Energy Absorption Evaluation of Auxetic Structure on Leading Edge Using Polycarbonate 3D Printing in Quasi-Static Lateral Load Test

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ABSTRACT

This study evaluates the energy absorption capability of 3D-printed polycarbonate auxetic structures applied to the leading edge of an aircraft. Three configurations were tested: triangle (A), half circle (B), and rectangle (C), through quasi-static lateral load tests with key parameters: energy absorption (EA), specific energy absorption (SEA), initial peak force (IPF), mean force (MF), and crush force efficiency (CFE). The test results show that the triangle structure (A) excels with an EA of 99.08 J, IPF of 40.41 Kn, MF ranging from 12.30 to 13.03 Kn, CFE of 34.078 Kn, and SEA of 1.738 J/kg. The half circle structure (B) shows a significant improvement in the second test, while the rectangle (C) tends to be stable but declining. Compared to the conventional honeycomb (EA ~59 J, IPF 6–8 Kn, MF 3–4 Kn), the triangle structure increases energy absorption by up to 68% and provides an initial resistance 5–6 times greater. These findings demonstrate the potential of auxetic structures, particularly the triangle geometry, as an innovative design to enhance the crashworthiness of aircraft leading edges.

Keywords: *crashworthiness, auxetic structure, polycarbonate, 3D printing, energy absorption, lateral compression, quasi-static test*

1. INTRODUCTION

One development in the aviation industry to enhance safety is the development of designs that prioritize crashworthiness. Crashworthiness is an important concept in aviation safety and will remain a key topic of discussion. (Supriatna & Suroso, 2017) Since the 1960s, efficiency and safety have become major issues in aviation. Materials with a high strength-to-weight ratio, such as metal alloys and composites, have been introduced to significantly reduce the weight of aircraft components. (Paz Mendez et al., 2020) Another ongoing challenge is bird strikes or Bird Aircraft Strike Hazard (BASH), which can cause serious damage and pose safety risks in aviation. (Certification & Flight, n.d.)

Energy absorption capability is crucial to maintaining the structural integrity of the aircraft. Various energy-absorbing concepts have been developed using fiber composites, cellular core structures, and metal-composite hybrids to withstand impact loads, including bird strikes and emergency landings. (Heimbs, 2013; Jacob et al., 2002; Yang et al., 2020; Magliaro et al., 2022)

Improving crashworthiness involves reinforcing the structure and materials so that the aircraft can withstand impacts while also absorbing energy. One method used is the application of lattice structures on the leading edge, inspired by honeycombs, tendons, salamander skin, and spongy bone. From this concept emerged auxetic metamaterial designs with a negative Poisson's ratio (NPR), offering unique mechanical properties: lightweight, stiff, strong, and highly energy-absorbing. (Bastola et al., 2024)

Three-dimensional re-entrant auxetic structures have been developed with modifications to conventional designs, innovative manufacturing techniques, and reinforcing materials. The results show superior mechanical properties such as high impact resistance, isotropic deformation, and crack resistance. (Bastola et al., 2024) 3D printed lattice designs have been proven to enhance mechanical properties while reducing component weight.

Based on the review, this study is focused on addressing two main issues: (1) what are the characteristics of energy absorption values in the leading edge cross-section design of an aircraft with an auxetic structure under quasi-static lateral load testing; and (2) what is the mechanism of the fracture pattern generated in the cross-section design.

In line with these research questions, the objective of this study is to analyze the characteristics of energy absorption and the fracture pattern mechanism of the leading edge cross-section design based on auxetic structure. This research is expected to provide theoretical benefits by contributing to the development of Knowledge about auxetic structures in aircraft design, as well as practical benefits in the form of innovative leading edge cross-section designs that are more resilient, lightweight, and have high energy absorption capacity.

2. METHOD

2.1. Research Design

This study used an experimental approach with the research flowchart as shown in Figure 1.

