Mechanical Properties of Metallic and Hybrid Polyurethane Foam Sandwich Composites

M. Atef Gabr, Ramadan El Gamsy,Mohamed HazemAbdelLatif

Abstract—Sandwich materials is one of the most commonly used in all applications due to lightness, durability and reliability with proper strength, toughness and rigidity. However, in recent times their use has increased significantly because of their widespread in structural applications which used in building systems. Structural sandwich panels generally used in Egypt comprise polyurethane foam core and high strength flat steel faces bonded together using separate adhesives by RIM technique. Previously, PU Foam core was sandwiched with same thin 2 faces material. In this work, the Metallic-PU and hybrid-PU sandwich composites were prepared by hand lay-up technique. Metallic-PU sandwich composites contained commercial purity Aluminum (Al) or Galvanized steel sheets (G.S) with different thicknesses as upper and lower facesheets with Commercial polyurethane (PU) foam (ρ = 45 Kg/m^3) in core with different thicknesses. Hybrid sandwich composites contained Aluminum/LDPE composite sheets (Al-c) or fiberglass/polyester composite sheets as upper facesheet and galvanized steel sheets as lower facesheet with PU foam in core with different thicknesses. These modifications lead to enhancing the mechanical properties of polyurethane sandwich panels with limited increase of sandwich panel weight. the Compression & 3-point bending tests were carried out on different sandwich composites. Specific bending flexural strength was calculated for different sandwich composites and the effect of changing the facesheet material, thicknesses and PU foam core thickness on the mechanical behavior of PU sandwich composites were studied.

Keywords—— Hybrid Sandwich Panel, Mechanical Behavior, PU Foam, Sandwich Panel, 3-point bending, Bending Flexural strength, specific bending flexural strength, failure patterns.

1 INTRODUCTION

Composite sandwich structure is widely used in aerospace, marine applications, prefabricated structure and cold trucks where there is need for lightweight structures with high flexural stiffness. The basic concept of these structures is the separation of relatively stiff, strong and thin facesheets by a lightweight and thicker flexible core. The overall performance of sandwich composites depends on the material properties of the constituents (facesheets, adhesive and core), geometric dimensions and types of loading and the modified sandwich plate designs introduce ductile interlayers, such as polyurethane or hard rubber, as well as elastomeric foam, inserted and bonded between the exposed outer face sheet and the core. These can reduce the risk of delamination cracking in different ways. Under a given contact force, the stiff polyurethane or PUR interlayer limits deflection of the outer face sheet, and it also helps to shieldthe structural foam core from crushing, by absorbing a part of the facesheet deflection[1].

There are a lot of types of sandwich panel structure preparation techniques such as vacuum bagging technique[2, 3] and Vacuum assisted resin transfer molding (VARTM)[4-6] and hand lay-up technique. Each technique has its advantages and disadvantages but hand lay-up technique is the recommended technique used in research scale due to its simplicity andpromptness[7, 8] . HoweverReactioninjectionmolding technique(RIM)is moresuitableformassproductionuse [9].

Previousworkhasbeenorientedtomeasuretheeffectofchanging in corewithmultipletypesof materialsandallpreviousscopes [2-12]that have explained mechanicalbehaviorofvarioustypes ofcore such as polyurethane foam or p.v.c foam or metallic foam or honeycomb with differences in its densities or thicknesses with the same material of both facesheetslaminates.

This paper is oriented into 2 main categories, the first category called Metallic-PU sandwich composites which uses galvanized steel sheets and commercial purity aluminum sheets as facesheets with commercial polyurethane foam in core and the second category called Hybrid-PU sandwich composites when using galvanized steel sheets as a lower facesheet however using fiberglass/polyester composite sheets or Aluminum composite sheets as upper facesheets with commercial polyurethane foam in core as shown in Figure 1 and also providesoverallviewfor themechanicalbehaviorof mentioned sandwich compositesto improveitsmechanicalpropertieswith higher compactnessinsizetosatisfy manufacturers andcustomer needs.

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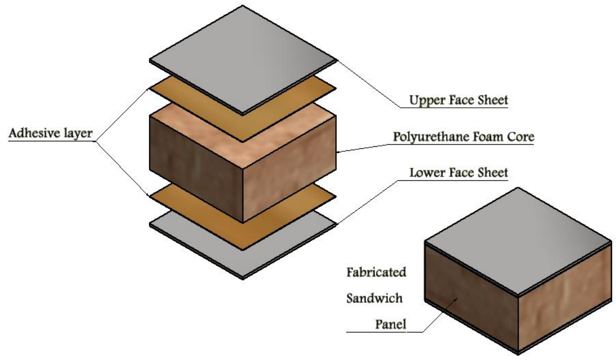

Figure 1 Polyurethane sandwich composite

2 EXPERIMENTAL WORK

2.1 Materials

In this work 6 different materials were used:

2.1.1 Commercial Polyurethane (PU) foam sheets 10,20&30 mm thickness with density = 45 kg/m^3 were supplied byCairo foam factory.

2.1.2 Galvanized steel sheets (G.S) 0.5,1&2 mm thickness supplied by local market with chemical composition as shown in Table 1.

