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ORIGINAL ARTICLE

Crashworthiness Design for Trapezoid Origami Crash Structure

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ABSTRACT – Corrugations can be considered to be one of the ways to improve the mechanical properties of thin-walled structure in terms of manipulation of surface area. However, this theory requires further validation through experimentation of different materials. Although many research works have been done towards the corrugated shell structures, the flexibility of corrugated sheets of thermoset composite material remains unknown. This study focused on the effects of surface area manipulation by using trapezoid origami structure which is trapezoidal folded lobe shape on the absorbed energy and mechanical properties of Epoxy reinforced with S-type fibreglass. Then the trapezoidal folded lobe shape design was drawn by using AutoCAD which consist of the design of the corrugated composite sheets and the design of trapezoidal folded lobe shape mould. Moreover, the fabrication of the Aluminum mould was done by using a CNC milling machine according to the drawing. So, a compression moulding machine will be used to fabricate the composite structure. Therefore, the vibration and compression tests were carried out to perform a study on the behaviour of the trapezoidal folded lobe thermoset samples and to investigate their deformation behaviour respectively. Based on those tests, the results are shown that the trapezoidal origami samples have higher virtual stiffness than the flat samples, and the trapezoidal origami crash thin wall absorbs 40 % more energy in Y-axis direction compared to in X-axis direction.

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Crashworthiness; Trapezoid origami, Epoxy-fibreglass composite, Automotive application, Energy absorption, Mechanical properties; Structural design

INTRODUCTION

In recent times, many types of research were performed to create a protective structure against impact during an accident. To ensure the safety of the passengers, a thin-walled structure will be act as an energy absorber during impact as it is more versatile and efficient. Recently, the automotive industry has focused to reduce the bodyweight of a car without disregarding the crashworthiness of the vehicle. Hence, the industry is required to guarantee high energy absorption using a sheet as thin as possible. According to Song, the collapse modes for both conventional straight structure and origami structures were natural modes which limit their energy absorption capacity [1]. Subsequently, the design of the protective structure will absorb intense impact by avoiding linear elastic deformation, unlike traditional flat structures. Therefore, some imperfections which are deliberately applied to the structure such as grooves, corrugations and dents to control the collapse mode and lower the peak force.

The implementation of thin-walled structure that acts as an energy absorption system which undergoes impact loading using suitable design of their global geometry has attracted researchers' attention. The researchers have been striving to design structures with a specific capacity of energy absorption with less total weight during a crash. To evaluate the specific energy absorption capacity of the protective structure, the mechanical behaviour was examined [2-5].

Abramowicz and Wierzbicki have come up with super folding element theory which predicts the mean crushing force of square tubes [6]. A simple cave-in mode of circular tubes has proposed. An approximate theory has derived for predicting the mean crushing force. Moreover, the crash boxes of diamond origami were investigated and studied with the crash boxes of trapezoid origami. Based on those comparative results, the energy absorption of trapezoid origami crash structures is extremely higher than the diamond origami crash structures [7].

Most of the manufacturers in automotive industry required to satisfy both reduction of body weight and improvement of crashworthiness and so, regarding crash box, it is required to guarantee high energy absorption using a sheet as thin as possible. Conventional flat design of the steel has a well-known level of stiffness but low flexibility which make it has lower ability to absorb impact energy which causes less protection to the passenger during a collision. Introducing a special origami pattern to the conventional flat structure is also an alternative way to control the collapse mode. This technique is used in different fields like aerospace, medicine and automotive engineering [8-10]. The basic idea of Origami Theory is to obtain super folding element during a crash that gives better energy absorption to the conventional square structure. Furthermore, researchers have experimentally and numerically investigated a novel tube with origami patterns to study on the application of origami that acts as energy absorption devices. Apart from metal and alloy materials, a number of studies also were performed on polymer composite material application on vehicle parts. The reduction on

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the total weight of the beam by using composites material will not sacrifice the safety measure because composites is lighter, more secure and can make a fuel-proficient vehicle [11-14].

