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Research Article

Mechanical Properties of Sandwiched Construction with Composite and Hybrid Core Structure

Emad Kadum Njim,[1] **Hussam Raad Hasan**,[2] **Muhsin J. Jweeg**,[3] **Muhannad Al-Waily**,[4] **Alaa Ali Hameed**,[5] **Ahmed M. Youssef**,[6] **and Fahmi M. Elsayed**[6]

[1]*Ministry of Industry and Minerals, State Company for Rubber and Tires Industries, Najaf, Iraq*
[2]*Najaf Directorate, Martyrs Foundation, Council of Ministers, Baghdad, Iraq*
[3]*College of Technical Engineering, Al-Farahidi University, Baghdad, Iraq*
[4]*Department of Mechanical Engineering, Faculty of Engineering, University of Kufa, Kufa, Iraq*
[5]*Department of Computer Engineering, Faculty of Engineering and Natural Sciences, Istinye University, Istanbul 34396, Türkiye*
[6]*College of Engineering and Technology, American University of the Middle East, Kuwait City, Kuwait*

Correspondence should be addressed to Emad Kadum Njim; emad.njim@gmail.com

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In the field of lighter substitute materials, sandwich plate models of composite and hybrid foam cores are used in this study. Three core structures: composite core structure and then the core is replaced by a structure of a closed and open repeating cellular pattern manufactured with 3D printing technology. It finally integrated both into one hybrid open-cell core filled with foam and employed the same device (WBW-100E) to conduct the three-point bending experiment. The test was conducted based on the international standard (ASTM-C 393-00) to perform the three-point bending investigation on the sandwich structure. Flexural test finding, with the hybrid polyurethane/polytropic acid (PUR/PLA) core, the ultimate bending load is increased by 127.7% compared to the open-cell structure core. In addition, the maximum deflection increased by 163.3%. The simulation results of three-point bending indicate that employing a hybrid combination of PUR-PLA led to an increase of 382.3%, and for PUR–TPU by 111.8%; however, the highest value recorded with PUR/PLA, which has the slightest stress error among the tests. Also, it is reported that when the volume fraction of reinforced aluminum particles is increased, the overall deformation becomes more sufficient, and the test accuracy improves; for example, rising from 0.5% to 3%, the midspan deflection of composite (foam-Al) is increased by 40.34%. There were noticeable improvements in mechanical properties in the 2.5% composite foam-Al.

1. Introduction

The use of engineering materials in various industrial applications has gone through pleasant stages and ranged from traditional materials and alloys known for decades to composite materials at the beginning of the 1970s, and then the emergence of functionally graded materials in the 1980s of the last century, and finally the emergence of a new class of materials, which is metamaterials in the in recent decades [1, 2]. Composite structures have long been known for their advantages over unreinforced materials, and their usefulness in various industries has led to their widespread use. These structures are gaining attention in many applications, such as aerospace, automobile, power generation, construction, and marine, because of the advantages such arrangements offer, including lightweight, a high specific stiffness strength-to-weight ratio, and high specific strength. In addition to the above features, the mechanical properties of composite structure are extraordinary, and it also possesses a low elongation at break, a high tensile modulus, and excellent availability [3, 4]. As a result of their unique and controllable properties, composite and hybrid core structures have attracted the attention of researchers to work in the field of laminated composites and sandwich structures. Sandwich structures consist of top and bottom faces (made of aluminum, functionally graded materials, piezoelectric, or composite faces) separated by a lightweight core layer. Generally, the most common materials used in sandwich structure construction

were metals, composites, polymers, and foam [5–7]. However, the manufacturing requirements for producing metal-based sandwich panels differ from those for composite sandwich panels.

Composite materials are formed by combining two or more materials to achieve advantageous combinations of conflicting properties. Composites are cost-effective and environmentally friendly, which has led to their recent evaluation as a means to enhance the performance of sandwich structures through various modeling techniques. As a result, researchers focused on developing effective strategies for fabricating sandwich structures and employing multiple materials, such as metal alloys [8], honeycomb [9], functionally graded materials [10, 11], and metamaterials [12, 13]. Sandwich structures, made of metal or polymer, are widely recognized as optimal designs for withstanding bending loads. The flexural property plays a crucial role in determining the mechanical behavior of a sandwich structure.

Additionally, the choice of core material, particularly polymer foam cores, has been extensively studied to enhance flexural properties [14–16]. Hybrid engineering science has advanced quickly in recent years, and composite structure strength has also increased. As a result, there is an increased need for effective energy absorption under static and dynamic loading. Therefore, researchers are primarily interested in improving the mechanical characteristics of hybrid structures and achieving lightweight objectives.

In hybrid structures, different material grades incorporate the most advantageous material properties into one structure, enabling a dynamic design. A hybrid structure typically combines low weight with good mechanical and thermal properties. As a result of the different material properties of the constituent materials, hybrid structures have numerous beneficial properties [17]. The central flexural testing aspect is to determine flexural strength and modulus. Flexural strength and modulus are not fundamental compared to tensile and compressive properties; depending on the load applied, three-point and four-point flexure tests are frequently used as flexural test techniques [18]. Using experiments and finite element simulation, Jiang et al. [19] evaluated sandwich composite flexural performances with fiber skins and corrugated core. Along with the fast development of additive manufacturing and unique mechanical properties of composite structures. This fabricating technique has attracted the attention of many researchers; for example, Subramaniyan et al. [20] review that fused deposition modeling is a vital printing process for making thermoplastic components. Sandwich structures provide new opportunities in various areas since their core may be expanded and changed to suit our requirements-focused analysis of polytropic acid (PLA) and PLA composite materials to enhance flexibility. Additionally, PLA generates a tenth as many potentially dangerous ultrafine particles as acrylonitrile butadiene styrene. Saravanan et al. [21] investigated the hybrid epoxy nanocomposite and the impact of nanographene reinforcement on mechanical performance.

de Oliveira [22] used three-point bending tests to evaluate sandwich panels with a bamboo core with varying dimensions, packing geometries, and facing materials. Comparing the mechanical performance of the proposed sandwich panels to commercially available similar structures, which are often employed in the automotive and aerospace sectors, is impressive and competitive. Djemaoune [23] studied a numerically three-point bending test used to assess the flexural performance of the damaged and repaired panel by comparing it to the values of the intact panel. The work achieved included building and discussing appropriate models between the repaired panel's flexural responses and the design specifications for replacing the core plug. Furthermore, an optimization approach is used to identify the optimal core plug replacement parameters of the suggested repaired panel flexural performances.

