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Design and Additive Manufacturing of Sandwich Composites with Different Core Structures via Fused Deposition Modelling (FDM)

Gözde Zorman[a,*], Hurşit Sefa Aydın[a], Cihan Kaboğlu[a], Deniz Uzunsoy[a]

Department of Metallurgy and Material Science Engineering, Bursa Technical University, Turkey
(ORCID: 0000-0002-7351-1675), gozdezorman10@gmail.com
(ORCID: 0000-0002-4048-0067), hursit.aydin@btu.edu.tr
(ORCID: 0000-0002-6249-0565), cihan.kaboglu@btu.edu.tr
(ORCID: 0000-0002-2515-7624), deniz.uzunsoy@btu.edu.tr

Abstract

This study investigates the mechanical properties and core evaluation of sandwich structures fabricated using the Fused Deposition Modelling (FDM) additive manufacturing method. In this research, acrylonitrile butadiene styrene (ABS), a matrix material most preferred for its mechanical strength in industrial applications, was utilized. Specimens featuring two distinct core configurations specifically, conventional honeycomb and re-entrant structures were successfully produced. In order to determine the mechanical performance of the ABS sandwich composites, fabricated the using FDM and these honeycomb and re-entrant geometry cores, quasi-static compression and 3-point bending tests were performed. The experimental results revealed that honeycomb core structures performed better in terms of load-bearing capacity, with a maximum quasi-static compression load (11.105 kN) and a highest bending load (1.265 kN). These high strength values indicate that honeycomb geometries are well suited to applications that demand high degrees of rigidity and substantial load-bearing capacity. In contrast, re-entrant auxetic cores exhibited higher ductility than honeycomb cores under three-point bending. Due to the negative effects of Poisson's ratio, this advanced design can disperse and spread energy over the entire structure, thereby enhancing its mechanical performance. Furthermore, the minimal standard variations identified in the results have validated repeatability, structural strength and manufacturing quality and of the FDM process in academic and engineering studies. In summary, experimental findings demonstrate that honeycomb cores offer enhance load-bearing capacity and rigidity. In contrast, re-entrant auxetic cores are more suitable for designs requiring high ductility and structural flexibility under quasi-static conditions.

Keywords: FDM, Sandwich Structures, Honeycomb Core, Re-entrant Core, Mechanical Performance

1. Introduction

Composite materials consist of two or more than two phases and are designed to provide improved mechanical, thermal, or chemical properties. Typically, these materials consist of two main fundamental components. These two components are the matrix and the reinforcement phase. This structure facilitates the development of lightweight materials possessing high specific strength and stiffness. These properties have contributed to the widespread preference of composite materials in aerospace, automotive, construction, and defense application [1]. The production of composite materials is carried out using different techniques. Traditional manufacturing contains hand lay-up, hot pressing, resin transfer molding (RTM), pultrusion and vacuum infusion. Thermoset matrices such as epoxy and polyester are commonly used in these processes. These

* Corresponding author
E-mail addresses: gozdezorman10@gmail.com
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materials offer advantages such as recyclability and relatively short processing times. Due to their properties, demand for recyclable materials is leading to a significant increase in interest in thermoplastic matrix composites [2].

FDM is a material extrusion-based additive manufacturing methodology in which thermoplastic filaments are melted and fabricated layer by layer according to a CAD model. This process enables the production of complex structures with less material waste and lower production costs [3-4]. Therefore, optimizing process parameters and improving internal structural design are essential for enhancing mechanical behavior. The selection of thermoplastic materials is highly effective in the mechanical behavior of FDM-fabricated components. Acrylonitrile Butadiene Styrene (ABS) is one of the commonly preferred polymer materials due to its balanced mechanical properties, including high impact resistance, toughness and thermal stability [5-6]. In contrast, Polylactic Acid (PLA) exhibits higher hardness but lower ductility due to its brittle nature. It is commonly utilized in prototyping applications owing to its ease of processing [7]. Thermoplastic materials such as Polycarbonate (PC) and Polyamide (PA) offer good thermal resistance and mechanical performance, making them suitable for high-performance applications [2]. Material selection, inter-layer quality, and uniform bonding angles are all critical factors in the manufacturing of composites produced with the FDM method. ABS is a thermoplastic polymer that is widely used in FDM manufacturing processes [8]. In the ABS polymer, the acrylonitrile component offers chemical resistance; while butadiene adds high toughness and impact resistance to the structure and styrene improve the material's rigidity, thereby ensuring good processability. ABS is widely applied in structural and lightweight engineering components subjected to compressive and flexural loads due to its balanced mechanical properties [8-9].