Table 1 chemical compositions of galvanized steel sheet

	Chemical Composition						
G.S	C%	Si%	Mn%	P%	S%	Cr%	Mo%
	0.0402	0.0087	0.1691	0.0234	0.004	0.0123	0.005
	Co%	Cu%	Nb%	Ti%	V%	W%	Pb%
	0.01	0.0055	0.0021	0.001	0.0277	0.01	0.005
	Zn%	Sn%	Al%	Sb%	Ni%	Fe%	
	0.001	0.0025	0.0194	0.005	0.0664	99.61	

2.1.3 Commercial purity Aluminum sheets (Al) 0.5,1&2 mm thickness supplied by local market with chemical composition shown in Table 2.

Table 2 chemical composition of aluminum sheet

	Chemical Composition						
Aluminum	Si%	Fe%	Cu%	Mn%	Mg%	Zn%	Ni%
	0.0499	0.3436	0.0005	0.0029	0.002	0.0191	0.0579
	Sn%	Ti%	Sb%	V%	Co%	Cr%	Pb%
	0.0005	0.0115	0.0005	0.0473	0.0003	0.002	0.001
	Al%						
	99.46						

2.1.4 Fiberglass sheets (F.G) 3mm thickness with crossed fiber oriented containing 4 layers of fiberglass with polyester resinwere supplied by Cairo foam factory.

2.1.5 Aluminum composite sheets (Al-C) 3 mm thickness containing LDPE 2.2 mm thickness sandwiched with 0.4 mm sheet thickness commercial purity aluminum were supplied by Almaxco Company.

2.1.6 Two components Polyurethane adhesive ADEKIT P 4302 POLYOL and P 4004 ISOCYANATE were supplied by Axson technologies company.

2.2 Preparation of specimens

3-pt bending test specimens were prepared according to ASTM C-393.
Hand layup technique was used in this research as follows:

1- PU Foam sheetswerecarefullycutandvisually inspectedtoensure thatthePUfoamisfreeofbubblesand damages.
2- Face sheets must be free of dust, rust, oil and water.
3- Face sheets were cut into pieces by using shearing machine.
4- Two components Polyurethane adhesive were prepared by mixing them with certain quantities. handling time and curing according to manufacturer instructions
5- Adhesive was uniformly spread on facesheets.
6- Sandwich composite was constructed by adhering faces on foam core
7- Polyurethane foam was compressed on both face sheets by using roller to let the excess adhesive material extract and, to assure that no bubbles were formed.
8- Sandwich composite was cured under 10 kg static load for 24 hours.

2.3 Different structures of Metallic and Hybrid PU sandwich composites

PU foam with 10, 20, 30 mm thickness was sandwiched with different upper and lower face sheets. The used lower face sheet was 0.5, 1, 2 mm galvanized steel. While, the upper face sheets were 0.5, 1, 2 mm galvanized steel & 0.5, 1, 2 mm Aluminum & 3 mm F.G & 3 mm Aluminum-rubber composite as shown in Figure 2,3,4&5 .

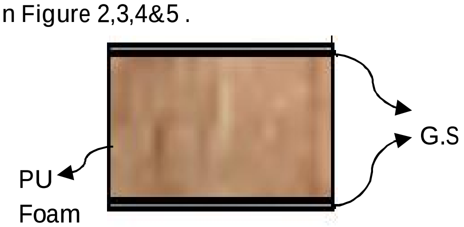

Figure 2 G.S sandwich panel (Metallic-PU sandwich composite)

Figure 3 Al sandwich panel (Metallic-PU sandwich composite)

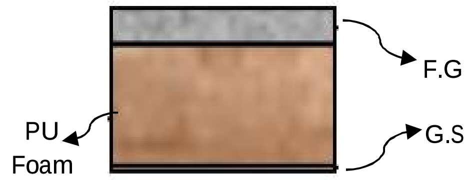

Figure 4 F.G sandwich panel (Hybrid-PU sandwich composite)

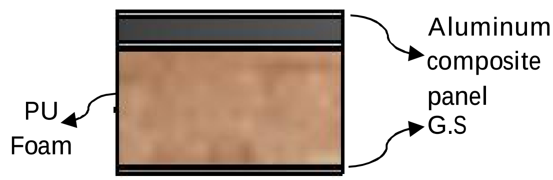

Figure 5 Al-C sandwich panel (Hybrid-PU sandwich composite)

Designation of specimens:

XX	(Th.)	C	(Th.)	ZZ	(Th.)
Type of Lower face sheet material	Thickness of Lower face sheet	Type of Core material	Thickness of Core	Type of Upper face sheet material	Thickness of Upper face sheet

3 TESTING

3.1 Three-point bending test

3-point bending testswere carried out on WDW 10 KN Universal testing machine. The tested samples were carefully placed between the three bending rollers as shown inFigure 6according to ASTM C393.

