Flexural Behavior of Sandwich Panels made of FRP Composites: Synthetic and Natural Fibers

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FLEXURAL BEHAVIOR OF SANDWICH PANELS MADE OF FRP COMPOSITES: SYNTHETIC AND NATURAL FIBERS

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ABSTRACT

Sandwich panels made of fiber-reinforced polymer (FRP) skins and light-weight core materials have the potential to be effectively used in several structural applications such as cladding, decking, and roofing panels. The FRP skins resist the tensile and compressive stresses resulting from the flexure induced by transverse loadings and the core resists shear stresses, serves as insulation, and separates the FRP skins at a desired distance to provide required moment of inertial. In this study, two types of fiber materials, namely synthetic (glass) and natural (flax) fibers, as well as two types of core materials, namely polypropylene honeycomb (thickness: 6.4, 12.7, and 25.4 mm; density 80 kg/m^3) and cork (thickness: 11 and 22 mm; density 200 kg/m^3) core materials were used to make sandwich panels. A total of 105 small-scale sandwich beam specimens (50 mm wide × 200 and 350 mm long) were prepared and tested under four-point bending. The load-deflection behavior, strength, stiffness, and failure mode of the specimens were evaluated. Also, an analytical model was adopted to compute the flexural stiffness, shear rigidity, and core shear modulus of the sandwich panels. The analytical results showed a good agreement with the test results. Overall, the natural fiber and core materials showed a promising structural performance compared to their synthetic counterparts.

KEYWORDS: Composite, Polymer, Natural Fiber, Flax, Glass, Cork, Honeycomb, Sandwich.

1. INTRODUCTION

Sandwich structures made of fiber-reinforced polymer (FRP) skins and light-weight core materials are very effective systems in high-performance applications where minimum weight is required. The two thin, stiff, and strong FRP skins resist the tensile and compressive stresses resulting from the flexure induced by bending moments and axial forces. The light-weight, low-density, and low-strength core resists shear forces, serves as insulation, and separates the FRP skins at a desired distance to provide required moment of inertial for the structure. As a result, the bending strength and lateral stiffness of sandwich structures are much larger than those of a single solid plate of same total weight made of the same materials as the skins (Zinno et al. 2008). Some of the earliest applications of sandwich structures in the 20th century were in aircraft industry (Allen 1969). This was followed by an expansion into the aerospace, automotive, and marine industries (Fam et al. 2016). In civil engineering, there are many applications such as cladding, decking, and roofing panels that can benefit greatly from sandwich structures.

Sandwich panels with FRP skins used in civil engineering related applications are typically made of glass FRP (GFRP) skins separated by a low-density foam. Synthetic fibers such as glass fibers are made of non-renewable resources and their production typically emits significant greenhouse gases contributing to the global warming. Moreover, it is very difficult to recycle them at the end of their life span. As a result, GFRPs are typically sent to landfills that are filling up fast. Natural fibres extracted from plants (e.g. flax, hemp, jute, and etc.) are good examples of renewable materials that offer several economical, technical, and ecological advantages over synthetic fibers. FRP composites made of natural fibers have much potential at the end of their life span for recycling and degradation, depending on the type of the polymer used. The worst case scenario is the incineration of natural FRPs to generate power, which reduces their volume significantly to fly ash and bottom ash with many potential applications in concrete industry. In addition, there are some natural light-weight materials (e.g. cork) that can be potentially a replacement for synthetic core materials.

In this study, two types of fiber materials, namely synthetic (glass) and natural (flax) fibers, as well as two types of core materials, namely polypropylene honeycomb and cork core materials are used to make sandwich panels. A number of small-scale sandwich beam specimens are prepared and tested under four-point bending. The load-deflection behavior, strength, stiffness, and failure mode of the specimens are evaluated. Also, an analytical model is adopted to compute the flexural stiffness, shear rigidity, and core shear modulus of the sandwich panels.

2. EXPERIMENTAL PROGRAM

2.1 Test Matrix

A total of 105 sandwich specimens which varied in size were made to be tested under four-point bending. Flax fabrics (F) bonded to cork (C) using resin were being compared to glass fabrics (G) bonded to honeycomb (H) using the same resin. The variables that were being compared were the fiber materials, number of layers, core material, core thickness, and the specimen span. These comparisons were flax fabric vs. glass fabric, 0 to 2 layers, cork vs. honeycomb of different thicknesses and two spans of 150 mm or 300 mm. These different variations of specimens can be seen in Table 1. Five identical specimens were made for each case.

