SEISMIC PERFORMANCE OF FOAM FILLED TUBULAR STEEL BRACES

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ABSTRACT

An experimental investigation is conducted considering the use of pourable and expandable closed-cell polyurethane foam as fill material in the voids of circular hollow structural section braces used in seismic applications. In contrast to concrete-filled tubes, the foam infill is able to limit additional weight to the structure while increasing ductility, reducing the proclivity to locally buckle, and increasing energy dissipation under cyclic loads. To assess the performance of the filled braces, hollow and filled braces of equivalent section size are subjected to quasi-static inelastic cyclic loading until fracture with the brace behavior analyzed with respect to the onset of local buckling and energy dissipation capacity. The presence of the foam is able to delay the onset of local buckling, thereby increasing the fracture life and ductility of the brace leading to increased resilience and a more predictable and stable structural response.

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Seismic Performance of Foam Filled Tubular Steel Braces

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An experimental investigation is conducted considering the use of pourable and expandable closed-cell polyurethane foam as fill material in the voids of circular hollow structural section braces used in seismic applications. In contrast to concrete-filled tubes, the foam infill is able to limit additional weight to the structure while increasing ductility, reducing the proclivity to locally buckle, and increasing energy dissipation under cyclic loads. To assess the performance of the filled braces, hollow and filled braces of equivalent section size are subjected to quasi-static inelastic cyclic loading until fracture with brace behavior being analyzed with respect to the onset of local buckling and energy dissipation capacity. The presence of the foam is able to delay the onset of local buckling, thereby increasing the fracture life and ductility of the brace leading to increased resilience and a more predictable and stable structural response.

Introduction

Hollow structural section (HSS) braces are often used in steel braced frames to control lateral drift and dissipate seismic energy through buckling in compression and yielding in tension. Their popularity stems from advantageous properties, such as excellent compression and tension behavior, high strength-to-weight ratio, and aesthetic appeal. Numerous researchers have investigated the performance of HSS braces and have identified their susceptibility to premature fracture under inelastic cyclic loading soon after the occurrence of local buckling [1, 2]. To delay the initiation of local buckling, thus prolonging their fracture life, research has been conducted on the use of concrete filled HSS bracing members. Studies performed by [3, 4] indicated that the presence of concrete is able to improve brace ductility, with more improvement shown in sections with larger width-thickness ratios and smaller slenderness ratios. This finding is a result of less slender braces being relatively short, thus requiring larger plastic rotation and higher

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compressive strains at the plastic hinge to achieve a given drift level compared to more slender braces [5]. Additionally, both studies proved that concrete infill was effective in increasing the post peak capacity of bracing members in tension and compression. However, for seismic applications in which reduced mass may be beneficial, the use of concrete may not be optimal. Also, the inability to adopt concrete fill as an in-situ retrofit strategy hinders its consideration in seismic applications.

The use of a light-weight, high energy dissipating material may be a better alternative, as it has the added benefit of limiting seismic weight while being able to provide increased energy dissipation under larger deformations. A material that inherently satisfies these criteria is polyurethane foam. The use of foam fill has been extensively explored in the automotive and aeronautical industries due to its ability to increase crashworthiness through its dissipative properties, while also allowing collision protection structures to abide by stringent weight limits [6]. Furthermore, studies have shown that foam-filled tubes offer substantial improvement in energy absorption capacity under axial compression when compared to that of empty tubes [7, 8]. Additionally, foam fill can be implemented as a retrofit option due to its ability to be placed as a liquid and expand as it hardens to fill a void.

The objective of this study is to determine the ability of lightweight, high energy dissipating polyurethane foam to enhance the performance of steel bracing members subjected to inelastic cyclic loading. As such, an experimental program is undertaken that allows for comparisons to be made between the behavior of filled and empty tubes with respect to the ability to prolong stable behavior prior to local buckling and increase energy dissipation. The results provide an initial indication of whether diameter-to-thickness ratio limits can be relaxed and what potential section sizes benefit most from the inclusion of foam fill.

**Test Program**

In order to evaluate the behavior of foam-filled braces under a representative seismic loading, increasing cyclic displacements are quasi-statically applied to four brace specimens. The braces are identified according to whether they are filled or empty (FB for “filled brace” or UB for “unfilled brace”) and by section size. The specimen designations are shown in Table 1 along with salient geometric properties. The circular hollow section (CHS) members are cold formed structural tubing fabricated from Japanese STK400 steel. The nominal specified minimum yield stress, $F_y$, is 235 MPa and the specified minimum ultimate tensile strength, $F_u$, is 400 MPa. Tensile coupons were removed from the CHS braces and tested to provide average values for the actual material properties (Table 1). The nominal diameter-to-thickness ratios, $D/t$, are chosen to fall either below the code prescribed limit for highly ductile bracing members or between the highly ductile and moderately ductile limits as defined in the 2016 AISC Seismic Provisions [9]. The limiting $D/t$ ratios for moderately ductile and highly ductile members are 32.1 and 27.4, respectively, assuming nominal properties.
Table 1. Brace properties