Sandwich structures are lightweight, porous composites with a large specific surface area and high stiffness. In comparation to traditional reinforced materials, sandwich structures have shown significantly better fatigue life and impact resistance. These structures are eventually used extensively in various high-performance fields, including aerospace, automotive, marine, wind energy, and architectural applications [10-11]. Sandwich composite structures are widely used in advanced engineering applications requiring lightweight design and high strength [3]. The geometric properties of unit cells are known to determine the mechanical properties of lattice structures. These materials cellular materials are used in the core designs of sandwich structures offering high specific strength, low weight, fracture toughness, and energy absorption properties [10]. Honeycomb structures are commonly employed in industrial applications due to their high mechanical properties [12]. It has been demonstrated by experimental studies that sandwich structures with honeycomb cores are stiff and lightweight [3–13]. However, the manufacture of complex honeycomb geometries with conventional methods can involve several processing and assembly steps. To address this issue, Additive Manufacturing (AM) technology has been shown as a possible alternative for sandwich panels. As highlighted in a 2002 Boeing patent, thermoplastic honeycomb structures produced using AM offer enhance manufacturing efficiency and broader design possibilities compared to conventional core materials [9]. However, auxetic structures indicating Negative Poisson's Ratio (NPR) have recently become an alternative to honeycomb structures [14]. In contrast conventional structures, materials possessing a NPR exhibit unique behaviors, such as axial expansion under tensile and compressive forces. This severalizing characteristic significantly improves physical properties, like density, stiffness and fracture toughness [9]. Due to their enhanced flexibility, high shear resistance, and exceptional energy dissipation capacities, re-entrant structures are considered optimum core materials in the development of sandwich panels [15]. In a study conducted by Cava et al., the compression properties of different cellular structures were evaluated using different thermoplastic polymers. In this study consequences showed that the ABS auxetic core material with a re-entrant pattern and 1 mm wall thickness provided the best compressive strength compared to PLA, HIPS, and PET-G [15]. Similarly, Kaveloglu et al. investigated the compressive behavior of FDM-fabricated honeycomb core structures carried out of PLA and ABS. The obtained results indicated that increasing the cell wall thickness improved the compressive strength of both materials,

and that this effect was observed more distinctly in ABS. Furthermore, while ABS exhibited more ductile characteristics, PLA demonstrated a relatively more rigid response [16].

Although the current literature has proven the design flexibility of FDM technology and the mechanical potential of various materials, there is still a need for comparative mechanical performance analyses of different cellular core designs under the same operating conditions. Accordingly, this study investigates the mechanical performance of sandwich composites containing honeycomb and re-entrant cores. These materials are produced from ABS material via the FDM method. Our aims to clarify the most suitable application by evaluating the characteristic behavior of the structures in question under compression and three-point bending tests; to reveal the differences between rigid and load-bearing applications of honeycomb structures and flexible, energy-dissipating and lightweight designs of re-entrant structures; and to provide a structural evaluation for new generation lightweight engineering components.

2. Material and Method

In the present study, sandwich composite structures with different core geometries were produced using Acrylonitrile Butadiene Styrene (ABS) as the thermoplastic matrix owing to its balanced mechanical properties and wide range of industrial applications. The specimens were designed with honeycomb and re-entrant (auxetic) core geometries and manufactured using the fused deposition modeling (FDM) technique. ABS thermoplastic was used for filament production. White-colored ABS pellets (density: 1.04 g/cm^3) supplied by LG Chem were procured from PORIMA Polymer Technologies Inc. The ABS filament was produced using a POLARTEK single-screw extruder located at Bursa Technical University. The extruder consists of three heating zones. The ABS pellets were fed into the hopper and processed at a screw speed of 5 rpm. The temperature gradually increased along the barrel from 220 °C to 225 °C and finally to 230 °C. The extruded filament, with a diameter of 1.75 mm, passed sequentially through a hot water bath at 50 °C and a cold-water bath at room temperature for controlled cooling. The filament diameter was continuously monitored using a single-axis sensor system. Finally, the filament was wound onto a spool and dried in an oven at 80 °C for 24 hours prior to printing.

