Hindawi
International Journal of Polymer Science
Volume 2021, Article ID 8855952, 10 pages
https://doi.org/10.1155/2021/8855952

Research Article

Experimental Investigation on the Mechanical Properties of a Sandwich Structure Made of Flax/Glass Hybrid Composite Facesheet and Honeycomb Core

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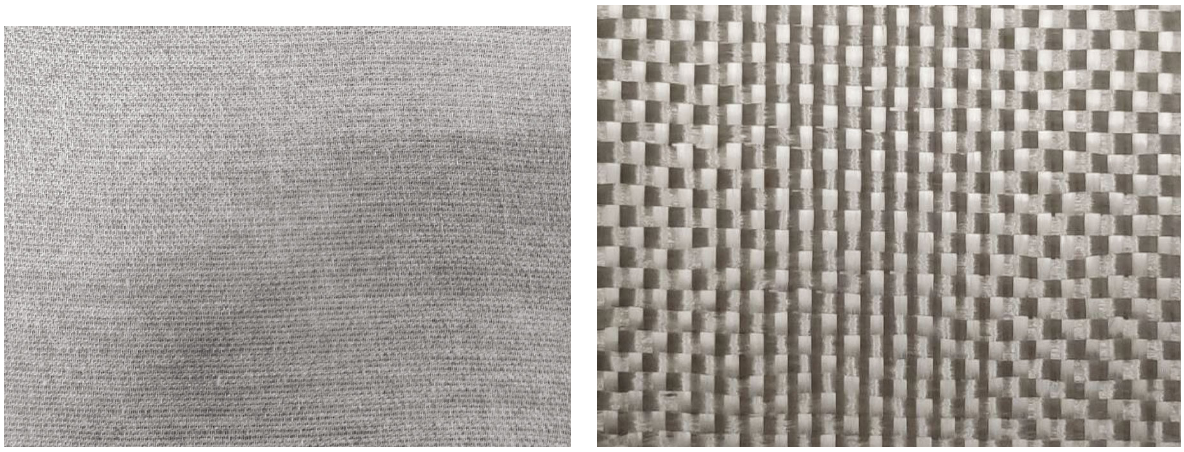
Received 30 September 2020; Revised 25 January 2021; Accepted 10 February 2021; Published 11 March 2021

Academic Editor: Hairul Abral

This research is aimed at developing the sandwich structure with a hybrid composite facesheet and investigate its mechanical properties (tensile, edgewise compression, and flexural). The combination of renewable and synthetic materials appears to reduce the weight, cost, and environmental impact compared to pure synthetic materials. The hybrid composite facesheets were fabricated with different ratios and stacking sequence of flax and glass fibers. The nonhybrid flax and glass composite facesheet sandwich structures were fabricated for comparison. The overall mechanical performance of the sandwich structures was improved by increasing the glass fiber ratio in the hybrid composites. The experimental tensile properties of the hybrid facesheet and the edgewise compression strength and ultimate flexural facing stress of the hybrid composites sandwich structures were achieved higher when the results were normalized to the same fiber volume fraction of glass composite. The hybrid composite sandwich structure showed improved compression and flexural facing stress up to 68% and 75%, respectively, compared to nonhybrid flax composites. The hybrid composite using glass in the outer layer achieved the similar flexural stiffness of the nonhybrid glass composite with only a 6% higher thickness than the glass composite sandwich structure.

1. Introduction

The sandwich structures are known for their high bending strength and stiffness at low weight. They are composed of two thin facesheets (FS) and a thick core. The FS is dense, strong, and stiff and carries the inplane load, while the core material, which supports the shear and transverse loads, is relatively low in density [1]. The honeycomb core sandwich structures are being utilized as a primary load-carrying carrying structure in aerospace, railways, automobile, and marine applications [2]. The typical usage of the sandwich composite was reported in aircraft interiors such as floor panels, interior walls, food-handling galleys, and passenger storage racks [3]. The fiber-reinforced composite has become increasingly of interest as an FS material because of durability, damage tolerance, and offers better strength to weight ratio than conventional metal counterparts [4]. The synthetic fibers such as glass, carbon, and aramid are preferred as a reinforcement in composite materials [5]. However, they have few limitations due to environmental impacts such as nonbiodegradability, complicated recycling process, disposal requirements, and emission of greenhouse gasses [6]. These drawbacks provide an increasing interest in using natural fiber composites. They are used in automobile, building, construction, packaging,



(a) (b)

Figure 1: Reinforcement for composite FS: (a) flax fabric and (b) glass fabric.

