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Bending Behavior of 3D Printed Polymeric Sandwich Structures with Various Types of Core Topologies

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Abstract

In this study, bending performance and energy absorption capabilities of sandwich structures with different types of core topologies. Specifically, four types of core geometries including circular, hexagonal, square, and triangular were investigated. Sandwich structures were fabricated using Fused Deposition Modelling (FDM) 3D printing method using polylactic acid (PLA) and carbon fiber reinforced polylactic acid (CF-PLA). The material properties of PLA and CF-PLA were determined via tensile test. Three-point bending tests were performed to achieve the energy absorption performance of sandwich structures. The findings of the bending test show that the core topology has a substantial impact on sandwich constructions' capacity to absorb energy. In particular, the EA value of the sandwich structure with a circular core is %111, %106, and %449 higher compared to sandwich structures with hexagonal, square, and triangular core geometries, respectively. Additionally, it has been observed that the use of different materials affects the energy absorption capacity of sandwich structures. The SEA values of sandwich structures manufactured from circular and hexagonal core geometries of PLA material are approximately 3.1 and 1.5 times higher, respectively, compared to sandwich structures manufactured from CF-PLA material.

Keywords: 3D printing, carbon fiber-reinforced PLA, energy absorption, fused deposition modelling, sandwich structure

Research Article

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1. Introduction

Sandwich structures are monolithic constructions consisting of two outer surfaces with high tensile and compressive strength, lightweight, resistant to moisture and corrosion, and resistant to fire, along with a lightweight inner core structure that provides shear strength [1,2]. Due to these characteristics, sandwich structures are widely used in various architectural structures, aviation, shipbuilding, aerospace, and automotive industries, as well as in components such as aircraft wings and tail parts, motorcycle helmets, wind turbine blades, fixed barriers, and sports equipment [3–7]. The mechanical performance of sandwich structures depends on the material properties used for construction, the geometry of the face sheets, and particularly the design of the core topology. When looking at the studies in the literature, it can be observed that lattice structures, foams, cellular structures, auxetic structures, honeycombs, square, and triangular geometries are commonly used as core geometries in sandwich structures [8–10]. Several researchers have studied a wide variety of face sheets and core materials in order to improve the impact resistance and energy absorption potential of sandwich structures used in various engineering structures. For example, Zhao et al. [11] studied the deformation and damage mechanisms, dynamic behaviors and energy absorption capabilities of aluminum foam sandwich structures subjected to low-velocity impact, with a particular emphasis on evaluating the influence of face sheet thickness, density and core height on the impact resistance and optimal design of such structures. Wang et al. [12] investigated the out of plane ballistic performances of aluminum sandwich panels with different core geometries such as hexagonal, reentrant, circular, triangular and square. Jin et al. [13] carried out numerically blast resistance and dynamic responses of the sandwich structures with auxetic reentrant honeycomb cores. Wang et al. [14] presented in their paper the development and optimization of a novel sandwich panel with a three-dimensional double-V Auxetic (DVA) structure core, aimed at achieving isotropic mechanical behavior and providing air blast protection, through parametric numerical modeling and optimization techniques. Taghipoor et al. [15] discussed the influence of lattice-core geometry in sandwich panels through experimental and numerical analyses, analyzing three types of steel lattice cores under axial impact loading, and comparing the experimental and numerical results to evaluate parameters like specific energy absorption. It was concluded that the geometric configuration of the core components exerts a substantial influence on the mechanical performance of sandwich structures.

Traditional manufacturing methods, where the outer surfaces and inner core parts of sandwiches are produced separately and then assembled together, are both complex and costly. Therefore, there is a demand for a manufacturing method that facilitates the production of the outer surfaces and various complex-shaped inner cores as a single piece. The geometries of the core in sandwich structures are determined based on the mechanical requirements of the target applications. Therefore, it is also necessary to thoroughly investigate the functional properties arising from the geometry of the inner core structure and demonstrate their suitability for the intended application. Technologies that allow for flexible design and manufacturing of the inner core shapes in sandwich structures are needed. Recent advancements in 3D printing or additive manufacturing (AM) technologies have enabled the production of cellular materials with more complex architectures [16–20]. Researchers have recently conducted studies on various core topologies of additive manufacturing-produced sandwich structures, examining their behavior under different types of loadings. For instance, Vyavahare and Kumar [21] focused on the numerical and experimental investigation of fused deposition modeling (FDM) fabricated re-entrant auxetic structures made from ABS and PLA materials, analyzing the influence of geometric parameters on strength, stiffness, and specific energy absorption under compressive loading, as well as optimizing these parameters to enhance performance while minimizing weight and fabrication time. Zoumaki et al. [22] fabricated biodegradable starch-based sandwich materials by using maize starch-based films as skins and 3D-printed polylactic filaments (PLA) as the core, and investigated the tensile properties of the skins through the preparation of conventional and nanocomposite films with various reinforcement combinations. Najafi et al. [18] performed a study to examine and compare the mechanical characteristics, such as energy absorption, Young's modulus and compressive strength of fully integrated 3D printed polymeric sandwich structures with different auxetic core topologies (anti-tetra chiral, re-entrant, arrowhead), as well as conventional honeycomb structures, fabricated using the FDM 3D printing method. Additionally, Choudry et al. [23] conducted a comprehensive investigation involving both numerical simulations and experimental tests. Their study focused on a 3D printed sandwich structure with an auxetic core. They specifically examined the mechanical properties and performance differences between a modified re-entrant structure and a conventional re-entrant auxetic core. Moreover, Zeng et al. [24] investigated the failure mechanisms and bending performance of the integrated continuous fiber reinforced composite trapezoidal corrugated sandwich structures with different geometric configurations manufactured by FFF 3D printing.

