EXPERIMENTAL AND NUMERICAL COMPRESSIVE TESTING OF ALUMINUM FOAM FILLED MILD STEEL TUBULAR HAT SECTIONS

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Abbreviations:

CAD	- computer aided drawing
CPU	- central processing unit
FE	- finite element
HSLA	- high strength low alloy

Keywords: Aluminum Foam, Hat Sections, Compressive Testing

ABSTRACT

This research deals with the experimental and numerical testing of aluminum foam filled mild steel tubular hat sections under axial compression conditions. The presence of aluminum foam within the tubular hat section provides a means of stabilizing the buckling process of the tube under axial compression. This method of applying internal support allows for a greater number of folds to be observed in the axial crushing of the hat sections and hence an increase in the energy absorption of the tube filled with aluminum foam, compared to a regular hat section without the presence of metallic foam.

Experimental testing was conducted on mild steel tubular hat sections with and without the presences of aluminum foam within the tube. Load/displacement curves were developed from the experimental tests and integrated to determine the energy absorption capabilities of the tubular hat sections and the influence of the metallic foam. Finite element simulations, using LS-DYNA, were conducted on numerical models of the experimental testing procedure. An acceptable engineering correlation between the experimental and numerical testing methods was observed. This paper will present and compare the experimental and numerical observations from the compressive tests and also provide information on the energy absorption capacity of the tubular hat sections.

INTRODUCTION

A number of researchers (for example see [1] and [2]) have investigated the axial crushing of tubular structures under static and dynamic loading conditions. These structures exhibit excellent stroke efficiencies and specific energy ratios as energy absorbers. Furthermore, they are generally inexpensive and can be easily implemented into designs which require energy absorption. One of the important concerns in utilizing tubular structures as energy absorbers is the peak load which must be applied to initiate the buckling of the tubes. Often geometrical discontinuities are added to the tubular structures as "buckling initiators" to cause the buckling process to occur at lower applied loads.

As well, researchers (for example [3], [4], and [5]) have also studied axial crushing on aluminum foam filled tubes and concluded that inclusion of the metallic foam significantly enhances the energy absorption characteristics of the foam filled tubular structures. The foam material internally stabilizes the plastic buckling process of the tube and thus provides support for the tube and increases the number of folds and energy absorption of the tube.

This paper discusses some of the experimental and numerical work conducted by the authors in investigating the axial crushing of mild steel tubular hat sections filled with aluminum foam with densities less than 400 kg/m^3. Qualitative and quantitative observations are presented for both experimental and numerical testing methods and a comparison on the energy absorption capabilities of the tubular sections with and without foam is presented.

APPROACH

Experimental Testing Method

Axial crush testing was performed on hat-section tubes using an Instron machine in quasi-static conditions. In addition to an empty tube, tubes containing various densities of aluminum foam were also tested. Due to complexities in maintaining an exact foam density during manufacturing, it is difficult to obtain consistent densities among samples so variations in the foam densities were encountered and five different aluminum foam core regions of the hat sections were developed. The densities of the metallic foam cores were 190 kg/m^3 (7% aluminum foam), 200 kg/m^3 (7.4% aluminum foam), 230 kg/m^3 (8.5% aluminum foam), 270 kg/m^3 (10% aluminum foam), and 337 kg/m^3 (12.5% aluminum foam). The cores were placed within the spot welded hat section tubes. An adhesive was placed around the surfaces of the aluminum foam which was in contact with both the mild steel hat section and the metallic foam. A slight heat treatment was required to cure the adhesive and ensure a good bond between the aluminum foam and mild steel existed. A high strength low alloy steel was selected as the material for the hat section and material properties of the HSLA steel were provided by Stelco.

Front and top views illustrating the geometry of the hat section is presented in Figure 1. The total height of the tube was 300 mm and the approximate cross-sectional area available for aluminum foam was 51 mm by 87 mm. Twelve spotwelds were used to join the curved and flat sections of the tubular structure.

