International Journal of Engineering and Technology, Vol. 5, No. 1, 2008, pp. 11-24

ENERGY ABSORPTION OF FOAM-FILLED STEEL EXTRUSION UNDER QUASI-STATIC OBLIQUE LOADING

A. E Ismail
Faculty of Mechanical and Manufacturing Engineering, Tun Hussein Onn University of Malaysia,
Parit Raja, Batu Pahat, 86400 Johor, Malaysia
Email: emran@uthm.edu.my

ABSTRACT

The structures of the vehicle during the crushing processes or accidents are not only experienced directly or axially collisions but sometime these structures are crushed off-axially. Therefore, it is very crucial things to study whether or not a foam-filled column capable to support the oblique compression forces efficiently and effectively. In this work, polyurethane foams with different densities are filled into steel extrusion tubes. Foam densities used are 100, 200 and 300 kg/m^3*. High attentions are given during the process of fabricating the foam-filled structures due to high pressure resulted from the chemical reactions in order to minimize the pressure loss which interrupted the foaming processes. Different wall thicknesses are used ranging between 1.0 to 3.0mm. The foam-filled structures are compressed quasi-statically at constant cross-head displacement at 10mm/min. During the crushing process, all the structures are aligned obliquely at* 0°*,* 5°*,* 10° *and* 15°*. Experimental results showed that both foam density and wall thicknesses are the key factor in determining the crashworthiness behaviors but when the structures are exposed to the oblique loading, energy absorption capability decreased accordingly as loading angles increased. This decrement is due to high bending moment applied to the structures and it is also act as crush initiator and the introduction of oblique loading only affected in the region of elastic deformation but when the deformation reaches plastic region no significant effect is observed. All the structures are progressively collapse with different wave-length of the lobes. From the observation of sectioned samples used, there is good interaction between foam and wall observed for higher density polymeric foam resulted in higher energy absorption performances.*

Keywords*: foam-filled structures, polyurethane foam, energy absorption, crashworthiness, progressive collapse.*

INTRODUCTION

Vehicle crashworthiness has been improving in recent years with attention mainly directed towards reducing the impact of the crash on the passenger. Efforts has been spent in experimental research and in establishing safe theoretical design criteria on the mechanics of crumpling, providing to the engineers the ability to design vehicle structures so that the maximum amount of energy will dissipate while the material surrounding the passenger compartment is deformed thus protecting the people inside [1]. 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 and Megid [7] proposed a modified and representative unit cell model employed to study the crush behaviour of closed cell foam.

ISSN 1823-1039 ©2008 FEIIC

Currently, research into modelling the mechanical response of cellular solids is progressing on two fronts: (i) phenomenological models and (ii) unit-cell based models. Ford and Gibson [6] developed a skeletal unit-cell to model open-cell foams and implemented dimensional arguments to relate the strength and elastic constants of the unit-cell to its relative density. They extended this model to closed-cell foam and used it to identify the prominent modes of failure under multiaxial loads. Santonsa and Wierzbicki [8] developed a closed cell model for metallic foams, based on careful examination of the foam morphology. The theoretical solution was in agreement with the experimental findings and finite element simulations. Meguid *et al.* [9] modified the model in [11] to better reflect the morphological features of closed-cell aluminium foams, and implemented it to study the effects of three dimensional density gradients on the deformation patterns, crush behaviour, and energy absorption characteristics. The localization patterns and the normalised crush load–deformation curves were compared with in-plane and transverse crushing experiments and found to be in good agreement. Alexander [10], and Pugsley and Macaulay [11] presented the earliest analytical treatment of the quasi-static axial crushing of thin-walled cylinders for both symmetric and asymmetric modes of collapse. Their treatment is based on an idealised folding mechanism and rigid plastic material model and the work component necessary to form plastic hinges in the cylinder. Abramowicz and Jones [12, 13] enhanced Alexander's solution by considering the incremental variation in dissipated energy with varying circumferential strain rather than considering its mean value. They found reasonable agreement between the analytical results and experimental findings under quasi-static test conditions for a wide range of diameter-to-thickness ratios. Wierzbicki and Bhat [14] developed a moving hinge solution for the axisymmetric collapse mode during axial crushing of cylindrical tubes. This model allows the prediction of the complete load–displacement history. Grenestedt [5] implemented a strip method and the moving hinge solution to evaluate load displacement relations for both axisymmetric and asymmetric collapse modes and found good agreement between analytical and experimental results under quasi-static and dynamic conditions.

Most of the research mentioned above dealing with the axial energy absorption under quasi-static compression loads. Several of research publications have been found and the results are quite different from each others. Therefore, this paper attributes to study the energy absorption capabilities of foam-filled tubes under oblique compression forces. Different foam densities and wall thickness are used in this experiment. Constant cross-head displacement is used to compress the columns quasi-statically at 10mm/min. Force versus displacement curve for each column is recorded automatically and the energy absorption capability is determined and the final crushed columns are sectioned to study the foam and wall interactions and its relation with energy absorptions.

MATERIALS AND EXPERIMENTAL

Polymeric foam and foam-filled steel extrusion preparations.

The study was undertaken on a deep drawn 50 x 50 mm mild steel tube with a wall thickness of 1.0, 1.5, 2.0, 2.5 and 3.0 mm used in this study. Tables 1 and 2 show the typical mechanical properties and chemical compositions of steel used, respectively.

Table 1: Mechanical properties of steel used [7].

Ultimate tensile strength	Yield tensile strength	Elongation at break	Modulus of elasticity	Poisson's ratio	Density
420 MPa	350 MPa	15%	200 GPa	0.25	7.8 – 8.0 g/cc

Table 2: Chemical compositions of the steel used [15].

Carbon	Iron	Manganese	Phosphorous	Silicon	Sulfur
0.03 - 1.25 %	80.0-98.0 %	0.2 -16.0 %	< 0.0500 %	0.0 -0.5 %	<0.05 %

The tubes filled with polyurethane foams are 200 mm in length. Chosen tube lengths are mainly dictated to avoid buckling behaviour which would result lower energy absorption. Polyurethane foam was prepared using Polyol and Isocynate in the liquid forms. The foam liquids (Polyol and Isocynate) were mixed using 100:110 ratio, respectively and the liquid mixtures were poured into steel extrusion after mechanically stirred for 2 minutes at low stirring speed (20 rpm) in order to have homogenous cellular materials. After the mixture of polyol and isocynate is poured into the tubes, proper attention is given so that there is no pressure loss out of tubes. Both ends of the tubes are tightly fixed using mechanical clamping mechanisms and silicon rubber sealed around the interface between tube and clamp. If the pressure lost during the foaming process, the desired density is unobtainable. Three different densities were prepared; 100, 200 and 300 kg/m^3. The example of empty and foam-filled tubes produced is shown in Figures 1a and 1b.