This study aims to utilize the effects of a trapezoidal folded lobe to extend the capabilities of a conventional structure of energy absorption. The trapezoidal folded lobe can deliver flexibility towards the structure and improve the performance as it has the ability to absorb impact by deforming to a certain extent. The design of such mechanisms treads a fine line between achieving adequate stiffness in order to exert sufficient force at the end-effector, and yet be flexible enough. Furthermore, a trapezoid folded lobe design also can be prepared and developed using the composite materials of epoxy fibreglass by the stamping process which can reduce the fabrication time and cost and enhances the crashing energy absorption by manipulating the surface area.

METHODOLOGY

Material Selection

Prepreg of Epoxy reinforced with an S-type fiberglass woven (Prepreg Epoxy-Fiberglass, US ROCK WEST COMPOSITES) was chosen in this application for its high strength to weight ratio and its durability.

Design of Trapezoidal Folded Lobe Shape and Fabrication of Mould

In Figure 1, the trapezoidal shape was designed, 25 mm × 25 mm the trapezoidal base, 10 mm the trapezoidal height, 25mm the trapezoidal mountain edge, 103˚ the trapezoidal dihedral angle. In addition of that, trapezoidal origami mould was designed 200 mm × 200 mm as shown in Figure 2. For both of them, it had used CAD software which is AUTOCAD according to the desired geometry dimension. Then, an Aluminium 6061 plate was cut using CNC milling according to the trapezoid origami structure profile which is trapezoidal folded lobe shape as shown in Figure 3. Aluminium 6061 is selected due to its good mechanical properties, high corrosion resistance and high strength-to-weight ratio and easier to fabricate.

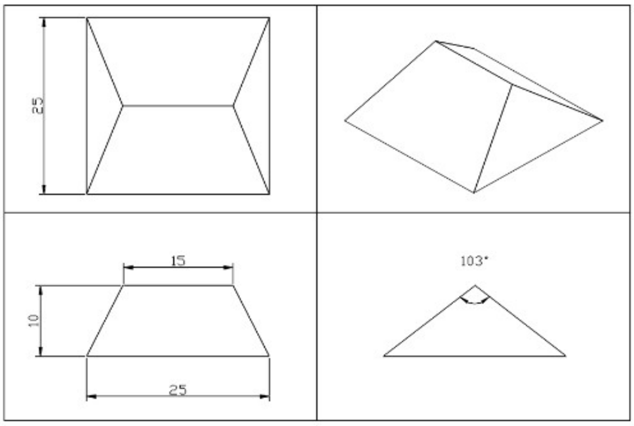


Figure 1. 3D model design of single trapezoidal folded lobe (all dimensions are in mm).

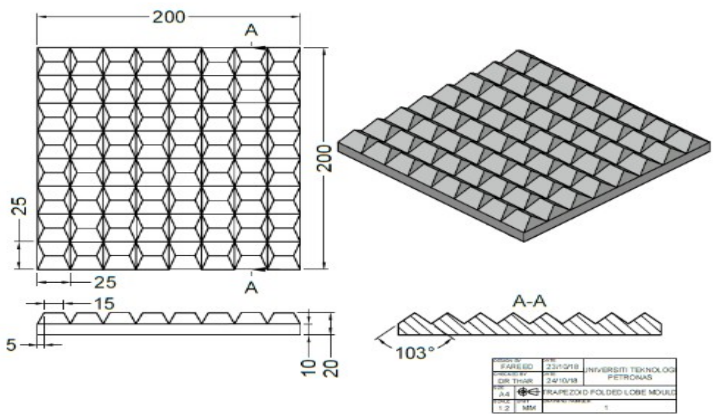


Figure 2. 3D model design of trapezoidal folded lobe shape mould (all dimensions are in mm).