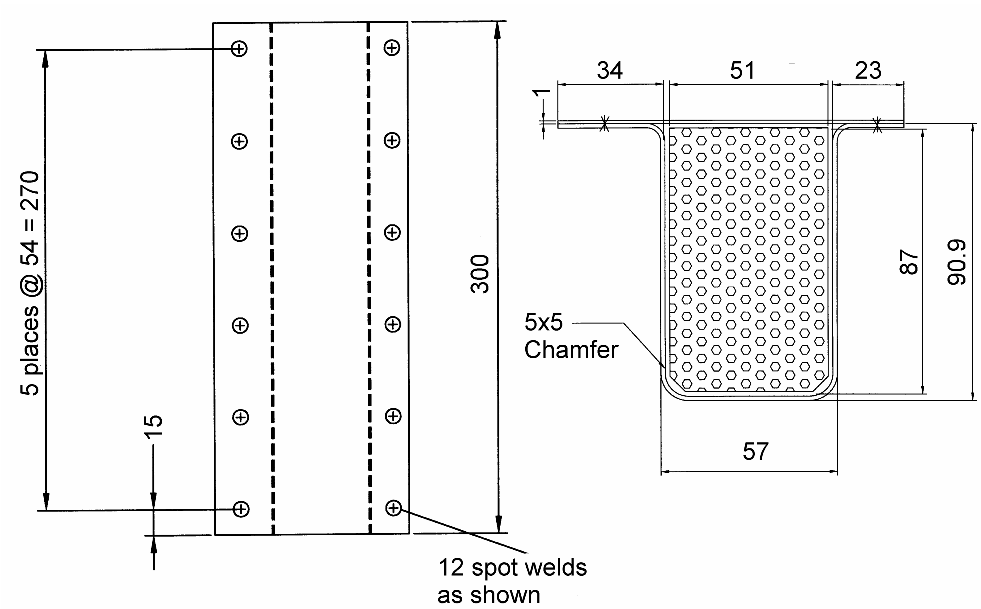

Figure 1. Hat section geometry (all dimensions are in mm).

Experimental observations are presented in the form of a load versus displacement curve and this curve is integrated to obtain energy versus displacement. The influence of the presence of the aluminum foam on the energy absorbed by the tubular structure during the crushing is an important aspect of this investigation. Furthermore, changes in the loading profile and the general deformation of the tubular hat section is also an important consideration.

Finite Element Model Development and Simulation

From the hat section geometry a CAD model of the tubular structure was developed and used to discretize the geometry into a finite element (FE) model using FEMB. 17930 quadrilateral shell elements were utilized for the hat section. This included the bent region and the straight section which, when welded together, forms the tubular hat section. 12 numerical spot welds were used to model the physical spot welds. Since the location of the numerical spot welds are dependent upon nodal positions, nodes as close as possible to the actual spot weld positions were selected and used to constrain the motion of these selected nodes using the CONSTRAINED_SPOTWELD keyword command in LS-DYNA. Failure of the spot welds was not considered, however, experimental verification of this assumption was required. A large number of shell elements were required for the hat section to ensure that an acceptable mode of deformation was achieved during the crushing process.

The aluminum foam core was modeled using 39648 hexahedron solid elements from the geometry provided. Similar to the tubular hat section FE model, a large number of elements were used to extensively discretize the aluminum foam core in an effort to properly reproduce the deformation experienced by the metallic foam core.

A stationary rigid wall definition was utilized as a method of supporting the hat sections during the crushing process and a rigid plate (developed from 400 shell elements employing a rigid material model) was modeled as the moving crosshead with a prescribed downward motion. The displacement of the numerical rigid plate was prescribed at a considerably high rate than was conducted experimentally, however, rate effects were not considered and it is assumed that inertial effects are insignificant.

To qualitatively illustrate the effects of filling the hat section with aluminum foam, both non-filled and filled tubular sections were modeled side by side and the crushing process for both structures was considered during the same simulation. An illustration of the FE model of both filled and non-filled tube geometries is provided in Figure 2 (the rigid crosshead plates have been removed).

