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LATERAL CRUSHING OF SINGLE AND MULTI-CELL THIN-WALLED CIRCULAR TUBE UNDER A QUASI-STATIC LOADING

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Abstract

The thin-walled structure is widely used as an energy absorption system due to low cost, easy availability and lightweight. Furthermore, the energy absorption performance of a multi-cell thin-walled tube has been reported to perform better compared to a single thin-walled tube. This paper addresses the energy absorption capacities of single and multi-cell thin-walled circular tubes under quasi-static lateral loading. The quasi-static compressive lateral loading test was performed to identify the deformation behaviour and energy absorption of singular and multi-cell thin-walled circular tubes. Thin-walled circular tubes are made of mild steel with 3.85 mm thick, 60.3 mm diameter and height 20 mm were under quasi-static compression test. While other single circular tubes with the same thickness and height with different 128 mm diameter were under the same compression condition to compare the energy absorption with a multi-cell tube. The results show that the energy absorption performance of multi-cell thin-walled circular tubes is superior compared to that of a single thin-walled circular tube.

Keywords: Crashworthiness, Energy absorption, Multi-cell, Thin-walled tubes.

1. Introduction

Thin-walled tubes are widely used in crashworthiness application as energy absorption structures. The term "crashworthiness", according to Lu and Yu [1], is the condition of a vehicle or structure under impact. Energy absorber has good crashworthiness when the protection structure or vehicle's occupants and contents sustain less damage after a crash event. Thin-walled structures are commonly used as energy absorbers for their good performance of energy absorption, low cost and lightweight application. Various geometries or shapes are mostly used as energy absorption. It is reported by Nia and Hamedeni [2], among those tubes, circular tubes are more efficient than the square tubes in energy absorption application.

Over the past few decades, relentless efforts have been done by researchers to enhance the energy absorption performance of structures through analytical, experimental and numerical methods [3-10]. Until now, multi-cell structures have been employed in the energy absorption application due to superior energy absorption performance compare with the single cell [11-16]. In addition, multi-cell thin-walled tube supposedly performed significantly better than single thin-walled circular tube since a substantial amount of kinetic energy can be dissipated through plastic deformation compared with a single cell. One of the advantages of tubes under lateral loading is its capability producing a smooth load-displacement response during bending collapse mode. Furthermore, tubes under lateral loading also generated stable deformation mode despite applying off-axis loading [17].

The objectives of this paper are to investigate the crash response and energy absorption capacity of single and multi-cell thin-walled circular tubes under lateral quasi-static loading. To accomplish the aim, the compression test was performed under quasi-static lateral loading to evaluate the energy absorption capacities of these structures. Three samples for each case (single-D60.3, single-D128 and multi-cell thin-walled tubes) were tested to ensure the accuracy of the results.

2. Experimental Work

Experimental work consists of two tests, tensile test and quasi-static compression test. The tensile test was performed in order to determine the material properties of mild steel circular tube. Quasi-static compression test under lateral loading was conducted for a single and multi-cell thin-walled circular tube to determine the energy absorption performance.

2.1. Material properties

Mild steel circular tube was used for the single and multi-cell thin-walled tubes. The tensile test was conducted by using Universal Testing Machine INSTRON 5982 with loading speed 5 mm/min as shown in Fig. 1. The true stress-strain curve was obtained from the tensile test and the test samples were prepared according to ASTM E8M. This standard method is suitable for the tensile test sample obtained from a tabular structure. Table 1 shows the material properties obtained from the tensile test.