and storage industries, due to low density, high specific strength and stiffness, environmentally friendly, renewable, low production cost, and better damping properties [7]. Still, these composites are limited to nonstructural applications due to poor mechanical properties [8]. There are different techniques reported to improve the mechanical properties of natural fiber composites. Besides all methods, hybridization is the most effective technique by using a combination of natural (flax, kenaf, jute, and sisal) and synthetic (carbon and glass) reinforcement [9]. Zhang et al. [10] investigated the mechanical properties of flax/glass hybrid composites. They indicated that the addition of glass fiber improved the tensile properties of the flax hybrid composite. Saidane et al. [11] proved that the hybridization of flax and glass fibers improved the moisture resistance and Young's modulus compared to the natural fiber composite. The stacking sequence of natural and synthetic fabric plies in laminated composites has a significant effect in terms of load transfer. The alternate stacking of natural and synthetic fiber layers in laminated composites proved to have better interlaminar shear strength [12, 13]. Selver et al. [13] found that using glass fiber in the outer layer in flax/-glass and jute/glass hybrid composites provided better flexural strength than glass in the middle layer.

There are few studies reported on the mechanical properties of a sandwich structure using flax fiber composites as an FS material with different core materials like cork core, foam core, and balsa wood [14–16]. Sadeghian et al. [17] investigated the flexural behavior of a sandwich composite made of the flax fiber composite with a cork core and glass fiber with a polypropylene core. They found that the shear rigidity and flexural stiffness of the 12 mm thick polypropylene core with one glass layer exhibited comparable results with a 22 mm thick cork core with two flax fibres layers. However, they did not compare the specific flexural stiffness of the sandwich structure.

The research published relating to the flax fiber composite as an FS material of sandwich structure has focused on the fundamental understanding of the flexural performance and core properties (density, cell size) of the sandwich structures. However, no study reported improving the mechanical performance of the honeycomb sandwich structure using `the flax/glass hybrid composite as an FS material with a honeycomb core. Therefore, this study is aimed at investigating the tensile, edgewise compression, and flexural (3-point bending) properties of the hybrid FS sandwich structure made from flax and glass composites. The effects of fiber type, their ratios in the hybrid composites, and fiber volume fraction on the mechanical properties were analyzed with experimental and normalized results.

Table 1: Specifications of reinforcement fibers [8, 18].

Properties	Biotex™ flax	E-glass
Density (g/cm^3)	1.5	2.5
Tensile strength (MPa)	500	2000-3000
Tensile modulus (GPa)	50	70-75
Elongation at brake %	2	2.5-3
Fiber diameter (ɥm)	20	25
Fiber length (cm)	100	—
Cellulose (%)	64-71	—

2. Experimental Details

2.1. Material. Flax and E-glass reinforcement were utilized in woven mats to fabricate the composites FS as shown in Figure 1. The flax fabric and glass fiber were procured in woven mats from the Easy Composite, UK. Table 1 shows the individual properties of the fibers [8, 18]. The Epoxamite® 100 epoxy resin with slow hardener 103 was used as a matrix. The specifications of this epoxy resin are reported in the literature [19]. The aluminium honeycomb 5052 grade was used as the core material with cell size (distance between two opposite cell walls) and thickness of 3.2 mm and 8 mm, respectively. The aluminium honeycomb core and the epoxy adhesive film were acquired from Hexcore industries based in Jiangsu, China. The areal density and standard shear strength of the adhesive film are 300 g.m^{-2} and 15 MPa, respectively.

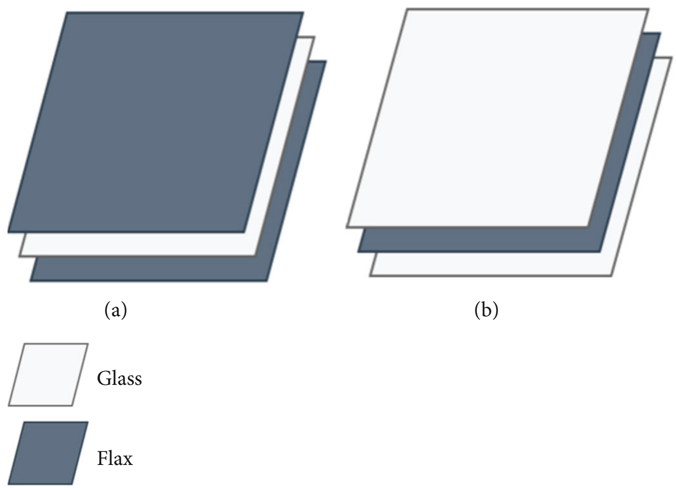


Figure 2: Fabric stacking sequence of composite laminates: (a) H1 hybrid and (b) H2 hybrid.