<table>
<thead>
<tr>
<th>Bracing member</th>
<th>Diameter $D$ (mm)</th>
<th>Thickness $t$ (mm)</th>
<th>Length $L$ (mm)</th>
<th>Diameter-to-thickness ratio $D/t$</th>
<th>Slenderness ratio $\lambda$</th>
<th>$F_{y,measured}$ (MPa)</th>
<th>$F_{u,measured}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UB8932</td>
<td>89.1</td>
<td>3.2</td>
<td>1575</td>
<td>27.8</td>
<td>70.1</td>
<td>382</td>
<td>464</td>
</tr>
<tr>
<td>FB8932</td>
<td>89.1</td>
<td>3.2</td>
<td>1575</td>
<td>27.8</td>
<td>70.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UB11445</td>
<td>114.3</td>
<td>4.5</td>
<td>1575</td>
<td>27.8</td>
<td>54.8</td>
<td>344</td>
<td>411</td>
</tr>
<tr>
<td>FB11445</td>
<td>114.3</td>
<td>4.5</td>
<td>1575</td>
<td>25.4</td>
<td>54.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^{[a]}$ $\lambda$ is calculated using pin to pin distance

Fig. 1 provides a schematic of the test setup and a typical cross-section of a foam filled brace. The entire lengths of the filled braces are filled with the liquid foam poured through a 24 mm diameter hole in the center of the top endplate prior to expanding and solidifying. Cross sections taken from the foam filled braces after testing revealed that few voids occurred during the filling process and a considerable bond is achieved between the polyurethane foam and the steel.

All of the braces are tested in a four-pin frame and are oriented at a 45° angle with respect to the bottom wide flange beam. Endplates welded to the CHS brace are bolted to mechanical pin connections using high strength bolts so as to provide a moment free end condition. The pin connections are configured to only allow the braces to buckle in the plane of the frame. The loading protocol (Fig. 2) consists of two cycles each to 0.1, 0.25, 0.5, 0.75, 1, 1.5, 2, 3, and 4% story drift until brace fracture occurs. Displacements are applied by a hydraulic jack and lateral load is measured using a load cell at the loading point. Brace contraction and elongation is measured using average measurements from linear displacement transducers located on either side of the frame along the brace length between the pins. Surface strains are measured by longitudinal strain gauges distributed along the brace with more strain gauges concentrated in the plastic hinge region.

Figure 1. Test setup and typical cross-section of a foam filled brace (units: millimeter)
The fill material used in this study is a pourable, expanding closed-cell polyurethane foam that is commonly used for flotation, insulation and void fill applications. The foam is a two-part liquid mixture that when combined in equal portions, expands to form a rigid solid that is approximately four times its liquid volume at ideal conditions. The expansion is temperature critical, with higher temperatures generally leading to greater expansion. The selected foam has a free rise density of 256 kg per m$^3$ (16 lb per ft$^3$). This foam density is chosen based on its ability to enhance energy dissipation and limit local buckling for three and four point bending tests [10].

To evaluate the behavior of the foam and assess its homogeneity, two foam specimens are extracted from F8932 and FB11445 at different sections along the length of the brace and are subjected to monotonic compressive loading using a 98 kN hydraulic uniaxial testing apparatus. The extracted foam is cut into 38.1 mm cubes and the compressive load is applied to the top and bottom of the cubes with flat plates. The cubes are loaded at a rate of 0.25 mm/s until a deformation level of 25.4 mm is achieved (67% strain). Average values of relevant mechanical properties are reported below in Table 2. As shown in Table 2, there is significant variation in the measured properties between the two bracing members. This finding suggests that the foam is sensitive to external factors such as how well the two liquid components are mixed and ambient temperature when the foam is poured. It should be noted that the foam properties from specimens extracted from FB11445 show less variability when compared to that of specimens extracted from F8932. This finding may be explained by the fact that only one pour was needed to fill FB11445 as opposed to two pours for F8932 due to differences in foam expansion.