In their study, Kumaar et al. [24] investigated a hybrid composite combining natural and synthetic fibers in a sandwich arrangement, incorporating glass fiber as the upper and lower layers. This composite proved safe and capable of providing superior surface quality to conventional plastics used in aircraft interiors. Notably, Sample 4, which consisted of bamboo, banana, jute, glass fiber, and 60% epoxy, exhibited high flexural strength.

The high strength and hardness of aluminum foam sandwiches (AFS) make them highly suitable for various engineering applications. Consequently, numerous recent endeavors have been aimed at developing and designing such composite structures [25–27].

Yang et al. [28] presented a novel compound casting with a hot-rolling approach to manufacturing foamable precursor sandwiches (FPS), and AFS were produced by subsequent foaming. According to the findings, increasing the rolling pass can enhance AFS's interface bonding quality, FPS's cell homogeneity, and FPS's ability to foam.

In their study, Han et al. [29] examined the impact and bending characteristics of three skin configurations of the composite structure consisting of carbon fiber and aluminum honeycomb core. The results revealed that the bending energy absorption of the dactyl-inspired sandwich honeycomb structure was measured at (29,556.5 N mm). This value demonstrated an increase of (278.3%) compared to the plain-woven skin sandwich-structural honeycomb (7,812.2 N mm) and a 115.4% increase compared to the unidirectional skin sandwich-structural honeycomb (13,719.6 N mm). Ashraf et al. [30] used honeycomb sandwich construction with the hybrid composite face sheet, and various kenaf and glass fiber ratios are examined for their mechanical characteristics (tensile, edgewise compression, and flexural). The outcome showed that raising the glass–fiber ratio in a hybrid face sheet considerably enhanced the sandwich structure's mechanical performance.

Based on zig–zag theory, computational methods (finite elements), and practical testing, Khoshgoftar et al. [31] studied the behavior of three-layered sandwich plates under flexural bending. According to the findings, auxetic lattices (i.e., negative Poisson's ratio) have higher bending strength and lower out-of-plane shear stresses than conventional lattices. Numerous scholars have proposed various novel core structures to increase the mechanical properties of sandwich structures. Consequently, the flexural stiffness of composite

panels made of glass fiber reinforced skins and honeycomb core under three-point bending was studied by Alshahrani and Ahmed [32] and Zhang et al. [33]. In their study, Diniz et al. [34] demonstrated that modifying the manufacturing parameters, the skins, and the core materials of sandwich composite structures can effectively enhance the mechanical properties, structural performance, and failure modes of sandwich composite structures.

An et al. [35] investigated the mechanical properties of designed and optimized composites using experimental analysis by thermoset 3D printing composites with different printing parameters. It was found that the prepared polymer composite samples exhibited excellent mechanical properties along the printing direction and thermal conductivity filler content. A selective laser melting process creates open-cell Kelvin foam structures from stainless steel powder 316L. Virtual triaxial experiments are systematically studied with multicell numerical models, validated with uniaxial compression results [36]. The mechanical behavior of aluminum foam (AF)/polyurethane (PU) interpenetrating phase composites (AF/PU composites) is investigated using a series of monotonic and cyclic compression tests [37].

Composite sandwich panels were experimentally examined under three-point bending conditions to determine the layering effects of various cores on strength and energy absorption [38–40]. In addition, the compressive mechanical behaviors of the multilayered corrugated sandwich panels were studied by Chen et al. [41] to examine the effect of core configuration on failure mechanisms and energy absorption using experimental and numerical investigation. According to Hajizadeh et al. [42], a sandwich structure with open-cell aluminum foams was studied for its quasistatic compressive behavior in terms of its relative density, plateau stress, energy absorption capacity, specific energy absorption, and energy absorption efficiency. All parameters except the energy absorption efficiency decreased with increasing NaCl particle size.

A static compression test and the structural and mechanical behavior of the steel plate-polyurethane foam composite protective structure based on foam characteristics and geometrical properties were presented [43, 44]. Recently, further research was carried out to investigate the performance of aluminum foam-filled composite sandwich structures [45–47]. A complex cell structure of aluminum foam has been studied both experimentally and numerically by Brekken et al. [48]. Using a PLA metal core, rubber layers, and an aluminum skin on the top and bottom of the beams, Al-Shablle et al. [49] investigated the static and dynamic performance of composite face sandwich plate strengthened by two types of nanoparticles (Al_2O_3 and SiO_2). In flexural loading conditions, composite sandwich panels made from glass laminated with Al-reinforced epoxy skins and polymer foam core materials are examined for energy absorption [50].

An analytical and numerical method examines thermal buckling characteristics for a composite plate structure with a range of nano fractions. The mechanical properties of the nanocomposites have been experimentally tested and validated [51]. Xu et al. [52] utilize experiments and finite element simulations to optimize the mechanical properties of a foam-filled re-entrant aluminum honeycomb composite structure. A numerical and experimental study was performed to study the bending and shear response characteristics of the double-skin composite sandwich panels made of Al-foam core and steel sheets in terms of three-point bending tests [53]. In a subsequent article, a multimaterial composite sandwich structure was designed and fabricated by Yang et al. [54]. Several works may be referred to for the finite element analysis of laminated composite structures in static response. A FEM and laboratory experiments were used to evaluate the impact of geometrical properties on energy absorption characteristics.

Three-point bending, compression, and impact tests were conducted on composite panels, using optimization algorithms to minimize mass and maximize energy absorption [55]. Based on different sequences of face-sheet reinforcement, Afolabi et al. [56] described a lightweight composite panel material that can be used as a structural component. The properties of the sandwich composites were measured in terms of compressive, tensile, and flexural strength. An experimental and numerical study was conducted by Njim et al. [57] to study the flexural properties of sandwich beams reinforced with nanoparticles (Al/Al_2O_3). Furthermore, further studies have been conducted on composite structure design, testing, and evaluation [58–60].

As the introduction states, composite structures have found extensive applications across various fields, leading to numerous studies focusing on their mechanical behavior. Initially, these studies were predominantly experimental and numerical, accompanied by some theoretical investigations. Previous research has been conducted to explore low-density cellular structures as potential alternatives to solid materials in order to preserve or enhance performance.

