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Development of Aluminum Honeycomb Cored Carbon Fiber Reinforced Polymer Composite Based Sandwich Structure

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Abstract: Lightweight composite sandwich structures are laminated composite structures that are composed of thin stiff face sheets bonded to a thicker lightweight core in between. These structures have high potential to be used in marine, aerospace, defense and civil engineering applications due to their high strength to weight ratios and energy absorption capacity.

In this study, composite sandwich structures were developed with carbon fiber reinforced polymer composite face sheets and aluminum honeycomb core materials with various thicknesses. Carbon fiber/epoxy composite face sheets were fabricated with lamination of $[0/90]_s$ carbon fabrics by vacuum infusion technique. Al honeycomb layers were sandwiched together with the face sheets using a thermosetting adhesive. Mechanical tests were carried out to determine the mechanical behavior of face sheets, Al cores and the composite structure. Effect of core thickness on the mechanical properties of the sandwich was investigated.

Keywords: Sandwich structures, carbon fiber, epoxy, aluminum honeycomb, mechanical properties, vacuum infusion

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1. Introduction

Composite sandwich structures have been used in many applications ranging from satellites, aircraft, ships, automobiles, rail cars, wind energy systems to bridge constructions due to their light weight, high flexural and transverse shear stiffness, and corrosion resistance [1, 2]. Moreover, these structures are capable of absorbing large amounts of crash energy in the event of a sudden collision [3].

In a sandwich structure, the bending loads are generally carried by the force couple formed by the face sheets while the shear loads are carried by the lightweight core material. The face sheets are strong in tension and compression, as compared to the low-density core material whose main purpose is to provide a high moment of inertia. The low-density of the core material results in low panel density; therefore, under flexural loading, sandwich panels have higher specific mechanical properties relative to the monocoque structures. Hence, sandwich panels are very sufficient in carrying bending loads. Under flexural loading, face sheets form a force couple so that one laminate is under compression and the other is under tension. Meanwhile, the core resists transverse forces and stabilizes the laminates against global buckling and local buckling. The resulting structure provides increased buckling and crippling resistance to shear panels[4, 5]. In addition, the composite action is defined as the ratio between the bending moment of the couple and the overall bending moment. In general, the bending resistance of the panel is totally resisted by the couple when no localized loads are involved. In case of localized effects, additional local bending moments in the face sheets and high interfacial stresses between the face and core may occur which reduces the contribution of the couple to the over bending moment resistance or the composite action [6].

Core section generally is selected as a low density material or structure, such as metallic or polymeric foams, hexagonal and square honeycomb cells and various truss systems [7]. Although a variety of cell configurations are available, hexagonal honeycomb core is by far the most commonly used core configuration [8]. This configuration is widely commercially available, as it is commonly based on thermoplastics (PP), Kevlar, Nomex, aluminum and natural fabrics [9–13].

Mechanical behavior of sandwich structures including flatwise tensile, flatwise and edgewise compression, flexural, shear and impact properties widely investigated experimentally and modelled as reported in the literature [11, 13–15]. Both quasi-static and dynamic mechanical

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behavior of Al honeycomb based sandwich structures were investigated in various studies [3, 8, 16–21]. Also, the effect of core thickness on the impact properties of the sandwiches was investigated by Chi et. al. [22]. It was observed that increasing the core thickness delay the onset of core densification and decrease back plate deflection and tearing. In larger size sandwich structures, core discontinuities may also occur. Discontinuity effects on quasi-static loads were also investigated by Fotsing et. al.[23]

Face sheet and core material bonding is one of the important aspect in sandwich structures. In the literature, different approaches were proposed to strengthen the bonding region in order to increase structural performance of the sandwich composite, which include introducing aramid reinforced thermoset layers to face core interface [20, 24, 25]. In order to measure bonding strength at the interface of face sheet and core, several techniques mostly based on peeling of the face from the core were employed [26, 27].

The aim of this study is to develop manufacturing routes of carbon fiber reinforced polymer (CFRP) face sheet/aluminum (Al) core based sandwich structures and investigate the mechanical behavior of those structures with various core thicknesses. For this purpose, CFRP composite face layers were fabricated by vacuum infusion technique. Composite face and Al core materials were laminated together by an adhesive joining technique. Flatwise compression (FC), Flatwise Tensile (FT), Edgewise compression (EC), Mode I peel strength and flexural bending (3PB) tests were carried out on composite sandwich specimens. Constituents of the sandwich structures were also tested mechanically and a conclusion is drawn for an optimized sandwich structures.

2. Experimental

Unidirectional (UD) carbon fiber based fabrics (Metyx ™ CWUD 500A) were used as the reinforcement constituent of the composite face sheets. Epoxy resin (Momentive ™ MGS L160) with hardener (Momentive ™ MGS H160) was used as the matrix material. Aluminum honeycomb core materials with hexagonal cell configuration (with cell size of 10 mm) were provided by 6Gen Panel Aerospace Shipbuilding Panel Industry of Turkey. Three different core thicknesses; 6, 21 and 46 mm were used for the manufacturing of the composite sandwich panels. The cell wall thickness of the Al honeycomb core materials was measured by using Nikon™ optical microscope.

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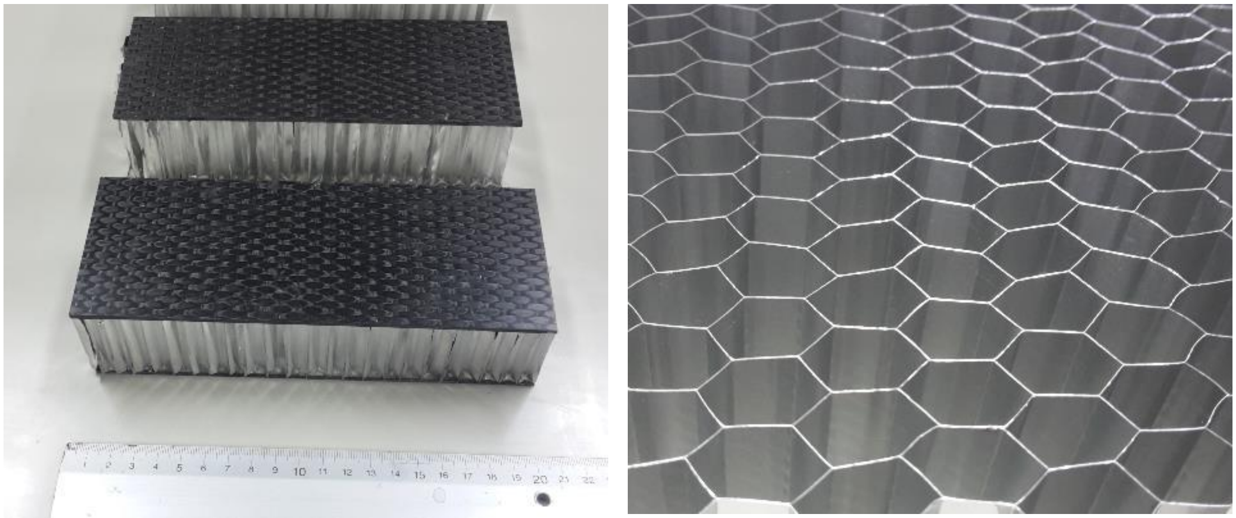

(a) **(b)**

Figure 1. Image of (a) manufactured carbon face sheet / Al honeycomb sandwich structures, (b) Al honeycomb core material

Composite sandwich panels consisting of carbon fiber/epoxy face sheets and aluminum honeycomb core materials with various thicknesses were manufactured. Figure 1 is an example image of the sandwich structures fabricated within this study. Flow chart of composite sandwich fabrication is given in Figure 2. At the first stage, composite face sheets were produced by vacuum infusion technique. Dry carbon fabrics were placed on a smooth infusion table with a stacking sequence of $[0/90]_S$. The infusion parts were prepared by using infusion materials such as vacuum bag, etc. The resin was allowed to flow through the entire fabric network, while the part was kept under vacuum. After completion of the infusion, the parts were allowed to cure at room temperature followed by post-curing for 12 hours at 80^0C. Test specimens were cut into desired dimensions by water-cooled diamond saw according to relevant ASTM standards. In order to improve bonding at face sheet/core interface, one surface of the composite face sheets was sanded with 80-grit sandpaper and cleaned by acetone. Face sheets and core materials were bonded together by a polyurethane (PU) based adhesive. The adhesive was applied onto the sanded surface of composite facesheets and they were sandwiched together with Al cores. The sandwiched specimens were laminated at room temperature under the pressure of 10 kPa. Curing was applied in an oven at 60°C for 35 minutes and post-curing was performed at room temperature for seven days for completion of curing of adhesive material.

