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REGULAR PAPER

Investigation of the mechanical properties of polyurethane foam-filled FDM-printed honeycomb core sandwich composites for aircraft

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Abstract

Sandwich composites are widely used in aerospace materials thanks to their low weight and high strength properties. The purpose of this study is to observe the effects of polyurethane foam filling on honeycomb core structures produced by additive manufacturing in terms of mechanical strength and moisture absorption properties. Within the scope of the study, honeycomb structures were produced by a 3D printer using polylactic acid (PLA) filament. Then, the honeycomb core was filled with polyurethane foam, which is supplied in liquid form. After the core material was given its final form, it was combined with an epoxy and carbon fibre facesheet material using the vacuum infusion technique. After the sandwich composite production was completed, in-plane compression, three-point bending, shear, and moisture absorption tests were applied. The polyurethane foam filling greatly increased the mechanical strength, but slightly more moisture absorption occurred in this structure compared to a hollow honeycomb structure.

Nomenclature

Definitions, acronyms and abbreviations

3D	three dimensional
ASTM	American society for testing materials
EPP	expanded polypropylene
FDM	fused deposition modeling
H	sandwich composite with hollow honeycomb core
MDI	methylene diphenyl isocyanate
PLA	polylactic acid
PMDI	polymeric methylene diphenyl isocyanate
PMI	polymethacrylimide
PUF	sandwich composite with polyurethane foam-filled honeycomb core

Symbols

$^{\circ}C$	degrees Celsius
b	specimen width
c	core material thickness
d	sandwich thickness
F_s^{ult}	core shear ultimate strength in the three-point bending test

G	core shear modulus in the shear test
L	specimen length
P	instantaneous force on specimen
P_{max}	ultimate force to failure
S	span length
σ	facing stress in the three-point bending test
$\sigma_{ultimate}$	ultimate edgewise compressive strength
σ_{facing}	ultimate facing strength for edgewise compression
u	displacement value
γ	core engineering shear strain
τ	core shear stress in the shear test
t	nominal facing thickness
t_{fs}	thickness of a single facesheet
t_{total}	thickness of the sandwich composite
w	width of specimen

1.0 Introduction

The use of composite materials is increasing in many sectors, thanks to their light mass and high mechanical performance properties. Since the lightness of the structural mass is very important for the aerospace industry, the use of composite materials has also increased over the years in the manufacture of aircraft. Especially by using materials such as carbon, glass, or Kevlar, the mentioned lightness and high mechanical performance properties are obtained from composite materials. As shown in Fig. 1, Airbus and Boeing aircraft, which are the leaders in the production of commercial aircraft, have the highest composite material usage rates, with 53% in the A350 XWB model and 50% in the B787 model, respectively [1, 2].

Toozandehjani et al. stated that the most widely used materials among structural composite materials in the aerospace industry are laminar composites and sandwich composites [3]. In 1924, T. von Karman and P. Stock designed and patented a glider plane by using sandwich applications on its fuselage structure. This application can be considered the first use of sandwich structures in aircraft. In 1983, Airbus used a sandwich composite application in the rudder section of the A310 model. The development and application of sandwich structures are still in progress and have great potential in commercial aircraft. A wide variety of sandwich composite applications are found in Airbus aircraft, for example, in the radome, aerodynamic fairings, engine covers and some control surfaces [4]. The structure of a sandwich composite consists of two outer face materials adhered to the core part. Xiong et al. (2019) stated that the core materials in sandwich composites should be both light and able to withstand the loads on the structure. Accordingly, the commonly used core materials are honeycombs, foam cores, corrugated cores, lattice cores and foldcores [5, 6]. In honeycomb core structures, since the cells in the structure are hollow, the facesheet materials and the core can only be combined by bonding from the cell walls. Therefore, since the bonding area between the facesheet and the core will be limited, it may cause surface debonding under bending and compression loads. In addition, a crack in the facesheet material of the honeycomb core sandwich composite may lead to moisture being absorbed into the cells. Considering the moisture absorption and temperature changes in the working environment of an aircraft, this may cause deterioration and shorten the life of the structure [7–9]. Due to these disadvantages observed in honeycomb structures, academic and industrial communities have recently carried out studies on polymeric foam cores. Although both materials have a cellular structure, the polymer foam structure attracts great attention in the literature because it contains more cells in smaller sizes and can absorb impact energy more efficiently compared to conventional honeycomb structures [10, 11]. Evonik Industries has stated that polymethacrylimide (PMI) foams provide improved damage tolerance compared to honeycomb structures. Evonik stated in 2014 that the Rohacell Hero PMI foam core provides lower manufacturing costs, lower part weight and safer construction compared to a typical honeycomb core design. These foam-based sandwich composites have been used by Airbus in structural

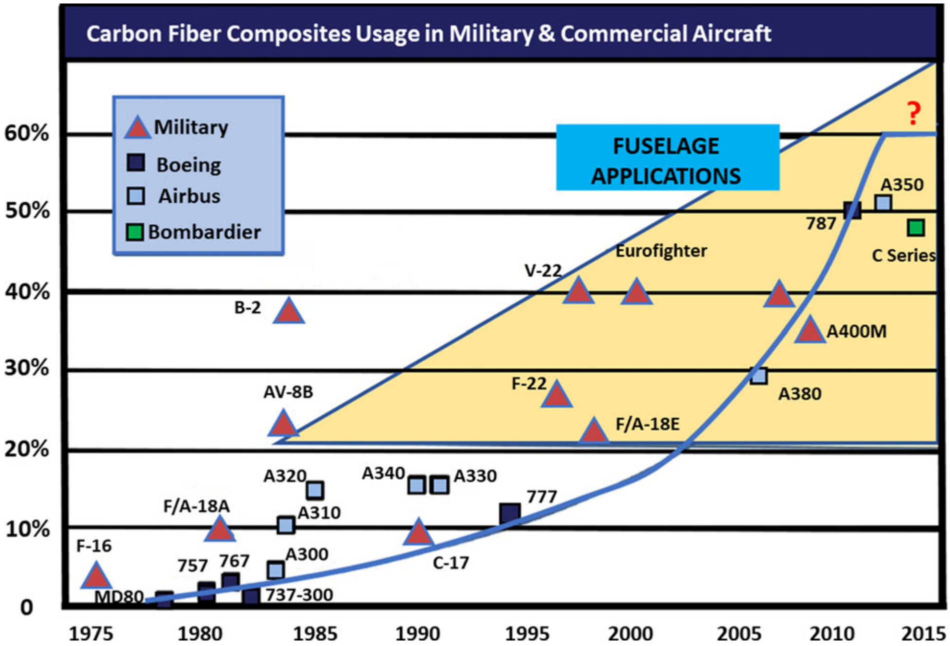

Figure 1. Carbon fibre composite usage ratios of military and commercial aircraft [1].