This work proposes a design concept that uses thin metals at the face sheets to maximize rigidity by carrying the main tensile and compressive loads and extremely lightweight thick and low-density polymer and hybrid cores to increase the moment of inertia to optimize the performance of these structures further and to keep the stability of the whole structure. Creating new materials with improved toughness and lightness is the goal of hybrid composite materials design. It is not possible to improve all of them simultaneously; therefore, the design objective is to find a new combination that is as effective as possible in suiting the desired specifications. This research studies the development of sandwich foam core reinforcement in a composite or hybrid environment. The ongoing investigation will test the flexural strength of a new hybrid sandwich structure made of aluminum metal on both sides and a composite foam core. First, two structures, one open- and the other closed-cell are designed, fabricated, and tested. The numerical simulation was then carried out for the same samples using the finite element software ANSYS 2021 R1. The conclusions drawn from this paper will be beneficial in designing sandwich construction with composite and hybrid core structures. Accordingly, this work is highly relevant to researchers working in composite structures. It can guide worldwide

Table 1: Material properties of the reinforced core and skins used in the experiments.

Material	Property		
	Density (kg/m^3)	Young's modulus (Gpa)	Poisson's ratio (ν)
PLA	1,360	1.175	0.30
TPU	1,450	0.833	0.30
Foam (PU)	0.0382	100	0.30
(Al) Powder 7429-90-5	2,710	68	0.33

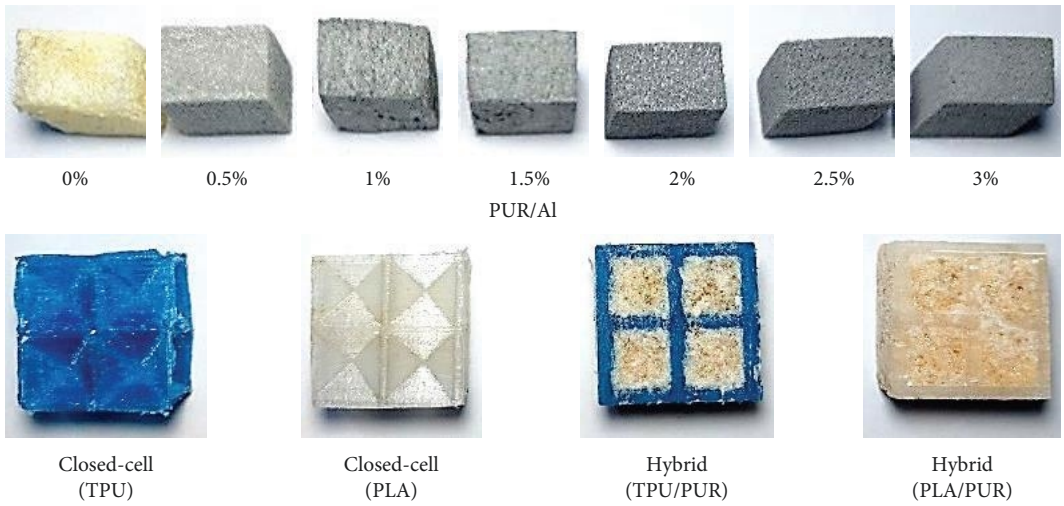


Figure 1: Porous and solid samples.

researchers where this work can be a starting point for future research in the design and mechanical behavior analysis of composite and hybrid core structure constructions. This work has been organized as follows: in Section 2, an experimental study of the leading composite and hybrid core samples that have been used in the design of composite laminates structure is conducted; in Section 3, a FEM subjected to a three-point bending load is employed using ANSYS software tool for simulation and verification of experimental results; and in Section 4, the results are applied to various cases of the core structure. Finally, Section 5 presents the conclusions.

2. Experimentally Work

2.1. Materials. An additive manufacturing technology, 3D printing can avoid moulds and produce high-quality products. It enables individuals and companies to create intricate designs at low costs by forming them layer by layer. The different matrices of composites can be categorized into thermoplastic and thermoset printing. Thermoplastic materials can be classified into functional composite materials that can control thermal management systems and porous materials that can manipulate superior mechanical properties. For this study, two types of additively manufactured, PLA and thermoplastic polyurethane developed by FlashForge (Hangzhou, Zhejiang, China) and obtained from the local market, were employed for 3D printing, with a standard diameter of 1.75 mm. Each type has distinct characteristics and applications that distinguish it from the second type.

Furthermore, a solid polymeric foam from polyurethane, considered a unique material used for thermal insulation supplied by Henkel Polybit (Germany), is used. Also, the THOMAS BAKER company adopted a fine aluminum powder with microsize (Al Powder 7429-90-5). Table 1 shows the characteristics of the materials used.

2.2. Sample Preparation. This work's sandwich structure comprises aluminum face sheets and a composite core of polyurethane (PUR) foam reinforced with aluminum microparticles. In addition, the foam core is replaced by another core structure with a closed and open repeating cellular pattern of polylactic acid (PLA) and thermoplastic polyurethane (TPU) manufactured using 3D printing technology. The last case study involves integrating both cores into one hybrid open-cell core filled with PUR foam. The models employed in the flexural experiment are demonstrated in Figure 1. Designing structural core, including draw structure by AutoCAD 2022 software and then exporting to slicer software Creality Slicer, with the required settings employing a G-code file, then printed with a 3D printer. The printer used in this work is a personal printer type Creality CR-10 V3, as demonstrated in Figure 2. For PUR/Al, the printed samples are manufactured by varying porosity constituents from 0% to 3% [61–63].

