

Study of multi-cell thin-walled tube with various configuration under lateral loading

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Abstract. Thin-walled structure is one of the common structures that is widely used as an energy absorber due to inexpensive, high availability and lightweight. Moreover, the multi-cell structure is known as a useful method to elevate the effectiveness of thin-walled structures in crashworthiness. Energy absorber performance of multi-cell thin-walled tube structure is known to be greater than the single thin-walled tube. This is due to the limitation of plastic hinge zones of single tube during lateral loading condition. This paper presents the effect of multi-cell configuration on energy absorption responses under lateral loading condition. Experiment and numerical approach were used in this research. The validation of finite element model (FEM) was conducted by comparing the load-displacement responses and deformation mode of a quasi-static compression test. Multi-cell configuration study was performed to identify the energy absorption performance of multi-cell thin-walled tube with different arrangements. The results reveal that an increasing number of cells will increase the energy absorption capacity of multi-cell structure. The additional number of tube cells contribute to the increases of the contact joint between each tube consequently this generate additional permanent plastic-hinges.

1. Introduction

Recently, thin-walled structures are used in crashworthiness application due to their light weight, lower cost, and ease of production. The term crashworthiness is the ability of a vehicle or structure to withstand impact. Energy absorbers have good crashworthiness when the protected structure or vehicle's occupants and content sustain less damage after the crash event. The thin-walled tube was used widely as an energy absorber due to their good performance of energy absorption under a variety of loading condition. Therefore, various geometries, configuration, and shapes of thin-walled tubes have been widely investigated by previous researchers. Various section geometries of thin-walled tubes were investigated by Nia et al. [1] to analyze their energy absorption performance. The results revealed that the circular tube outperformed other geometries in terms of energy absorption efficiency.

A circular thin-walled tube under lateral loading was commonly investigated as an energy absorber device [2-4]. Generally, the geometrical parameter is the main factor that influences the energy absorption behavior of a circular tube. Gupta et al. [5] found that minimal diameter and thicker tube wall of the circular tube have better energy absorption performance under lateral loading condition. Similar results were also found by Barautaji et al. [6] where a greater energy absorption was found in tubes with the lower diameter and thicker tube wall. In addition, Barautaji et al. also revealed that the



width of circular thin-walled tube has less influence on specific energy absorption (SEA). According to Reid and Reddy [7], a single circular thin-walled tube under lateral loading produce four stationary plastic hinges. Owing to the limitation of plastic hinges zones of circular tube, a few researchers suggested applying external constraints to generate more plastic hinges thus will enhance the energy absorption performance. In addition, nested tube structures also purposed by previous researchers for a better energy absorption performance [8-12]. Under lateral loading condition, this system is capable to efficiently dissipate kinetic energy with minimal crush zone. Olabi et al [13] improved the nested tube system by inserting two small tabular bars between the space gaps of each tube. The result shows that inserting two tabular bars improved energy absorption performance. Moreover, an elliptical tube under lateral compression was investigated by Wu and Carney [14]. The results revealed that the elliptical tube has better energy absorption performance and crushing efficiency than the regular circular tube.

The paper aims at addressing the configuration design issues of the multi-cell structure under the lateral loading condition. A various of multi-cell thin-walled tube configuration designs were purposed to investigate its influence on energy absorption performance. A finite element software, LS-DYNA was employed to construct the model of multi-cell structure under lateral loading. The validation of the finite element model (FEM) was conducted by comparing the load-displacement responses and deformation mode of a quasi-static compression test.

2. Finite element modelling

LS-DYNA finite-element software was employed to simulate multi-cell thin-walled tube under lateral loading. This finite element (FE) model consists of three main parts. The impactor is a moveable rigid body that was modeled to vertically moved in one direction. A stationary plate was also modeled as a rigid body with all translation and rotations being fixed. To simulate quasi-static lateral loading, prescribe motion rigid was used in this numerical model to avoid any dynamic effect. The multi-cell thin-walled tube was modeled using piecewise linear material model. Automatic surface to surface contacts were defined between each part to avoid any penetration. Mesh convergence study was conducted, and it was found that 1.5mm is an optimum mesh size that produces converged solution within a reasonable time.