Next, a rubber mould was fabricated using a compression moulding machine. A rubber piece was placed into the cavity of a mould that has a dimension of 200 mm × 200 mm and in between the mould and rubber will lie the trapezoidal folded lobe shape aluminium sheet. The male mould was fitted onto the female mould and it was placed into the compression moulding machine. The platens were preheated to 200 °C before the process [15]. Then, the rubber material was pressed against the Aluminium sheet with enough temperature and pressure to ensure the rubber piece acquires the origami profiles of the fabricated Aluminium sheets. After adequate information gathering is done, the parameters were controlled during the stamping process to ensure good and acceptable results are shown in Table 1.

The rubber was chosen for the material of the female mould because of its benefits which include simple process and cost-effectiveness. Furthermore, the sample and male mould will not be damaged when any error happened during the experimental process, such as increased pressure. Figure 4 shows the rubber mould which took the shape of the trapezoidal folded lobe.

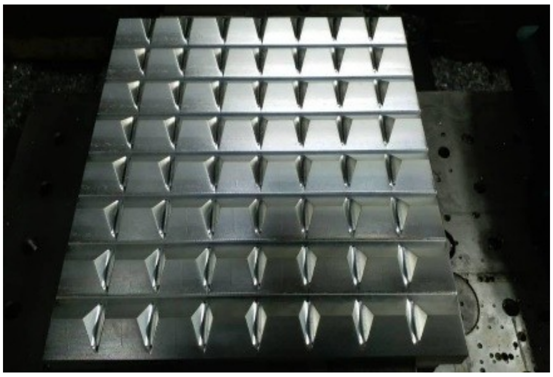


Figure 3. Trapezoidal folded lobe aluminium mould (male).

Table 1. Stamping process parameters to fabricate rubber mould (female).

Parameters	Thermoset
Die temperature	200 °C
Stamping pressure	25 tonnes
Hold time	15 minutes
Material temperature	No preheating
Pressing speed	19 cm/s

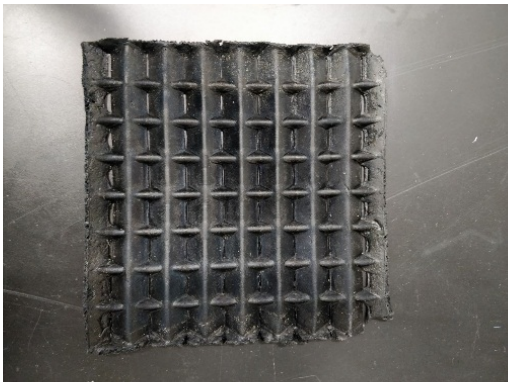


Figure 4. Trapezoidal folded lobe rubber mould (female).

Fabrication of Trapezoidal Folded Lobe Composite Sheet

The process to fabricate trapezoidal folded lobe composite sheet was basically the same as the previous process to fabricate the female mould. Also, the composite sheet consisted of two of plies of prepreg epoxy-fibreglass. Fibre orientations in the ply were 90° and 0°. Besides, the volume fraction of ply was 50% RC. Then the prepared prepreg epoxy-fibreglass laminate was placed onto the patterned sheet at the male mould. Moreover, the female mould was placed onto the composite laminate. Next, the male mould was fitted onto the female mould for compressing and the composite laminate was compressed under controlled parameters as shown in Table 2. Figure 5 shows the prepreg epoxy-fibreglass laminate that has been pressed according to the mould design. After that, the laminate was left to be cooled at room temperature, 26 °C and it was hardened to the desired origami profiles. The previous procedure was repeated to all samples. Therefore, the hardened laminates were ready for the next step to prepare the specimens for testing.