The three-dimensional geometrical models of the specimens were prepared based on ASTM D7336/D7336M-16 (standard test method for determining the quasi-static compression properties of polymer and polymer matrix composite materials) and ASTM C393/C393M (standard test method for evaluating the flexural stiffness, core shear strength, and face sheet–core interaction of sandwich composites under three-point bending loading). The compression and bending test specimens were manufactured using a Prusa i3-based fused deposition modeling (FDM) 3D printer. The printing parameters used during the fabrication process are presented in Table 1.

Table 1. The Printing Parameters of FDM

Parameters	Values
Filament Diameter	1.75 mm
Nozzle Diameter	0.6 mm
Layer Height	0.3 mm
Nozzle Temperature	250 °C
Bed Temperature	110 °C
Printing Speed	40 mm/s

The core geometries forming the basis of the sandwich panels were designed using AutoCAD software. In this study, a honeycomb structure and a re-entrant (auxetic) structure were selected. The geometrical parameters of the core structures are presented in Table 2. Based on these parameters, cell wall thickness (t), unit cell wall length (l), cell height (h) and relative densities (ρ/ρ_s) of both structures were optimized to enable a direct comparison of their mechanical performance.

Table 2. Geometrical properties of honeycomb and re-entrant core structures

Core Type	*t (mm)*	*l (mm)*	*h (mm)*	ρ/ρ_s
Honeycomb (HC)	0.6	1.5	1.8	0.46
Re-entrant (RE)	0.6	1.5	1.8	0.51

In order to evaluate the mechanical performance and characteristic behavior of the produced sandwich structures, quasi-static compression and 3-point bending tests were performed. The testing procedures and specimen dimensions were determined in accordance with the international standards ASTM D7336/D7336M-16 for compression tests and ASTM C393/C393M for three-point bending tests. Figures 1 and 2 present the panel dimensions of the honeycomb and re-entrant core structures, along with images of the corresponding test specimens.

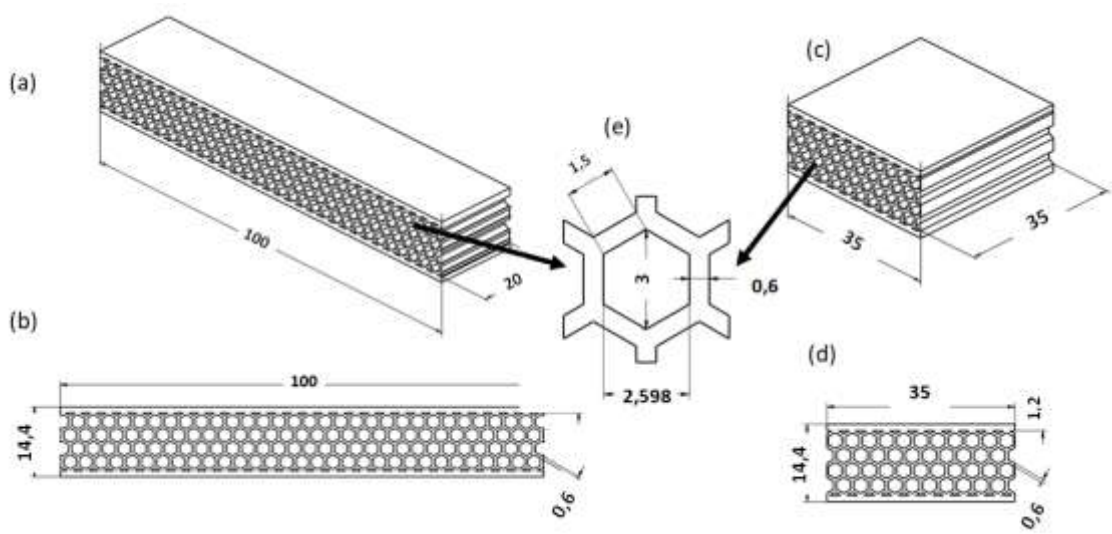

Fig. 1. (a) Core structure of honeycomb bending test specimen; (b) Honeycomb core structure; (c) Honeycomb bending test specimen; (d) Honeycomb compression test specimen (e) Detailed geometric dimensions of the single honeycomb unit cell