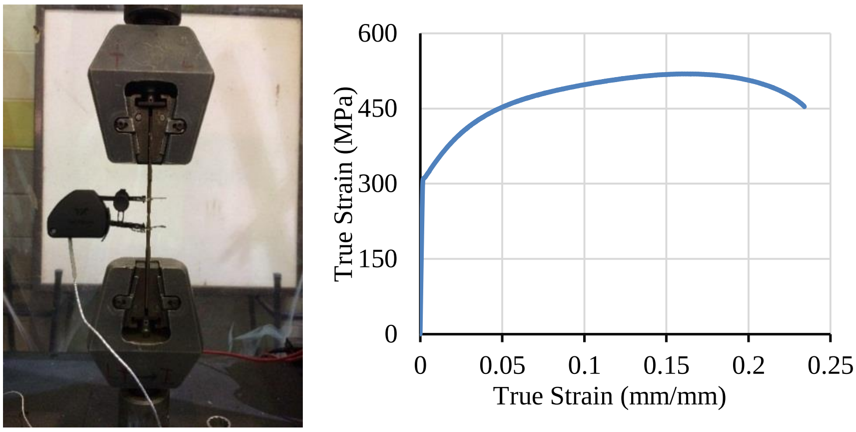

Fig. 1(a) Tensile test set-up by using INSTRON 5982, (b) True stress-strain of mild steel.

Table 1. Material properties of mild steel tube.

	Young's modulus E (GPa)	Poisson's ratio (v)	Density (kg/m^3)	Yield Stress (MPa)	Ultimate tensile stress (MPa)	Ductility (%)
Mild steel	200	0.3	7220	401.13	451	26.40

2.2. Sample preparation

Single and multi-cell thin-walled tubes were prepared by cutting the mild steel tubes into 20 mm height (h) by using Wire Cut Electrical Discharge Machine. The samples were made from 3.85 mm thick (t) and 60.3 mm diameter (D) of mild steel tubes in consideration of availability and cost-effectiveness. The multi-cell tube is a combination of three single circular tubes (60.3 mm diameter). To form multi-cell tubes, each tube was welded together by using Tungsten Inert Gas (TIG) welding. Figure 2 shows the schematic diagram of circular thin-walled tube. While another circular tube with the same thickness and height with different 128 mm diameter were under the same compression condition to compare the energy absorption with the multi-cell tube. Figure 3 shows the configuration of each circular tube side by side with each total height measured from the bottom until the top of the tube as illustrated. Total height is 128 mm, 112 mm and 60.3 mm for the large single thin-walled tube, multi-cell thin-walled tube and small thin-walled tube respectively.

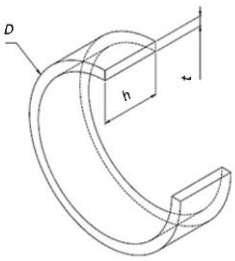

Fig. 2. Schematic diagram of thin-walled circular tube.

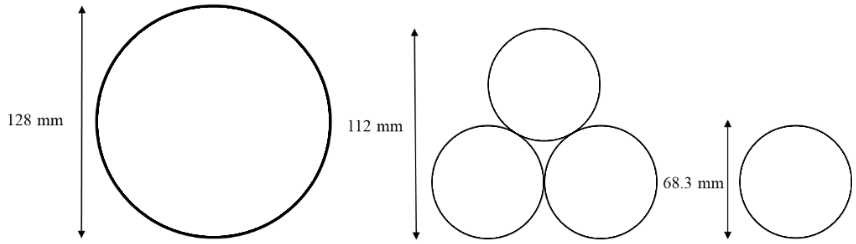

Fig. 3. Schematic diagram of thin-walled circular tube configuration.

2.3. Experiment procedure

The quasi-static analysis of single and multi-cell thin-walled tube under lateral compression loading have been investigated using an experimental technique. Realistically, this energy absorber devices are usually applied under higher velocity impact however it is preferable to examine the quasi-static loading first due to energy absorber under dynamic loading condition with the same pre-dominant geometrical generated similar response. In addition, dynamic loading tests can be replaced by conducting quasi-static tests since the experimental setup for dynamic loading is much difficult compared with the quasi-static experimental setup. Moreover, the deformation mode and energy absorption of the energy absorber structure under low impact velocity are relatively similar to structures under quasi-static loading [17].

The compression test of the single and multi-cell thin-walled tubes were carried out using INSTRON machine under quasi-static loading. The constant rate of compression loading apply for single and multi-cell tubes are 5 mm/min. This loading rate was chosen due to ensure there was no dynamic effect. The compression machine has two jaws, the upper one is moveable and the lower one is stationary. The tubes sample is set in between two jaws horizontally and is compressed laterally as illustrated in Fig. 4. The maximum load cell of this machine is 50 kN. The compressive load was stopped when the desired compressive displacement required, which is 75 percent of its original height. To ensure the repeatability and accuracy of the results, three compression test of single and multi-cell thin-walled tubes were tested.