Currently, most research on reinforced polymers uses fiber reinforcements, but they have application limitations. Therefore, further research on the mechanical behavior of carbon fiber filament-based 3D-printed structures for industrial applications is required. Fused Deposition Modeling (FDM) -based 3D printing of fiber-reinforced polymers presents several advantages across different industries, with a specific focus on automotive and aerospace sectors. This study aims to research the energy absorption capabilities and mechanical behavior of different core sandwich structures manufactured with carbon fiber-reinforced PLA (CF-PLA) and PLA materials by the FDM process. Four different core topologies e.g. circular, hexagonal, square and triangular were used for sandwich structures. The present study focuses on the effects of core geometries and different materials on the energy absorption capabilities and mechanical behavior of sandwich structures. The sandwich structure specimens underwent three-point bending tests. This study stands out from the previous paragraphs by focusing on the exploration of energy absorption capabilities in monolithic sandwich structures with varied core geometries produced using additive manufacturing techniques.

2. Experimental details

2.1. 3D printing of sandwich structures

The sandwich structures with four different core topologies shown in Figure 1 were printed on a FDM 3D printer. In here, h_c is the height of triangular, square and hexagonal inner wall, d is diameter of circular core structures and tc is the thickness of core structures. Dassault Solidworks software was used to design the CAD model of sandwich structures that is demonstrated in Figure 2. In this figure, t_s is the thickness of sandwich structures sheets, L is the length of sandwich structures and h is the height of core structure. Additionally, w represents the width of the sandwich structures. The geometrical dimensions for both sandwich and core structures were demonstrated in Table 1.

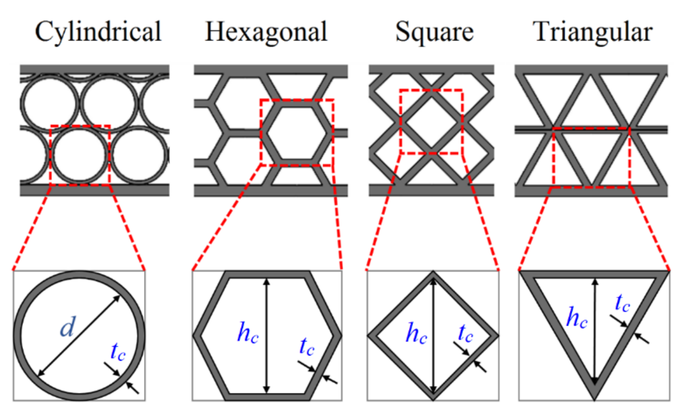


Fig. 1. Unit cell configurations of core structures

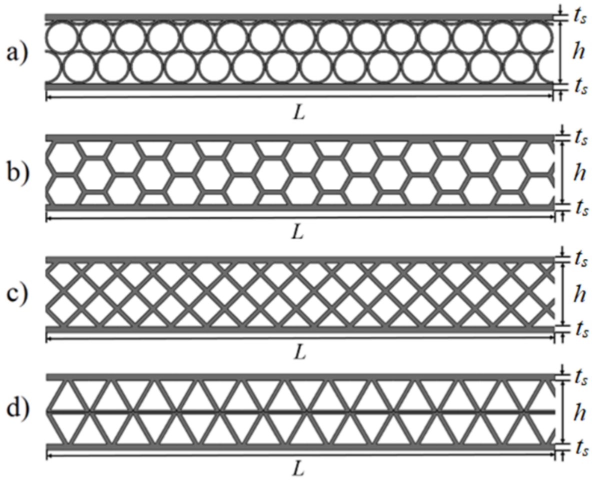


Fig 2. CAD models of sandwich structures with a) circular, b) hexagonal, c) square and d) triangular cores

Table 1. Geometrical parameters of sandwich and core structures.

d (mm)	*h_c* (mm)	*t_c* (mm)	*L* (mm)	*t_s* (mm)	*h* (mm)	*w* (mm)
7	7	1	120	1.5	15	30

Table 2. The parameters for the 3D printing process of PLA and carbon fiber-based PLA filament on an FDM machine.

