UNIVERSITI TEKNOLOGI MARA

CONFERENCE PROCEEDING

ICITSBE 2012

1ST INTERNATIONAL CONFERENCE ON INNOVATION AND TECHNOLOGY FOR SUSTAINABLE BUILT ENVIRONMENT

16 -17 April 2012

Organized by:
Office of Research and Industrial
Community And Alumni Networking
Universiti Teknologi MARA (Perak) Malaysia
www.perak.uitm.edu.my

PAPER CODE: GT 01

FINITE ELEMENT SIMULATION OF SQUARE AND CIRCULAR POLYSTYRENE FOAM FILLED SUBJECTED TO TRANSVERSE QUASI-STATIC LOADING

Akbar Othman[1] and Mohd Fahrul Hasan[2]
[1]Department of Mechanical Engineering, Polytechnic Port Dickson, Malaysia
akbar@polipd.edu.my
[2]Department of Material and Design Engineering, Universiti Tun Hussein Onn Malaysia, Malaysia
fahrul@uthm.edu.my

Abstract
Thin-walled columns are used in a broad range of vehicular applications and especially as crash absorber elements. Crushing characteristics of absorbed energy in terms of quasi-static loading under transverse condition were crucial factors especially in finite element study. A numerical study is presented in this paper to investigate the energy absorption of polystyrene foam-filled on circular and square hollow 2024T aluminum alloy subjected to lateral compression. The failure mode of the polymeric foam-filled tube structures has been successfully simulated. The predicted compressive load displacement is in agreement with experimental results from reference literature. The energy absorption ability of the metallic structure due to plastic deformation in a crushing process is evaluated by comparison with the tube structure without filler. The results indicate that the energy absorption of a cellular material-filled tube structure is superior to the tube without filler.

Keywords: Energy Absorption, Lateral Compression, Finite Element Analysis, Polystyrene Foam, ABAQUS Explicit 6.10

1. Introduction

Column metallic structure cross-sections are frequently used as energy absorbing structural elements. Progressive collapse characteristic of tubes under lateral loading has been studied in the past by several authors under different loading conditions. Sinha and Chitkara conducted experimental and theoretical studies of rings of square cross section under in-plane loading. They analyzed the stability of the vertical arm of the tube by taking into account the initial out of straightness and analyzed the post collapse behavior by assuming the plastic hinges at mid points of each arm. They also estimated the collapse load for tubes of rectangular section subjected to oppose line loads by assuming a diamond pattern of plastic hinges on the sides of tube sections. Kecman employed limit analysis to study the collapse behavior of tubes of rectangular and square sections and derived the formulae relating the hinge moment with the associated angle of rotation. Gupta and Sinha have presented the results of experiments and analysis concerning the post collapse behavior of square tubes when compressed symmetrically between orthogonally placed indenters of narrow width, and asymmetrically between one such indenter and a flat rigid platen.

This paper presents a study of lateral collapse behavior of circular and square tubes subjected to lateral transverse compression between two parallel flat platens. A computer simulation model for the above compression process has been proposed and analyzed using commercial finite element software of ABAQUS version 6.10 finite element codes. The wall-thickness and cross-sectional dimensions were varied to observe their effect on the deformation characteristics. The validation process has been carried out to make comparison from numerical and experimental results of the energy absorption. The deformed shapes of the specimens at different stages of compression have been plotted to study and analyze the deformation mechanism of the tubes. Contours of different components of stress and strain rate tensors and nodal velocity have been plotted to get a clear insight into the mechanism of deformation during the collapse.

