Numerical modelling of steel tubes under oblique crushing forces

A.E Ismail*,1, M.Q Abdul Rahman2, N. Nezere1, S. Jamian1, K.A Kamarudin1, M.K Awang1, M.K Mohd Nor1, M.N Ibrahim1, M. Rasidi Ibrahim1, M. Zulafif Rahimi1, Mohd Fahrul Hassan1, Nik Hisyamudin Muhd Nor1, A.M.T Ariffin1, Muhamad Zaini Yunus1

1Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat, 86400 Johor, Malaysia.
2Centre for Diploma Studies, Universiti Tun Hussein Onn Malaysia, Batu Pahat, 86400 Johor, Malaysia.

*emran@uthm.edu.my / al_emran@hotmail.com

Abstract. This paper presents the numerical assessment of crushing responses of elliptical tubes under crushing forces. Based on the literature survey, tremendous amount of works on the axial crushing behaviour can be found. However, the studies on the oblique crushing responses are rarely found. Therefore, this work investigates numerically the elliptical tubes under compressions. The numerical model of the tubes are developed using ANSYS finite element program. Two important parameters are used such as elliptical ratios and oblique angles. The tubes are compressed quasi-statically and the force-displacement curves are extracted. Then, the area under the curves are calculated and it is represented the performances of energy absorptions. It is found numerically that the introductions of oblique angles during the crushing processes decrease the crushing performances. However, the elliptical-shaped tubes capable to enhance the energy absorption capabilities. On the other hand, the elliptical-shaped tubes produced the enhancement on the energy absorption capabilities.

1. Introduction

Crashworthiness is a field of knowledge deals with the capability of structures to protect the driver and passengers inside the vehicle during collisional event. The performances of such structures are strongly related with the materials used to fabricate the structures, speeds and the types of collisions [1]. The details of the fundamental aspects of the crashworthiness can be found in [2] and the main consideration is to investigate the capability of any structures to absorb the crash energy in controlled manner. It is determined by calculating the area under the curve of force-displacement response. According to the literature survey, most of the works conducted in determining the energy absorption performances are based on the axial crushing forces [3-12]. Gupta and Abas [3] developed a mathematical model of axial crushing of cylindrical tubes. It is assumed that the folding curves or lobes are straight and the variations of circumferential strain are also taken into account. It is found that the predicted results showing reasonably good agreement with experimental works.

Hong et al. [4] investigated the crushing responses of triangular steel tubes under quasi-static compression. The deformation curves and collapse modes are observed experimentally. Both the analytical and numerical predictions are compared with the experiments to build an effective method
to predict the mean crushing force of the triangular tubes. Tarigopula et al. [5] conducted the axial crushing of thin-walled high strength steel sections under dynamic and static loading. Various collapse modes have been identified and the associated energy absorbing characteristics are assessed. It is observed that top-hat sections absorb more energy than square sections. Fan et al. [6] studied the quasi-static axial compression of thin-walled tubes with different cross-sectional shapes. The main objective of this work is to investigate the corners within the tubes capable to absorb the crushing energy effectively. It is found that the ratio of D/t larger than 50 offers the optimum shape for the thin-walled design sections.

Lack of works found to investigate the crushed energy when the structures are compressed obliquely [7-10]. Some works on the oblique energy absorption performances are presented. Azimi and Asgari [7] developed a new bi-tubular conical-circular structure for improving crushing behavior under axial and oblique impacts. It is showed that filling the structures with foam not produce better crashworthiness characteristics while bi-tubular configurations effectively improve the crushing and energy absorption performances especially under oblique loading. Djamaluddin et al. [8] optimized the foam-filled double circular tubes under axial and oblique loading. It is found that under 30° oblique loading, foam-filled empty double tube is the best choice for energy absorbing applications.