Parameter	**Unit**	**Value (PLA)**	**Value (CF-PLA)**
Printing temperature	[°C]	205	210
Substrate temperature	[°C]	60	70
Diameter of nozzle	[mm]	0.4	0.4
Thickness of layer	[mm]	0.2	0.2
Infill density	[%]	100	100
Print speed	[mm/s]	50	50

Sandwich structures were produced using the FDM process, one of the most popular 3D printing methods. To produce the 3D parts using this technique, the printer melts the filament and extrudes from it through a small nozzle. FDM is faster, quite easy and more affordable than other 3D printing techniques. It is also very suitable for producing models, prototypes and parts for low-volume production commonly used in the FDM 3D printing industry. Following the design of the sandwich structures, the Ultimaker Cura program was used to transform the 3D model into data appropriate for the 3D printer and set the process parameters. All specimens were manufactured in accordance with the same direction to eliminate the effect of additive manufacturing's anisotropic nature. Table 2 contains a listing of the parameters for the 3D printing process. Filaments (PLA and carbon fiber-based PLA) with 1.75 mm diameter were used.

2.2. Mechanical tensile properties

For manufacturing the sandwich structures (core and face sheets), Polyactic acid (PLA) and Carbon fiber based Polyactic acid (CF-PLA) were used as a material of filament. To determine the PLA and CF-PLA filament material properties, tensile test specimens were prepared according to ASTM standard D638 and tested. Table 3 demonstrates the averaged material properties of PLA and CF-PLA filament obtained from test results. The tensile tests were made in Shimadzu Universal Test Machine using 10 kN load cell. A constant loading rate of 2 mm/min is applied to tensile specimens during testing. Moreover, to verify that the results were accurate and repeatable, each test was carried out a minimum of three times. The dog bone shaped PLA and CF-PLA specimens for the tensile test are illustrated in Figure 3.

Table 3. Mechanical properties of 3D printed PLA and CF-PLA materials.

	Young's modulus (E)	**Ultimate strength**	**Strain at max stress**	**Density**
PLA	2.4 GPa	51.2 MPa	0.024	1.24 g/cm^3
CF-PLA	31.16 GPa	202.05 MPa	0.013	1.77 g/cm3

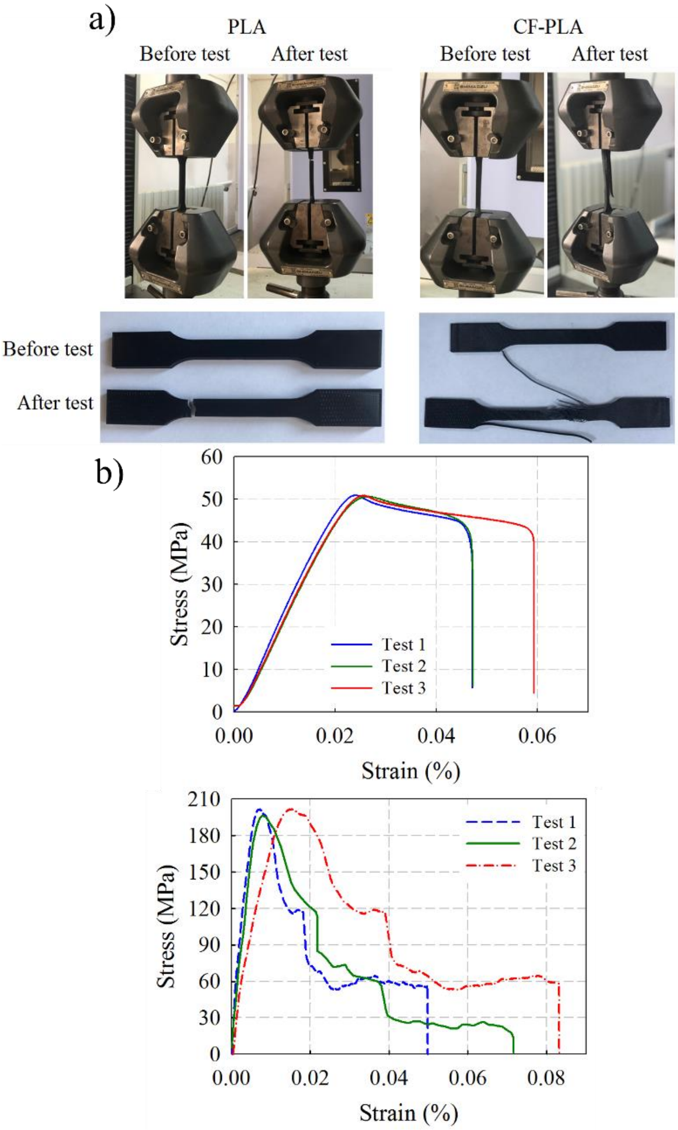


Fig.3. a) 3D-printed PLA and CF-PLA dog-bone tensile test specimen, b) the relationship between stress-strain for a PLA and CF-PLA specimen that was 3D-printed and subjected to tensile loading.