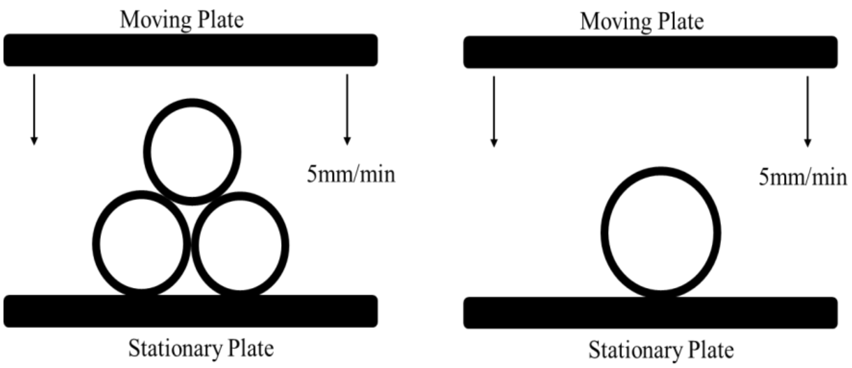

Fig. 4. Schematic diagram of multi-cell and single thin-walled circular tube under quasi-static compression loading.

2.4. Energy absorption indicator

The energy absorption performance of the structures can be assessed by several criteria. Some of useful energy absorption indicator such as specific energy absorption capacity, total energy absorption and crush force efficiency is calculated to evaluate the energy absorber performance. The energy absorption capacity of the thin-walled tube can be determined by calculating the area under the load-displacement curve.

$$E(d) = \int_0^d F(x)dx \tag{1}$$

The energy efficiency indicator is another important response to identify the efficiency of energy absorber performances. The energy efficiency indicator is given as follows.

$$e_E = \frac{E}{F * l} \tag{2}$$

where F is the maximum force identified from the load-displacement curve, while the original length of the energy absorber device is denoted as l. Energy absorber with an ideal rectangle load-displacement response has a maximum value of energy efficiency.

The energy absorbed per unit mass, SEA (kJ/kg), also known as the specific energy absorption is an essential criterion to determine energy absorption capability of unit material by evaluating the ratio of absorbed energy to the structural mass.

$$SEA = \frac{E}{m} \tag{3}$$

The specific energy absorption is considered an essential energy absorption indicator for design a lightweight energy absorber structure. Different energy absorber can be evaluated by comparing the specific energy absorption to determine to the most efficient performance of energy absorber for a given mass. Furthermore, specific energy absorption also a useful parameter when weight reduction is important. The abovementioned energy absorption indicators have prevalently been employed in previous studies [2, 5, 8, 9, 17, 18].

3. Results and Discussion

The three best results of the load-displacement curve obtained from the compression test for small single, large single and multi-cell thin-walled circular tubes are presented in Figs. 5 to 7 respectively. Based on the results of the thin-walled tubes compression test, the crush responses of three tubes sample shows a similar crushing pattern throughout the crushing process.

The small and larger single circular thin-walled tube under lateral loading both produces a smooth load-displacement curve. This kind of load-displacement characteristic usually occurs under lateral loading over axial loading. Moreover, under lateral loading, small single circular thin-walled tube produces a low initial peak load approximately around 3000 to 4000 N as shown in Fig. 4. While the large single thin-walled tube with diameter 128 mm produce initial peak load around

1400 N much lower than small single thin-walled tube as shown in Fig. 5. Since it is always suggested to minimise the initial peak load of an energy absorber device. This is due to the high initial peak load of energy absorber can cause more damage to the protected structures. Furthermore, Fig. 7 shows the load-displacement curve of multi-cell thin-walled tube. The initial peak load of multi-cell thin-walled tubes is around 5000 to 5500 N, approximately 30 percent and 70 percent higher compared to small and large single thin-walled tubes respectively. The multi-cell thin-walled tubes produce a smooth load-displacement curve until around 65 mm displacement, subsequently, the load increases rapidly due to the deformation of the two bottom thin-walled circular tubes.