Vibration Test

Vibration test was done towards the flat and trapezoidal folded lobe samples to find and compare the stiffness of the samples. From the testing, voltage vs time graph can be obtained, and the stiffness of each sample can be calculated. Two layers sample with a dimension of 145 mm × 145 mm will be tested for an isotropy flat sample (its properties is symmetric) and trapezoidal folded sample in both Y-axis and X-axis directions. The iron beam with a length of 0.73 m was lifted and released at 3.5 cm from the initial position to apply impact force towards the sample for free vibration. Then this test was repeated three times for each sample to calculate the average values. Also, the data obtained from the test were then analysed. Figure 6 shows the setup for vibration testing.

Table 2. Stamping Process Parameters to Fabricate Trapezoidal Sheet.

Parameters	Thermoset
Die temperature	200 °C
Stamping pressure	2 tons
Hold time	8 mins
Material temperature	No preheating
Pressing speed	19 cm/s

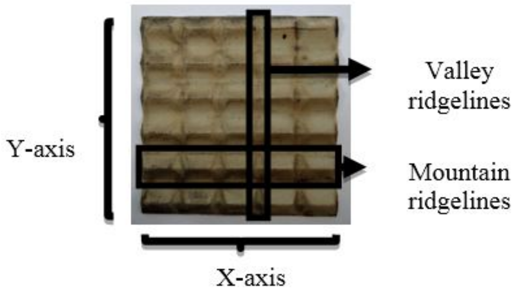


Figure 5. Trapezoidal folded lobe composite material.

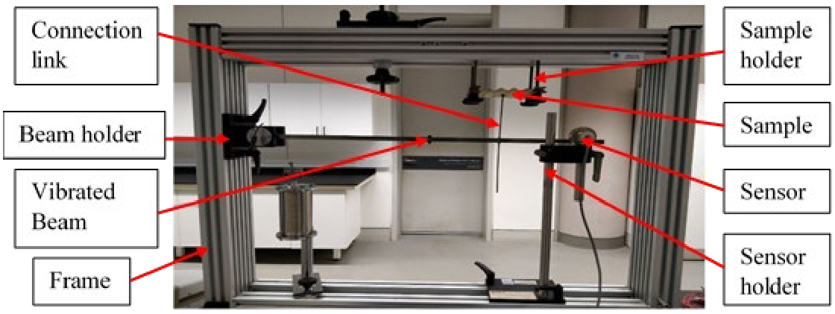


Figure 6. Setup for free vibration test.

In-plain Compression Test

Crushing test was introduced here in term in-plane compression test. It was done to investigate the deformation behaviour of the trapezoidal folded lobe and flat thermosets. The samples were compressed under the quasi-static crushing load using a universal testing machine. The compression test was done in Y-axis and X-axis directions of trapezoidal folded lobe samples to investigate the deformation in both directions as shown in Figure 5. Also, it was done for flat samples. The compression test of the specimens was provided data of the force-displacement curve of the corrugated thermoset samples and flat samples, as well. Then, data obtained was analysed and the property of each sample was discussed to see their potential energy absorber.

The corrugated thermoset samples were cut to 125 mm × 125 mm. Then, the samples were compressed using a loading plate with a thickness of 10 mm between two smooth rigid walls which spaced at 11 mm to prevent the sample from buckling as shown in Figure 7. The loading plate pushed the trapezoid folded lobe sample at 5 mm/min in X-axis and Y-axis direction respectively. For certainty, a compression test was repeated for each sample three times.

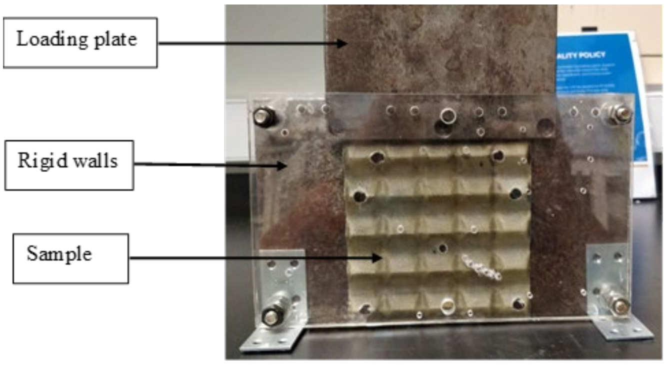


Figure 7. Setup for compression test.

