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Research Paper

Collapse Behavior and Energy Absorption Characteristics of Design Multi-Cell Thin Wall Structure 3D-Printed Under Quasi Statistic Loads

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Abstract

Crashworthiness is a passive device that has an important function as an absorbing component of the impact energy resulting from an accidental event. The main problem in the crashworthy design is the dimensional limitation on the front end of the vehicle with the driver so that most of the energy absorption is limited. Besides, the complexity of crashworthiness design is difficult to make conventionally. This research aims to find out the effectiveness of crashworthiness design in energy absorption and the resulting deformation patterns. Crashwortines are made in a multi-cell shape using PLA material and printed using a 3D printing raise machine. Crashworthiness is produced with four variation shapes of a Multi-cell circle (MCC), Multi-Cell square (MCS), Multicell pentagonal (MCP), and Multi-Cell pentagonal circles (MCPC) with a side thickness of 2 mm and a length of 150 mm. Experimental quasi-static testing is carried out in the frontal direction using a UTM machine at an operating speed of 2mm/s. The results of the study show that the design of the crash box of the pentagon circle has a significant increase in the energy absorption value of 62.49%, which can be recommended in future impact resistance tube designs. The characteristics of the deformation pattern and the failure resulting from the crashworthiness tend to form the pattern of the bending lamina failure. Failures can occur due to plastic fold, elastic bend, and pressure deformation mechanisms followed by new folding formations (lobes).

Keywords: Energy absorption; Crashworthiness; Quasi-Static; Multi-Cell; Thin-Wall Structure; PLA 3D Printed

1. Introduction

Traffic accidents are one of the severe problems that affect many countries around the world. The accident resulted in loss of life, serious injuries, and enormous material losses [1]–[3]. Despite many efforts to improve vehicle safety, accidents have repeatedly occurred with devastating impacts. One known method of improving vehicle safety is by designing thin structures (**Figure 1**) that can be sacrificed to absorb impact energy (Crashworthiness) [4], [5].

In the automotive and commercial industries, safety and structural performance are critical factors in the design process. Proper structural design is required to increase the level of safety in the event of an accident or impact [6], [7]. The main challenge in structural design is the limitation of the dimensions at the front end of the