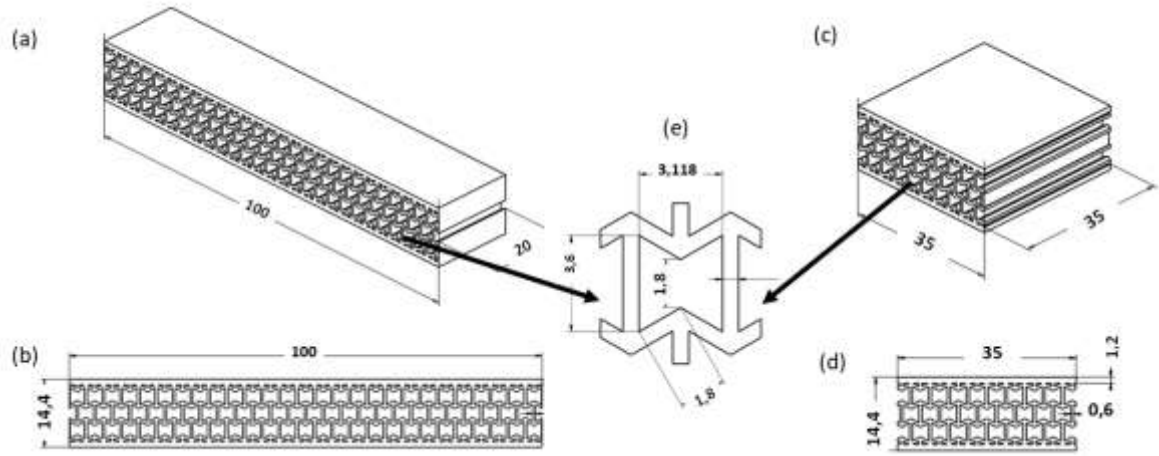

Fig. 2. (a) Core structure of re-entrant bending test specimen; (b) Re-entrant core structure; (c) Re-entrant bending test specimen; (d) Re-entrant compression test specimen (e) Detailed geometric dimensions of the single re-entrant unit cell

Compression tests were conducted in accordance with ASTM D7336/D7336M-16 to determine the quasi-static compression behavior of the 3D-printed sandwich core structures. The experiments were performed on sandwich compression specimens with dimensions of 35 × 35 × 14.4 mm using a WAW-300D servo-hydraulic universal testing machine under room temperature conditions and a constant loading rate of 2 mm/min. Three-point bending tests were performed in accordance with ASTM C393 standard. The experiments were performed on specimens with dimensions of 20 × 100 × 14.4 mm using a WAW-300D servo-hydraulic universal testing machine under a constant crosshead speed of 3 mm/min. At least three repetitions were carried out for each specimen group, and the experimental results were evaluated by calculating the arithmetic mean of the repeated measurements.

3. Results and Discussion

The sequential stages of the experimental tests conducted to observe the mechanical response and failure mechanisms of the additively manufactured ABS sandwich composites are presented in Figure 3.