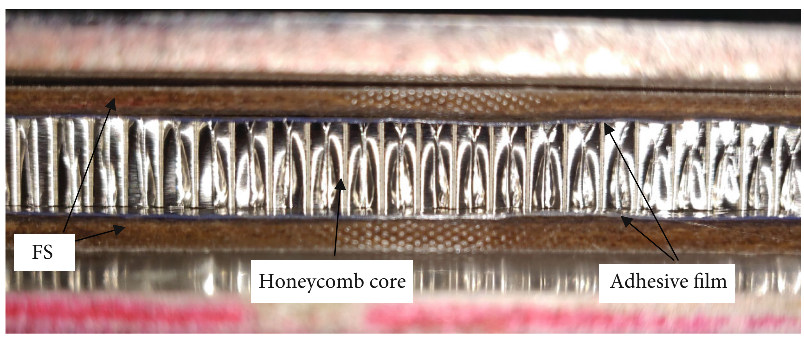


Figure 3: Curing of the composite sandwich structure.

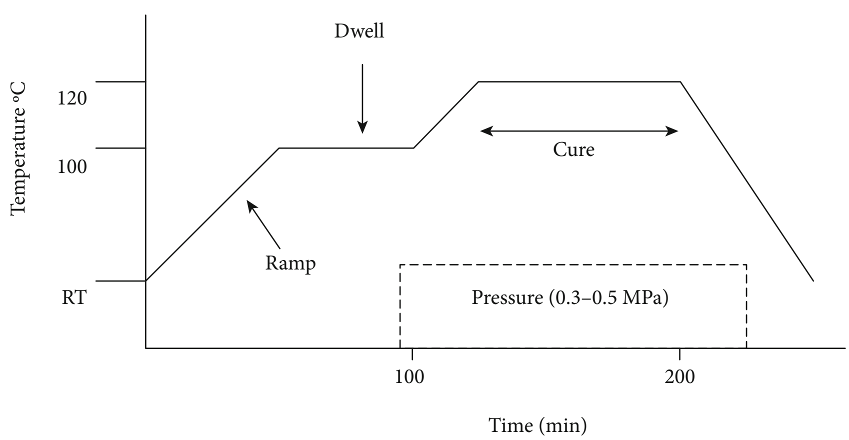
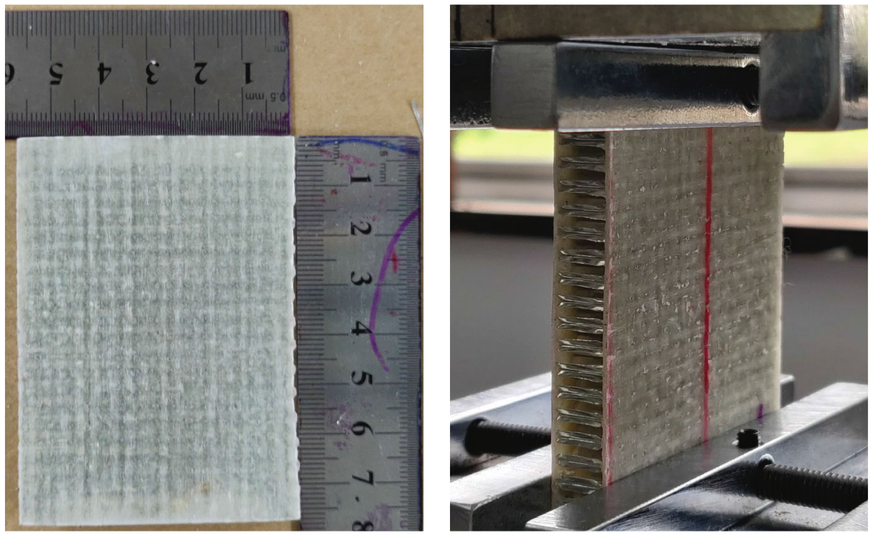


Figure 4: Curing profile of composite structures in hot-press.

2.2. Sandwich Structure Fabrication. The honeycomb core sandwich structures were fabricated using the precure technique. This precure fabrication process was comprised of two stages. In the initial process, the composite FS were fabricated, followed by FS bonding with the core using adhesive film in the subsequent process. The hybrid and nonhybrid composite FS were precured in the vacuum infusion process with various stacking sequences of the flax and glass fabric plies, as shown in Figure 2.

The peel-ply treated surface of the precure composite FS was used for secondary bonding with the core. The epoxy adhesive film was applied to the peel-ply treated surface of the FS to fabricate the sandwich structure, as described by Farooq et al. [20]. The whole assembly was placed in hot-press for bonding and curing of the adhesive film, as shown in Figure 3. The curing profile of the sandwich structure in the hot-press is given in Figure 4. The intermediate dwell time was taken at 100°C for one hour, followed by curing at 120°C [4]. The



(a) (b)

Figure 5: Edgewise compression test: (a) actual specimen size and (b) experimental setup.

