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RESEARCH ARTICLE

Estimation of three-point bending behavior using finite element method for 3D-printed polymeric sandwich structures with honeycomb and reentrant core

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Abstract: Sandwich structures are known as ultra-light porous materials. Because the structure has advantages in terms of acoustics, fatigue, and impact resistance that conventional stiffened plates cannot match, it has become a popular material in aerospace, automotive, marine, windmill, and architectural applications. One promising method for decreasing production waste and enhancing flexural stress is to employ additive manufacture (AM) technologies for sandwich structure manufacturing. In this study, polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and polyethylene terephthalate glycol (PETG) sandwich structures with reentrant and honeycomb cores were designed and then to compare the stress distributions in these sandwich composites, a finite element analysis (FEA) was used. According to the findings, higher flexure stresses and specific energy absorption were obtained in the reentrant sandwich structures compared to honeycomb sandwich structures. A minimum equivalent stress value was found in the ABS material, while a maximum equivalent stress value was found in the PLA material.

Keywords: Sandwich Structures, 3D printing, Finite Element Analysis, Three-point Bending

1. Introduction

A sandwich structure is a porous ultra-lightweight material with a large specific surface area and high specific stiffness. Acoustics, fatigue, and impact resistance are all advantages of the sandwich structure that conventional stiffened plates cannot match. Therefore, sandwich structures have become a popular material in aerospace, automotive, marine, windmill, and architectural practices [1-2]. The application of additive manufacturing (AM) techniques for sandwich structure manufacturing is one promising technique for decreasing production waste and improving lateral stiffness. Additive manufacturing has been employed in industries that require a small number of complicated parts because AM can create net-shaped parts that would be impossible to build using traditional manufacturing methods. Moreover, AM has the ability to build interior geometries that would otherwise be impossible to achieve using a typical milling technique [3].

Sandwich structures contain a lightweight core between two thin solid face-sheets having strong flexural rigidity on top and bottom surfaces. The lightweight core connects the face-sheets with minimal weight gain, resulting in high resistance to bending and buckling, as well as excellent energy absorption and shear stiffness. Transverse shear and compression loads are carried by the lightweight cores, whereas in-plane and flexure loads are carried by the solid face sheets [2]. A sandwich structure's structural and energy absorption capabilities, and also the failure mechanism, are all influenced by the geometrical parameters, material, and core design. Among all possible core designs, honeycomb and reentrant core have been extensively investigated. Castro et al. [4] examined the mechanical performance of three different 3D printed sandwich structure core designs. Chang et al. [5] studied the reentrant and the honeycomb sandwich structure experimentally and numerically. Zaharia et al. [6] investigated the mechanical behavior of 3D-printed sandwich structures having honeycomb, diamond-celled and corrugated core designs. Ingrole et al. [7] worked on the energy absorption and mechanical behavior of the 3D-printed sandwich structures having reentrant cores and compared them with the sandwich structures having honeycomb cores.

Honeycomb core is a popular choice for secondary structure applications due to its high mechanical properties.

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They are rigid and lightweight, and they can absorb a lot of energy when subjected to shockwaves and impact loads, which makes them ideal for sports equipment (e.g. helmets) and vehicles (e.g. bumpers). Several analytical, computational, and experimental studies showed that sandwich structures having honeycomb cores are rigid, lightweight, and when they are crushed, they absorb a lot of energy, especially in the out-of-plane direction [2,3,8]. Auxetic structures have lately gained a lot of interest since they have the uncommon property of thickening when stretched; that is, they have negative Poisson's ratios. One of these sorts of the core is reentrant core since it has a negative Poisson's ratio [8,9]. A negative Poisson's ratio coefficient for a material could result in increased indentation resistance, improved bending stiffness, shear resistance, and improved dielectric characteristics for microwave absorbers. Reentrant cores have a wide range of possible applications including engineering fields such as vibroacoustic, packaging, biomedicine, sensors, and automotive engineering [10-11]

In the literature, polylactic acid (PLA) is mostly used to make 3D printed sandwich structures. The choice of core material, on the other hand, has an impact on a sandwich structure's high stiffness, strong impact resistance, and great strength-to-weight ratio [3,12]. In the present study, polylactic acid (PLA), acrylonitrile-butadiene-styrene (ABS), and polyethylene-terephthalate-glycol (PETG) sandwich structures with reentrant and honeycomb cores are designed using CAD software. The stress distributions in these sandwich structures are then compared using a finite element analysis (FEA). In addition, the influence of the different core materials is examined and their potential in structural applications is indicated.