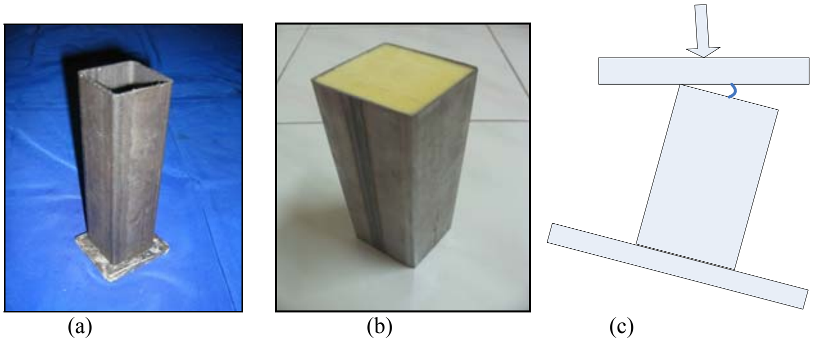

(a) (b) (c)

Figure 1: (a) Empty steel tubes, (b) foam-filled steel tubes used under this investigation and (c) experimental set-up for oblique compression force on foam-filled structures.

Microstructure

The microstructures of the foams are also observed for each foam density. It is very crucial thing to study the influence the foam morphology on the energy absorption capability. Scanning electron microscope (SEM) is used to observe the microstructures. Before the observation is conducted, the surface of the foam was coated by gold layer coating. This coating is conducted on the foam surface is to prevent electro charging which is interrupted the observation process.

Crushing test

Quasi-static compression tests on empty and filled tubes and foam samples were conducted using a controlled displacement SHIMADZU AG-I universal testing machine with a displacement rate of 1.0mm/min. Force-displacement curves for each sample were recorded automatically. Several different loading angles are used 0, 5, 10 and 15°. All the samples are aligned according to those angles as shown in Figure 1c. The corresponding average crushing loads (P_a) of the tested tubes were calculated using the equation (1). This is meant that the load fluctuated during the crushing process was smoothened by summing up minimum and maximum loads and dividing with the number of total points of maximum and minimum.

$$P_a = \frac{\int P ds}{\delta} \qquad (1)$$

Where P, P_a, δ and ds are the applied load, mean load, crushed distance and change in displacement along the force-displacement curve, respectively. The areas under the curves were calculated by multiplying average crushing load with crushed distances. The areas under the curves represent the energy absorbed during the crushing process. The energy absorption performance, E can be calculated using equation (2).

$$E = \int P ds \qquad (2)$$

Where E is energy absorbed by the structures, P is a applied force and ds is a small distance of the displacement along the force-displacement curve. Other crashworthiness parameter is also determined such as force ratio. Force ratio is very important to be considered because it is represent the force reduction just after linear elastic deformation. Higher force ratio indicates higher tendency of the column collapse catastrophically therefore inducing low energy absorbed by the column.

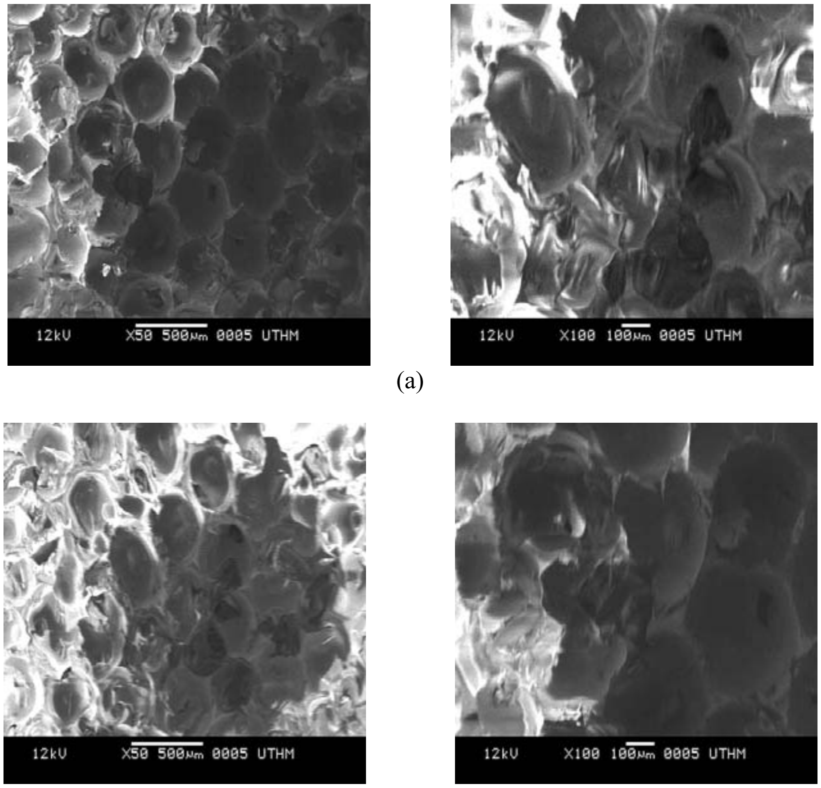
Crushing mechanism observation

In this observation, only final collapse mechanisms are presented to study the influence of tubes geometries and foam densities on the quasi-static energy absorption performance. The most important parameter in this observation is the formation of folding pattern with different wave length. The difference in the wave length of folding pattern determines the capability of the structures to absorb the crushed energy. The compressed tubes are also sectioned to examine the foam interaction with tube wall.

