et al. 2005, Goggins et al. 2006). Comparatively less research has focused on concrete fill in CHS braces, but

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a recent study by Sheehan and Chan (2014) indicated that concrete fill is able to prolong brace fracture life, thus providing an increase in energy dissipation. While these studies provide insight on how void-filled HSS will perform under large cyclic loads, the fill material may not be optimal for seismic applications where increased seismic mass can lead to larger seismic forces. The proposed polyurethane foam fill circumvents this concern, as it is nearly ten times less dense than normal weight concrete. Furthermore, a recent experimental investigation has shown that the foam fill is capable of impeding the onset of local buckling at the mid-length of CHS braces, thus leading to a greater fracture life and enhanced energy dissipation (Ammons et al. 2018).

This paper briefly describes the test program used to calibrate and validate finite element models of empty and foam-filled CHS braces that are subsequently used to conduct a parametric study considering a variety of diameter-to-thickness (*D/t*) and global slenderness (*KL/r*) ratios. The results from the parametric study are presented with emphasis placed on determining whether sections with the foam fill and larger *D/t* ratios can be appropriate for seismic braced frame applications.

2 Experimental Program

Two sets of equivalent size empty and filled braces fabricated from Japanese STK 400 steel are subjected to symmetric reversed cyclic loading. The lateral loading history consists of two cycles each to story drifts of 0.1, 0.25, 0.5, 0.75, 1, 1.5, 2, 3, and 4% or until brace fracture considering a brace orientation of 45° and a story height of 1753 mm. The braces are tested in a four-pin loading frame with the braces attached to mechanical pin connections via endplates that are welded to the brace ends and bolted to the connections (Figure 1). The pin connections are oriented to only allow for rotation within the plane of the frame, and are used to limit variation and uncertainty in brace performance that may arise from the design and fabrication of gusset plates. Axial elongation of the braces is measured between the pins and is taken as the average of values measured using LVDTs (Linear Variable Differential Transformers) located on either side of the frame adjacent to the pin connections. Further information on the steel material properties, loading protocol, and tested brace geometries can be found in Ammons et al. (2018).

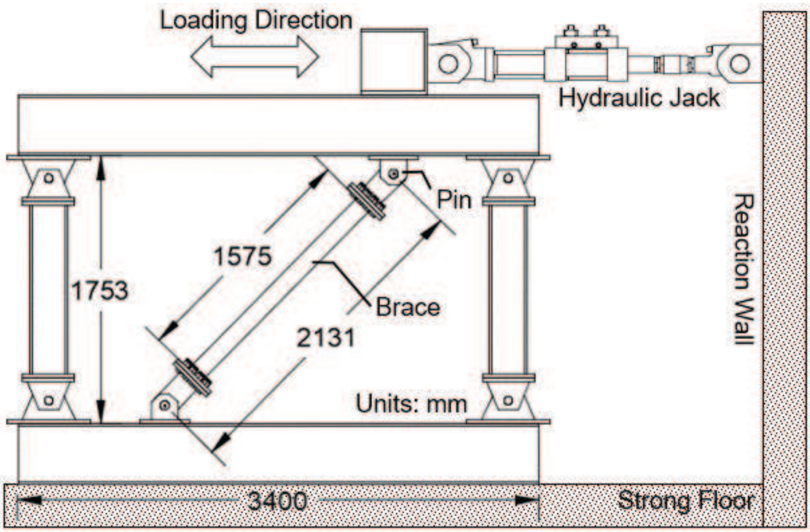


Figure 1. Test setup.

3 Finite Element (FE) Modeling

3.1 *Modeling details*

Finite element models are developed to provide further insight into the performance of foam-filled CHS braces under large cyclic loads. Abaqus version 6.17 (Abaqus 2017) is used to create all models. Leveraging symmetry with respect to loading, geometry and boundary conditions, one-quarter of the brace is modeled (Figure 2). The symmetric boundary conditions restrain out of plane displacement and restrict rotations about the axes that are perpendicular to the respective out of plane directions. Axial deformation corresponding to the experimental loading history is applied to the pin reference point (Figure 2), which corresponds to the center of the pin shown in Figure 1. The nodes that lie on the surface of the brace end have rotation and displacement constrained to the rotation and displacement of the pin reference point. A global imperfection is introduced by scaling the first mode shape produced by an eigenvalue analysis to produce a maximum deformation at the mid-length of the brace of 1.58 mm (L/1000) (Kumar and Sahoo 2018), which provides buckling loads in close agreement to the experimental results.