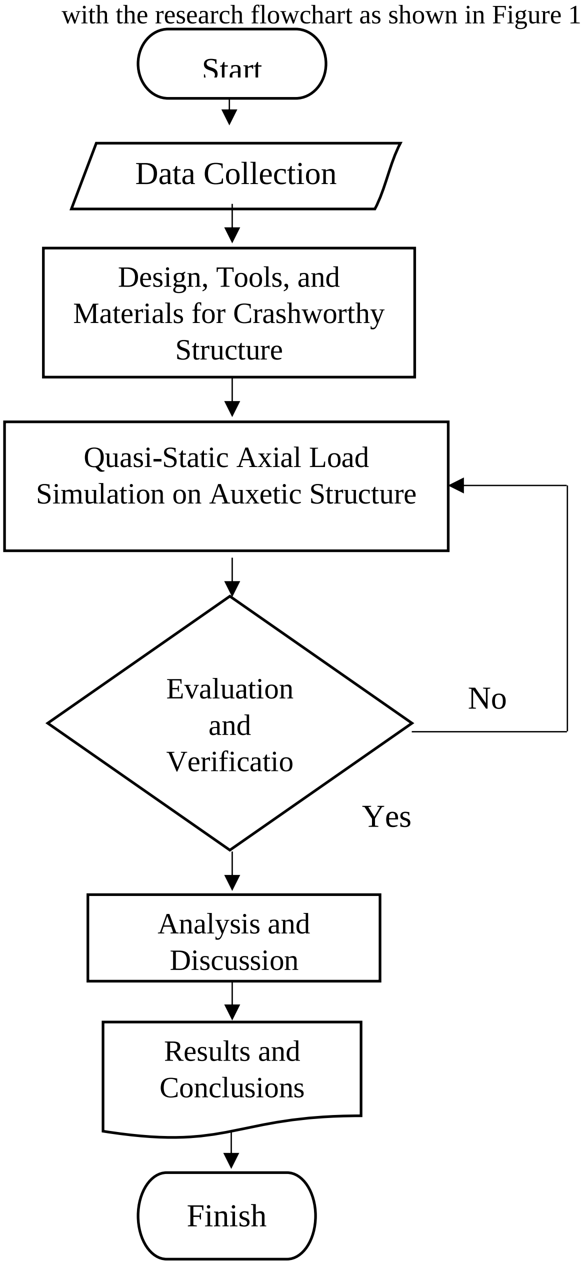

Figure 1. Research Flowchart

2.2. Research Variables

Three types of variables were used:

- Independent variable: the shape of the auxetic structure (square, wave, triangle) tested using a Universal Test Machine.
- Dependent variable: energy absorption values of the test specimens.
- Control variables: test parameters kept constant, including specimen mass (849 g), test speed (0.02 m/s), length (114 mm), width (30 mm), and wall thickness (3 mm).

2.3. Application of Auxetic Structure on Leading Edge

The auxetic structure was applied to the nose rib leading edge to enhance energy absorption from impacts (e.g., bird strike). Due to its negative Poisson’s ratio, the material can more effectively dampen forces and maintain aerodynamic shape, thereby reducing the risk of structural damage (Grima et al., 2005).

2.4. Material and Design

Polycarbonate was used as the material because of its high strength and impact resistance. The crashworthiness design had dimensions of 3 mm thickness, 114 mm length, and 30 mm width.

Table 1. Polycarbonate Material Properties

Property	Value	Unit
Density	1.12	g/cm³
Tensile Strength	54.88	MPa
Flexural Strength	63.41	MPa
Flexural Modulus	1073	MPa
Elongation at Break	150.24	%

(Source: Esun 3D, 2019)