parts providing flexible and innovative designs [10–13]. Polymer foam core structures, which provide a higher bonding area in the core material, are able to spread impact loads on them more efficiently distribute loads more effectively, and minimise moisture absorption. Especially due to the increased bonding area, the surface debondings that occur between the face material and the core material under bending and compression loads are minimised. The mechanical properties of the core material and the quality of the adhesion bonds between the core and the face material determine the mechanical properties of the structure under bending load in sandwich composites. Although it has superior properties compared to traditional honeycomb cores, polymeric foam materials exhibit low mechanical strength when used in their pure form due to the hollow structure content of the cells in the foam structure. These foams should be strengthened with different additives according to the area where they will be applied and made suitable for these applications [9]. In polymeric foam core structures, when a crack occurs, this crack spreads very quickly and covers the entire structure, and it is very difficult to detect the area where this crack starts [14]. The continuity of the structure is important for the aerospace industry as the resulting crack will create a discontinuity in the sandwich structure that may cause damage to the entire aircraft [15]. The failures that occur in honeycomb and polyurethane foam core structures and the disadvantages of these structures have been mentioned above. Instead of using these structures separately as core materials, studies that seek solutions to the mentioned disadvantages by using them together were reviewed. The articles that focus on increasing the energy absorption and mechanical strength of thin cell-walled honeycomb structures draw attention to the importance of using low-density filling materials, such as carbon fibre tubes, polystyrene closed cells, aluminum foams, metallic tubes and polymeric foams. Since polymeric foam filling was used within the scope of this study, studies on honeycomb structures with polymeric foam filling were examined [9, 14, 18]. D'Mello and Waas investigated the axial crush response of 3-cell, 7-cell and 19-cell specimens with uniaxial quasi-static crush tests to observe the effect of polyurethane foam filling in their study. After the initial failure, polyurethane foam filled honeycombs carried a higher load than unfilled honeycombs due to the lateral wall support provided by the foam filling. They observed that the normalised load carrying capacity of the filled honeycomb was similar for the 3-cell, 7-cell and 19-cell specimens [16]. In another study, D'Mello and Waas investigated the energy absorption under uniaxial in-plane compression of a “composite” circular cell honeycomb. Within the scope of the study, polycarbonate honeycomb structure was filled with polydimethylsiloxane (PDMS). They observed synergistic energy absorption in the filled specimen and explained this using digital image correlation (DIC) and finite element (FE) methods. Three important design parameters were determined according to the fracture mechanics of the filled honeycomb. These parameters are the relative stiffness of the filling material and the honeycomb, Mode I fracture strength and Mode I fracture toughness [17]. Mozafari et al. investigated the effects of polyurethane foam filling in aluminum honeycomb cores under in-plane compression loads. In order to observe the effects of the density of the foams on the compressive strength, polyurethane foams of different densities were used, and quasi-static compression tests were carried out. The effects of foam filling an aluminum honeycomb core on in-plane mechanical properties (such as mean crushing strength, absorbed energy and specific absorbed energy) were analysed experimentally and numerically. The results showed that the foam filling of the honeycomb core can increase the in-plane crush strength by up to 208 times and the specific absorbed energy by up to 20 times [18]. Liu et al. investigated the effects of expanded polypropylene (EPP) filling an aluminum honeycomb core structure instead of traditional polyurethane foams under out-of-plane and in-plane compression loads. In order to observe the effects of foam density, three different densities of foam filling were applied. When the results are compared with hollow aluminum honeycomb structures, EPP foam-filled panels increased the average crushing strength from 34.791% to 120.219% and the energy absorption increased from 46.765% to 179.474% under out-of-plane compression loads, while the average crushing strength under in-plane compression loads is increased from 1320% to 4567% and energy absorption is also increased from 15,450% to 30,397%. The foam-filled honeycomb structure did not have a significant effect on out-of-plane compression loads. Foam density had a significant effect on the load carrying and energy absorption capacities. The increase in foam density resulted in an increase in energy absorbed and specific energy absorption at in-plane compression loads [19]. Roudbeneh et al. examined unfilled and polyurethane foam-filled honeycomb panels of three different densities on aluminum honeycomb structures under the high-speed impact test. By examining the energy absorption of foam-filled honeycomb structures, it was found that the energy they absorb is greater than the sum of the foam or thin cell-walled honeycomb structures [20]. Jayaram et al. investigated the behaviour of polyester pin reinforcement application under compression and low velocity impact loads in foam-filled honeycomb core sandwich panels. According to the results obtained, when added to foam-filled honeycomb core sandwich structures this type of reinforcement significantly improved compression and low-velocity impact properties [21]. Zhang et al. investigated the behaviour of EPP filling in an aluminum honeycomb core structure instead of traditional polyurethane foams under dynamic impact loads. In order to observe the effects of foam density, three different densities of foam filling were applied. Compared to the hollow honeycomb structure under the same impact velocity, the average strength increased by 15% to 72.5% [22]. Yan et al. produced honeycomb structures with the fused deposition modeling (FDM) technique using PLA filament and filled these structures with PMI foam. The mechanical performance of the structure under in-plane and out-of-plane compression loads was investigated both experimentally and numerically. According to the in-plane compression test, the elastic modulus increased by 296.34%, the compressive strength increased by 168.75%, the energy absorption per unit volume increased by 505.57% and the energy absorption per unit mass increased by 244.22%. For foam-filled honeycomb under out-of-plane compression, the compressive strength increased by 23.5%, but there was virtually no improvement in elastic modulus and energy absorption [23]. Mohamadi et al. investigated three different variations of aluminum honeycomb structures (hollow honeycomb structure, pure polyurethane elastomer filled structure and glass microballoon reinforced polyurethane elastomer filled structure) quasi-static compression and low velocity impact behaviour. In the quasi-static compression test, they found that the elastomer addition to the honeycomb cells did not have a significant effect on energy absorption as it only increased this by 20%. The addition of glass microballoon particles to the elastomers reduced the weight of the structure and increased energy absorption [24]. Safarabadi et al. investigated the buckling behaviour of a sandwich composite with Nomex honeycomb cores (unfilled and polyurethane foam-filled core structures) and glass-epoxy face materials experimentally and with numerical models. Within the scope of their study, the buckling behaviour, critical buckling load, and energy absorption of four different sandwich composites were investigated. Experimental results showed that the presence of polyurethane foam increased the critical buckling load by 14% when the load was in the fibre direction. The presence of polyurethane foam increased the critical buckling load by 73% when the load was perpendicular to the fibres [25].

In this study, a honeycomb core structure was obtained from a PLA filament with the FDM technique using a 3D printer, and this core material was filled with polyurethane foam. A new sandwich composite was obtained by combining the polyurethane foam-filled core material and carbon fibre facesheet materials with epoxy resin. In-plane compression, three-point bending, shear and water absorption tests were performed on this new material proposed within the scope of the study. In order to evaluate the performance of the proposed material, a second honeycomb and facesheet sandwich composite structure was produced with the same process but left with a hollow core and the same tests were applied.

2.0 Materials and methods

The core of the sandwich composite produced in this study was produced from a PLA filament using the FDM technique, the produced honeycomb core was then filled with polyurethane foam. After the core material production was completed, it was combined with the vacuum infusion technique using carbon fibre face material and epoxy resin. In this section, the production steps of the proposed material and the mechanical test studies carried out after production are detailed.

2.1 Design and manufacturing of the core structure

The honeycomb structures were planned and designed for production through CATIA V5R21 software. $50 \times 50 \times 2\,\text{cm}^3$ and $30 \times 30 \times 2\,\text{cm}^3$ honeycomb structures were specified in order to obtain a sufficient number of samples for the mechanical tests required for the study. As seen in Fig. 2, the edge length of a cell of designed honeycomb structures is 13mm, and the cell wall thickness is 3mm. The honeycomb structures were made in the form of regular hexagons and their interior angles are 120°.

To produce the honeycomb structures, 1.75mm diameter PLA filament and a desktop-type 3D printer were used. The layer thickness value of the production was determined as 0.2mm by considering the nozzle diameter. The printing speed value was determined according to the characteristics of the 3D printer. Other parametre values adjusted for production are given in Table 1. Images of the production process achieved with these parametres are given in Fig. 3.

The next step after the completion of the production of the honeycomb structures was to fill the gaps in the honeycomb structure with polyurethane foam. Since the polyurethane foam filling process was carried out inside the honeycomb structure no adhesive was used between the FDM-printed honeycomb structure and the polyurethane foam. Note that the polyurethane foam components are supplied in liquid form. The supplied polyurethane foam consists of polyol and polymethylene polyphenylene isocyanate and 4,4’-methylenediphenyl diisocyanate (PMDI) components at a density of $34 \pm 2\ \text{kg/m}^3$. Using the manufacturer’s datasheet, the mixing ratio between the polyol and polymeric MDI was determined to be 100/120 by weight, respectively. The filling process was carried out in the mold to ensure it was filled correctly and homogeneously. To produce enough foam in the mold, the mass value was obtained by taking the difference between the mold volume and the honeycomb structure volume and using the density value in the manufacturer’s datasheet. If too much polyurethane foam mixture is poured into a closed mold, expansion will occur during foaming, which may cause cracks in both the honeycomb and the foam structure. To prevent the cracks that may occur with the expansion of the foam, the dimensions of the mold were determined to be 1cm more than the dimensions of the honeycomb structure. In order to allow the foam to expand during the curing process between the mold dimensions and the honeycomb structure, to prevent overflow, and to provide uniform and complete filling by providing space to fill the voids in the honeycomb structure, 1cm margin was determined as a result of the manufacturer’s

Table 1. *3D printer parameters adjusted for the production of the honeycomb structures*