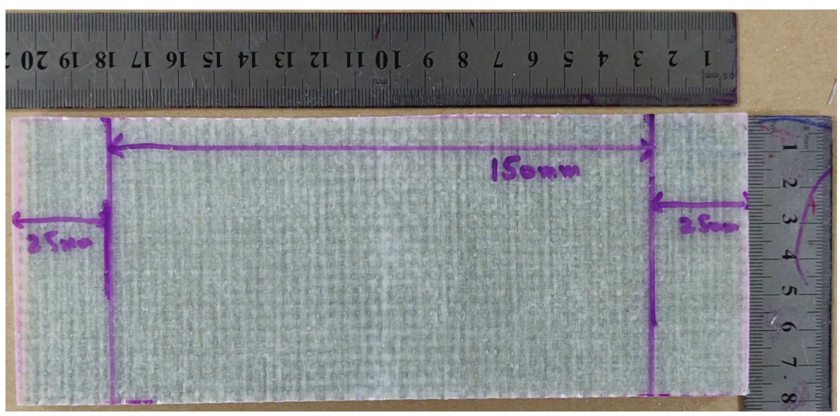


Figure 6: specimen prepared for flexural testing (3-point loading).

required specimens as per standard size for testing were cut from the fabricated panel of 300 mm × 300 mm.

2.3. Characterization. The tensile properties of flax, glass, and hybrid composites FS were performed to determine the strength and modulus of the FS materials. According to the ASTM D3039, the tensile test was performed with a crosshead speed of 2 mm/min [21]. The 150 mm span length and 25.4 mm width of each composite FS type were prepared for the tensile test as per standard guidelines. The modulus of elasticity of each composite FS was calculated by the ratio of change in stress to the change in strain from the slope of the chord between 0.1% and 0.3% strain. The edgewise compression test was conducted to determine the ultimate compression strength of the sandwich structures as per standard ASTM C364 with a crosshead speed of 0.5 mm/min [22]. The specimen size and experimental set-up for the edgewise compression test are given in Figure 5.

The flexural test (3-point loading) was performed to determine the facing stress of the sandwich structure. The specimen dimensions were taken as per ASTM C393 standard configuration with a crosshead displacement of 3 mm/min [23]. The specimen size for the flexural test was taken as standard configuration given in ASTM C393. The actual specimen for the flexural test is shown in Figure 6.

The specimens of each type were tested five times at loading conditions, and their average values and standard derivation were calculated as per standard. The mechanical testing (tensile, edgewise compression and flexural) was carried out on the Instron 3382 Universal testing machine. The experimental density of the composite specimens was computed using a digital densimeter by measuring the weight of the samples in the air and water according to the ASTM D792 standard [24]. The fiber volume fraction of each cured composite FS was calculated using equation (1) [13]. The thickness, fiber volume fraction, and density of each composite FS are given in Table 2.

$$V_f = \frac{\left(w_f/\rho_f\right)}{\left[\left(w_f/\rho_f\right) + \left(w_r/\rho_r\right)\right]}, \tag{1}$$

Table 2: Properties of composite laminates.

FS laminate	FS thickness (mm)	Total fiber volume fraction V_f	Fiber weight fraction (%)		FS density (g.cm^{-3})
			Glass	Flax	
Flax	1.1 ± (0.05)	0.26	0	100	1.17 ± (0.02)
H1	1.3 ± (0.05)	0.297	57	43	1.30 ± (0.02)
H2	1.1 ± (0.05)	0.326	75	25	1.45 ± (0.03)
Glass	0.8 ± (0.05)	0.415	100	0	1.66 ± (0.03)

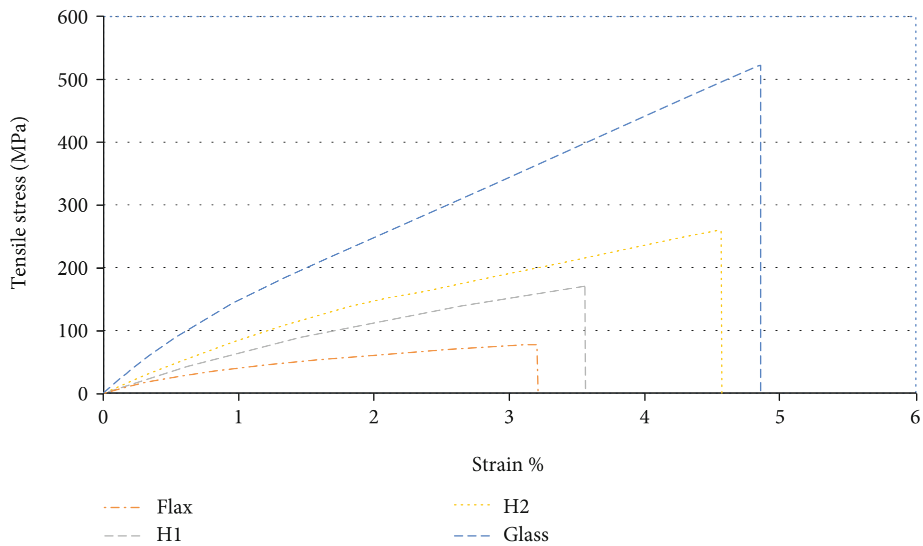


Figure 7: Stress-strain curves of tensile loading.