2.3. Methods. The instrument (WBW-100E) was employed to conduct the three-point bending experiment based on the international standard (ASTM-C 393-00). Depending on the standard, the dimensions of the samples were selected, and

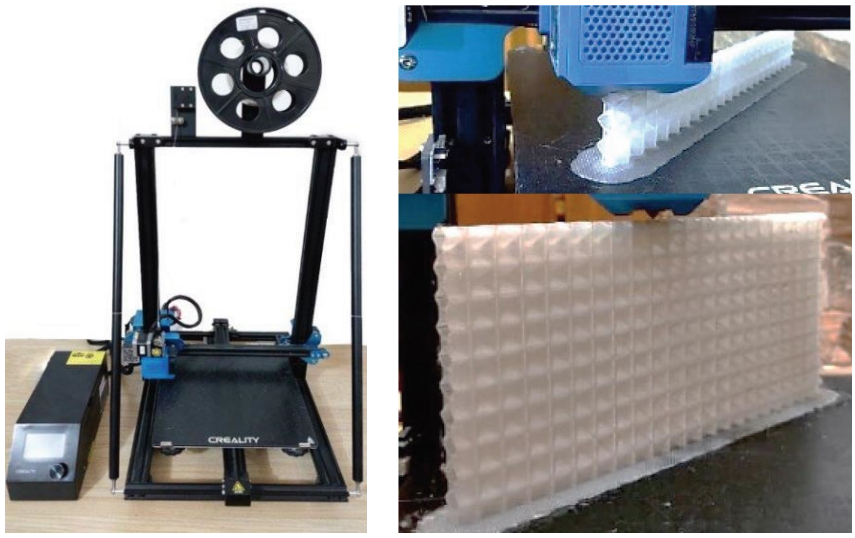


Figure 2: 3D printer Creality CR-10 V3.

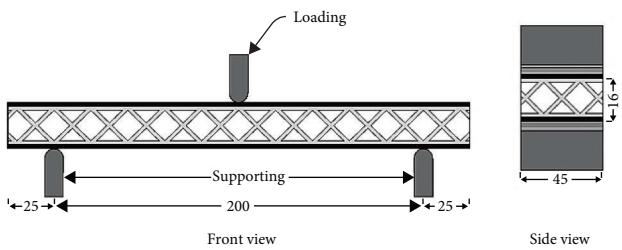


Figure 3: Flexural three-point load sample dimensions (mm).

Table 2: Test sample details.

Core type	Samples	Material	Details
Foam	7	PUR/Al	0%–3%
Open cell	2	PLA and TPU	3D printed
Closed cell	2	PLA and TPU	3D printed
Hybrid	2	PUR/PLA and PUR/TPU	3D printed and PUR

the span length covers the (actual examination) distance between the supports, while the distance after the supports has to be 5 cm; Figure 3 indicates the demanded dimensions. So, all specimens are of the exact dimensions with 45 mm in width, 16 mm in thickness, and 200 mm in span length (the space between supports). Therefore, the total specimen length is 250 mm.

Table 2 illustrates details of 13 samples used in the flexural test, while flexural testing samples are demonstrated in Figure 4. The three-point loading test setup is shown in Figure 5. Testing was conducted at a constant speed of 5 mm/min. According to (ASTM-C 393-00) standard, the core layer shear stress can be obtained from the following equation [64]:

$$\tau = \frac{P}{(d+c)b}, \tag{1}$$

where τ is the core layer shear stress, b is the specimen width, d is the total height, c is the core height, and P is the recorded load that could be yielded or ultimate according to calculation. The face bend stress is calculated as follows:

$$\sigma = \frac{L \cdot P}{2tb(d+c)}, \tag{2}$$

where σ is the face bend stress, t represents facing height, and L indicates span length.

3. Finite Element Analysis

The simulation aims to fabricate a sandwich composite with more tensile and flexural strength, increasing its mechanical properties. Based on the finite element model (FEM) and 3D

Figure 4: Flexural testing samples.

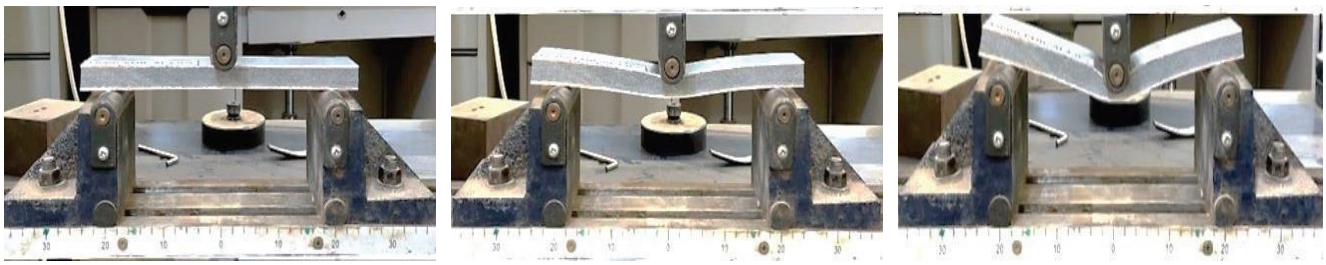


Figure 5: Three-point loading flexural test setup.

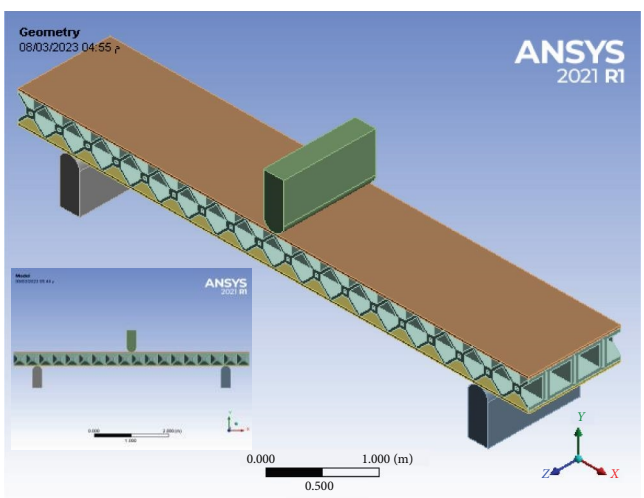


Figure 6: A generated three-dimension beam for the closed-loop model.