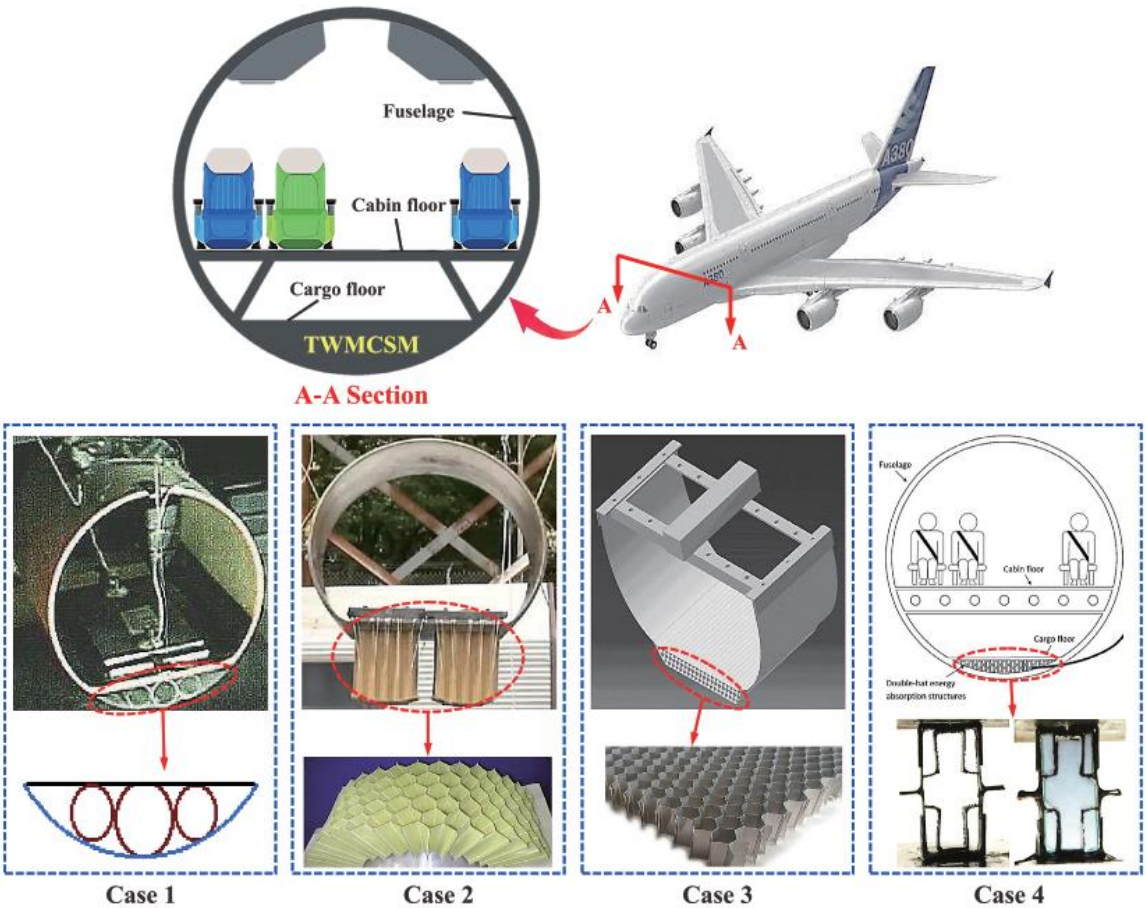

Figure 1. Application of thin-walled aircraft structure [8]–[10]

vehicle so that most of the energy absorption is limited [11], [12]. To obtain good energy, various design considerations need to be taken into account such as shape, dimensions, and material [13]–[16]. As well as crashworthiness design with multi-cell shape TWMCS containing interconnected ribs on the external thin wall [10]. Comparative studies have shown that multi-cell designs have higher energy absorption and more stable impact response [17], [18]. The highly complex shape and dimensions of multi-cell crashworthiness provide a major challenge in developing them. In addition, the use of lightweight materials such as polymer composite materials, PLA is attracting the attention of researchers due to its improved mechanical properties. Various industrial components have used composite materials as energy-absorbing structures to improve impact resistance and lightweight [10], [19]. With advances in 3D printing technology and PLA materials, opportunities emerged to replace metals with thin PLA structures that meet the same, or even better, safety standards [20].

Today, 3D printing technology with polymer materials has evolved rapidly in various applications. This technology enables the manufacture of three-dimensional objects from a wide range of materials with a high degree of rigidity and varied complexity, such as complex forms such as Multi-Cell and Multi-Segment [21]–[23]. One of the increasingly popular materials for 3D Printing processes is PLA (Polylactic Acid) or polylactide [24]. PLA is a strong, environmentally friendly material and potentially an attractive alternative to structural components in a range of applications, including the automotive industry [25]. The advantages of 3D-printed PLA are the ease of manufacturing process, relatively low production costs, and the potential for designing more accessible complex structures [26]–[28].

The application of 3D printing technology in this engineering field has opened up new opportunities in designing complex geometry on crashworthiness. With the hope of delivering a better impact performance tube. The study presented investigations into the design and evaluation of crashworthiness of multi-cell thin wall structures using Polylactic Acid (PLA) as the main material, made through 3D printing techniques. This thin structure is expected to offer advantages such as lighter weight, efficient energy absorption properties, and ease in manufacturing processes compared to traditional metal structures.

2. Method

2.1. Material and Design

With a complex shape on a multi-cell model, the crashworthiness is made using PLA (Polylactic Acid) material to obtain a high specific energy absorption (SEA) value. In this case, the PLA filament material is selected and received from the Czech Fillamentum Company with a diameter of 3 mm. The mechanical properties of the PLA material printed with 3D printing can be seen in **Table 1**. The crashworthiness design is made with four shapes of the multi-cell circle (MCC), multi-cell square (MCS), multi-cell pentagonal (MCP), and multi-cell pentagonal circles (MCPC), with each having a side thickness of 2 mm, a length of 150 mm and an outer diameter of 75 mm [29]–[31]. The design of the crashworthiness tube can be seen in **Figure 2** and **Figure 3**.

Table 1. Properties material PLA

Density	Yield strength	Tensile modulus	Flexural strength	Flexural modulus	Elongation
1.24 g/cm^3	60.5 Mpa	3600 Mpa	83 Mpa	3800 Mpa	6 %