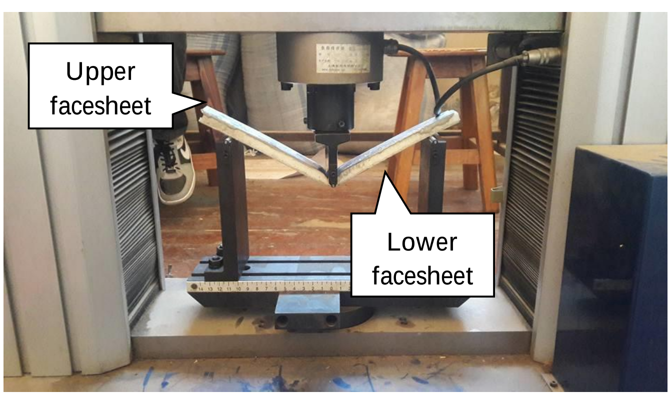

Figure 6 three point bending test for test specimen using Universal Testing Machine

Bending stress was calculated by using the following formula (1):

$$\sigma = \frac{3PL}{2bh^2}$$

Where:
σ: Bending strength (MPa)
P: Load at Mid span (N)
L: Span Length (mm)
b: Width of the specimen (mm)
h: Thickness of the specimen (mm)

3.2 Compression test

Compression tests of sandwich composites specimens were carried out on WDW 10KN Universal testing machine as shown in Figure 7 according to ASTM D1621.

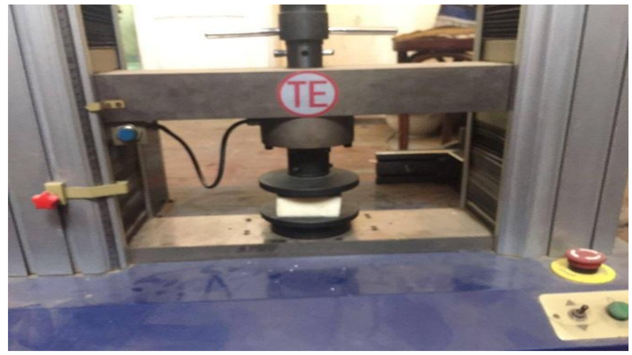

Figure 7 compression test for test specimen using Universal Testing Machine

3.3 Weight Measurement

The weight of sandwich composites specimens was measured by Digital Sensitive Balance Adam Company having an accuracy of 0.01 gm.

3.4 Density Measurement

The density of the sandwich composites specimens was measured according to ASTM C271.

4 RESULTS AND DISCUSSION

4.1 Effect of preparation techniques on the bending flexural behavior of G.S- PU sandwich composites:

Tested specimens were prepared using two different techniques: hand layup and vacuum bagging technique and tested in 3-point bending. Slight difference in load displacement curve was found as shown in Figure 8.

Hence hand lay-up technique is recommended due to its simplicity in preparation and its low cost and setting time compared to vacuum bagging technique.

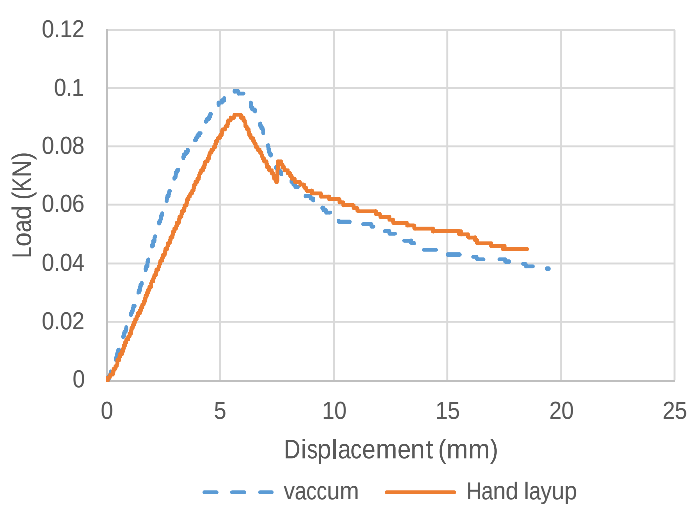

Figure 8 flexural strength for same test specimen prepared by 2 different preparation techniques

4.2 Bending behavior for Metallic and hybrid PU sandwich composites

Sandwich composites having galvanized steel as lower facesheets of 0.5 mm thickness ,10 mm PU core thickness and different upper facesheet materials as shown in Figure 2,3,4&5were tested in 3-pt bending.

The load displacement curve showed a typical behavior in which the load increases up to the maximum value, beyond which it gradually decreased. This is shown in Figure 9 for upper facesheet of galvanized steel, in Figure 10 for an upper facesheet of Aluminum and in Figure 11 for an upper facesheet of Aluminum composite. When the fiber/polyester composite was used as the upper facesheet, the drop from the maximum bending load was abrupt due to the lower ductility of the composite as shown in Figure 12.