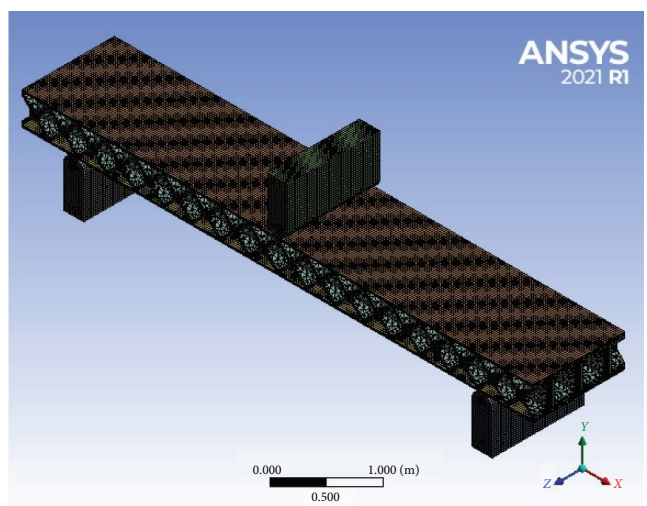


Figure 7: The mesh of the closed-loop model.

measurements of the bending parameters, usually, ANSYS tools were used to evaluate the reliability of the experimental results [65–68]. Hence, various polymer beams were investigated to predict flexural bending characteristics. Typical composite beams have deficient transverse shear properties because their cores are softer than their faces. Therefore, general-purpose shell elements were selected for this study. Using the SHELL99 composite element type presented in the ANSYS 2021 R1 design modeler, the model has been generated, as shown in Figure 6, and the concept of model boundary constraints was developed after the convergence mesh research was completed, as shown in Figure 7. The number of elements of the generated closed-loop model was 24,375,086 with total nodes of 6,762,414, while for open-loop, it was 199,940 elements with 678,538 nodes (see Figures 8 and 9). The remote displacement is applied gradually, and the reaction force at supports can be used to evaluate the maximum bending load; the results include total deformation, energy, and stresses.

The mechanical properties of the suitable material can be determined using experimental work results and then inserted into ANSYS' engineering library view, which exhibits a new class of material properties used. The simulation

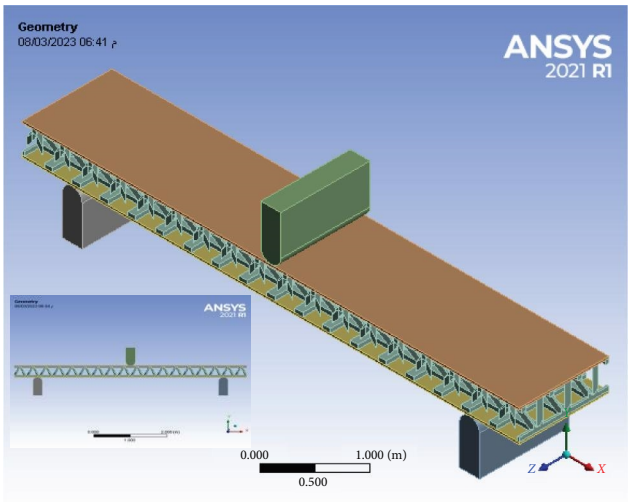


FIGURE 8: A generated three-dimension beam for the open-loop model.

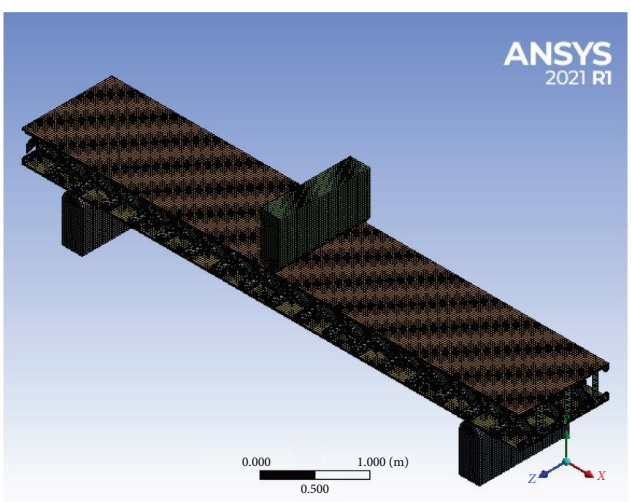


FIGURE 9: The mesh of the open-loop model.

aims to fabricate a sandwich composite with more tensile and flexural strength, increasing its mechanical properties.

4. Results and Discussion

Three-point load results are an Excel sheet with load and deflection data. Extracting the ultimate load and deflection, also estimating yield load and deflection by the method of 0.2% deflection as the way of 0.2% strain. In addition, Equations (1) and (2) can be used to calculate the face bending and core shear stress. A composite core, a structural core, and a hybrid core can produce three types of results. Figures 10–13 depicts the experimental and numerical force–displacement curves for PLA and TPU owing to tensile tests following ASTM standard D638 [69], respectively. According to the results, it is found that simulation by ANSYS software gives good convergence, which indicates that 3D printing manufacturing is a suitable method for designing and fabricating polymer samples.

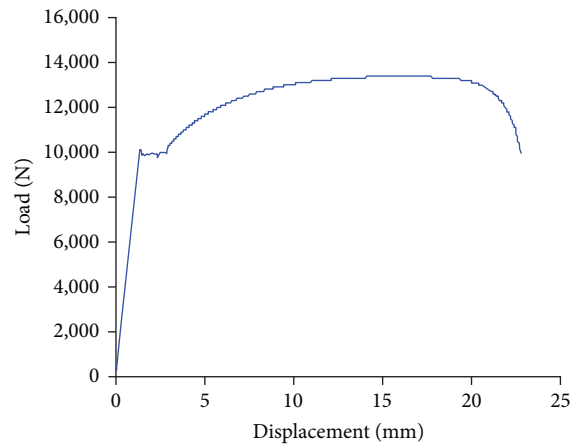


FIGURE 10: The experimental force–displacement curve for PLA samples.

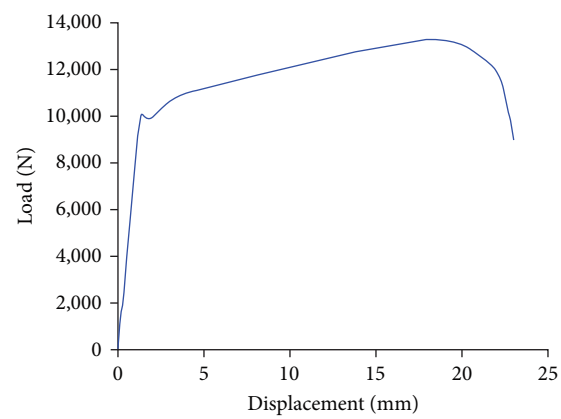


FIGURE 11: The numerical force–displacement curve for PLA samples.