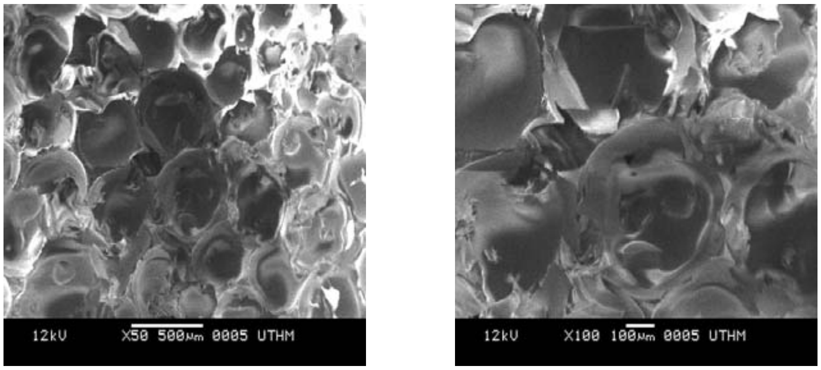
RESULTS AND DISCUSSION

Foam microstructures

Many cellular solids are excellent energy absorbers owing to their deformation at a nearly constant level over a wide range of strain [16]. Due to high porosity, foam in general can undergo large inelastic strain that include an initial linear elastic behavior, followed by a plasticity-like stress plateau where the foam cell starts to crush and finally a steep densification regime where the foam densifies rapidly. Therefore the observation of foam morphology is essential and important to study the effect of foam morphology on the energy absorption performances. Figure 2 shows the foam morphology for different foam densities. From the SEM observations, it is found that when the foam density increases, the size of the foam is increased and the shape of the foam also changes from irregular to regular geometries. All the foam morphologies are categorized as closed-foam cell. It can be predicted that the higher the porosity level of the foam, the more strain the specimen can accumulate before being fully densified during the compression. On the other hand, the irregular shape of the foam capable to initiate the localized plasticity at the hinge of the cell wall. This phenomenon results the crushed foam reaches saturation phase quicker and therefore, the performance of energy absorption is lowered. In comparisons, the cell wall is very thin and the ridge is also thin and rather straight for 300kg/m^3 foam density compared to others. Similar results are obtained from Toshio *et al.* [17], Chris. *et al.* [18], McCullough *et al.* [19] and Subhash. and Liu. [20].



(b)



(c)

Figure 2: The microstructures of the foams at different foam densities, (a) 100 kg/m^3, (b) 200 kg/m^3 and (c) 300 kg/m^3.

Uni-axial compression behavior of the foams

The compressive response of the foam can be found in Figure 3. All of the foams showed a similar compressive response exhibiting three distinct regions. The first regime is a linear elastic response, where the stress is proportional to the strain, the second regime is a plateau where the stress is linearly constant and the final regime is a nonlinear which is increased in the stress for a small increase in the strain due to the densification of cellular material where the cells have totally collapsed and the cellular walls come into contact. The compressed foams indicated that the plateau stress increased with increasing the foam density. The strain at which the densification starts decreases with increasing foam density. This characteristic related to the number of cells wall collapse. As mentioned earlier, the 300 kg/m^3 foam density accumulated higher yield and plateau forces. Figure 3 also agreed with the foam morphology as shown in Figure 2. Due to the high porosity, foam in general can undergo large inelastic strains that include an initial linear elastic behavior, followed by a plasticity like stress plateau where the foam cells start to crush and finally a steep densification regime where the foam densifies rapidly. At lower density (100 kg/m^3), a small drop in the stress level or mean stress of fluctuating compression stress after the linear elastic line. The densification regime starts at lower strains for low density foam and becomes steeper with increasing foam density as shown in Figure 3. The higher the porosity level, the more strain the sample can accumulate before being fully densified during compression. The initial porosity can be calculated using equation (3) in order to measure the level of porosity of the foam [18]:

$$\% \text{ Porosity} = \left(1 - \frac{\rho_o}{\rho_s}\right) \text{x } 100 \tag{3}$$

Where ρ_0 is the initial bulk density and ρ_s is the solid material density that is assumed to be a constant. The material detail of the foam can be obtained from open literature [19-20].

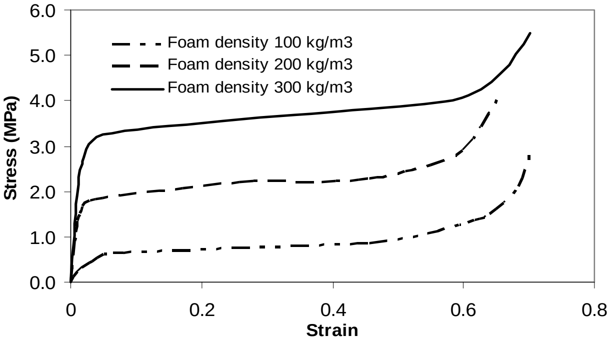


Figure 3: The response of polymeric foam of different densities under compressive loadings.

The plateau stresses are determined from the initial flat regions of the curves as marked in Figure 4 and the corresponding average plateau stress values of polymeric foams are listed in Table 1. The plateau stress, σ is found to be well fitted with power-law of strengthening equation (4) [21]:

$$\sigma = K\rho^{n} \tag{4}$$

Where K and n are constants and ρ is the foam density in kg/m^3. The values of K and n are 0.8718 (MPa) and 1.3141, respectively.

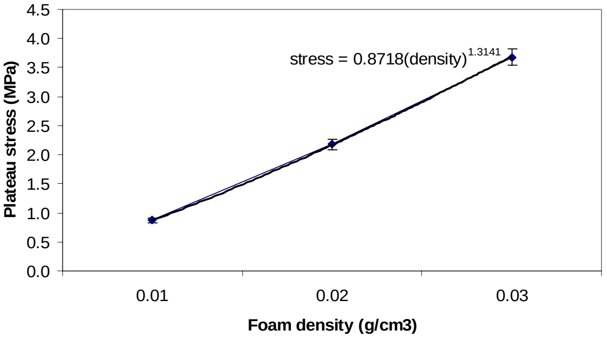


Figure 4: The relationship between plateau stresses to foam density.

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

From Figure 4, the energy absorbed by the foams are determined and presented in Figure 5 for each foam density. Obviously, it is shown that the densities play an important role in increasing the performance of energy absorption. High porosity content controlled the plastic collapse of the foam wall through localized porous wall buckling determines the collapsible mechanisms of the foam.

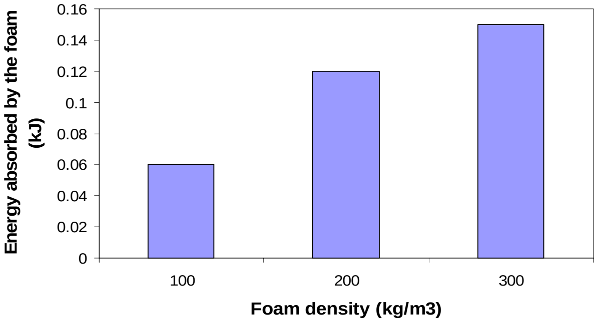


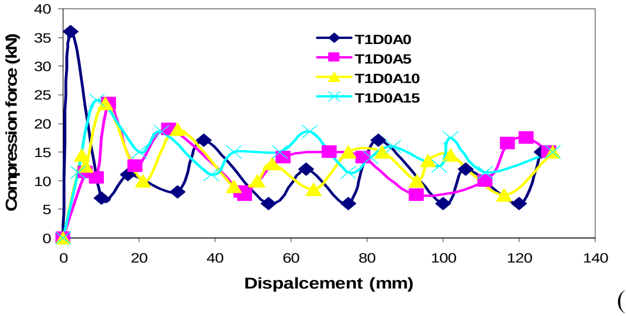
Figure 5: The effect of foam density on the energy absorption capability.