Parameters	Values
Layer height	0.2 mm
Initial layer thickness	0.3 mm
Nozzle temperature	210 °C
Print speed	200 mm/s
Nozzle diameter	0.6 mm
Raster angle	±45°
Cooler	0% - 100%

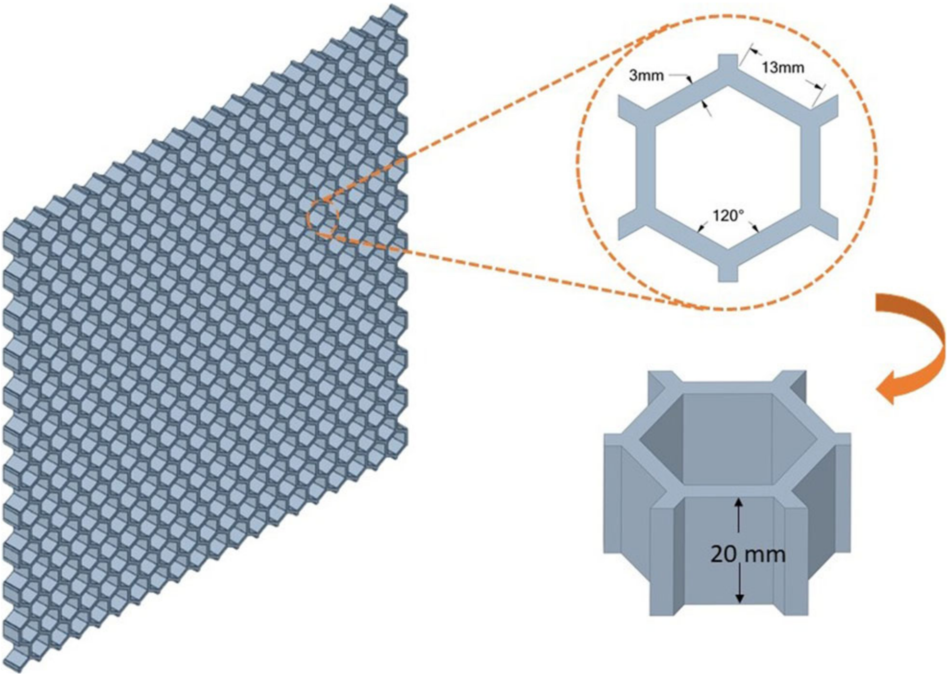

Figure 2. *The designed honeycomb structure and the geometric features of a cell of this structure.*

instructions and various production trials. Overall, as a result of production trials, the 1cm margin provided a suitable zone to accommodate the expansion and curing properties of the foam, resulting in a well-filled and structurally better honeycomb structure. After filling with foam, any polyurethane foam that exceeded the honeycomb structure limit due to the size of the mold was smoothed with sandpaper. Figure 4(a) shows the process of filling the honeycomb structure with polyurethane foam, and Fig. 4(b) shows the sanding process.

2.2 Sandwich composite manufacturing

To observe the effects of polyurethane foam filling, the FDM-printed hollow honeycomb cores were produced. Sandwich composites were obtained by using the same carbon fibre fabric and the same epoxy resin system for both core materials. The vacuum infusion method was used to combine the polyurethane foam-filled honeycomb structure with carbon fibre facesheet materials. Epoxy resin was first applied to the facesheet materials by using the hand lay-up method and then these were made into

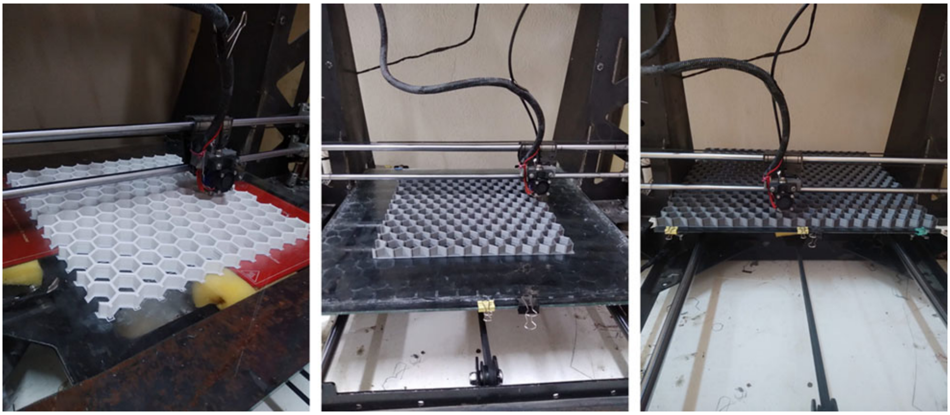

Figure 3. *Production of honeycomb structures with a 3D printer.*

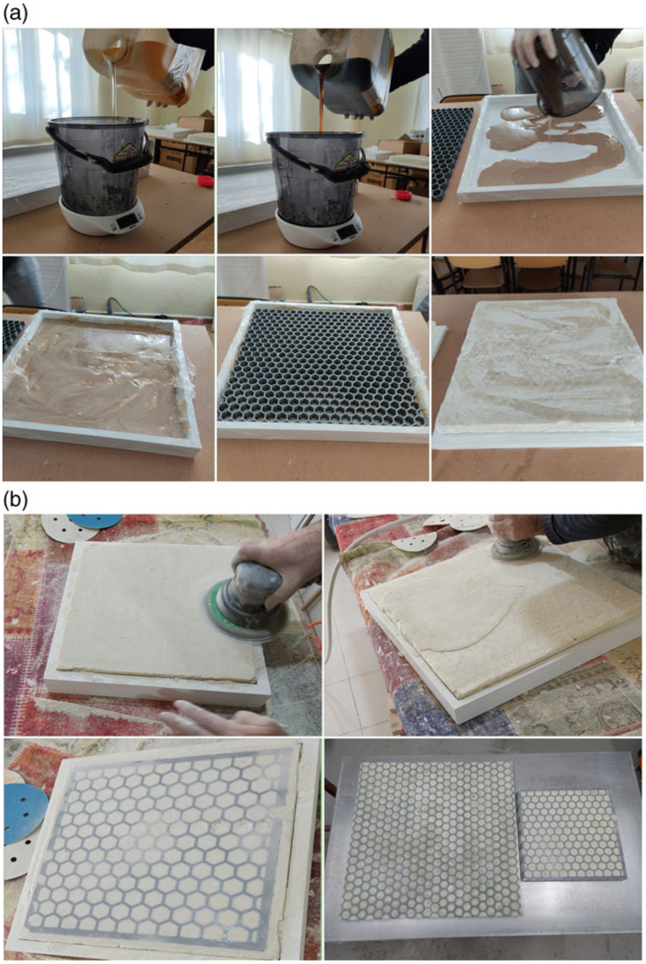

Figure 4. *Filling the honeycomb structure with foam (a) pouring the polyol and isocyanate mixture into the mold, (b) sanding after the foaming reaction.*

Table 2. Materials and manufacturing techniques used in sandwich composite manufacturing

Facesheet material	Resin system	Core material	Manufacturing technique
Plain woven carbon fibre fabric with 4 plies on each side	Epoxy resin	FDM-printed hollow honeycomb	Hand lay-up + Vacuum bagging
		FDM printed polyurethane foam-filled honeycomb	Vacuum infusion