Table 2. Polyurethane foam mechanical properties

<table>
<thead>
<tr>
<th>Bracing member</th>
<th>Tested (Average)</th>
<th>Reported*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Elastic modulus</td>
<td>Compressive yield strength</td>
</tr>
<tr>
<td>FB8932</td>
<td>117.0 (MPa)</td>
<td>1.9 (MPa)</td>
</tr>
<tr>
<td>FB11445</td>
<td>55.9 (MPa)</td>
<td>0.9 (MPa)</td>
</tr>
</tbody>
</table>

Experimental Results

Hysteretic curves of normalized lateral load versus story drift (based on the test setup) are shown in Fig. 3 for all four specimens, where the lateral load has been normalized by the lateral load causing initial yielding of the brace. The lateral load causing initial yielding is calculated considering the average elastic modulus and yield stress obtained from the tensile coupon specimens and the average yield strain from the brace tests. These values are then used to extract the corresponding lateral load when the average value of all strain gauges on the brace achieves the yield strain. In general, both filled and empty braces behave as conventional steel braces with asymmetric behavior in tension and compression. Yielding of the braces in tension provides stable energy dissipation, while brace buckling in compression is characterized by deterioration of strength and stiffness, subsequently leading to a reduction in energy dissipation.

In general, the brace behavior preceding fracture is similar for the filled and unfilled braces. Initially, all specimens undergo elastic deformation up to the 1st cycle of 0.5% story drift. Deformation in the specimens at this point is not visually observable. After yielding, in-plane global buckling follows soon after with each brace assuming the shape of a half sine-wave (Fig. 4a). Visual observations indicate that the overall buckling mode between filled and unfilled braces is essentially the same. Global buckling of all braces is characterized by large lateral deformations at the midpoint of the brace. Following global buckling of the braces a plastic hinge begins to form at the brace mid-length, with local buckles developing and becoming more pronounced with each successive compressive cycle (Fig. 4b). Soon after the initiation of local buckling, small cracks begin to form in the buckled region at the midpoint of the brace until fracture (Fig. 4c and 4d). It is observed that the presence of foam is able to delay the initiation of local buckling, thus leading to a prolonged brace fracture life.
Figure 4. Photographs of UB8932 upon (a) initial global buckling, (b) local buckling at the brace mid-length, (c) initiation of small cracks prior to fracture, and (d) fracture at the brace midpoint.

The normalized lateral force versus lateral displacement curves (Fig. 3) indicate the potential for incorporating foam fill into traditional seismic design practices. An advantage of the foam fill is that it does not significantly influence the elastic stiffness of the brace (within 2%) or the yield strength of the brace (within 3%) compared to the unfilled braces. These minimal differences suggest that traditional seismic design practices can be followed without having to explicitly consider the influence of foam fill on brace behavior.

Compression resistance envelopes obtained from normalized lateral force-drift plots are shown in Fig. 5. In general, this figure suggests that the presence of the foam improves the post-buckling response when compared to equivalent unfilled sections. Furthermore, it is interesting to note that the foam fill delayed the first instance of global buckling for the 114.3 mm diameter specimen (Fig. 5a). The unfilled 114.3 mm diameter brace undergoes global buckling during the first 0.5% drift cycle in compression leading to a significant decrease in capacity from 311 kN to 182 kN in the subsequent cycle. Meanwhile, the filled 114.3 mm diameter brace was able to maintain 92% of its maximum capacity out to the 1st compressive excursion to 0.75% story drift. This delay in global brace buckling is significant in that it prolongs the number of cycles prior to the initiation of local buckling. The empty brace also exhibits a 41% reduction in post-buckling compressive capacity with the subsequent cycle as opposed to a 31% reduction for the filled brace.

For the 89.1 mm diameter brace (Fig. 5b), the foam fill is not able to delay global buckling, but does lead to a small decrease in the degradation of the capacity of the brace. The post-buckling compressive capacity decreases by 56% for the empty brace compared to 49% for the filled brace. This difference in capacity is maintained until the initiation of local buckling in the filled brace during the 1st compressive excursion to 2% story drift. The larger difference in compression resistance for the 89.1 mm diameter braces when compared to that of the 114.3 mm diameter braces is likely due to the larger slenderness ratio of the smaller diameter braces (70.1 as opposed to 54.8). As with the 114.3 mm diameter specimen, once local buckling initiates, no significant difference is seen between the capacity of the filled and unfilled braces with subsequent cycles. However, for both specimens the presence of the fill allows for one additional cycle prior to fracture.
Figure 5. Compression resistance envelopes for (a) 114.3 mm diameter specimens and (b) 89.1 mm diameter specimens