Force-displacement diagram for foam-filled structures

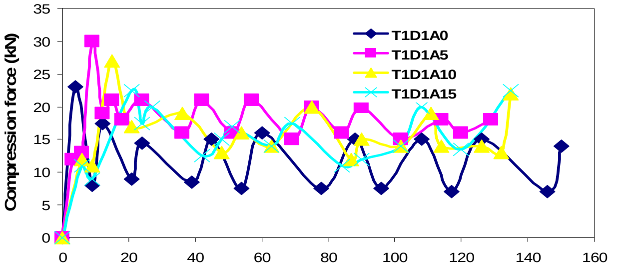
The example of force versus displacement curves of tube thickness, 1.0 mm filled with 0, 100, 200 and 300 kg/m^3 polyurethane foam densities is shown in Figure 6. In this work, D0, D1, D2 and D3 represent foam densities for 0, 100, 200 and 300kg/m^3, respectively. The empty and foam-filled tubes are quasi-statically compressed using different loading angles 0, 5, 10 and 15°. These loading angles are represented as A0, A5, A10 and A15 respectively. Two regions of the compression response can be seen in Figure 6. The first deformation is linear elastic response which is the applied force is directly proportional to the displacement. The second response is fluctuation stage; this region represent load fluctuated during the progressive collapse of the tubes and the final stage cause the compression force increases gradually at short crushed distance due to densification of the tubes. This stage is not shown in the diagram because the compression process is stopped when the deformation reached 80% of the total tube length. Obviously, most of the tubes are progressively collapse but different force versus displacement curves are seen for different tube condition especially on the mean force of fluctuating compressive loading and on the force reduction after the linear elastic deformation. When the foam-filled tubes are compressed off-axially, the linear elastic lines of the tubes shifted for several degrees of rotations compared to empty tubes. The rotation of the elastic line is due to bending moment when the tubes are compressed eccentrically. The plastic deformation started at the tip of the tubes and propagated downward of the tubes. This site also served as stress concentration site and then triggered the progressive collapse of the tubes. Figures 6a – 6b depicted that when the foam density increased, peak and mean forces also increased accordingly. One of the crashworthiness factor that must be considered is force ratio and it is indicated the force reduction just after linear elastic deformation. This ratio is very important because it is strongly related to energy absorption performance. Large force ratio indicated that higher tendency of the column to be catastrophically failed. This ratio is defined as:

$$\text{Force ratio} = \frac{F_{Peak}}{F_{Mean}} \tag{5}$$

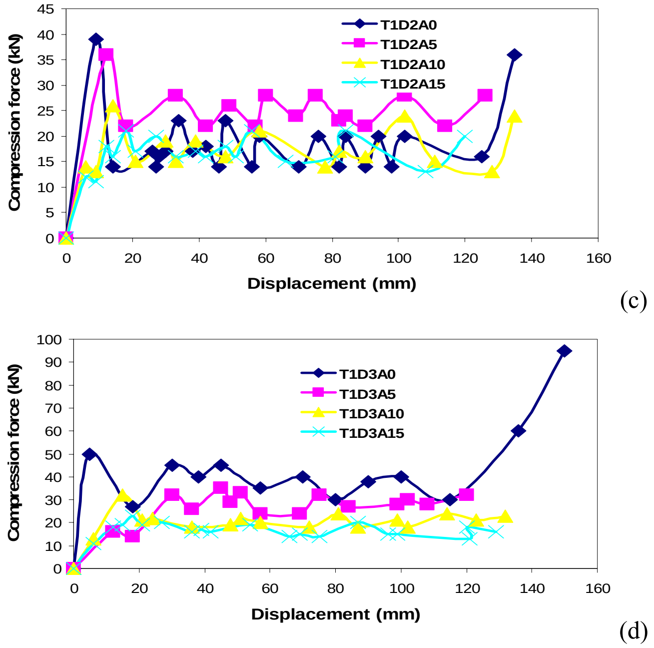
Where F_{Peak} is a maximum force of the linear elastic line and F_{Mean} is a mean force of the fluctuating plastic deformation region. Obviously, Figure 6 shows that by filling the foam into steel tubes reduced the force ratio. The force ratio is reduced when the foam density increased. Loading angles only shifted the elastic line to the right and in the region of plastic deformation, loading angle is significantly affected in fluctuating the compression force. There is no significant correlation between loading angles with mean forces that can be seen in Figure 6.



(a)



(b)



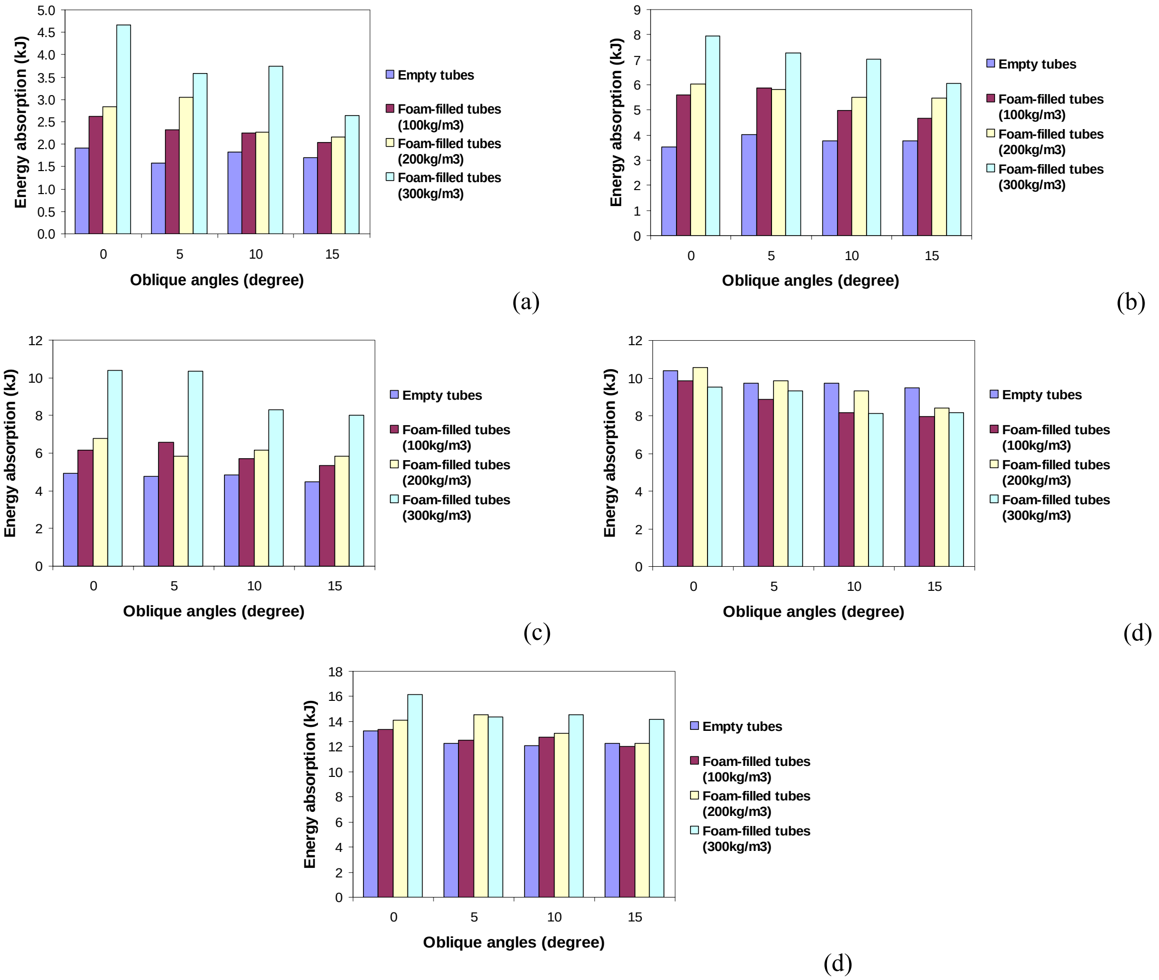
(c)