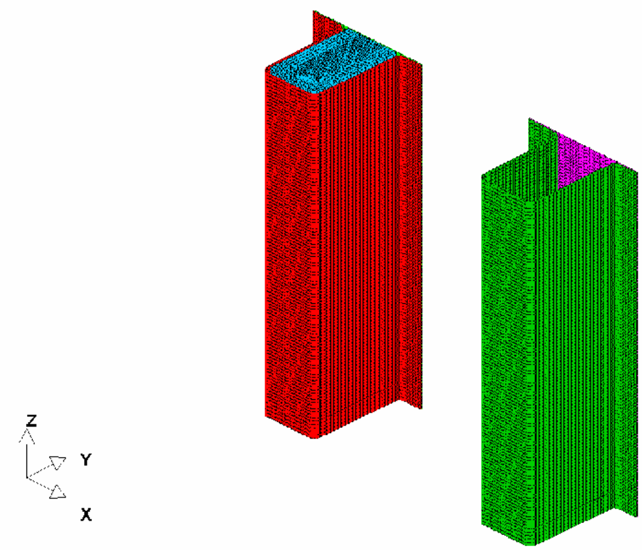

Figure 2. FE model of filled and non-filled hat sections.

The element formulation selected for the mild steel hat section was the Belytschko-Tsay shell element and a piecewise linear plasticity model (material type 24) was utilized to describe the material behaviour of the HSLA steel. Rate effects were not considered in the steel.

A 1 point corotational solid element formulation (solid element formulation 0) was selected for the aluminum foam. This formulation is applicable only to *MAT_MODIFIED_HONEYCOMB and in this element formulation the local (element) coordinate system follows the element rotations and is preferred for simulations in which the material is fixed in space [6]. As previously indicated, material type 126 was utilized for the aluminum foam and an engineering stress/strain curve under axial compression was utilized for determination of the material properties needed for input in the material model. A stress/strain curve for a 405 kg/m^3 aluminum foam density was available and utilized in the material model. The yield condition under shear stress/shear strain behaviour was assumed to be one-half of the yield condition under normal stress/normal strain conditions. This assumption has been previously validated based upon past results which the authors have found from previous material characterization investigations.

Contact was modeled using three different algorithms for the unfilled foam hat section. The first contact algorithm was used to model interactions between the moving crosshead plate and the hat section (CONTACT_AUTOMATIC_NODES_TO_SURFACE). The second contact algorithm was utilized to numerically model contact between the entire hat section on to itself. This was accomplished using the CONTACT_AUTOMATIC_SINGLE_SURFACE keyword command. Finally a stationary rigidwall definition was used to model contact between the hat section and the stationary crosshead support. For the hat section filled with aluminum foam three similar numerical contact schemes were employed, however, an additional contact algorithm to model the adhesive was utilized. Based upon experimental tests conducted to determine the strength of the adhesive in normal and shear loading conditions the adhesive added little or no structural support to the system. A trial simulation utilizing a TIEBREAK contact option was conducted and little or no differences in simulation results was observed. An increase in CPU time was experienced and hence the TIEBREAK option was omitted in further simulations. To model contact between the metallic foam and the HSLA hat section steel the part identification number for the aluminum foam was added to the segments considered in the CONTACT_AUTOMATIC_SINGLE_SURFACE algorithm.

DISCUSSION OF RESULTS

In an effort to compare the experimental and numerical results directly, experimental observations from the hat section filled with 337 kg/m^3 (12.5% aluminum foam) density foam were compared to the numerical model which contained an aluminum foam with approximate density of 405 kg/m^3 (15% aluminum foam) as this was the only material model available for the aluminum foam. Material information for the other density foams was not available for utilization in the numerical material model.

Experimental Testing Results

The experimental testing of the hat sections illustrated that the presence of the aluminum foam significantly increase the stability of the buckling process (folding of the hat section side walls after elastic buckling has occurred). Three photographs illustrating the deformation shapes of the filled and unfilled hat sections are provided in Figure 3 to Figure 5. In these illustrations the 337 kg/m^3 (12.5% aluminum foam) density foam was enclosed within the hat section.

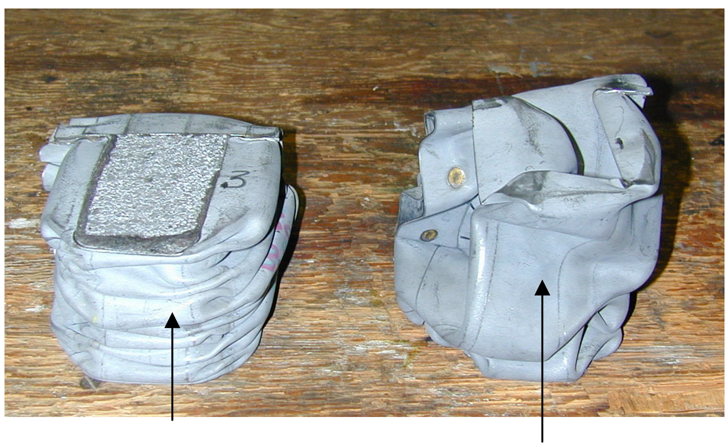

Figure 3. Front view of experimental specimens.