The empty and filled braces are modeled with four-node shell elements (S4R) with one integration point. The polyurethane foam is modeled with three-dimensional eight-node continuum elements (C3D8R) with one integration point. To improve computational efficiency and accurately capture the local buckling expected at the brace mid-length, the mesh is partitioned into two distinct regions. A mesh size of 1.875t, where t is the design wall thickness of the brace (AISC 2016a), is employed in the plastic hinge region based on the results of a mesh convergence study. The remainder of the brace utilizes a more coarse mesh with a typical element size five times larger than that employed in the plastic hinge region.

A general contact algorithm is employed to define the interaction between the foam and the steel brace. Tangential behavior is defined using a penalty friction formulation with a friction coefficient of 0.3. A friction coefficient of 0.3 denotes that the critical value at which slip occurs between the two surfaces is 30% of the normal contact pressure. Normal behavior is defined using hard contact with the allowance of separation after contact. Specifying this behavior permits an indefinite amount of contact pressure when the two surfaces are in contact and zero contact pressure when there is clearance between the two surfaces. The validity of the allowance of separation after contact definition has been visually confirmed by cutting the filled braces after testing, revealing that the foam had indeed separated from the steel within the plastic hinge region.

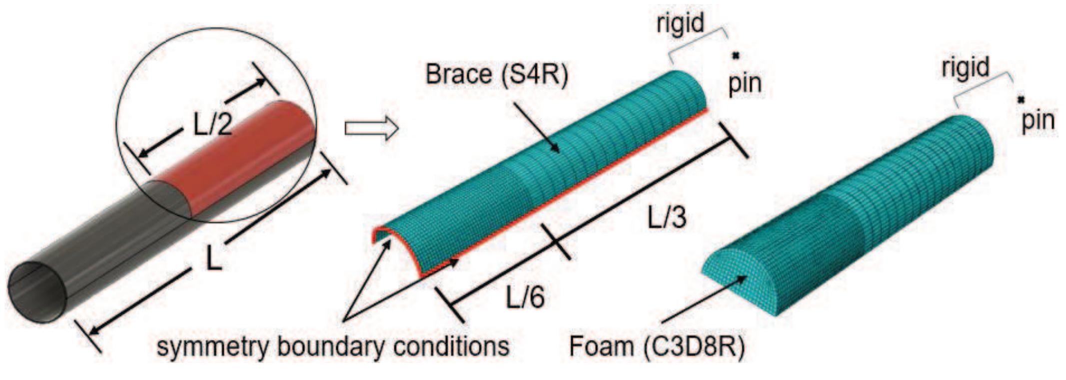


Figure 2. FE modeling details.

3.2 *Material properties*

3.2.1 *Steel*

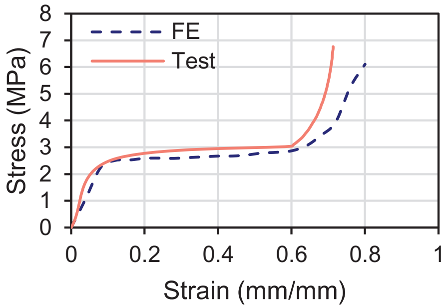
A nonlinear, combined isotropic and kinematic hardening model is employed to capture the behavior of the steel braces under cyclic loading. Referring to Table 1, σ_0 is the yield stress at zero plastic strain, C_1 and γ_1 account for the translation of the yield surface in stress space, while Q_∞ and b define the expansion or contraction of the yield surface in stress space and the rate at which this occurs. The steel material properties used for the parametric study are based on coupon data from A500 Gr. B/C (dual certified) steel. The previously mentioned FE modeling techniques are still used, but the material model parameters are changed from those used during calibration and validation (Japanese STK 400 steel) to establish conclusions for typical U.S. CHS braces.

Table 1. Parametric study steel material parameters.