(d)

Figure 6: Force versus displacement of 1.2 mm thick tubes compressed using different loading filled with different foam densities, (a) 0 kg/m^3, (b) 100 kg/m^3, (c) 200 kg/m^3 and 300 kg/m^3.

Effect of oblique angle on the energy absorption performance.

The influence of energy loading angles on the energy absorption capabilities of foam-filled steel extrusions are presented in Figure 7 which are compressed quasi-statically and obliquely using different loading angles. Obviously, the effect of oblique angles are significantly affected the performance of energy absorptions. Generally, for axially and obliquely compressed foam-filled steel extrusions, the energy absorption increased as increasing the foam density. However, these energies decreased gradually when the foam-filled tubes are compressed obliquely. Its show that the eccentricities of the loads are played an important role in decreasing the capability of the structures to absorb more crushing energy. This is due to higher bending stress which is initiated the stress concentration and created the localization of the plastic hinge at the sharp wall corner. The increment of the energy absorptions are also contributed to restraining effect of the foam density. This effect restrains the fold formation during the progressive collapse of the extrusion walls and it has been discussed detail in [22]. Further energy absorbed improvement is observed for thicker tube wall. According to the collapse mechanism observations, the number of plastic folds increases as the thickness of the extruded tubes increases. This behaviour causing less severe localized bending contributed to higher energy absorbed. When the wall tube thickness increased, the energy absorption capabilities of the foam-filled structures for both axially- and obliquely-compressed loadings are also increased significantly. As wall tube thickness increase, the energy absorbed is no longer dependent on the foam density and wall thickness. According to Figures 7d and 7e, the energy absorbed by the tubes is not strongly affected when the tubes filled polymeric foam. Even higher foam density only increased the energy absorption performance slightly. Contrarily, when the structures are compressed obliquely no significant energy absorption increased.



(a) (b)

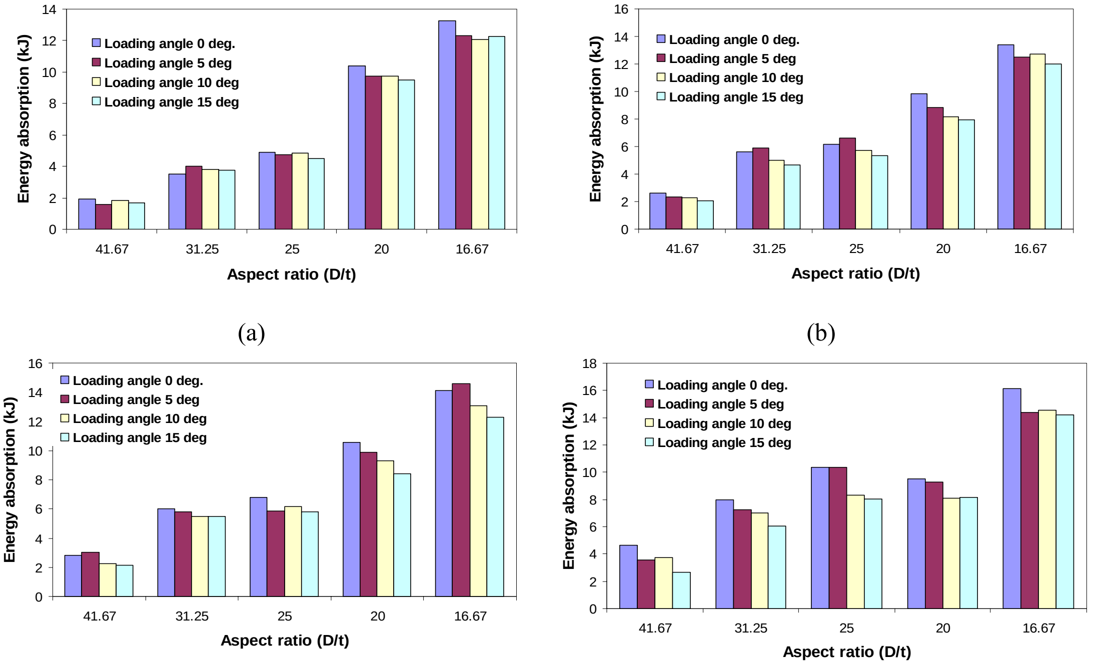
(c) (d)

(d)

Figure 7: Effect of energy absorption on the oblique angles for different density of foam-filled steel extrusion with different thickness (a) 1.0 mm, (b) 1.5 mm, (c) 2.0 mm (d) 2.5 mm and (e) 3.0 mm.

Effect of aspect ratio on the energy absorption.

The influence of aspect ratios on the energy absorption of the foam-filled structures for different loading angles is presented in Figure 8. The average energy absorbed for all type of the structural conditions are considerably similar to each other but tubes filled with 300 kg/m^3 foam density capable to absorb more crushing energy compare to other foam-filled tubes. Most of the initial plastic deformation started at the upper end and propagate downward progressively. The formations of plastic folds are strongly related to the aspect ratio. Aspect ratio is defined as the ratio between internal diameters with wall thickness. The decrement of aspect ratio causing the energy absorption to increase dramatically especially for lower foam density as shown in Figures 8a – 8c. According to Salamah [21] summarized that the tubes filled with higher foam density able to absorb more crushed energies. The crushing behaviour is studied experimentally and numerically and found that the results from both stidues are relatively well agreed. While, Reedy *et al.* [22] have presented the effect of low density polyurethane foam on the axial crushing of the thin-walled (D/t = 600) circular metal tubes under quasi-static and dynamic loading conditions, they found that the stability of crushing is improved by the presence of a filler such as polyurethane foam and the increase in the crushing load is not only because of the crush strength foam but also because of its effect in changing (i) the mode of deformation and (ii) the compressibility of the tube wall, both of which increase the mean crush strength of the tube.