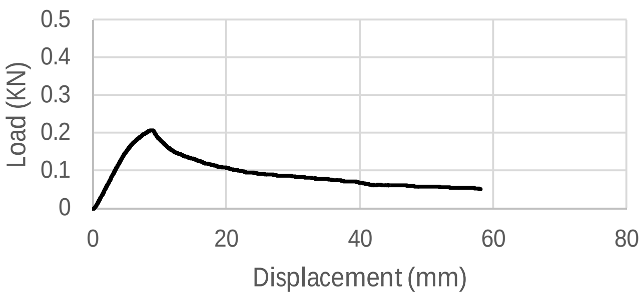

Figure 9 Typical 3-pt Bending test for G.S-PU sandwich composite

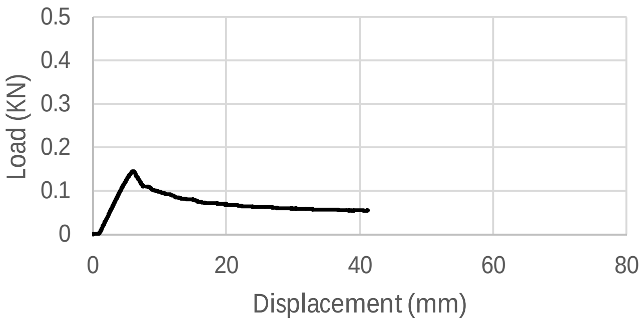

Figure 10 Typical 3-pt Bending test for Al-PU sandwich material

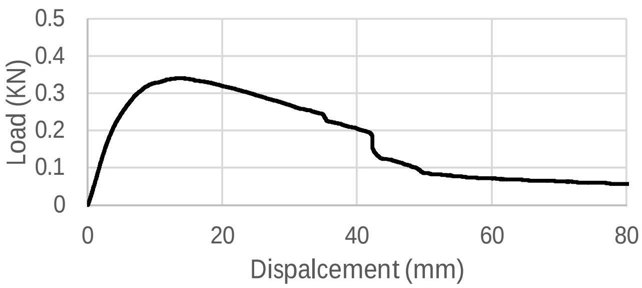

Figure 11 Typical 3-pt Bending test for Al composite sandwich

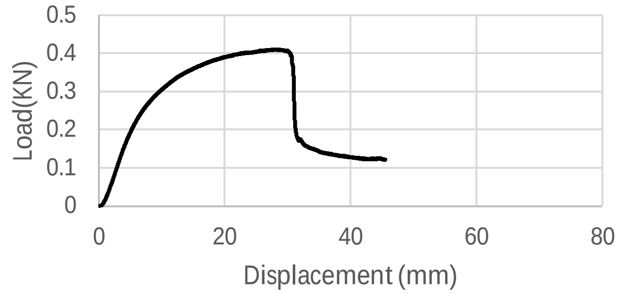

Figure 12Typical 3-pt Bending test for F.G sandwich material

4.3 Effect of changing upper face sheet materials on specific bending flexural strength of PU sandwich composites.

4.3.1 Metallic-PU sandwich composites

When 10 mm PU foam core sandwiched with 0.5 mm thickness galvanized steel sheet as lower facesheet and 0.5 mm galvanized steel sheet or commercial purity aluminum sheet as upper facesheet, bending flexural strength was calculated as mentioned in eq. (1) and given in

Table 3 and plotted in Figure 13.

Since the weight is important factor in utilizing the sandwich composites in several engineering applications, the specific bending flexural strength was calculated using the following equation and given in

Table 3 and plotted in Figure 14.

$$Specfic\ bending\ flexural\ strength\ (kN.m/kg) = \frac{max.\ bending\ strength\ at\ midspan\ (Mpa)}{density\ \left(\frac{Kg}{m^3}\right)} * 1000$$

Table 3Specific Bending flexural strength of Metallic-PU sandwich composite with different facesheet material

Specimen	Bending flexural strength (Mpa)	Density (kg/m³)	Specific Bending flexural strength (KN.m/kg)
G.S (0.5) C (10) G.S(0.5)	14.167	714	19.85
G.s (0.5) C (10) Al (0.5)	9.535	595	16.03

As depicted from Figure 13 when changing upper facesheet material from Al to G.S, bending flexural strength of Metallic-PU sandwich composite increased from 9.535 to 14.167 MPa by 48.6%.

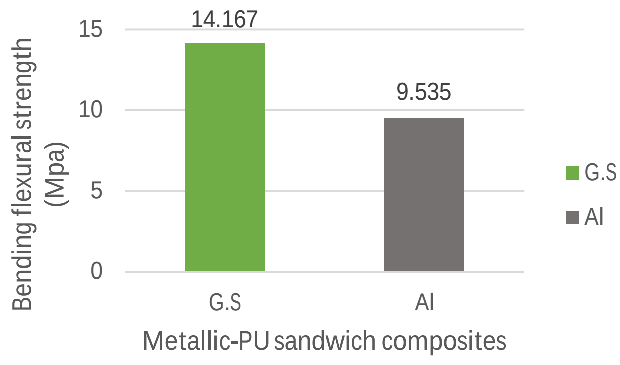

Figure 13 Bending flexural strength of Metallic-PU sandwich composite

As shown Figure 14 , G.S-PU sandwich composite exhibited superior specific flexural bending strength compared with Al-PU sandwich composite which increased from 16.03 to 19.85 kN.m/kg by 23.83%.

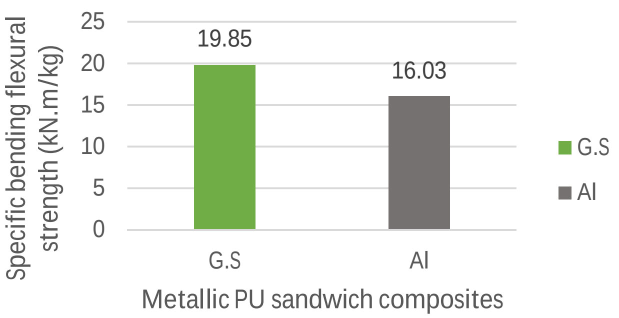

Figure 14specific bending flexural strength of Metallic-PU sandwich composite

4.3.2 Hybrid-PU sandwich composites

Hybrid-PU sandwich composites generally consist of several layers from different materials. The used materials contained 0.5 mm galvanized steel as a lower facesheet, 10 mm PU core and fiberglass/polyester composite sheet or Aluminum/LDPE composite sheet as an upper facesheet.

