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Experimental and Analytical Behavior of Sandwich Composite Beams: Comparison of Natural and Synthetic Materials

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ABSTRACT: In this study, the flexural behavior of sandwich composite beams made of fiber-reinforced polymer (FRP) skins and light-weight cores are studied. The focus is on the comparison of natural and synthetic fiber and core materials. Two types of fiber materials, namely glass and flax fibers, as well as two types of core materials, namely polypropylene honeycomb and cork are considered. A total of 105 small-scale sandwich beam specimens (50 mm wide) were prepared and tested under four-point bending. Test parameters were fiber types (flax and glass fibers), core materials (cork ad honeycomb), skin layers (0, 1, and 2 layers), core thicknesses (6 to 25 mm), and beam spans (150 and 300 mm). The load-deflection behavior, peak load, initial stiffness, and failure mode of the specimens are evaluated. Moreover, the flexural stiffness, shear rigidity, and core shear modulus of the sandwich composites are computed based on the test results of the two spans. An analytical model is also implemented to compute the flexural stiffness, core shear strength, and skin normal stress of the sandwich composites. Overall, the natural fiber and cork materials showed a promising and comparable structural performance to their synthetic counterparts.

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

1. INTRODUCTION

Sandwich composites made of fiber-reinforced polymer (FRP) skins and light-weight core materials are very effective systems in high-performance structural 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 out-of-plane loadings. 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 sandwich structure. As the 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 [1]. Some of the earliest applications of sandwich structures in the 20th century were in aircraft industry [2]. This was followed by expansion into the aerospace, automotive, and marine industries [3]. In civil engineering, there are many applications such as cladding, decking, and roofing panels that can benefit greatly from sandwich structures.

Sandwich composites with FRP skins used in engineering applications are typically made of glass FRP skins separated by a low-density foam or honeycomb core. 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 the result, glass FRPs 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 economic, technical, and ecological advantages over synthetic fibers [4-9]. FRP composites made of natural fibers have many potentials at the end of their life span for recycling and degradation, depends on the type of the polymer used. The worst case scenario would be the incineration of natural FRPs to generate electricity, which reduces the volume of materials significantly to fly ash and bottom ash with many potential applications in concrete industry [10]. In addition, there are other natural light-weight materials such as cork that can be potentially implemented as a replacement for conventional synthetic core materials.

Cork has a cellular structure similar to that of a honeycomb and its cells are mostly formed by suberin, lignin, and cellulose. This cellular configuration has a strong influence on the mechanical properties of cork-based materials [11-12]. Natural cork is expensive and is mainly used as bottle stopper in wine industry. The manufacturing process generates a lot of cork waste which are used to produce cork granulates. The granules with a specific size and volumetric mass are mixed with a glue and other additives to produce agglomerated cork products [13]. There are many researches about using agglomerated cork boards as the core of sandwich composites. For example, Reis and Silva [14] studied the flexural and shear behavior of different sandwich specimens with carbon FRP skins and cores of different cork agglomerates. The study showed that commercial cork-based boards are suitable for application as a sandwich core materials but that they are not optimized for it as the failure occurs in the material used to glue the cork granules in the cork agglomerates.

In order to enhance the behavior of cork, Castro et al. [12] aimed to fabricate cork agglomerates from cork granules and epoxy resin to enhance the mechanical properties of the cork when integrated as core materials in sandwich structures with carbon FRP skins. Cork agglomerates with enhanced mechanical performance were fabricated and tested under mechanical loading. The results revealed that cork agglomerates performance essentially depends on the cork granule size, its density, and the bonding procedure used for the cohesion of granulates, and these parameters can be adjusted in function of the final application intended for the sandwich composite. The results also allow inferring that optimized cork agglomerates have some specific properties that confirm their superior ability as a core material of sandwich composites when compared with other conventional materials.