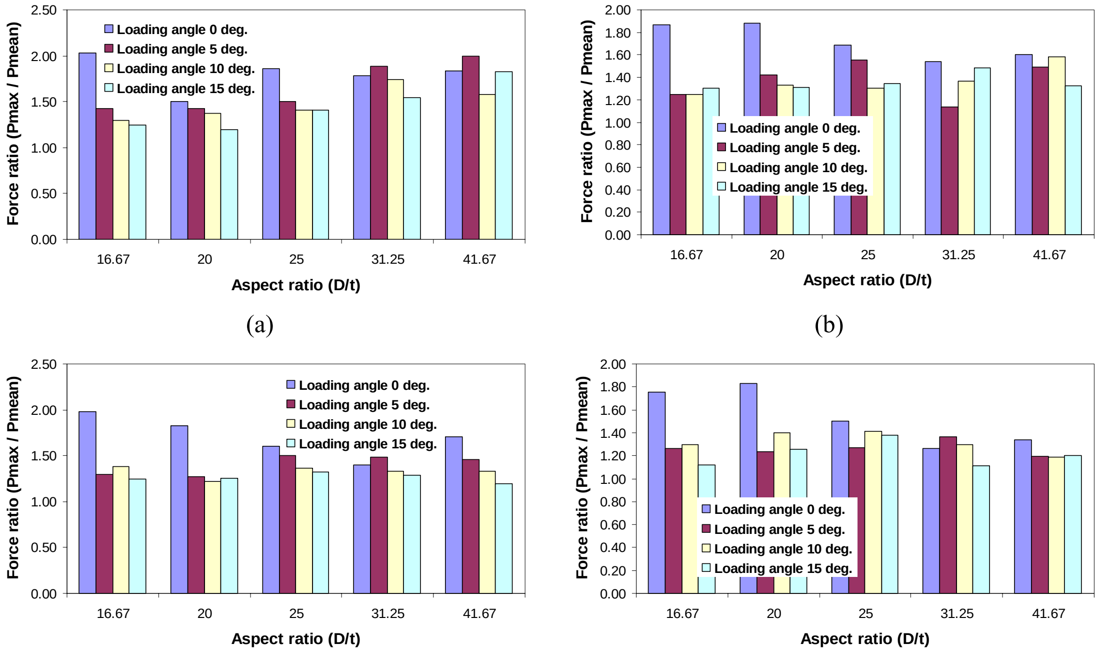
(a) (b)

(c) (d)

Figure 8: The effect of aspect ratio on the energy absorption compressed using different loading angles for (a) empty tube, (b) 100 kg/m^3 foam density, (c) 200 kg/m^3 foam density and (d) 300 kg/m^3 foam density.

Effect of aspect ratio on the forces ratio

The force ratio is defined as the ratio between maximum and mean forces. This ratio indicates whether the material collapsed in stable or progressive manner (high ratio) or catastrophic behaviour (low ratio). In this work, aspect ratio is defined as the ratio between outer diameter and wall thickness (D/t). Figure 9 shows the influence of aspect ratio on the force ratio for different type of tubes and loading angles. Figure 10a reveals the effect of aspect ratio on the force ratio for empty tubes. It is found that thicker wall tube produced low force ratio. It is mean that the tubes collapse downward in progressive manner with localized buckling around the tube wall and high initial compression force is required in forming the first lobe. From the force-displacement curves shown in the previous section that the large force ratio reduction occurred during the progressive collapse for empty tubes. Plastic deformation localization around the tube wall is strongly dependent on the aspect ratio but when the tubes are filled with polymeric foam, the force ratio is high. It is indicated that the tube collapse progressively with producing higher energy absorption, because higher compression forces are required to overcome the elastic and plastic deformation at the end of the column. Significant force ratio variations occurred for empty tubes showing that high tendency of empty tube collapse in catastrophic manner. When the polymeric foam is introduced into the steel extrusion, force ratio is reduced effectively. This behaviour showing that foam played an important role in strengthening the tube wall and then increasing the compression force to produce localized buckling of the tube wall.



(a) (b)

(c) (d)

Figure 9: The effect of aspect ratio on the force ratio of the empty and foam-filled tubes loaded using different loading angles, (a) (a) empty tube, (b) 100 kg/m^3 foam density, (c) 200 kg/m^3 foam density and (d) 300 kg/m^3 foam density.

Crushing Mechanisms

The crushing mechanisms of the empty and foam-filled steel extrusion tubes are presented in Figure 10. The energy absorption associated to these crushed structures was presented in Figure 8. According to those figures, the energy absorption capability is strongly related to aspect ratio of the tube geometry and the foam density. Another physical appearance that can be used to evaluate the performance of energy absorption of the column is the number of folding or wave-length of the tube wall. For columns compressed axially, the number of lobes increased as increasing the foam density from 4 to 5. The thickness of the individual lobe is also different due to the interaction between foam and wall. The detail on discussing the effect of foam and wall interaction can be found in [23]. In other work [24], this interaction is related to the formation of localized plastic hinges around the wall. Three mathematical modes are utilized in predicting the crushing mechanisms of the foam-filled columns [25, 26, 27]. For axially compressed columns, all the lobes are symmetrical. When the columns are obliquely compressed, the asymmetrical lobes are observed due to eccentric bending stress instead of compression force. Similar folding patterns can be seen for the structures compressed eccentrically. It is showed that foam played an important role in strengthening the steel tubes. The folding patterns or geometries produced more severe when higher oblique loading angles are used. Higher stress concentrated at the left side of the structures huge plastic deformation occurred at this region. Large plastic deformation leading to induced large compressive displacement and then reducing the capability of energy absorption as shown in Figure 9. When 3.0 mm thick wall tube is used, the present of foam into the tube does not affect the energy absorption performance significantly. From the observation for 15^0 loading angle, the number of lobes is similar to each other even higher foam density is used. This behavior is strongly supported by Figure 10d where the energy absorbed by the structures is almost unchanged while showing insignificant energy absorption capability compares to low wall thickness.