2. Materials and Method

The geometric features of the designed (by the CATIA V5 software) honeycomb and reentrant sandwich structures are given in Figure 1.

The finite element analysis (FEA) was performed using commercial software ANSYS to simulate the behavior of sandwich structures during three-point bending tests. The properties of materials used in the analysis are given in Table 1.

Table 1. Properties of PLA, ABS, and PETG

Properties\Material	PLA	ABS	PETG
Young's Modulus (Pa)	3,45E+09	2,39E+09	2,95E+09
Poisson's Ratio	0,39	0,399	0,33
Yield Strength (Pa)	5,41E+07	4,14E+07	5,3E+07
Tangent Modulus (Pa)	0,1	0,1	0,1
Shear Modulus (Pa)	1,241E+09	8,5418E+08	1,109E+09
Bulk Modulus (Pa)	5,2273E+09	3,9439E+09	2,89223E+09
Density (kg/m³)	1250	1040	1375

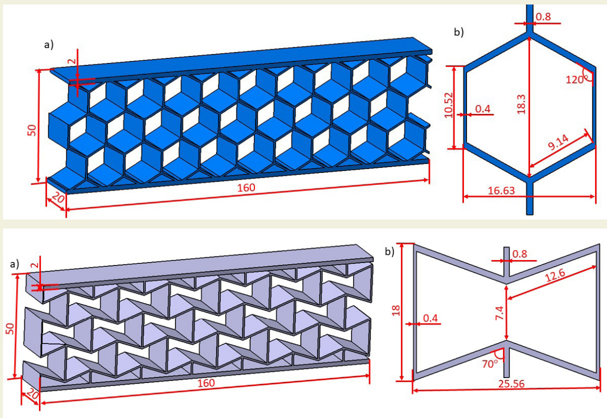

Figure 1. Dimensions of designed sandwich structures by using CATIA V5 for FEA bending test a) honeycomb, b) reentrant

Sandwich structures under a quasi-static three-point bending load were simulated in accordance with ASTM C393/393M-20 as shown in Figure 2. The load was applied by a center 10 mm diameter roller, the supports were two exterior 10-mm diameter cylindrical rollers, and the span length was 125 mm. In the FEA analysis, the bottom support rollers were fixed, and the central roller was given a displacement of 60 mm in the z-direction. Structural steel was chosen as the material of the rollers. The material properties of the sandwich structures in the geometry were assigned as PLA, ABS and PETG for each analysis and mesh structure were determined. The meshing was performed with quad/tri elements using an automatic methodology. Mesh model was given in Figure 2. The average element quality, aspect ratio and skewness for the reentrant model were 0.90324, 1.3409, 0.19042, respectively. The honeycomb model's average element quality, aspect ratio and skewness were, respectively, 0.93323, 1.3254, and 0.14108. For the reentrant model, the nodes and elements were 46073 and 37560, while for the honeycomb model, they were 62181 and 34560. The analysis was carried out in ANSYS 2021 R2 workbench and the results were received.

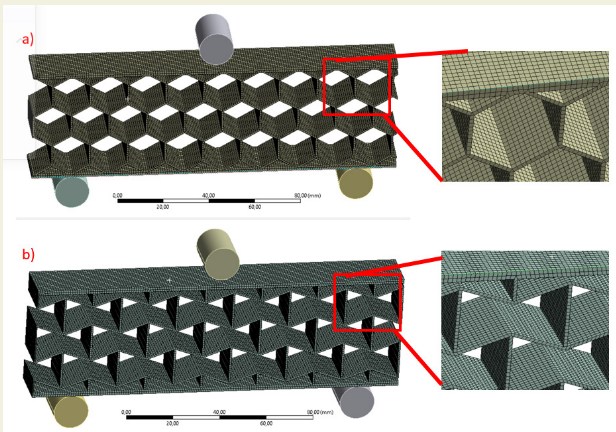

Figure 2. Three-point bending test simulation and meshing of sandwich structures a) honeycomb, b) reentrant

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The highest stress experienced by the specimen under a given load is known as flexural stress. The maximum stress experienced in correspondence to the outer surface (at the midway) using the geometry, boundary conditions, and load configuration was estimated as:

$$\sigma = 3FL/2wd^2 \qquad (1)$$

In Eq.(1), F is the load at the considered point and it is expressed in [N]. w is the width, L is the length and d is the height of the sandwich structure.