Table 1: Test matrix.

#	Specimen ID	Skin fiber material	Skin layers	Core material	Core thickness (mm)	Span (mm)
1	F0-C11-S150	Flax	0	Cork	11	150
2	F1-C11-S150	Flax	1	Cork	11	150
3	F2-C11-S150	Flax	2	Cork	11	150
4	F0-C22-S150	Flax	0	Cork	22	150
5	F1-C22-S150	Flax	1	Cork	22	150
6	F2-C22-S150	Flax	2	Cork	22	150
7	F1-C11-S300	Flax	1	Cork	11	300
8	F2-C11-S300	Flax	2	Cork	11	300
9	F1-C22-S300	Flax	1	Cork	22	300
10	F2-C22-S300	Flax	2	Cork	22	300
11	G0-H6-S150	Glass	0	Honeycomb	6.4	150
12	G1-H6-S150	Glass	1	Honeycomb	6.4	150
13	G0-H12-S150	Glass	0	Honeycomb	12.7	150
14	G1-H12-S150	Glass	1	Honeycomb	12.7	150
15	G0-H25-S150	Glass	0	Honeycomb	25.4	150
16	G1-H25-S150	Glass	1	Honeycomb	25.4	150
17	G0-H6-S300	Glass	0	Honeycomb	6.4	300
18	G1-H6-S300	Glass	1	Honeycomb	6.4	300
19	G0-H12-S300	Glass	0	Honeycomb	12.7	300
20	G1-H12-S300	Glass	1	Honeycomb	12.7	300
21	G0-H25-S300	Glass	0	Honeycomb	25.4	300

F=flax FRP skin; G=glass FRP skin; C=cork core; H=Honeycomb core; S=span

2.2 Material Properties

For flax FRP skins, a 275 g/m^2 stitched unidirectional flax fabric was used. The fabric was made of flax fibres with the density of 1.5 g/cm^3, diameter of 20 μm, tensile strength of 500 MPa, elastic modulus of 50 GPa, and rupture strain of 2% reported by manufacturer. Figure 1 shows the tensile behavior of flax FRPs. For glass FRP skins, a 955 g/m^2 stitched unidirectional glass fabric was used. The figure also shows the tensile behavior of glass FRPs. The tensile properties of FRPs obtained from direct tensile tests by Hristozov et al. (2016). Five identical tensile coupons were tested for each material as shown in Figure 1. The dotted lines in the figure show the elastic modulus of the materials. For making both flax/cork and glass/honeycomb sandwich panels, a vinyl ester resin catalyzed with 1.25% methyl ethyl ketone peroxide (MEKP) was used. The resin was cured at room temperature for 24 hours and post-cured for 2 hours at 138°C was reported by manufacturer to have the tensile strength of 82 MPa, elastic modulus of 3.72 GPa, and rupture strain of 7.9%.

For sandwich panels with flax FRP skins, prefabricated cork sheets (300 x 600 mm) with 11 mm thickness and the density of 200 kg/m^3 (reported by manufacturer) were used. As a thicker cork sheet was not available at the time of the experimental study, two 11 mm thick cork sheets were bonded together using the resin to make 22 mm thick cork sheets. For sandwich panels with glass FRP skins, prefabricated honeycomb sheets (1200 x 2400 mm) with the density of 80 kg/m^3 (reported by manufacturer) and 8mm diameter cylindrical polypropylene (PP) cells were used. The cells were covered with veil and film barrier to prevent resin filling the cells. Three honeycomb sheets with nominal thickness of 6.3, 12.7, and 25.4 mm were used. With considering the veil and film barrier, the actual thickness of the sheets was measured as 6.33, 12.91, and 25.75 mm, respectively. Their overall density was also measured as 145, 110, and 91 kg/m^3, respectively.