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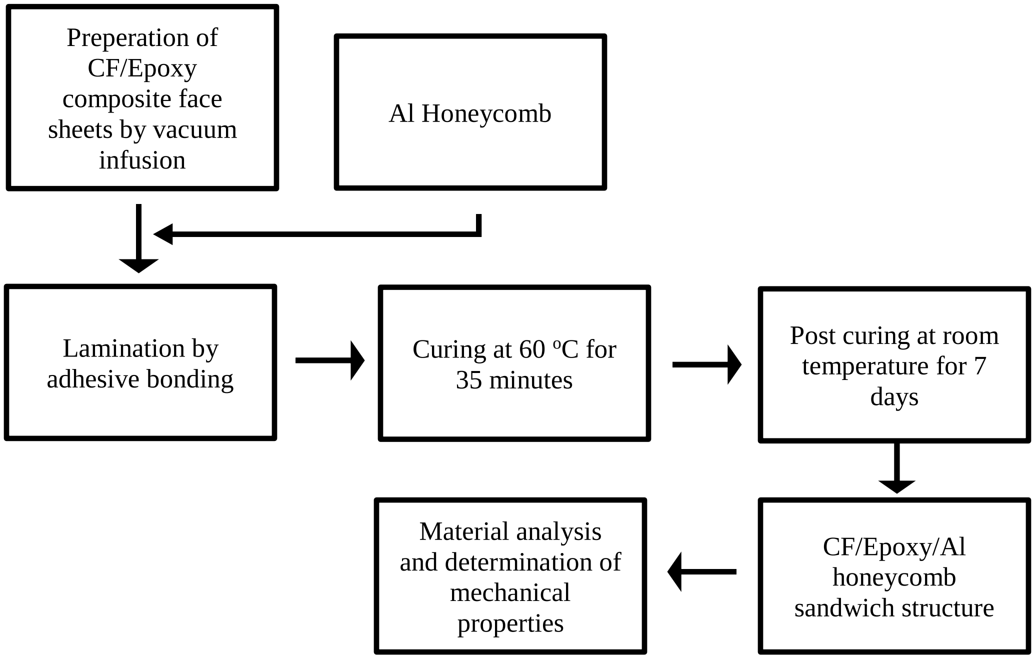

Figure 2. Flow chart of composite sandwich structure manufacturing.

2.1. Determination of Mechanical Properties

Understanding of mechanical behavior of composite sandwich panels relies generally on individual mechanical properties of core and face sheet materials. Mechanical behavior of sandwich structures in addition to core and face sheet materials was investigated. All mechanical tests were conducted using a Shimadzu™ AG-IC 100 kN Universal testing device. At least five specimens were tested for each property.

2.1.1. Core Properties

The flatwise compressive strength and modulus of the Al honeycomb core materials were determined according to ASTM C365M-11a. Flatwise compression test specimens were cut into square shape with 70 mm edge for each core thickness using a cutter. The tests were performed at a crosshead speed of 0.5 mm/min.

2.1.2. Face Properties

ASTM D 3039M-14 was used to determine the tensile strength and modulus of the composite face sheets. Test specimens were sectioned from the composite panels with 25 mm in

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width, 2.5 mm in thickness, 250 mm in length. The specimens were tested at a cross head speed of 2 mm/min. ASTM D 6941-14 was used to measure the compressive strength and modulus of the composite face sheet panels. Compression test specimens with 13 mm in width and 140 mm in length were cut from face sheet panels using a diamond saw. Tests were performed at a crosshead speed of 1.3 mm/min. Specimens were tested placing to fixture apparatus and forces versus stroke values were recorded. The flexural test method was used to determine the flexural strength and modulus of the composites according to ASTM D 790-15. Test specimens with 13 mm in width, 2.5 mm in height and 100 mm in length were sectioned from the face sheet panels using a diamond saw. Specimens were tested by using a 3-point bending apparatus with a span to thickness ratio of 32. Specimens from composite face sheets were tested at a crosshead speed of 4.37 mm/min. During the test, force vs. deflection of the beam was recorded. The interlaminar shear strength of the composite specimens was determined performing short beam shear (SBS) tests according to ASTM D2344-13. The SBS specimens 18 mm in length, 3 mm in height and 6 mm in width were cut from the composite face sheets. The length to thickness ratio and span to thickness ratio were 6 and 4, respectively. The crosshead speed was 1 mm/min.

2.1.3. Sandwich Properties

The flatwise compressive strength, modulus and energy absorption characteristics of the composite panels were determined according to ASTM C 365M-11a. Compression test specimens were sectioned and the tests were performed using the mechanical test machine at a crosshead speed of 0.5 mm/min. Test specimen surfaces were square with 70 mm in edge dimensions. Flatwise tensile test method (ASTM C 297M-15) was used to determine the ultimate flatwise tensile strength. Flatwise tensile test specimens were cut into square shape with 50 mm edge for each core thickness using a diamond saw. Tests were performed at a crosshead speed of 0.5 mm/min. Edgewise compression test method (ASTM C 364M-07) was used to determine the compressive properties and energy absorption characteristics of flat structural sandwich construction in a direction parallel to the sandwich face sheet. Failure modes of the composite sandwich panels were detected. The tests were performed using the mechanical test machine at a crosshead speed of 1.7 mm/min. The flexural test method (ASTM C 393M-11) was used to measure the core shear stress, facing bending stress and panel bending stiffness of the composite sandwich panels. For this purpose, three-point bending test specimens for each thickness were cut into 75 mm in width and 200 mm in length. Tests were performed using the mechanical test machine at a crosshead speed of 5 mm/min. Span was selected as 90 mm for 6 and 21 mm core thickness, and 100 mm for 46 mm core thickness. Mode I interfacial peel strength of the composite sandwich structures was measured using ASTM D 5528-13 test method. The specimens were sectioned from large sandwich panels with the width of 25 mm and length of 150 mm for each core thickness. The initial pre-crack length (a_0) was about 62.5 mm. The specimens were tested at crosshead speed of 5 mm/min. The cross-head displacement was measured by the universal test machine. Composite face sheet/Al core peel strength was calculated based on the load required to separate bonded materials by dividing the unit width.

3. Results and Discussion

The cell wall thicknesses were measured based on optical microscopy. Figure 3 shows microscope images of Al honeycomb core cross-sections for various core thicknesses. Based on the images captured the average wall thickness was measured as 45.3 ± 3.7, 43.5 ± 1.9 and 44.1 ± 3.1 µm for 6, 21 and 46 mm core thicknesses, respectively.

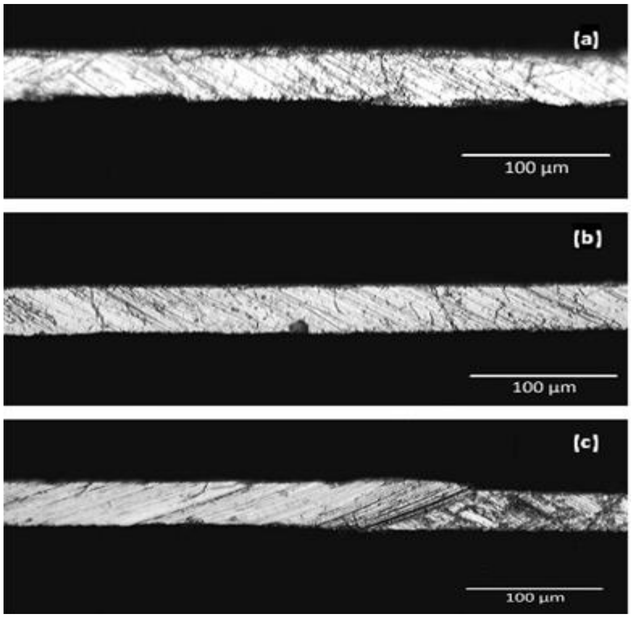

Figure 3. Optical microscope images of Al core materials cross-sections for (a) 6, (b) 21 and (c) 46 mm thickness cores (Magnification: 20X)

