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Study on Mechanical Behavior of Double Corrugation Surface Structure of Thermoset Composite

Husam Kareem Mohsin Al-Jothery[1*], Thar M Albarody[2]

[1]Mechanical Engineering Department, College of Engineering, University of Al-Qadisiyah, Al-Diwaniyah 58001, Qadisiyah, Iraq

[2]Department of Mechanical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar 32610, Perak, Malaysia

[*]Email: husam.mohsin@qu.edu.iq

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Abstract

Transforming the thin-wall structure from 2D to 3D to enhance the flexibility and strength of materials is an interesting research area regarding fabricating techniques and engineering properties. This study investigated the double corrugation surface structure for fiberglass-reinforced epoxy thermoset composite to improve the mechanical properties of designed composite materials. Three groups of corrugated samples (2, 4, and 6 layers) were fabricated for testing. The resulting corrugated thermoset composites were tested through tensile and compressive tests. The results illustrated that the tensile strength of a flat sample was 14.28% and 27.74% higher than the one of the double corrugated surface samples on the x-axis and y-axis directions, respectively. Then, the design showed a tremendous increase in the elongation of more than 13 times compared to the flat sample at a relatively slight expense of strength. Besides, the result also showed that the material's compressive strength improved drastically when the number of layers increased from two to six. It was presented that the increase in the number of double corrugated surface structure layers leads to a rise in energy absorption. Therefore, the highest energy absorption was 241.62 J of 6 layers-double corrugated surface sample.

Keywords: Fiberglass-epoxy composite; Hot pressing process; Mechanical properties; Mould fabrication; Quadrilateral mesh

1. Introduction

Origami is the Japanese art of forming 3D geometries by using 2D sheets. Nowadays, it refers to all folding/corrugating practices of materials. In other words, origami presents the technique of converting a 2D thin-wall structure into a 3D, especially complex shape. This process attracted engineers' and mathematicians' attention because of its endless possibilities in engineering applications, such as automobile and aerospace. Current specific applications of corrugated structures in many advanced engineering technologies are solar energy (cells), crash structures, and advanced deployable structures [1]-[3]. There are many variations of origami techniques for different purposes.

In some cases, the surface area of an origami structure may be reduced for deployment reasons or even increased for mechanical strength provisions. The perfect example of the increase in flexibility or material rigidity is corrugation, which has long been used by the manufacturing fiberboard industry. This variety is considered highly directional. Also, it significantly depends upon the direction of applied forces [4]-[6].

Folding reduces the total surface area of an object, thus making it more compact. This has triggered interest in the engineering community due to its extended possibility in deployable structures with diverse examples ranging from folding solar cells for space explorations to self-deployable medical stent grafts to emergency shelters [7]-[9]. These applications focus on the same issue of space limitation, which shares similar key advantages. A design of interest to many researchers is a corrugated pattern called Miura-Ori, with certain parallelograms connected through creases of "ridges" and "furrows." The pattern allows parallelogram facets to be undeformed while the structure collapses in just one direction [10]-[12].

Corrugations have a powerfully positive influence on the mechanical properties of materials. That influence is either to raise the strength of the corrugated structure or to enhance the flexibility of the structure. It depends on how the corrugated pattern is attained. According to earlier studies, it was suggested that the strength and flexibility of thin-walled sheets could be manipulated to fulfill the needs of the type and size of local patterns (corrugations, folds, dimples, etc.) [13], [14].

However, researchers have a larger scope of parameters that can be adjusted to provide a combination of high strength with light weight (high strength/weight ratio) [15]-[17]. For some aircraft designs, the capabilities of corrugated structures to raise stiffness without significant additional weights have shown their utilization as external skins [18], [19]. Recently, other researchers have worked on a thin-wall corrugation design to raise energy absorption called a conical corrugation tube (CCT). It is intended to mimic the pattern of coconut trees [20]. They found that the suggested design shows a high energy absorption performance. Also, it has the ability to control and predict energy absorption performance. So, the conical corrugation tube structure is highly recommended for absorbing energy, such as an automotive crash box [21].