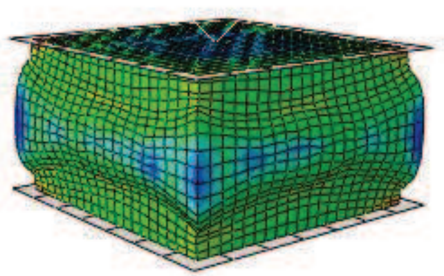
Young's Modulus (MPa)	σ_0 (MPa)	C_1 (MPa)	γ_1	Q_∞ (MPa)	b
192500	358.5	2655	15	96.5	4

3.2.2 *Polyurethane foam*

The crushable foam with a volumetric hardening material model is employed to capture the behavior of the foam. An extensive number of uniaxial compression tests on foam cubes is used to characterize the foam behavior (Wei 2017), with a representative test specimen chosen for the material model calibration. Stress-strain data from the experimental calibration test is compared with a simulation performed in Abaqus (Figure 3a), and it is shown that good agreement is achieved. The deformed configuration from the simulation matches the experimental behavior well, further supporting the validity of the material model (Figure 3b). The elastic modulus and compression yield strength are taken as 25.5 and 2.5 MPa, respectively. The Poisson's ratio is taken as 0.2, while the compression yield stress and hydrostatic yield stress ratios are taken as 1 and 0.1, respectively.



(a)



(b)

Figure 3. Foam material model calibration (a) stress-strain comparison (b) simulation.

3.3 *Validation of FE techniques*

Using the preceding modeling techniques in conjunction with average material properties obtained from coupon tests of the Japanese STK 400 steel, the finite element modeling approach is calibrated and validated against the experimental tests. The calibrated finite element models for both the empty and filled braces are based on experimental data from equivalent size braces with nominal diameters and wall thicknesses of 89.1 mm and 3.2 mm, respectively. Figure 4 provides a comparison of the experimental and numerical hysteretic curves for the empty and filled brace.

The simulated hysteretic loops for the empty and filled braces agree well with the corresponding experimental results. The percent error for the elastic stiffness, critical buckling load, and maximum tensile resistance are 10.1%, 5.1%, and 3.8%, and 11.3%, 2.5%, 1.6%, respectively, for the empty and filled brace. This comparison demonstrates the validity of the modeling techniques and the ability to accurately capture empty and filled brace behavior under large cyclic loads.

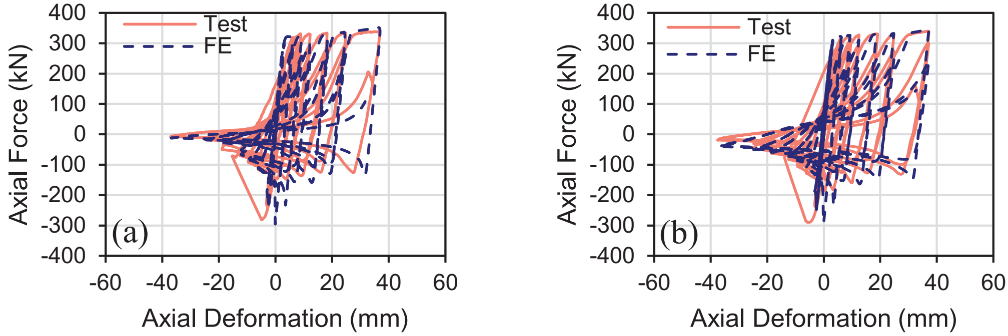


Figure 4. Experimental versus FE hysteretic curves for an (a) empty and (b) filled brace.

4 Parametric Study Results

Nine different CHS brace sizes are considered for the parametric study, with *D/t* and *KL/r* ratios ranging from 23.1 to 41.3 and 41 to 95, respectively (Table 2). This set of brace members is selected to provide a range of *KL/r* ratios that are commonly found in seismic design, and to provide *D/t* ratios that satisfy and extend beyond the moderately ductile (30.1) and highly ductile (25.7) limits stipulated in the AISC Seismic Provisions (AISC 2016b), calculated using a yield strength of 317 MPa and an elastic modulus of 200 GPa. For each section size an empty and foam filled brace are simulated. The loading protocol employed is the same as that used in the experimental tests.

Table 2. Parametric study section properties.

D × t (mm × mm)	Diameter-to-Thickness Ratio, *D/t*	Slenderness Ratio, *KL/r*	Brace Length, *L* (mm)
HSS 127 × 4.8	28.7	49	1575
HSS 244.5 × 6.4	41.3	61	4575
HSS 177.8 × 6.4	30.0	60	3075
HSS 127 × 4.8	28.7	95	3575
HSS 152.4 × 7.1	23.1	41	1575
HSS 190.5 × 9.5	21.5	80	4575
HSS 152.4 × 4.8	34.5	88	4075
HSS 152.4 × 4.8	34.5	41	1575
HSS 152.4 × 7.1	23.1	90	4075

4.1 *General behavior*

In general, the foam-filled braces behave similarly to their empty counterparts with respect to elastic stiffness and tensile strength. For all section sizes considered, the difference between the elastic stiffness for empty and filled braces is less than 1% with the filled braces being stiffer than the empty braces. This result is similar to the behavior observed in the experimental tests, where the difference in elastic stiffness of the empty and filled braces was less than 2%. Furthermore, in all cases the parametric study results show a difference in tensile strength between the empty and filled braces of less than 1%. These minimal differences in stiffness and strength fulfill the intended purpose of the foam fill, which is to provide improved ductility, energy dissipation and a more stable structural response while not altering brace strength.