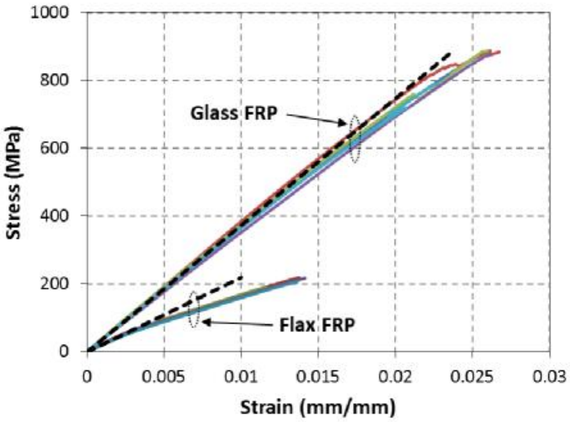

Figure 1: Tensile properties of FRP skins

2.3 Specimen Fabrication

Generally the core material either cork board or honeycomb was approximately 600 x 900 mm to begin as shown in Figure 2. Creating such large sandwich panels allowed the work be more efficient and be able to test a large amount of specimens in a timely manner. The size of the panels were selected to fit into fume hood. The wet lay-up method was used and the resin was applied in layers with a roller. Since the cork boards came as 11 mm thick, in order to create 22 mm thick core, two boards were bonded using the resin. The same resin was used to bond flax fabrics onto cork boards as bonding glass fabric onto the honeycomb boards. The flax fabric came in shorter widths than the cork boards, so using more than one fabric in parallel was required while bonding the materials together. The glass fabric was wide enough to fit over a honeycomb board. After one layer of either flax fabric on cork board or glass fabric on honeycomb board was applied, if a second layer of fabric was required it was added, subsequently. After at least 24 hours, the other side of the board was covered with the same procedure. The sandwich panels were then left to cure for at least 7 days at room temperature. After the curing process was complete, the specimens were cut into 50 mm wide strips using a band saw. This was followed by cutting them to either 200 mm long or 350 mm long specimens. A micrometer was used to measure the thickness and width of each specimen at three locations and averaged.

Figure 2: Specimen preparation and test setup

2.4 Test Setup and Instrumentation

A four point bending setup was used for all specimens with a different loading span proportional to the supporting span. The load was applied from the top down with a universal testing machine as shown in Fig 3. The loading span (L) was equal to 2/11 of the supporting span (S) per ASTM D7249 (2006) and ASTM D7250 (2006). It means for the supporting span of 150 and 300 mm, the loading span was 27.27 and 54.55 mm; respectively.

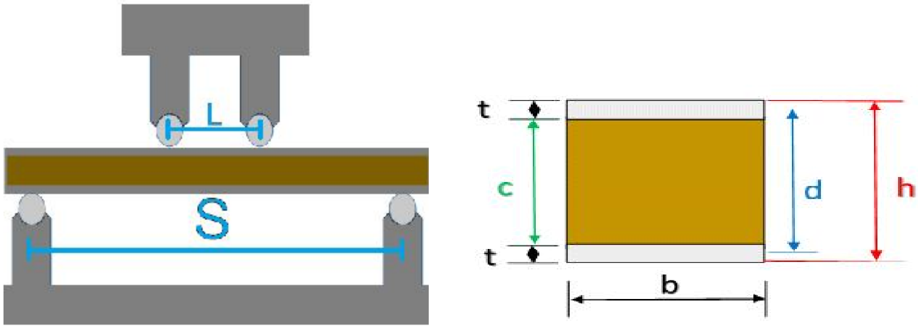

Figure 3: Four-point bending and sandwich beam cross-section

3. RESULTS AND DISCUSSIONS

The summary of the results are shown in Table 2. Five identical specimens were tested for each case. The mean and standard deviation (SD) of the peak load, initial stiffness, and the deflection at peak point of the five identical specimens plus their failure mode are provided in Table 2. As identified in the table, the failure modes of the specimens can be categorized as: (a) indentation; (b) cork core shear failure; (c) skin buckling; (d) core shear; (e) core shear/buckling; (f) core crushing; and (g) core tensile rupture. Indentation failure is a function of the out of plane compressive strength of the core and the area over which the load is applied. Cork sandwich specimens with one layer of flax FRP skin and short span (i.e., F1-C11-S150) were susceptible to indentation failure, however increasing the number of flax FRP layers (i.e., F2-C11-S150) prevented indentation failure and switched the failure to the shear failure of the core.

The main failure mode of cork sandwich specimens was core shear failure with inclined cracks in the core. For the short cork sandwich specimens with 22 mm thick cork (i.e., F1-C22-S150 and F2-C22-S150). For the long cork sandwich specimens with one layer of flax FRP and 11 mm thick cork (i.e., F1-C11-S300) again indentation was the failure mode. However, adding one more layer of flax FRP (i.e., F2-C11-S300) changed the failure mode to the buckling of the compressive skin in the constant moment region, where the bending moment is maximum. Specimen F1-C22-S300 with thicker cork failed by indentation due to the thin skin. Adding one layer of flax FRP (F2-C22-S300) changed the failure to typical core sheer failure. Overall, the thickness of flax FRP demonstrated a significant role to switch the failure mode from either indentation to core shear failure.