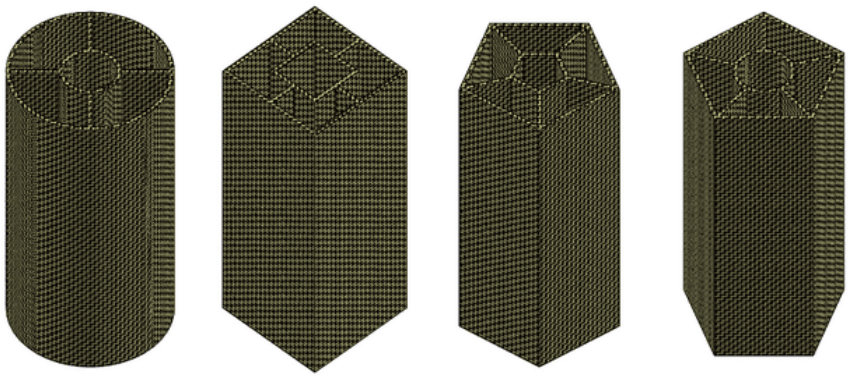

Figure 2. 3D design crashworthiness (a) Multi-cell circle (MCC) (b) Multi-cell square (MCS) (c) Multi-cell pentagonal (MCP) (d) Multi-cell pentagonal circle (MCPC)

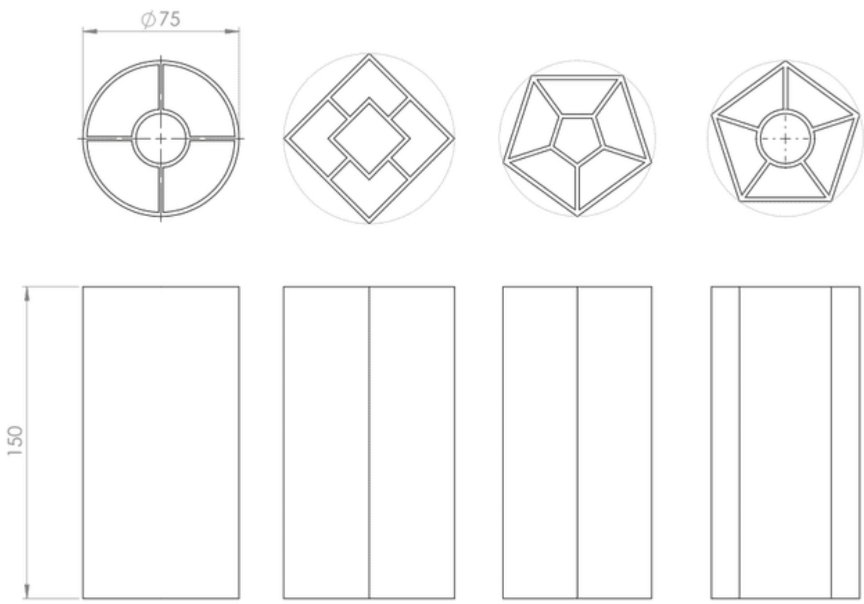

Figure 3. 2D design crashworthiness (a) Multi-cell circle (MCC) (b) Multi-cell square (MCS) (c) Multi-cell pentagonal (MCP) (d) Multi-cell pentagonal circle (MCPC)

2.2. *Crashhwortines Manufacturing Process*

Crashworthiness was produced in this study using the RAISE 3D PRO 2 PLUS device. The sample printing process was done using the Fused Deposition Modelling (FDM) 3D printing method, as shown in **Figure 4**. The fused deposition modeling (FDM) process is performed by melting a PLA filament to the melting point in the nozzle extruder and storing it on a build platform. The XY movement will be used to form the layer on the crashworthiness design, whereas the movement on the Z field is used to create layer thicknesses up to a crashworthy height of 150 mm. Process parameters of crashworthiness printing with 3D printing tools can be seen in **Table 2**.

2.3. *Quasi-Static Test*

Experimental crashworthiness was carried out with quasi-static testing directly in the lab using the UTM machine. (universal testing machine). Quasi-static testing aims to obtain data on force reactions and observation of mechanical fractures during testing. The test was carried out with an impactor impacting the crashworthiness specimen at a constant speed of 2 mm/s at a distance of 100 mm. A quasi-static test scheme can be seen in **Figure 5**.