The FE model results of multi-cell structure were validated against the results of the compression test carried out by using the Instron machine. The compression test of multi-cell thin-walled tubes was performed under quasi-static lateral loading with a constant loading rate of 5 mm/min. The validation was done by comparing the load-displacement curve, energy absorption responses, and deformation mode. The total energy absorption (TEA) values were identified by calculating the area under load-displacement curve. Meanwhile, the SEA is donated as the ratio of total absorbed energy against the structural mass. Figure 1 shows the load-displacement curve between numerical and experimental results of a multi-cell thin-walled tube subjected to lateral loading. Nevertheless, the predicted path of the load-displacement curve is slightly off compared to the experimental curve during the compression displacement around 55mm. This is due to the two bottom tubes of numerical model deforming sooner than experimental condition. Particularly, this situation happens due to the effect of the welding section which increases the strength of the multi-cell structure. Consequently, the additional material on the welding section affected the plastic hinge and deformation of multi-cell structures.

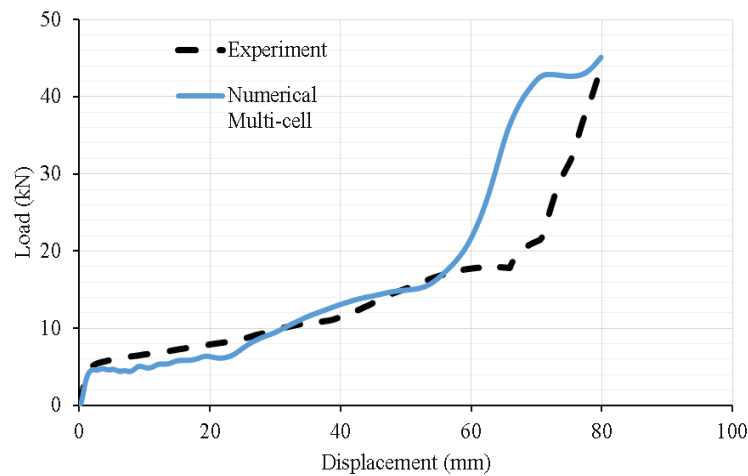


Figure 1. Load-displacement curve of multi-cell thin-walled tube.

Nevertheless, the final stage of deformation mode of the numerical model produced a similar result as the experiments shown in Figure 2. However, the buckling effect on the tube wall is present on the deformation mode of FE model. The reason for the discrepancy was attributed to the ignorance of the welding effect of FE model.

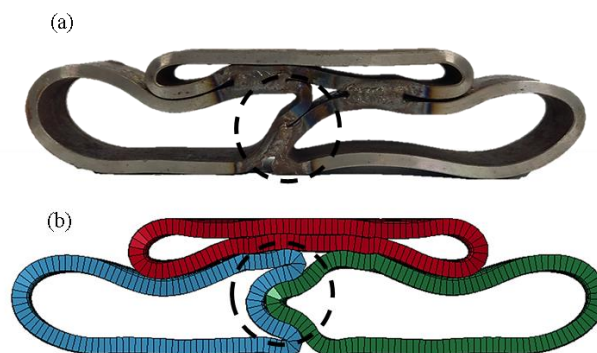


Figure 2. Deformation mode of multi-cell thin-walled tube (a) experiment and (b) numerical.

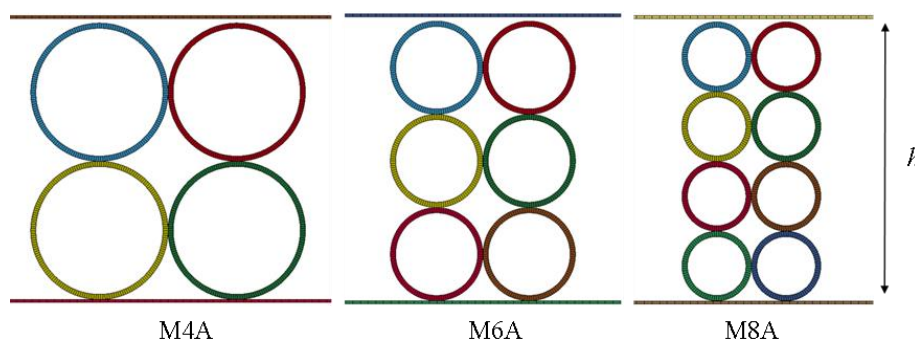
The percentage error between numerical and experimental results was presented in Table 1. The numerical model was capable to predict the initial peak load (F_{peak}) in which the percentage error does not exceed 10 percent. Moreover, the percentage error of SEA is within an acceptable range. The discrepancy is due to the differences of load-displacement produces by numerical and experimental approaches.