Honeycomb sandwich specimens did not demonstrate any indentation failure due to the structure of the honeycomb cells. They also did not show any skin buckling as one layer glass FRP skin was thicker and stiffer than one layer flax FRP skin. Sandwich specimens with the thinnest honeycomb (i.e., G1-H6-S150 and G1-H6-S300) demonstrated a shear failure in the core. However, the sandwich specimens with thicker honeycombs showed a combination of shear and buckling of the core. It seems the buckling was triggered by more slender cell walls. For the case of specimens without skins, the honeycomb showed an excessive plastic deformation due to crushing of the core at the compressive side. The cork specimens without skins failed due to rupture at the tension side. Overall, the cork boards demonstrated a tensile strength lower than the honeycomb boards, however the weakness is compatible with the strength level of flax FRPs compared to glass FRPs.

Table 2: Summary of test results

Specimen ID	Peak load (N)		Initial stiffness (N/mm)		Deflection at peak load (mm)		Failure mode
	Mean	SD	Mean	SD	Mean	SD	
F0-C11-S150	20.86	1.88	1.78	0.39	29.40	2.97	Tensile rupture
F1-C11-S150	501.58	57.38	132.88	9.14	7.58	1.40	Skin buckling
F2-C11-S150	839.10	13.61	174.75	9.50	12.26	0.45	Core shear
F0-C22-S150	98.24	5.24	18.98	2.65	9.52	5.53	Tensile rupture
F1-C22-S150	786.76	46.74	217.69	20.74	8.35	0.62	Core shear
F2-C22-S150	1189.96	219.41	267.69	15.91	13.49	1.04	Core shear
F1-C11-S300	316.17	22.26	41.74	3.23	12.54	1.78	Core crushing
F2-C11-S300	583.53	17.78	64.25	0.72	20.75	0.90	Core shear
F1-C22-S300	437.70	19.86	73.13	4.14	9.85	0.73	Skin buckling
F2-C22-S300	1004.76	29.29	107.04	10.64	23.36	1.93	Core shear
G0-H6-S150	25.78	1.71	2.50	0.18	23.92	1.72	Core crushing
G1-H6-S150	562.71	13.49	153.65	6.31	9.6186	0.44	Core shear
G0-H12-S150	73.04	4.72	10.05	0.51	16.80	1.03	Core crushing
G1-H12-S150	862.57	24.82	268.03	12.22	5.45	0.15	Core shear/buckling
G0-H25-S150	169.92	20.17	56.79	7.85	10.69	1.40	Core crushing
G1-H25-S150	1412.95	25.18	499.97	9.21	4.77	0.04	Core shear/buckling
G0-H6-S300	8.56	0.54	0.30	0.02	53.20	2.39	Core crushing
G1-H6-S300	479.10	9.15	44.71	2.37	19.67	0.26	Core shear/buckling
G0-H12-S300	31.80	2.48	1.43	0.10	48.80	2.39	Core crushing
G1-H12-S300	799.88	19.60	101.67	6.16	13.45	0.31	Core shear/buckling
G0-H25-S300	70.22	4.62	8.82	2.62	33.59	2.50	Core crushing
G1-H25-S300	1354.36	33.13	214.99	6.49	10.77	0.23	Core shear/buckling

3.1 Load-Deflection Responses

3.1.1 Flax/Cork Sandwich Composites

Figures 4(a) and 4(b) show the typical load-deflection behavior of flax/cork sandwich beams with 150 and 300 mm span, respectively. It should be mentioned that for each case five identical specimens were prepared and tested, however only one curve (the one that was the closest curve to the average) out of five curves was selected and presented in the figures. All specimens have a short linear behavior followed by an ascending non-linear behavior up to a peak point and then a descending branch to failure. Typical failure was shear failure of the core, however in some cases the buckling failure of the compressive skin controlled the failure. No tensile rupture of the skin was observed.