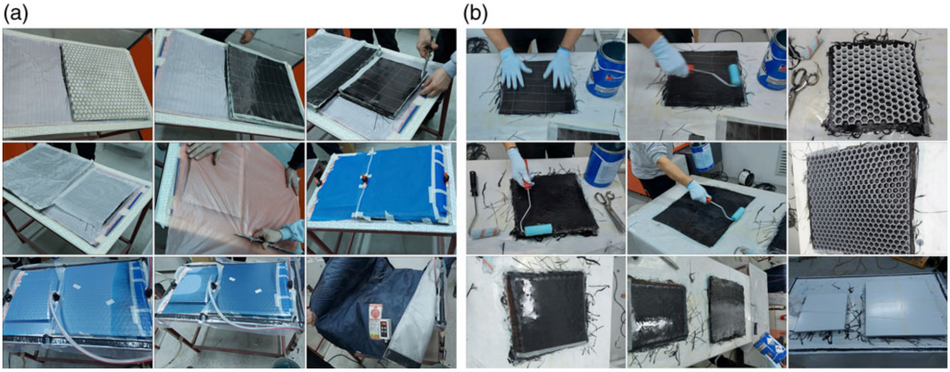

Figure 5. *Images of sandwich composite production (a) sandwich composite production with a polyurethane foam core using the vacuum infusion technique, (b) sandwich composite production with a hollow honeycomb core using hand lay-up and the vacuum bagging technique.*

a sandwich composite with the vacuum bagging method. This method was chosen as, in the vacuum infusion method, the epoxy resin fills all the gaps under vacuum and this prevents the core material from showing its true mechanical strength. Therefore, to prevent this situation, first, the hand lay-up and then the vacuum bagging method was used in the hollow honeycomb structure. In the production of the sandwich composites, 284 g/m^2 plain-woven carbon fibre fabrics supplied by DowAksa Advanced Composite Materials Ind. Ltd. were used as the facesheet material. This carbon fibre fabric is of standard modulus grade and, additionally, there are polyester fibres woven at 20cm spaces to increase the strength in the carbon fibre fabrics. During the production of the sandwich composite, the DTE1200 + DTS1151 epoxy resin system supplied by the Duratek Epoxy and Polyurethane Systems company was used and no external cure was applied to the facesheet and core materials. The materials and production techniques used for this study are shown in Table 2 and the images of the production process of the sandwich composites are shown in Fig. 5(a) and (b). In the vacuum infusion and vacuum bagging methods, the epoxy resin was left to cure with a vacuum blanket at 75 °C for 24 hours. The average facesheet material thickness of the produced sandwich composite samples was 2.05 ± 0.4mm. In weight, average values of 11.95 ± 0.60kg/m^2 were obtained in the sandwich composite specimens with a polyurethane foam-filled core and 12.07 ± 0.19 kg/m^2 in the sandwich composite specimens with a hollow core.

2.3 Edgewise compression test of the sandwich composites

The edgewise compression test was applied to the sandwich composites with a foam-filled honeycomb core and hollow honeycomb core structure at 0.5 mm/min using a 100 kN load cell in a Schimadzu AG-IC test device according to the ASTM C364/C364M-16 standard. For the sandwich composites with both core structures, five specimens of 90 × 90 × 25 mm^3 dimensions were used. In this test method, the specimens are subjected to a monotonically increasing compression force parallel to the plane of the face of the sandwich structure.

2.4 Three-point bending test of the sandwich composites

The three-point bending test was applied to the sandwich composites with a polyurethane foam-filled honeycomb core and a hollow honeycomb core at 1mm/min using a 100 kN load cell in a Schimadzu AG-IC test device according to the ASTM C393/C393M-20 standard. For the structure with each core type, five specimens of 200×75×25 mm^3 dimensions were used and the opening of the span length was set to 114 mm.

2.5 Shear test of the sandwich composites

The shear test was applied to the sandwich composites with a foam-filled honeycomb core and a hollow honeycomb core in a Schimadzu AG-IC test device according to the ASTM C273/C273M-20 standard at a speed of 2 mm/min. For both structures, four specimens of 270 × 75 × 25 mm^3 dimensions were used. The specimens were subjected to monotonically increasing shear force parallel to the plane of the faces of the sandwich structure.

2.6 Water absorption test of the sandwich composites

This test method is based on the determination of the amount of water absorbed by leaving the sandwich composite in a certain humidity condition and then measuring the mass increase in the specimens. Within the scope of the test performed according to the ASTM C272/C272M-18 standard, five specimens of 75 × 75 × 25 mm^3 dimensions were used and the sandwich composite samples were exposed to water for 192 hours.

3.0 Results and discussion

3.1 Edgewise compression test results

The in-plane compression properties of the produced sandwich composites were analysed under the compression load applied in a parallel direction to the sandwich structure. In addition, the failure modes occurring in the sandwich composite specimens were determined. According to the mechanical test results, a force-displacement graph was obtained for each sample group. When the graph in Fig. 6 is examined, the sandwich composite with a hollow honeycomb core exhibited a linear curve up to the value of 14183.13 N. Small-scale fractures started in the structure and the applied load was decreased down to 8265.63 N. At this stage, the structure with a hollow core continued to resist the compression load. As can be seen in the graphic, this structure resisted compression load up to 37615.60 N, after this point core – facesheet separation occurred. When the sandwich composite with a core filled with polyurethane foam was examined, it showed greater strength by exhibiting a linear curve up to a force value of 45534.38 N. After this force value, cracks started in the polyurethane foam structure at the interface between the facesheet material and the core. For this reason, the force value was decreased to the value of 22456.25 N, after this point, the core-face material showed resistance to the compression load up to the value of 47793.75 N. In all test specimens of the sandwich structures with a hollow honeycomb core, all failure modes that occurred were core-facesheet separation. The main reason for the separation of the core and face material is the separation of the interface bonds due to the shear force between these two surfaces. Core-facesheet separation failure was observed in only one specimen of the polyurethane foam-filled sandwich composites. In other polyurethane foam-filled specimens, defects such as buckling of the face material and cracks between the core and the face material occurred. Failures occurring in both specimen types are shown in Fig. 7.

Average maximum force, average facing compressive strength and average ultimate compressive strength values for specimens with a hollow honeycomb core and polyurethane foam-filled honeycomb core are given in Table 3. Here, the term ‘average facing compressive strength’ refers to the average in-plane compression strength of the facesheet material of the sandwich composite. According to the

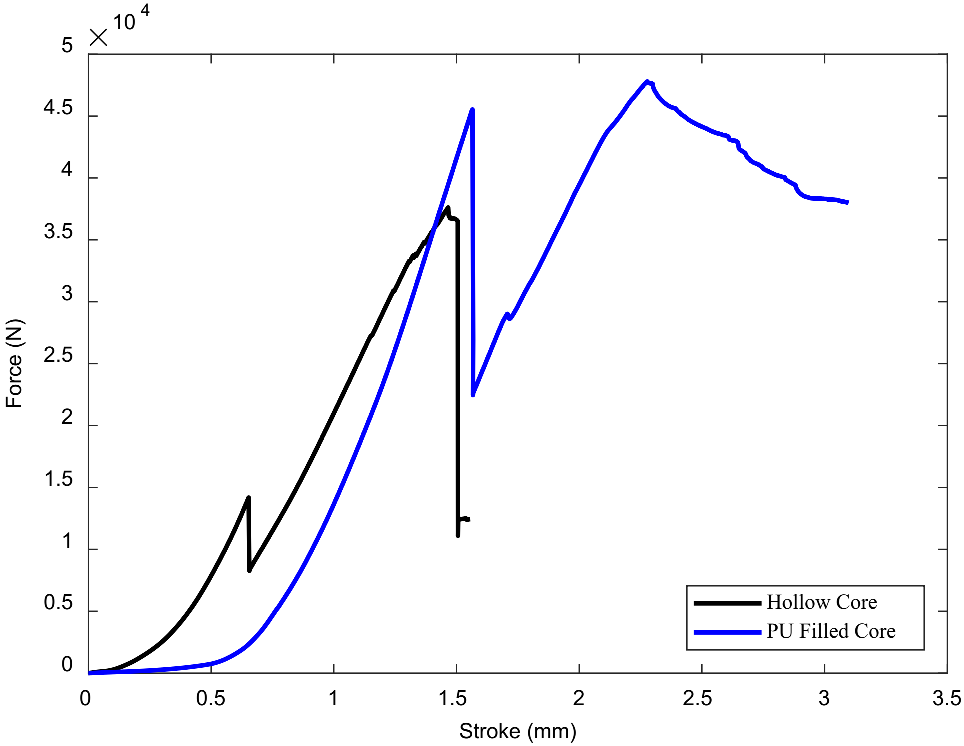

Figure 6. Force-displacement graph of specimens with a hollow honeycomb core and a polyurethane foam-filled honeycomb core under edgewise compression load.