The effect of defect on the tube wall under oblique loading is investigated experimentally and numerically by Nia et al. [9]. The collapse initiators are used to improve the progressive collapses. Using buckling initiators, results in increase of crush force efficiency about 19.54%, 50.77% and 44.14% for 7°, 14° and 21° loading angles, respectively. In order to increase mean crushing load and therefore, better energy absorption, initiators must be located at the top end of the tube especially for ones with greater loading angles. Reyes et al. [10] investigated experimentally and numerically the energy absorbing capability of obliquely loaded square thin-walled aluminum columns. The results of their works are also compared with Eurocode 9. For thin-walled columns, the load increases up to the peak load, and then falls drastically. However, when the wall thickness is increased, the shape of the force-displacement curves changes. The large drop from the initial peak force disappears, and for temper T4, the force level remains higher than the initial force for the whole displacement. Investigations of crushing responses of natural fiber reinforced composites are found in [11-17]. Based on the literature survey conducted recently, it has no found the investigations studied on the effect of elliptical geometries on the crushing response of thin-walled structures. Therefore, this paper presents numerically the crashworthiness behavior of steel tubes under oblique loading conditions. The crushing aspects and mechanisms of the tubes are analyzed and discussed in term of oblique angles and elliptical ratios.

2. Methodology

The tube is made of mild steel and two types of fibers are separately used to warp over the cylindrical surfaces of the tubes. The characteristics of the materials are tabulated in Tables 1 and 2. The internal diameter of the tube, D = 58 mm with a thickness of 1 mm. The total height is 170 mm. There are three thicknesses of the composite layers are used such as 0.5, 0.8 and 1.0 mm and all steel tubes are warped with three layers of composites. In order to simulate the oblique responses of the hybrid tubes, four oblique angles are used such as 5°, 10°, 15° and 20°. On the other hand, instead of circular steel tubes, elliptical-shaped tubes are also investigated. There are six elliptical ratios are used namely 0.5, 0.8, 1.0, 1.2, 1.5 and 1.8. The purpose of using elliptical shaped tubes is to study the role of geometries on the energy absorption capabilities. The effects of composite orientations on the crushing responses are also studied. Three types of orientations are used where these angles are measured with respect to the horizontal axis. These angles are +45°, +60° and +90°.

Both steel tube and composite layers are modeled using shell element considering the Belytschko-Tsay formulation available in ANSYS explicit program. It is used a reduced integration technique and capable to accelerate the computational. There are three main bodies are considered such as rigid moving and stationary plates. The moving plate is placed on the top of the tube while the stationary plate is positioned at the bottom edge. Both plates are assumed as a rigid element. The material
behavior of the steel tube is modeled to follow the bilinear kinematic hardening according to the Table 1. On the other hand, composite damage criterion is based on the Chang and Chang damage criterion. Eroding-Single-Surface is used to identify the contacting surfaces. The contact between rigid plates and the tube is modelled using Automatic-Surface-to-Surface. It is also capable to capture a reaction forces between such two surfaces. The friction coefficient between composite layers and steel surface is 0.2 and Contact-Tie-Brake-Nodes-Only contact algorithm is assumed between these two surfaces considering the shear force is 0.1kN. Figure 1 shows the validation of the present model with an existing model obtained from Huang et al. [14]. It is revealed that both models are well agreed while Table 3 lists the average and maximum forces for a comparison purpose. It is indicated the differences between maximum and average forces are 1.4 and 1.7%, respectively showing the present model is well accepted. On the other hand, Figure 2 reveals the deformations of the tubes when quasi-statically compressed.

Table 1: Mechanical and physical properties of steel tube.

| Property                  | Value          |
|---------------------------|----------------|
| Density, $\rho$           | $7.82 \times 10^{-6}$ kg/mm$^3$ |
| Modulus Young, $E$        | 207.2 GPa      |
| Yield Strength, $\sigma_y$| 235 MPa        |
| Poisson’s ratio, $\nu$    | 0.33           |