Epoxy fiberglass and carbon fiber are widely utilized in the automotive industry, where flexibility is preferred for crashworthy designs. While improving the strength of a material, reinforcement typically introduces rigidity in a structure, which is unfavorable in applications where energy absorption is needed. Previously, our study showed that the trapezoidal folded lobe composite can raise the flexibility of the composite at the expense of composite strength [4]. Therefore, the corrugated structures can be further enhanced by implementing a double corrugation surface (DCS) thermoset composite of fiberglass-reinforced epoxy. The double corrugated surface pattern is also named quadrilateral mesh, which is inspired by the well-known origami design "Miura-Ori."

In this study, the mold for the DCS structure is designed and manufactured. The hot-pressing process is applied to fabricate the designed samples. The tensile test is carried out to study the tensile strength, tensile yield strength, tensile modulus of elasticity, and elongation. In addition, the compressive test is figured out to study the compressive strength, compressive yield strength, compressive modulus of elasticity, and energy absorption. However, the designed pattern's impact on composite material's strength and flexibility are evaluated in our study for enhancing the tensile and compressive properties of the fiberglass-reinforced epoxy composites according to a number of layers.

2. Methodology

There are three main steps for experimentally conducting this research. The first step is mold manufacturing, the second is fabricating the specimens, and the third is test preparation, as illustrated in Fig. 1.