2. Finite element modeling of lateral collapse of thin-walled foam-filled section

The finite element commercial software of ABAQUS version 6.10 was used throughout the analysis. The simulation process has two differences geometry cross-section of tubes, which is a circular and square tube. Shell elements are used to model structures in which one dimension is significantly smaller than the other dimensions, and the stresses in the thickness direction are negligible. Then a solid element was modeled to foam filler material. Generally three-dimensional solid and shell elements are available with three different formulations, general-purpose, thin only and thick only. General-purpose shell elements are valid for use with both thick and thin shell problems. Furthermore, all general purpose shell and solid elements consider finite membrane strains. All special-purpose shell elements assume finite rotations; however, they assume small strains. The thin-only shell elements enforce the Kirchhoff constraints; that is, plane sections normal to the midsection of the shell remain normal to the mid surface. An energy absorber can be defined as a system that converts, totally or partially, kinetic energy into another form of energy. Energy converted is either reversible as the pressure energy in compressible fluids or irreversible, such as involving plastic dissipation energy associated with the permanent deformation of a solid. The total work done (W) during the axial crushing of the cones are equal to the area under the load/displacement curve and is evaluated as:

$$W = \int Pds \tag{1}$$

where, P is the force acting on the tube. Therefore the specific energy absorption per unit mass, E is recognized as:

$$E = \frac{W}{m} \quad 2)$$

where, m is the crushed mass of the thin-walled tube. It was assumed that thin-walled aluminum extrusion has only isotropic strain hardening, and for quasi-static loading, the strain rate effects on the yield strength were neglected due to the relatively low overall average load rate used in the tensile tests. For dynamic loading, the effect of strain rate was included in the finite element model using the Cowper–Symonds constitutive equation given by the following relation:

$$\dot{\varepsilon}_p = D^t \left(\frac{\sigma_d}{\sigma_s} - 1 \right)^{q^t} for \mapsto \sigma_d \geq \sigma_s \tag{3}$$

where σ_d is the dynamic flow stress at a uniaxial plastic strain rate ε_p, σ_s, the associated static flow stress, and the constants D^t and q^t are tube material parameters. Equation (3) is an overstress power law that was incorporated into the finite element model. In this study of the lateral collapse of cylindrical thin-walled foam-filled tube, the energy absorption capacity of tubular members under lateral loading can be determined by modeling it with shell and solid finite elements. The study was examined in two-dimensional where lateral loading is imposed by two rigid plates which are shown in Figure 1. Reddy and Reid investigated the lateral compression of tubes with side constraints and found the energy absorbed in a constrained system is three times more than that of free system. In this study also two types of numerical simulation were carried out. In the first study, the effect of wall-thickness of tube on the energy absorption was investigated. The tube has two different shapes which is circular and square cross section. The material for all modeling of thin-walled tube was aluminum 2024-T4 alloy. The thickness of the tube was set at 1.0, 1.5, and 2.0 mm. The total time value for crushing time, (t) was found to be 0.02 s for all analysis modeling. Then, the second stage of this study was to investigate the effect of density of foam-filler material on the energy absorption. The foam of polystyrene type was selected on density of 100 kg/m^3 and overall data were listed in Table I. The other important parameter of representing crushing event is boundary condition. Based on quasi-static simulation, the explicit step with boundary condition of velocity was selected which was 1 m/s and amplitude data was adopted into quasi-static simulation.

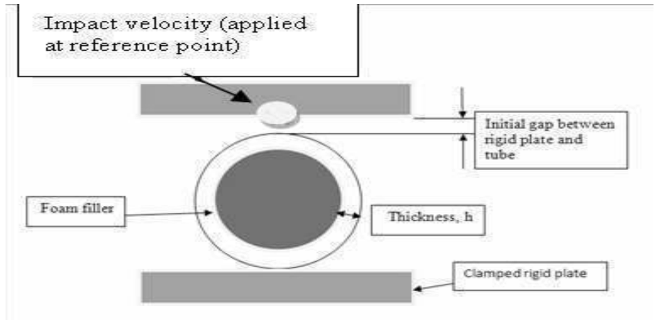

Figure 1: Finite element modeling of lateral collapse of foam filled tube

The tubular step was used and maximum total time of amplitude value was 300. In structural analyses, boundary conditions are applied to those regions of the model where there displacements and/or rotations are known. Such regions may be constrained to remain fixed or may have specified non-zero displacements and/or rotations. In this model the fixed-free condition has been used where the top section of the tube is constrained completely and, thus, cannot move in any direction. The bottom section, however, is fixed in the horizontal direction but is free to move in vertical direction.