Table 3: Tensile force, strength, and modulus of the composite laminates.

FS laminate	Avg. ultimate load (kN)	Tensile strength (MPa)	Normalized tensile strength (MPa)	Avg. modulus (GPa)	Normalized modulus (GPa)
Flax	2.64 ± (0.12)	94.6 ± (3.4)	151.0	5.3 ± (0.13)	8.45
H1	6.02 ± (0.32)	182.3 ± (9.9)	254.8	7.5 ± (0.96)	10.5
H2	6.74 ± (.51)	241.2 ± (18.4)	303.4	10.5 ± (1.53)	13.2
Glass	9.14 ± (0.78)	449.8 ± (36.8)	449.8	15.5 ± (1.11)	15.5

where V_f is the volume fraction of fiber, w_f is the weight of fiber, w_r is the weight of resin, ρ_f is the density of fiber, and ρ_r is the density of the resin.

3. Results and Discussion

3.1. Tensile Test. The stress-strain curves of the glass, flax, and hybrid composites are illustrated in Figure 7. It showed that the glass fiber composite showed higher failure strain compared to the flax composite. The hybrid composite H2 showed higher elongation than H1 because of the higher volume fraction of glass fiber in the H2 hybrid composite. The possible explanation of the higher elongation in the glass composite was higher elongation at break of glass than flax fiber, as given in Table 1. These findings are supported by similar results concluded by Zhang et al. [10].

The tensile force, strength, and modulus of all composite laminates are given in Table 3. The experimental results showed that the hybrid composites significantly improved the tensile strength and modulus compared to the flax composite. The tensile strength was improved by around 92.7% and 155% in H1 and H2 hybrid composites, respectively. The hybrid composite H1 and H2 showed improved tensile modulus by 42% and 98%, respectively. The higher tensile strength and modulus of H2 hybrid composite compared to H1 indicated that the results were improved by increasing the glass fiber volume content in the hybrid composites. The results showed that the glass fiber composite had the highest tensile strength and modulus compared to flax and

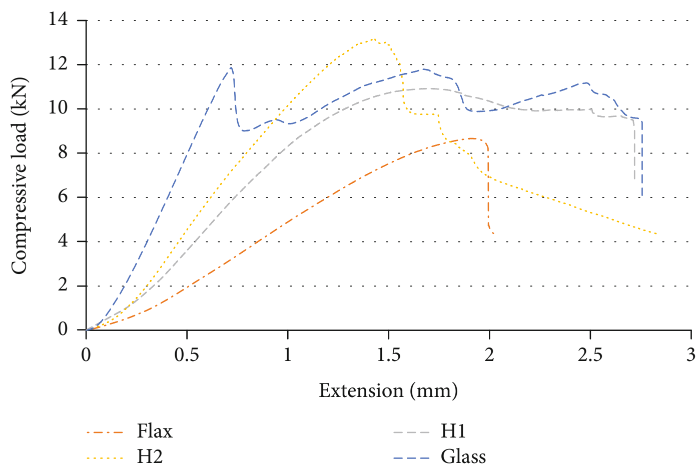


Figure 8: Load-extension curves of edgewise compression.

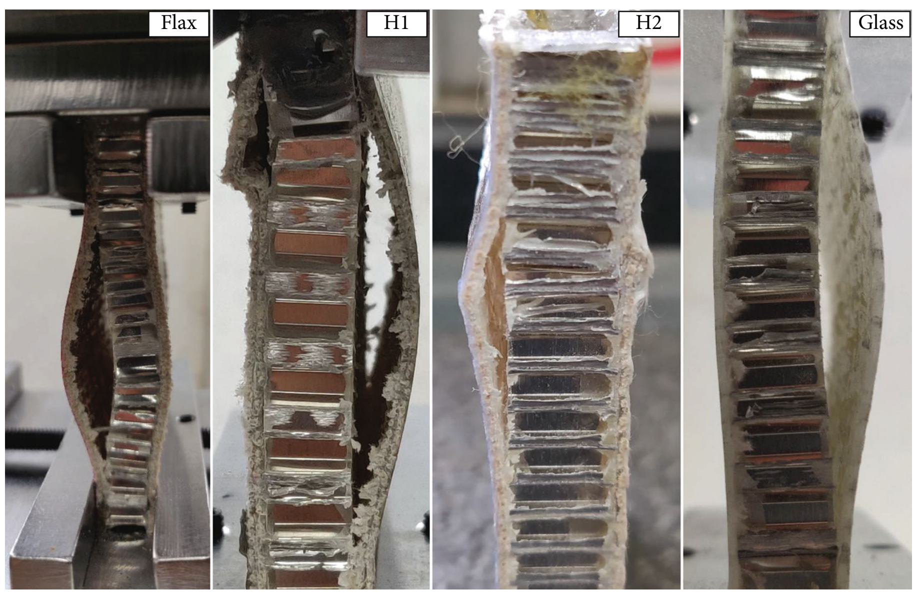


Figure 9: Failure mode of sandwich structures through edgewise compression.