2.3. Three-point bending tests

Three-point bending tests were applied to the sandwich specimens according to the ASTM C393 standard to research the energy absorption capabilities of these structures produced by FDM. Three-point bending experimental test mechanisms for samples of all core geometry were demonstrated in Figure 4. 10 kN load cell and 2 mm/min displacement rate were used to test sandwich specimens in Shimadzu Universal test machine. The intermediate opening of the support points in 3-point bending tests is 90 mm. The diameter of the lower fixed supports and the effect test device is 10 mm. Three different specimens of each core structure topology were tested to achieve the correct results and reliability of the tests.

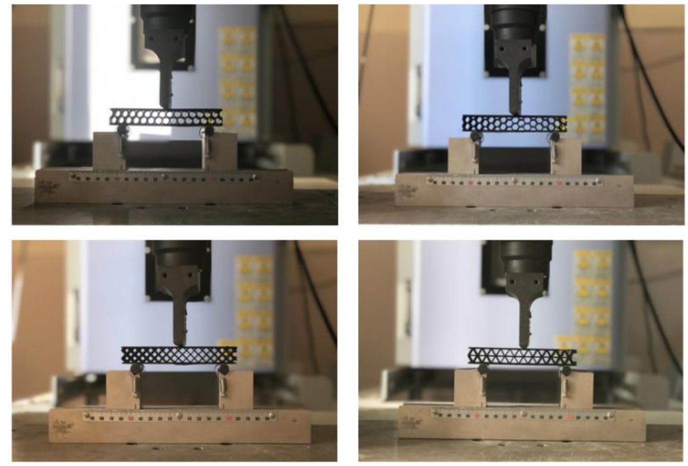


Fig.4. Three-point bending test configuration for energy absorption analysis of 3D printed sandwich structures.

2.4. Energy absorption indices

It is crucial to establish the crash criteria in advance in order to accurately evaluate the crashworthiness performance. Energy absorption EA, mean crushing force MCF (absorbed energy per maximum displacement), the specific energy absorption SEA (energy absorbed per mass), peak crush force PCF (maximum force) and crush force efficiency CFE (mean crush force per peak crush force) are frequently used to assess the energy absorption capabilities of energy absorbers. The following formula is used to calculate the EA, which stands for the total absorbed energy throughout the actual crushing period:

$$EA = \int_0^d F(x)dx \tag{1}$$

where d is deformation distance and $F(x)$ is the instantaneous load during crush.

By dividing the total energy absorbed by the actual crushing distance, the MCF is computed which can be calculated as follows:

$$MCF = \frac{EA}{d} \tag{2}$$

The capacity of a structure to absorb energy in relation to its mass is measured using the SEA, which can be defined as the total absorbed energy per unit mass (m). [25-27]. It is calculated with the following equation:

$$SEA = \frac{EA}{m} \tag{3}$$

Higher EA, SEA, and MCF indicate that the absorber structures have superior crashworthiness performance [28-31]. The PCF is the greatest crush force experienced throughout the crushing distance. In terms of passenger safety, the PCF that is too high poses a threat [28-32]. The CFE is given as the following equation and refers to the MCF value per unit PCF value:

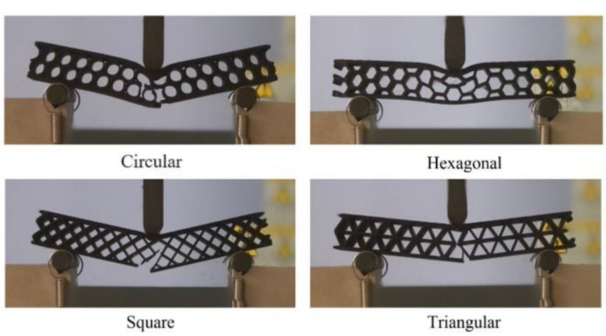
$$CFE = \frac{MCF}{PCF} \tag{4}$$

Since the uniformity of the force-displacement curve is determined by the CFE, higher values are preferable to increase the impact resistance of structures [33,34].

3. Results and Discussion

As shown in Figure 5, a constant load of 10 kN was applied to the sandwich structures manufactured by using four different core structures as circular, hexagonal, square, and triangular. Figure 5 represents the deformations of the sandwich structures after three-point bending tests. The sandwich structures with different inner core geometries of the same dimensions have undergone varying deformations in response to the applied constant load. With the increase of the transmitted load from the beginning of the test, the bonds near the two free ends are bent first and thus the rear faceplate is suddenly bent. Crack formation and elongation were determined for both PLA and CF-PLA materials in all core geometries except hexagonal structure. As the hexagonal core sandwich structure gradually collapsed, the structure has a constant load bearing capacity. Consequently, in this specific honeycomb core sandwich configuration, deformation primarily took place in the upper section of the honeycomb cores, where they experienced compressive stress on the top surface, as opposed to the fracture failure mechanism observed in the other core structures.