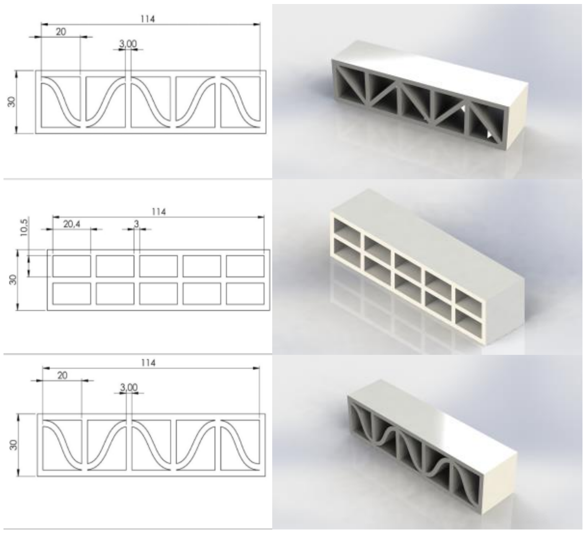

Figure 2. 2D and 3D Auxetic Structure Design

Crashworthiness Design Fabrication Process Samples were printed using Raise 3D Pro 2 Plus by Fused Deposition Modelling (FDM). Polycarbonate filament was melted through the nozzle and deposited layer-by-layer according to the test impact design geometry.

2.5. Quasi-Static Lateral Load Testing

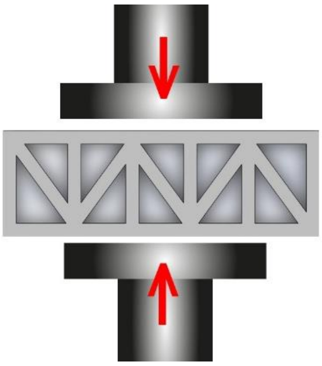

Figure 3. Quasi-Static Lateral Load Testing

Testing was conducted with an MTS E64 300kN machine using a quasi-static lateral load. The process included:

- Preparing and precisely installing the specimens.
- Setting the machine parameters according to Table 3.2.
- Recording real-time data using a microcontroller connected to a computer.
- Documenting the testing process.
- Analyzing data with Microsoft Excel and Origin Lab.

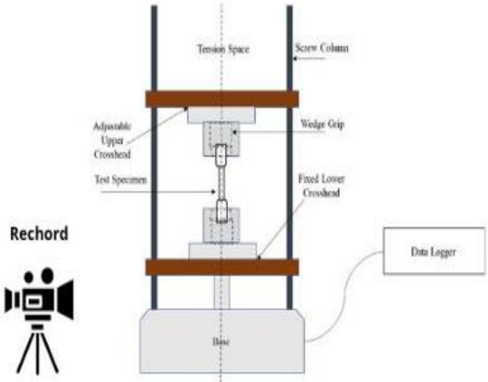

Figure 4. testing scheme

Table 2. UTM Machine Settings

Parameter	Value	Unit
Test Rate	20.00	mm/min
Preload Speed	0.033	mm/s
Strain End Point	40.000	mm/mm
Data Acquisition Rate	10.0	Hz
Preload	0.004	kN
Platen Separation	30.000	mm
Width	120.000	mm
Thickness	30.000	mm

(Source: MTS, 2025)

Table 3. MTS E64 300kN Machine Specifications

Specification	Value
Model	E64.305
Rated Force Capacity	300 kN
Column Configuration	6
Test Zones	Dual
Piston Stroke	100 mm/min
Piston Speed	0.5–180 mm/min
Crosshead Speed	270 mm/min
Test Width	405 mm
Max Tensile Space	620 mm
Max Compression Space	670 mm
Round Specimen Diameter	6–32 mm
Flat Specimen Thickness	2–25 mm
Compression Platen	150×150 mm
Frame Dimension	1950×805×660 mm
Weight	1500 kg

(Source: MTS, 2013)

2.6. Data Processing Method

Data analysis included energy absorption (EA), mean force (MF), crush force efficiency (CFE), and specific energy absorption (SEA). The parameters were calculated using the following equations:

$$EA = \int_0^d f(\delta)d(\delta) \quad (1)$$

$$MF = \int_0^d f(\delta)d(\delta) \quad (2)$$

$$CFE = \frac{MF}{IPFC} x\, 100 \quad (3)$$

$$SEA = \frac{EA}{m} \quad (4)$$

Where:

- EA = energy absorbed (J),
- MF = mean force (kN),
- IPFC = initial peak crushing force (kN),
- SEA = specific energy absorption (J/kg),
- m = mass (kg).