3.1. Core Property Test Results

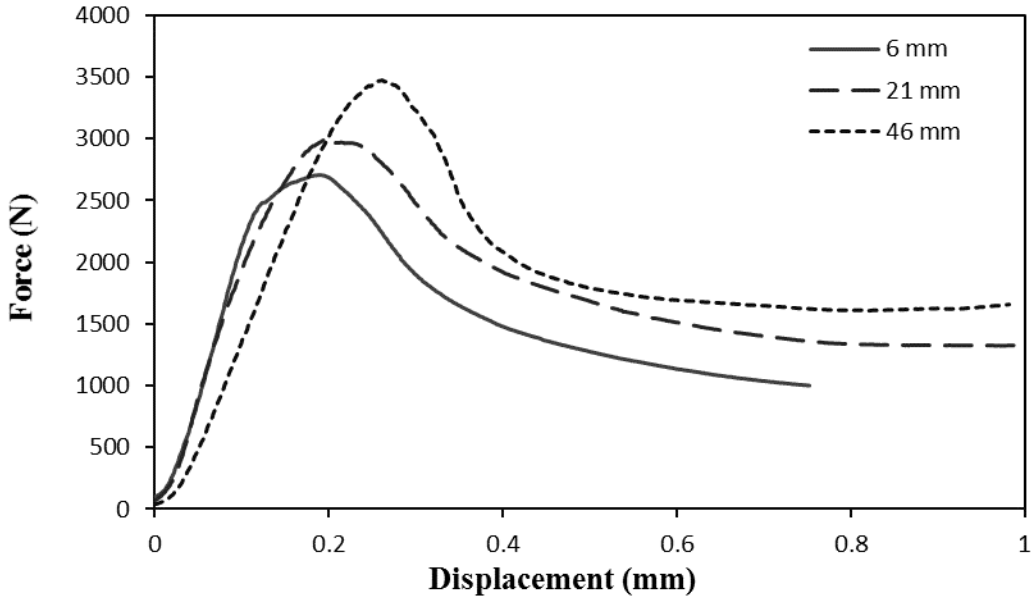

Figure 4. Comparison of typical flatwise compressive behavior of Al based honeycomb core materials for various core thicknesses

Figure 4 shows the typical comparison force-displacement curves of Al honeycomb core materials for three different core thicknesses under flatwise compressive loads. Deformation modes of the Al core materials are shown in Figure 5. All specimens showed similar trend at the initial stage of the compression loading. Up to some displacement level, core materials exhibit elastic deformation behavior. After certain values, the core cell walls start to buckle and then sudden collapse occurs. As the core thickness increases, the maximum force levels were observed to increase slightly. The average flatwise compressive strength and modulus values are also summarized in Table 1 as a function of the core thicknesses. It was found that the compressive strength and modulus values of Al honeycomb increase as the core thickness increases.

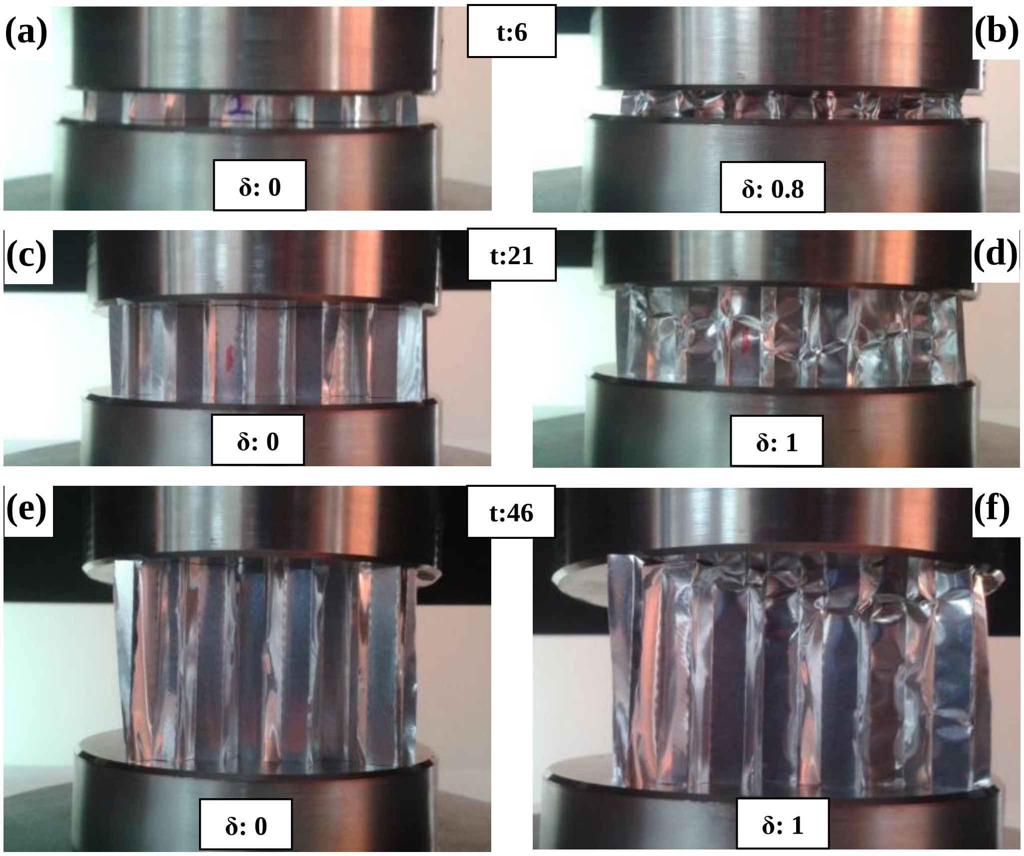

Figure 5. Images of flatwise compression test specimens; before (a-c-e) and after (b-d-f) loading (t : thickness in mm, δ : displacement in mm)

Table 1. Summary of flatwise compression test results of Al honeycomb core

Core thickness (mm)	Elastic Modulus (MPa)	Strength (MPa)
6	38 ± 7.4	0.62 ± 0.02
21	100 ± 20.6	0.67 ± 0.05
46	148.7 ± 16	0.70 ± 0.01

3.2. Face Material Properties

Table 2 summarizes mechanical properties of carbon fiber/epoxy composite face sheets. Stress-strain response of the composite face sheets for all properties was observed to be almost linear up to the maximum stress values reached, and then failure of the specimens occur followed by a sudden load drop. In the initial stage, the composite exhibits elastic deformation behavior and fracture start near to maximum stress level. In compression mode, it was observed that the specimens fail with buckling and shear deformation. It is note-worthy that the observed failure modes are the expected modes for compression test as shown in Figure 6.

Table 2. Summary of face sheet mechanical property test results

Face Sheet Mechanical Property		Avg. Value with Std. Dev. (+/-)
Tensile	**Modulus (GPa)**	61.4 ± 4
	Strength (MPa)	672 ± 16
	Failure Strain	1.06 ± 0.07
Compressive	**Modulus (GPa)**	78.90 ± 6.70
	Strength (MPa)	368 ± 24.8
	Failure Strain	0.46 ± 0.06
Flexural	**Modulus (GPa)**	42.03 ± 5.43
	Strength (MPa)	640.5 ± 35.9
	Failure Strain	1.55 ± 0.14
Interlaminar Shear Strength (MPa)		39.3 ± 1.8

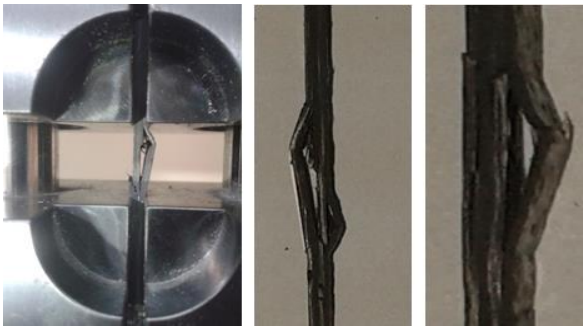

Figure 6. Images of the compression test set-up (left) and the test specimen after compressive loading (middle, right)

3.3. Mechanical Behavior of Composite Sandwich Structures

Typical load-displacement curves of carbon/epoxy faced/Al honeycomb core based composite sandwich structures under flatwise compression are shown in Figure 7. As seen in the figures, the force values initially increase linearly. A relatively large drop of the force is observed, followed by a plateau region in which the stress is almost constant as the deformation is progressed. Above the maximum force level, the cell walls collapse suddenly due to the bending and local buckling of the cell walls. The maximum load level decreases gradually with increasing the core thickness of composite sandwich structures. Bending and local buckling of the cell walls occurs at lower load levels as the thickness of the core increases. This results with a decrease in compressive strength of the sandwich structures fabricated with thicker core materials. After some displacement level, the sandwiches continue to crush in cell walls and the buckling continues simultaneously. A relatively higher energy absorption values were calculated for the sandwiches containing thicker cores. The average specific absorbed energy ($E_{s,a}$), was calculated as 0.060, 0.055 and 0.057 kJ/kg for sandwiches with 6, 21 and 46 mm core thickness,respectively.

