Parametric Study of Bio-Inspired Thin-Walled Tubes Impacted under Axial and Oblique Loadings

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Abstract. Thin-walled structure is widely used as energy absorber in automotive industries due to its superior crashworthiness characteristics. In these recent years, many studies had been performed to design the new shapes of thin-walled tube that are inspired by a biological component, especially from animals and plants. This research aims to conduct a parametric study of bio-inspired thin-walled tubes to enhance the energy absorption characteristics. Two designs of bio-inspired thin-walled tubes had been proposed in this study. The tubes were impacted under axial and oblique loadings by using a finite element analysis software. The results show that the proposed designs provide better energy absorption capacity and specific energy absorption compared to the conventional tube at different thicknesses and diameters. The trend of the results obtained from this study can be used to improve the design of bio-inspired thin-walled structure in the future.

1. Introduction
Thin-walled tube is one of the energy absorber device that is commonly used to absorb kinetic energy during an impact event. Commonly, the automotive industries used thin-walled tube structure as the impact absorber in the automobile. There have many studies that had been conducted to improve the efficiency of this structure, which is measured by energy absorption characteristics [1]. These works have been conducted by designing the tubes with various geometries, shapes and materials [2]. Besides that, there have also many studies that performed modification of thin-walled structure by applying groove, cut-out, multi-cell and many more [1].

In these recent years, designing a thin-walled tube inspired by a biological structure has been a new field for researchers to explore [3]. This idea is adopted from the natural environment, for example, how the plants and animals had survived to undergo various evolutions through all thousands of years. The previous thin-walled tube designs are inspired from bamboo, horsetail, honeycomb, beetle, horns, bone, cattail and many more [4]. Bio-inspired design has shown a promising future when it proved to enhance the energy absorption capacity over the conventional thin-walled tube design. For example, bamboo is a lightweight biological compounded material with higher stiffness–mass ratio than some metallic materials such as aluminium and steel [5]. Zou et al. [6] proposed a new shape of thin walled-tube inspired by the bamboo and the result had successfully improves the energy absorption capacity and...
specific energy absorption (SEA). However, further improvement should be performed to reduce the high value of initial peak load in bio-inspired design. In this study, two modified shapes of thin-walled tube that are inspired by the bamboo vascular will be proposed. The modified thin-walled tube will be impacted under axial and oblique loadings by using a finite element model. The energy absorption characteristics such as energy absorption (EA), specific energy absorption (SEA), initial peak load (IPL) and crush force efficiency (CFE) will be compared and discussed at the end of this study.

2. Designs and Methods
This study proposes two designs of thin-walled tube, namely as Design 1 and Design 2, as shown in Figure 1(a) and (b), respectively. These designs are inspired by the micro-architecture of the vascular bundle in the bamboo structure, as shown in Figure 2. These designs are adapted from Dayong et al. [7], where the initial design is customized in circular profile and rearranged in the form of three small circles in one big circle as shown in Figure 1.

![Figure 1. Top view of the proposed thin-walled tube designs: (a) Design 1 and (b) Design 2.](image)

![Figure 2. The microstructure of the vascular bundle in a bamboo structure [7].](image)
The explicit FE code LS-DYNA was used to simulate the axial and oblique impact on the proposed tubes. The details explanation of FE model has been discussed by Ahmad et al. [8]. Figure 3 shows the arrangement of moving mass, thin-walled tube and stationary mass in the FE model. The moving mass is only allowed to move in downward motion with a given initial velocity and the stationary mass is constrained in all axes.

![Figure 3. Development of FE model for (a) axial loading and (b) oblique loading.](image)

The four-node Belytschko-Tsay shell elements with five integration points through thickness was applied to model the tube wall. The interface between the moving mass and the tube was generated using “auto nodes to surface” contact with the static and dynamic frictional coefficients are set as 0.3 and 0.2, respectively. A 2.0 to 2.1 mm size of the shell element was employed to the tube, based on the previous mesh convergence study conducted by Ahmad et al. [9]. Aluminium alloy AA6061-T6 was used as the material of the tube with the value of Young’s modulus $E = 68.9$ GPa and Poisson’s ratio $\nu = 0.33$. The tube was modelled using material model 024 (piecewise linear plasticity) in LS-DYNA. To ensure the reliability of the FE model, it was compared to the experimental results as discussed by Ahmad et al. [8]. Although there are some differences between the FE model and experimental results, the differences are within the acceptable range of scientific error in a dynamic event with less than 15% of percentage error in overall energy absorption characteristics.