2.1 Material properties of modeling

Numerical analyses were carried out to simulate the lateral crushing of aluminum extrusions of 2024-T4 alloy with different weight based on wall-thickness and cross-section shapes of specimens. Aluminum 2024-T4 alloy was used for column material since the material properties could be modeled as isotropic with good accuracy and negligible strain rate sensitivity was evident for this alloy. The basic material properties required for this model are given in Table I, while the structural geometry is given in Table II. All the specimens were 100 mm high (H), 70 mm maximum radius for circular tube and width of 70 x 70 mm for square profile of the tube (D1) and wall thickness varied of 1.0, 1.5, and 2.0 mm. The collapse of tubes under lateral loads can be treated as a two-dimensional problem, assuming that the tube is significantly longer than its diameter (L≥D), and the load and deformation do not vary in the transverse tube direction which called plane strain conditions. The empty tube models are modeled with reduced-integration four-node shell elements (S4R) from the general purpose program ABAQUS. All the parameters used for empty tubes and foam-filled tubes are same in the simulation. The foam-filled models are modeled with three-node linear plane strain triangle element. In ABAQUS/Explicit, crushable foam model is based on the plasticity theory. In the current study, the foam-filler which located inside the tube was modeled as crushable foam model with volumetric or isometric hardening. Thus, the input data to the hardening law by only specifying, in the usual tabular form, the value of the yield stress in uniaxial compression as a function of the absolute value of the axial plastic strain. The properties of each part which created in the part module were defined through sections module in ABAQUS/CAE. Two sections were created for two materials defined when input of material data.

2.2 Validation of the Finite Element Model

The proposed finite element model was validated by comparing the predicted absorbed energy and the deformed shapes at different stages of the compression process with those found from the experiments. To compare the experimental and computer simulation deformed profiles the tube specimen aluminum circular hollow was carried out and presented in Figure 2. The data result from experimental and simulation was compared with energy absorption, mean load, total compression and peak load, respectively and listed in Table III. The good agreement was find out with comparison of both data. The calibration of both result of deformation can be observed and they match very well. In this study, the deformation patterns of an empty tube and foam-filled tube were observed. When the quasi-static lateral load was applied, the cylinder deform to oval shape mode. By the time increase, the empty and foam-filled tube models were compressed to the deformation form of the aluminum 2024-T4 alloy tube until the final stage of failure. The fastest deformation happened subjected to the cylindrical tube without foam. The deformation was decreased by filing polystyrene foam into empty tube for every thickness. The deformation period was influenced by the quasi-static load applied. As the amplitude motion of 500 for all total time, the load will increase of deformation lateral collapse and the time taken for model to achieve the deformation pattern will be decreased.

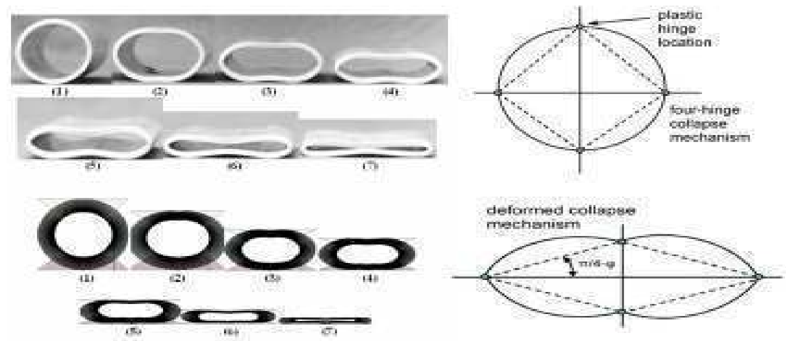

Figure 2: Verification and validation of material model and Collapse mode of deformed mechanism of lateral collapse