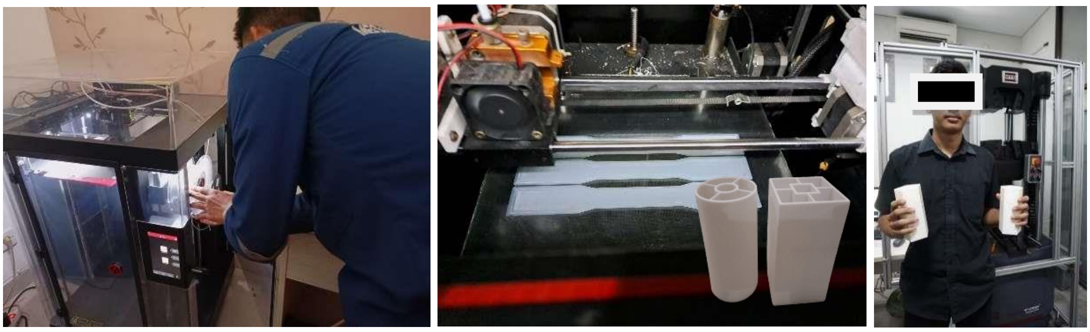

Figure 4. Printing process with 3D printing

Table 2. Parameters used in experimental design

Parameter	Setting
Nozzle temperature	225 °C
Filament width	0.3 mm
Layer height	0.2 mm
Fill density	25%
Printing speed	40 mm/s
Layer orientation	X-axis
Infill pattern	Linear
Slice	Ultra High Quality
Support Material	PLA filaments
Build plate temperature	65 °C

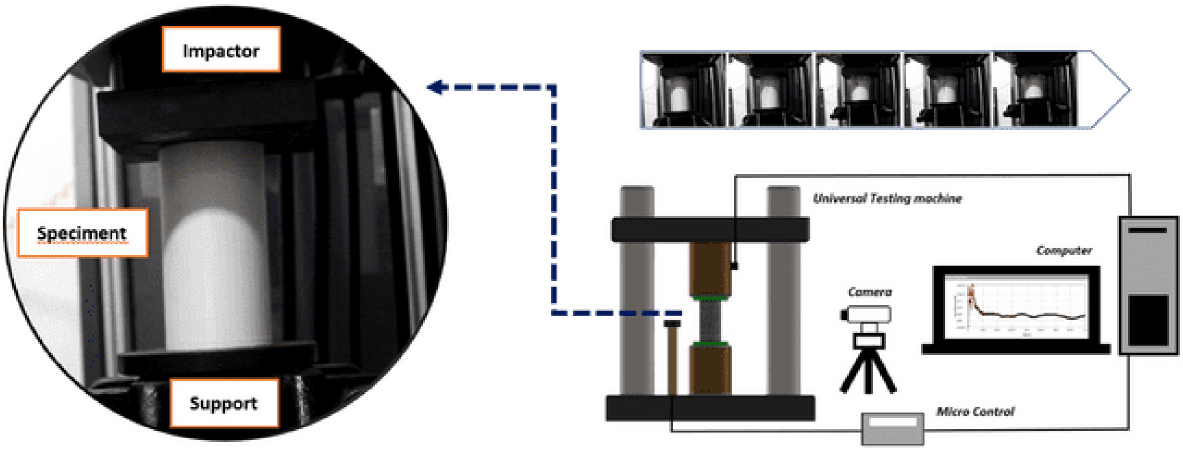

Figure 5. Experimental quasi-static test scheme

2.4. *Crashworthiness performance*

Some standard criteria used to evaluate impact efficiency include SEA (Specific Energy Absorption), MF (Mean Force), IPFC (Initial Peak Force), CFE (Crush Force Efficiency), and EA (Energy absorption) [20], [29]. The absorption energy (EA) is the total energy absorbed during the impact, which can be calculated based on the area below the load-displacement curve. The absorption of energy can be calculated mathematically using the following integral equation.

$$EA = \int_0^d f(\delta)d\delta \tag{1}$$

F(δ) is the destroyer style, and the distancing distance

MF (Mean Force) is the average load of a destroyer on an energy absorber that changes to a stable form, defined by a mathematical equation.

$$MF = \frac{1}{d}\int_0^d f(\delta)d\delta \tag{2}$$

CFE (Crush Force Efficiency) is the average ratio for a destroying force, which can be calculated by dividing the mean force (MF) by the initial force or Initial Peak Force (IPFC).

$$\text{CFE} = \frac{MF}{IPFC} x\ 100 \tag{3}$$

SEA (Specific Energy Absorption) is a criterion used to measure the energy absorbed (EA) of each unit of mass. This is an essential indicator of the ability of structures to absorb energy. SEA can be calculated using mathematical equations.

$$\text{SEA} = \frac{EA}{m} \tag{4}$$

3. Result and Discussion

3.1. *Crashworthiness Characteristics*

In the frontal collision mechanism, the force that occurs will push the crashworthiness and turn into strain energy through the folding mechanism, where the amount of energy absorption capability is obtained from the area under the reaction force-displacement curve. The results of the response force-displacement curve from the quasi-static experimental test results can be shown in **Figure 6**.

Figure 7 shows that each crashworthiness design responds differently to different force reaction values. Where higher responses contribute to higher energy absorption values, the MCPC design appears to have the highest response, followed by the MCP, MCC, and MCS crashworthiness forms. It seems that some of the characteristics of the tube appear to occur on the force-displacement curve.