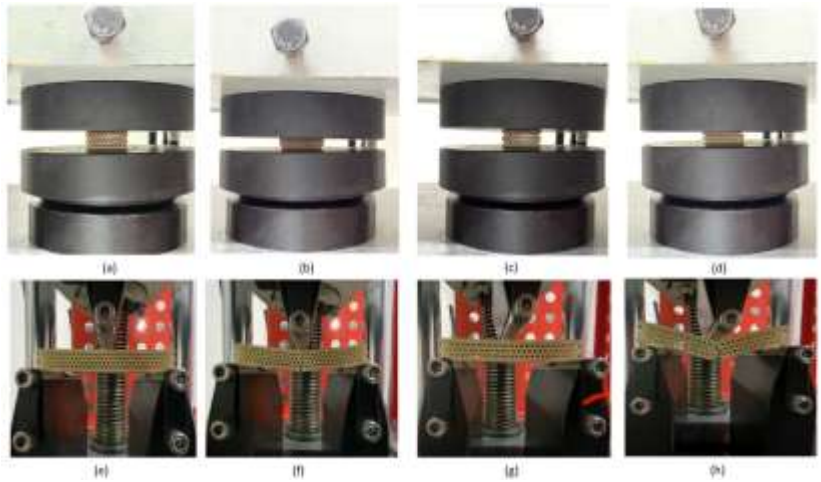

Fig. 3. Compression test stages: (a-b) Initial state and final deformation of the honeycomb specimen; (c-d) Initial state and final deformation of the re-entrant specimen; Three-point bending test stages: (e-f) Initial and failure stages of the honeycomb structure; (c–d) Initial and failure stages of the re-entrant structure

The continuous mechanical response of additively manufactured ABS sandwich structures with conventional honeycomb and re-entrant (auxetic) core geometries under quasi-static compression loading is comparatively illustrated through the load-displacement curves.

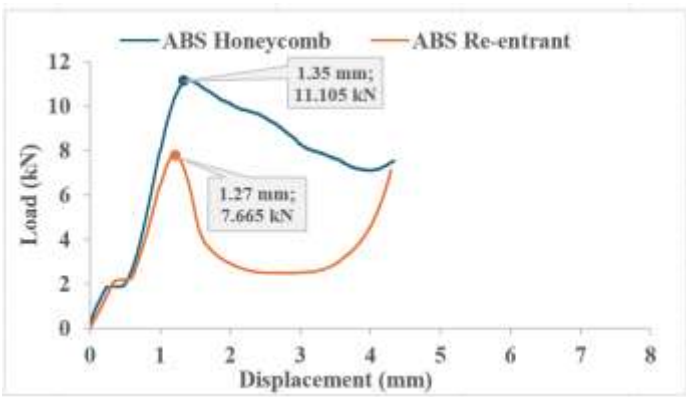

Fig. 4. Load–displacement curves of ABS honeycomb and re-entrant sandwich structures under quasi-static compression loading

As shown in figure 4, both structures exhibit an initial linear elastic response. However, the ABS Honeycomb structure demonstrates higher stiffness and load-bearing capacity than the ABS Re-entrant structure. The honeycomb specimen reaches a maximum load of 11.105 kN at a displacement of 1.35 mm, whereas the re-entrant specimen records its first peak load of 7.665 kN at 1.27 mm. The better peak load of the honeycomb structure can be explained to the alignment of its cell walls mainly parallel to the quasi-stati direction. This configuration enhances buckling resistance through efficient and continuous axial load transfer provided by the cell walls. Therefore, the structure offers high resistance to early buckling and maintains its

stability even at higher load levels [17-18]. Conversely, the re-entrant structure exhibits a sharper drop after the initial peak load. It enters a low-load plateau region within an approximate displacement range of 2 to 4 mm. This behavior can be explained by the negative Poisson's ratio characteristic of auxetic structures. These structures aim to contract and fold inwards rather than expanding laterally during the quasi-static compression load. The progressive inward collapse of the cells enables the controlled dissipation of deformation energy [19].

The maximum quasi-static compression load and standard deviation of the sandwich structures are presented in Table 3. The low standard deviation values for the honeycomb (0.07 kN) and re-entrant (0.035 kN) structures indicate high repeatability and consistency in the experimental results [19]. The small variation in maximum quasi-static compression load suggests good manufacturing quality and structural uniformity [20-21]. In particular, the lower deviation in the re-entrant structure shows more consistent deformation and failure behavior.

Table 3. Maximum Quasi-Static Compression Load (F_{max}) and Standard Deviation Values (S.D) of ABS

Material	Fmax	S.D.
ABS Honeycomb	11.105 kN	(±) 0.07
ABS Re-entrant	7.665 kN	(±) 0.035

The experimental load-displacement curves of sandwich composites with additively manufactured conventional honeycomb and re-entrant (auxetic) ABS cores under three-point bending conditions are comparatively illustrated in Figure 5.

