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Experimental study on crashworthiness in double crush tubes of polylactic acid material

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Abstract

The crush tube for crashworthiness is one of the automotive components crucial for absorbing impact energy when an accident occurs. It is necessary to pay attention to determining the crush tube material depending on the automotive components used. The research aims to analyze the ability to absorb energy in double tubes of Polylactic Acid material made on a 3D Printing machine to test the compression. The double crush tube combines a round outer tube and an inner tube which varies in shape: round, triangular, rectangular, pentagonal, hexagonal, hexagonal, and octagonal. The method is to create samples of crush tubes using a 3D printer machine and then conduct experimental compression testing to obtain a graph of the distribution load for each crush tube. The crashworthiness parameters used are absorption of specific energy (SEA), maximum collapse force (Fmax), and efficiency of crush force (CFE). The results obtained by the smallest total energy absorption (TEA) of 98.77 Joules were for a tube in a heptagonal shape. Meanwhile, the tube that absorbs the most energy is a round tube of 149,154 Joules.

Keywords

Crashworthiness, Polylactide acid, Compression test

Introduction

Nowadays, transportation is one of the most important needs of society, be it land, sea, or air transportation. Almost everyone in the world uses transportation if they want to travel to a place even though the distance is relatively close. However, in using this means of transportation, drivers cannot escape the risk of traffic accidents.

To reduce the impact of accidents caused when an accident occurs, transportation manufacturers use crush tubes. The use of crush tubes has become mandatory for every transportation industry such as cars, buses, trains, and airplanes [1]. The main function of the crush tube is as an energy absorber which is placed at the front of the vehicle to reduce the severity of accidents that occur when an accident occurs [2].

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The crush tube in crashworthiness is a thin-walled automotive component that has a variety of cross-sectional shapes. A square-shaped tube has been analyzed to determine the maximum impact force, specific energy absorption, and efficiency of the impact force that occurs [3][4]. In addition, research on the comparison of the cross-sectional shape of the crush tube between circle, square, and rectangle has been carried out where the circular cross-section absorbs more specific energy than the two crush tube cross-sections [5].

Analysis using the finite element method on crashworthiness has often been used to simulate crush tubes and determine the resulting absorption power. As done by Javier Paz Mendez et al. analyzing crashworthiness on aircraft components with numerical design models [6]. Simulation research using the finite element method was also carried out to determine the impact value on the Indonesian EN 15227 fast train [7]. Finite element analysis comparing experimental case was studied to get the best-absorbed energy in double tube shape [8].

The automotive industry in the manufacturing sector continues to transform to support efficiency in component manufacturing. One form of transformation is by using 3D Printing technology in the manufacturing process of automotive components [9]. Studies of crush tubes with multiple frames using PLA material printed using 3D printing have been carried out experimentally [10]. Research on thin-walled crush tubes by utilizing the filling of the inside of the tube using material from 3D Printing to determine the absorption energy produced by the tube [11]. However, according to Marpaung et al., polylactic acid (PLA) is an environmentally friendly polymer that has brittle properties so low-density polyethylene (LDPE) is mixed to obtain polymer biocomposites [12]. Based on research conducted by Gopalakrishna et al. concluded that polycarbonate material has an energy absorption capacity that can be calculated when compared to other metal cross-sections such as aluminium 6061-T6 [13].

This introduction aims to understand the urgency of improving transportation safety by optimizing crush tubes to highlight the potential of advanced materials using polylactic Acid. Additionally, manufacturing techniques of additive 3D printing play a crucial role in achieving these improvements. From this background, it is necessary to conduct an Experimental Study on Crashworthiness in Double Crush Tubes of Polylactic Acid Material.

Method

Sample Preparation

The manufacturing stage uses an additive manufacturing method to create the samples of crush tubes. The type of tube used is a double tube where the outer tube is circular and the inner tube is varied. The inner shapes that are varied are round, triangular, square, quadrilateral, pentagon, hexagon, heptagon, and octagon. The double tubes of inner variation shapes affect the absorbed energy with the variation of round, triangular, square, quadrilateral, pentagon, and hexagon [14]. The number of samples for each variation is one [15]. In the process, the loading is carried out axially by placing the crush tube object immovable. From the results, the best absorption value of each double crush tube will be known.