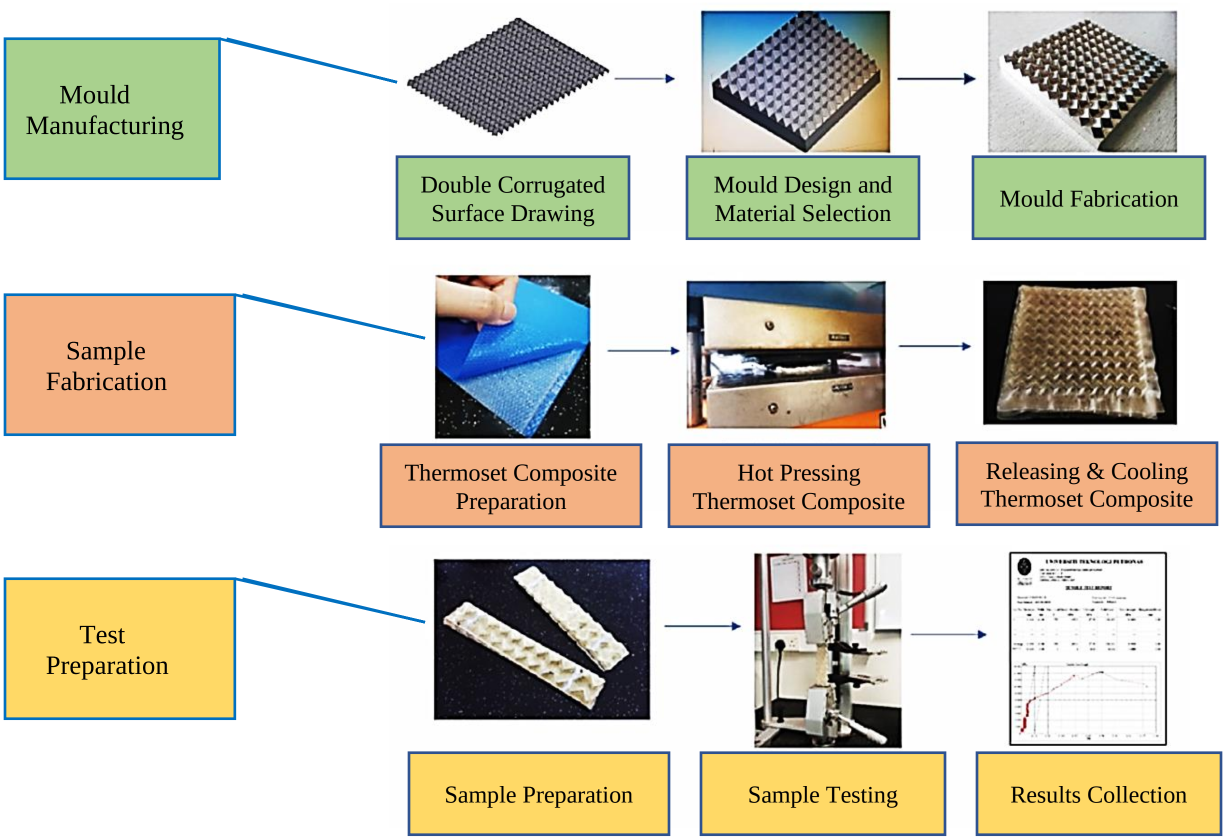

Figure 1. The steps of research study.

2.1. Materials Selection

Clear crystal epoxy (CCE) and s-type fiberglass fabric were used in this study to fabricate a thermosetting composite. This is because it has good heat resistance, high tensile, compressive, and bending strengths, low shrinkage during the curing process, high corrosion resistance, and high adhesion. Besides, it is helpful for many applications, such as automotive applications. The fabric was purchased from "ROCK WEST COMPOSITES, US ."S-type fiberglass is made from a higher-strength glass fabric, improving tensile strength and increasing the elastic modulus while maintaining lightweight properties [3]. Also, the fiberglass fabric has angles (0˚/90˚) to provide the same mechanical properties in both the x-axis and y-axis. On the other hand, the selected CCE has durable mechanical properties and is suitable for many applications in different fields, such as automotive and aerospace applications.

2.2. Mould Manufacturing

The AutoCAD software was used to draw and design a male mold with a double corrugation surface pattern. Then, the male mould was fabricated using 6061 aluminum alloy blocks by CNC machine. This is because it is fordable and has high mechanical properties. The dimensions of the fabricated male mold with a double corrugation surface pattern was 200 mm × 200 mm, which serves as one of the moulds to produce the shape on the thermoset composite. The female mold was fabricated using the aluminum sheet by hot pressing. The aluminum male mould was used to stamp on the aluminum sheet to produce a similar shape (double corrugated surface pattern), as shown in Fig. 2. It was pressed with a mould temperature of 200 °C, a pressure of 10 tons, and a hold time of 15 minutes to ensure the corrugated profile on the aluminum block was transferred onto the aluminum sheet [3], [4]. The aluminum sheet was then left to be cooled and hardened before being suitable for use as a mould.

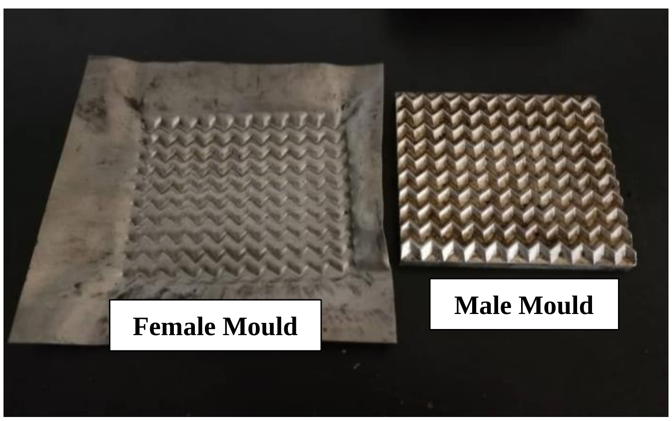

Figure 2. Manufactured mould.