Figure 4. Side view of test specimens.

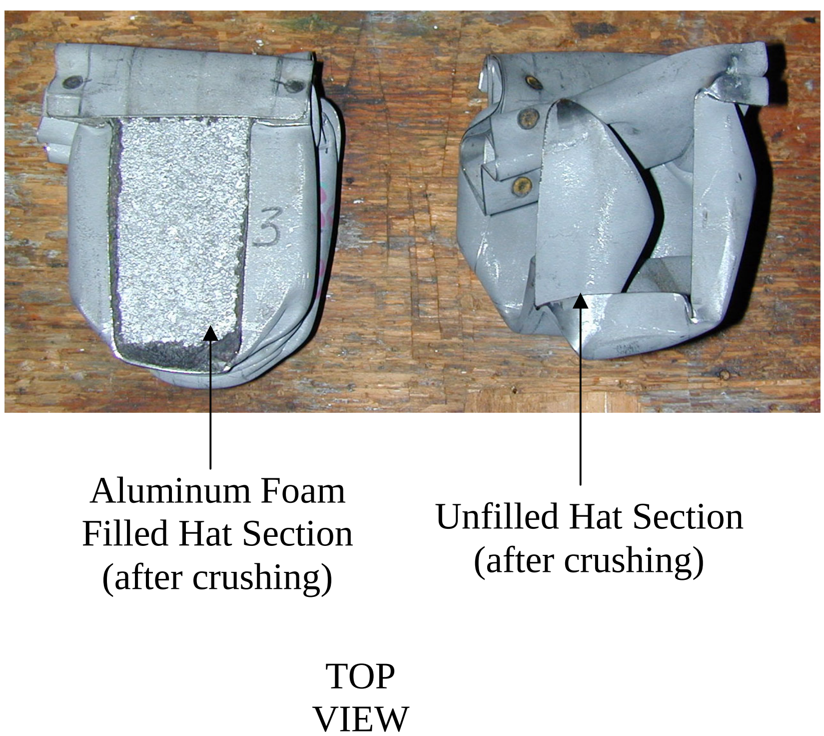

Figure 5. Top view of test specimens.

Based up experimental observations it was estimated that approximately 11 folds were found to occur for the aluminum foam filled hat section while only approximately half the number of folds was observed on the unfilled hat section. Since the number of folds in related to the energy absorption characteristics of the structure it is expected that the foam filled hat section will exhibit greater energy absorption. Furthermore, little or no failure of the spot welds was observed in any of the experimental tests. Hence the assumption that the spot welds would not fail was valid.

The testing equipment also provided load versus displacement curves during the crushing of the test specimens. These curves will be presented in the *Experimental / Numerical Comparison* section.

Finite Element Simulation Results

Figure 6 through Figure 8 illustrate the deformation predicted by LS-DYNA in the crushing of the filled and unfilled hat sections. Although the deformation is not identical to the experimental findings, there is a strong relationship between the numerical and experimental results based upon these illustrations (and those illustrations already presented). The number of folds predicted by LS-DYNA is very similar to the deformations found experimentally. Qualitatively the deformation shapes of both the unfilled and aluminum foam filled hat sections are very similar. Figures 6 through 8 illustrate the hat section with 405 kg/m^3 aluminum foam density.

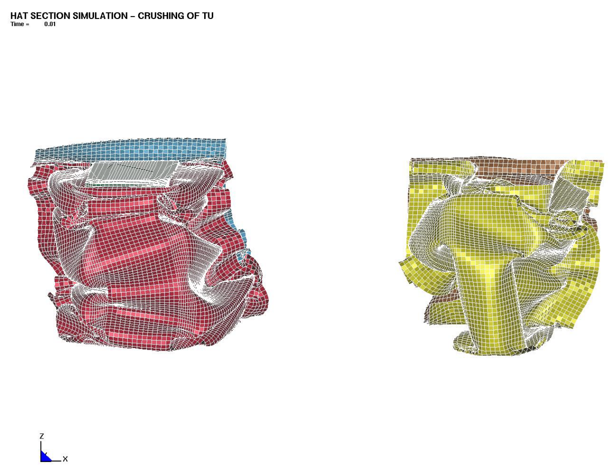

Figure 6. Front view of the deformation predicted by LS-DYNA.