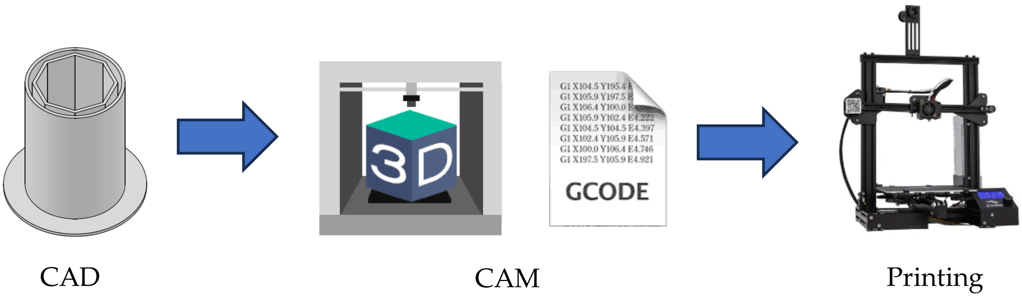

Figure 1. Specimen manufacturing process

The specimen is prepared by applying the additive manufacturing process using a 3D Printer machine shown in Figure 1. The type of material tested is Polylactic Acid (PLA) in the form of a filament roll printed on a 3D Printer machine. The printing process through CAD design preparation using Autodesk Inventor software. In the CAD process, it is necessary to adjust the size of the simulation. Furthermore, the CAM process is carried out to determine the nozzle path of the 3D Printer machine when printing the specimen. The output from CAM is in the form of a G-Code program. Then the G-Code program transfer process is carried out to the 3D Printer machine for printing (Table 1).

Table 1. 3D Printing Parameter set

Parameter	Value
Layer Height	0.2 mm
Nozzle Temperature	220 °C
Bed Temperature	50 °C
Nozzle Diameter	0.4 mm
Filament PLA Diameter	1.75 mm

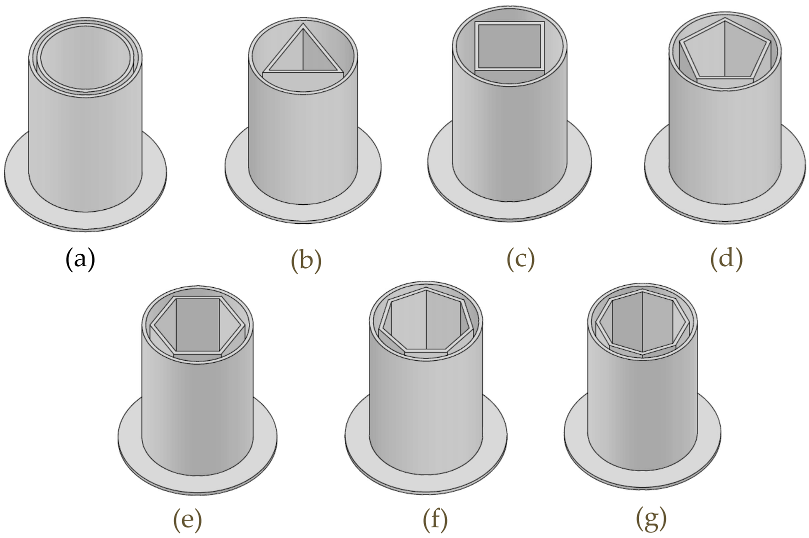

Figure 2. Double crush tube specimens (a) round, (b) triangular, (c) rectangular, (d) pentagon, (e) hexagon, (f) heptagon, (g) octagon

The geometry of the crush tube for the outer tube has a diameter of 35 mm. The inner tube with varying shapes takes the outermost cross-section as Ø30 mm. The inner tube where the cross-section shape varies has the same cross-section width for each variation. The double tube has a base cross-section to combine the outer and inner tubes with a size of Ø50 mm.

Data Analysis

Crashworthiness parameters are factors used to measure the ability of a tube to absorb energy. The peak load is the highest load required to cause significant permanent deformation and distortion of a component. It is important for crashworthiness parameters for two reasons. First, during low-velocity and low-energy impacts, no permanent deformation should occur, as this would be considered damage to the structure. Second, the peak load is often the maximum load observed on a useful specimen of an energy-absorbing device because it has a direct effect on the loading of passengers in the vehicle.