hybrid composites due to the higher total fiber volume since the glass fiber carried most of the load. The experimental results of tensile strength and modulus were normalized with the common fiber volume fraction to compare better while the samples have different total fiber volume fractions. The results were normalized by multiplying the ratio of the common fiber volume fraction of the glass composite (0.415) to the actual fiber volume of the composite using equation (2) and equation (3), respectively [13]. The normalized tensile strengths of flax and hybrid composites were improved compared to the experimental results, as given in Table 3. The results showed that the normalized tensile strength was increased with the increasing glass fiber volume ratio in the hybrid composites. The normalized H2 hybrid composite improved tensile strength by 19% compared to the H1 hybrid composite. The glass fiber composite still showed the higher normalized tensile strength compared to flax and hybrid composites. The possible reason was due to the better strength of glass than flax fiber, as given in Table 1.

Table 4: Edgewise compression force and strength of the composite sandwich structure.

FS laminate	Avg. load (kN)	Compression strength (MPa)	Normalized compression strength (MPa)
Flax	8.9 ± (0.29)	58.1 ± (1.93)	89.3
H1	11.3 ± (0.46)	79.1 ± (3.2)	112.6
H2	12.8 ± (0.55)	106.3 ± (4.57)	133.1
Glass	13.0 ± (0.44)	148.4 ± (5.07)	148.4

Table 3 showed the improvement in the tensile modulus of flax and hybrid composites when the results were normalized. The H2 hybrid composite attained 85% of the tensile modulus of the glass fiber composite when the results were normalized to the same glass fiber volume. However, the glass composite still showed the higher modulus when the

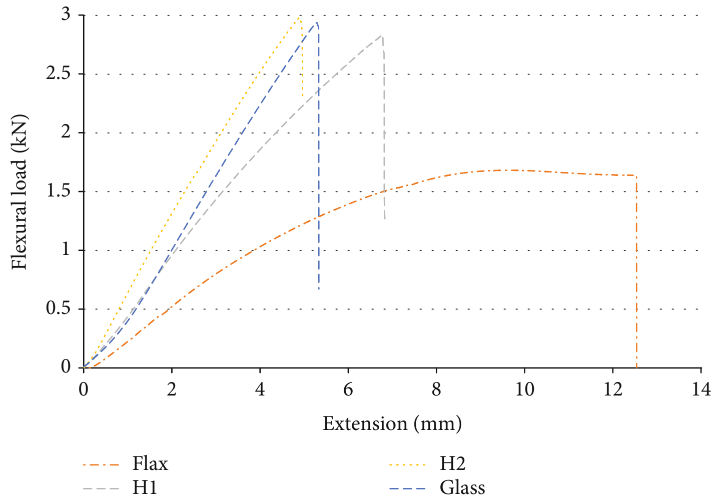


FIGURE 10: Load-extension curves of the flexural test.

composites were normalized to the same fiber volume fraction due to better fiber-matrix adhesion of glass than flax fiber [11].

$$\sigma_n = \frac{\sigma}{\mathrm{Vf}} \times \mathrm{Vf}_c, \quad (2)$$

$$E_n = \frac{E}{\mathrm{Vf}} \times \mathrm{Vf}_c, \quad (3)$$

where σ_n is the normalized strength, σ is the strength of the composite (MPa), E_n is the normalized modulus (GPa), E is the modulus of the composite (GPa), Vf is the actual fiber volume, and Vf_c is the common fiber volume fraction.

3.2. Edgewise Compression Strength. The edgewise compression or inplane compression test was conducted to evaluate the performance of the sandwich structure through the compression loading applied on the edges of FS. The compression performance is the relevant design parameter because the bending strength of the sandwich structure is affected by the poor compression performance [25]. Figure 8 shows the load-extension curves of flax, glass, and hybrid composites through compression loading. The flax composite curve revealed a linear elastic behavior and showed abrupt failure due to the adhesive failure between FS and core. The glass and hybrid composites showed similar elastic performance followed by the softening phase before failure. The face wrinkling initiated the failure in glass and hybrid composites due to matrix cracking in the composite FS, followed by FS debonding, as shown in Figure 9.

