RELAXING CURRENT DUCTILITY REQUIREMENTS IN TUBE-BASED SEISMIC MOMENT FRAMES

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Special and intermediate steel moment frame systems are popular in seismic regions of the U.S. due to their ability to resist lateral loads through flexure and shear in the columns and beams. Recent studies have shown the potential for completely tube-based moment frames where both the beams and columns are designed with rectangular (RHS) and square (SHS) hollow structural sections. However, the use of RHS and SHS in seismic moment frames is limited due to the stringent ductility requirements that are necessary to ensure proper development of the section's plastic moment capacity and stable behaviour during reversed cyclic loading. An expanding and lightweight polyurethane foam is considered to fill the voids of RHS and SHS beams in their plastic hinge region. The presence of the foam has been experimentally shown to inhibit local buckling and provide additional energy dissipation capacity limiting the amount of damage to the beam. A computational parametric study is conducted featuring fifteen pairs of beams to explore the effects of the foam-fill across a wide range of sections with varying local slenderness ratios. The performance improvements with the foam-fill are evaluated with respect to maximum moment capacity, energy dissipation and ability to meet intermediate and special moment frame specifications. The results of this study suggest that the ductility requirements for foam-filled RHS and SHS beams can be relaxed.

Keywords: Hollow structural sections, Seismic, Polyurethane foam, Ductility, Moment frames.

1 Introduction

Steel moment resisting frames, especially intermediate (IMF) and special moment frames (SMF), are commonly used in seismic prone regions of the U.S. due to their ability to resist lateral loads while dissipating seismic input energy in a stable and efficient manner. The moment frame relies on the formation of plastic hinges in specific locations such as the ends of beams and at the column bases in order to form a stable energy dissipation mechanism and prevent the occurrence of a soft story. Therefore, it is important to ensure stable plastic hinging occurs without being disrupted by local buckling, which can greatly reduce the maximum capacity of the member and cause it to behave in a less ductile manner.

Previous investigations by Fadden and McCormick (2012) and Fadden (2013) into the cyclic performance of hollow structural sections (HSS) have shown the viability of these sections as major components of a steel moment resisting frame, but their use may be limited due to the stringent local slenderness requirements that are needed to ensure proper ductile behavior is obtained. In an effort to improve the seismic performance of HSS beams and address the ductility

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requirements, Wei (2017) and Flores Carreras et. al. (2018) considered using a polyurethane foam-fill to provide stability in the plastic hinge region and increase the energy dissipation capacity of the member. These experimental tests showed the foam's ability to delay and reduce the severity of local buckling in HSS beam members resulting in a more ductile behavior with less moment capacity degradation when compared to their unfilled counterparts. Further, the results suggest the possibility of relaxing the current ductility requirements for HSS beams in IMF and SMF when incorporating the foam-fill in the member.

However, the lack of a large sample size of either experimental or validated computational data on the effects of utilizing a foam-fill across a wide range of HSS beams with varying local slenderness ratios has prevented establishing new ductility limits for these sections. This paper begins to address this matter by calibrating and validating a finite element model to existing experimental data of empty and foam-filled HSS beams under fully reversed cyclic loading and then conducting a parametric study that includes fifteen pairs of HSS. The performance improvements of utilizing the foam-fill are measured with respect to maximum moment capacity, energy dissipation, and the ability to meet IMF and SMF ductility requirements (i.e. maintaining 80% of the maximum moment capacity at two percent and four percent drift, respectively). The effects are explored for a wide range of width-thickness and depth-thickness ratios and the results suggest less stringent limits for foam-filled HSS beams.

2 Experimental Basis

A finite element model is developed taking into account previous experimental data of both empty and foam-filled beams under cyclic loading (Fadden 2013, Flores Carreras 2018). The test setup for the empty HSS is comprised of a 1.54 m long cantilever beam member to which cyclic displacements are applied at the free end through a slotted-hole pin connection. This type of connection prevents inducing both an axial load and a moment at the free end. The loading protocol follows the one prescribed by the American Institute of Steel Construction (AISC) Seismic Provisions (2016) for prequalifying beam-to-column moment connections and consists of a progression of incremental story drift cycles up to 0.08 rad. The test setup remains identical for the foam-filled beams with the addition of the polyurethane foam spanning 1.5 times the plastic hinge length to make sure the foam is present within all regions that experience inelasticity.

