Crushing Behavior of Foam Filled Steel Extrusion

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ABSTRACT

The concern of vehicle structural integrity and safety is given highly considerable amount of research and development by engineers and scientist world wide. Weight reduction of structures without compromising the structural durability is the important aspect because weight is strongly related to fuel consumption. In this work, rigid polyurethane foam is used to fill into steel extrusions. Different foam density is used to reinforce the steel tubes and at the same time different steel wall thickness also adopted to study the crushing behavior under quasi-static compression loading loaded at different angles. Force versus displacement of each column condition is recorded automatically, compared and analyzed. The area under the curve represent the energy absorbed by the column and the column length is properly designed to prevent buckling which will be resulted catastrophic failure leading to low energy absorption capability. Then, the final crushed columns are analyzed to study the correlation with the crushing characteristics. It is found that the energy absorption increased when increasing the foam density but when the tube wall reached a maximum thickness, the foam density no longer affected to increase the energy absorption.

Keywords: *Energy absorption, foam-filled tubes, oblique compression loading, polyurethane foam*

Introduction

Structural crashworthiness becomes an essential requirement in the design of automobiles, rail cars and aerospace application. In the last two decades, many investigators have studied the axial crush behavior of thin-walled metallic tubes as well as composite tubes (Babbage & Mallick, 2005). Particularly polymeric foam filled composite panels are widely being considered these days for structural use in aircrafts and satellites, and functional use in automotive bumpers, roofs and door beams for improving the crashworthiness of vehicles which will ultimately reduce the damage of the vehicles and increase safety of the passengers during crushing. Industrial production of foamed metals is now established for applications like sandwich structures, panels, foam-filled crash absorbers, heat exchangers and so on (Meguid et al., 1999).

Research into the collapse of thin-walled sections filled with foam fillers was first investigated by Thornton (1980). He conducted quasi-static and dynamic axial compression tests for polyurethane foam-filled thin walled sections. He pointed out that noticeable increase in specific energy absorption (SEA) is possible with using thin sections made of high-density low-strength alloys such as mild steel. Similar findings were reached by Lampinen and Jeryan (1982), who also investigated the effects of cross section geometry on the energy absorption characteristics. The crushing loads of foam filled tubes are therefore found to be higher than the sum of the crushing loads of foam (alone) and tube (alone) mainly due to this effect. Studies on crushing behavior of the honeycomb and foam filled box columns also showed that the effect of filling on the column crushing load was similar when the strong axis of honeycomb was through and normal to the compression axis, proving that both axial and transverse strength of the filler were effective in increasing the crushing load of filled tube (Hanssen et al.,2000).

Literature Review

Much type of energy absorbing devices and structures are currently used ranging from metallic and composite materials. Each type of materials has their own advantages and disadvantages. In the last two decades, foam-filled structures are given much attention in research and development to be used in the crashworthiness applications. Polymeric foam is one of the candidates because of their specific strength and stiffness in addition of their capability to absorb energy in collision condition. Polymeric foam-filled tubes or structures have been introduced in the automotive applications to reduce the overall weight of the vehicle and improve fuel economy. However, this structure must be designed carefully so that they can absorb energy in a controlled manner, bringing the passenger compartment to rest without exposing the passengers to high acceleration or deceleration levels that may cause serious injuries [2]. Of Particular interest to this study is the use of structural foams in automotive components. Foam is currently being used as a filler material in bumper and as reinforcement in roof and door beams. Foam has been the subject of numerous experimental and numerical and theoretical investigations. Baumeister *et al.* [3] emphasize the integration of foam materials in the automotive body structure for energy absorption. Sugimura *et al.* [4] and Grenestedt [5] assessed the role of cell morphology and imperfections in governing the basic properties of foams such as stiffness, yield strength and fracture resistance. Ford and Gibson [6] developed microstructural models to examine the mechanisms responsible for differences in tensile and compressive strength observed in cellular materials. Cheon S.S and Megid S.A [7] proposed a modified and representative unit cell model employed to study the crush behaviour of closed cell foam.