The average edgewise compression force and strength are given in Table 4. It indicated that the experimental results of edgewise compression strength were improved by increasing the glass fiber volume content. The compression strength was enhanced by 25% and 68% by H1 and H2, respectively, compared with the flax composite. The glass fiber composite showed the highest compression strength than flax and hybrid composites due to the higher fiber volume fraction and better stiffness of glass than flax fiber. The experimental results of the hybrid composites were normalized to the same glass fiber volume using equation (2), as described in tensile testing. The compression strength of the flax and hybrid composites was achieved higher when the results were normalized (Table 4). The normalized compression strength of the H2 hybrid composite showed comparable results by approaching 92% compression strength of the glass fiber composite.

TABLE 5: Flexural load and facing stress of the composite sandwich structures.

FS laminate	Avg. load (kN)	Avg. facing stress (MPa)	Normalized facing stress (MPa)
Flax	1.61 ± (0.057)	80.5 ± (2.86)	128.4
H1	2.80 ± (0.12)	116 ± (4.66)	165.4
H2	2.82 ± (0.22)	140.8 ± (11.3)	178.2
Glass	3.06 ± (0.19)	218 ± (13.7)	218

3.3. Flexural Test. The peak loads reached by each sandwich structure are shown in the load-extension curves (Figure 10). The failure extension through the bending of sandwich structures was significantly affected by the stacking sequence and relative fiber volume ratio of glass fiber in composite FS. The glass and H2 hybrid composites that possessed the outer glass fiber layer in FS showed more resistance to the bending load than H1 and flax composites. This behavior was due to the high stiffness of glass compared to flax fiber [13].

Table 5 shows the flexural load and flexural facing stress of the sandwich structures. The experimental results indicated that the facing stress of the hybrid composites was improved with increasing the glass fiber content. The H1 and H2 hybrid composites showed the improved facing stress by around 44% and 75%, respectively, compared with the flax composite. The glass fiber composite showed higher flexural facing stress than flax and hybrid composites due to the higher total fiber volume fraction. The flexural facing stress of flax and hybrid composites was normalized as described in tensile using equation (2) to compare the same fiber

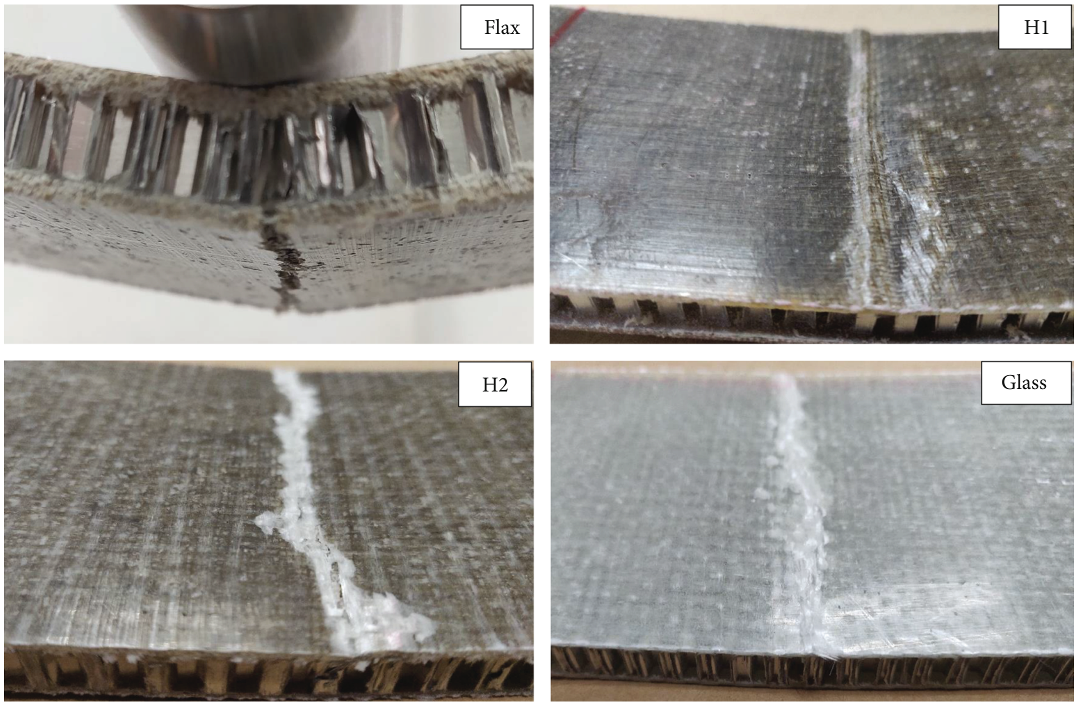


Figure 11: Collapse mode of sandwich structures subjected to the flexural test.

Table 6: Dimensions and flexural stiffness of the composite sandwich structures.