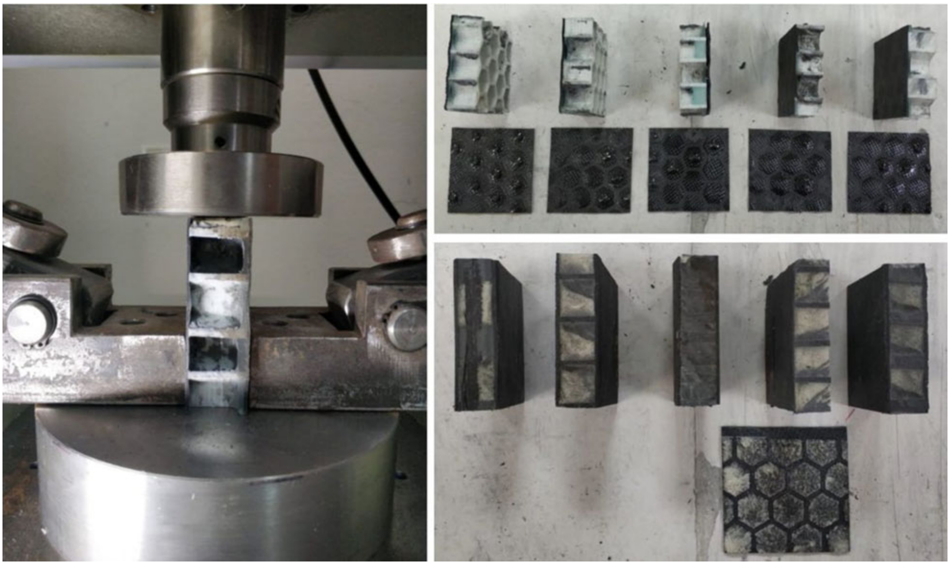

Figure 7. Specimens during and after the edgewise compression test.

Table 3. *Edgewise compression test results of hollow and polyurethane foam-filled specimens*

Specimens	Maximum force (N)	Facing strength (MPa)	Ultimate compressive strength (MPa)
H1	41925.00	16.64	140.81
H2	27115.60	10.69	94.95
H3	37615.60	15.21	137.06
H4	28593.80	11.54	125.15
H5	10853.80	4.39	37.84
Avg. of hollow specimens	33812.50 ± 7126.47	13.52 ± 2.86	124.50 ± 20.80
PUF1	12622.50	6.02	39.75
PUF2	54137.50	24.88	157.24
PUF3	47793.80	21.86	123.53
PUF4	42214.10	19.62	125.11
PUF5	57584.40	27.36	185.04
Avg. of PU-filled specimens	50432.45 ± 6816.19	23.43 ± 3.39	147.73 ± 29.33

ASTM C364 standard, this term provides the evaluation of the compressive properties of facesheet of sandwich composite along the direction parallel to the plane of the sandwich facing. H5 and PUF1 specimens were not included in the calculation of the average and standard deviation because they showed insignificant values compared to the other specimens in their group. The facing strength and ultimate compressive strength values in Table 3 were calculated using Equations (1) and (2). In these equations, P_{max} denotes the ultimate force prior to failure, w denotes the width value of the specimen, t_{fs} denotes the thickness of a single facesheet, and t_{total} denotes the total thickness of the sandwich composite.

$$\sigma_{ultimate} = \frac{P_{max}}{w\left(2t_{fs}\right)} \tag{1}$$

$$\sigma_{facing} = \frac{P_{max}}{wt_{total}} \tag{2}$$

Figure 8(a) shows cracks between the face and core material, while Fig. 8(b) shows face buckling and crack failure in the polyurethane filled core.

3.2 Three-point bending test results

In the three-point bending test of sandwich composites with a hollow honeycomb core and polyurethane foam-filled core, the specimens were subjected to a bending moment perpendicular to the plane of the sandwich structure as seen in Fig. 9. In addition to the displacement value against the applied force within the scope of the test, the core shear stress and the stress values in the face material were obtained and the failure modes were evaluated. In the hollow honeycomb core structure, damages in the form of inward bending of the load-applied region and consequently core crushing or separation of the face material from the core were observed. In some specimens, bending cracks spreading along the core depth were observed. In the polyurethane foam-filled structures, inward bending of the load-applied region and resultant core cracks, core shear crack failures and surface separation in some areas were observed in the core structure. Figure 10 shows the force-displacement graph for hollow and polyurethane foam-filled specimens.

The average core shear strength, average facing stress and average maximum force values obtained as a result of the three-point bending tests of hollow and polyurethane foam-filled specimens are given in Table 4. The core shear strength and face stress values in Table 4 were calculated using

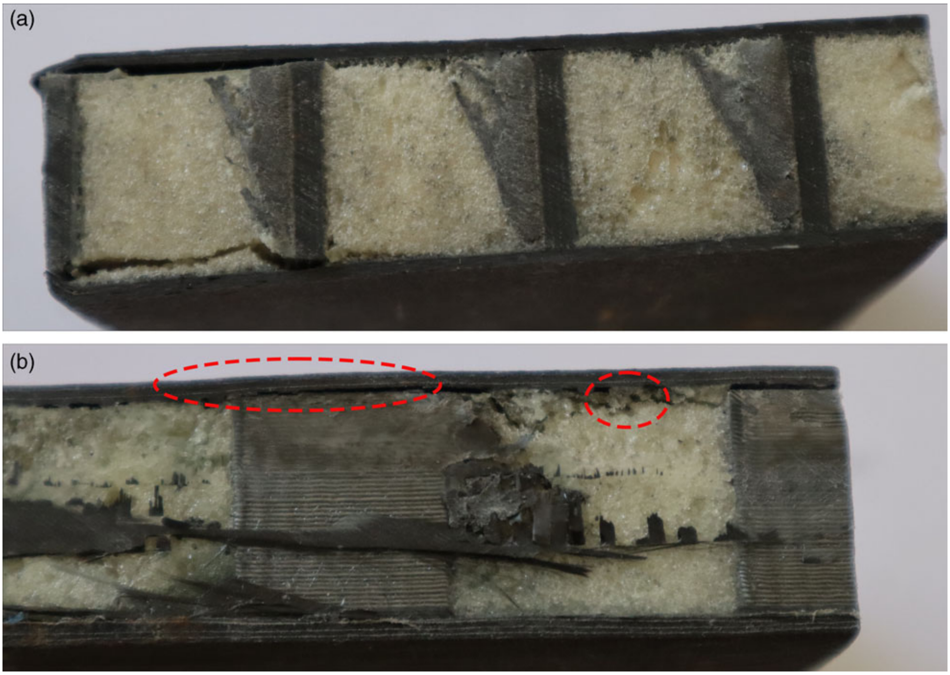

Figure 8. *Failures in the sandwich structure filled with polyurethane foam; (a) face-to-core cracks, (b) face buckling and cracks in foam filling.*

Equations (3) and (4). In these equations, F_s^{ult} is the ultimate core shear strength, σ is the facing stress, P_{max} is the maximum force prior to failure, d is the thickness of the sandwich structure, c is the thickness of the core structure, b is the width of the sandwich structure, S is the span length of the lower jaws and t is the thickness of the facesheet material.

$$F_s^{ult} = \frac{P_{max}}{(d + c)\, b} \tag{3}$$

$$\sigma = \frac{P_{max} S}{2t\, (d + c)\, b} \tag{4}$$

Figure 11 shows the failures that occurred in the sandwich composites with hollow honeycomb cores. In the structure in Fig. 11(a and c), core crushing occurred and, accordingly, core-face debonding and cracks occurred in the core. Figure 11 (b, d and g) show that the core cracks that occurred in some specimens progressed vertically along the FDM-printed core, and finally, Fig. 11 (e, f and h) show shear cracks in the core and the consequent core-face debonding damages that occurred in some specimens.

In the sandwich composites with a polyurethane foam-filled core in which the three-point bending test was applied, the initial damage was generally observed as the formation and propagation of a crack at the face-core interface in the compression volume region. This crack is parallel to the axis of the structure and this first crack extended to the test support. After this damage, the crack progressed along the thickness of the core with the applied load and reached the undamaged face. In the third and final step, the debonding of the face and the core began. The general damage that occurred in the polyurethane foam-filled samples is shown in Fig. 12. The core-face debonding, core shear cracks and the progression of the cracks are shown in detail in Fig. 13(a and b).