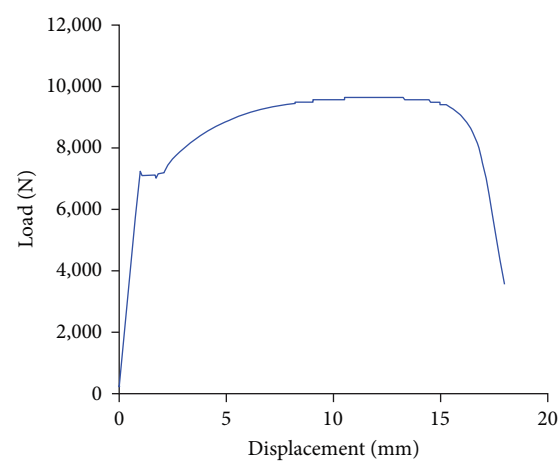


FIGURE 12: The experimental force–displacement curve for TPU samples.

4.1. Composite Core Result. The data obtained from this investigation exposed that the tensile strength and modulus, elongation at break, and bending strength of PUR/Al specimens are increased with the weight of aluminum particles.

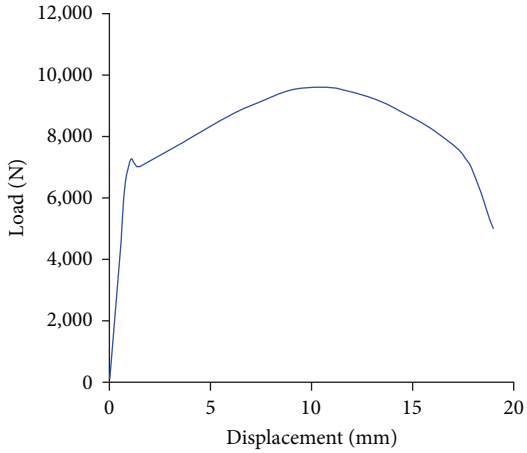


Figure 13: The numerical force–displacement curve for TPU samples.

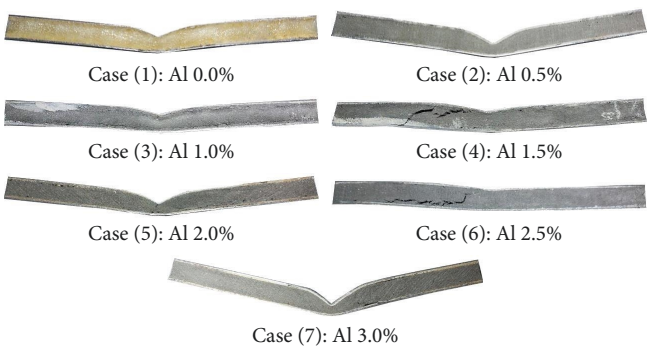


Figure 14: Flexural foam PUR/Al specimens after testing.

Case (1) is a reference specimen with pure PUR. Data investigation revealed that during the flexural test, the maximum load reached 0.34 kN, accompanied by a maximum deflection of 5.95 mm, estimating a yield load of 0.31 kN, and a deflection of 5.19 mm. In Case (2), with an (Al) ratio of 0.5%, adding PUR led to a maximum load of 0.38 kN and a maximum deflection of 6.52 mm. The aluminum particles improve the weak bonds of PUR Foam and, as a result, increase shear strength; thus, the flexural of the sandwich structure rises.

In the specimen of Case (3), the (Al) ratio rose to 1.0%, which yields an increase in the ultimate load to 0.4 kN and deflection to 13.85 mm, representing an advance to the previous case, the following Case (4), as an (Al) ratio of 1.5%. The maximum load increased to 0.44 kN with 6.27 mm in deflection; reinforcing bonds by adding aluminum granules increases shear resistance and maximum load. The (Al) supported particle amount of 2.0% in the posterior Case (5) led to a maximum of 0.48 kN load and a deflection of 12.38 mm. As (Al) extends to 2.5% of (Al) in Case (6), resulting in a maximum load of 0.52 kN and maximum deflection of 9.36 mm, the increase in shear strength reached the highest value, as shown in Table 2. Beyond the 2.5% Al ratio, as demonstrated in Case (7) (Figure 14) with an (Al) ratio of 3.0%, the maximum load dropped to 0.36 kN with a lower of 10.93 mm in maximum deflection; with the increase of Al particles relative to the bonding material of PUR foam, these particles surround PUR particles and prevent them from interacting and thus lead to the formation of brittle material. Figure 14 demonstrates foam PUR/Al specimens after testing. To calculate face bending stress and core shear stress, Table 3 states the results of a flexural test of composite (foam-Al). Further, flexural bending stress results presented in Table 3 agree with a rule of mixtures up to 3% Al.

Increasing (Al) particle proportions resulted in increased ultimate and yield loads by 11.7%, 17.6%, 29.4%, 41.2%, 53%, and 5.9%, respectively, and by 10%, 17.7%, 32.6%, 46.3%, 58.3%, and 2%, respectively, showing that the maximum (Al) amounts should not exceed 2.5% as shown in Figure 15 while the degrading the Al particles reducing mechanical characteristics of the structure significantly. Extending (Al) amounts beyond 2.5% generally makes structures more brittle. Throughout the experiment program, the load was fixed at 0.34 kN for all specimens to examine how the reinforced particles influenced beam deflection under that load (Figure 16). By adding 0.5%, 1%, 1.5%, 2%, and 2.5%, respectively, the midspan deflection reductions were 13.2%, 19%, 31.2%, 38.4%, and 47.3%. Adding 3% Al increases the deflection by 9.8%.

With aluminum particles added at an increasing (Al) amount of 0%–3% by the flexural test of each sample, Figure 17 demonstrates the association between load and deflection for each ratio. The improvement is clear to sight, and the highest results with the maximum (Al) amount of 2.5%; for the (Al) amount of 3%, the results are opposite, and the curvature drops. The reason may be that the stiffness of the whole structure containing 2.5 (Al) particle percentage will be maximum, while the behavior of the samples tends to be more brittle and has a remarkable ability to breakdown beyond the ratio (3%).

Table 4 compares composite (foam-Als) experimental and numerical flexural test results. It can be observed that the variations are more evident when the (Al) ratio is smaller and less critical for large percentages. Again, there was a reasonable agreement between the experimental and numerical results, with a maximum discrepancy of 10% in most cases. This indicates that specimens fabricated by additive manufacturing were fabricated adequately and can be used in various industrial applications.