2.3 Preparation of Thermoset Composite

The thermoset composite sheets were prepared for hot stamping via a hand layout method. Then, they were placed into the double corrugated surface, the male mold and the female mold. Afterward, the composite sheets were fabricated in the hot compression machine using corrugated/ flat surfaces and several composite laminae. Besides, the epoxy-to-hardener ratio was one-third for fabricating the composites. For all fabricated thermoset composites, the parameters of the hot compression machine were kept the same during the pressing process. The temperature of the plates, the applied pressure, and the hold time were 120 ˚C, 2 tons, and 10 min, respectively. After stamping, the thermoset composite was released and cooled at room temperature, as shown in Fig. 3.

Figure 3. Fabricated thermoset composite.

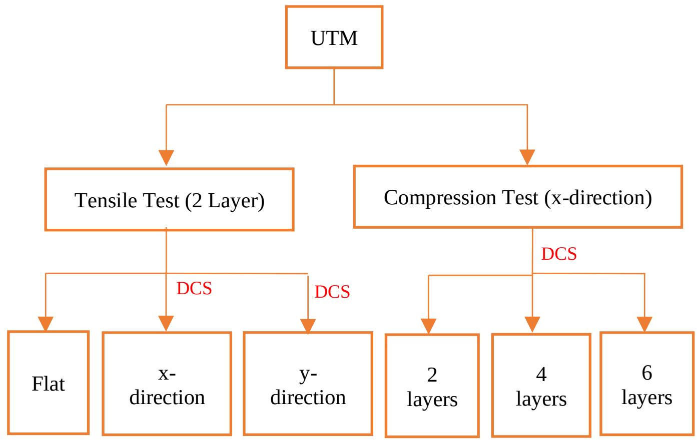

Figure 4. The flowchart of flat and double corrugation surface composite samples' testing.

2.4 Mechanical Tests

Thermoset composite materials' tensile and compressive tests took place to estimate the tensile strength, yield strength, modulus of elasticity, elongation, compressive strength, and energy. They were conducted using a universal testing machine (UTM), as shown in Fig. 4. For tensile strength, two groups of thermoset composites were tested, which were flat and corrugated composites, and both consisted of two laminae. ASTM D882 is used for the tensile, and the dimensions of the sample were 20 mm width × 120 mm length. In addition, the corrugated one was tested according to the x-axis and y-axis directions. The collected data from the tensile test were analyzed to investigate the tensile/yield strengths and the allowable flexibility. For compressive strength, three groups of thermoset composites were tested based on the x-axis direction, and they consisted of two, four, and six laminae, respectively. The dimensions of the sample were 150 mm width × 150 mm length. The setup of the compressive test was like that of our previous works [3]. The collected data from the compressive test were analyzed to investigate the compressive/yield strengths and the absorbed energy. Fig. 5 illustrates the testing directions of the fabricated thermoset composite.

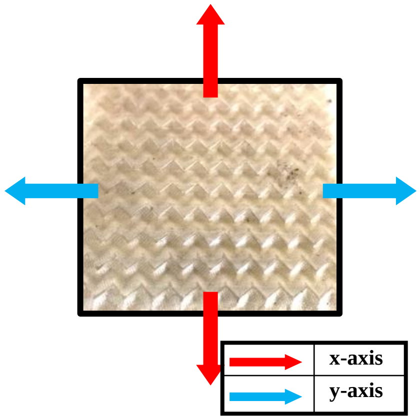

Figure 5. Axes directions of the test.

3. Results and Discussion

3.1 Tensile Test

For the tensile test, a total of six double corrugation surface samples were tested: three on the x-axis and three on the y-axis. Another three flat samples were tested on one axis only since there were no patterns to distinguish the axes, and the orientation of the fabric was 0˚/90˚. Then, the mean value was presented as a result. In addition, the failed samples during the test were ignored, and the test was repeated using a new sample, following the implemented test's standard. Therefore, the mechanical properties of the corrugated samples are compared to the flat sample in terms of tensile strength, modulus of elasticity, yield strength, and elongation, as shown in Fig. 6.