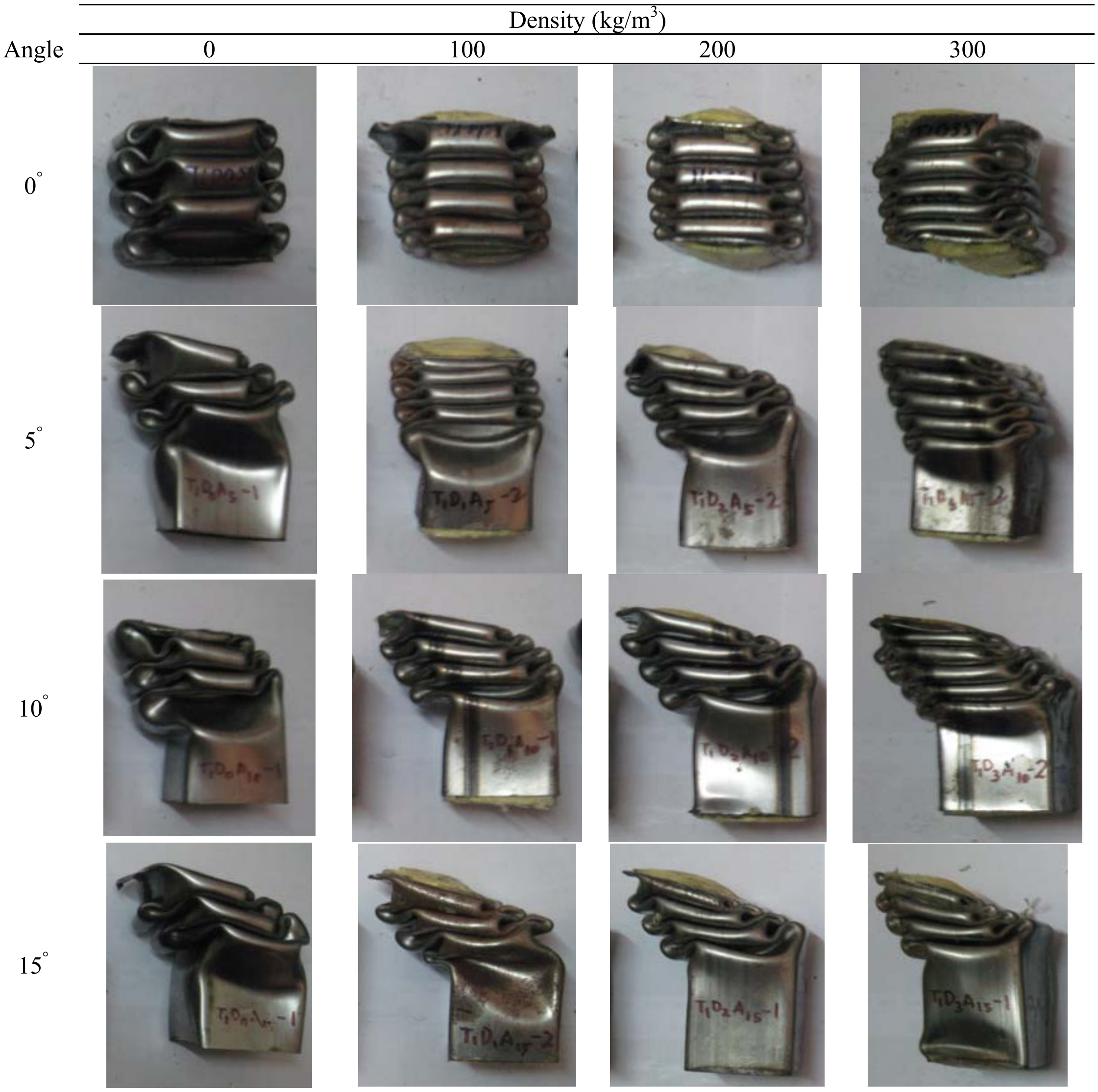


Figure 10: The effect of foam densities and loading angles on the crushing mechanisms of foam-filled steel extrusion under quasi-static compression loading of 1.0 mm wall thickness filled with different foam density.

Foam-wall interaction

The behaviour of the interface between wall and foam is shown in Figure 11. Foam-filled column with higher foam density reveal a symmetrical shape compared to the low density foam-filled columns on the other hand it is still progressively collapse but the final crushed column is asymmetrical. The rigid foam (300 kg/m^3) provided a strong elastic-plastic foundation at the interface and it plastic flow is better than low density foam. This behaviour modified the number of lobes or wave-length with increasing the performance of energy absorption. The encroachment of the column wall into the foam allows an additional compression force and retarded the formation of folding. This retardation of the localized buckling is strongly related to higher energy absorbed during the crushing process. For low density foams, better plastic foam flow is observed and fully occupied into the plastic folds and asymmetry folding pattern formed during the progressive collapse. In Figure 11d shows that for high foam density, symmetric folding pattern with interfacial debonding between foam and tube wall which is lead to high energy absorptions. Since all the structures are designed to prevent global buckling, most of the deformation started at the upper end and progressively collapse downwards without any severe fracturing at any localized fold corners. According to Hanssen, *et al.* [16] described the interaction effect as the following that the increased number of lobes created by introducing foam filler causes the force level of the foam-filled columns to be significantly higher than that of the combined effect of non-filled column and foam alone. Similarly to their results, the interaction effect is prominent in the high density foam filled into the extrusions with creating one additional lobe compares to lower density foam which is produced higher energy absorptions.

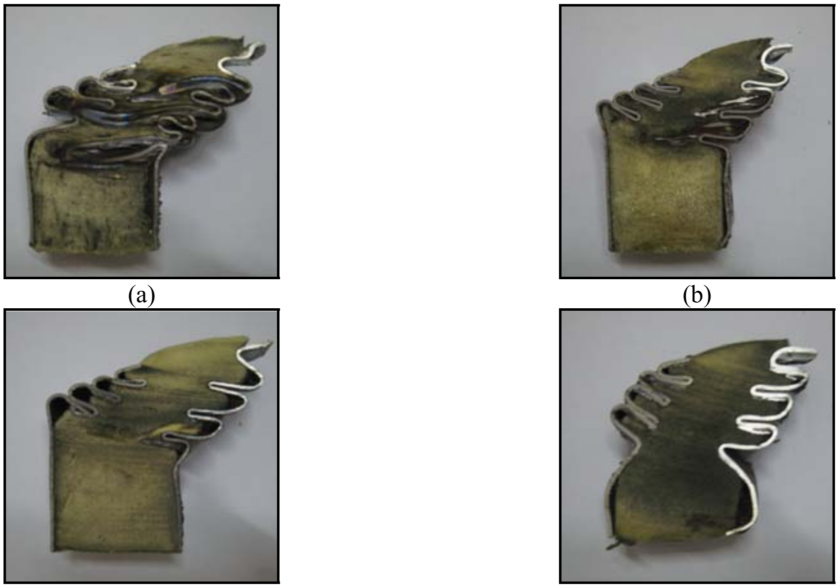

(a) (b)
(c) (d)

Figure 11: Foam and tube wall interactions of foam-filled steel extrusions compressed at 15° oblique angle of (a) 1.5 mm thick wall filled with 100 kg/m^3, (b) 1.5 mm thick wall filled with 200 kg/m^3, (c) 1.5 mm thick wall filled with 300 kg/m^3 and (d) 3.0 mm thick wall filled with 300 kg/m^3.