The experimental results show that the foam-fill has minimal effect on the maximum moment capacity of the member, but the foam is able to mitigate the effects of local buckling by reducing the amount of moment capacity degradation that occurs with continued cycling. Figure 1 shows the results for a moderately ductile section (b/t = 22.8 & h/t = 39.9) without and with foam-fill.

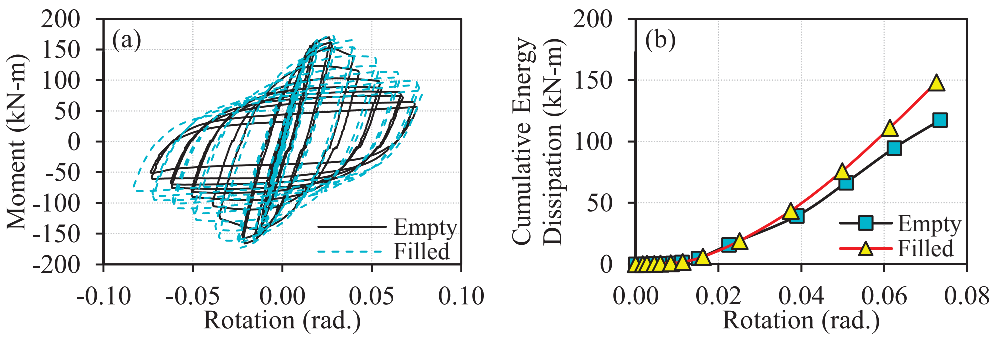


Figure 1. Comparison of the (a) hysteretic behavior and (b) cumulative energy dissipation for an empty and foam-filled HSS 254.0×152.4×6.4.

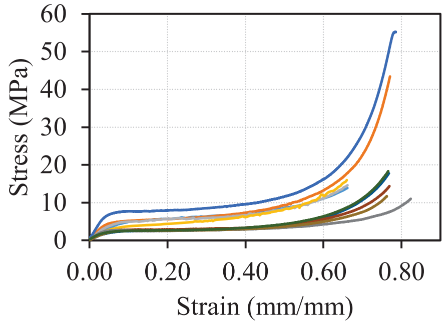


Figure 2. Monotonic compression test results from multiple polyurethane foam specimens.

2.1 *Polyurethane foam properties*

The fill material is a two-part liquid that expands and hardens once mixed together to form a closed-cell, rigid polyurethane foam. The fact that the foam initially is in the form of a liquid makes it convenient as it can easily be poured inside the HSS member. Some variability is observed in the stress-strain behavior of the foam, but the overall behavior shows an initial elastic portion followed by a plateau due to crushing and ultimately hardening due to consolidation (Figure 2). The foam has a density of 256 kg/m^3 and typical elastic modulus values are around 48.3 MPa. For a more detailed discussion on the monotonic and cyclic properties of the fill material, see Wei (2017).

3 Development of the Finite Element Model

The finite element model seeks to replicate the experimental test setup and loading conditions while making some modifications to improve computational efficiency (Figure 3). The model

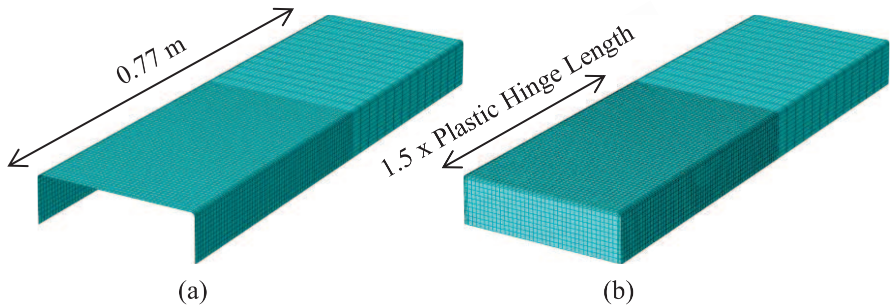


Figure 3. Finite element quarter model for (a) empty and (b) foam-filled HSS beams.