RESULT AND DISCUSSION

Vibration Test

The graph of voltage vs time graph was obtained from the computer after the testing was performed. Figure 8 (a-c) shows the graph obtained from 2-layer samples with a dimension of 145 mm × 145 mm of trapezoidal laminate in X-axis direction, trapezoidal laminate in Y-axis direction and flat laminate. There was no guideline and standards that can be followed as it is a new testing. From Figure 8 (a-c), the maximum oscillation decreased from time to time which termed damping effect. The damping effect was caused when the sample absorbs energy from the shock impact force and the energy was converted into another type of energy. So, the stiffness of the trapezoidal folded lobe composite sheet can be determined by using Equation.1[8, 16].

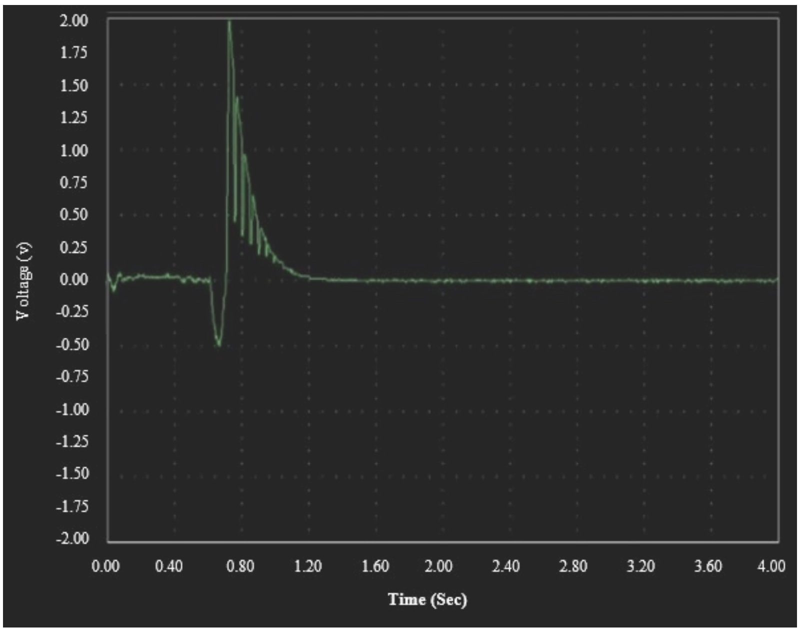
$$f = \frac{1}{2\pi}\sqrt{\frac{3ka^2}{mL^2}} \tag{1}$$

Where f is frequency, a is position of the small rod from the initial position of the beam, m is weight of the beam, L is length of the beam and k is stiffness of sample. Based on the setup, the value of the position of the small rod from the initial position, weight and length of the beam can be obtained which are a = 0.65 m, m = 1.68 kg, L = 0.73 m. The frequency can be calculated based on the graphs. The testing was repeated 3 times for each sample to determine their average stiffness value. The data obtained was calculated and recorded in Table 3.