As shown in Figure 4(a), the 11 mm thick cork specimens (i.e. without FRP skin) are very weak and flexible. The 22 mm thick cork specimens has higher stiffness and strength, as expected. Comparing the behaviors of specimens F1-C11-S150 and F0-C11-S150 imply that applying only one layer of flax FRP at each side of the 11 mm thick cork increases its strength and stiffness, significantly. Considering the specimen F2-C11-S150 shows that applying two layers of flax FRP increases both strength and stiffness further more. The same trend is noticeable for the 22 mm thick cork when one and two layers of flax FRP are applied at each side. The figure also shows that F1-C22-S150 is slightly stiffer than F2-C11-S150, however slightly weaker. Figure4(b) shows that there is a significant improvement in terms of both strength and stiffness for the specimens with two layers of flax FRP with respect those of with one layer. There is also a significant improvement in term of the area under the curves which shows a greater energy absorption capacity for the long specimens with two layers of flax FRP.

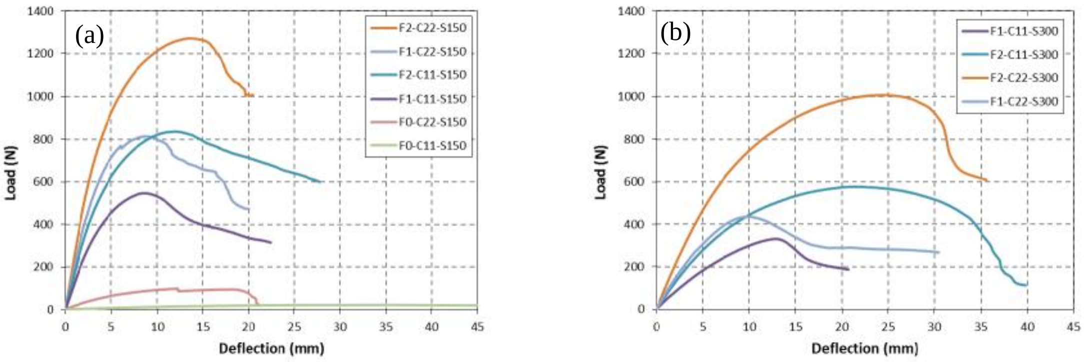

Figure 4: Load-deflection response of flax/cork sandwich composites: (a) S=150 mm; (b) S=300 mm

3.1.2 Glass/Honeycomb Sandwich Composites

Figures 5(a) and 5(b) show the typical load-deflection behavior of glass/honeycomb sandwich beams with 150 and 300 mm span, respectively. Similar to the flax/cork sandwich beams, only one curve out of five curves was selected and presented in the figures. As shown in the figures, all specimens have a short linear behavior followed by an ascending non-linear behavior up to a peak point and then a descending branch to failure. Typical failure was shear failure of the core, however in some cases the buckling failure of the compressive skin controlled the failure. No tensile rupture of the skin was observed. The figures show that the 25 mm thick honeycomb cores without skins are weak and flexible, where the crushing of the compressive region of the core controls the failure. The honeycomb cores with 12 and 6 mm were weaker (see Table 2) and are not shown in the figures. With adding one layer of glass FRP at each side of the cores, the failure mode typically were changed to shear failure of the core along buckling of the cell walls. For the curves with more sudden drop after the peak load, the core buckling was more dominant. Figure 5(a) shows that the specimen G1-H6-S150 has peak load of about 563 N with a gradual descending branch indicating a core shear failure. With increasing the thickness of the core to 12 and 25 mm, the peak load increases to 863 and 1413 N, respectively. However, the descending branch shows that core buckling is the dominant failure mode. The same behavior can be seen in Figure 5(b). The figures show that increasing the core thickness increases the stiffness of the specimens significantly.

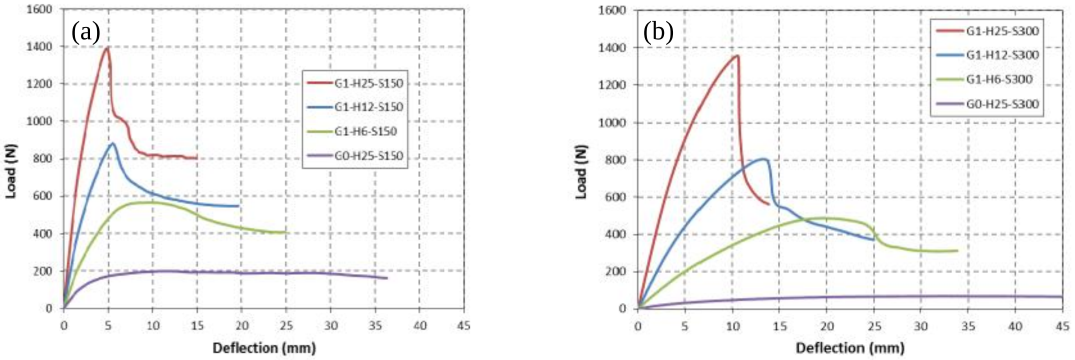

Figure 5: Load-deflection response of glass/honeycomb sandwich composites: (a) S=150 mm; (b) S=300 mm