Table 1. Comparison between experimental and numerical result multi-cell.

	SEA (J/kg)	F _{peak}
Experiment	933.84	1.45
Numerical	848.13	1.3
Error	14.6 %	7.7 %

3. Multi-cell configuration

This section presents the result of a multi-cell configuration study of the variables cells number with constant height and the total weight of energy absorber. There are three different multi-cell configurations as shown in Figure 3. The height is maintained at 181.5 mm and the total weight of 0.564 kg. Each multi-cell configuration has a different dimension of tube diameter and thickness as tabulated in Table 2.

**Figure 3.** Multi-cell configuration of M4A, M6A, and M8A.**Table 2.** Formatting sections, subsections and subsubsections.

	M4A	M6A	M8A
Diameter, mm	90.75	60.50	45.38
Thickness, mm	3.43	3.50	3.58
Weight per cell, kg	0.141	0.094	0.071

The results revealed that increased the cell number will increase the SEA and TEA values thus enhancing the energy absorption performance. The M8A multi-cell configuration with 8 number of cells absorbed the highest energy throughout plastic deformation in comparison to M6A and M4A multi-cell structures as shown in Figure 4. The SEA produced by M8A is more than 2 and 4 times superior than M6A and M4A respectively, even each multi-cell configuration structure has a similar amount of total weight available. Consequently, it shows that the multi-cell configuration of M8A is applicable as an energy absorber structure that has limited stokes length and space and capable of generating superior SEA response.

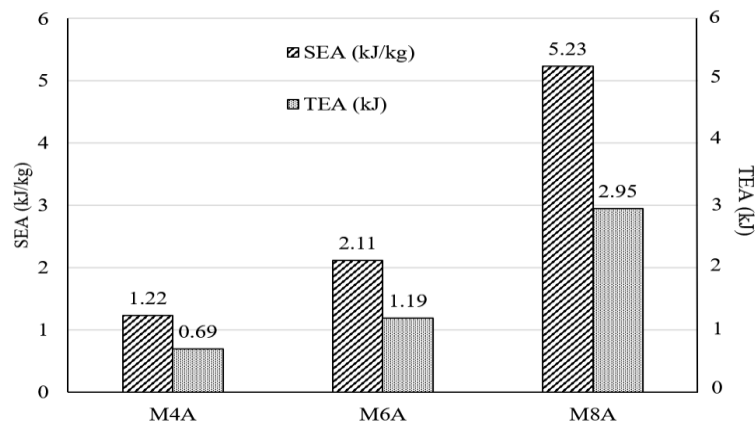


Figure 4. The effect of multi-cell configuration on SEA (kJ/kg) and TEA (kJ).

Moreover, adding the number of circular tube cells will increase the total energy absorption. The additional cell number will enhance the strength and rigidity of the energy absorber structures. Also, the additional cell number offers more material for multi-cell structure to absorb energy throughout permanent plastic deformation. The rigidness of the structure also depends on the contact joint between each circular tubes of multi-cells structures. Higher contact joint will generate additional plastic hinges thus improve the energy absorption performance. M8A produce more permanent plastic hinges due to contact joint than other multi-cell configurations as shown in Figure 5. A circular tube able to generate four plastic hinges located at end of horizontal and vertical axes. Adding more cell will generate additional plastic hinges during the process of crushing.