The Bending flexural strength was calculated and given in Table 4 and plotted in Figure 15.

Table 4Specific Bending flexural strength of Hybrid sandwich composites with different facesheet material

Specimen	Bending flexural strength (Mpa)	Density (kg/m³)	Specific bending flexural strength (KN.m/kg)
G.s (0.5) C (10) F.G (3)	17.75	587	30.24
G.S (0.5) C (10) Al-C (3)	18.57	563	32.99

As depicted from Figure 15 when changing upper facesheet material from F.G/polyester to Al/LDPE composite sheet, bending flexural strength of Hybrid-PU sandwich composite increased from 17.75 to 18.57 Mpa by 4.6%. However, specific bending flexural strength of Hybid-PU sandwich composite increased from 30.24 to 32.99 kN.m/kg by 9% as shown in Figure 16.

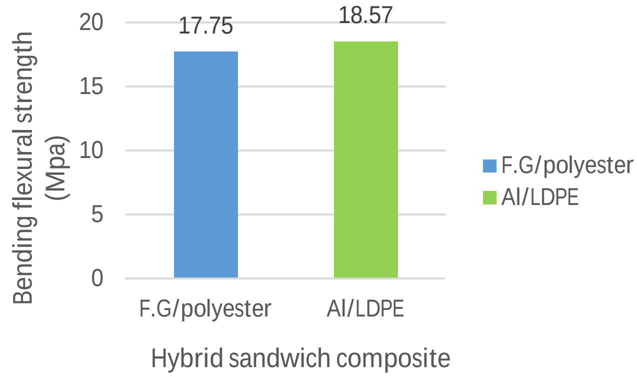

Figure 15 bending flexural strength of Hybrid sandwich composite

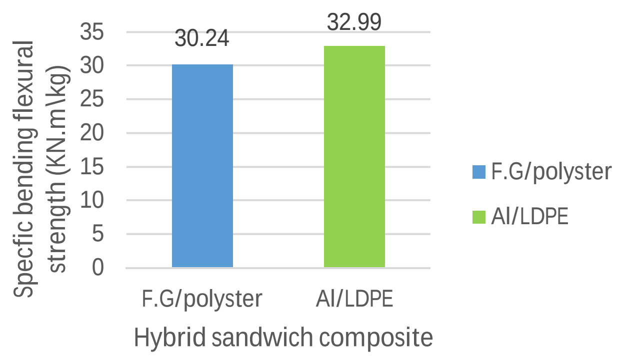

Figure 16 specific Bending flexural strength for Hybrid sandwich composite

4.4 Effect of changing face sheet thickness on flexural bending behavior of Metallic-PU sandwich composite

4.4.1 G.S-PU sandwich composites

As depicted from Figure 17, Metallic-PU sandwich composites having 2 mm thickness of galvanized steel sheets as a lower and upper facesheets showed a superior bending flexural behavior to those 0.5 and 1 mm sheet thickness. When increasing galvanized steel facesheet from 0.5 to 1 mm, stiffness of G.S-PU sandwich composite increased from 11.1 to 17.63 N/mm by 58.8%. However, increasing the facesheet thickness from 0.5 to 2 mm, resulted in considerable increase in the composite stiffness from 11.1 to 37.46 N/mm by 237.5% making it attractive for several engineering applications.

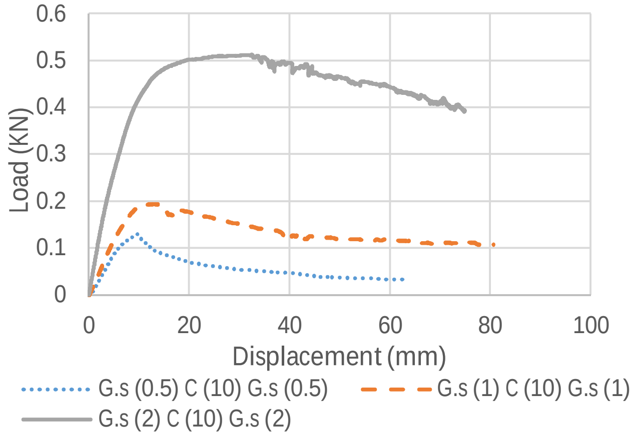

Figure 17 Typical 3-pt bending test for three different samples galvanized steel material with PU core 10 mm using different facesheet thickness

It is worth noting that increasing facesheet thickness was accompanied with increasing in Bending flexural strength. When increasing G.S facesheet thickness from 0.5 to 1 mm, bending flexural strength ofG.S-PU sandwich composite from increased 14.167 to 16.74 Mpa by 18.2 %. However, increasing G.S facesheet thickness from 0.5 to 2 mm, bending flexural strength of G.S-PU sandwich composite increased 14.167 to 26.64 Mpa by 88% as shown in Figure 18. On the other hand, specific bending flexural strength decreases when facesheet thickness increases due to the rise in overall density of the sandwich composite.