Failure mechanisms of the sandwich structures during compressive loading were also observed as illustrated in Figure 8. It was seen that the cell wall crushing and core buckling are the main mechanisms, occurred within the sandwiches due to flatwise compression. It was also seen that the failure modes of the Al core change due to the change of core thicknesses.

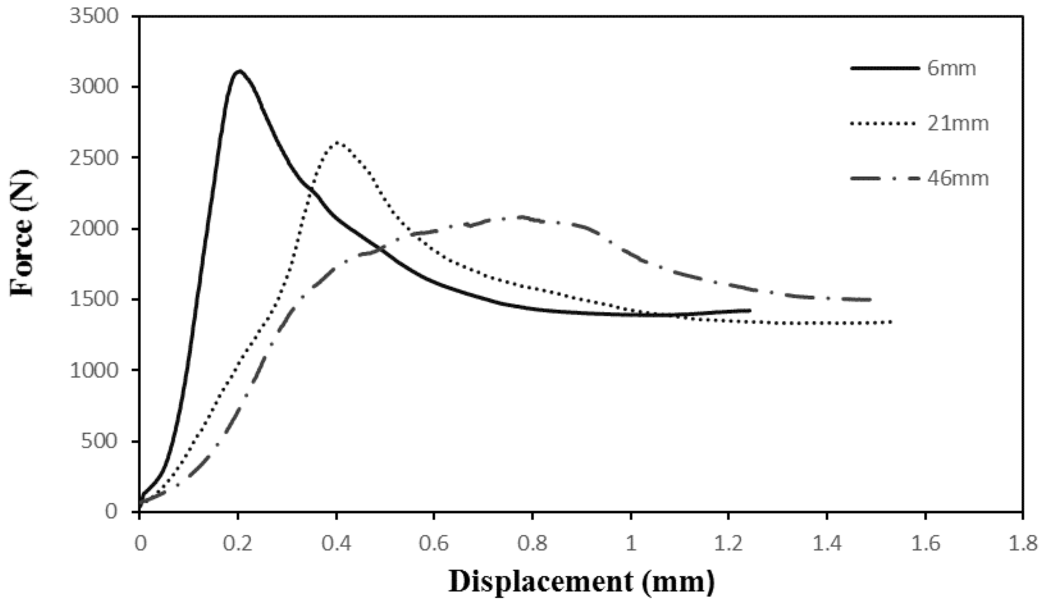

Figure 7. Typical force-displacement curves of composite sandwich structures for various core thicknesses obtained from the flatwise compression tests.

The average flatwise compression strength and modulus values of composite sandwich structures for various core thicknesses are presented in Table 3. Although the strength values decrease, the compressive modulus values were found to be increased due to the increase in core thickness.

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Table 3. Summary of flatwise compression test results for carbon-epoxy/Al honeycomb composite sandwich structures with various core thicknesses

Core thickness (mm)	Elastic Modulus (MPa)	Compressive Strength (MPa)
6	13.52 ± 3.00	0.56 ± 0.094
21	18.20 ± 5.41	0.44 ± 0.080
46	45.00 ± 12.80	0.41 ± 0.045

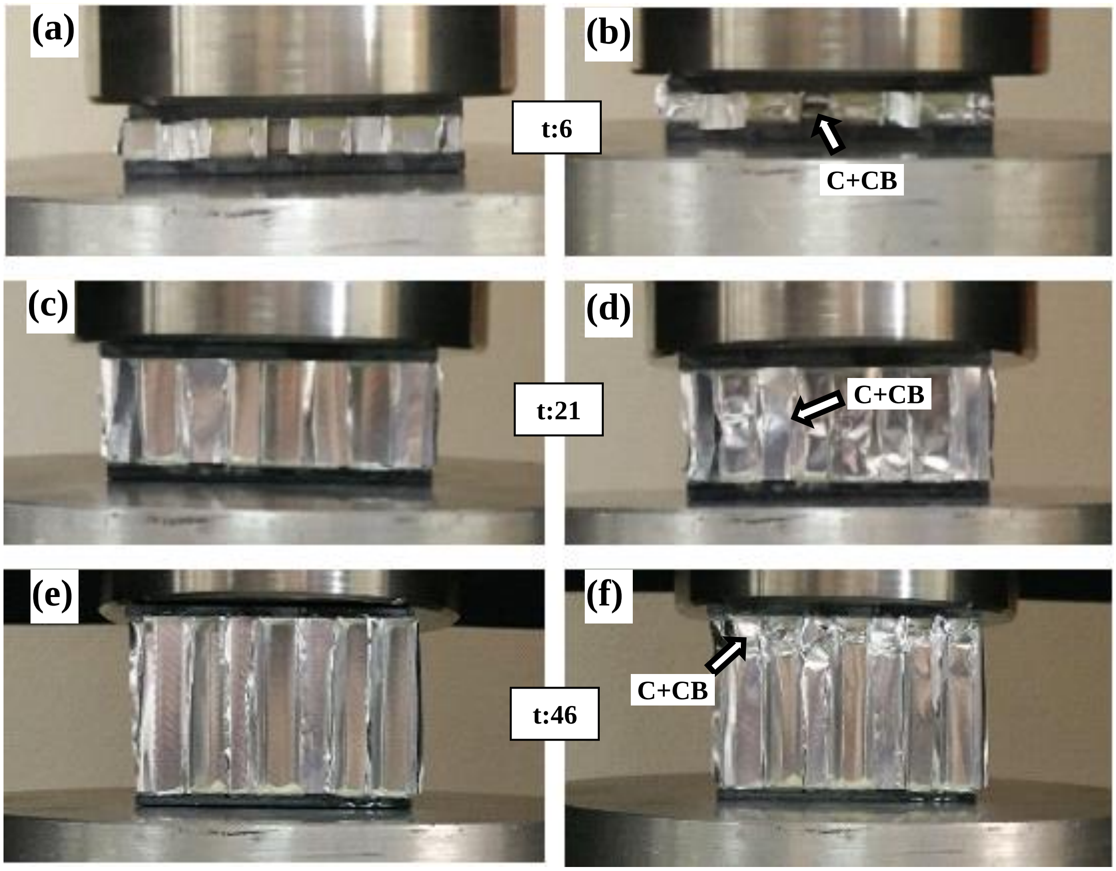

Figure 8. The images of flatwise compression test samples of the composite sandwich structures; before (a-c-e) and (b-d-f) after the tests (C: crushing, CB: core buckling, t: core thickness in mm)

Collapse sequence images and representative force-displacement curve and the corresponding specific absorbed energy ($E_{s,a}$) graph of the composite sandwich structure under flatwise compression are presented in Figure 9.

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After the maximum load level, a large drop at load level was observed followed by the plateau region where the stress was almost constant under increasing deformation. This increase in load capacity at this region is due to the densification of the folded cell walls [28]. In Figure 9.b, an example graph of specific absorbed energy (absorbed energy/weight of the composite, $E_{s,a}$) is also shown. Deformation of the structure under compressive load is illustrated by the images given in Figure 9.a. Above the maximum load level, bending of the cell walls occurred with further displacement as shown in the figures.