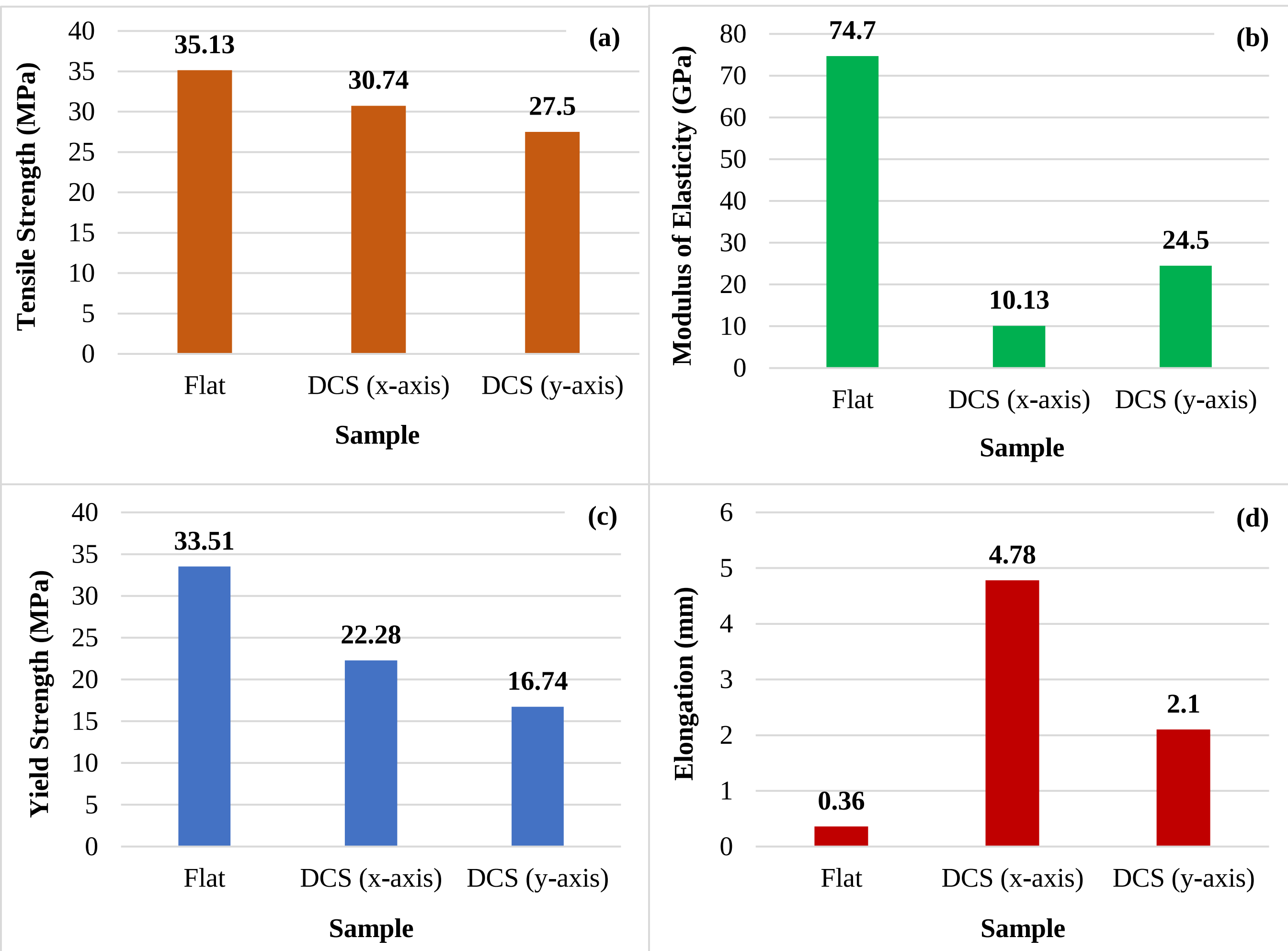

Figure 6. Tensile test of flat and double corrugation surface composite samples: (a) Tensile strength, (b) Modulus of elasticity, (c) Yield strength, and (d) Elongation.