Methods and Materials

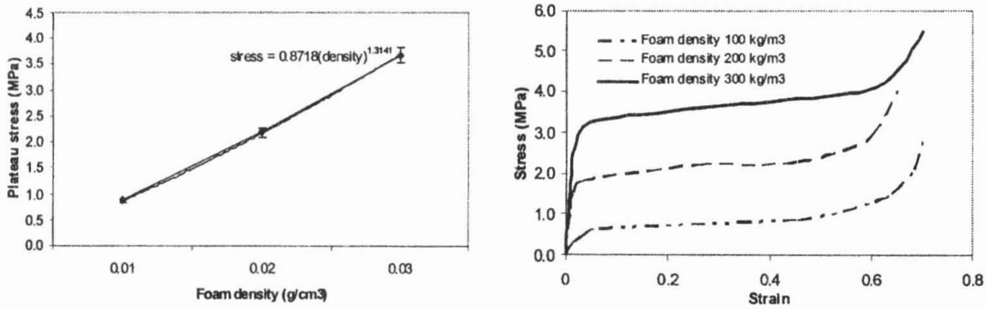
Foam-filled tubes are produced by filling polyurethane foam into steel extrusions. The rigid polyurethane foam is produced by mixing the liquids of polyol and isocynate. The mixture is mechanically stirred at constant speed 10rpm and then the mixture is poured into the tubes immediately and special attention is given so that no pressure formed during the foaming process is lost for this purpose both ends of the tubes are tightly closed where silicon rubber is used to seal at contact interface between flat plates and the end of the tubes. 200mm tube length is selected to avoid buckling results low energy absorption. After half an hour, mechanical clamps are removed and the foam-filled steel tubes are quasi-statically compressed at constant cross-head displacement 1.5mm/min. Force versus displacement is recorded automatically and can be obtained in-real time from the computer. Then the fluctuated compression forces are smoothened or averaged in order to obtain the mean crush force. This force is then multiplied with crushed distance and it is represented the performance of energy absorbed by the foam-filled steel tubes. The progressive collapses of the foam-filled tubes are monitored to study the localized buckling of the tube wall and the final crushed shapes are only presented in this paper.

Results and Discussion

Figure 1 shows the compression behavior of the rigid polyurethane foams under quasi-static compression forces. Figure 1a reveals that the compression response of the foam increased with increasing the foam density. Three distinct regions can be found, (i) the first region is the linear elastic deformation where the foam deformed elastically as increasing compression force, (ii) the second region is the plateau region where the foam deformed plastically without showing force increments, in this region, wall of the foam elastically deformed and progressively collapse downward as increasing compressive forces and lastly (iii) the densification region is the region when the force is steeply increased, this is due to all the wall of the foams are totally collapse or densified therefore very small foam deformation occurred for a large amount of compressive loadings. Figure 1b shows the relationship between plateau stress with foam density. It is found that plateau stress is strongly related to foam density.