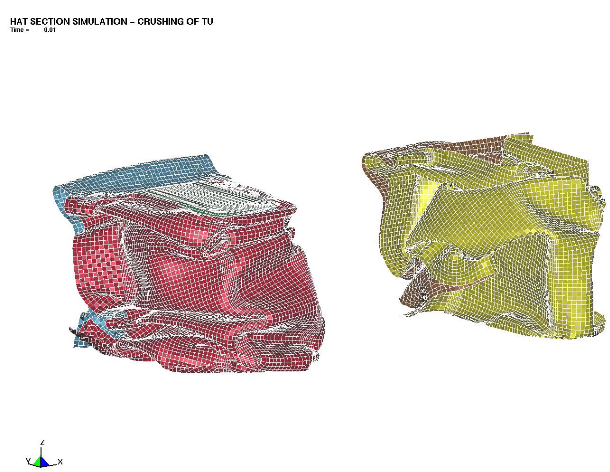

Figure 7. Frontal/Side view of the deformation predicted by LS-DYNA.

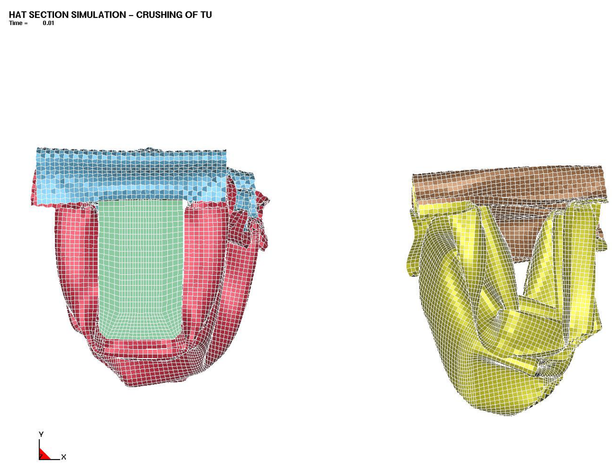

Figure 8. Top view of the deformation predicted by LS-DYNA.

Experimental / Numerical Comparison

Since an acceptable qualitative comparison between the experimental and numerical results was observed, comparison of the load versus displacement curves for both the unfilled and filled hat sections was completed between the experimental testing results (337 kg/m^3 aluminum foam density) and numerical simulation (405 kg/m^3 aluminum foam density) observations. Furthermore, the energy absorbed by the hat shaped structure was also determined through integration of the load versus displacement profile. Figure 9 and Figure 10 present the load/displacement and energy absorbed/displacement curves respectively.

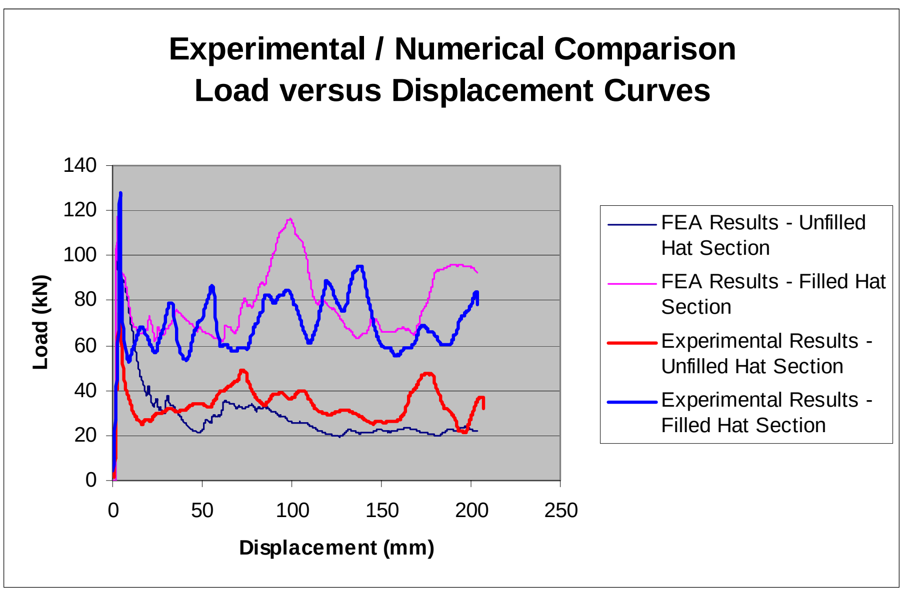

Figure 9. Load versus displacement curves for both experimental and numerical tests.