3. RESULTS AND DISCUSSION

3.1 Characteristics of Energy Absorption Results

3.1.1 Experimental Results of Force Reaction

Testing on three auxetic structures (triangle, half circle, rectangle) showed different force reaction patterns.

A. Triangle (a1–a2): average peak load of 39.13 Kn, with a2 exhibiting progressive crushing and a stable residual plateau of 5–10 Kn up to a displacement >10 mm.
B. Half circle (b1–b2): average peak strength of 36.14 Kn, with longer displacement in b2 (>12 mm) and residual load of 8–12 Kn, despite having lower initial strength.
C. Rectangle (c1–c2): lowest peak strength (34.12 Kn), yet c2 maintained residual load of 8–15 Kn up to 6 mm displacement.

Based on this, it can be concluded that the triangle excels in maximum strength, the half circle in total deformation, while the rectangle, although having the lowest strength, still shows more stable post-peak deformation.

3.1.2 Energy Absorption Values

Calculations using originlab indicate differences in energy absorption among the structures.

Table 4. Energy absorption values for multi-cell hybrid crash box

Variation	Specimen (1)	Specimen (2)
Auxetic triangle	51,204 j	99,083 j
Auxetic half circle	48,065 j	93,603 j
Auxetic rectangle	45,246 j	90,507 j

Based on this, it can be concluded that the rectangle showed the highest energy absorption value in the second test, but differences among the structures are influenced by geometry and deformation patterns.

3.1.3 Comparison of Energy Absorption Values

The average absorbed energy indicates that the triangular structure (Triangle) has the highest value (≈75 J), followed by the Half Circle (≈70 J), and the Rectangle (≈67 J). This pattern shows that the triangular shape can distribute stress more evenly, making it more effective at absorbing energy compared to the other two shapes. The Half Circle performs fairly well due to its curved shape, which allows for a longer deformation, while the Rectangle tends to be less optimal because of stress concentration at its corners.

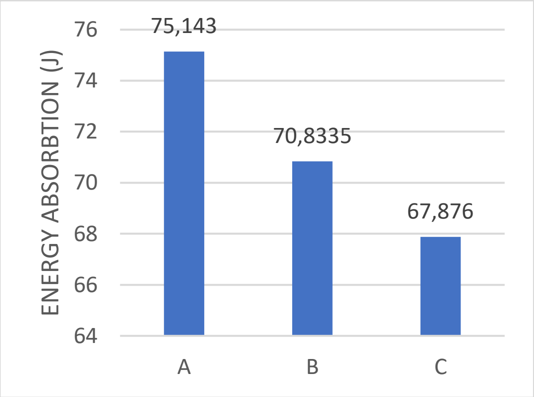

Figure 5. Chart comparison of energy absorption values

3.1.4 Initial Peak Force (IPF)

Test results show that the Triangle experienced an increase in IPF from 38.25 Kn to 40.41 Kn, indicating a better ability to withstand initial loads. In contrast, the Half Circle showed a decrease from 37.03 Kn to 35.60 Kn, reflecting a less stable distribution of the initial load. Meanwhile, the Rectangle increased from 32.68 Kn to 35.77 Kn, although its values remained below those of the Triangle. Thus, the Triangle can be said to have the strongest initial resistance in enduring impact loads.