Recently, Lakreb et al. [15] studied the mechanical performance of sandwich composites made of cork agglomerate as core material and pine wood veneer as skins. The results suggested that these sandwich panels may be used as construction materials for paneling or partition walls. Also, Hachemane et al. [16] studied the impact behavior of a cork sandwich composite with jute FRP skins. The results show that the maximum force and the damage size are influenced by the cork density and the impact energy. More recently, Ferreira et al. [17] studied the mechanical behavior and fire resistance of sandwich wall panels composed of thick cork agglomerate (hereafter called cork) plates and glass FRP skins. It was found that the sandwich panels have substantially higher fire resistance than those using synthetic materials in their core.

Based on the literature, it can be conclude that cork sandwich composites have many potentials, however majority of research were concentrated on skins made of carbon and glass FRPs. As cork is a natural material, it is important to study the cork sandwich composites with FRP skins made of natural fibers rather than synthetic fibers. In this study, two types of fiber materials, namely glass and flax fibers, as well as two types of core materials, namely polypropylene honeycomb and cork materials are considered for sandwich composites. A number of small-scale sandwich beam specimens were prepared and tested under four-point bending. The strength, stiffness, and failure mode of the specimens are evaluated. Also, an analytical model is developed to compute the flexural stiffness of the sandwich composites.

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 bonded to cork using resin were being compared to glass fabrics bonded to honeycomb 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 different variations of specimens can be seen in Table 1. Five identical specimens were made for each case. Some cork and honeycomb specimens were tested without skin (i.e., 0 skin layer) for comparison. Two spans of 150 mm and 300 mm were selected to have enough test data to evaluate the flexural stiffness, shear rigidity, and core shear modulus of the sandwich composites regardless of their spans. The test specimens are identified with the specimen identification (ID) as FX-CY-SZ and GX-HY-SZ; where F stands for flax FRP, G stands for glass FRP, C stands for cork, H stands for honeycomb, and S stands for span. In addition X stands for the number of layer of each skin, Y stands for the thickness of the core material, and Z stands for the span of the beam specimens. For example F2-C22-S150 is a sandwich beam with two layers of flax FRP skins and 22 mm thick cork core tested with 150 mm span.

2.2. Material Properties

For flax FRP skins, a 275 g/m^2 stitched unidirectional flax fabric was used (manufacturer: Composite Evolution, Chesterfield, UK). 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. For glass FRP skins, a 955 g/m^2 stitched unidirectional glass fabric was used (manufacturer: Fibre Glast, Brookville, OH, USA). For making both flax/cork and glass/honeycomb sandwich composites, a vinyl ester resin catalyzed with 1.25% (by weight of the resin) methyl ethyl ketone peroxide (MEKP) was used (manufacturer: Fibre Glast, Brookville, OH, USA). The resin cured at room temperature for 24 hours and post-cured for 2 hours at 138°C was reported by the manufacturer to have the tensile strength of 82 MPa, elastic modulus of 3.72 GPa, and rupture strain of 7.9%.

Five identical dog-bone shape tensile coupons of flax and glass FRPs with an overall dimension of 25 x 165 mm were prepared using hand lay-up method and tested according to ASTM D638 [18]. A 30 kN universal testing machine with a displacement rate of 2 mm/min and a 25 mm gauge length extensometer sensor was used. Figure 1 shows the tensile test results based on nominal thicknesses of 1.0 and 1.5 mm of flax and glass FRP, respectively. The average tensile strength of flax and glass FRPs was 207.42 and 865.35 MPa, respectively. The dotted lines in Figure 1 show the elastic modulus of flax and glass FRPs with the average values of 21.94 and 37.37 GPa, respectively. As shown in Figure 1, the glass FRPs have almost a linear behavior up to the rupture, however flax FRPs have a bilinear behavior with a transition zone at a strain ranging from 0.002 to 0.003 mm/mm and a secondary slop of almost two-third of the initial slope.

For sandwich composites with flax FRP skins, commercial cork sheets (600 x 900 mm) with 11 mm thickness and the density of 200 kg/m^3 (reported by manufacturer) were used (manufacturer: Cleverbrand Inc., Cheektowaga, NY, USA). 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 composites with glass FRP skins, commercial 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 (manufacturere: Plascore Inc., Zeeland, MI, USA). The cells were covered with veil and film barrier to prevent resin filling the cells. Three honeycomb sheets with nominal thickness of 6.3 mm (0.25 in.), 12.7 mm (0.5 in.), and 25.4 mm (1 in.) were used. With considering the veil and film barrier, their 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. As the cells of all three honeycomb sheets were covered with similar veil and film barrier, the overall density of the thinnest honeycomb sheet was the largest.