3. Results and Discussions

The force, flexure stress, equivalent von mises stress, and internal energy values after FEA analysis of the sandwich samples are given in Table 2. Specific energy absorption (SEA) is a significant measure for assessing the energy absorption of sandwich structures. It is defined as the sandwich structures' unit energy absorption efficiency, expressed as [13]:

$$\text{SEA}=Absorbed\ Energy/Mass \qquad (2)$$

Table 2. FEA analysis of the sandwich structures

	Force Reaction (N)	Mass (g)	Flexure stress (MPa)	Equivalent (Von-mises)(MPa)	Specific energy absorption (J/g)
PLA-reentrant	2152,6	41,448	41,329	53,650	2,845
ABS-reentrant	3106,6	31,349	59,646	41,046	2,846
PETG-reentrant	2956,0	37,680	56,755	51,951	3,066
PLA-honeycomb	1234,6	38,120	23,704	54,053	2,197
ABS-honeycomb	1945,9	28,833	37,361	41,353	2,358
PETG-honeycomb	2591,6	34,655	49,758	52,938	2,604

The overall trend in Table 2 showed that higher specific energy absorption were obtained in the reentrant sandwich structures compared to honeycomb sandwich structures. By comparing the sandwich structures with reentrant and honeycomb core designs, it should be highlighted that the reentrant core absorbed more energy than the honeycomb core. One of the main reasons is that the inner density of the core in the reentrant was higher than in the honeycomb core design [13]. Moreover, SEA was increased from PLA to PETG. The reason for this is that PETG is a denser material that requires more effort to flexure and, as a result, absorbs more energy.

According to the three-point bending test results, the reentrant design showed increased flexure stresses, as shown in Figure 3. It can be observed that the reentrant core took the maximum amount of load under flexure. At reentrant sandwich structure, each layer of the cores fails one at a time under compression loading, leading up to a higher strain of failure of the samples. After the failure of each layer, the structures come to an equilibrium and can take further loading until the failure of the next layer. This phenomenon is often referred to as snap-through instability. Due to this type of failure, this structure tends to have a higher flexure strength compared to honeycomb [8, 14]. The flexure stress of the PETG sandwich structure with reentrant core (~56 MPa) was the highest followed by the PETG sandwich structure with honeycomb core (~49 MPa).