Table 1: Average Plateau Stress Values of Polymeric Foams

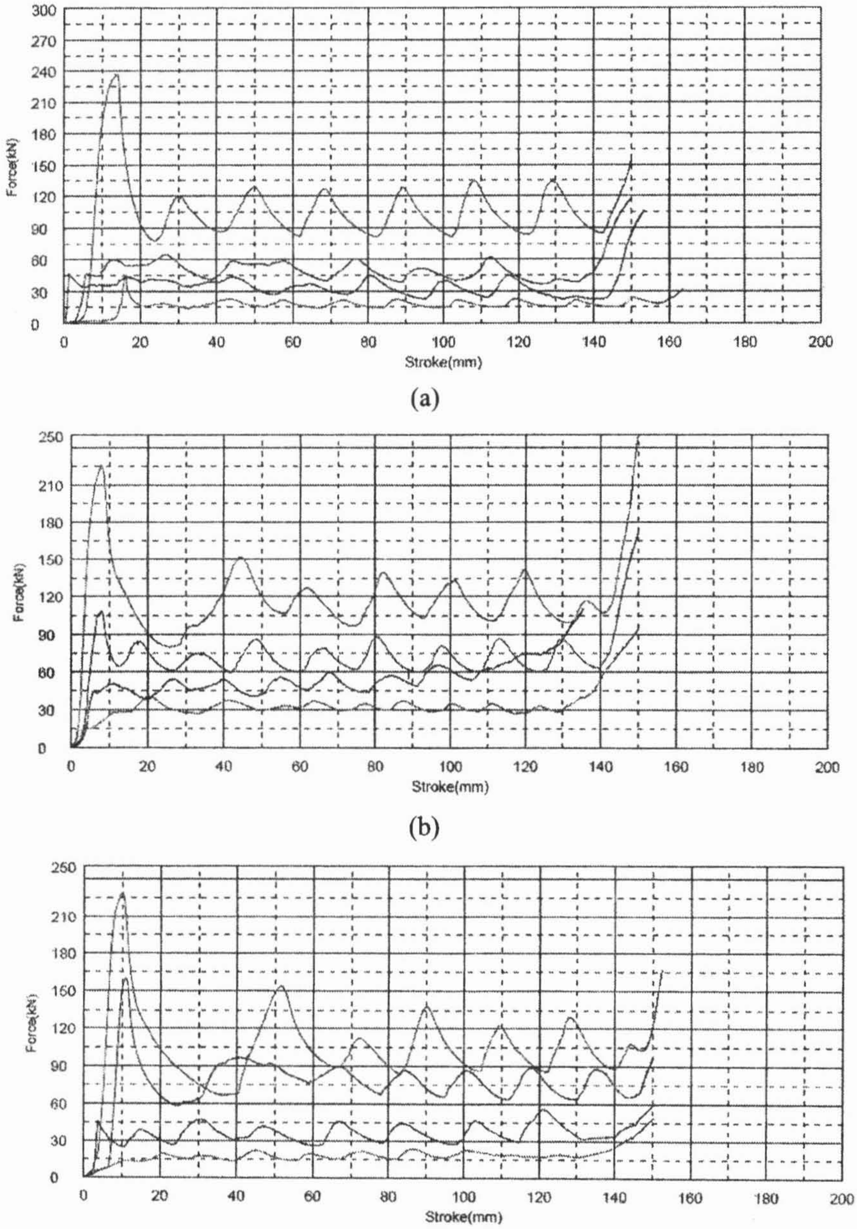
Foam density (kg/m^3)	Plateau stress (MPa)
100	0.87
200	2.18
300	3.68



(a) (b)

Figure 1: (a) Force versus Displacement of the Different Foam Densities and (b) The Relation between Plateau Stress and the Foam Density.

Force versus displacement diagram of the foam-filled steel extrusions compressed quasi-statically are shown in Figure 2. Three different regions clearly observed for the compressed structures and all the samples are progressive collapse downward as increasing compression loadings. Force fluctuation can be observed after the linear elastic deformation. This behavior is strongly related to the formation of localized plasticity around the tube wall then localized buckling occurred. The localization of the buckling responsible to create progressive collapse of the structures which is produced higher energy absorption of those structures (the area under the curve). When the thicknesses of the tubes are increased, the compression response of the foam-filled steel extrusion also increased. Figure 2a shows that there is no significant compression response for 1.0, 1.5 and 2.0mm wall tube thickness when filling 100kg/m^3 foam density. This is due to the fact that at this level of density can not be restrained the plastic deformation of the tube wall but when the foam density is increased as in Figures 2b and 2c, the response of force versus displacement of foam-filled tubes are also increased significantly. One of interest thing found in this work is for 3.0mm thick wall tube, filling polyurethane foam into the mentioned tubes does not change the compression response. From Figure 2 reveals that the peak force of the linear elastic deformation is unchanged. Figure 3 shows the final crushed foam-filled steel extrusions. Different numbers of lobes are observed for different foam density and wall thickness. For wall thickness less than 1.5mm, the number of lobes or wave length is about 5 while for thickness greater than 2.0mm the wave length is 4. This is the evidence to induce different force versus displacement response of the different wall thickness and foam filled into the tubes also contributed to the increment of energy absorption of the structures.