Specific Energy Absorption (SEA) indicates the total energy absorbed (TEA) in the impact of destroying a structure equal to the area under the load-displacement curve (F). Where,

$$TEA = \int_0^{\delta} F \, d\delta \qquad \ldots\ldots\ldots(1)$$

Therefore, specific energy absorption is defined as the energy absorbed per unit mass (m) of material as given in equation 2.

$$\mathrm{SEA} = \frac{TEA}{m} \qquad \ldots\ldots\ldots(2)$$

Where m is the impact weight of the component.

When the loading process occurs, the load will increase sharply due to the stress from the maximum impact displacement. Thus, this maximum displacement is the important component displacement. Meanwhile, the size efficiency or parameter of the energy absorber is determined as the ratio of the maximum displacement to the total length of the component. This is known as stroke efficiency.

The average crush load is also known as the mean load. Mean crush load (F_{mean}) is defined as the energy absorbed divided by the distance traveled (ΔL).

$$F_{mean} = \frac{TEA}{\Delta L} \qquad \ldots\ldots\ldots(3)$$

This is the ratio of the energy absorbed in the impact zone to the impact distance.

The average and peak loads are important parameters to determine because they are directly related to the deceleration that will be experienced by the occupants in the vehicle. The best way to measure this is to determine the ratio between the average load and the peak load. And this ratio is the crush force efficiency. If the ratio is close to one, the absorber is crushed at a value close to the peak load, thus minimizing the desired deceleration change. On the other hand, if this ratio is far from unity, it indicates that there is a rapid change in deceleration and this is dangerous to have in designing a vehicle.

$$CFE = \frac{F_{mean}}{F_{peak}} \times 100\% \quad ....(4)$$

Energy Absorption Efficiency (EAE) is the proportion of the average impact force of the multi-cell tube and the specimen cell tube. EAE aims to increase the normal crushing strength of the multi-cell tube. To compare the results of the multi-cell tube, F_{mean} is the mean crushing force, which represents the average force during the deformation. F_{max} is the maximum crushing force, which is the peak force experienced during the deformation.

$$EAE = \frac{F_{mean\ multi\ cell\ tube}}{F_{max\ single\ cell\ tube}} \quad ....(5)$$

Results and Discussion

Compression Test

Figure 3. (a) Preparation for compression testing (b) results of compression testing

The compression testing process was carried out at the Makassar Job Training Center with the maximum capacity of the universal testing machine of 0.5 kN. From the compression test results, the maximum strength value of the tube was obtained during the test (Figure 3). The experimental test data obtained were compared with the simulation results. The purpose of the comparison was to validate the simulation value. The double tube was positioned between the press and the support in the middle. The compression speed given in the machine setting was 3.5 mm/min.

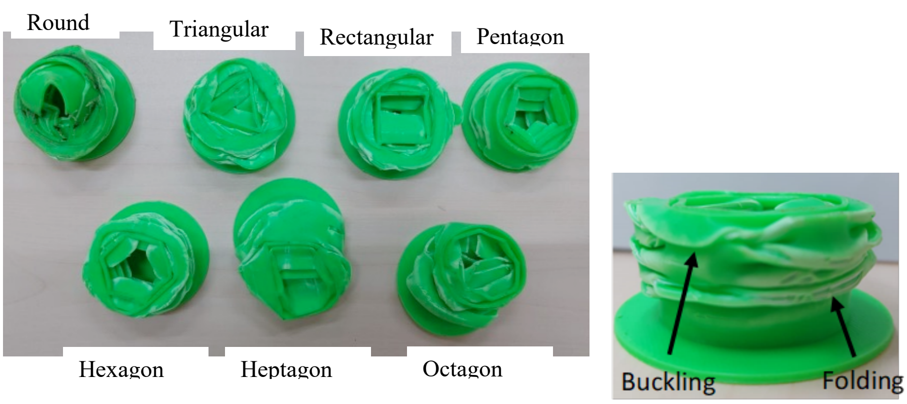

Figure 4. Deformation mode

Figure 4 shows the deformation of double tubes. The deformation of each double tube is seen in Figure 4. It can be seen that all double tubes do not have any fragments that have come loose from the tube wall, either the outer tube or the inner tube. In addition, there were no fractures as a result of the compression tests carried out on all specimens. From the deformation results on the double tube, it was found that there was still buckling around the surface of the specimen. However, folds to absorb energy are more dominant.