As depicted from Figure 19 and Table 5 when facesheet thickness increased from 0.5 mm to 1 mm, specific bending flexural strength of G.S-PU sandwich composite decreased from 19.85 to 14.81 kN.m/kg by 25.4 %. However, increasing facesheet thickness from 0.5 to 2 mm,specific bending flexural strength of G.S-PU sandwich composite decreased from 19.85 to 13.28 kN.m/kg by 33%.

Table 5Specific Bending flexural strength of G.S-PU sandwich composites with different facesheet thickness

Specimen	Bending flexural strength (Mpa)	Density (kg/m³)	Specific bending flexural strength (kN.m/kg)
G.s(0.5) C (10)G.s(0.5)	14.167	714	19.85
G.s(1) C (10)G.s(1)	16.74	1131	14.81
G.s(2) C (10)G.s(2)	26.64	2007	13.28

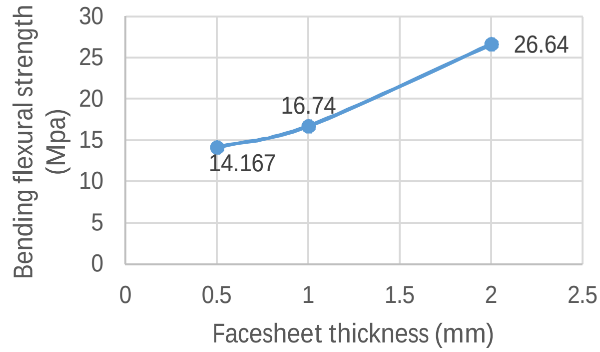

Figure 18 Effect of G.S facesheet thickness on Bending flexural strength of G.S-PU sandwich composite

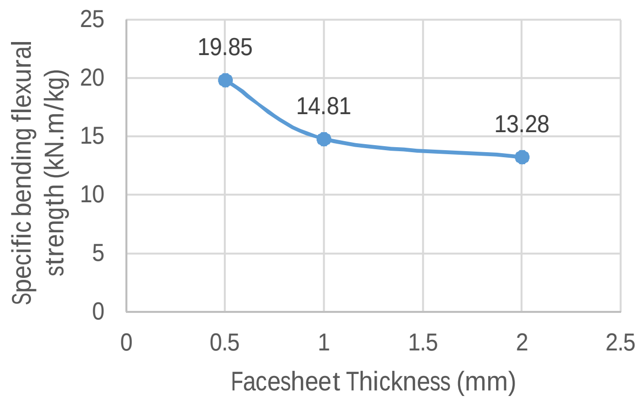

Figure 19 Effect of changing galvanized steel facesheet material thickness on specific bending flexural strengthof G.S-PU sandwich composite

4.4.2 Al-PU sandwich composites

Bending flexural behavior of Al-PU sandwich composite has similar performance as G.S-PU sandwich composite as shown before in Figure 17.

When increasing aluminum facesheet thickness from 0.5 mm to 1 mm, bending flexural strength of Al-PU sandwich composite increased from 9.535 to 13.5 Mpa by 41.6% however increasing Al facesheet thickness from 0.5 mm to 2 mm, bending flexural strength of Al-PU sandwich composite increased from 9.535 to 20.52 Mpa by 115% as shown in Figure 20 which given in Table 6.

Table 6Specific Bending flexural strength of Al-PU sandwich composites with different facesheet thickness

Specimen	Bending flexural strength (Mpa)	Density (kg/m³)	Specific bending flexural strength (kN.m/kg)
G.s(0.5) C (10)Al(0.5)	9.535	595	16.03
G.s(1) C (10)Al(1)	13.5	879	15.36
G.s(2) C (10)Al(2)	20.52	1396	14.7

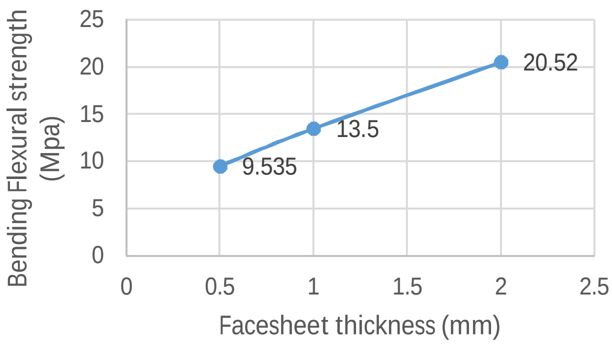

Figure 20 effect of Aluminum facesheet thickness on bending flexural strength of Al-PU sandwich composite

As depicted from Figure 21,specific bending flexural strength has slightly decreased with increasing aluminum facesheet thickness, when increasing aluminum facesheet thickness from 0.5 to 1 mm,specific bending flexural strength of Al-PU sandwich composite decreased from 16.03 to 15.36 kN.m/kg by 4 % however increasing from 0.5 to 2 mm, specific bending flexural strength of Al-PU sandwich composite decreased from 16.03 to 14.7 kN.m/kg by 8%.