### 3. Results and Discussion

Several simulations were conducted to measure the effect of wall thickness and tube’s outer diameter on the energy absorption characteristics for conventional tube and the proposed tubes (Design 1 and Design 2). In order to compare the results between the tubes, the length of the tube is kept constant at 240 mm and the semi-apical angle for oblique loading is fixed at $20^\circ$.

#### 3.1. Effect of varying thickness on energy absorption characteristics for axial and oblique loadings.

In order to study the effect of thickness on the impact responses, the diameter of the biggest and the smallest circle (refer Figure 1) are kept constant at 100 mm and 10 mm, respectively. It should be noted that the diameter of the largest circle in Figure 1 is referred for the diameter of conventional circular tube. Figure 4 shows the results of energy absorption characteristics when the thickness of the tube is varied from 0.5 mm until 1.5 mm. The symbol ‘0°’ in the figure indicates for axial loading condition, while the symbol ‘20°’ indicates for oblique loading, where a 20° of semi-apical angle was applied.
Figure 4. Effect of wall thickness and loading angle on energy absorption characteristics; (a) energy absorption capacity, (b) initial peak load, (c) specific energy absorption (SEA) and (d) crush force efficiency (CFE).

In general, an optimum energy absorber has the following energy absorption characteristics; high value of energy absorption capacity (EA) and specific energy absorption (SEA), low value of initial peak load (IPL) and unity value of crush force efficiency (CFE). It can be observed from Figure 4 that the value of EA, SEA and IPL increased significantly with increasing of wall thickness. Besides that, it can be summarized that the proposed designs (Design 1 and 2) had successfully improved the value of EA and SEA. For example, when a 1.5 mm tube is impacted under axial loading, the energy absorption of Design 1 is 52.44 % higher than the conventional tube while for Design 2, it’s energy absorption is 58.56 % higher than the conventional tube. However, for initial peak load (IPL) and crush force efficiency (CFE), the conventional tube provides better results compared to the proposed designs. This finding indicates that the proposed designs are more suitable in impact applications that require lightweight structure, but not involve with human safety. However, the conventional tube is found to be more suitable to be applied in crashworthiness application such as in passengers vehicle as it provides better results in terms of IPL and CFE. Besides that, Design 2 performs better than Design 1 in most conditions under axial loading.
but vice-versa for the condition under oblique loading. However, it should be noted that Design 2 always provide better results of IPL compared to Design 1 at any thicknesses values and loading directions.

3.2. Effect of varying diameter on energy absorption characteristics for axial and oblique loadings.

In this section, the thickness and inner diameter of the tubes are fixed at 1.5 mm and 10 mm, respectively. The outer diameter is varied with 100 mm and 120 mm. The results of energy absorption characteristics when different tubes (conventional circular tube, Design 1 and Design 2) impacted under axial and oblique loadings are shown in Figure 5.

![Figure 5](attachment:image.png)

**Figure 5.** Effect of diameter and loading angle on energy absorption characteristics; (a) energy absorption capacity, (b) initial peak load, (c) specific energy absorption (SEA) and (d) crush force efficiency (CFE).
Figure 5 shows that EA and IPL values increased with increasing of the tube’s diameter. However, the results of SEA and CFE are independent to the tube’s diameter. For axial loading, the increasing of energy absorption capacity in conventional tubes, Design 1 and Design 2 are 8.3 %, 30.0 % and 0.9 %, respectively when the diameter is increased from 100 mm to 120 mm. Besides that, for oblique loading, the increasing of energy absorption capacity in conventional tubes, Design 1 and Design 2 are 6.6 %, 28.8 % and 53.4 %, respectively. The huge differences in Design 1 in axial and oblique loadings are due to the increase length of the rib structure.

4. Conclusion
In conclusion, the proposed designs of bio-inspired thin-walled tubes show superior characteristic in energy absorption capacity and specific energy absorption, compared to the conventional circular tube. It was found that the thickness of the thin-walled tube plays a significant factor on the results of energy absorption characteristics. Comparing the two kinds of the proposed designs, Design 2 provides better energy absorption characteristics results compared to Design 1 in axial loading but Design 1 showed to be better in oblique loading. Improvements should be conducted in the future to improve the results of initial peak load (IPL) and crush force efficiency (CFE) in bio-inspired thin-walled tube.

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