considers a quarter of the complete HSS beam by reducing the length in half and removing half of the cross section by making a cut along the length in a direction perpendicular to the section's strong axis of bending. The portion of the beam that is kept corresponds to the side that has a fixed boundary condition and the length of the model is always longer than the plastic hinge length of the section. A multi-point beam constraint is used between the free edge of the HSS model and a reference point 1.54 m from the fixed end. The loading protocol is applied to the reference point and is transmitted to the beam through the previously mentioned constraint. This approach allows the model to capture all of the inelastic behavior that occurs in the beam, which is primarily what dictates the behavior of the section. A comparison of the resulting hysteresis from the quarter model and the one obtained from a finite element model of the complete HSS member confirms the validity of the modeling approach.

3.1 *Model details*

S4R shell elements are used to model the HSS member. C3D8R solid elements are used to model the polyurethane foam-fill. A dense mesh size of 6.35 mm elements is applied to the HSS and the foam up to a distance equal to 1.5 times the plastic hinge length of the section. The remaining region has a coarser mesh size of 25.4 mm elements. The mesh on the corners of the HSS and the foam is divided to contain at least four elements along the arc. The corner radius is assumed as two times the design wall thickness. An elastic spring support is used to calibrate and validate the finite element model in order to match the experimental boundary conditions, which have some rigid body rotation occurring at the fixed end of the beam. This boundary condition is later changed to a perfectly fixed support for the parametric study.

The foam-filled HSS model includes a penalty contact interaction with a static friction coefficient of 0.3 between the outer foam faces and inner beam walls. This approach prevents element pass-through and provides a good representation of the interaction between the steel and the foam as no bonding is observed in the experimental tests. An initial local imperfection in the shape of the first buckling mode is applied to both the beam and the foam. The magnitude of the local imperfection is chosen as half of the maximum allowable imperfection prescribed by the American Society for Testing and Materials (ASTM) for cold-formed tubular shapes (2018). This magnitude was chosen after a parametric study showed it provided good agreement in the maximum moment capacity across multiple section sizes between the experimental and finite element results. Fracture is not taken into account in the model as it typically occurs at drift levels of 7% and 8%, well above what is expected to occur during a typical earthquake.

3.2 *Model calibration and validation*

The finite element model is calibrated to match the experimental data from the HSS 254.0×152.4×6.4 tests and validated using the results from the HSS 203.2×152.4×6.4 and HSS 254.0×203.2×6.4 sections. The model of the empty beam member is first calibrated and validated before adding the foam-fill. When the foam is added to the model, no other changes are made in order to ensure any changes in performance are solely due to the presence of the fill material.

The steel section is partitioned to apply different material properties to the beam flats and the beam corners. This approach aims to take into account the different material properties observed between the flats and corners of an HSS member due to the effects of cold working. The effects include a higher yield strength, but lower ductility in the corner sections. A more in depth discussion on the effects of cold working can be found in Fadden and McCormick (2014). A combined kinematic and isotropic hardening law is used as the material model for the steel section. The kinematic parameters are obtained from stress-strain data of multiple monotonic tension steel coupon tests; the isotropic parameters are determined through an iterative approach. Relevant material properties used in the finite element model are presented in Table 1.

The polyurethane foam fill is modeled with a crushable foam material model with isotropic hardening, a compression yield stress ratio of one, and a plastic Poisson's ratio of zero. The hardening curve is obtained from multiple monotonic compression tests of 38.1 mm foam cube specimens (Figure 2) and is selected to represent the average behavior of the tested foam.

Table 1. Steel material properties used in the finite element model.

HSS Region	Elastic Modulus (GPa)	Yield Strength (MPa)	Isotropic Hardening Parameters		Kinematic Hardening Parameters	
			Q_∞ (MPa)	b	C (MPa)	γ
Flats	195	393	96.5	6	3423	26.3
Corners	202	497	46.2	6	14220	295