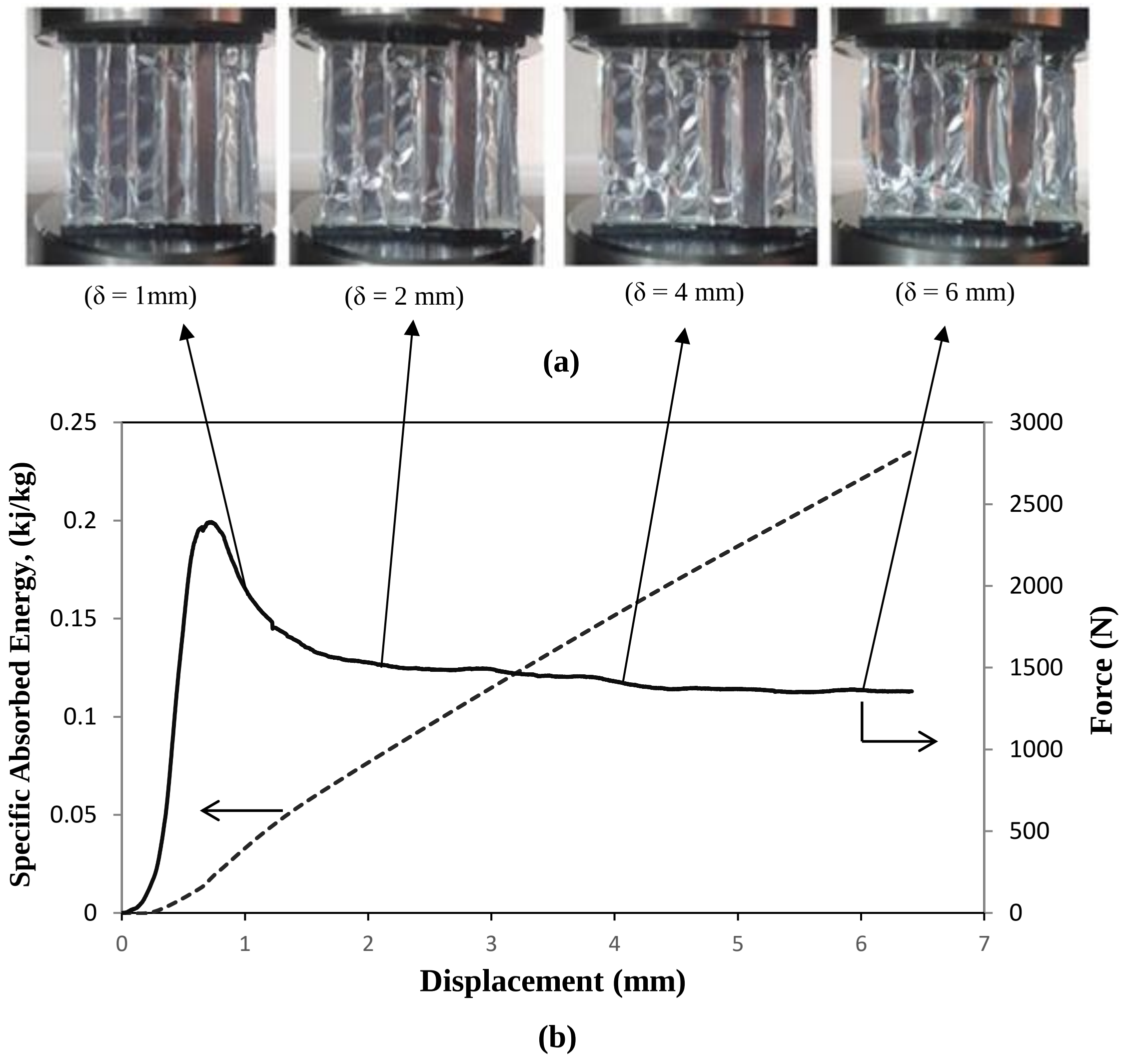

Figure 9. (a) Collapse sequence images and (b) representative force-displacement curve and the specific absorbed energy ($E_{s,a}$), graph of the composite sandwich structures under flatwise compression (core thickness is 46 mm)

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For flatwise tensile loading, the force-displacement curves of carbon-epoxy / Al honeycomb composite sandwich structures for various core thicknesses were obtained as shown in Figure 10. Response of the material is almost linear up to the failure point and it exhibits an elastic behavior in this range. Adhesive failure was observed at the composite face sheet/Al core interface due to Mode I flatwise tensile loading of the sandwiches, as seen in Figure 11. As described before, a PU based adhesive glue was used to bond face sheets and core materials together. Due to relatively lower strength of the bonding region, interfacial failure occurred. The average ultimate tensile strength and maximum force values for sandwich structures with various core thicknesses are given in Table 4.

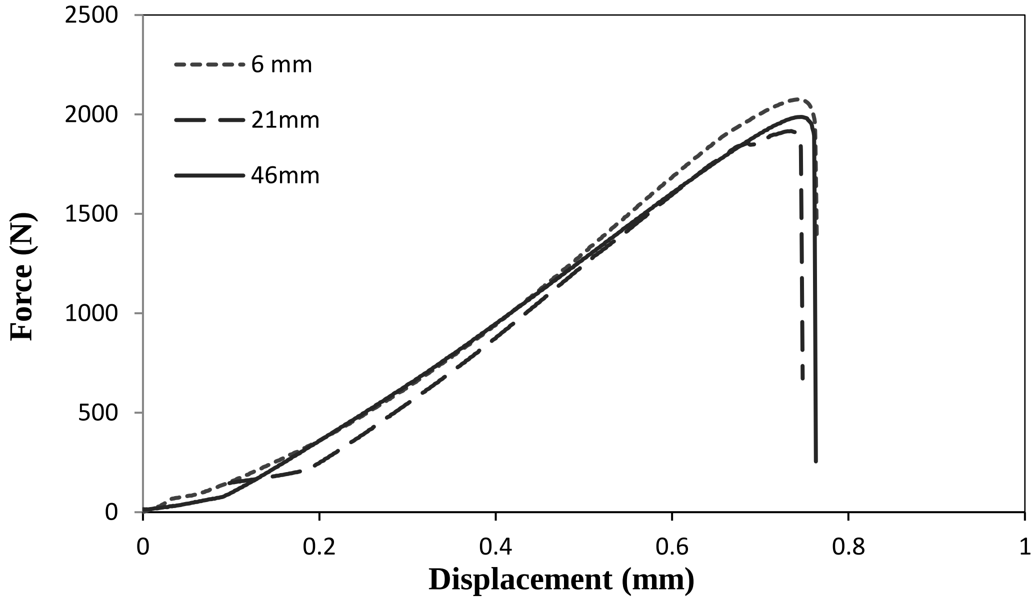

Figure 10. Force-displacement curves of the composite sandwich structures under flatwise tension (core thickness is 6 mm)

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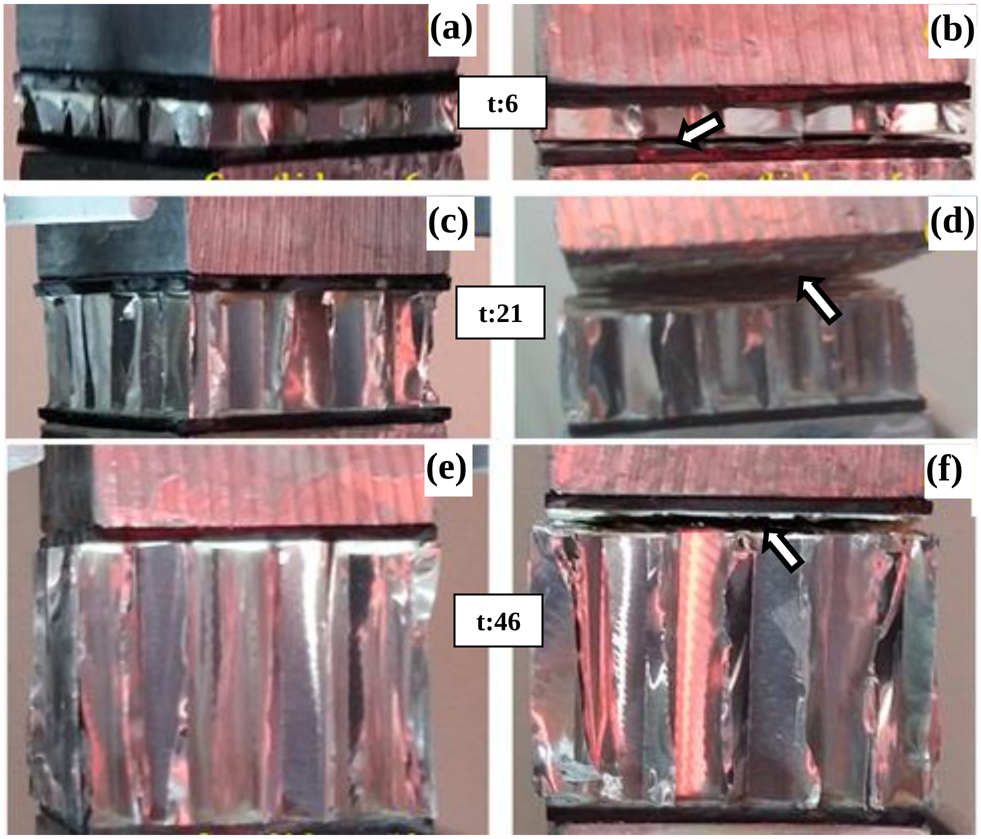