The design of the MCP and MCPC tubes tends to have better characteristics compared to the MCC and MCS tubes. At the time of charging up to 77.88 kN, the tube still shows stability and linear elastic behavior. Where the displacement increases in proportion to the style applied and the folding mechanism occurs. Once the given style reaches the next level, the new crashworthiness undergoes plastic deformation. This can be called a peak yield where the new tube will undergo permanent deformations after folding. This allows the area of the load-displacement curve to become larger.

The design of the MCC and MCS tubes shows the characteristics that, at the initial stage, given loading up to a load increase of ±55.58 kN, the tubes reach the point of structural failure and undergo fracture and collapse. This can allow the area below the curve on each tube to be small. In addition, the load-displacement curve shows a slight advantage over the MCC tube compared to the MCS tube. This can happen because the square shape of the mCS tube can initiate cracks due to

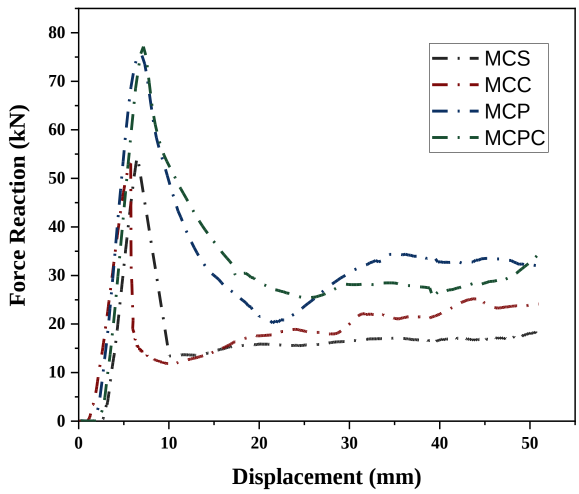

Figure 6. Force-displacement characteristic of multi-cell thin wall structure tubes

Figure 7. Collapsed specimens (a) Multi-cell square (MCS) (b) Multi-cell circle (MCC) (c) Multi-cell pentagonal (MCP) (d) Multi-cell pentagonal circle (MCPC)

frontal loading. The circular shape of the MCC tube shows a linear behavior of elasticity. It is slightly more stable because the impact energy can be passed on to the tension energy even though the style applied is still relatively small.

From the load-displacement curve, the energy absorption values on each crashworthiness tube design can be calculated, as seen in **Figure 8**. In sequence, the energy absorptions on each MCPC tubing design are 2,316 Joules, MCP 1,887 Joules, MCC 995.124 Joules, and MCS 868.568 Joules.

A rise follows an increase in the crashworthiness's Energy absorption (EA) value in Specific energy absorption (SEA). The SEA value can indicate the ability of a structure and material to absorb energy during a collision. The MCS crashworthiness design has SEA values of 3,743.427 J/Kg, MCC 4326.626 J/kg, MCP 8,098.712 J/ Kg, and MCPC of 9,855.319 J/ Kg. The difference in the SEA value is influenced by the weight and complexity of the design, as seen in **Table 3**. In multi-cell pentagonal design, circles tend to have