3.2 Calculation of Flexural and Shear Properties

The mid-span deflection of a sandwich beam with identical facings in flexure is given as follows:

$$[1]\quad \Delta = \frac{P(2S^3-3SL^2+L^3)}{96D} + \frac{P(S-L)}{4U}$$

where Δ = sandwich beam mid-span deflection in mm, P = total applied force in N, S = support span length in mm, L = load span length in mm (L = 2S/11 in this study), D = flexural stiffness in N-mm^2, and U = transverse shear rigidity in N. Given deflections and applied forces from results of testing the same sandwich beam with two different loading configurations, the flexural stiffness, D, and the transverse shear rigidity, U, can be determined from simultaneous solution of the deflection equation (Eq. 1) for the two loading cases. The core shear modulus can then be calculated as follows:

$$[2]\quad G = \frac{U(d-2t)}{(d-t)^2 b}$$

where G = core shear modulus in MPa, d = sandwich thickness in mm, and b = sandwich width in mm, t = facing thickness in mm. It should be noted that the equations in this section are applicable for the linear part of the force-deflection response of the sandwich beams. In this study, two standard four-point loading configurations were performed based on ASTM D7249 (2006). The configuration #1 was performed using S1=300 mm ($L_1=2S_1/11=54.54$ mm) and the configuration #2 was performed using $S_1=150$ mm ($L_1=2S1/11=27.27$ mm). Using Eq. 1, the solution to calculate the flexural stiffness, shear rigidity, and core shear modulus for each selected value of load is given as follows:

$$[3]\quad D = \frac{33P_1S_1^3\left(18048-161051S_2^2/S_1^2\right)}{247808\Delta_1\left(121-72P_1S_1\Delta_2/P_2S_2\Delta_1\right)}$$

$$[4]\quad U = \frac{11979P_1S_1\left(9024S_1^2/S_2^2-161051\right)}{484\Delta_1\left(1299456P_1S_1^3\Delta_2/P_2S_2^3\Delta_1-19487171\right)}$$

where P_1 and P_2 = applied forces in N, Δ_1 and Δ_2 = mid-span deflection in mm, S_1 and S_2 = support span lengths in mm, L_1 and L_2 = load span lengths in mm related to configuration #1 and #2; respectively. Then the core shear modulus can be calculated using Eq. 2. For each specimen, the flexural stiffness, shear rigidity, and core shear modulus were calculated for a series of applied forces up to the proportional limits of the two loading configurations. Values were calculated for a minimum of 10 force levels evenly spaced over the linear range. As five identical specimens were tested for each case, the procedure were repeated and the average values were calculated. The results are presented in the sections below.

3.2.1 Flexural Stiffness

Figure 6 shows the variation in flexural stiffness (D) of glass/honeycomb and flax/cork sandwich composites calculated using Eq. (3). Fig. 6(a) shows that with increasing the honeycomb core thickness from 6 to 25 mm, the flexural stiffness increases from about 43 to 617 MN-mm2. It means that sandwich panels with 25 mm honeycomb core (i.e. 4 times thicker than 6 mm honeycomb core) has flexural stiffness 14 times of the one with 6 mm honeycomb core. Figure 6(b) shows that the flax/cork sandwich composites with two layers of flax FRP are almost 2 times stiffer than those ones with one layer of flax FRP. Also, doubling the cork thickness almost doubles the stiffness. Overall, the stiffness of 22 mm thick cork with two layers of flax FRP is comparable to that of 12 mm thick honeycomb with one layer of glass FRP.