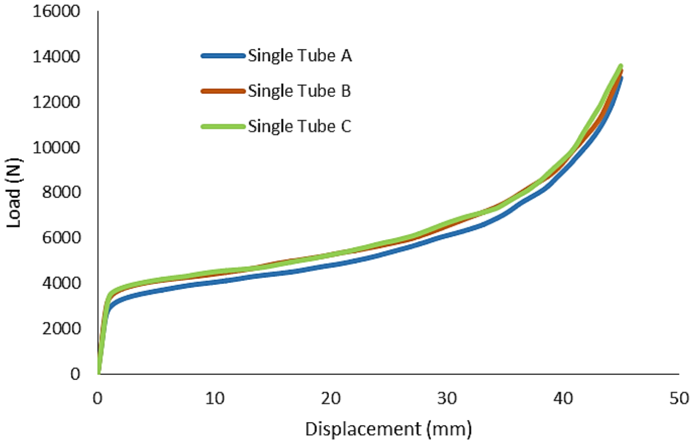

Fig. 5. Load-displacement curve of small single thin-walled circular tubes.

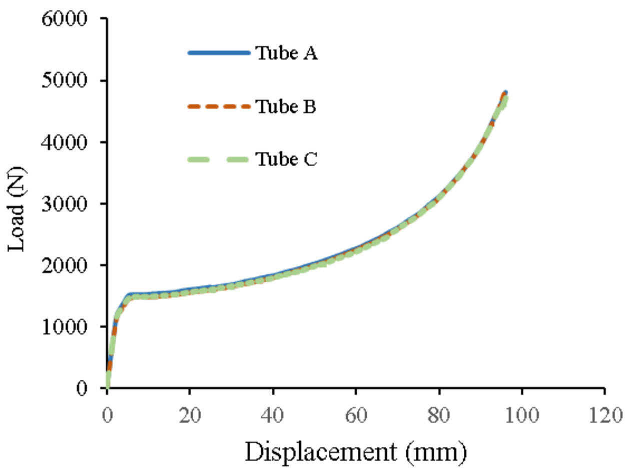

Fig. 6. Load-displacement curve of large single thin-walled circular tubes.

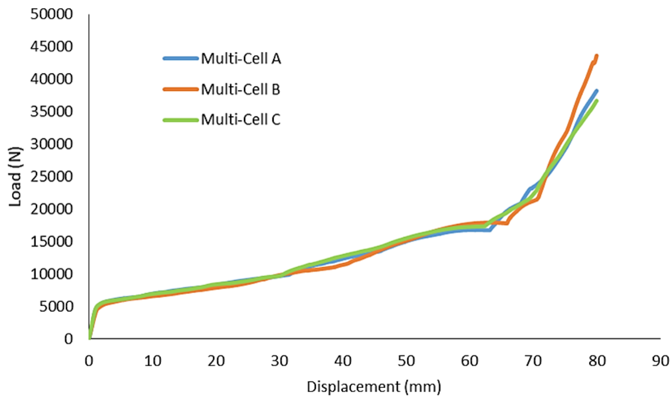

Fig. 7. Load-displacement curve of multi-cell thin-walled circular tubes.

The energy absorption responses of the small single tube, large single tube and multi-cell thin-walled tubes are tabulated in Tables 2 to 4, respectively. However, despite the better energy absorption performance of multi-cell thin-walled tubes, it seems that the specific energy capacity is not significantly improved from both single tubes since the multi-cell thin-walled tube is heavier than the single thin-walled tube.

Hence, this kind of energy absorber device is not recommended for lightweight structure application. Moreover, a single thin-walled tube is more efficient absorbing energy than a multi-cell thin-walled tube since a single thin-walled tube exhibits more stable collapse mode throughout the crushing process.

Small single circular tube with diameter 60 mm have greater energy absorption compare to the large single circular tube with diameter 128 mm. This is due to that the larger tube plastic hinge has small material subjected to form plastic deformation. Nevertheless, results also revealed that small single circular tube has significantly superior specific energy absorption than large single circular tube despite the larger single circular tube have higher displacement stroke.