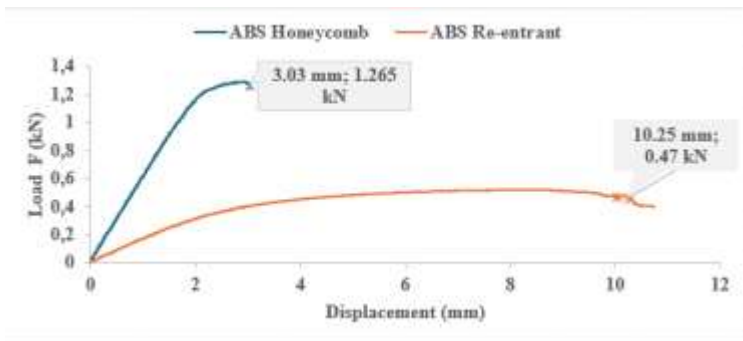

Fig. 5. Three- Point Bending of ABS honeycomb and re-entrant sandwich structures under quasi-static compression loading.

An analysis of the flexural behavior demonstrates a distinct performance gap between the two cellular configurations regarding their load-bearing capacity and flexibility. The conventional honeycomb structure (ABS Honeycomb) achieved its ultimate flexural load of 1.265kN at a displacement of 3.03 mm. Otherwise, the re-entrant core structure (ABS Re-entrant) exhibited meaningfully higher flexibility, recording its peak flexural load of 0.47 kN at a longtime displacement of 10.02 mm. The high initial stiffness and flexural strength of the honeycomb structure are attributed to its elongation-dominated vertical cell walls, which effectively transfer shear stresses between the upper and lower face sheets. On the other hand, due to its inwardly curved support struts, the re-entrant geometry exhibits a bending-dominated deformation mechanism [21-22]. This

condition reduces the maximum load-bearing capacity. It provides significantly higher ductility and stable deformation; therefore, it enables the attainment of elongation values up to 10.02 mm without fracture [20].

Table 4 presents the maximum flexural load and standard deviation values of the sandwich structures. In the three-point bending validation test, the conventional honeycomb core demonstrates superior manufacturing repeatability, exhibiting a low standard deviation (S.D.) value of 0.035 kN. The horizontal and vertical cell walls of the core enable the homogeneous deposition of material during the FDM printing process in this way minimizing internal defects and micro voids during the printing step [22]. In contrast, the ABS re-entrant configuration exhibited higher relative scatter, with a standard deviation of 0.044 kN relative to a lower peak load of 0.5 kN. This increased variability can be primarily attributed to the complex toolpath required for the inclined and re-entrant structural elements [23]. Frequent nozzle reorientation and changes in movement direction during FDM fabrication often led to localized micro-defects or minor extrusion inconsistencies [24].

Table 4. Maximum Flexural Load and Standard Deviation Values Under Three-Point Bending

Material	Fmax	S.D.
ABS Honeycomb	1.25 kN	(±) 0.035
ABS Re-entrant	0.5 kN	(±) 0.044

4. Conclusion

In this study, honeycomb and re-entrant core structures with comparable relative densities were designed and manufacturing via FDM technology. The mechanical performance of ABS sandwich composites was investigated through mechanical tests.

- The honeycomb structure demonstrated higher rigidity and peak load capacity (Fmax = 11.105 kN) than the re-entrant structure (Fmax = 7.665 kN).
- The honeycomb core showed higher flexural strength (Fmax = 1.265 kN). In addition to this, the flexure-dominated re-entrant structure exhibited superior ductility and flexibility, opposition displacements of up to 10.02 mm without damage.
- Honeycomb structures are perfect for rigid, load-bearing applications; re-entrant structures are highly suitable for lightweight engineering designs requiring continuous energy distribution and flexibility.
- Future studies will investigate the use of different high-performance polymers or multi-material 3D manufacturing method to include the high-load sustainability (Fmax) of honeycomb structures with the advanced failure strain characteristic of auxetic re-entrant designs.

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Conflicts of Interest: The authors declare no conflict of interest

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