All the models deformation modes occurred similarly. In this simulation, the deformation time for total time was 0.02 s and total time amplitude motion was 1 equal to 500 based on tubular step value of amplitude data. Both empty tube and foam-filled tube models were simulate in the same step time as mentioned above to get a consistent results. The deformation pattern of 1.0, 1.5, and 2.0 mm wall-thickness model of quasi-static amplitude velocity were 1 m/s and 500, respectively. The model assumes linear elastic behavior prior to the formation of the four plastic hinges, and perfectly plastic behavior upon activation of the collapse mechanism, the deformation pattern of the model will be considered as in Figure 3. Generally, the exact mode of deformation is difficult to predict as imperfection in the geometry influence the initial buckling. The initial imperfection in the tube was considered which lead to a symmetric mode of collapse and initiate the collapse occurs. Nevertheless, the overall collapse pattern is considered satisfactory for the purpose of the present work.

Table 1: Material properties of aluminum 2024-t4 alloy and dimension of tubular for finite element modeling

	Item	Details	
		Type (tube)	
		Round	Square
1.	Length (mm)	100	100
2.	Diameter/Width of Tubular (mm) (Fixed)	70	70 x 70
3.	Aluminum Foam Density kg/m³	0 832	0 832
4.	Wall-Thickness (mm)	1.0 1.5 2.0	1.0 1.5 2.0

Aluminum 2024-T4 alloy	Stress (Pa)	Strain
E (Pa) (71.9E9)	306.031E6	0
	367.350E6	0.019
Density ρ (kg/m³) 2767.99	389.394E6	0.039
	407.510E6	0.058
	423.825E6	0.076
Poisson ratio υ (0.34)	439.095E6	0.095
	453.686E6	0.113
	467.801E6	0.131
	481.570E6	0.148
	495.076E6	0.165

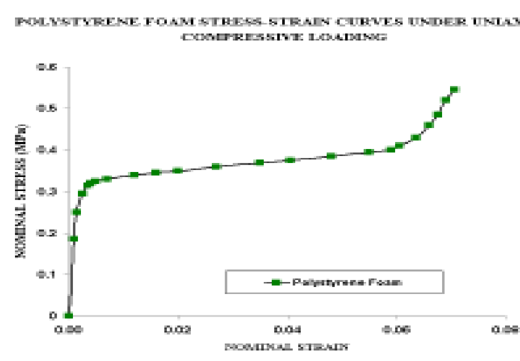

Table 2: Validation of experimental and numerical analysis

Parameters	Experimental	Numerical	Error (%)
Total compression (mm)	65	70	7.1
Peak load (kN)	20	25	20
Mean load (kN)	11	15	26.6
Absorbed energy (kJ)	0.85	1.2	29

3. Result and Discussion

3.1 Effect of wall thickness

The analysis result for the each wall-thickness with different with and without foam give a good agreement with the increasing in wall-thickness will increase the energy absorption capability for both empty and foam-filled tube models. The effect of wall-thickness on the energy absorption of an empty tube under quasi-static loading is shown in Figure 4 to 5. The figure showed that 2.0 mm wall-thickness model had the highest energy absorption capability among others.

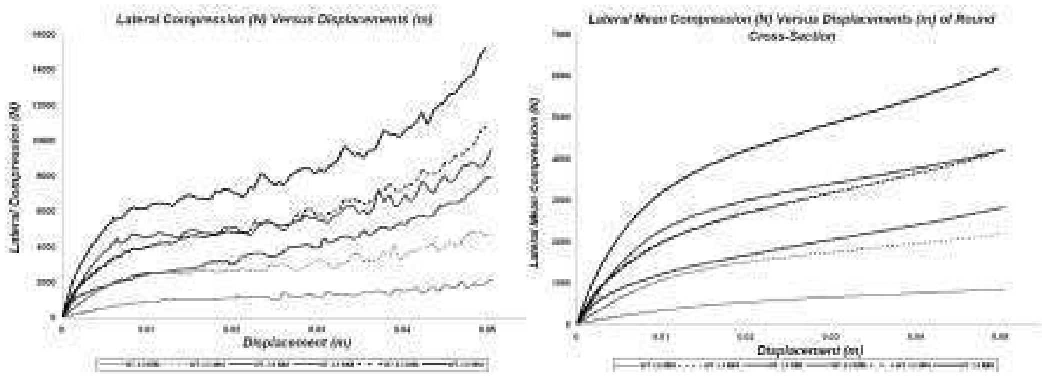

Figure 3: Quasi-static lateral load (N) versus displacement (m) type of circular tube profile (Black – with foam; Red without foam) [Wall-Thickness = 1.0, 1.5, and 2.0 mm]