Properties such as facing stress and core shear strength play a critical role in defining the flexural properties in sandwich composites [9, 26]. Three-point or four-point bending tests are used to determine the mentioned properties. Another important aspect of the bending test is that it can be used to evaluate the adhesion area between the core and the facesheet [27]. In the polyurethane foam-filled core

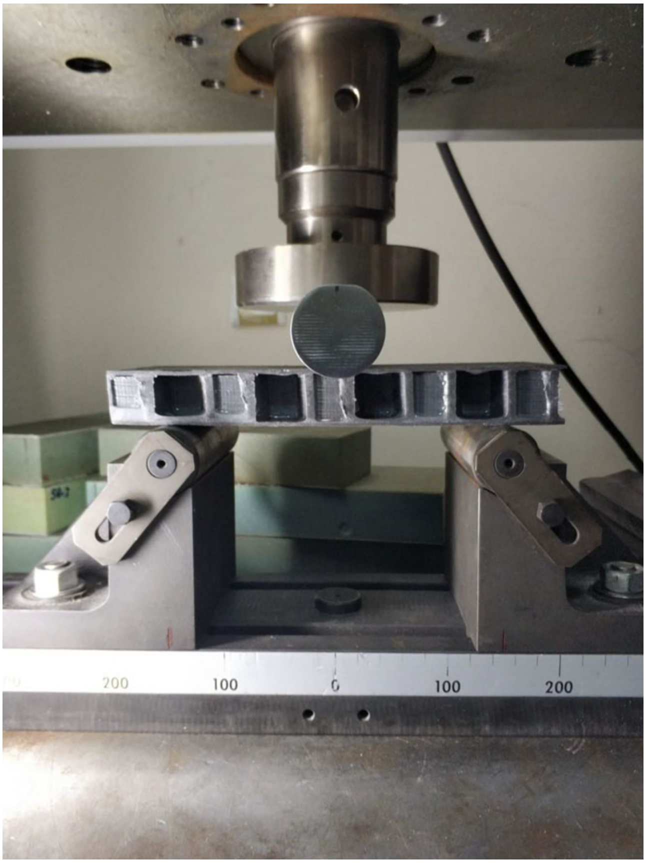

Figure 9. *Three-point bending test applied to specimens.*

structure, core-facesheet debonding did not occur until the maximum force value was reached, which can be observed when the curve of the foam filled structure is examined in the graph in Fig. 10. From this, it is understood that the polyurethane foam filling increases the adhesion quality between the core-facesheet material. Table 4 shows that, due to the stiffness effect of the polyurethane foam filling on the core material, the structure with the PU foam-filled core exhibits significantly higher core shear strength compared to composites with a hollow core. Although the same type of failures under bending occurred in both the polyurethane foam-filled core and the hollow honeycomb cores, a significant increase in bending fracture load was obtained with the polyurethane foam filling. The increase in the performance of sandwich composites is seen not only in the core structure but also in the facesheet material, as can be seen in the facing stress column in Table 4. Although the polyurethane foam filling increased the core shear strength and facing stress, it failed in energy absorption (toughness) as seen in Fig. 10. The polyurethane foam-filled core reached the maximum force value without any failure, however, it showed a sudden break after the first damage, that is, it could not show progressive failure. Similar to our study, in a study in the literature, it was observed that polyurethane foam filling did not have a positive effect on energy absorption. In their study, Montazeri et al. produced honeycomb structures using PLA and TPU filaments, filled with polyurethane foam and subjected to a three-point bending load. They observed that foam filling significantly increased the energy absorption and specific energy absorption capacities of TPU-based structures, while foam filling decreased the energy absorption and specific energy absorption capacities of PLA-based structures. The main reason for the negative effect of foam filling on PLA-based structures is that the elastic modulus of polyurethane foam is lower than that of PLA. It is assumed that using a stiffer foam material to fill cellular PLA structures will increase the energy absorption capacity

Table 4. *Three-point bending test results of hollow and polyurethane foam-filled specimens*

Specimens	Maximum force (N)	Core shear Strength (MPa)	Facing stress (MPa)
H1	3671.41	1.17	28.48
H2	3621.25	1.09	18.89
H3	4914.69	1.49	26.60
H4	4246.56	1.29	23.40
H5	3479.22	1.05	18.06
Avg. of hollow specimens	3986.63 ± 595.65	1.22 ± 0.18	23.08 ± 4.59
PUF1	8091.88	2.52	52.70
PUF2	8041.25	2.47	47.83
PUF3	7921.25	2.50	50.80
PUF4	7232.50	2.26	50.88
PUF5	8187.50	2.51	52.21
Avg. of PU-filled specimens	7894.88 ± 382.53	2.45 ± 0.11	50.88 ± 1.89

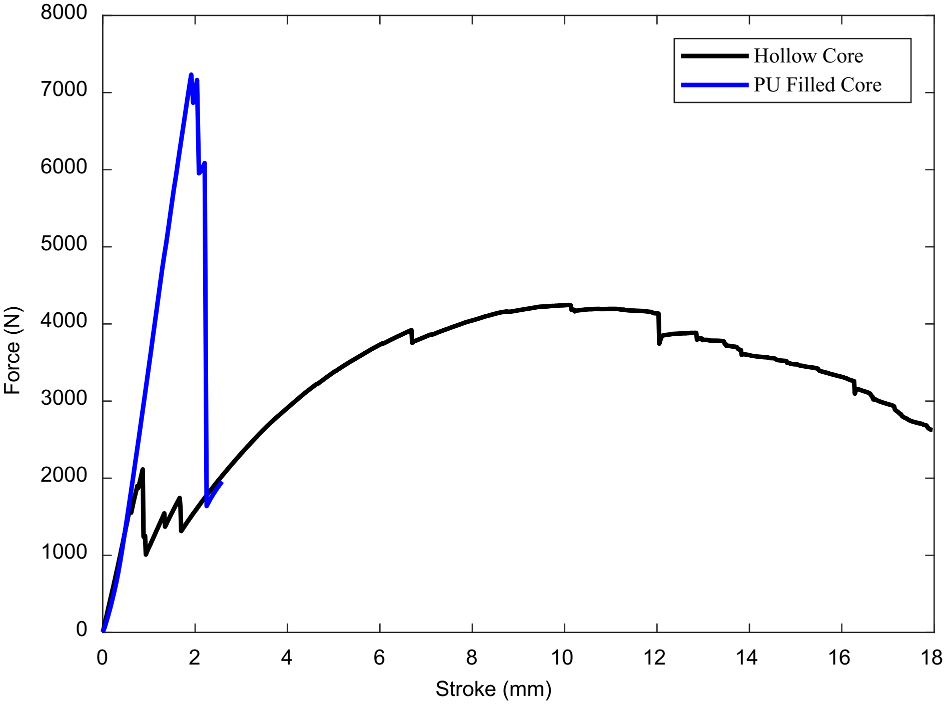

Figure 10. *Average force-displacement graph for the three-point bending testing of hollow core and polyurethane foam-filled specimens.*

of the resulting structure [28]. Similarly, since the elastic modulus of the polyurethane foam used is lower than the modulus of the PLA material, it can be said that the toughness value is low.

3.3 Shear test results

In the shear test, the specimens were exposed to a monotonically increasing shear force parallel to the face parts of the sandwich structure. In order to transfer the shear force to the structure, metal plates were attached to the face parts of the sandwich composites and the opposing force was applied. Maximum

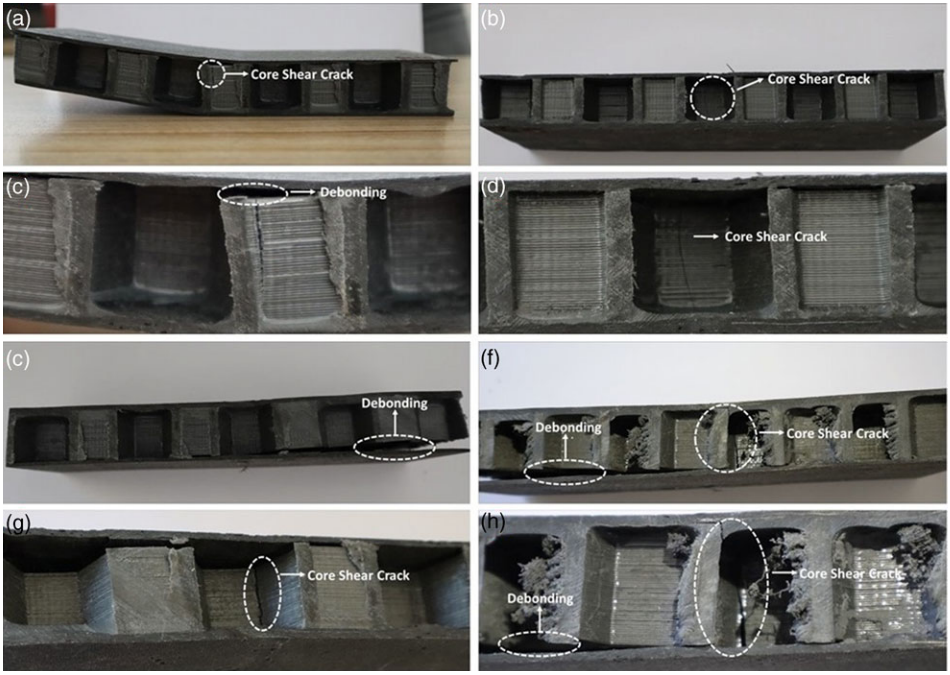

Figure 11. *Failure modes of hollow honeycomb core sandwich composite specimens from the three–point bending test.*