FS laminate	Width, b (mm)	Sandwich structure thickness, d (mm)	Flexural stiffness, D ($N.m^2$)	Weight of sandwich panel ($g.cm^{-2}$)	Specific flexural stiffness ($N.m^{2/}(g.cm^{-2})$)
Flax	75	10.2 ± (0.05)	18.19 ± (0.23)	0.45	40.2
H1	75	10.6 ± (0.05)	31.93 ± (1.04)	0.46	69.3
H2	75	10.2 ± (0.05)	36.12 ± (2.87)	0.44	82.0
Glass	75	9.6 ± (0.05)	36.10 ± (1.73)	0.38	95

volume fraction composites. The experimental facing stress of hybrid composites was achieved higher when the results were normalized to the same glass fiber volume, as given in Table 5. The normalized results indicated that the facing stress was improved by increasing the glass fiber ratio in the hybrid composites, which was due to the better strength of glass fiber than flax fiber. The normalized H2 hybrid composite showed improved facing stress by approaching 82% facing stress of the glass composite.

Figure 11 shows the fractured sandwich structures subjected to the three-point flexural loading. This type of failure in a sandwich structure is caused by face yielding, and it generally occurs when the FS materials exceed their allowable stress or strain [26]. The failures observed in glass and hybrid composites were due to compression or upper FS failure, while the flax composite showed lower FS failure. The possible reason for the lower FS failure was due to the lower tensile strain of the flax composite compared to the glass and hybrid composites, as discussed in the tensile testing.

The flexural stiffness of the sandwich structures was calculated using equation (4) as per ASTM D7250 [27]. Table 6 shows the flexural stiffness of the sandwich structure. The flexural stiffness of the glass and H2 hybrid composite showed similar results using the same number of reinforcement layers in composite FS. In contrast to the previous research reported by CoDyre et al. [16] that the similar flexural stiffness of one layer of the glass composite FS sandwich structure was achieved using the three layers of flax fiber. The higher FS thickness of the H2 composite (1.1 mm) compared to the glass composite (0.8 mm) balanced the lower modulus to achieve the similar flexural stiffness. The flax and H1 hybrid composite showed lower flexural stiffness than glass and H2 hybrid composites, but the difference was not significant. The comparable flexural thickness of the flax and H1 hybrid composite was due to the higher thickness of flax and H1 sandwich structures [17].

The specific flexural stiffness was calculated by the ratio of actual flexural stiffness to the areal density or weight of the sandwich structure since the glass, and hybrid composites had different density and FS thickness. The areal density of the sandwich structure was calculated by adding the weight of FS, core, and adhesive film. The glass fiber composite FS had lower weight than that of hybrid composites due to the lower thickness of FS. The glass composite sandwich structure exhibited higher stiffness to weight ratio because of the lower areal density and higher modulus of glass composite FS. The relative ratio glass fiber volume showed a significant effect on the specific flexural stiffness of hybrid composites FS. The hybrid laminates with the outer glass fiber layer (H2) that had higher specific flexural by around 18% compared to H1, as given in Table 6.

$$D = \frac{E_f\left(d^3 - C^3\right)b}{12}, \tag{4}$$

where D is the flexural stiffness, E_f is the FS modulus, d is the sandwich structure thickness, c is the core thickness, and b is the width of the specimen.

4. Conclusion

The mechanical properties of the hybrid composite FS sandwich structures were analyzed at different loading conditions (tensile, edgewise compression, and flexural) for different fiber volume ratios of flax and glass fibers. The overall mechanical properties of composite FS and sandwich structures were improved with the increasing glass fiber content. The H2 hybrid composites using glass in the outer layer showed improved tensile strength and modulus by around 155% and 98%, respectively, compared with the flax composite FS. The H2 hybrid composite achieved 85% modulus value of the glass composite when the results were normalized to the same glass fiber volume. The edgewise compression strength was improved around 68% by the H2 hybrid FS, compared with the flax composite sandwich structure. The normalized H2 hybrid composite achieved a 90% compression strength of the glass composite. The flexural facing stress of the sandwich structure was increased up to 75% by H2 hybrid FS compared to flax composite facing stress. The H2 hybrid composite achieved about 82% of the flexural facing stress of the glass fiber composite when the results were normalized. The H2 hybrid composite showed similar flexural stiffness to glass composite with only a 6% increase in the H2 hybrid sandwich thickness than the glass composite sandwich structure. However, the specific flexural stiffness (flexural stiffness to weight ratio) results showed that the glass fiber composite had 15% higher specific flexural stiffness than the H2 hybrid sandwich structure.

Data Availability

All data included in this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors would like to thank and sincere appreciation to the Aerospace Manufacturing Research Centre (AMRC) and Department of Aerospace, Universiti Putra Malaysia, for providing the lab facility to conduct this study. The Universiti Putra Malaysia funded this research work under FRGS (5540205).

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