The mechanism of the initiation of the first fold is the same regardless of the edge conditions. While the development of the first fold and hence the load compression history during the folding process will depend on the edge conditions, the formation of the subsequent folds and the further progressive crush behavior of the tube becomes independent of the edge conditions after the first fold has been formed. During post crush and middle post crush step, as the tube is compressed, its wall tends to move radially outwards, due to a Poisson's effect and axial shortening. However, the movement of the ends of the tube will be resisted by the frictional forces between the plate and the end of the tube.

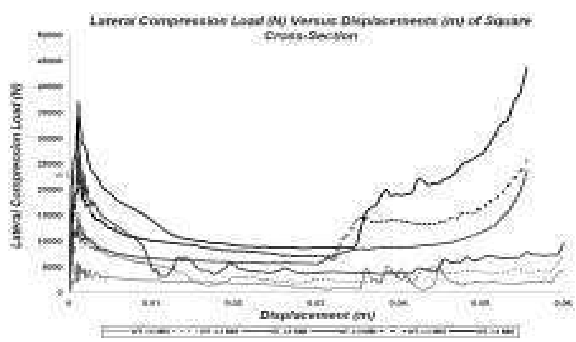

Figure 4: Quasi-static lateral load (N) versus displacement (m) type of square tube profile (Black – with foam; Red - without foam) [Wall-Thickness = 1.0, 1.5 and 2.0 mm]

The result in the ends of the tube were lagging behind the rest of the tube wall and hence the initiation of the first outward buckle. This behavior that controls the accumulation energy absorbed by the tube will continue to occur until the next step has taken place. At the step of material densification the tube's wall was dense in which the structure behaves as a rigid body and produced a resistance towards excess of the load. Finally, there will be 0 (zero) amount of energy being absorbed by the tube at the final crush step.

3.2 Failure mode of quasi static lateral collapse

To understand the pattern of deformation occurring during lateral compression of tubes, the compression process is divided into three stages, referred to as the initial, intermediate, and final. The progress of deformation during lateral compression of circular tubes is typified by the collapse pattern. Initial tube profile is convex over its whole periphery. Therefore, there is only a line contact between the tube and the platen, creating stress concentration at and around. In the initial stage of compression, therefore, deformation is mainly restricted to zone I (or the site of the first plastic hinge). However, the area of contact gradually builds up and the portion of tube the boundary flattens out. The load required to continue compression tends to increase (see Figure 4 to 5). Increase of contact area and strain hardening of material in zone I lead to gradual decrease of rate of deformation in zone I. The site of dominant deformation next shifts to zone II. This marks the beginning of the intermediate stage of compression, and formation of the second plastic hinge around a tube. However, the required load is higher as compared to that in stage I. This is because for a given load the magnitude of bending moment at lowers than that. With increasing downward movement of the platen, the character of platen tube contact undergoes marked change. The first plastic hinge moves outward and still further away. As this happens, there is loss of contact over the boundary of edge. If the platen load was to remain unchanged, the bending moment in zone II would actually decrease. To compensate the decrease in the so called 'moment arm' the platen load increases. In the final stage of the compression process, point to comes quite close to the horizontal axis and the curvature in zone II starts increasing at a high rate. This necessitates increase of bending moment in zone II, and the corresponding load also increases sharply.