The tensile strength of a flat composite sample is 35.13 MPa, as shown in Fig. 6a. The flat sample has the highest tensile strength compared to the quadrilateral-mesh composite samples in both directions, the x-axis and y-axis. This is because the corrugations work as joints, reducing the tensile strength. On the other hand, the tensile strength of DCS samples on the x-axis and y-axis direction are 30.74 and 27.5 MPa, respectively. The tensile strength percentage of DCS samples on the x-axis is 11.78% higher than the one on the y-axis. In addition, the tensile strength percentage of a flat sample is 14.28% and 27.74% higher than the tensile strength of the DCS samples on the x-axis and y-axis directions, respectively. The process of pattern transformation works on a slight drop in the composite stiffness because of the stress concentration at the sharp edges. Where the bent glass fibers lose some of their strength. However, the strength of DCS composite samples is lower than the flat composite samples.

A flat composite sample's tensile modulus of elasticity is 74.7 GPa, as shown in Fig. 6b. It is higher than the tensile modulus of elasticity of DCS samples in both directions (x-axis and y-axis). The differences between a flat composite sample's tensile modulus of elasticity and the x-axis and y-axis DCS samples are approximately 637.41% and 204.9%, respectively. These findings prove that the corrugated surfaces lose some strength because of formed edges. At the formed edges of composite material, the strength is divided into two components that give the applied forces a higher effect on dropping the strength of composite material. However, the folded surfaces play a crucial role in reducing the modulus of elasticity. The difference between the tensile modulus of elasticity of the corrugated sample in the x-axis direction and the one of the corrugated sample in the y-axis direction is -58.65%, which means the stiffness in the x-axis is less than the one in the y-axis direction because the bending of fiberglass on the x-axis is more than the one on the y-axis.

Fig. 6c shows the tensile yield strength of flat and corrugated samples. The tensile yield strength of a flat composite sample is 33.51 MPa. Also, a flat sample's tensile yield strength percentage is 50.4%. It is 100.18% higher than the ones of the x-axis and y-axis corrugated samples, respectively. At the same time, the tensile strength percentage of the DCS on the x-axis is 33.1% higher than the tensile strength of the DCS on the y-axis. These results ensure the tensile strength of tested samples is found. Fig. 6d illustrates the values of elongation of tested samples. The tensile elongation of a flat sample is 0.36 mm. The elongations of the DCS sample on the x-axis and the DCS sample on the y-axis samples are 10.13 and 24.5 mm, respectively, as presented in Fig. 6d. According to the comparison between a flat sample and others, the elongation percentage of a flat sample is 85.48% and 61.29% lower than the elongation of DCS samples on the x-axis and y-axis, respectively. This reveals that the DCS design can significantly enhance the flexibility of thermoset composite in both directions, the x-axis and y-axis. This is because the surface area of DCS samples is higher than that of flat samples. Besides, the designed corrugated samples are 3D, and the flat samples are 2D. Consequently, the design of DCS is useful for crashworthiness applications.

On the other hand, the elongation of DCS samples on the x-axis is higher than that of DCS samples on the y-axis, which is approximately 166.67%. This reveals that the foldability on the x-axis is greater than that on the y-axis. This is because the dihedral angle of DCS on the x-axis is wider than the angle of DCS on the y-axis. These findings agree with our previous studies [3], [4], and others [22], [23].