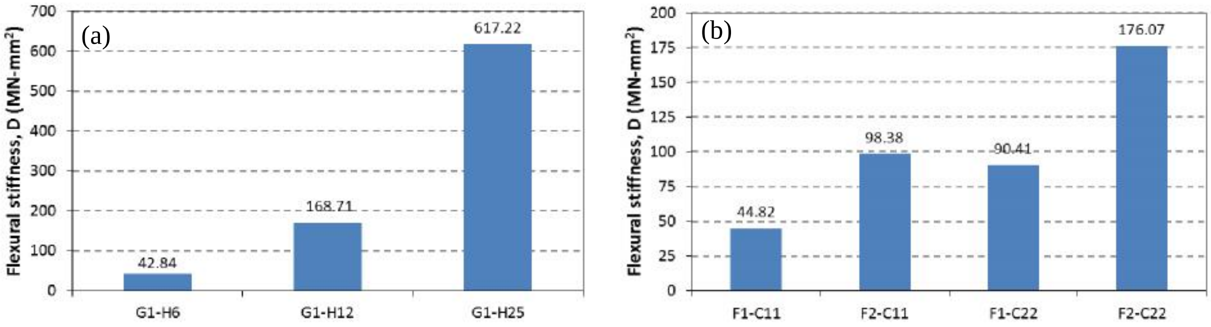

Figure 6: Variation in flexural stiffness of (a) glass/honeycomb and (b) flax/cork sandwich composites

3.2.2 Transverse Shear Rigidity

Figure 7 shows the variation in transverse shear rigidity (U) of glass/honeycomb and flax/cork sandwich composites. Figure 7(a) shows that the transverse shear rigidity of glass/honeycomb sandwich composites increases with the thickness of the core. For example, by increasing the honeycomb core thickness from 6 to 25 mm, the transverse shear rigidity increases from 6.2 to 16.2 kN. Figure 7(b) shows that increasing both skin thickness and cork thickness increases the transverse shear rigidity. Overall, the transverse shear rigidity of 22 mm thick cork with two layers of flax FRP is comparable to that of 12 mm thick honeycomb with one layer of glass FRP.

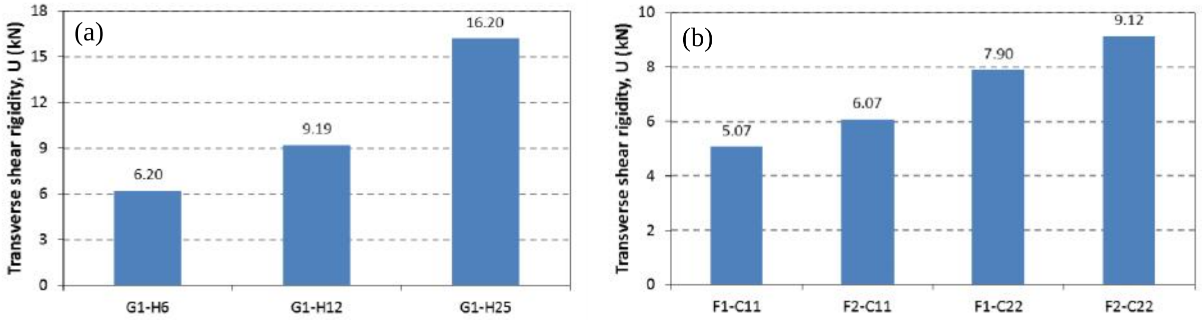

Figure 7: Variation in transverse shear rigidity of (a) glass/honeycomb and (b) flax/cork sandwich composites

3.2.3 Core Shear Modulus

Figure 8 shows the variation in core shear modulus (G) of glass/honeycomb and flax/cork sandwich composites. Figure 8(a) shows that with increasing the honeycomb core thickness, the core shear modulus decreases, slightly. This could be due to the fact that thinner honeycombs have shorter cells with more continuity to the top and bottom veil and film barrier. Figure 8(b) shows that the core shear modulus of flax/cork sandwich composites is not the function of the skin thickness, as expected. Thicker cork has slightly less shear modulus, which could be the result of the bonding two cork board together. Overall, the average core shear modulus of the honeycomb and cork board is 12.38 and 7.02 MPa, respectively. The cork board has a shear modulus 44% less that the honeycomb boards.

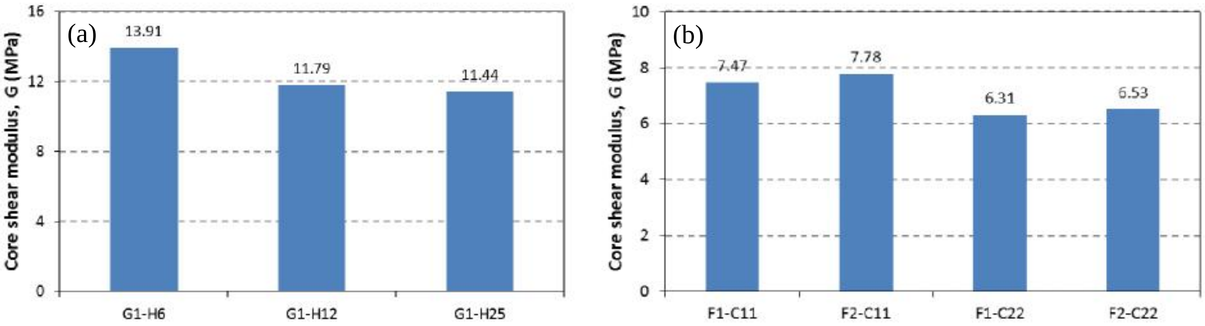

Figure 8. Variation in core shear modulus of (a) glass/honeycomb and (b) flax/cork sandwich composites