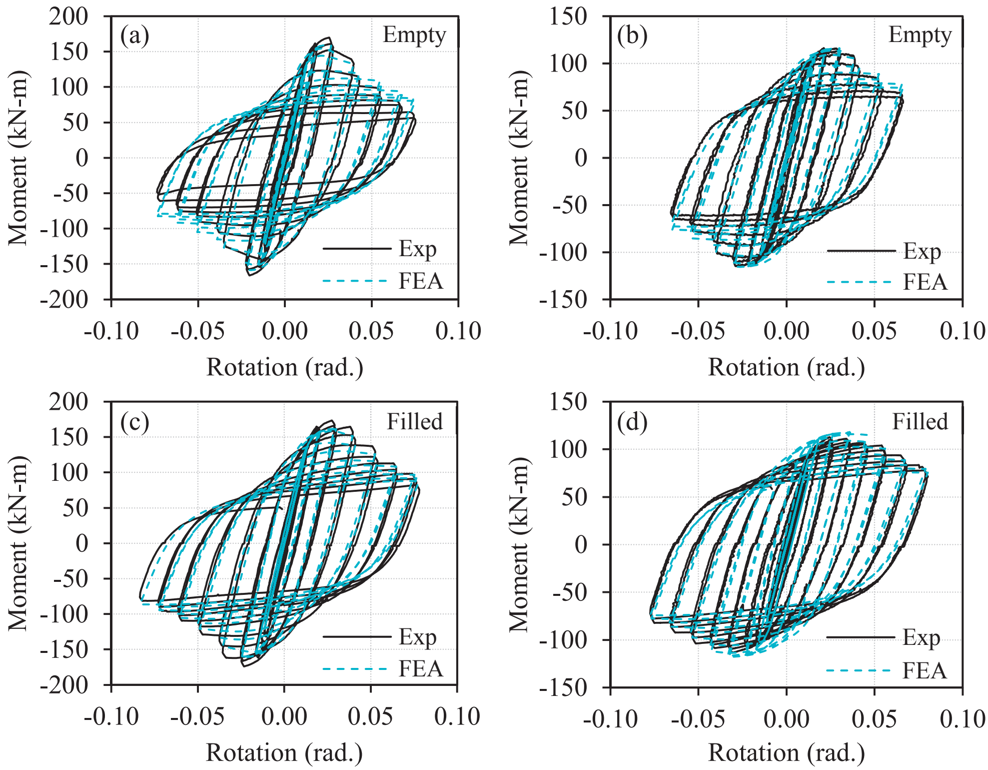


Figure 4. (a and c) Finite element model calibration to empty and filled HSS 254.0×152.4×6.4 experimental results. (b and d) Model validation to HSS 203.2×152.4×6.4 experimental results.

Comparing the moment-rotation response of the finite element model to the experimental data (Figure 4) shows the model is able to capture the hysteretic behavior of both empty and foam-filled beams. The maximum moment capacity of the finite element models stay within 4.2% on average of the experimental results. At 4% and 6% drift, the average percent difference in moment capacity is 5.7% and 13.6%, respectively. The models also exhibit similar cumulative energy dissipation throughout the loading protocol and stay within 6.5% on average at the 6% drift cycle. These measures indicate the model is capable of replicating the overall performance of the HSS members, including those that are filled with the polyurethane foam.

4 Parametric Study

A computational parametric study is conducted that includes 15 pairs (empty and foam-filled) of HSS beams with width-thickness and depth-thickness ratios that range between 9.9 to 31.5 and

14.2 to 57.1, respectively. Table 2 shows the selected HSS as well as relevant information on the length of the foam-fill and the ductility rating. The parameter range is selected as it allows for a study of the effects of the foam-fill on sections that meet high, moderate, and no ductility criteria for A500 Gr. B HSS. The width-thickness limits are calculated based on the equations provided by the AISC Seismic Provisions (2016) and are 14.5 and 26.3 for the highly and moderately ductile criteria, respectively. The sections that do not meet either of these criteria are labeled as having low ductility in Table 2. The limits are calculated using the measured elastic modulus and yield strength of the HSS flats (Table 1).

Table 2. List of sections included in the computational parametric study.