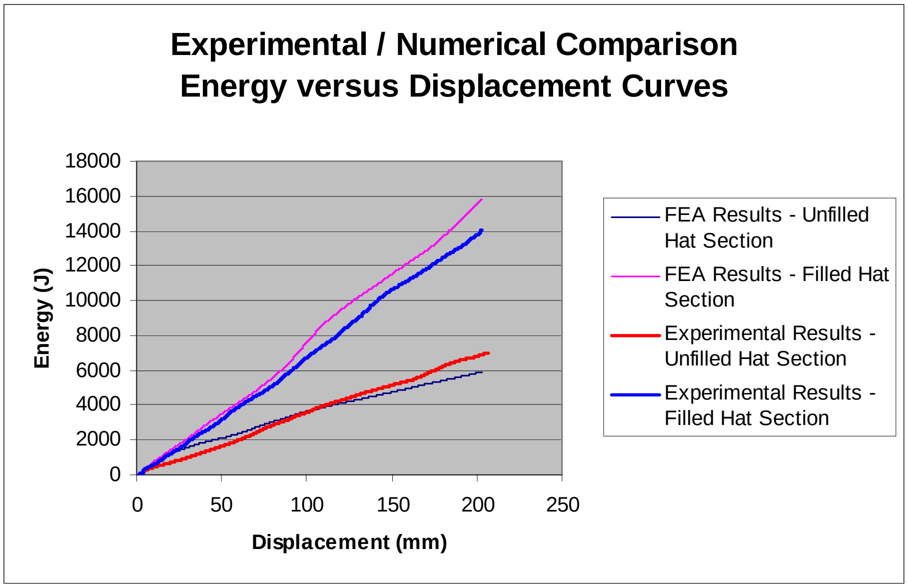

Figure 10. Energy absorbed versus displacement curves for both experimental and numerical tests.

Comparisons made between experimental and numerical tests (from Figures 9 and 10) illustrate that the load/displacement profile is somewhat similar for both the unfilled and filled aluminum foam hat sections. For the foam filled structure the loading magnitude is to some extent over predicted, especially within the 75mm to 125mm deflection range and at large deformation (displacements greater than 175mm). Through the mathematical operation of integration, the variation in the experimental/numerical results is not as significant and the energy absorbed versus displacement curves illustrate an acceptable engineering correlation.

It is observed that with the addition of foam into the hat sections the load profile is significantly increased (approximately twice as large as the unfilled hat sections). Furthermore, the energy absorbed by the hat structure is also approximately 2 to 3 times larger than the energy absorbed by the unfilled hat section. These observations are more predominate at larger deformations.

These results should be expected as the presence of aluminum foam within the hat section significantly increases the internal stability of the hat section during the plastic buckling process. The increase in stability results in a larger number of folds being produced and hence a significantly larger amount of energy absorbed in the crushing process.

CONCLUSIONS AND SUMMARY

Experimental and numerical compressive testing of unfilled and aluminum foam filled hat sections were conducted within this investigation. Comparisons of load/displacement and energy absorbed/displacement curves illustrated an acceptable engineering correlation between experimental findings and LS-DYNA simulation results.

Generally, the plastic crushing load for the numerical foam filled tubular structure was over predicting the results found experimentally, this may be attributed to differences in the deformation shape of the tubes as well as the variation in the foam density used in the numerical model (which had a slightly higher foam density (15% aluminum) than the experimental test specimen (12.5% aluminum)). The load profile for the numerical model of the unfilled tubular structure generally under predicted experimental observations, although results were generally considerably closer than differences found with the foam filled hat section.

Based upon both experimental and numerical observations the inclusion of foam within the tubular structure increased the plastic buckling load by a magnitude of approximately two. Similar increases on the energy absorbed were also noticed for the foam filled hat section. These results were found to occur in both the experimental tests and numerical simulations.

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