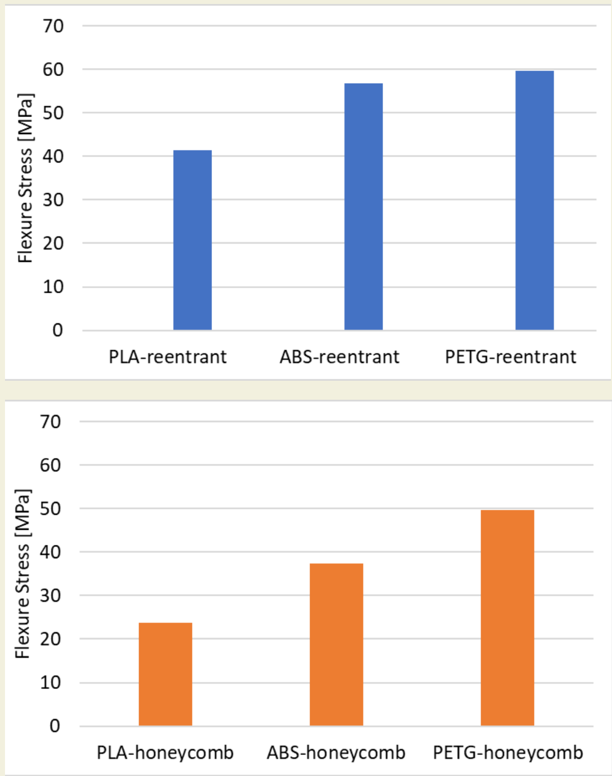

Figure 3. Flexure stress of a) reentrant b) honeycomb structures

Figure 4 shows the equivalent (Von-Mises) stress values after the three-point bending test, which show that the highest Von-Mises stress occurred in the PLA sandwich structure, which was prone to failure. On the top and bottom layers of the core, the largest equivalent Von-Mises stresses were concentrated. In the light of these results, for reentrant core design, a minimum equivalent stress value of 41.046 MPa was found in the ABS material, while a maximum equivalent stress value of 53.65 MPa was found in the PLA material for reentrant core design. Similarly, for the honeycomb core design, the ABS material had a minimum equivalent stress value of 41.353 MPa, whereas the PLA material had a maximum equivalent stress value of 54.053 MPa. This can be because PLA is brittle material than ABS.

The filament type that is selected has a significant impact on the environment as well. PETG material is the most environmentally friendly, whereas ABS material is the least environmentally friendly. PLA have received widespread praise as a renewable, plant-based, and biodegradable replacement for plastics made from petroleum [15]. Furthermore, it is evident from the comparison (Figure 4) that the PETG is appropriate for sandwich structures that need high flexure strength. PETG has a strong shock resistance and load carrying capacity because the resultant monomers are larger than the parent monomer ethylene glycol following the crystallization process [16].

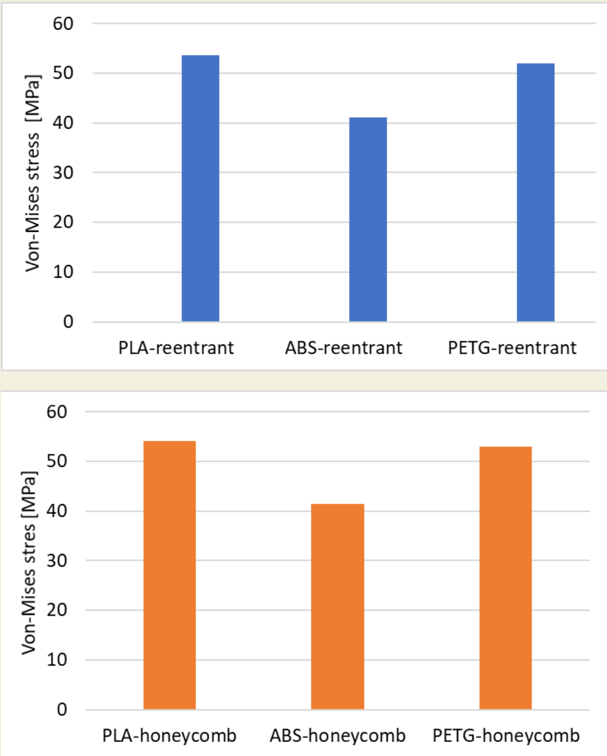

Figure 4. The equivalent (Von-Mises) stress a) reentrant b) honeycomb structures

As shown in Figure 5 and Figure 6, the reentrant core of the sandwich structure was attracted to the center of the panel due to the auxetic effect. The core material flew in a lateral direction towards the center, providing greater support for the flexure and resulting in a higher load level. The honeycomb core, on the other hand, showed no material concentration effect. The core in the central zone was compressed while those on the sides tended to expand away from the flexure center, indicating that the honeycomb core has a lower bending stiffness than the reentrant core. In addition, the auxetic reentrant core deformed consistently, distributing stress evenly [5-8].

Moreover, in the reentrant core design, the cores were more in a vertical position thus, the structure was stiffer. Many structural components in the three-point bending test are parallel to the z-axis direction of build orientation, and thus failure happens with loads orientated parallel to the z-axis. The honeycomb core had corners that are 120 degrees, whereas the reentrant core had corners that are 70 degrees. The reentrant core had fewer angle components in the z-axis direction. Thus, it may be concluded that it had a larger reinforcing effect in the loading direction and was, therefore, stiffer than the honeycomb core [8,17].