4.2. Structural Core Result. A sandwich structure with a 3D printed core and open cell specimen made of PLA, considered as Case (8), has a maximum load of 0.72 kN, a maximum deflection of 2.91 mm, an estimated yield load of 0.66 kN, and a yield deflection of 2.18 mm. This is achieved by replacing the foam core with a 3D-printed open-cell core (PLA rigid plastic).

In Case (9), using the same open-cell specimen only with a different material (TPU nonrigid plastic), the maximum load is dropped to 0.12 kN with a maximum deflection of 22.48 mm. In the following Cases (10) and (11), they used

Table 3: Flexural test results of composite foam-Al.

Case	Al (%)	δ_{max} (mm)	P_{max} (kN)	δ_y (mm)	P_y (kN)	τ_{max} (MPa)	τ_y (MPa)	σ_{max} (MPa)	σ_y (MPa)
1	0.0	5.95	0.34	5.19	0.31	0.25	0.23	25.18	23.28
2	0.5	6.52	0.38	5.34	0.34	0.28	0.25	28.15	25.65
3	1.0	13.85	0.40	6.93	0.37	0.29	0.27	29.63	27.40
4	1.5	6.27	0.44	5.49	0.41	0.32	0.30	32.59	30.88
5	2.0	12.38	0.48	7.52	0.46	0.35	0.34	35.55	34.07
6	2.5	9.36	0.52	6.21	0.49	0.38	0.36	38.52	36.85
7	3.0	10.93	0.36	5.38	0.32	0.26	0.23	26.66	23.76

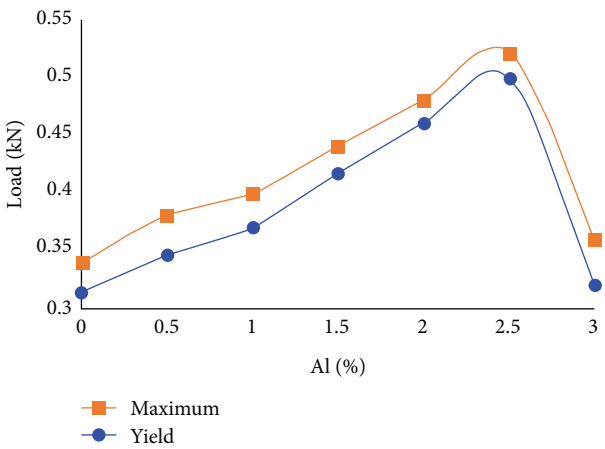


Figure 15: Relation of adding micro-Al to flexural load.

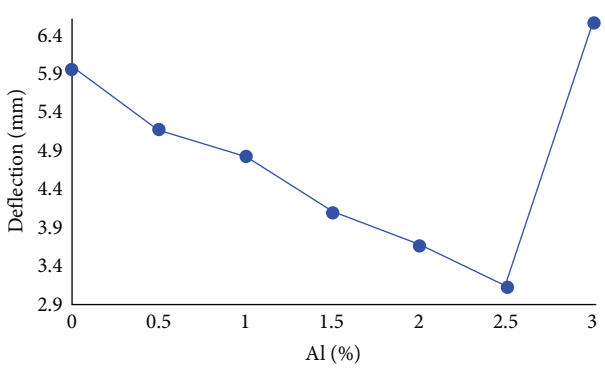


Figure 16: Micro-Al addition reduces deflection under a fixed load.

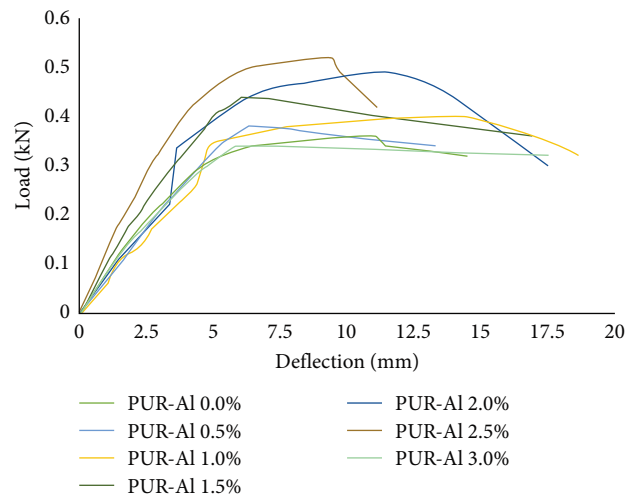


Figure 17: Load-deflection curve of the PUR flexural test at different (Al) amounts.

closed-cell specimens with PLA and TPU, respectively. For the last two instances, PLA is still higher than TPU with the closed cell structure, and both materials achieved the requirements as illustrated in Table 5. Figure 18 demonstrates structural (open and closed cell) specimens after testing.

Table 6 compares the experimental and numerical flexural results for open and closed beams. The results suggest that open-type TPU samples exhibit more deformation than other types due to their lower strength. A good agreement was observed between numerical simulations and experimental results, contributing to a more accurate analysis of mechanics when loop design, core metal type, and geometric sizes were considered.

4.3. Hybrid Core Result. A set of new results for laminated composite structures with various lamination schemes, volume fractions, and core materials are presented. Specific differences in flexural bending characteristics, including bending load and deformation of composite beams, have been highlighted. Analyzing the performance of hybrid specimen Case (12) with PLA and PUR yields estimating a yield load of 1.56 kN and central deflection of 7.00 mm. Here, it is noticed that the maximum load is 1.64 kN, and the maximum deflection is 7.67 mm. Moreover, Case (13) results of the hybrid specimen with TPU and PUR cause a maximum recorded load of 0.72 kN and maximum deflection of 7.68 mm. In addition, the hybrid structure showed the highest flexural strength due to strengthening the weak bonds of the foam material with the open cell structure, as the foam surrounds the cell's struts, thus giving them extra strength. Figure 19 demonstrates hybrid specimens after testing.

Result of replacing foam core with structural core with 3D printed material (PLA and TPU). For the open-cell structure with PLA, the rise in max. load by 111.7%, while TPU

Table 4: Experimental and numerical flexural test results of composite foam-Al.