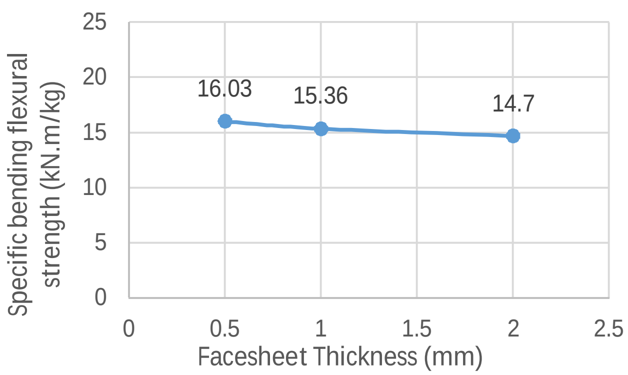

Figure 21 Effect of changing Aluminum facesheet material thickness on specific bending flexural strength of Al-PU sandwich composite

4.5 Effect of changing polyurethane core thickness on specific bending flexural strength of G.S-PU sandwich composites

Increasing core thickness in sandwich composite is important parameter which affects in sandwich composite strength. Thus, G.S-PU sandwich composites are developed to illustrate the relation between bending flexural strength & specific bending flexural strength w.r.t PU foam core thickness as shown in Figure 22,23.

G.S-PU sandwich composites consist of 0.5 mm facesheet thickness on upper & lower facesheets with different polyurethane foam core thickness 10, 20 and 30 mm. Bending flexural strength & specific bending flexural strength were shown in Table 7.

Bending flexural strength of G.S-PU sandwich composites decreased significantly with increasing PU foam core thickness due to increasing span length together with the increase in specimen length according to ASTM C393.

When increasing PU foam core thickness from 10 to 20 mm, bending flexural strength of G.S-PU sandwich composite decreased from14.167 to 9 Mpa by 36.5%. However, PU foam core thickness increased from 10 to 30 mm, bending flexural strength of G.S-PU sandwich composite decreased from 14.167 to 7.2 Mpa by 49% as shown in Figure 22.

Table 7Specific Bending flexural strength of G.S-PU sandwich composites with different core thickness

Specimen	Bending flexural strength (Mpa)	Density (kg/m^3)	Specific bending flexural strength (kN.m/kg)
G.s(0.5) C (10)G.s(0.5)	14.167	714	19.85
G.s(0.5) C (20)G.s(0.5)	9	451	19.96
G.s(0.5) C (30)G.s(0.5)	7.2	350	20.58

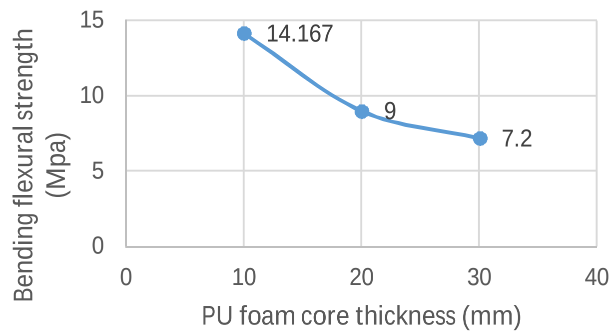

Figure 22 Effect of PU foam core thickness on bending flexural strength of G.S-PU sandwich composites

Although bending flexural strength has decreased with increasing core thickness but the density of sandwich composite has also decreased with increasing PU foam core thickness thus resulting in slight increase in specific bending flexural strength with PU foam core thickness as shown from Figure 23.

As depicted from Figure 23 when PU core thickness 10 to 20 mm, specific bending flexural strength of G.S-PU sandwich composite increased from 19.85 to 19.96 kN.m/kg by 0.6%. However, PU core thickness 10 to 30 mm, specific bending flexural strength of G.S-PU sandwich composite increased from 19.85 to 20.58 kN.m/kg by 3.7%.

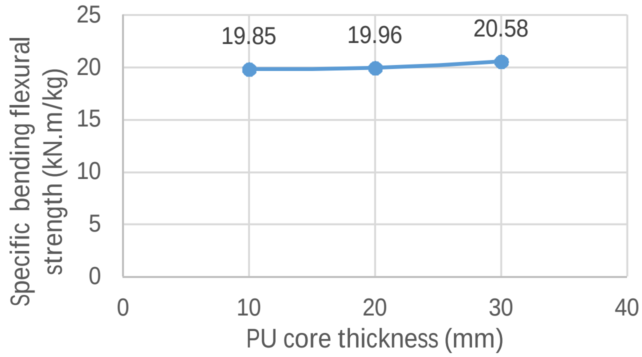

Figure 23 Effect of PU foam core thickness on specific bending flexural strength of G.S-PU sandwich composites

4.6 Compressive behavior of G.S-PU foam sandwich composite

G.S-PU sandwich composites exhibited superior compressive behavior w.r.t PU foam without facesheets as depicted from load displacement curves in compression shown in Figure 24.

It is worth noting that changing the facesheet material had a negligible effect on the compressive behavior of the sandwich composites as shown in Figure 25 when using 0.5 mm galvanized steel sheet as a lower facesheet, 30 mm PU foam core and 0.5 mm galvanized steel sheet or Aluminum sheet as an upper facesheet.