CONCLUSION

Based on the above experimental investigation of empty and foam-filled steel extrusion tubes under oblique compression mode have been studied and the following conclusions have been reached. Foamed rigid polyurethane has considerably higher energy absorbability due to the existence of a large plateau stress region in the stress-strain curve under a compression load. Energy absorbed by the foam increased as increasing the foam density and it due to higher porosity content because large amount of inelastic deformation can be supported compared to low density foam materials. In the case of foam-filled tubes, the energy absorption performance is strongly related to the foam density filled into the tubes. This is because polymeric foam provided a constraint mechanism of the tube wall and higher compression force is required to plastically deform the tubes. But the energy absorbed by the foam-filled tubes is not affected significantly when the maximum aspect ratio is reached. Generally, oblique energy absorption decreased as increasing the loading angle of the compression forces. Oblique angles played an important role in determining the energy absorption capability of the foam-filled tubes. For the tubes loaded obliquely, the first plastic deformation initiated at the contact tip of the tubes and easily propagated down. In the same time, bending moment is created instead of axial compression force therefore reducing the energy absorption capability.

ACKNOWLEDGE

Author acknowledges to Ministry of higher education of Malaysia (MOHE) and also to the Center for research management (PPI) in Tun Hussein Onn University of Malaysia (UTHM) for providing financial supports under Fundamental Research Grant Scheme (FRGS) Vot. 0263.

REFERENCES

[1] A.G Mamalis, D.E Manolakos, G.A Demosthenous, M.B Ioannidis (1989). *Crashworthiness of composite thin-walled structural components.* CRC Press

[2] Mahmoud Abdel-Haq (2002). Constraint effects on energy absorption in unidirectional polymeric composite "PMC" tubes. PhD dissertation, Wayne state University, Detroit, Michigan USA.

[3] Baumeister J., Banhart J, and Weber M. (1997). Aluminum foams for transport industry. Materials & Design **18**: 217-220.

[4] Sugimura Y., Meyer J, He M. Y., Bart Smith H. and Grenestedt J.L. (1997). On the mechanical performance of closed cell al alloy foams. Acta Materialia **45**: 5345-5259.

[5] Grenestedt J.L, (1998). Influence of wavy imperfection in cell walls on elastic stiffness of cellular solids. Journal of the Mechanics & Physics of Solids **45**: 29-50.

[6] Ford C.M, and Gibson L.J, (1998). Uniaxial strength asymmetry in cellular materials: An analytical model. International Journal of Mechanical Science **40**: 251-552.

[7] Cheon S.S, and Meguid S.A, (2004). Crush behaviour of metallic foams for passenger car design. International Journal of Automotive Technology **5**(1): 47-53.

[8] Santosa S, Wierzbicki T. (1998). Crash behavior of box columns filled with aluminum honeycomb or foam. Computer and Stuctures **68**: 343–67.

[9] Meguid SA, Cheon SS, and El-Abbasi N. (2002). FE modelling of deformation localization in metallic foams. Finite Element Analysis and Design **38**: 631–43.

[10] Alexander JM (1960). An approximate analysis of thin cylindrical shells under axial loading. Quarter Journal of Mechanics and Applied Mathematics **13**: 10–5.

[11] Pugsley A, and Macaulay M. (1960). The large scale crumpling of thin cylindrical columns. Quarter Journal of Mechanics and Applied Mathematics **13**: 1–9.

[12] Abramowicz, W. and Jones, N. (1997). Transition from initial global bending to progressive buckling of tubes loaded statically and dynamically. International Journal of Impact Engineering **19**(5–6): 415–437.

[13] Abramowicz, W. and Jones, N. (1986). Dynamic progressive buckling of circular and square tubes. International Journal of Impact Engineering **44**: 243–270.

[14] Wierzbicki T. and Bhat S.U. (1986). A moving hinge solution for axisymmetric crushing of tubes. International Journal of Mechanical Science **28**(3): 135–151.

[15] Ibrahim, MHI (2006). The effect of buckling towards the strength of FRP pultruded columns. MEng. Thesis Universiti Teknologi Malaysia (UTM), Malaysia.

[16] Hanssen, A.G, Langseth, and M. Hopperstad, O.S (2000). Static and dynamic crushing of square aluminum extrusion with aluminum foam filler. International Journal of Impact Engineering **24**(4): 347-383.

[17] Toshio Kurauchi, Norio Sato, Osami Kamigaito, Noboru Komatsu. (1984). Mechanism of high energy absorption by foamed materials-foamed rigid polyurethane and foamed glass. Journal of Material Science **19**: 871-880.

[18] Chris Barlow, Vioin Kumar, Barian Flinn, Rajendra K. Bordia, and John Weller. (2001). Impact strength of high density solid state microcellular polycarbonate foams. Journal of Engineering Materials and Technology **123**: 229-233.

[19] McCullough K.Y.G, Fleck N.A, and Ashby M.F (1999). Uniaxial stress-strain behaviour of aluminium alloy foams. Acta Materilia **47**(8): 232-2330.

[20] Subhash G., and Liu Q. (2004). Crushability maps for structural polymeric foams in uniaxial loading under rigid confinement. Experimental Mechanics **44**(3): 289-294.

[21] Salamah Y. Maaita (2004). Effects of constrained foam deformation in aluminium tubes under quasi-static and dynamic axial compression loading. PhD dissertation, Wayne State University, Michigan.

[22] Reedy T.Y, and Hall R.J (1998). Axial compression of foam-filled thin-walled circular tubes. International Journal of Impact Engineering **7**(2): 151-217.

[23] Halit Kavi, A. Kaan Toksoy, and Mustafa Guden. (2006). Predicting energy absorption in a foam-filled thin-walled aluminum tube based on experimentally determined strengthening coefficient. Materials and Design, **27**: 263-269.

[24] Toksoy AK, Tanoglu M, Guden M, and Hall IW. (2004). Effect of adhesive on the strengthening of aluminum foam-filled circular tubes. Journal of Material Science, **39**: 1503-6.

[25] Alexander JM. (1960). An approximate analysis of the collapse of thin cylindrical shells under axial loading. Quarter Journal of Mechanics and Applied Mathematics, **13**: 10-5.

[26] Signace AA, Elbosky H, and Reddy TY. (1995). On the eccentrity factor in the progressive crushing of tubes. International Journal of Solids and Structure, **32**: 3589-602.

[27] Wierzbicki T, Bhat SU, Abramowicz W, Brodkin D. Alexander (1992). Revisited - a two folding elements model of progressive crushing of tubes. International Journal of Solids and Structure, **29**: 3269-88.