(a)



(b)

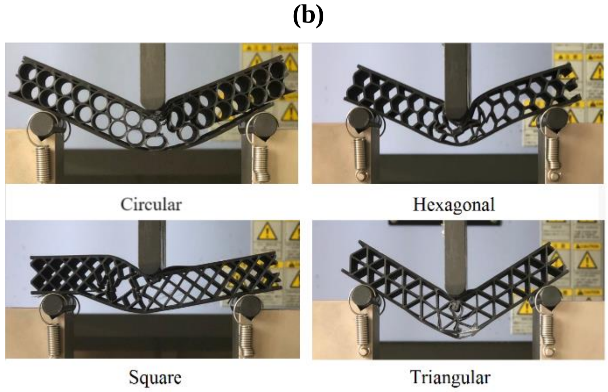


Fig.5. Deformations of sandwich structures under three-point bending test for a) PLA and b) CF-PLA materials

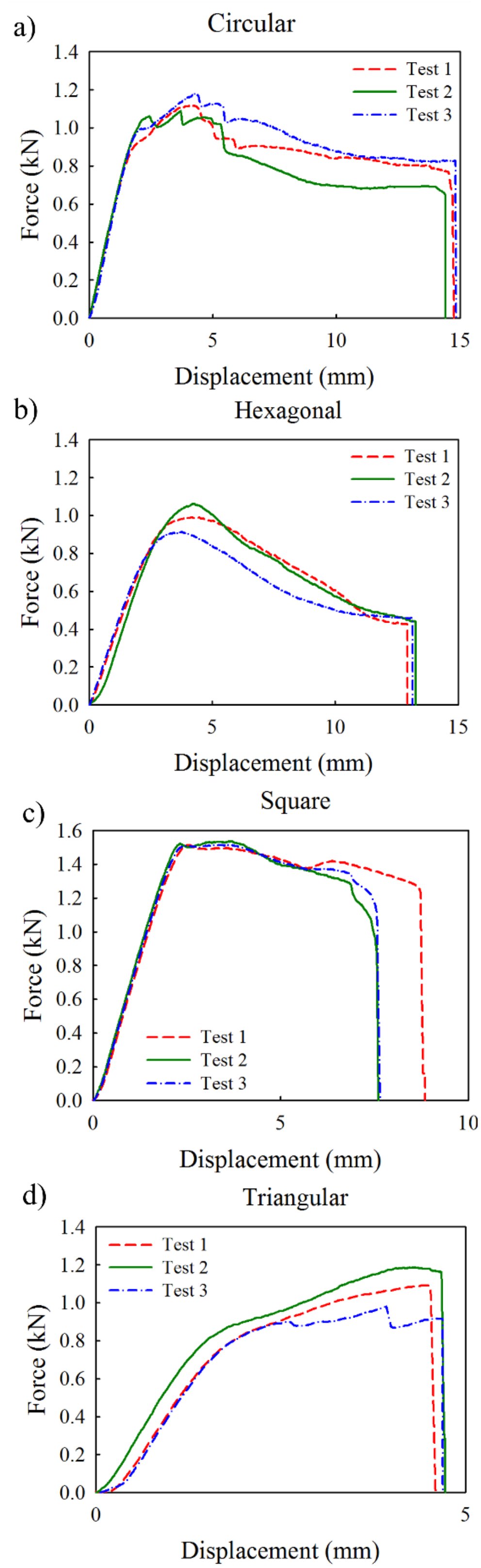


Fig.6. Force-displacement curves of sandwich structures with different core configurations PLA a) circular, b) hexagonal, c) square and d) triangular

In Figure 6, the curves depicting the relationship between force and displacement for sandwich structures manufactured from PLA materials are presented, showcasing four distinct core structures subjected to three-point bending by experimental tests. Firstly, the initial deformation behavior of all sandwich structures is linear. This shows that the deformation in the sandwich structures is elastic due to the crushing of the core structures of the sandwich structures and the bending of the sheet on the upper surface. Once the yield strengths of both the sheet and core structures are reached, subsequent to the elastic phase, the structure undergoes a transition into the plastic phase, and these results in the propagation of deformation changes toward the cellular core. The progressive collapse of the core structures results in improved energy absorption capacity of the sandwich structures. Experimental results show that the core topology has an effective role in the force displacement graph. The load-displacement curves of sandwich structures had similar changes for different types of core structures. The square core sandwich structure has the highest bending stiffness and maximum strength, while the circular core sandwich structure has the lowest bending stiffness and largest bending displacement. In addition, it has been observed that the sandwich structure with a circular core is more ductile than the sandwich structures with other core topologies. As can be seen from the figures, the circular core structure has 1.16, 1.81 and 3.22 times more displacement values than the hexagonal, square, and triangular core structures, respectively.