Table 2: Mechanical properties of carbon and e-glass fibres reinforced epoxy composites

| Property                        | Carbon/ Epoxy | E-glass/ Epoxy |
|---------------------------------|---------------|----------------|
| Density, $\rho$ (g/cm$^3$)      | 1.53          | 1.80           |
| Longitudinal Modulus, $E_A$ (GPa)| 135           | 30.9           |
| Transverse Modulus, $E_B$ (GPa)   | 9.12          | 8.3            |
| In-plane Shear Modulus, $G_{ab}$ (GPa) | 5.67    | 2.8            |
| Minor Poisson’s Ratio, $\nu$    | 0.021         | 0.087          |
| Longitudinal Tension Strength, $X_t$ (MPa) | 2326       | 798            |
| Longitudinal Compressive Strength, $X_c$ (MPa) | 1236       | 480            |
| Transverse Tension Strength, $Y_t$ (MPa) | 51         | 40             |
| Transverse Compressive Strength, $Y_c$ (MPa) | 209        | 140            |
| In-plane Shear Strength, $S_{ab}$ (MPa) | 87.9        | 70             |

3. Results and discussion

Figure 3 shows the force-displacement curves of the empty tubes under different angles of crushing forces. It is seemed that the curves are almost similar except for the case of axial compression where both peak and fluctuation forces are relatively higher than other tubes. The peak forces are also strongly related with oblique angles. Increasing the angles reduced the peak forces. The reduction of peak forces are due to the fact that when the tubes are inclined the bending moment taking the place instead of axial compressive forces. Figure 4 shows the effect of oblique angles on the specific energy absorption performances. It is calculated by determining the area under the curves. The introductions of oblique angles capable to reduce the energy absorption capabilities.

Comparing between angles 0° and 5°, the tubes are slightly inclined thus producing insignificant bending moment effect. On the other hand, if 20° angle is used, the relative distance between 0° and 20° is large and consequently higher bending moment is obtained. Figure 5 shows the effect of elliptical ratios, a/b on the energy absorption capabilities. It is known that if a/b = 1.0, the tube shape is circular. It is indicated that if the ratio is less than 1.0, the performances of tubes to absorb crushing energy is insignificant. When a/b ratio increased, the energy absorption are also increased. However, increasing the energy absorption performances on the other hand increase the weight of the tubes due to the changes of geometries.

Figure 6 shows the effect of elliptical ratio, a/b on the force ratio. The force ratio is the division between average and maximum forces. It is indicated the force dropped after the tubes experiencing the peak force. According to Figure 6, the role of elliptical ratios on the force ratios are insignificant.
However, the force ratio is seemed to increase if the elliptical ratio is less than 1.0 when compared with the case of $a/b > 1.0$. Even though, the force ratio is slightly lowered but the capability of this kind of tube is higher than others.

Figure 7 depicts the effect of oblique compressive angles on the performances of energy absorptions when elliptical ratios are varied. In general, when the compressive forces are applied obliquely, the energy absorption capabilities are reduced. For a certain angle, the energy absorption also increased as the elliptical ratios increased. However, the reductions of energy absorption can be enhanced through the introduction of elliptical-shaped tube geometries even though the tubes are compressed obliquely. Figure 8 shows the progressive collapses of the empty tubes subjected to different oblique compressive forces. It is also observed that the first folding started at the upper edge specifically at the contact surfaces between the tube and the moving flattened plate and then the next lobes appeared after another. Figure 8(a) reveals the crushing mechanisms of the axially compressed tube. Based on the top view of the crushed tube, it is seemed that the tube wall folded symmetrically. However, when the oblique angles are introduced, different folding mechanisms occurred around the wall. This is due to the fact that when the tubes are oblique, axial force is not only the stress in the tube but bending stress is also played an important role. It is indicated that for obliquely compressed tubes, there are bulge at the bottom edge of the tubes. The severity of the bulges increases as the oblique angles increased.

![Figure 1: Force versus displacement for comparison between the present and existing models.](image1)

![Figure 2: Comparative deformations of (a) during progressive collapse and (b) top view of final deformations](image2)

| Forces      | Present Model | Huang et al. (2012) | Error (%) |
|-------------|---------------|---------------------|-----------|
| Average     | 39.5          | 40.2                | 1.74      |
| Maximum     | 100           | 101                 | 1.00      |

Table 3: Comparison between average and maximum forces with an existing model.
Figure 3: Force-displacement of empty tubes under different oblique compressive angles