3.2 Compressive Test

For the compressive test, the three groups of double corrugation surface samples were tested: the first group for two layers, the second, andyers, and the third group for six layers. Each group consists of three samples that are prepared for testing. The x-axis direction of the DCS design was chosen for applying the compressive load, owing to the high elongation compared with others. Then, the average values were presented as a result. In addition, the failed samples during the test were ignored, and the test was repeated using a new sample, following the implemented test's standard. Therefore, the mechanical properties of the second and third groups of corrugated samples are compared to the first group of corrugated samples in terms of compressive strength, compressive modulus of elasticity, compressive yield strength, and energy, as shown in Fig. 7.

The compressive strength of 6 layers-DCS sample is 188.67 MPa, which is higher than the compressive strength of other samples, as shown in Fig. 7a. The difference between the compressive strength of 6 layers-DCS samples and one of 2 layers-DCS and four layers-DCS samples are 826.21% and 218.94%, respectively. The dramatic increase of compressive strength with the rise in the number of layers presents a nonlinear trend. This is because of the sharp increase in the resistance of rims against compressive loads. Fig. 7b illustrates the compressive elastic modulus for the DCS sample to the number of layers. The modulus of elasticity of 6 layers-DCS sample is 37.81 GPa, which is higher than the modulus of elasticity of other samples. That means the increase in the number of layers leads to an increase in the modulus of elasticity, which is linear. The elastic modulus of 6 layers-DCS sample is 358.3% and 131.11% higher than that of 2 layers-DCS and 4-layer-DCS samples, respectively.

Fig. 7c shows the compressive yield strength of DCS samples (2 layers, 4 layers, and 6 layers). The yield strength of the 6 layers-DCS sample is 56.35 MPa, which is higher than that of 4 layers-DCS and 6 layers-DCS samples. The difference between the yield strength of the 6 layers-DCS sample and that of the 2 layers-DCS and 4 layers-DCS samples are 1254.57% and 163.65%, respectively. The significant increase of the yield strength with the increase in the number of layers shows the nonlinear trend because of the increase in rims resistance against the applied loads. Fig. 7d shows the energy absorption of designed DCS samples to the number of layers. The increase in the number of layers of DCS structure leads to a rise in energy absorption. The highest energy is 241.62 J of 6 layers-DCS sample. Therefore, a tremendous increment can be seen in the compressive yield strength and energy absorption of the designed DCS thermoset composite when layers are increased. A minimum number of laminae is recommended for engineering applications requiring high energy absorption and crashworthiness applications [21], such as aircraft body fuselage panels, since the material exhibits a higher elongation with reduced stiffness [18].