In Figure 7, the force deformation graphics obtained from the three-point bending test result of sandwich structures made of CF-PLA are shown. When Figure 7 is examined, elastic deformation is seen at the beginning, like the results of sandwich structure produced from PLA, while plastic deformation is observed after the yield point. Similarly, the experimental results show that the geometry of the core structure significantly affects the mechanical properties. From Figure 7, it is seen that the sandwich structure with the square core geometry has the highest strength value and the sandwich structure with the hexagonal core geometry has the highest ductility. For example, the maximum displacement value of the sandwich structure with hexagonal core geometry is 36%, 109% and 130%, respectively, compared to the sandwich structures with circular, square and triangular geometry. Moreover, for all core geometry topologies, the strength values of CF-PLA sandwich structures are lower than the strength values of PLA sandwich structures. While PLA clings to each other more tightly between and within layers, the bonds are weakened in the CF-PLA filament. Similar results are seen in Ref. [34] study in the literature.

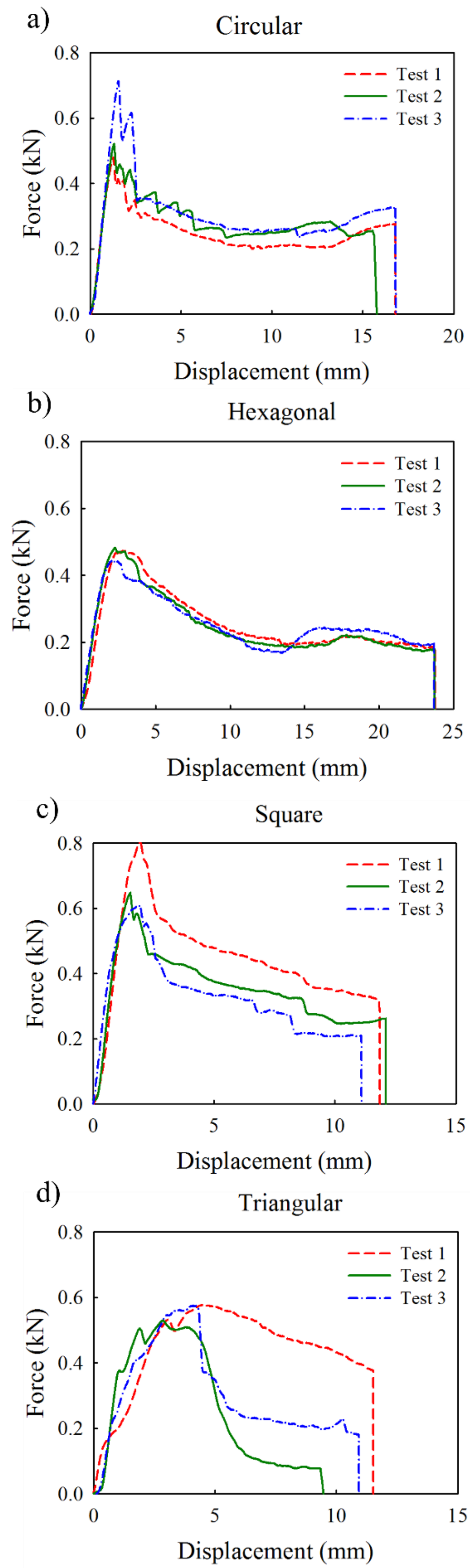


Fig.7. Force-displacement curve of sandwich structures of CF-PLA for a) circular, b) hexagonal, c) square and d) triangular core topologies

Figures 8 and 9 present a comparative analysis of energy absorption terms to explore how the core geometry influences the energy absorption capabilities of sandwich structures. Figure 8 illustrates the Energy Absorption (EA) and Specific Energy Absorption (SEA) values of sandwich structures. As discussed in Refs. [18, 23], it is evident that the absorption energy of sandwich structures is influenced by the core geometry. Upon examining the EA and SEA graphs, it can be observed that the sandwich structure with a circular core geometry exhibits significantly higher energy absorption capabilities for PLA material. Additionally, it demonstrates superior bending characteristics and is capable of sustaining the load for a much longer duration. As an example, the EA value of sandwich structures with circular core geometry is 111%, 106%, and 449% higher compared to the sandwich structures with hexagonal, square, and triangular core geometries, respectively. On the other hand, for the CF-PLA material the sandwich structure with hexagonal core geometry has the highest energy absorption. For example, the EA value of sandwich structures with hexagonal core geometry is about 29%, 36% and 64% higher than the sandwich structures with circular, square and triangular core geometries, respectively. Same as the EA values, the SEA value of the sandwich structure with a circular core geometry manufactured from PLA material is higher compared to the SEA values of sandwich structures with other core geometries. However, the SEA value of the sandwich structure with a hexagonal core geometry manufactured from CF-PLA material is higher than the SEA values of sandwich structures with other core geometries. For instance, The SEA value of the sandwich structure manufactured of PLA material with a circular core geometry is 1.8, 2, and 5.1 times higher than the SEA values of the sandwich structures with hexagonal, square, and triangular core geometries, respectively. Additionally, the SEA value of the sandwich structure with hexagonal core geometry manufactured of CF-PLA material is approximately 54%, 58% and 74% higher than the SEA values of the sandwich structures with circular, square, and triangular core geometries, respectively. Consequently, sandwich structures with circular and hexagonal core geometry emerge as superior choices for energy absorption applications for PLA and CF-PLA materials, respectively.