This is due to a larger diameter single circular tube have higher mass than small diameter but have poor total energy absorption. This can be concluded that increasing the diameter of a single circular tube under quasi-static lateral condition will not give benefit in energy absorption performance.

In addition, increase the circular diameter of thin-walled will reduce the stiffness of the energy absorber structure. Similar results also found by Baroutaji et al. [18] and Gupta et al. [19], towards the effect of circular tube diameter on the specific energy absorption.

The comparison of the load-displacement curve for each thin-walled circular tubes is depicted in Fig. 8. The best curve from the compression test was selected to represent each curve for multi-cell, small and large thin-walled tube. Based on the load-displacement curve, it is obvious that the multi-cell thin-walled tube exhibits significant higher energy absorption capacity.

While the large single thin-walled tube shows poor performance of energy absorption. Nonetheless, large and small single tubes produce smoother load-displacement curve compare to the multi-cell thin-walled tube. The results also revealed that the welding section on multi-cell thin-walled tube adding more strength of the joint therefore enhance the amount of total energy absorption. In addition, the welding section also increases the thickness on the plastic hinge. Hence, the additional material on the welding section will reduce the global buckling effect from occurring during lateral compression.

Figures 9 to 11 show the deformation mode of a small circular tube, large circular tube and multi-cell thin-walled tubes respectively. Figure 9 shows the deformation mode of single thin-walled circular tubes under lateral loading. When the load increases until it reached an elastic limit approximately 5 mm displacement, two plastic hinged are developed. After that, the strain hardening started to occur until it reached maximum displacement. Same deformation behaviour also happens on the large circular tube as shown in Fig. 10.

Meanwhile from Fig. 11, it can be seen that the multi-cell structure exhibits a symmetrically collapse around the vertical axis. The top circular tube start to deform initially followed by the two bottom circular tubes. It also shows that the two bottom circular tubes deformed simultaneously at the onset of the collapse. Both single and multi-cell circular tube deformed differently due to the fact that both tubes have different geometry and structure

Table 2. Energy absorption response of small single thin-walled circular tube.

	Tube A	Tube B	Tube C	Mean	Standard deviation	Coefficient of variance
Specific energy absorption (J/kg)	2627.24	2822.24	2853.47	2767.65	122.59	0.0443
Energy efficiency %	43.76	45.88	45.7	45.11	1.18	0.0261
Energy absorption capacity (J)	257.47	276.58	279.64	271.23	12.01	0.0443

Table 3. Energy absorption response of large single thin-walled circular tube.

	Tube A	Tube B	Tube C	Mean	Standard deviation	Coefficient of variance
Specific energy absorption (J/kg)	942.43	930.35	928.73	933.83	7.49	0.0080
Energy efficiency %	46.98	45.96	47.15	46.70	0.64	0.0137
Energy absorption capacity (J)	216.76	213.98	213.61	214.78	1.72	0.0080

Table 4. Energy absorption response of Multi-cell thin-walled circular tube.

	Tube A	Tube B	Tube C	Mean	Standard deviation	Coefficient of variance
Specific energy absorption (J/kg)	3808.3	3825.31	3842.99	3825.53	17.35	0.0045
Energy efficiency %	36.62	32.22	38.5	35.78	3.22	0.0900
Energy absorption capacity (J)	1119.64	1124.64	1129.84	1124.706667	5.10	0.0045

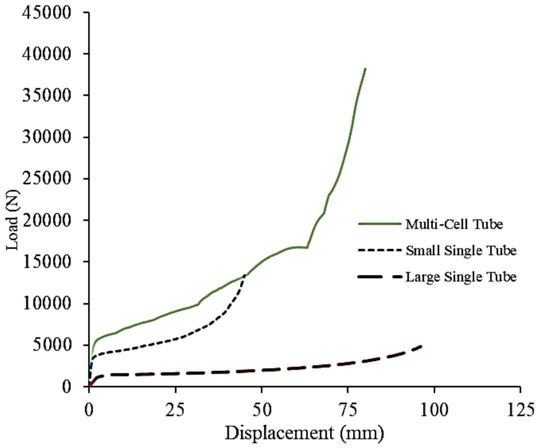

Fig. 8. Load-displacement curve of each thin-walled circular tubes.