**Foam Influence**

The $D/t$ ratio, 27.8, for the 89.1 mm diameter braces falls between the moderately ductile and highly ductile limits, 32.1 and 27.4, respectively, for the walls of round HSS, while the $D/t$ ratio, 25.4, for the 114.3 mm diameter braces falls below the highly ductile limit according to the 2016 AISC Seismic Provisions [9]. At these two diameter-to-wall thickness ratios, the influence of the foam fill on the brace behavior is substantial with respect to its ability to reduce the severity of local buckling and alter the local buckling mode. Local buckling in both sizes of the unfilled braces initiates during the second compressive excursion to 1.5% story drift and occurs at the midpoint of the brace, whereas for the filled braces local buckling is delayed until the 1st compressive excursion to 2% story drift. Furthermore, the foam is able to considerably reduce the severity of the local buckle, which limits the amount of local deformation the steel undergoes with each subsequent cycle leading to a delay in when the brace fractures. Fig. 6 provides photographs showing the severity of the local buckle for the 114.3 diameter unfilled and filled brace upon initiation of local buckling. The buckling in the unfilled brace is characterized by an inward indentation in the compression region, while the filled brace has two subtle wave-like indentations that protrude outward. This outward buckled shape in the foam filled member reduces the strain demands on the brace by dispersing the strain over a longer wavelength, consequently leading to an increase in fracture life. The filled braces fractured during the 1st tensile excursion to 4% story drift, while the unfilled braces fractured during the 2nd tensile excursion to 3% story drift. It is of interest to note that with continued cycling after the initiation of local buckling, the buckling pattern of FB11445 changes from outward to inward during the 1st compressive excursion to 3.0% story drift. The local buckle shape changes to resemble the shape typically seen in hollow specimens. This can be attributed to crushing of the foam as the brace begins to undergo larger lateral deformation and plastic rotation at the brace midpoint with an increase in drift level.
Fig. 6 (a) Local buckling after the second compressive excursion to 1.5% story drift (UB11445) and (b) local buckling after the first compressive excursion to 2.0% story drift (FB11445)

Fig. 7 provides the local buckle shape for the unfilled and filled 89.1 mm diameter brace at 2.0% story drift when local buckling first initiates for the filled brace. Visual observation confirms that there is a significant reduction in the severity of the buckled shape for the filled brace (Fig. 7b). Unlike the unfilled brace in which local buckling is characterized by a short inward half wave (Fig. 7a), the filled brace exhibits outward buckling that is less pronounced and has a smoother wave form. In contrast to FB11445, as the number of loading cycles increases, the buckled shape in FB8932 exhibits a combination of inward and outward buckling with inward buckling occurring where the foam has crushed. It is also of interest to note that the locally buckled region is shifted approximately 104 mm from the brace midpoint (identified by the welded stud). This is likely due to some non-homogeneity of the foam along the length of the brace.

Strain gauge data is also able to capture the beneficial effect of the foam fill. The strain gauges are located at quarter points along the brace circumference with four bands of gauges concentrated in the plastic hinge region at a spacing of 125 mm along the brace length, while a band of strain gauges also is located 125 mm from the face of each welded endplate. Figure 8a shows the strain variation after both braces have yielded and before the onset of local buckling. The strain is concentrated at the mid-length of the braces in the plastic hinge region with a notable reduction in strain for the filled brace. This marked reduction in strain can be attributed to the foam’s ability to delay the accumulation and concentration of strain that leads to fracture.
initiation. Similarly, in Fig. 8b, it is evident that the strain in the plastic hinge region for the filled brace is slightly smaller than that of the unfilled brace. The smaller discrepancy in the strain distribution for this section size when compared to the other larger section sizes can be attributed to the fact that both braces are still transitioning out of the elastic regime, thus a significant difference in strain is not expected.

Figure 8. (a) Strain distribution at the 2nd compressive cycle of 0.5% story drift for the 114.3 mm diameter specimens and (b) at 0.25% story drift during the 1st compressive excursion to 0.5% story drift for the 89.1 mm diameter specimens

Cumulative energy dissipated at each cycle of loading is presented in Fig. 9. Energy dissipation is calculated as the area enclosed by the lateral force versus displacement hysteresis loops for each full cycle of loading. For both section sizes the cumulative energy dissipated for the unfilled and filled specimens is nearly equal until the 2nd cycle to 1.5% story drift, which is where the initiation of local buckling occurred for both unfilled braces. After this cycle, the filled braces provide a consistent increase in cumulative dissipated energy in comparison with their equivalent unfilled brace. More specifically, both sizes of filled braces show an increase of 26% to 27% in the cumulative dissipated energy when compared to their unfilled counterpart. These large differences in dissipated energy can be attributed to the fact that the filled braces are able to undergo one more complete cycle of loading prior to fracture compared to the unfilled braces and that the foam fill provides enhanced energy dissipation by reducing local deformation.

Figure 9. Cumulative energy dissipation at each full cycle of loading for (a) 114.3 mm diameter specimens and (b) 89.1 mm diameter specimens
Conclusions

This paper presents results and observations from an experimental test program carried out on hollow and foam filled bracing members with the intent of evaluating the influence of foam infill on brace behavior. The results suggest that the expanding polyurethane foam is able to delay the initiation of local buckling in the plastic hinge region, thus providing increased ductility and energy absorption capacity. Future experimental testing and numerical simulations will consider a more comprehensive set of diameter-to-thickness and global slenderness ratios (larger than considered herein) to better characterize the influence of foam infill on brace behavior and determine the ability to expand current element slenderness limits when foam infill is present.

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