Figure 12. *Failures in polyurethane foam-filled specimens in the three-point bending test.*

displacement, shear stress, shear strain and core shear modulus values were calculated and evaluated from the obtained test data. The data from the shear test and the shear stress (τ), shear strain (γ) and core shear modulus (G) values were found using Equations (5), (6), and (7), respectively. In these expressions, τ is the shear stress, P is the force applied to the sample, L is the specimen length, b is the specimen width, γ is the shear strain, u is the displacement values in the specimen, c is the core material thickness

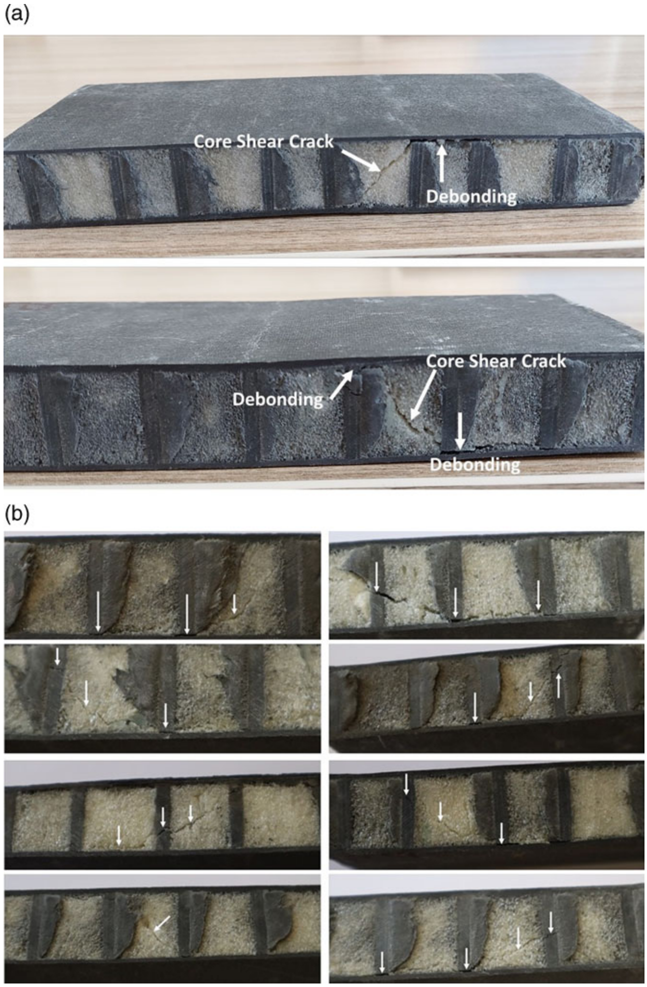

Figure 13. *Failures in polyurethane foam-filled specimens (a) core shear cracks and core-face debonding failure, (b) propagation of core shear cracks in all specimens.*

and G is the core shear modulus. The expression $\Delta P/\Delta u$ in Equation (7) represents the slope value obtained from the linear part of the force-displacement graphs of the specimens.

$$\tau = P/Lb \tag{5}$$

$$\gamma = u/c \tag{6}$$

$$G = \left(\frac{\Delta P}{\Delta u}\right)\frac{c}{Lb} \tag{7}$$

Shear stress, shear strain and core shear modulus values obtained using experimental data and Equations (5), (6), and (7) are given in Table 5. Since one specimen showed insignificant values for both sample types, their data are not included in Table 5 and these were not used in the average and standard deviation calculations. According to the data in Table 5, the stress-strain graph of sandwich composites with hollow and polyurethane foam-filled cores is given in Fig. 14.

When Fig. 14 is examined, the hollow honeycomb structure and the polyurethane foam-filled structure initially exhibited a linear behaviour and then showed a yielding behaviour with a peak load. After

Table 5. *Shear test results of hollow and polyurethane foam-filled specimens*

Specimens	Shear stress (MPa)	Shear strain (mm/mm)	Core shear modulus (MPa)
H1	1.72	0.074	3.34
H2	2.07	0.090	6.61
H3	1.82	0.079	8.82
H4	2.97	0.128	10.34
Avg. of hollow specimens	2.14 ± 0.57	0.093 ± 0.024	7.27 ± 3.03
PUF1	2.82	0.14	10.17
PUF2	3.53	0.18	10.55
PUF3	3.04	0.16	10.55
PUF4	3.56	0.18	10.64
Avg. of PU-filled specimens	3.24 ± 0.37	0.17 ± 0.019	10.47 ± 0.20

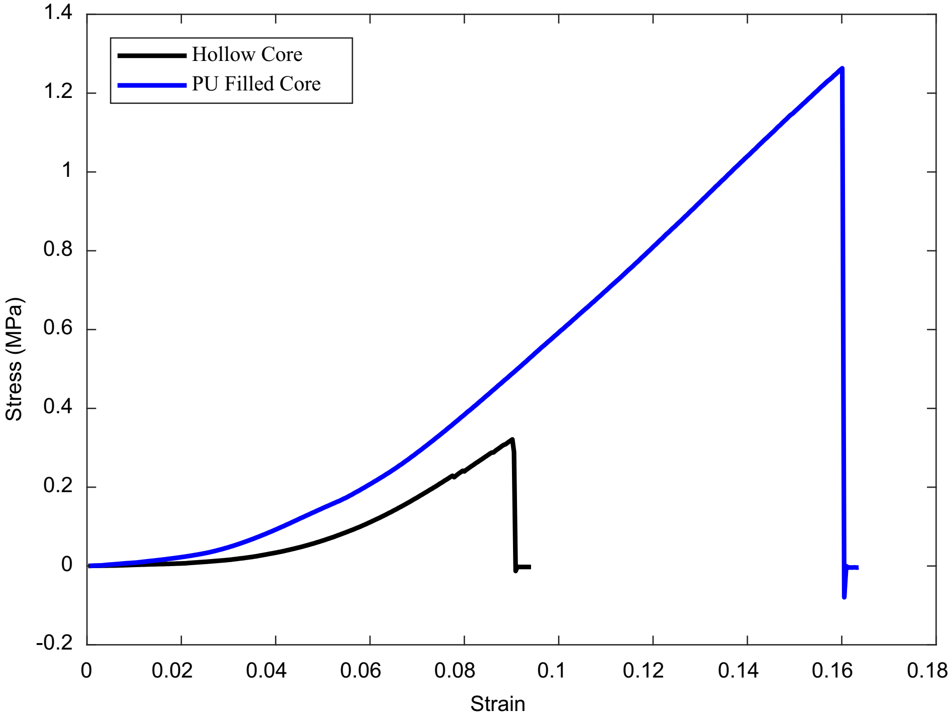

Figure 14. *Stress-strain graph of sandwich composites with hollow core and polyurethane foam-filled cores.*

the material reaches its peak load, its load-bearing ability is significantly reduced and the sandwich is separated from the bonding zone between the core and the facesheet material. In the graph, the peak stress value is 0.32 MPa in the structure with a hollow honeycomb core, while the peak stress value is 1.26 MPa in the structure with a polyurethane foam-filled core. As can be seen, the polyurethane foam filling provided an increase of approximately four times the maximum stress. This increase is due to the porous structure of the polyurethane foam, which provides good adhesion to the facesheet material. In the structure with a hollow honeycomb core, since the adhesion with the facesheet can only be achieved through the cell walls, it exhibited core–facesheet separation at lower stress values.