Fig. 9 indicates the peak crush force, mean crushing force and crush force efficiency values of sandwich structures with different core topologies and materials subjected to bending loading. As illustrated in the figure, considering both PLA and CF-PLA materials, since the displacement value of the sandwich structure with square core geometry is small, the MCF and CFE values are calculated higher than the sandwich structures with circular, hexagonal, and triangular core geometries according to the amount of energy it absorbs. For instance, for PLA material, the MCF values of sandwich structures with circular, hexagonal and triangular core geometries are 30%, 47% and 41% less than the MCF values of the sandwich structure with square core geometry. Same scenario CF-PLA material is seen to be similar in MCF value. The MCF value of the sandwich structure with a square core geometry manufactured from CF-PLA material is 45%, 53% and 9% higher than the MCF values of the sandwich structures with circular, hexagonal, and triangular core geometries, respectively. As a result, the results obtained from PLA material for sandwich structures with all core geometries have better MCF and CFE values than CF-PLA material.

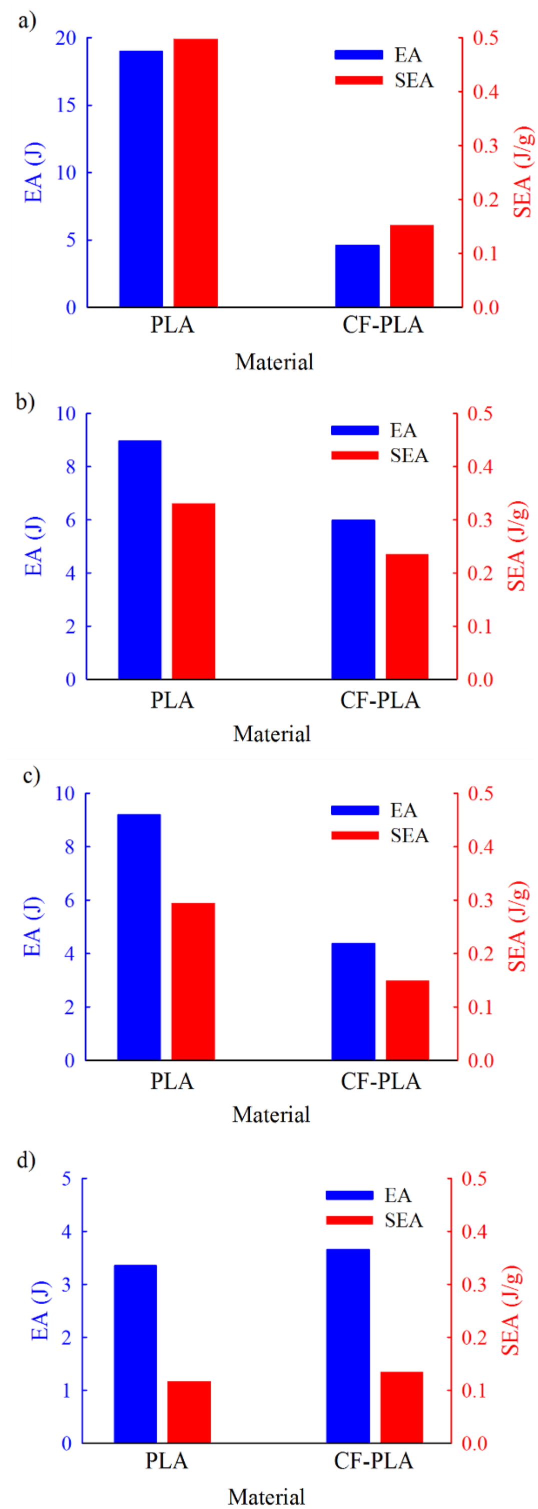


Fig.8. Energy absorption and specific energy absorption values of sandwich structures with different core topologies subjected to bending loading a) circular, b) hexagonal, c) square and d) triangular