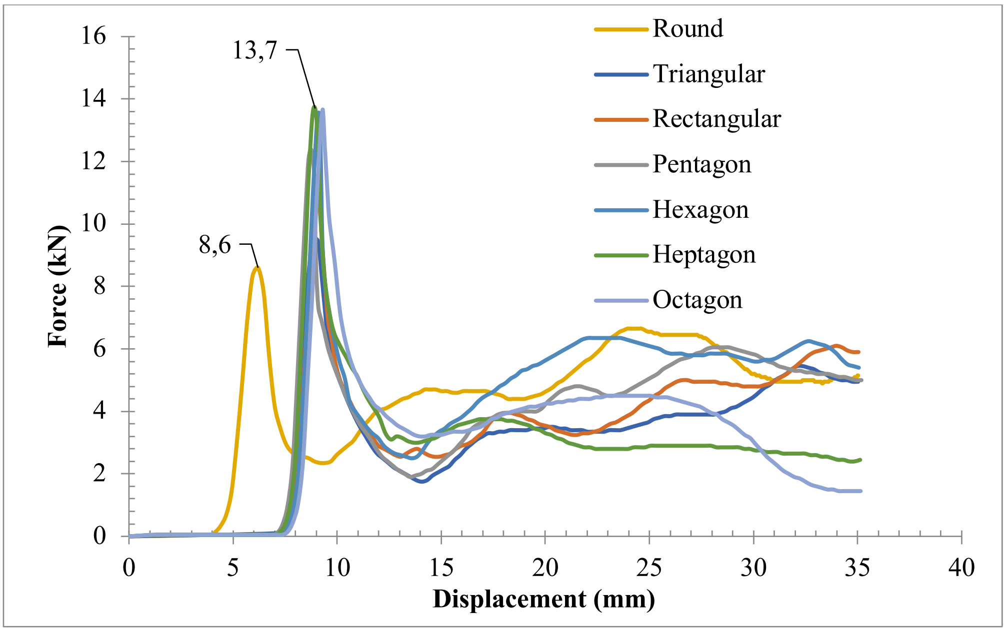

Figure 5. Graph of experimental test results for each double tube

Figure 5 shows the graph of the experimental test results in the compression test on a double tube with tubes in each type of tube varied. From the compression test, the results of the maximum energy absorption and force of each tube were obtained. It can been shown that the energy absorption results of each double tube. This diagram helps to see the variation in maximum strength that each shape can achieve, with the heptagonal shape having the highest value of 13.7 kN and the round is the lowest of 8.6 kN. However, it can be seen that the double tube with the outer tube in the shape of a hexagon and octagon almost has the maximum force value for energy absorption.

Parameter Analysis

Loading simulation with compression testing on double tube specimens where the inner tube shape is varied has been analyzed. From the simulation, crush parameters can be seen in Table 2. Some indicators displayed such as; total absorption energy (TEA), specific absorption energy (SEA), maximum load (Fmax), average load (Fmean), and crushing load efficiency (CFE). The weight of the specimen given is according to the density of the material and dimensions of each specimen. Due to the difference in shape, the weight of each specimen is also different as seen in Table 2. The weight value of the specimen can be found through Autodesk Inventor software. While the total distance of compression (displacement) is obtained from the simulation results. From each specimen, the total distance of compression is around 40 mm.

Table 2. Energy absorption parameters in double tubes with variations in the shape of the inner tube.

Inner Tube Shape	Parameter						
	Weight (kg)	Displacement (mm)	TEA (J)	SEA (kJ/kg)	Fmax (kN)	Fmean (kN)	CFE (%)
Round	0.015	35.03	149.15	9.94	8.6	4.26	49.52
Triangular	0.014	35.03	107.67	7.69	9.5	3.07	32.36
Rectangular	0.014	35.04	118.54	8.47	10.75	3.38	31.47
Pentagon	0.015	35.19	129.45	8.63	12.4	3.68	29.67
Hexagon	0.015	35.06	145.97	9.73	13.55	4.16	30.73
Heptagon	0.015	35.12	98.77	6.58	13.75	2.81	20.45
Octagon	0.015	35.15	107.67	7.18	13.65	3.06	22.44