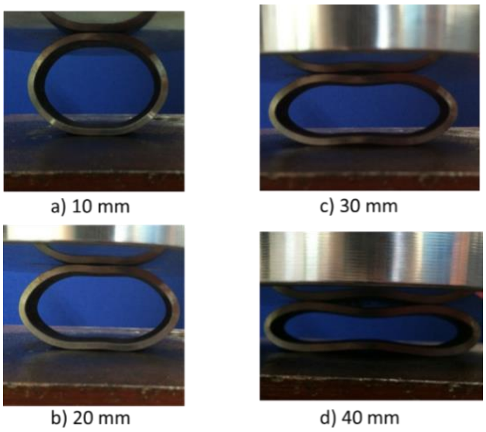

Fig. 9. Deformation mode of small single thin-walled circular tube under quasi-static lateral loading.

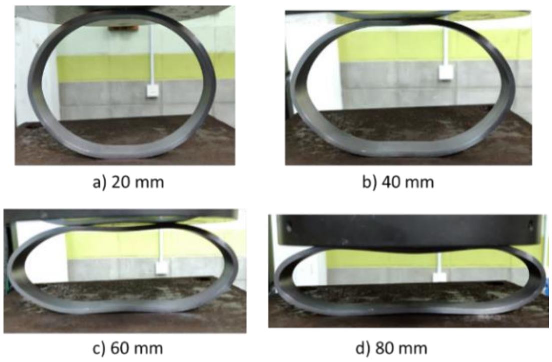

Fig. 10. Deformation mode of large single thin-walled circular tube under quasi-static lateral loading.

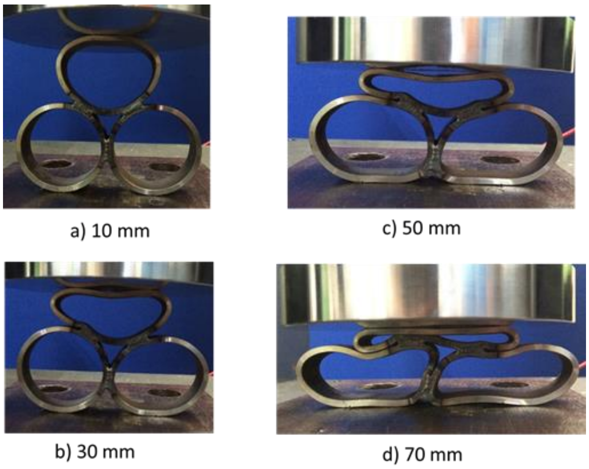

Fig. 11. Deformation mode of a multi-cell thin-walled circular tube under quasi-static lateral loading.

4. Conclusions

The compression test results for single and multi-cell thin-walled tube under quasi-static lateral loading are presented. The value of energy absorption, specific energy absorption and energy efficiency were also highlighted. The primary outcomes of this present study are as follows:

- Thin-walled tubes under lateral loading produce smooth load-displacement curve and low initial peak load.
- Multi-cell thin-walled tubes have higher energy absorption capacity compare to both large and small single tube.
- Both large and small single thin-walled tubes have better energy absorbing efficiency compare to multi-cell thin-walled tube due to its produce smoother load-displacement curve.
- Both large and small single thin-walled tubes have a lower initial peak load compare to the multi-cell thin-walled tube.
- The specific energy absorption of the multi-cell thin-walled tube is not significantly higher than that of large and small single thin-walled tubes. Hence, a multi-cell thin-walled tube is not preferable as an energy absorber for lightweight application.

For the future work, the numerical simulation for single and multi-cell thin-walled circular tube will be carried out by using LS-DYNA nonlinear explicit code, to predict the energy absorption effect for various geometries and configurations. Hence, it can provide the optimum energy absorption of Multi-cell thin-walled tubes.

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Nomenclatures

D	Diameter of tube, mm
$E(d)$	Total energy absorption, J
e_E	Energy efficiency indicator, %
F	Load, N
h	Height of tube, mm
l	Maximum displacement, mm
m	Total mass of energy absorber structure, kg
SEA	Specific energy absorption, J/kg
t	Thickness of tube, mm
x	Displacement, mm

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