(c)

Figure 2: The effect of wall thickness on the force versus displacement response of the foam filled steel extrusions for (a) 100kg/m^3, (b) 200kg/m^3 and (c) 300kg/m^3.

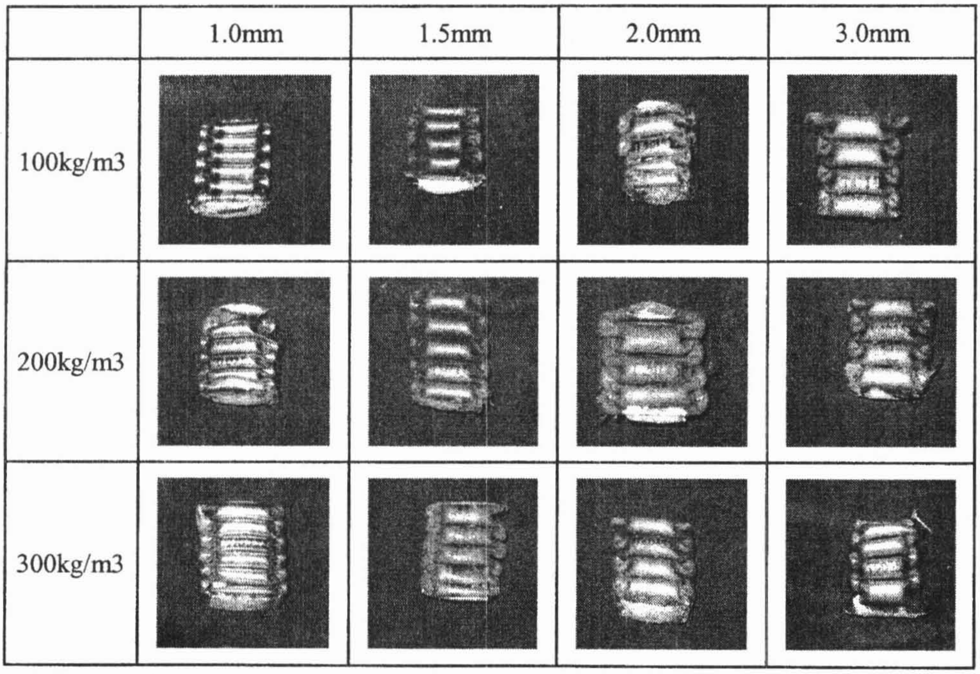


Figure 3: The Effect of Foam Densities and Wall Thicknesses on the Final Crushed Foam-Filled Steel Extrusions.

Conclusion

Quasi-static compression tests have been conducted to investigate the force versus displacement response of foam-filled steel extrusions. Different foam densities and wall thicknesses are used to produce foam-filled columns. It is found that the wall thickness played an important role in strengthening the steel extrusion under the compression loads and showing that the steel tubes capable to absorb more compression energy compared to thinner tubes. When a polyurethane rigid foam is filled into the steel extrusion, higher force versus displacement is observed especially for thinner wall tubes but for thicker tubes (3.0mm), the presence of foam inside the tubes do not significantly contributed to increase the compression response. For thinner wall thickness, foam constraint the plastic deformation of the tube wall very well consequently increased the compression forces. Different numbers of folding or wave length are observed for different wall thickness which is responsible to differentiate the compression response of the foam-filled steel extrusions.

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