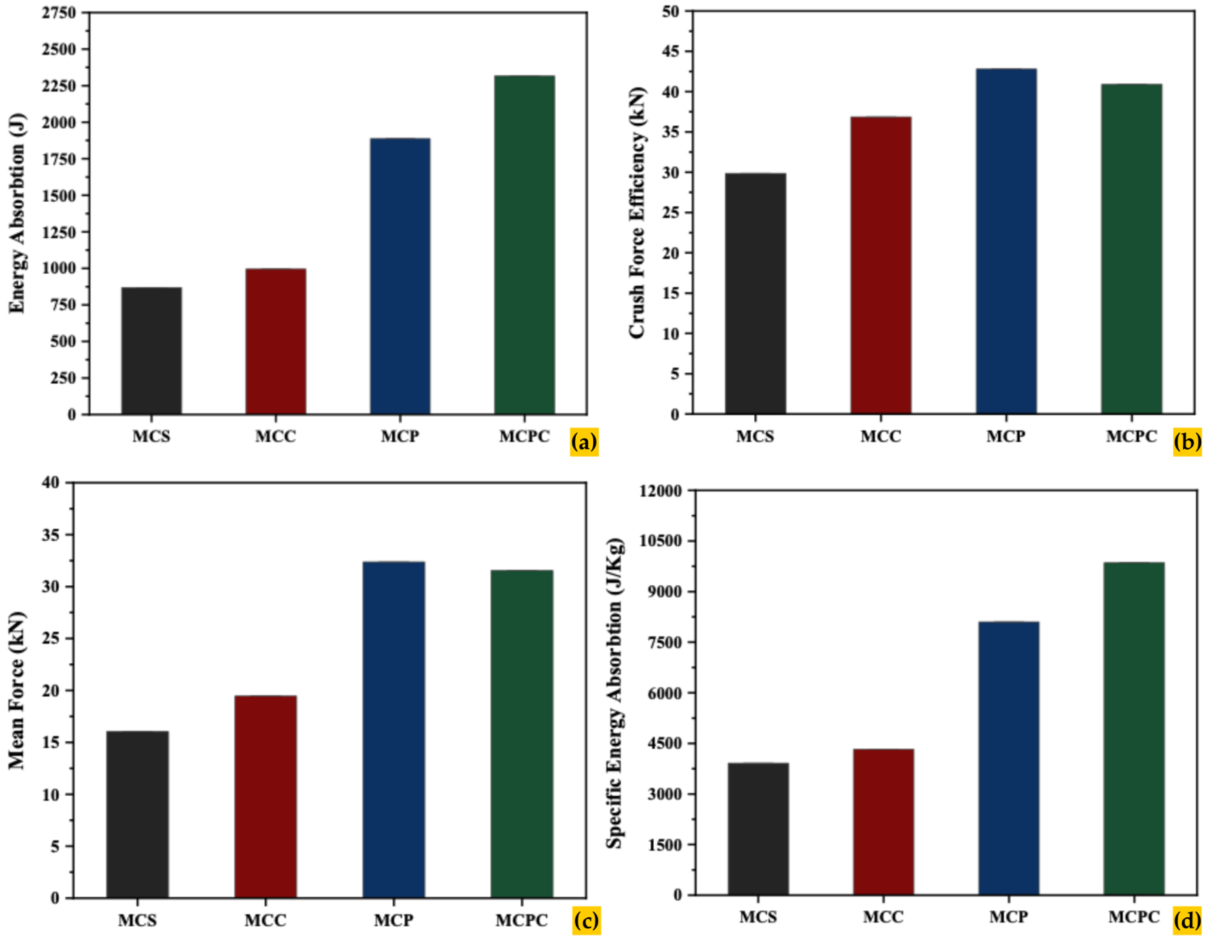

Figure 8. (a) Energy Absorption (EA) (b) Specific Energy Absorption (SEA) (c) Mean Force (MF) (d) Crush Force Efficiency (CFE)

Table 3. Calculation of Specific Energy Absorption (SEA)

Crashworthiness Design	Energy Absorbtion (J)	Weight average (g)	Specific Energy Absorbtion (J/Kg)
Multi-cell square (MCS)	868.568	232	3,743.427
Multi-cell circle (MCC)	995.124	230	4,326.626
Multi-cell pentagonal (MCP)	1,887	233	8,098.712
Multi-cell pentagonal circle (MCPC)	2,316	235	9,855.319

better energy absorption and SEA capabilities compared to other forms, such as multi-cell squares [11], [32], [33]. Initially, the design of a pentagonal circle had a more complex geometry. This can balance the distribution of the impact energy throughout the structure. The structure balance makes it essential to produce gradual and controlled deformation during the impact process, leading to minimal damage to the structure and excellent energy absorption [34].

Various studies mentioned that the performance of thin-walled tubes with multiple structures and shapes, such as square, pentagonal, hexagonal, or grid shapes, can be suggested for future crashworthiness in a new tube design [11], [32], [33]. The design of the multi-sell pentagonal circle tube has a better absorption of energy when compared to both multi-cell square shapes and multiple-cell circles. The pentagon design has a more complex geometry, allowing it to distribute the power of the impact evenly throughout the structure. So, it can produce gradual and controlled deformation during the impact, which leads to better energy absorption and less damage to the structure [32], [34]. The existence of a mechanism of gradual deformation in the multi-cell pentagonal design is also demonstrated by the increasing value of the superior mean force. Mean force can provide critical knowledge related to the design of each tube against a structure that can absorb and reduce energy during the impact [35]. The design of the MCS-shaped tube has mean force values of 16.03768 kN, MCC 19.46029 kN, and MCP 32.37253 kN. It is proven that the design of pentagon-shaped tubes such as MCP and MCPC can absorb more energy during impact. In contrast to the design of the multi-cell square and circle form tubes, they tend to have lower mean force values. The square design has a simple geometry, leading to localized deformation during the impact, producing lower mean forces and structures that suffer more damage.