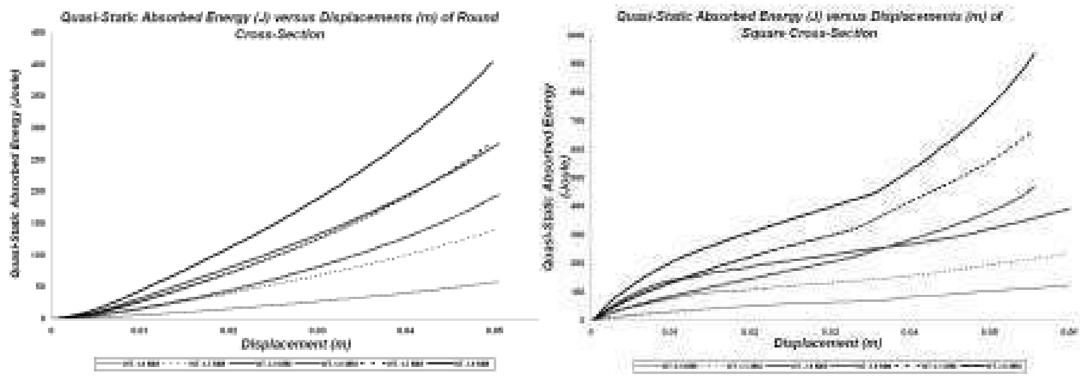

Figure 5: Quasi-static absorbed energy (Joule) versus displacement (m) type of circular tube profile (Black – with foam; Red - without foam) [Wall-Thickness = 1.0, 1.5 and 2.0 mm]

3.3 *Effect of circular and square profile on strain, internal, and absorbed energy as well as mean load efficiency*

There is a significant increase in the value of energy absorption when the polystyrene foam density is introduced into thin-walled tube. By refer to Figure 6, the highest energy absorption obtained at the 50% different compared to 0 kg/m3 density of polystyrene foam, then the wall-thickness can be effective when the thick of wall of tubing increased then that the energy absorption capability increased slightly 40 % of the optimization efficiency of crushing element. The energy absorption due to the foam filled increase depends on the cross-sectional area and the foam strength, which is by increasing the polystyrene foam percentages. However, the highest density of polystyrene foam almost of 1000 kg/m3 value can be strengthening the microstructure of filler materials. Compared to other foam filler, the crushable of foam filler would not depend on higher or lower value of density. Therefore properties of foam filler having different of microstructure foam. However, foam-filled model contribute higher energy absorption capability compared to the empty tube or 0 kg/m3 density of filler. The square tube profile had effective capability in term of lateral collapse and absorbed energy than circular tube profile it can be seen in Figure 6. The initial peak load of square highest than circular because the mechanism of the initiation of the first fold is not the same regardless of the edge conditions. Therefore the development of the first fold and hence the load compression history during the folding process will depend on the edge conditions, the formation of the subsequent folds and the further progressive crush behavior of the tube becomes independent of the edge conditions after the first fold has been formed. Compared to circular tube profile an easily be made of first folding of lateral collapse in the first crush zone. The quasi-static lateral collapse was modified to view the variation in energy absorption of the models. The three different energy values were compared and considered in graph showed in Figure 7 where empty and foam filled with variation of wall-thickness of 1.0, 1.5, and 2.0 mm, respectively. The results obtained are shown in Figure 6 in general. The result show that the energy absorption increase when the wall-thickness was increased and introduced foam filling into hollow tube was also increased strain, internal, and absorbed energy as well as mean load efficiency. The initial collapse load increases with quasi-static collapse and the higher collapse load leads to an increase in energy absorption. This characteristic was advantageous in the crashworthiness design which demand the maximum energy absorbed in a low speed collision environment. In Figure 6, the values of energy as well as lateral mean load collapse were calculated at fixed displacement of 50 mm.

4. Conclusion

The purpose of this study was to investigate the effect of foam filling on the quasi-static lateral collapse response and energy absorption characteristics of thin walled tubes using finite element simulations. Energy absorption response was quantified with respect to variations in the parameter of wall- thickness, foam density, and cross-section profile. The results have demonstrated the feasibility and superior performance of foam-filled cylindrical tubes as energy absorbers. The introduced polystyrene foam density of 100 kg/m^3 appears to be the percentage of foam that had the highest energy absorption capability. The energy absorption increase significantly as the foam densities increased under quasi-static lateral loading due to the presence of foam filler and interaction effect between foam core and cylindrical tube. For square tube profile exhibit better absorbed energy performance than circular tube profile respected to wall-thickness and introduce foam filing into thin-walled tube structure.