Figure 11. Images of flatwise tensile test specimen of the composite sandwich structures; before (a-c-e) and (b-d-f) after the tests (Interfacial failure region within the specimens are visible) (t : core thickness in mm)

Table 4. Summary of flatwise tensile test results for composite sandwich structures with various core thicknesses

Core thickness (mm)	Max. Force (N)	Ultimate Strength (MPa) (Mode I opening)
6	1943 ± 387	0.76 ± 0.15
21	1728 ± 370	0.67 ± 0.14
46	1510 ± 574	0.59 ± 0.22

Force-displacement curves of the sandwich specimens under edgewise compression are given in Figure 12. All of the specimens exhibit the similar behavior (pseudo-linear) up to certain deformation level and the buckling of the sandwich starts near to maximum force level. Failure mode was a combination of general buckling and interfacial de-bonding due to the shear at the interface between the core and the face sheet laminate. This collapse mode is known as 'sandwich panel column buckling' as also similarly described by Mamalis et al. [3].

It was observed that the load bearing capacity of the sandwich structures dramatically decreased after initial failure. A higher force level is required for propagation of the damage and this results with a high energy absorption of the structure [29]. Comparison of typical edgewise compressive behavior of the composite sandwich structures for various core thicknesses is shown in Figure 13.

For composite sandwich structures with various core thicknesses, the ultimate edgewise compressive strength and specific absorbed energy obtained from force-displacement curves were calculated and summarized in Table 5. It was found that the energy absorption capacity of the composite sandwich structures increasewith the increase of the core thickness.

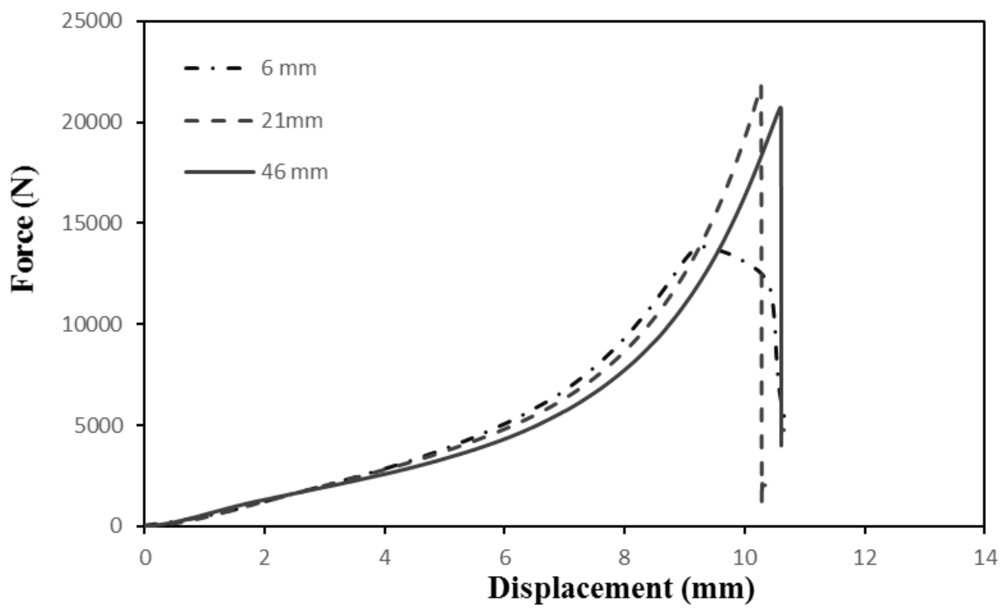

Figure 12. Comparison of typical edgewise compressive behavior of the composite sandwich structures for various core thicknesses

Table 5. The ultimate edgewise compressive strength and specific absorbed energy, $E_{s,a}$ of the composite sandwich structures with different core thickness

Core thickness of the sandwich composite (mm)	**Ultimate Compressive Strength (MPa)**	**Specific Absorbed Energy, $E_{s,a}$ (kJ/kg)**
6	37.8 ± 3.2	0.71 ± 0.1
21	67.8 ± 15.6	0.82 ± 0.1
46	72.2 ± 15.3	1.38 ± 0.4

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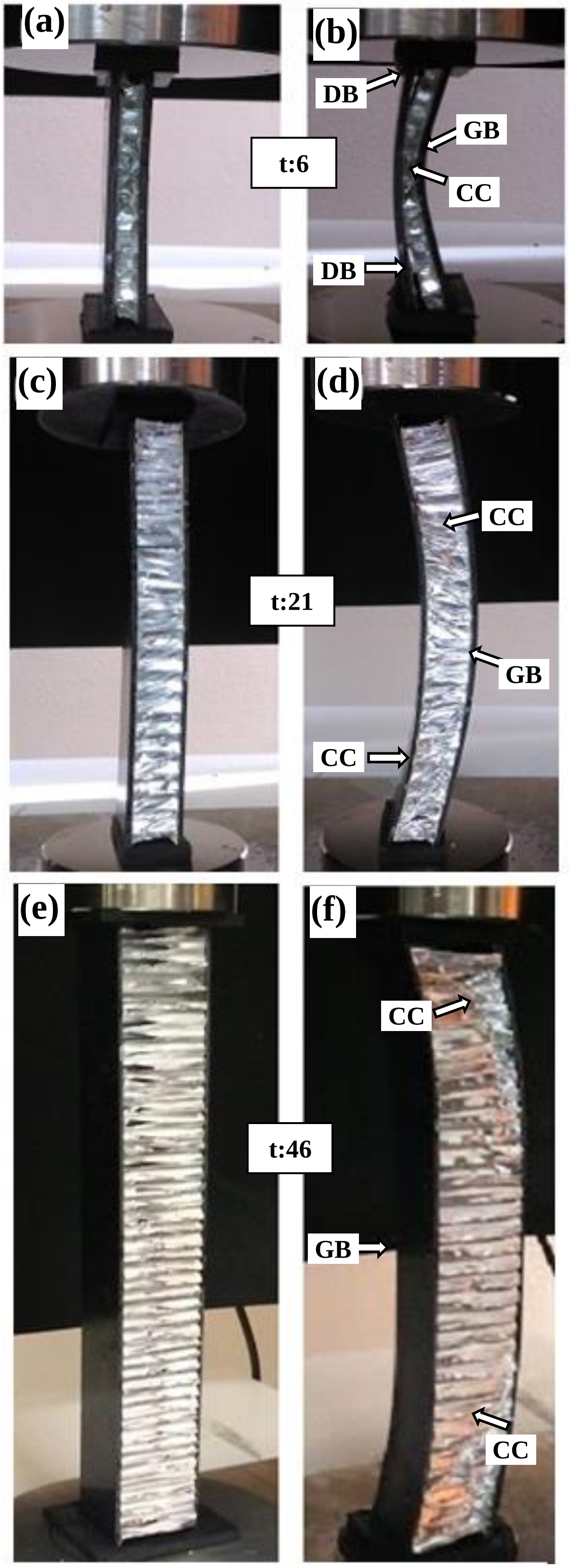

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Figure 13. Images of edgewise compression test specimens; before (a-c-e) and after (b-d-f) the tests (CC: core crushing, GB: global buckling, DB: debonding)

Figures 14 shows typical flexural bending force-displacement curves of the composite sandwich structures for various core thickness. It was observed that each sandwich structure has similar force-displacement curves and exhibit similar flexural behavior. However, the sandwich structure with 6 mm Al core exhibits relatively higher bending loads than those for other thicknesses. All of the specimens failed because of the inward local bending of the compression facing beneath the loading point, as shown in Figure 15. The failure progressed by crushing in the top facing and the core. The core's compressive strength and stiffness were inadequate to resist high local stresses; therefore, the local bending occurred [28]. Flexural cracks in the core were observed at the top of the sandwich beam but these cracks did not cause sudden failure. Final failure of the sandwich beam is due to compressive failure of the fiber composite skin followed by the debonding between the compressive skin and the core. This behavior is similar to the observation made by Manola et al. [30]. In their study, interface bond collapse occurred on sandwich structure once compressive failure was observed at the skin. There was also no visible failure of the bottom skin under tension [30]. Summary of the flexural test results of the composite sandwich structure is given in Table 6. The maximum core shear stresses and beam deflection decreased as the core thickness increases. On the other hand, it can be noted that the bending stiffness and panel shear rigidity increases while face sheet bending stress decreased with increasing core thickness.