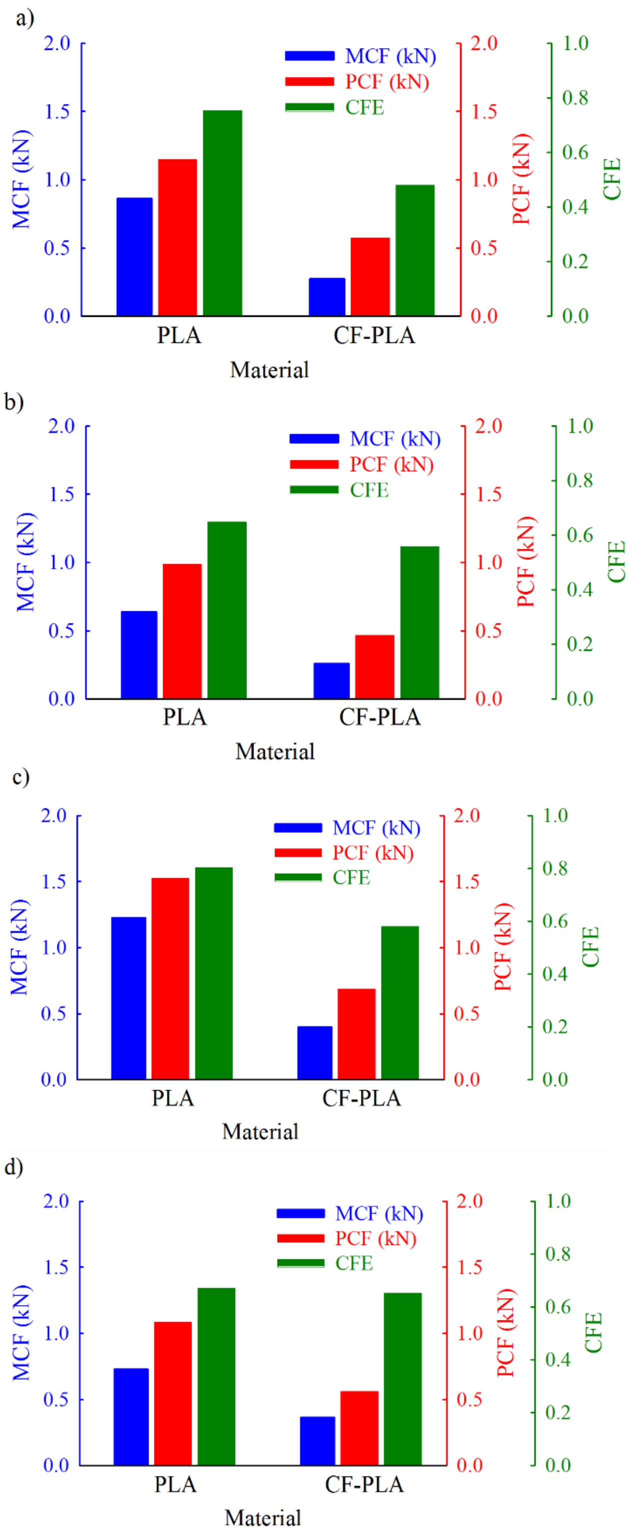


Fig.9. Mean crushing force, peak crush force and crush force efficiency values of sandwich structures with different core topologies subjected to bending loading

4. Conclusion

In this study, bending behavior and energy absorption capabilities of sandwich structures manufactured of PLA and 15% carbon fiber reinforced PLA material with four different core geometries including circular, hexagonal, square, and triangular core geometries using FDM method were investigated. The main findings of this study are summarized as follows:

- Using 3D printing technology, it is possible to produce sandwich structures as desired with different core geometries with unique properties and enhanced energy absorption capacity.
- The tensile strength of 100% filled carbon fiber reinforced PLA material is 200 MPa, which is 4 times higher than 100% filled PLA.
- While the modulus of elasticity was 2.4 GPa for PLA material, it increased approximately 13 times to 31.16 GPa for 15% carbon fiber reinforced PLA material.
- Normal PLA has better energy absorption properties under flexural loading compared to carbon fiber reinforced PLA produced in the same direction and having a fill angle. This is because PLA and carbon fiber have lower mechanical strength due to weak interlayer bonds.
- The study highlights the significant influence of core topology on energy absorption, overall deformation, and deformation mechanisms in sandwich structures. Among the different core geometries, the sandwich structure with a circular core demonstrates superior energy absorption capabilities compared to composite structures based on other core geometries. In sandwich structures manufactured of CF-PLA material, the sandwich structure with hexagonal core geometry is better.
- In the three-point bending loading, the energy absorption value of the sandwich structure for PLA material with a circular core geometry is significantly higher, showing an increase of 111%, 106%, and 449% when compared to the sandwich structures with hexagonal, square, and triangular core geometries, respectively.

In conclusion, the findings of this study offer valuable insights into the potential applications of sandwich structures in engineering. Specifically, they highlight the importance of utilizing these structures for designing systems with highly efficient energy absorption properties across a wide range of applications in the future. With this motivation, in a future study, the energy absorption performance of sandwich structures with auxetic core geometries will be thoroughly examined. Within this scope, the energy absorption performances under bending and compression loadings will be numerically investigated by varying the unit cell height, the number of unit cells in the core, and the unit cell thickness.

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Conflict of Interest Statement

The authors must declare that there is no conflict of interest in the study.

CRediT Author Statement

Merve Tunay: Conceptualization, Investigation, Methodology, Resources, Supervision, Visualization, Writing-Original Draft, Writing-Review&Editing

Mehmet Fatih Bodur: Resources, Investigation,

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