HSS Section	b/t	h/t	Foam Length (mm)	Ductility Criteria
203.2×152.4×7.9	17.6	24.5	391.2	Moderately
203.2×152.4×12.7	9.9	14.2	447.0	Highly
203.2×203.2×7.9	24.5	24.5	340.4	Moderately
254.0×152.4×4.8	31.5	54.5	396.2	Low
254.0×203.2×7.9	24.5	31.4	360.7	Moderately
254.0×203.2×9.5	19.9	25.7	375.9	Moderately
304.8×203.2×6.4	31.3	48.5	378.5	Low
304.8×203.2×7.9	24.5	38.2	386.1	Moderately
304.8×203.2×15.9	10.8	17.7	449.6	Highly
304.8×304.8×9.5	31.4	31.4	322.6	Low
355.6×152.4×6.4	22.8	57.1	459.7	Moderately
355.6×152.4×12.7	9.9	27.1	508.0	Highly
355.6×254.0×7.9	31.4	45.1	368.3	Low
406.4×203.2×7.9	24.5	52.0	431.8	Moderately
406.4×203.2×9.5	19.9	42.8	444.5	Moderately

4.1 *Influence of the foam-fill*

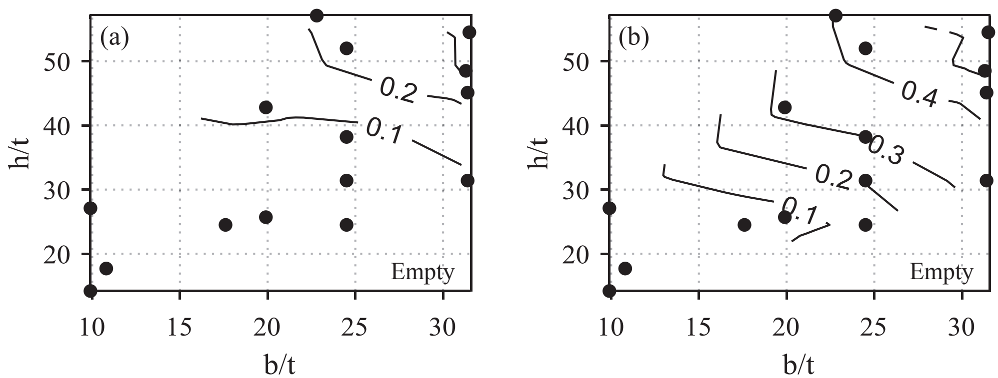
The presence of the polyurethane foam-fill has varying degrees of influence on the HSS depending on the local slenderness ratios of the section. Since the difference in stiffness between the foam and the steel HSS is significantly large, some degree of local buckling in the beam member is necessary for the foam to have any sort of effect on the behavior of the section. Due to this fact, highly ductile sections with low depth-thickness ratios such as the HSS 203.2×152.4×12.7 and HSS 304.8×203.2×15.9 benefit the least from the foam-fill, exhibiting little to no change in overall performance. However, some benefits can be seen in highly ductile sections with higher depth-thickness ratios due to the onset of local buckling at higher drifts. The improvements are observed in the HSS 355.6×152.4×12.7, which exhibits 11.2% less moment capacity degradation at the 6% drift cycle when filled. No degradation is observed at lower drifts due to being highly ductile.

On average, a 1.0%, 4.0%, and 6.8% increase of the maximum moment is observed due to the foam-fill for the high, moderate, and low ductility sections, respectively. Half of the empty sections with moderate ductility exhibit no moment degradation by the first 2% drift cycle while the other half show improvements from incorporating the foam: 4.3% less moment capacity degradation on average is observed for these cases. At the 4% drift cycle, seven of the eight moderately ductile filled HSS show less moment degradation. The eighth section (HSS 203.2×152.4×7.9) had no degradation at this cycle. Although the foam-fill has a noticeable effect on moderately ductile members, the degree to which it affects their behavior depends on their relative local slenderness ratio. Sections with low width-thickness ratios (HSS 254.0×203.2×9.5, HSS 406.4×203.2×9.5, and HSS 355.6×152.4×6.4) showed improvements, regardless of their depth-thickness ratio, of around 1.6% at 4% drift in terms of less moment degradation. On the other hand, the remaining sections with higher width-thickness ratios exhibit 11.5% less moment degradation on average at the 4% drift level.