4. ANALYTICAL STUDY

This section presents an elastic analysis of the sandwich beams tested earlier. Consider a sandwich beam with the cross-section as shown in Figure 3. The cross-section has a width b and total thickness h. Each skin has thickness t and the two skins are separated by a relatively thick core of thickness c. It is assumed that all three layers are perfectly bonded together so the sandwich beam acts compositely. Therefore, its flexural stiffness, D, is the sum of the flexural stiffness of both skins and the core, measured about the centroidal axis of the cross-section as follows (Zinno et al. 2008):

$$[5] \quad D = E_f \frac{bt^3}{6} + E_f \frac{btd^2}{2} + E_c \frac{bc^3}{12}$$

where E_f and E_c are the modulus of elasticity of skin and core, respectively, and d is the distance between the center lines of the upper and lower skins. In real sandwich beams, the second term (D_2) is invariably dominant. In fact, the first term (D_1) and the third term (D_3) amount to less than 1% of the second term when the conditions below are applicable.

$$[6] \quad \frac{d}{t} > 5.77$$

$$[7] \quad 6\frac{E_f}{E_c}\frac{t}{c}\left(\frac{d}{c}\right)^2 \geq 100$$

Table 3 summarizes the results of the analytical study. It is observed that he model overestimates the flexural stiffness of the last two sandwich beams (i.e. F1-C22 and F2-C22). As the 22 mm thick cork was made of two 11 mm thick cork sheets, a slight slip between the two sheets might be happened when the sandwich beam deflected in the experimental study. The slip could reduce the composite action of the sandwich cross-section to a partial composite action and result in a lower experimental flexural stiffness compared to the analytical flexural stiffness. Obviously, the analytical study implemented in this study is based on a perfect bond between components and does not consider the partial composite action. Further studies are needed to quantify the exact effect of slip and partial composite action. Also, using a single sheet of thicker cork is recommended for further experimental study to eliminate any slip.

5. CONCLUSION

In this study, two types of fiber materials, namely synthetic (glass) and natural (flax) fibers, as well as two types of core materials, namely polypropylene honeycomb and cork core materials were used to make sandwich panels. A number of small-scale sandwich beam specimens were prepared and tested under four-point bending. The load-deflection behavior, strength, stiffness, and failure mode of the specimens are evaluated. Overall, the flexural stiffness and transverse shear rigidity of 22 mm thick cork with two layers of flax FRP was comparable to those of 12 mm thick honeycomb with one layer of glass FRP. The cork board showed a shear modulus 44% less that the honeycomb boards. Also, an analytical model was adopted to compute the flexural stiffness, shear rigidity, and core shear modulus of the sandwich panels. The analytical results showed a good agreement with the test results. Overall, the glass/honeycomb specimens showed better performance compared to the flax/cork specimens. More research with different natural core materials is needed to improve the mechanical properties of bio-based sandwich composites.

Table 3: Comparison of modeling and test results

Specimen	Model: Flexural Stiffness Components (MN-mm^2)			Flexural Stiffness D, (MN-mm^2)		Modeling Error (%)	d/t	$6\frac{E_f}{E_c}\frac{t}{c}\left(\frac{d}{c}\right)^2$
	D_1	D_2	D_3	Model	Test			
G1-H6	0.43	42.65	0.18	43.26	42.84	0.97	5.76	237
G1-H12	0.39	149.78	0.80	150.98	168.71	-10.51	11.27	188
G1-H25	0.41	543.13	4.65	548.19	617.22	-11.18	20.97	117
F1-C11	0.12	41.48	0.30	41.90	44.82	-6.51	10.89	138
F2-C11	0.75	95.56	0.30	96.61	98.38	-1.80	6.51	317
F1-C22	0.11	155.34	2.53	157.98	90.41	74.74	21.45	61
F2-C22	1.27	351.93	2.53	355.73	176.07	102.04	9.59	139

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