Figure 9 shows the initial peak force value of each design's crashworthiness. The peak force value reflects the structure's ability at the initial moment of the impact. This phase indicates the peak strength generated by the structure undergoing a significant deformation. On the design of the tube, MCS has peak force values of 53.72 kN, MCC 52.781 kN, MCP 75.622 kN, and MCPC 77.134 kN. These values indicate that the design forms multi-cell pentagonal MCP and MCCP tend to be higher than the multicell MCS or MCC at the beginning of the impact. This is because many of the geometrics of the pentagonal tubes have angles that cause increased voltage concentration at the time of the effect. Significant evidence is seen in comparing square tube shapes with higher peak force characteristics compared to circular tubes. So, the sharp angles of the square tube are difficult to deform and cause a high risk of damage at the start of the impact, as shown in **Figure 7**. The results have been confirmed at a high initial peak force style followed by a significant decrease. To cope with this early high peak style, we need a wave-shaped tube design like a corrugated or bi-tubular tube that produces a controlled deformation [35], [36].

3.2. *Crashworthiness Deformation Pattern*

Crashworthiness deformation is a reaction to shape change due to an impact. Naturally, the crashworthiness tube undergoes some of the mechanisms of destruction behavior shown in **Figure 10**. Most of the energy of destruction is absorbed inside the fold aimed at reducing the reactions caused during the impact mechanism.

The deformation formed on the crashworthiness tube design begins with the initial stage of the style to combat the initial obstacle to the occurrence of deformations on the tube. At this stage, the tube undergoes various responses, such as laminate swelling behavior, fractures, and cracks that dominate deformity for all crashworthiness designs. The multi-cell square tube and the Multi-cell circle tend to experience a progressive destruction failure consisting of micro-fractural mechanisms that permeate the entire tube structure. The structural failure of the MCC tube is due to the square-shaped design having sharp sides that make it challenging to form folding mechanisms. The cutting process on the pipe occurs when the maximum load and drop suddenly form nonlinear fluctuations [37]. The final result of this deformation can allow crashworthiness to form debris so that the energy absorption decreases significantly compared to the Multi-cell circle (MCC) design [38]. In the multi-cell circular design (MCC), the cutting procedure enters the inner side hole or cavity so that debris accumulates at the bottom of the pulley, and the mating effect on the porous value is slightly superior.

The design of multi-cell pentagonal (MCP) and multi-cell pentagonal circles (MCPC) tend to have the failure of laminate swelling and forming folding mechanisms. As the load increases, it is seen that the tube expands and forces the inner side to create a fold (lobes), as shown in **Figure 8c** and **Figure 8d**. After reaching a fractural stretch in the high curved area of the lobes formation, it then breaks [39], [40]. The occurrence of lobes formation arrangement mechanisms may indicate