All of the sections with low ductility share essentially the same width-thickness ratio, but have varying depth-thickness. The two low ductility foam-filled HSS with the lowest depth-thickness ratios (HSS 304.8×304.8×9.5 and HSS 355.6×254.0×7.9) show the most improvement exhibiting an average of 14.5% less moment capacity degradation at the 4% drift cycle. A much smaller effect is observed on the remaining two sections that feature higher depth-thickness ratios, exhibiting 2.7% less moment capacity degradation at the 4% drift cycle. Similar results are observed in terms of energy dissipation. On average, the foam-filled HSS showed 18.3% and 8.2% higher cumulative energy dissipation at the 4% drift level for the low ductility sections with lower and higher relative depth-thickness ratios, respectively. These measures suggest that the foam-fill is capable of having a tangible effect on low ductility sections as long as their depth-thickness ratios are not too large.

4.2 *Ductility criteria*

The ability of a HSS to meet IMF and SMF criteria depends on being able to maintain 80% of the maximum moment capacity at 2% and 4% drift, respectively. These criteria are directly related to the limiting local slenderness ratios for moderately and highly ductile sections. Linearly interpolated contour plots are developed (Figure 5) from the parametric study results to explore the possibility of relaxing the current ductility limits for foam-filled HSS beams. Comparing the contour lines for the empty and filled sections at 2% drift shows that three sections (HSS 355.6x152.4x6.4, HSS 355.6x254.0x7.9, and HSS 406.4x203.2x7.9) that previously were not able to maintain 80% of their capacity are now able to due to the presence of the foam-fill, suggesting they can be used in an IMF. Similar results can be observed from the contour lines for the empty and filled HSS at 4% drift. In this case, three other sections (HSS 254.0x203.2x7.9, HSS 304.8x203.2x7.9, and HSS 304.8x304.8x9.5) are now able to maintain 80% of their maximum moment capacity because of the foam-fill, suggesting they meet SMF requirements.



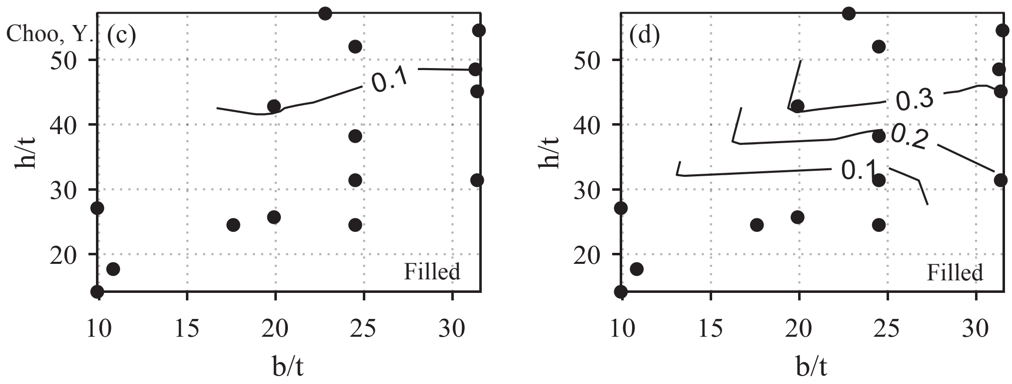


Figure 5. Contour plots showing the moment capacity degradation of the HSS in decimal percent at (a and c) 2% and (b and d) 4% drift for the empty and foam-filled section with respect to their local slenderness.

5 Conclusions

A computational parametric study is conducted on 15 pairs of empty and polyurethane foam-filled HSS beams to study the foam's ability to improve the seismic performance of the members by mitigating the effects of local buckling. The influence of the foam-fill is measured with respect to maximum moment capacity, reduced moment capacity degradation, increased energy dissipation, and ability to meet IMF and SMF ductility requirements.

Results from the parametric study show the foam-fill can have a significant effect on the cyclic behavior of a HSS beam, but the degree to which it influences the overall performance depends on the local slenderness ratios of the section. Highly ductile sections with low depth-thickness ratios do not benefit from the presence of the foam, while those with relatively higher depth-thickness ratios show some improvement at high drift levels. Moderately ductile sections with higher width-thickness ratios benefit more when compared to sections with a lower width-thickness ratios. In the case of HSS with low ductility, these sections see some benefit from the foam-fill as long as the depth-thickness ratio is not too high. The performance improvements due to the presence of the foam-fill result in more sections being able to meet the ductility requirements for IMF and SMF. The results suggest the possibility of relaxing the current local slenderness requirements for HSS beams that make use of a polyurethane foam-fill.

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