Figure 5 provides axial force versus story drift responses for two sizes of empty and filled braces. The behavior of the empty and filled braces for both brace sizes are similar, but there are notable differences in compressive strength and energy dissipation, where energy dissipation is defined as the area enclosed by the axial force-deformation curves. The filled HSS 244.5 × 6.4 ($D/t = 41.3$; $KL/r = 61$) brace is able to maintain nearly 60% of its compressive strength to the first compressive excursion to 1.5% drift (when local buckling initiates) compared to only 45% of the maximum compressive strength for the empty brace at the same drift level. Furthermore, the filled brace dissipates 23% more energy than the empty brace at the end of the first cycle to 1.5% drift. Similarly, the filled HSS 127 × 4.8 ($D/t = 28.7$; $KL/r = 49$) brace is able to maintain 44% of its compressive capacity to the second compressive excursion to 2% drift (when local buckling initiates) as opposed to 37% for the empty brace at the same drift level. This behavior leads to the filled brace providing a 26% increase in cumulative dissipated energy compared to the empty brace at the end of the second cycle to 2% drift. The aforementioned results suggest that the foam fill provides enhanced brace performance with greater benefits seen in braces with a larger D/t ratio.

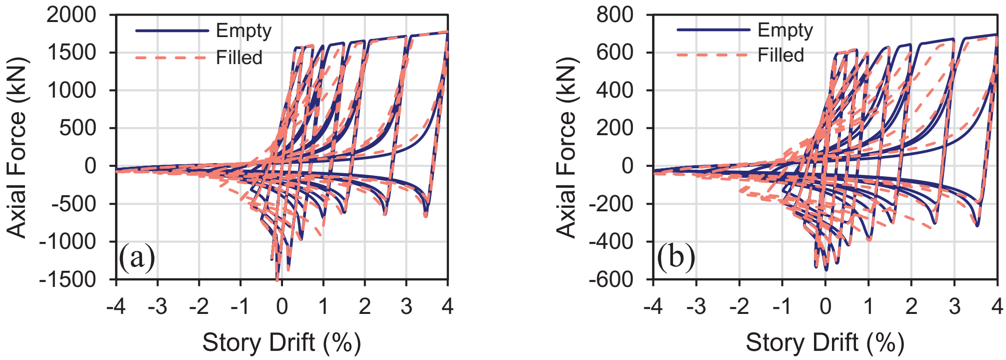


Figure 5. Hysteresis curves for (a) HSS 244.5 × 6.4 ($D/t = 41.3$) and (b) HSS 127 × 4.8 ($D/t = 28.7$).

4.2 *Local buckling*

The cycle that local buckling initiates at the mid-length of the empty and filled braces is determined based on visual observation of the FE time-history animations. Figure 6 provides the number of cycles to the initiation of local buckling plotted as a function of D/t (Figure 6a) and KL/r (Figure 6b). The previously mentioned loading protocol applied to the braces consists of two cycles each to nine increasing drift levels for a total of 18 cycles. For all section sizes considered the foam is able to delay the initiation of local buckling by at least two cycles with the largest delay in local buckling of six cycles occurring for the HSS 152.4 × 4.8 ($D/t = 34.5$; $KL/r = 88$). This section size falls well outside of the limiting D/t ratio for moderately ductile members, suggesting that considering the inclusion of the foam fill can warrant a relaxation of the D/t limits specified in the AISC Seismic Provisions (AISC 2016b). This postulation is further supported by the two and three cycle delay in local buckling for HSS 152.4 × 4.8 ($D/t = 34.5$; $KL/r = 41$) and HSS 244.5 × 6.4 ($D/t = 41.3$; $KL/r = 61$), respectively. In general, the number of cycles to the initiation of local buckling for the empty and filled braces decreases with increases in *D/t*, likely indicating earlier fracture for section sizes with larger *D/t* ratios (Figure 6a). Referring to Figure 6b, there is no distinct trend in regard to how effective the foam is at delaying local buckling as a function of *KL/r.* The inclusion of the foam fill appears to have a less pronounced effect on braces with a larger *KL/r* (>80); however, with the exception of the HSS 152.4 × 4.8 (*D/t* = 34.5; *KL/r* = 88), the filled braces all satisfy the moderately ductile limit, indicating their ability to withstand substantial inelastic deformation.