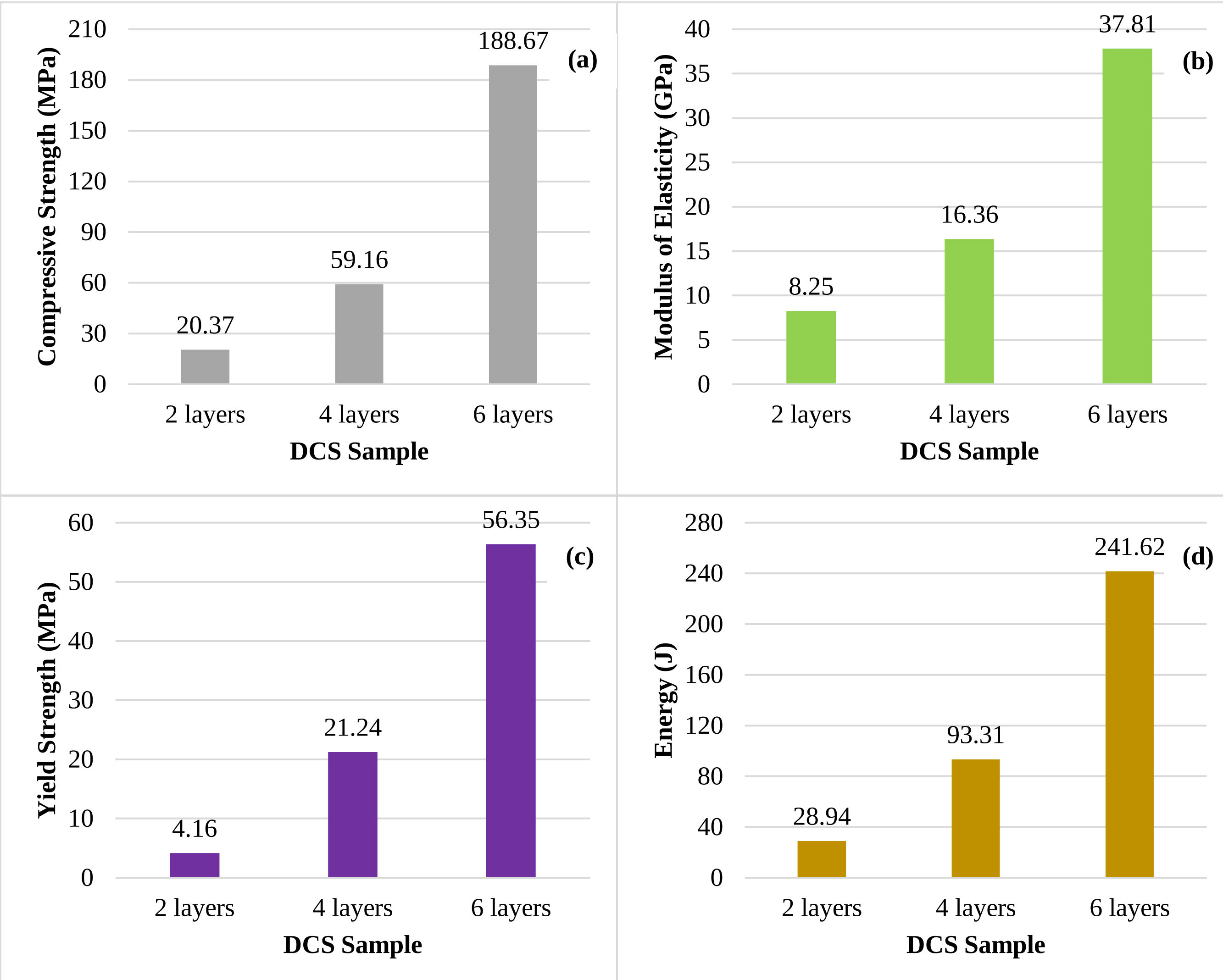

Figure 7. Compressive test of double corrugation surface composite samples according to the number of layers: (a) Yield strength, (b) Modulus of elasticity, and (c) Energy.

4. Conclusions

The origami-inspired double corrugation surface design has been shown to significantly improve the mechanical flexibility of the fiberglass-epoxy s-type thermoset composite material by increasing its elongation at break as opposed to the flat sample. However, this flexibility is achieved by slightly compromising the strength of the material. The corrugated thermoset composites were tested through tensile and compressive tests. The tensile strength of a flat sample was 14.28% and 27.74% higher than the one of the double corrugated surface samples on the x-axis and y-axis directions, respectively. Then, the design showed a tremendous increase in the elongation of more than 13 times as compared to the flat sample at a relatively slight expense of strength. Besides, the material's compressive strength improved drastically when the number of layers increased from two to six. It was presented that the increase in the number of double corrugated surface structure layers leads to a rise in energy absorption. The highest energy absorption was 241.62 J of 6 layers-double corrugated surface sample. The bending strength of the corrugated material has the possibility of showing otherwise, as can be seen in fiberboards. A three-point bend strength test is recommended for future investigation of this design to evaluate the relationship between the deflection of the material and the applied load.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Husam Kareem Mohsin Al-Jothery: Proposed the research problem, fabricated the mould, prepared all the samples and discussed the results.

Thar M Albarody: Utilized all the tests in this research, investigated the mechanical behavior of the origami structure, and discussed the results.

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