Figure 4: Effect of oblique angles on the specific energy absorptions

Figure 5: Effect of elliptical ratios on the energy absorption capabilities
4. Conclusion
In this paper, empty circular and elliptical tube columns are numerically investigated using ANSYS explicit finite element program. These different geometries of tubes are compressed quasi-statically and obliquely to obtain their crashworthiness characteristics. Several conclusions can be drawn as follows:
1. Axially compressed tubes offered better energy absorption performances compared with obliquely compressed tubes.
2. Force ratio for elliptical tubes have improved compared with the circular tubes. However, if the elliptical ratio is greater than 1.0, the force ratio is slightly decreased.
3. Under oblique compression conditions, the crushing response is low however the performance of energy absorption is improved by changing the circular into elliptical-shaped geometries.

Acknowledgement
Authors acknowledge Universiti Tun Hussein Onn Malaysia (UTHM) for financially supporting this work through the program of GIPS (Research Graduate Incentive Grant) vot. 1246.
Figure 8: Progressive collapses of the circular-shaped tubes under different angles of loading (a) 0°, (b) 5°, (c) 10° and (d) 20°
References

[1] Lu G and Yu TX 2003 Energy absorption of structures and materials Woodhead Publishing 1st Edition.

[2] Norman J 2012 Structural impact, New York: Cambridge University Press.

[3] Gupta NK and Abbas H 2000 Mathematical modeling of axial crushing of cylindrical tubes Thin-Walled Structures 38 335-375.

[4] Hong W, Jin F, Zhou J, Xia Z, Xu Y, Yang L, Zheng Q and Fan H 2013 Quasi-static axial compression of triangular steel tubes Thin-Walled Structures 62 0-17.

[5] Tarigopula V, Langseth MO, Hopperstad S and Clausen AH 2006 Axial crushing of thin-walled high-strength steel sections Int. Journal of Impact Engineering 32 847-882.

[6] Fan Z, Lu G and Liu K 2013 Quasi-static axial compression of thin-walled tubes with different cross-sectional shapes Engineering Structures 55 80-89.

[7] Azimi MB and Asgari M 2016 A new bi-tubular conical-circular structure for improving crushing behavior under axial and oblique impacts Int. Journal of Mechanical Sciences 105 253-265.

[8] Djamaluddin F, Abdullah S, Ariffin AK, Nopiah ZM 2015 Optimization of foam-filled double circular tubes under axial and oblique impact loading conditions Thin-Walled Structures 87 1-11.

[9] Nia AA, Nejad KF, Badnava H and Farhoudi HR 2012 Effects of buckling initiators on mechanical behavior of thin-walled square tubes subjected to oblique loading Thin-Walled Structures 59 87-96.

[10] Reyes A, Langseth M and Hopperstad OS 2003 Square aluminum tubes subjected to oblique loading Int. Journal of Impact Engineering 28 1077-1106.

[11] Ismail MA and Ismail AE 2015 Eccentric crushing behavior of high strength steel tubes Int. Journal of Mechanical & Mechatronics Engineering 15 100-104.

[12] Ismail AE and Sahrom MF 2015 Lateral crushing energy absorption of cylindrical kenaf fiber reinforced composites Int. Journal of Applied Engineering Research 10 19277-19288.

[13] Ismail AE and Hassan MA 2014 Low velocity on woven kenaf fiber reinforced composites Applied Mechanics and Materials 629 503-506.

[14] Huang MY, Tai YS and Hu HT 2012 Numerical study on hybrid tubes subjected to static and dynamic loading Applied Composite Materials 19 1-19.

[15] Roslan MN, Ismail AE, Hashim MY, Zainulabidin MH and Khalid SNA 2014 Modelling analysis on mechanical damage of kenaf reinforced composite plates under oblique impact loadings Applied Mechanics and Materials 465-466 1324-1328.

[16] Ismail AE, Zainulabidin MH, Roslan MN, Mohd Tobi AL and Muhd Nor NH 2014 Effect of velocity on the impact resistance of woven jute fiber reinforced composites Applied Mechanics and Materials 465-466 1277-1281.

[17] Eyvazian A, Mozafari H and Hamouda AM 2017 Experimental study of corrugated metal-composite tubes under axial loading Procedia Engineering 173 1314-1321.