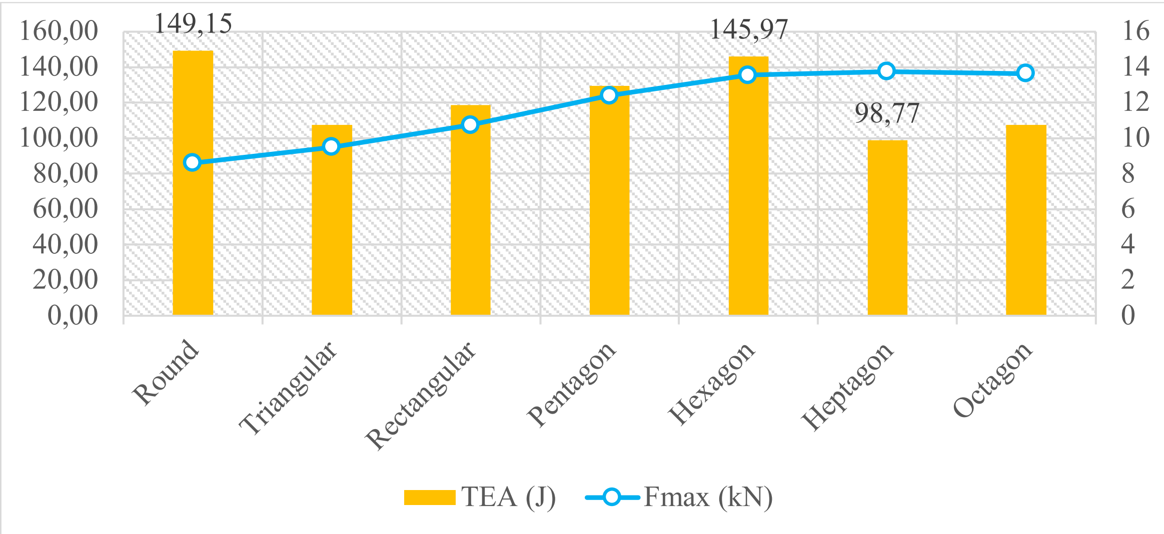

Figure 6. Graph of the Total Absorbed Energy and maximum force of compression

The total absorption energy can be known from the total value of the pressing force of each displacement on the specimen tube. In Figure 6, a graph of the total absorption energy on a double tube with variations in the shape of the inner tube is seen. The largest total absorption energy value is the round tube with 149.15 J. approaching the hexagonal tube of 145.97 J., while the heptagon tube gets the lowest total absorption energy value with 98.77 J. This graph also shows that although the round double tube has a low maximum value, it can absorb energy in total very high compared to other tubes. Then, the hexagon double tube in addition to having a high maximum force when absorbing energy also produces a large total absorbed energy.

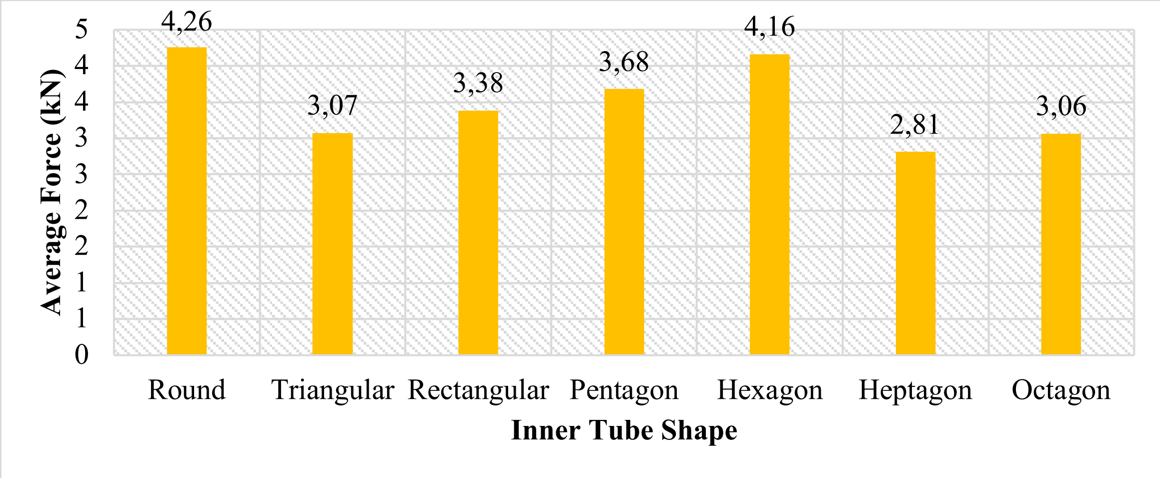

Figure 7. Graph of the average force values obtained on a double tube with variations in the shape of the inner tube.