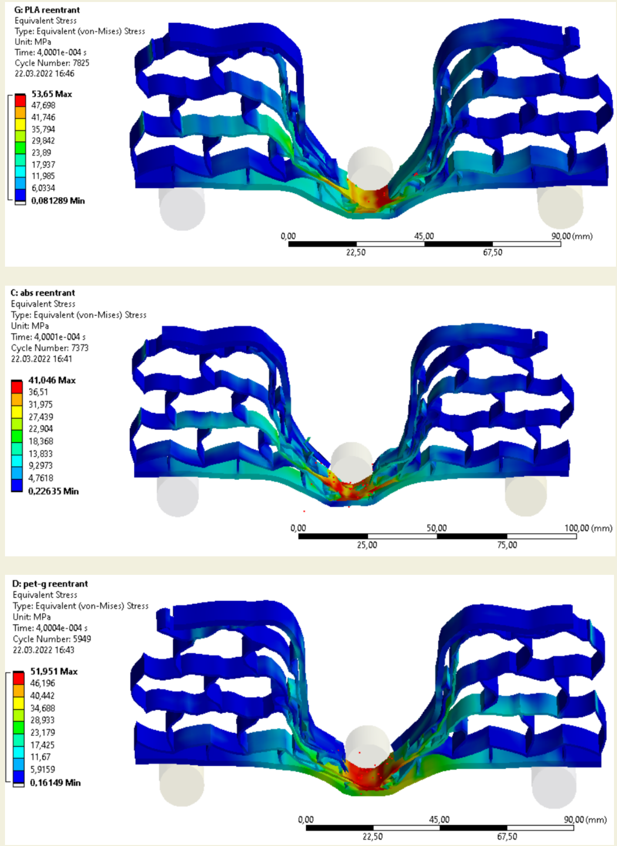

Figure 5. Equivalent stress distribution of sandwich structures with reentrant core a) PLA, b) ABS, c) PETG

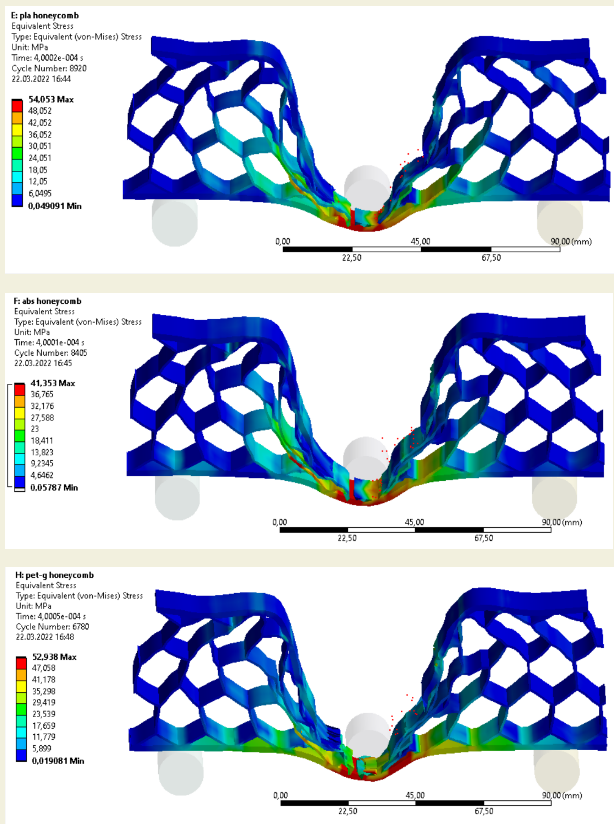

Figure 6. Equivalent stress distribution of sandwich structures with Honeycomb core a) PLA, b) ABS, c) PETG

4. Conclusions

PLA, ABS, and PETG sandwich structures with reentrant and honeycomb cores were designed using CATIA V5 software in this study, and then ANSYS finite element analysis software was used to compare the stress distributions in these sandwich composites. According to the results:

- Higher flexure stresses and specific energy absorption were obtained in the reentrant sandwich structures compared to honeycomb sandwich structures.
- The equivalent (Von-Mises) stress values after the three-point bending test showed that the highest Von-Mises stress occurred in the PLA sandwich structure, which was prone to failure.
- Minimum equivalent stress value of 41.046 MPa was found in the ABS material, while a maximum equivalent stress value of 53.65 MPa was found in the PLA material for reentrant core design.
- For the honeycomb core design, the ABS material had a minimum equivalent stress value of 41.353 MPa, whereas the PLA material had a maximum equivalent stress value of 54.053 MPa.

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