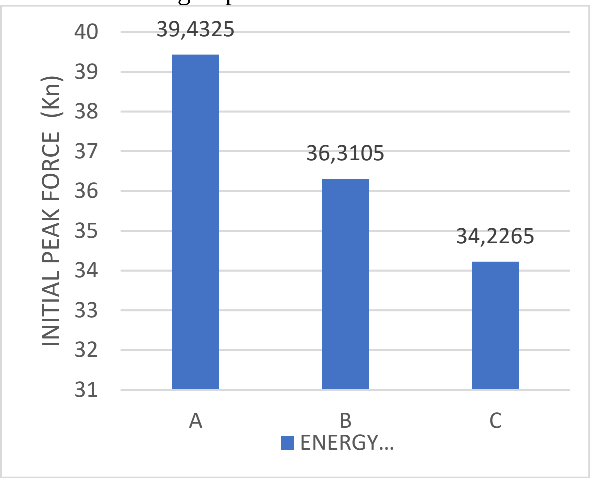

Figure 6. Chart initial peak force (IPF)

3.1.5 Mean Force

The average force values also demonstrate the dominance of the triangle. In two tests, the triangle recorded 13.03–12.30 Kn, which is higher compared to the half circle (9.89–11.69 Kn) and the rectangle (11.03–10.27 Kn). The increase in the half circle indicates an improvement in performance, whereas the rectangle tends to decline. This reinforces that the triangle consistently provides the highest average force throughout the deformation process.

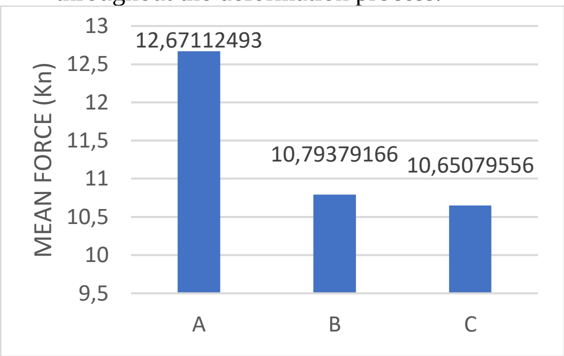

Figure 7. Chart main force

3.1.6 Crush Force Efficiency (CFE)

CFE represents the efficiency of energy absorption relative to peak force. The triangle maintains relatively stable and superior values, from 34.08% to 30.30%. The half circle shows a significant increase (26.72% to 32.85%), while the rectangle decreases (33.74% to 28.72%). From these results, it can be seen that although the triangle still leads, the half circle has competitive potential due to improvements in efficiency in the second test.

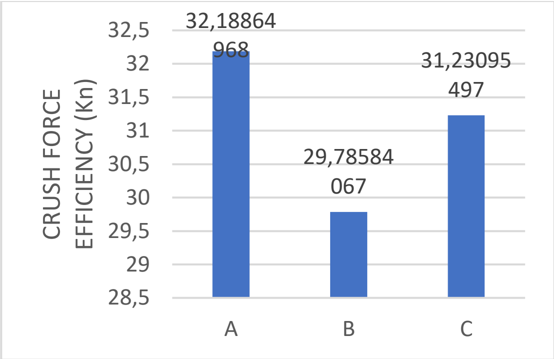

Figure 8. Chart crush force efficiency (CFE)

3.1.7 Specific Energy Absorption (SEA)

SEA calculations show that the triangle is the most efficient structure, with a value of 1.738 j/kg, followed by the half circle (1.642 j/kg) and the rectangle (1.588 j/kg). The high sea of the triangle indicates that the triangular geometry excels not only in the total energy absorbed but also in the energy efficiency relative to the structure's mass.