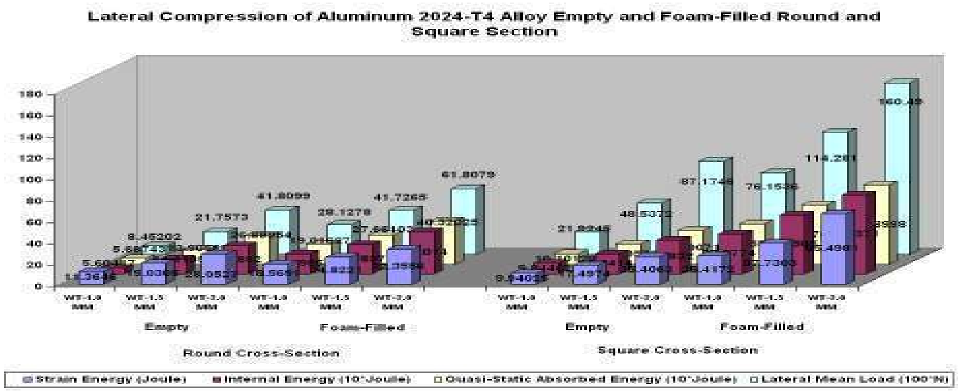

Figure 6 : Lateral compression of aluminum 2024-T4 alloy type of circular and square profile of strain energy (J); internal energy (10*J); quasi-static absorbed energy (10*J); lateral mean load (100*N) [Wall-Thickness = 1.0, 1.5, and 2.0 mm]

Acknowledgment

We would like to thank the members of the Computational Mechanics Group, Universiti Kebangsaan Malaysia for their constructive comments, encouragement, and support the commercial finite element ABAQUS version 6.10 theories and user's manual.

References

Ezra, A.A., Fay, R.J.. An assessment of energy absorbing devices for prospective use in aircraft impact situations. In: Hormone

G. Perron, N., (Eds). Dynamic response of structures.

Jones, N., Wierzbicki T. (1983).*Structural crashworthiness*. Butterworth & Co.: London

Gupta, N.K. (1996). *Plasticity and impact mechanics*. NewAge International (P) Limited: New Delhi, India.

Johnson, W., Reid, S.R. (1978). Metallic energy dissipating systems. *Appl Mech Rev*;3, pp. 277–88.

Mutchler LD. (1960). Energy absorption of aluminum tubing. *J Appl Mech* 1960;27:740–3.

DeRuntz ,J.A., Hodge, P.G. (1963). Crushing of a tube between rigid plates. *J Appl Mech* . 30, pp. 391–5.

Redwood, R.G.(1964). Discussion of (ref. 6) crushing of a tube between rigid plates. *J Appl Mech* . 31. pp. 357–8.

Burton RH, Craig JM. An investigation into the energy absorbing properties of metal tubes loaded in the transverse direction.

BSc (Engg) report (1963). University of Bristol, Bristol, England

Reid SR, Reddy TY. (1978). Effect of strain hardening on the lateral compression of tubes between rigid plates. *Int J Solids Struct* .14, pp. 213–25.

Sinha DK, Chitkara NR. (1982). Plastic collapse of square rings. *Int J Sol Struct*, 18, pp. 819–26.

Sinha DK, Chitkara NR. (1984). Determination of plastic collapse loads of rectangular tubes. *Acta Mechanica* . 5, pp.199–215.

Kecman D. (1983). Bending collapse of rectangular and square section tubes. *Int J Mech Sci* . 25(9/10), pp. 623–636.

Hibbit, Karlsson and Sorensen Inc. (2010). *ABAQUS 6.10 theory and user's manual*. Providence: Hibbit Karlsson and Sornesen Inc