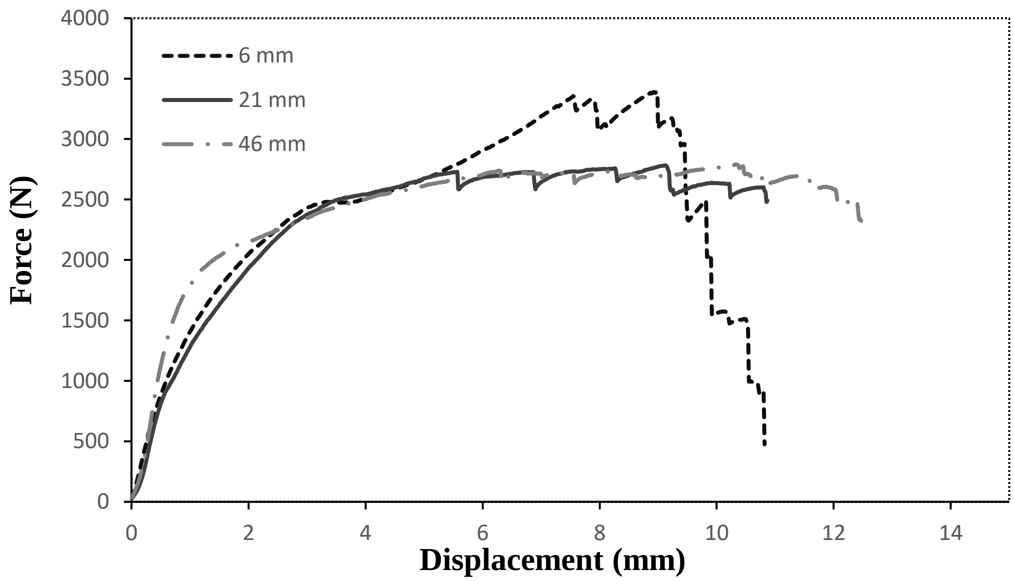

Figure 14. Comparison of typical flexural behavior of composite sandwich structures for various core thicknesses

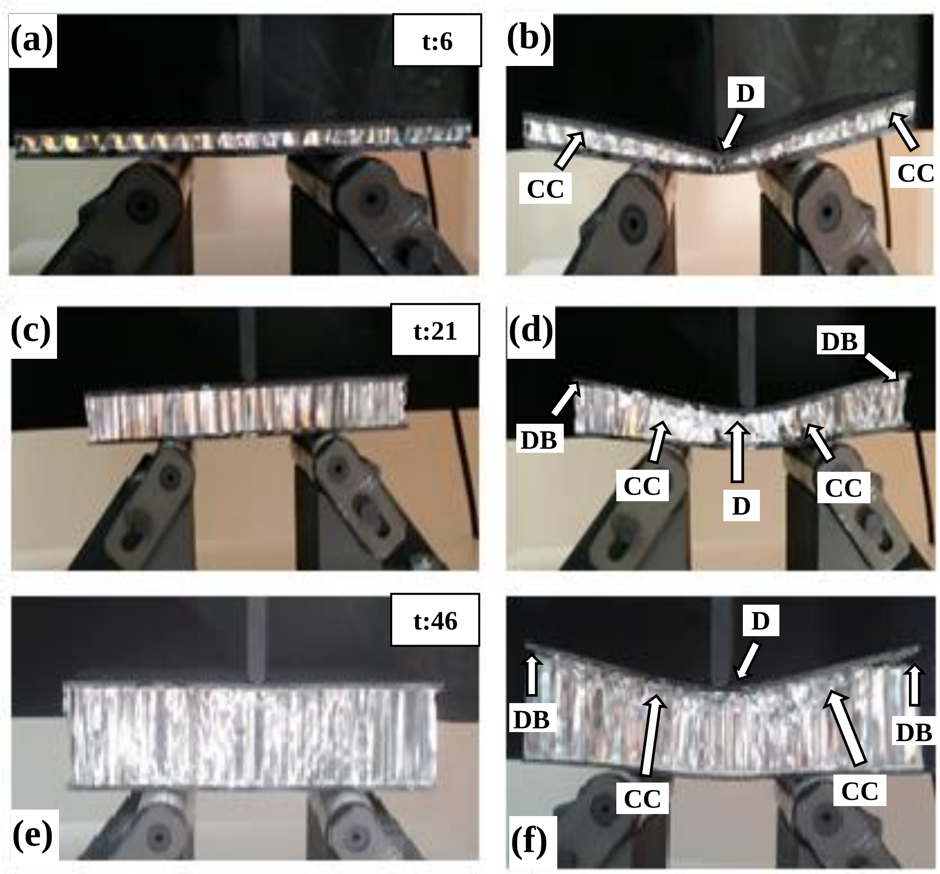

Figure 15. Images of flexural test specimens; before (a-c-e) and after (b-d-f) the tests (DB: debonding, CC: core crushing and D: delamination, t: core thickness in mm)

Table 6. Summary of the flexural test results of the composite sandwich structures

Core Thickness (mm)	Core Shear Stress (MPa)	Sandwich Beam Deflection (mm)	Panel Bending Stiffness ($Pa.m^4$)	Panel Shear Rigidity (N)	Face sheet Bending Stress (MPa)
6	2.85 ± 0.22	14.91 ± 1.26	361.2 ± 38.8	14078 ± 556	52.0 ± 4.4
21	0.84 ± 0.08	2.07 ± 0.14	5047.4 ± 112.2	78905 ± 2754	15.9 ± 0.9
46	0.45 ± 0.03	0.76 ± 0.04	35261.6 ± 670.5	210852 ± 2647	8.8 ± 0.2

Mode-I peel strength of the sandwich composites for various core thicknesses were measured as a function of the applied load and crack length. It was observed that the crack propagation was unstable resulting in sudden load drops. The average peel strength values were calculated for various core thicknesses,as summarized in Table 7. It was observed that there is no significant relation between the core thickness and applied force. As expected, peel strength value is not related with the honeycomb core and cell wall thickness increments. A relatively sudden and large crack propagation was observed. Images of the test specimens under Mode-I loading are shown in Figure 16. The fracture surfaces of face sheet and core were examined by Scanning Electron Microscope (SEM) (Figure 17). It was observed that adhesive failure at the Al core/composite face sheet interface was occurred. The spherical particles seen in the images are the filler material existing in the as-received adhesive. Adhesive layer failed due to applied tensile stress occured under Mode I loading. The smooth surfaces on the spherical fillers indicate a weak interface between filler and adhesive materials.