The average force value is obtained from the calculation of the total absorbed energy divided by the total distance of compression that occurs in the simulation (Figure 7). In the variation of the inner tube shape, the inner tube with a round shape has the largest average force value, which is 4.26 kN. While the inner tube with a heptagon shape has the lowest average force value, which is 2.81 kN. However, the inner tube in the form of a hexagon has an average force value that is almost the same as the pentagon shape, which is 4.16 kN. From these two inner tube shapes, there is only a very small difference in value.

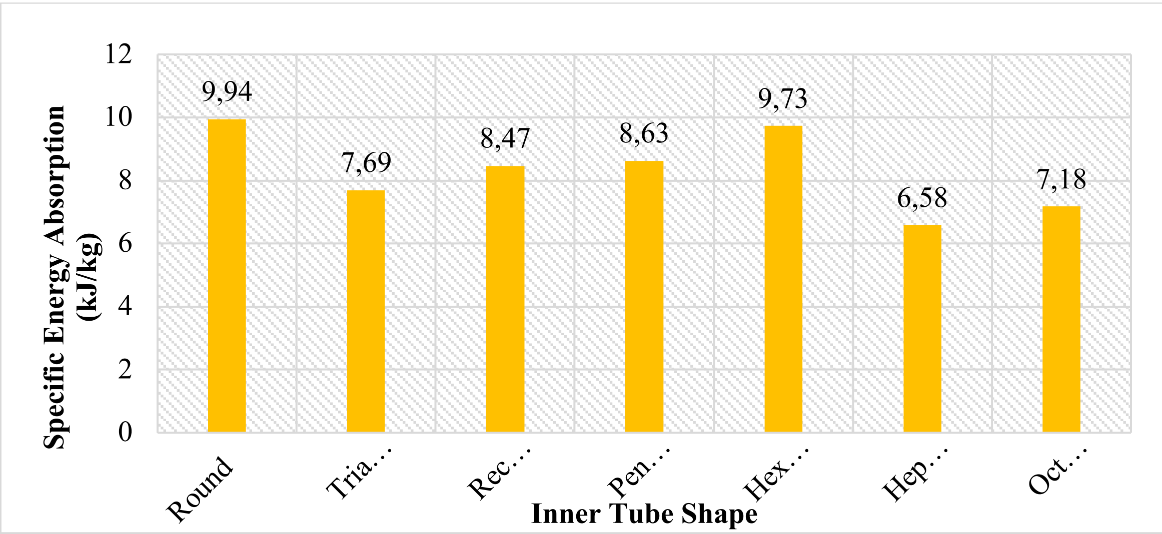

Figure 8. Graph of specific absorption energy values obtained in double tubes with variations in the shape of the inner tube.

Specific absorption energy is the total amount of energy obtained per unit mass of the tested specimen. Figure 8 shows the specific absorption energy value graphically on a double tube with various inner tube shapes. The mass of each specimen is different because it has a different inner tube shape. The difference in mass of the specimen will affect the specific absorption energy value obtained. It can be seen in the graph that the best specific absorption energy among each inner tube is the round tube. Then, the tube that absorbs the second-best specific energy is the hexagon tube.

Conclusion

The study Experimental Study on Crashworthiness in Double Crush Tubes of Polylactic Acid Material has been done with the following conclusions draw; (1) Among seven double tube specimens experimentally analyzed, the double tube with a round inner tube had better TEA with 149.15 J than other combinations, despite having the lowest maximum force of 8.6 kN. (2) The TEA of hexagonal inner tubes is not significantly different from that of round inner tubes with 145.97 J. Furthermore, the hexagonal inner tube has a maximum force (13.55 kN) that is about the highest. the hexagonal shape balances energy absorption and stiffness effectively, leading to comparable TEA with round tubes but at the cost of higher peak forces. This makes the hexagonal design more suitable for applications where stiffness is prioritized along with crashworthiness.

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