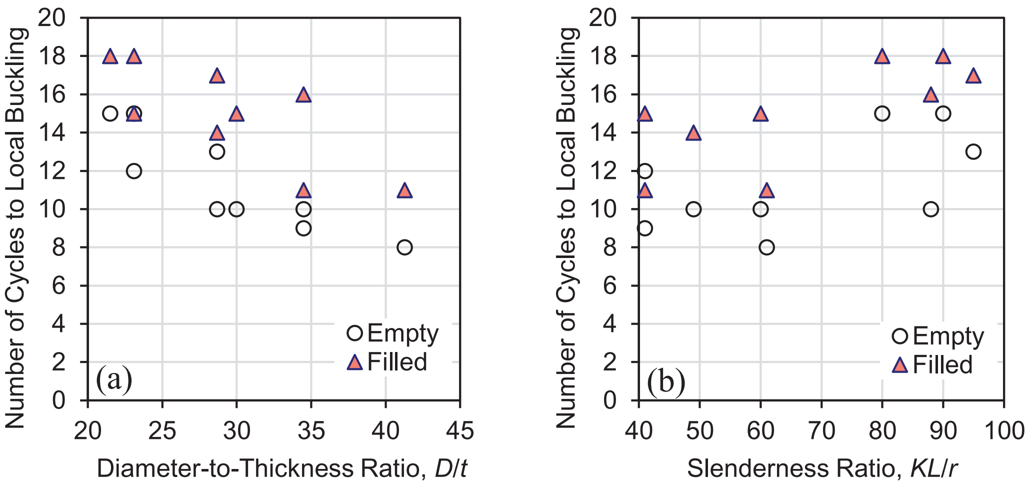


Figure 6. Number of cycles to local buckling versus (a) *D/t* and (b) *KL/r*.

4.3 *Energy Dissipation*

The ability of braces in braced frames to dissipate energy is critical for limiting damage and reducing the structural response of steel systems subject to earthquake loads. As such, energy dissipation capacity for the empty and foam-filled braces is examined. In general, the energy dissipated for each cycle of loading is nearly the same for empty and filled braces until the initiation of local buckling in the empty braces. After the occurrence of local buckling in the empty braces, the difference in energy dissipated during each cycle of loading for the empty and filled braces begins to increase with the filled braces providing greater energy dissipation. This increase in energy dissipation can likely be attributed to the crushing of the foam and the ability of the foam to reduce the rate of degradation of the compressive capacity of the brace. In general, increases in energy dissipation are minimal for more slender braces with a small *D/t* ratio, and larger in less slender braces with a large *D/*t ratio. The results suggest that the foam fill is most beneficial with respect to energy dissipation in less slender braces with a large *D/t* ratio because these braces are more susceptible to local buckling and thus stand to benefit more from the inclusion of the foam.

5 Conclusions

Data from an experimental study is used to calibrate and validate finite element models of empty and polyurethane foam-filled CHS braces under representative seismic loads. The resulting models are used to conduct a parametric study to assess the influence of foam fill on brace performance with respect to its ability to delay the initiation of local buckling and provide enhanced energy dissipation, while also providing an indication as to whether *D/t* limits specified in the AISC Seismic Provisions (2016b) can be relaxed when considering the inclusion of foam. The presence of the foam fill is able to delay the initiation of local buckling for all section sizes considered, with the foam fill being most effective in braces with larger *D/t* ratios, suggesting that *D/t* limits can be relaxed for foam-filled braces. The effectiveness of the foam for braces with a large *D/t* ratio is likely a result of these sections being more susceptible to local buckling, thus having a higher ceiling for improvement. As local buckling is a precursor to brace fracture, the ability to impede the onset of local buckling is critical for prolonging the fracture life of braces. Future work will employ a fracture model that can accurately predict the instant of brace fracture, and consider a greater number of sections with a large *D/t* ratio to better assess what section sizes benefit most from the inclusion of foam.

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