Table 7. Summary of Mode-I peel strength values

Core Thickness (mm)	Peel Strength (MPa)
6	1.15±0.26
21	1.12±0.48
46	1.69±0.93

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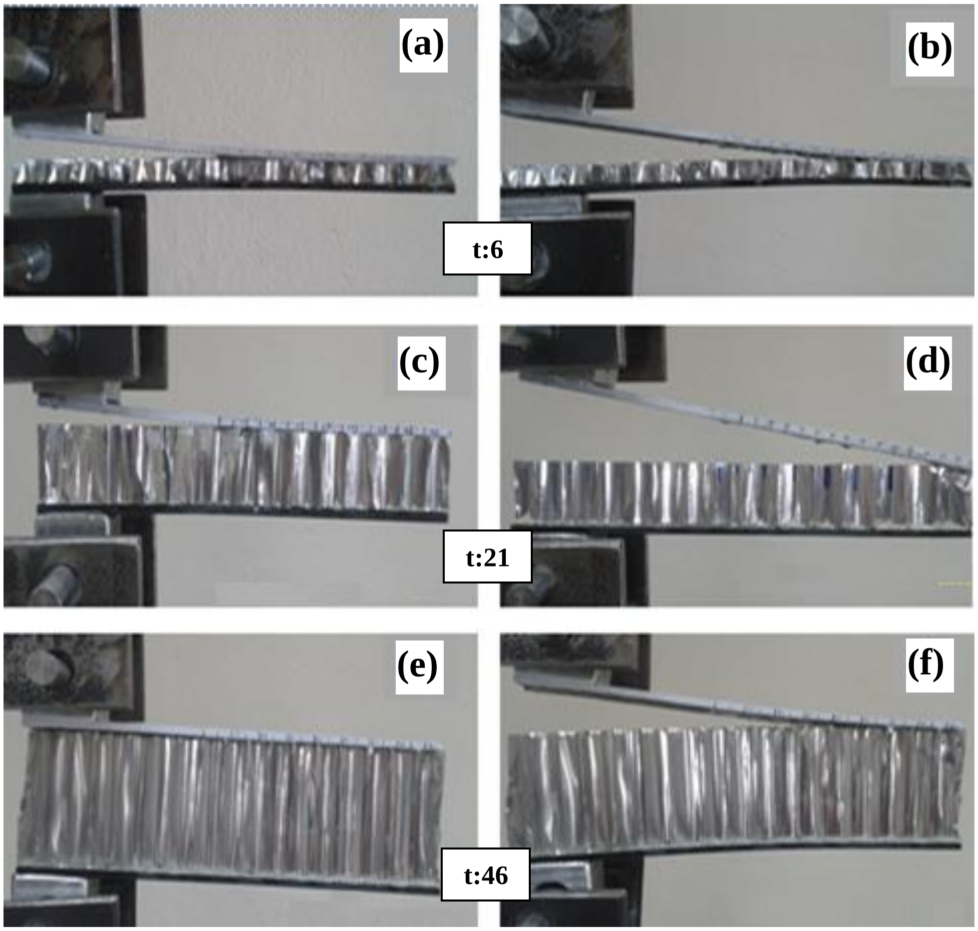

Figure 16. Mode-I Peel test specimens; at the beginning (a-c-e) and during (b-d-f) the tests. (t: core thickness in mm)

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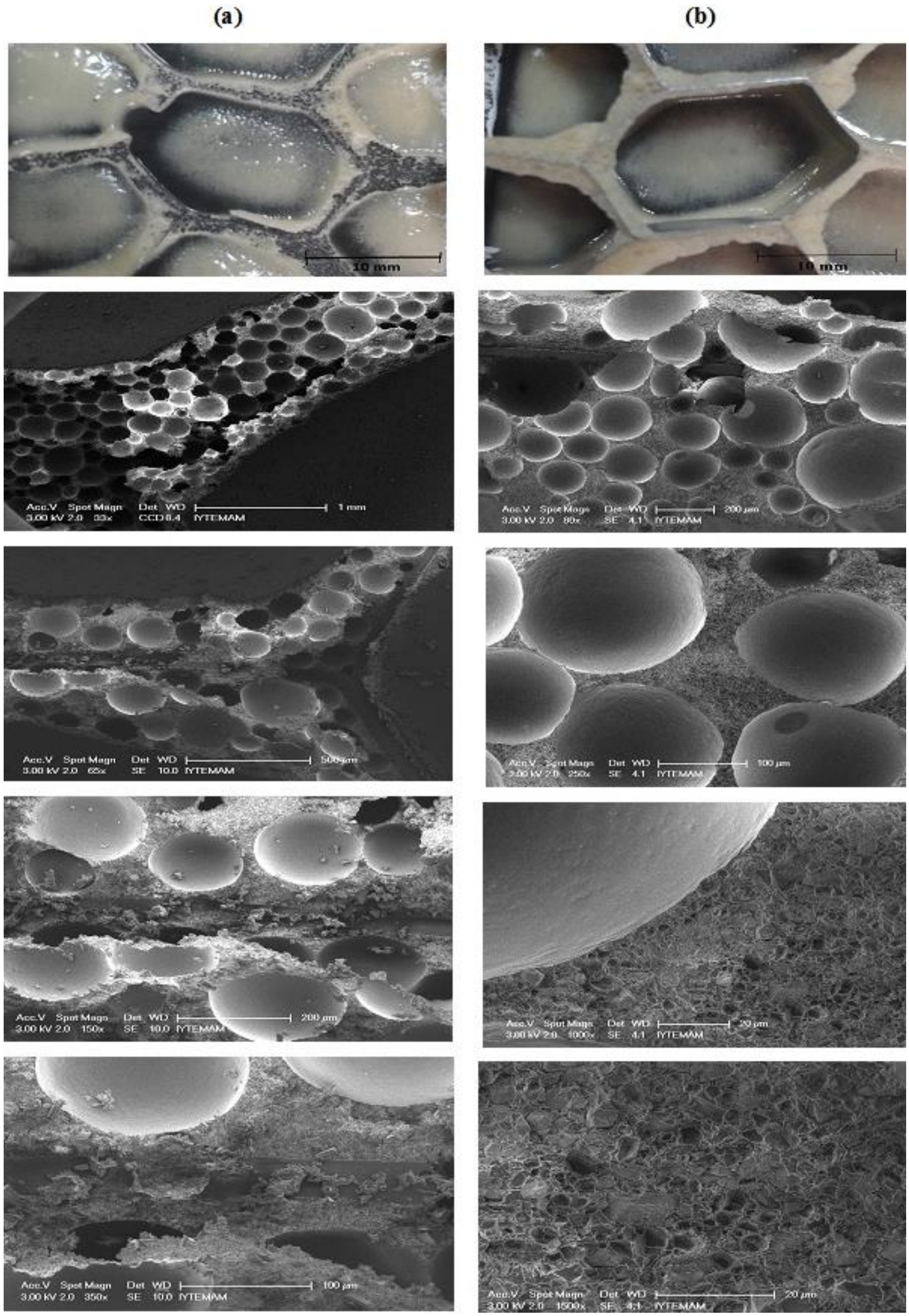

Figure 17. SEM fracture surfaces images of Mode-I test specimens; **(a)** the face sheet side, and **(b)** the core side of the specimen.

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4. Conclusions

In this study, composite sandwich structures composed of UD carbon fiber/epoxy face sheets and aluminum (Al) based honeycomb core were manufactured by vacuum infusion technique. Carbon fiber-epoxy/aluminum honeycomb sandwich structures were laminated by adhesion techniques with three different core thickness; 6, 21 and 46 mm to investigate the effects of core thickness on the mechanical properties of these structures. The mechanical behavior of the Al based honeycomb core material and carbon fiber/epoxy face sheets were also determined according to relevant ASTM test standards. The flatwise compression tests were carried out on the honeycomb core material. The results showed that the compressive strength and modulus of the core material increases with increasing thickness of the honeycomb. It was seen that honeycomb core cell walls buckled locally and densified with compression loading. For the sandwich structures, flatwise tensile, flatwise compression, edgewise compression, flexural and Mode-I peel tests were performed. It was observed that flatwise compression behavior and deformation of the composite sandwich structures with honeycomb core material are similar to those for Al core material itself. It was also observed that the face sheets had no significant effect on the flatwise compressive properties of sandwich structures. The sandwich structures failed in different modes depend on the core thickness; the core wall cells of the sandwich structures failed with buckling for relatively thinner cores, while the thicker cores failed with higher fraction of crushing under the same deformation. Energy absorption capacity increased with increasing core thickness of the composite sandwich structure due to the densification of the folded cell walls. During the edgewise compression tests, the face sheets of sandwich structure buckled, the interfacial debonding and core crushing was observed due to the shear at the interface between the core and the face sheet laminate. The failure combination was collapse mode called "sandwich panel column buckling". This collapse mode can be seen in thin structures which have lower crushing energy absorption. In thicker sandwich structures, the combination of global bending with core shear failure modes were observed and these sandwich structures contributed to the dissipation of the energy as well as higher average crushing load and compressive load uniformity. The complete failure occurred due to the core crushing followed by flexural cracking in the top face sheet. Although flexural cracks were observed at the top face of the sandwich beam, these cracks did not cause sudden failure due to the core crushing as in edgewise compression tests. Energy absorption capacity increased with core thickness increment. Final failure of the sandwich beam was due to compressive failure of the fiber composite skin followed by the debonding between the compressive skin and the core. As the core thickness increased, the amount of the core crushing and debonding at the interface increased. Three-point bending test results showed that core shear stress, sandwich beam deflection and face sheet bending stress decreased while the panel bending stiffness and shear rigidity increased with the core thickness increment. Mode-I peel and flatwise tensile test results were not affected with the core thickness, as expected.

In summary, the core thickness was found to be a critical parameter for the flatwise and edgewise compressive and flexural behaviors of the composite sandwich structures, although it has no effect to the bonding between the sandwich constituents.

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