Table 6. *Weight increases in sandwich composite specimens after the water absorption test*

Specimens	Percent weight increases (%*w*)
H1	1.39
H2	3.22
H3	1.86
H4	3.51
H5	2.96
Avg. of hollow specimens	2.59 ± 0.91
PUF1	3.56
PUF2	2.77
PUF3	2.97
PUF4	3.50
PUF5	2.51
Avg. of PU-filled specimens	3.07 ± 0.46

3.4 Water absorption test results

The sandwich composite samples were kept in a beaker of water for 192 hours as part of the water absorption test. After the specified time was completed, the mass increase values were measured in order to observe the moisture absorption of the sandwich composites. The mass increase values on a percentage basis are shown in Table 6. According to these values, an average of 2.59 ± 0.91% weight increase occurred in hollow honeycomb core sandwich composites, while an average of 3.07 ± 0.46% weight increase occurred in those with a polyurethane foam-filled honeycomb core. While the polyurethane foam-filled structure was expected to absorb less water, it absorbed 18% more water by weight than sandwich structures with hollow honeycomb cores. It is thought that the main reason for this situation is that the polyurethane foam is formed inside the core without using any adhesive, and therefore the pores formed between the foam and the structure absorb more water.

4.0 Conclusions

In this study, honeycomb core structures produced with a PLA filament using a 3D-printer with the FDM technique were filled with polyurethane foam and made into a sandwich composite with carbon fibre facesheet materials and epoxy resin. The materials produced were subjected to edgewise compression, three-point bending, shear and water absorption tests according to the relevant American Society for Testing and Materials (ASTM) standards. Within the scope of the study, the effects of the polyurethane foam filling made on the FDM-printed cores' mechanical and moisture absorption properties were investigated. In order to compare the effects of the polyurethane foam filling on these properties, a second honeycomb and facesheet sandwich composite structure was produced with the same process but left with a hollow core. Both produced composites were subjected to the same tests under the same laboratory conditions. According to the results obtained:

- In the edgewise compression test for sandwich composites with hollow honeycomb cores, the average facing strength was 13.52±2.86 MPa and the average ultimate compressive strength was 124.50±20.80 MPa; in sandwich composites with polyurethane foam-filled cores, the average facing strength was 23.43±3.49 MPa and the average ultimate compressive strength was 147.73±29.33 MPa. It was observed that the polyurethane foam filling increased the

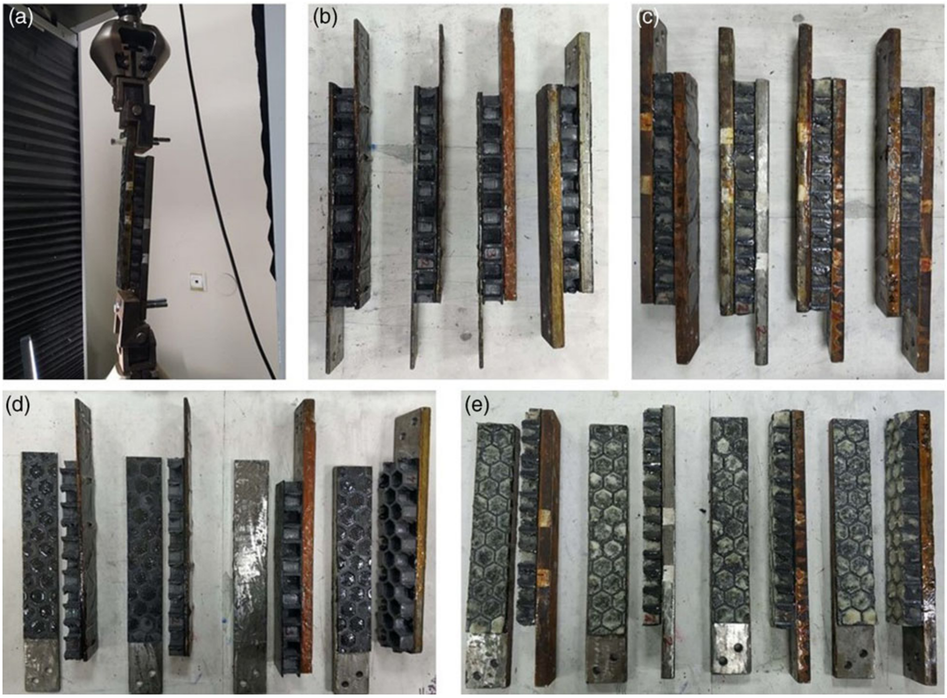

Figure 15. *Specimens before and after the shear test: (a) a specimen during the shear test, (b) sandwich composite specimens with a hollow core before the shear test, (c) sandwich composite specimens with a polyurethane foam filling before the shear test, (d) sandwich composite specimens with a hollow core after the shear test, (e) sandwich composite specimens filled with a polyurethane foam after shear test.*

average facing strength by approximately 74% and the average ultimate compressive strength by approximately 19%.

- In the three-point bending test for sandwich composites with hollow honeycomb cores, the average core shear strength was 1.22±0.18 MPa and the average facing stress was 23.08±4.59 MPa; in sandwich composites with a polyurethane foam-filled core, the average core shear strength was 2.45±0.11 MPa and the average facing stress was 50.88±1.89 MPa. It was observed that the polyurethane foam filling increased the average core shear strength by approximately 100% and the average facing stress by approximately 120%. In the three-point bending test, although the polyurethane foam filling increased the core shear strength and the strength of the facesheet material, it was not successful in energy absorption (toughness) compared to the hollow honeycomb core structure. It is stated in the results section that the foam filling for the proposed material was not successful in terms of energy absorption, in relation to the literature. The main reason for this situation is that the elastic modulus of the polyurethane foam is lower than the PLA material. The proposed structure exhibited more consistent results under three-point bending load and provided higher values of core shear strength and facing stress. However, the proposed material exhibited low energy absorption (toughness) value. If the proposed material is used as a structural material in aircraft, it will be subjected to bending loads continuously throughout its service life. This situation may create the perception that the material may be detrimental if used as aircraft structural. However, the most important advantage of polyurethane foams is that they can be used for different applications by adding many additives to their structures. This problem can be solved by using various foaming agents, fillers or nanoadditives that will increase toughness under bending load.

- In the shear test for sandwich composites with hollow honeycomb cores, the average shear stress was 2.14 ± 0.57 MPa and the average shear modulus was 7.27 ± 3.03 MPa; In sandwich composites with a polyurethane foam-filled core, the average shear stress was 3.24 ± 0.37 MPa and the average shear modulus was 10.47 ± 0.20 MPa. It was observed that the polyurethane foam filling increased the average shear stress value by approximately 51% and the average shear modulus value increased by approximately 44%.
- The moisture absorption characteristic of the structure was evaluated by examining the percent weight gain values that occurred in the structure with the water absorption test. According to the results, a weight increase of 2.59 ± 0.91% occurred in sandwich composites with hollow honeycomb cores and 3.07 ± 0.46% occurred in the polyurethane foam-filled sandwich composites.

The polyurethane foam filling applied to the core structures produced with the FDM technique significantly increased the in-plane compression strength, three-point bending strength, and shear strength of the sandwich composite forms of these structures. In addition to all these strength increases, weight measurements showed that the sandwich composite with the polyurethane foam-filled core is lighter than the sandwich composite with the hollow core. The reason the hollow honeycomb core structure is heavier is that more epoxy resin is filled into the gaps in the structure. In the polyurethane foam-filled core, the epoxy resin is only filled into the pores in the foam structure and the porous interfaces between the foam and the FDM printed structure, so a lighter structure is obtained compared to the hollow honeycomb core.

Sandwich composites with a polyurethane foam-filled core exhibited abrupt and non-progressive fracture. This situation is dangerous for aircraft structures, but it can be improved, and fracture toughness values can be increased thanks to the additives to the polymer structure. The main reason the foam-filled core sandwich composite exhibits low energy absorption, especially under bending load, is due to its polyurethane foam structure because cell size, cell wall thickness, cell density, viscosity and cell orientation factors are important among the factors affecting toughness in polyurethane foams. Various catalysts or chemical agents can be used to affect these factors during the production of polyurethane foam to increase fracture toughness. In addition, fracture toughness can be increased by adding nanoparticles, such as SiC, TiO_2, carbon nanotubes (CNT) and nanoclay, which increase the strength of the polyurethane foam and increase cell nucleation.

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