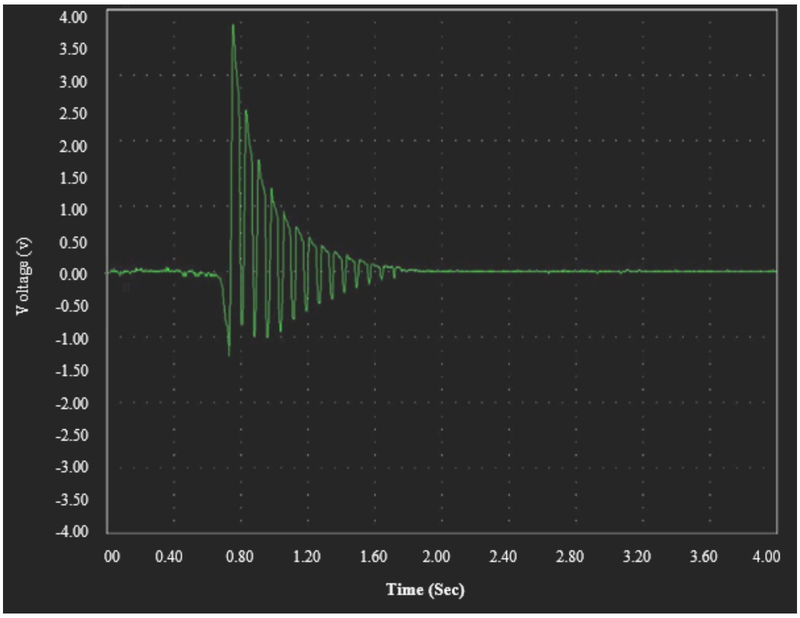
Table 3. Calculated virtual stiffness.

Sample no.	k (N/m)		
	X-Axis T. sample	Y-Axis T. sample	Flat sample
1	9218.10	4356.99	1936.44
2	9210.23	4382.31	1930.82
3	9187.78	4350.22	1933.68
Average	9205.37	4363.17	1933.64

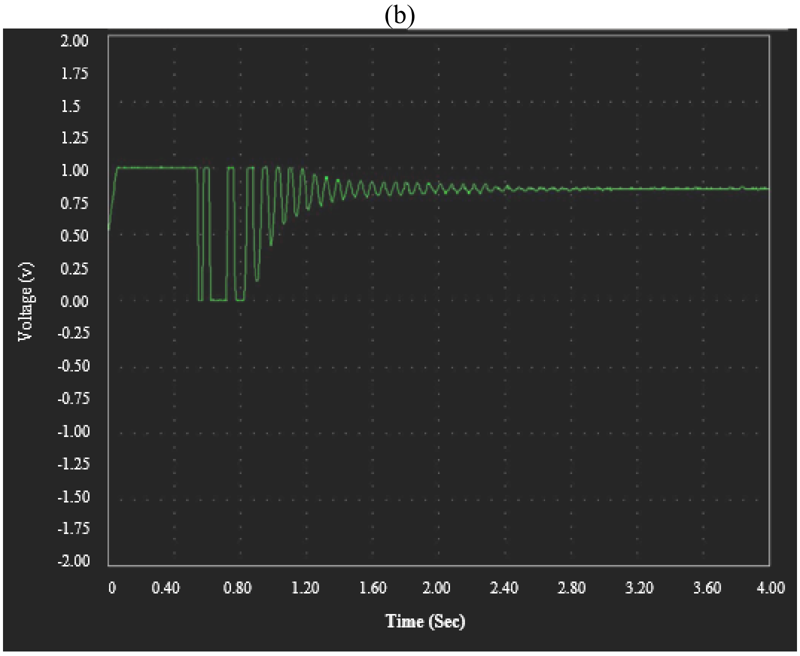
Based on Table 3, the corrugated thermoset sample has higher virtual stiffness in both X-axis and Y-axis direction compared to the flat sample. It is due to the effects of the facets of the trapezoidal folded lobe origami. The facets of the trapezoidal folded lobe sample contain a dihedral angle which makes it stiffer than the flat sample. In terms of energy, the surface energy of the trapezoidal origami sample is higher than the flat sample. Furthermore, the corrugated thermoset sample Y-axis direction has a lower virtual stiffness compared to the X-axis direction because of the dihedral angle associated with mountain ridgelines. In Y-axis direction, the sample was associated with 103° dihedral angle which makes it has a lower virtual stiffness and higher flexibility while the valley ridgelines in X-axis direction makes it stiffer, as shown in Figure 9. To put it another way, a dihedral angle increases the surface energy in Y-axis direction more than X-axis direction corrugated sample by offering bigger surface area with ridgeline which works as a hinge.