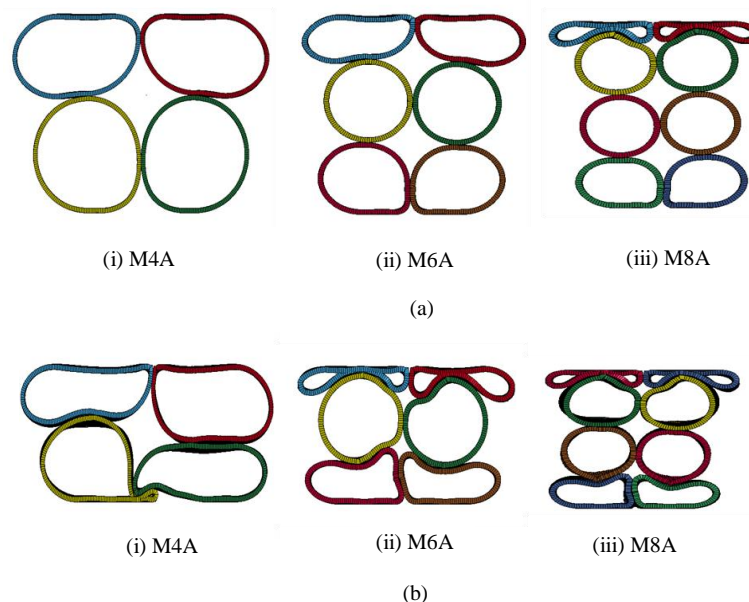


Figure 5. Deformation mode of different multi-cell configuration structure (a) deformation mode at 40 mm displacement (b) deformation mode at 70 mm displacement.

The results also show that among all these multi-cell configurations, M8A exhibit better energy absorption efficiency than another multi-cell configurations. The multi-configuration of M4A and M6A have almost similar energy efficiency. Figure 6 shows the energy absorption efficiency of M4A, M6A and M8A. In details, M8A produce 60 percent and 66 percent better energy efficiency e_E than both M4A and M6A respectively. This revealed that the M8A multi-cell configuration not only exhibits better energy absorption performance but also better efficiency in absorbing energy.

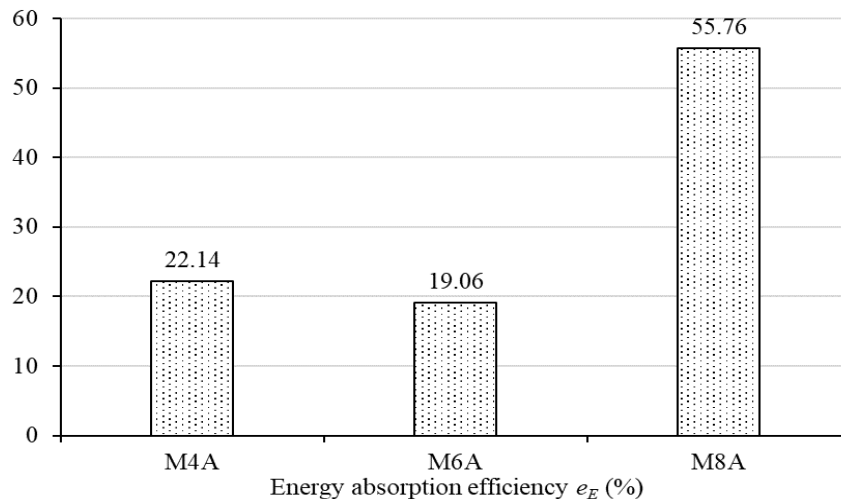


Figure 6. The effect of multi-cell configuration on energy absorption efficiency.

4. Conclusion

This paper presents the energy absorption performance of various multi-cell configuration under lateral loading. The validation of FE model was performed to ensure the accuracy and reliability of numerical model. In addition, the validation of FE model shows a good agreement with experimental results. The behaviour of various multi-cell configuration can be summarized as follows:

- M8A system with 8 number of tube cells generates superior SEA and TEA value than M4A and M6A with similar height and total weight. Therefore, M8A system is preferable for application of energy absorber with limited space and weight.
- Increasing the number of tube cells of multi-cell structure will increase the contact joint between each tube, consequently, this generate additional permanent plastic-hinges.
- M8A system produces 60 per cent and 66 per cent better energy efficiency in comparison to both M4A and M6A respectively.

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