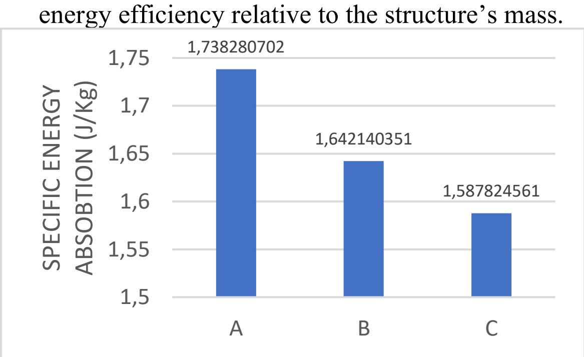

Figure 9. Chart specific energy absorption (SEA)

The triangular structure (a) records the best performance in EA (99.08 j), IPF (40.41 Kn), MF (12.30–13.03 Kn), CFE (34.08%), and SEA (1.738 j/kg). Compared to conventional honeycomb (EA 59 j, IPF 6–8 Kn, MF 3–4 Kn), the triangular structure can increase energy absorption capacity by up to 68% and initial strength by 5–6 times.

3.2 Deformation Pattern

Visual observations show:

- Triangle: controlled deformation, triangular pattern remains visible, even distribution of damage, best energy absorption.
- Half circle: large deformation on the sides and corners, faster local collapse compared to triangle.
- Rectangle: severe collapse, original shape lost, uneven bending patterns, worst energy absorption.

Based on this, it can be concluded that the auxetic triangle performs best in maintaining shape while absorbing energy, followed by the half circle, with the rectangle being the poorest performer.

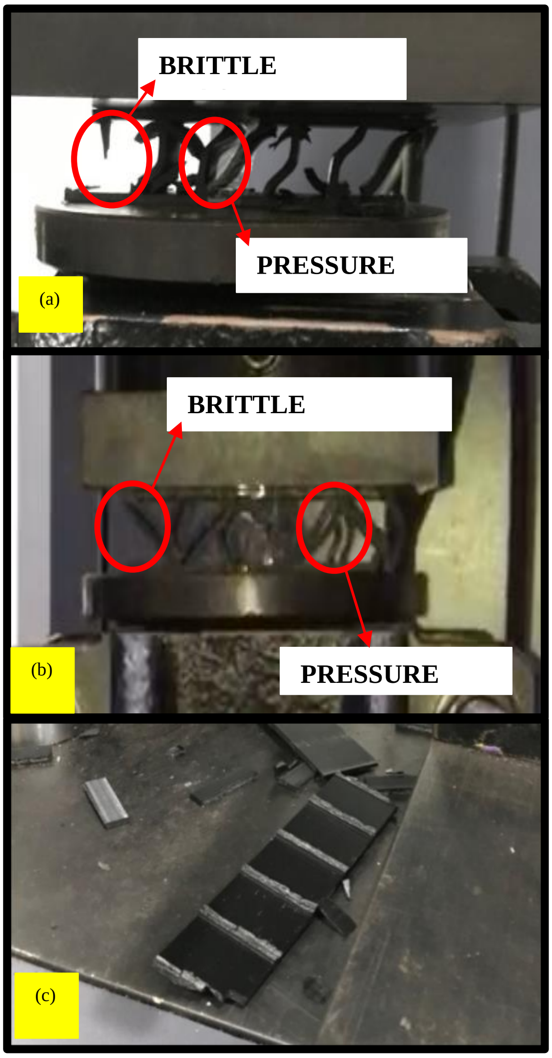

Figure 10. Crashworthiness deformation (a) Auxetic Half-circle (b) Auxetic Triangle (c) Auxetic Rectangle

4. CONCLUSION

This study confirms that the auxetic triangle structure (A) demonstrates the most superior crashworthiness performance compared to the half circle (B) and rectangle (C) structures. The triangle structure recorded the highest energy absorption of 75.14 J, an IPF of 40.41 kN, an MF of 13.03 kN, a CFE of 34.078 kN, and a SEA of 1.738 J/kg, proving it to be the most effective in absorbing energy and maintaining force efficiency. The deformation pattern shows that all structures initially experienced an increase in load until reaching the peak load, followed by a sharp decrease due to deformation, and a slight increase toward the end. Visually, the triangle exhibited uniform and controlled deformation; the half circle showed irregular damage on the sides and corners; whereas the rectangle experienced uniform deformation but with lower energy absorption.

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