(a)



(b)



(c)

Figure 8. (a) Free vibration of trapezoidal origami sample in x-axis direction, (b) free vibration of trapezoidal origami sample in y-axis direction and (c) free vibration of flat sample.

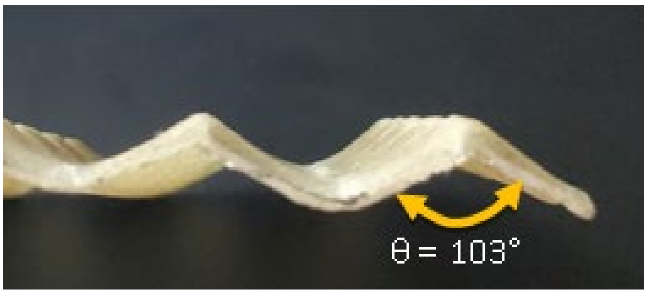


Figure 9. Dihedral angle of trapezoidal folded lobe.

In-plane Compression Test

The crashing test of the samples provides the data force-displacement curve of the corrugated thermoset composite. Based on crashing testing in Y-axis direction, the dihedral angle decreases which correspond to the folded sample at the end of the testing as shown in Figure 10 (a). The mountain ridgelines which are shown in Figure 5 that is parallel to the Y-axis direction contribute the most to the reaction force which mainly generated from the folding of all the ridgelines.

Then the reaction force in the in-plane compression in X-axis direction of the sample which was associated with the folding of valley ridgeline which was stiffer than the mountain ridgeline, as shown in Figure 10 (b). It shows that the sample has higher flexibility in Y-axis direction compared to the X-axis direction.

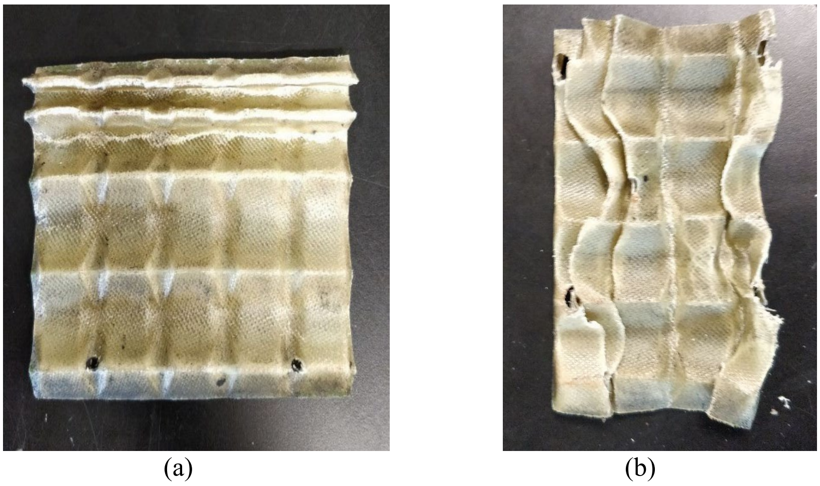


Figure 10. Sample compressed in (a) y-axis direction and (b) x-axis direction.

Based on the compression testing, force-displacement curves were plotted as shown in Figure 11. In both compression in X-axis and Y-axis direction, the corrugated samples start densification at 34 mm for compression in X-axis direction and 50 mm for compression in Y-axis direction, while, the densification of flat composite sample starts at 6 mm for compression (isotropy). So, the foldability at Y-axis direction of trapezoidal origami composite sample is higher than the foldability at X-axis direction of trapezoidal origami composite sample, and the foldability at X-axis direction of trapezoidal origami composite sample is higher than the foldability of flat thermoset composite sample. Moreover, the compression in X-axis direction of trapezoidal folded lobe origami thermoset composite sample shows a good repeatability compared to the compression in Y-axis direction probably due to the sample in Y-axis direction (perpendicular to mountain ridgeline) is more foldable than in X-axis (perpendicular to valley ridgeline), meanwhile, the compression of flat thermoset composite sample does not show any foldability.