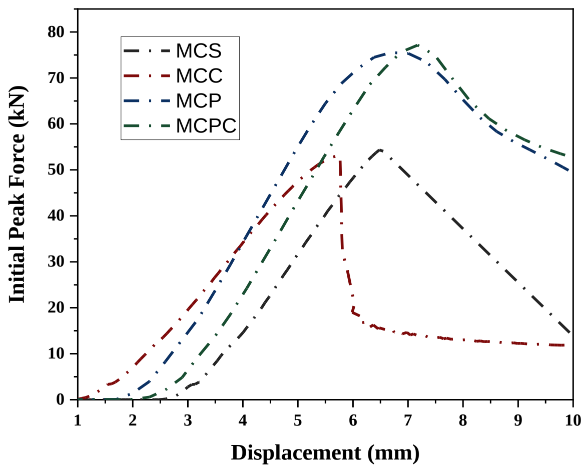

Figure 9. Initial peak force

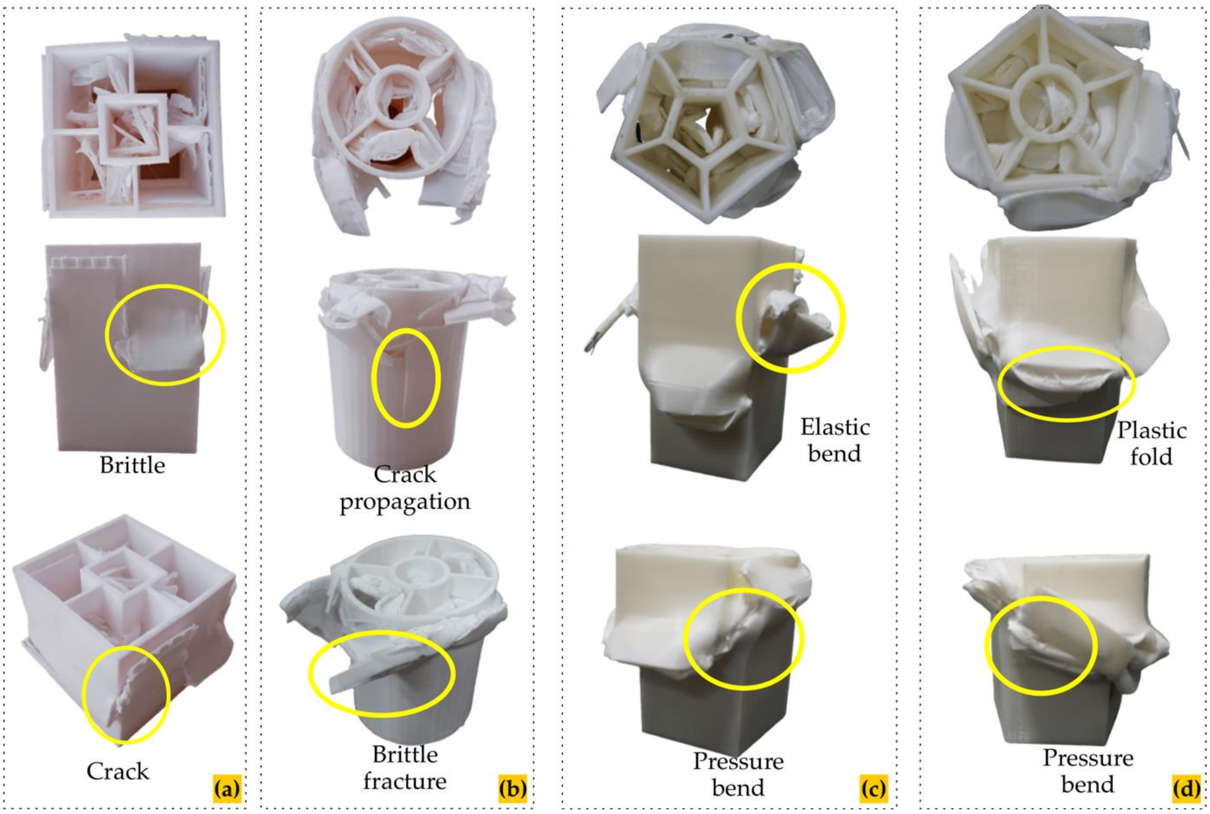

Figure 10. Crashworthiness deformation (a) Multi-cell square (MCS) (b) Multi-cell circle (MCC) (c) Multi-cell pentagonal (MCP) (d) Multi-cell pentagonal circle (MCPC)

that the energy of destruction can be well absorbed while the impactor strikes the test object. This result has been confirmed by the increased fluctuations of the average load during a superior continuing deformation.

In general, the complexity of the MCPC design provides new opportunities to increase the energy absorption performance but has limitations on the mean force and crush force efficiency. The slightly lower values of MF and CFE could be possible that the MCPC tube is still too stiff, although the folding mechanism has been done. To improve the mean force and crush force efficiency values of the tube, it is necessary to reduce the interconnected ribs on the external thin wall in the next design. In addition, design forms such as origami and corrugated tubes are highly recommended for further crashworthiness development [35], [41].

4. Conclusion

Experimental investigations with quasi-static tests on a polylactic acid poly-cell thin-wall structure tube design have shown that the pentagonal multi-cell design form can provide increased strength and absorption of future impact potential. The design complexity of a multi-cell tube with a pentagon circle shape (MCPC) significantly increases the absorptive value of energy by 62.49%. The increased absorptional value of such energy is followed by an Initial Peak Force (IPF) of 77.134 kN, Mean Force (MF) of 31.54373 kN, and Specific Energy Absorption (SEA) Value of 9,855.319 J/Kg. The characteristics of the deformation pattern and the failure resulting from the crashworthiness tend to form the pattern of the bending lamina failure. Failures can occur due to plastic fold, elastic bend, and pressure deformation mechanisms followed by new folding formations. (lobes). The formation mechanism of new formations can allow crashworthiness to absorb sound energy during the impact.

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Author's Declaration

Authors' contributions and responsibilities

W.A.W, A.H.S: the authors made substantial contributions to the conception and design of the study; W.A.W, B.J, MAC: the authors took responsibility for data analysis, interpretation and discussion of results; S.H.S.P, A.S, R.R, M.A.C: the authors read and approved the final manuscript.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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