Case	Al (%)	δ_{max} (mm) experimental	δ_{max} (mm) numerical	Discrepancy (%)	P_{max} (kN) experimental	P_{max} (kN) numerical	Discrepancy (%)
1	0.0	5.95	5.66	5.12	0.34	0.32	7.94
2	0.5	6.52	6.29	6.89	0.38	0.36	5.56
3	1.0	13.85	13.05	6.13	0.40	0.38	5.26
4	1.5	6.27	5.73	9.42	0.44	0.40	10.00
5	2.0	12.38	11.57	7.00	0.48	0.44	9.09
6	2.5	9.36	8.88	5.41	0.52	0.49	6.12
7	3.0	10.93	10.15	7.69	0.36	0.34	5.88

Table 5: The flexural test results for open and closed structures with PLA and TPU.

Materials	δ_{max} (mm)	P_{max} (kN)	δ_y (mm)	P_y (kN)	τ_{max} (MPa)	τ_y (MPa)	σ_{max} (MPa)	σ_y (MPa)
Open PLA	2.91	0.72	2.18	0.66	0.53	0.49	53.33	49.48
Open TPU	22.48	0.12	20.30	0.10	0.08	0.08	8.88	8.07
Closed PLA	5.95	0.96	5.24	0.89	0.71	0.65	71.11	65.92
Closed TPU	7.26	0.28	6.90	0.26	0.20	0.19	20.74	19.85
PLA–PUR	7.67	1.64	7.00	1.56	1.21	1.15	121.48	115.78
TPU–PUR	7.68	0.72	5.62	0.69	0.53	0.51	53.33	51.48

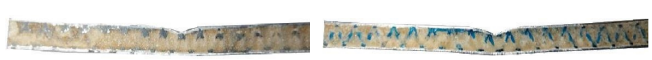
Case (8): Open-cell PLA Case (9): Open-cell TPU

Case (10): Closed-cell PLA Case (11): Closed-cell TPU

Figure 18: Flexural structural (open and closed cell) specimens after testing.

Table 6: Experimental and numerical flexural results for open and closed various polymer beams.

Materials	δ_{max} (mm) experimental	δ_{max} (mm) numerical	Discrepancy (%)	P_{max} (kN) experimental	P_{max} (kN) numerical	Discrepancy (%)
Open PLA	2.91	2.70	7.78	0.72	0.69	4.35
Open TPU	22.48	21.39	5.10	0.12	0.11	9.09
Closed PLA	5.95	5.45	9.17	0.96	0.89	7.87
Closed TPU	7.26	6.85	5.99	0.28	0.26	7.69
PLA–PUR	7.67	7.17	6.97	1.64	1.52	7.90
TPU–PUR	7.68	7.10	8.17	0.72	0.69	4.35



Case (12): Hybrid-PLA/PUR Case (13): Hybrid-TPU/PUR

Figure 19: Flexural hybrid specimens after testing.

dropped by 64.7%, for the closed-cell design in PLA rose by 166.6%, and TPU decreased by 17.64%. The tremendous result came through employing a hybrid with PUR; for the combination of PUR–PLA, there was an improvement rise of 382.3%, and for PUR–TPU, it was 111.8%, the highest value recorded with PUR/PLA. The result of flexural with both structural and hybrid cores is demonstrated in Figure 20.

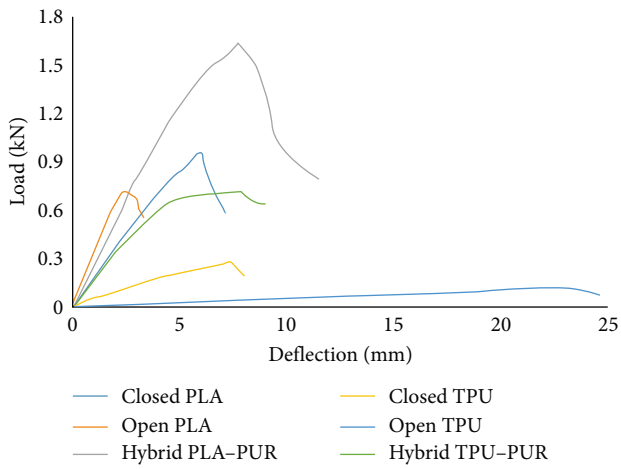


FIGURE 20: Load-deflection curve of the flexural test for the sandwich plate with structural and hybrid core.

5. Conclusions

(1) The experiment confirmed that the mechanical strength of the polymer-reinforced composites was generally higher than that of other types; adding filler foam to a composite structure can significantly impact its performance and improve its durability.

(2) Converting a solid material or replacing a foam form with a cellular pattern effectively reduces both mass cost and maintains its performance.

(3) Compared to foam/Al cores (0%, 0.5%, 1%, 1.5%, 2%, 2.5%, and 3% aluminum), the core foam–aluminum sandwich plate (2.5% aluminum) deflects less as deflection is reduced by 47.3%.

(4) A cellular pattern, created by replacing a solid material with a cellular design, is one of the most effective ways to reduce a product's mass and cost while maintaining its performance.

(5) A structural core made of open cells can be converted into a closed structure by filling the space between the open cells with another material, such as foam, which creates a hybrid design that meets the engineer's expectations in terms of performance.

(6) A hybrid structure provides an excellent combination for improving mechanical properties in various situations.

(7) Compared to an open-cell core structure, the hybrid structure core has a 127.7% higher ultimate flexural load and a 163.3% higher maximum deflection than an open-cell core structure.

(8) The three-printing method is a suitable and efficient way to design a hybrid and composite structure due to the lower cost; for example, the three-printer model with dimensions $(25 \times 25 \times 2)$ cm and a density of 100 kg/m^3 costs 25 dollars with a printing time of more than 24 hr.

(9) Specimens with PLA–PUR cores performed better in terms of yield strength and ultimate stress.

(10) Hybrid composite structures can reduce stresses and deformation and enhance overhaul mechanical performance.

(11) For future work and to identify the performance of sandwiched construction with the composite and hybrid core structure for static and dynamic properties in detail, it is suggested to modify the present work by discussing failure mode and studying the fracture surfaces of failed specimens using a scanning electron microscope device. Furthermore, change how sandwich components are combined, apply (pretension or posttension) to attach faces to the core, and use nanocoatings in coating surfaces, thus strengthening the sandwich parts and protecting against environmental factors, notably water absorption. Finally, studying the ecological effects, such as temperature, chemical solvents, gases, and water absorption, is suggested.

Data Availability

Data will be made available upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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