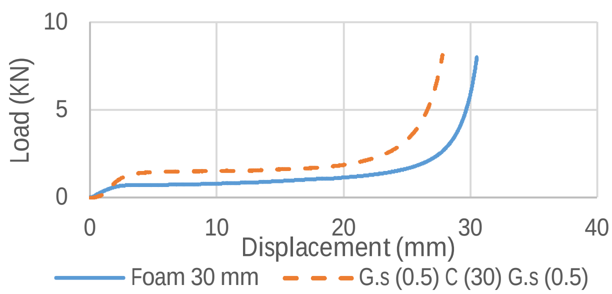

Figure 24 Typical compression test on PU foam and G.S-PU foam sandwich composite.

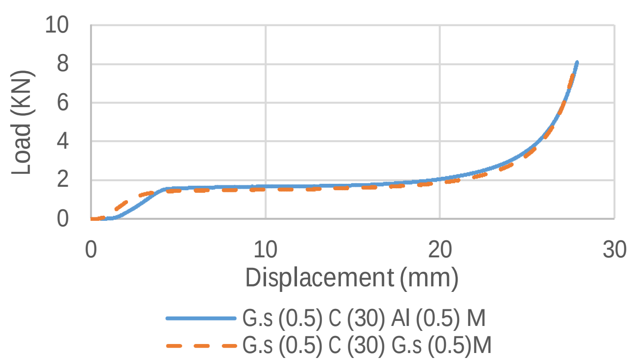

Figure 25 Typical compression test on different types of PU sandwich composite.

4.7 Cases of failures and proposed solutions

Throughout our research work, the sandwich composites exhibited several failure patterns as shown in the following figures:

4.7.1 Failure pattern I

A localized deformation in the mid span of bending samples as shown in Figure 26 came probably from using a small diameter roller support or high test speed or both.

Figure 26 failure pattern in G.S(0.5) C(10) G.S(0.5)

When decreasing the rate of the bending test from 5mm/min to 1mm/min, the localized deformation of the specimen disappeared from specimen after the test as shown in Figure 27.

Figure 27 successful failure pattern after localized deformation elimination for G.S (0.5) C (10) G.S (0.5)

4.7.2 Failure pattern II

Failure in mid span of bending samples as shown in Figure 28The failure started as a crack in fiberglass sheet followed with crack in PUfoamcore.

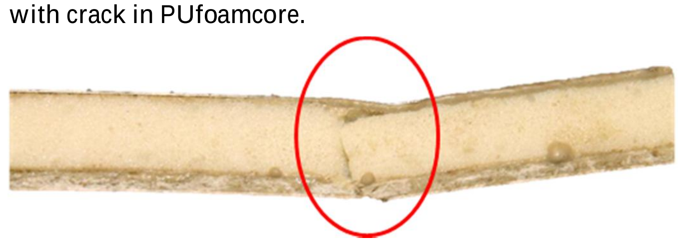

Figure 28 failure pattern in G.S (0.5)C(10)F.G(3)

4.7.3 Failure pattern III

A delamination at upper and lower face sheet as shown in Figure 29The delamination comes from poor distribution of glue on the face sheets especially on the edges and occurs when using insufficient static load during curing.

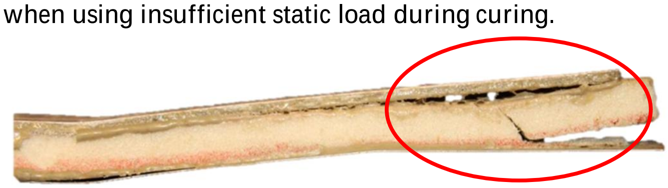

Figure 29 failure pattern in G.S(0.5) C (10) F.G(3)

4.7.4 Failure pattern IV

There are two different failure modes as shown in Figure 30 . Firstly, in zone 1 a crack in PU core caused by air bubbles in PU foam, second as in zone 2 a delamination which comes from poor bonding between facesheet and core.

Figure 30 failure pattern in G.S(0.5) C (10) Al-c (3)

5 Conclusion

5.1 Hand lay-up is the simplest method to prepare a sandwich sheet.

5.2 In the Metallic-PU sandwich composites, for the same thickness, the specific bending flexural strength is increased by 23.83% when changing the upper face sheet from Al to GS.

5.3 In the hybrid sandwich composites, for the same thickness, specific bending flexural strength of Al/LDPE-PU sandwich composite increased by 9% w.r.t F.G/polyester-PU sandwich composite.

5.4 For the same upper and lower facesheet material in the Metallic-PU sandwich composites, as the facesheet thickness increases the bending flexural strength increases. However, the specific bending flexural strength decreases due to the increase in the density of the sandwich composites.

5.5 For the same facesheet material and thickness in Metallic-PU sandwich composites, as the thickness of PU foam core increases the bending flexural strength decreases due to increase of the span length w.r.t. the sandwich thickness. However, the specific bending flexural strength exhibits slight increase.

5.6 Increasing core thickness leads to a slight increase in specific strength of sandwich due to the decreases in the density of the sandwich composites.

5.7 Changing facesheet materials and thicknesses has a limited effect on compression strength of sandwich composites.

5.8 Decreasing testing speed will lead to elimination of localized deformation.

5.9 Inhomogeneous distribution of the polyurethane adhesive will lead to the delamination of facesheets from the PU core.

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