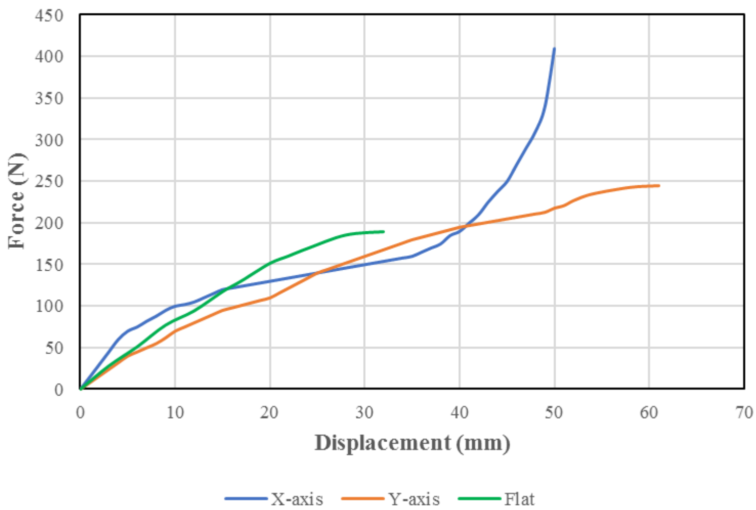


Figure 11. Force-displacement curves of compression in x-axis and y-axis direction.

Furthermore, based on the force-displacement curve, the trapezoid folded lobe sample can be compressed up to 63% of its original length in Y-axis direction and up to 38% of its original length in X-axis direction, as shown in Figure 11. The result shows that the corrugated sample in Y-axis direction was more flexible compared to the corrugated sample in the X-axis direction. Apart from that, the in-plane compression testing indicates that the trapezoidal folded lobe absorbs 40% more energy in Y-axis direction than in X-axis direction. Therefore, the absorption energy capacity is mainly depending on the dihedral angle. Besides, the flexibility of the flat thermoset composite sample is obviously less than the trapezoid folded lobe samples in Y-axis direction and X-axis direction. Similar results have been published for other origami structures [7, 9, 10, 14].

CONCLUSION AND RECOMMENDATION

A trapezoidal folded lobe composite material was investigated for its ability to absorb impact and also trigger a high-performance collapse mode. Trapezoid folded structures will be able to undergo large deformations within their working life, typically remaining within the elastic limits of the material. Precisely, a trapezoid folded structure can produce a lightweight part with high strength, creating space for the designer to tailor the stiffness properties to the required behaviour which is not possible with conventional square structure. Trapezoid folded structure also can increase passenger safety compared to the conventional square structure as it can absorb high impact through plastic deformation of the origami pattern.

The aluminium patterned plate which acts as a male mould, rubber mould and trapezoidal folded lobe composite sheet has been successfully fabricated. Furthermore, vibration testing also has been successfully done to find the specific mechanical properties of the sample. Based on the testing, it can be concluded that the trapezoid folded lobe sample has a higher virtual stiffness compared to the flat sample. Apart from that, the crashing test has been introduced on terms of in-plane compression test and this latter has been successfully done towards the sample to investigate the deformation behaviour. Hence, the testing indicates that the trapezoidal folded lobe absorbs 40% more energy in the Y-axis direction than in the X-axis direction due to the dihedral angle that increases the surface area and thus increases energy absorption capacity.

There are few recommendations to increase the stiffness and flexibility which can increase the number of layers. The increase of the number of layers will result in the increase the strength, which can be used in many applications. However, more experiments with a variety of corrugated profiles need to be done to increase the knowledge of structural and mechanical behaviour of corrugation.

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