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. Although the panels were small enough to fit safely into the relatively small fume hood available in the laboratory. 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 (see Figure 2). 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 25 mm overhang was provided at each support, so 200 mm long specimen has a span of 150 mm. A micrometer was used to measure the thickness and width of each specimen at three locations and averaged for further calculations.

2.4.Test Setup

As shown in Figure 3, a four-point bending setup was used for all specimens with a different loading span proportional to the supporting span. The loading span (L) was equal to (2/11) of the supporting span (S) per ASTM D7249 [19] and D7250 [20]. The load was applied from the top down using a 30 kN universal testing machine. The tests were displacement controlled with the rate of 2 mm/min. The beam specimens were tested with a simply supported span with 25 mm overhang at each end.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The summary of the test results plus their failure mode are presented in Table 2. As 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 are provided.

3.1. Failure Modes

As demonstrated in Figure 3, the failure modes of the specimens can be categorized as: (a) skin indentation; (b) cork core shear failure; (c) skin buckling; (d) core shear; (e) core shear/buckling; and (f) core crushing. Indentation failure is a function of the out of plane compressive strength of the core and the area over which the load is applied (see Figure 3a). 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 (see Figure 3b). For the short cork sandwich specimens with 22-mm thick cork (i.e. F1-C22-S150 and F2-C22-S150), the core shear was the failure mode. 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 (see Figure 3c). 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 (see Figure 3d). 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 (see Figure 3e). For the case of specimens without skins, the honeycomb showed an excessive plastic deformation due to crushing of the core at the compressive side (see Figure 3f). The cork specimens without skins failed due to rupture at the tension side. The cork core tensile rupture is not shown in the figure. 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.

3.2. Load-Deflection Responses

3.2.1. Flax/Cork Sandwich Composites

Figures 4(a) and 4(b) demonstrate the typical load-deflection behavior of flax/cork sandwich beams with 150 and 300 mm spans, respectively. 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 were selected and presented in the figures. As shown, all specimens have a short linear behavior followed by an ascending non-linear behavior up to a peak point and then it is followed by a descending branch. As discussed, the typical failure was shear failure of the core, however the indentation or buckling of the top skin controlled the failure in the specimens with thin skins. No tensile rupture of the bottom skin was observed as expected.

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 the specimens F1-C11-S150 and F0-C11-S150 implies 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. Figure 4(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 to those 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 specimens with two layers of flax FRP.

3.2.2. 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 spans, respectively. Similar to flax/cork sandwich beams, only one curve out of five curves were selected and presented in the figures. Typical failure was shear failure of the core, however in some cases it was accompanied with buckling of the cells. As expected, 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 6 and 12 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 changes to shear failure of the core along buckling of the cell walls for thicker cores. 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 average 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). Overall, the figures demonstrate that increasing the core thickness increases the strength and stiffness of the specimens, significantly. It should be noted that each curve shown in figures represents a curve approximately located in the middle of all five curves of five identical specimens. Thus, the selected curve may show a slight difference from the corresponding average peak load and stiffness reported in the text.

3.2.3. Comparison of Flax/Cork and Glass/Honeycomb Sandwich Composites

A comparison between Figure 4 and Figure 5 demonstrates that the short flax/cork specimens with 11 mm thick cork and two layers flax FRP skins (F2-C11-S150) with an average strength of 839 N have comparable behavior to the short glass/honeycomb specimens with 12 mm thick honeycomb and one layer glass FRP skins (G1-H12-S150) with an average strength of 863 N. The glass/honeycomb specimens have an average initial stiffness 52% larger than that of the flax/cork specimens. Also, the corresponding long glass/honeycomb specimens (i.e., G1-H12-S300) have an average strength and initial stiffness 34% and 59%, respectively, larger than those of long flax/cork specimens (i.e., F2-C11-S300).

3.3. Calculation of Flexural and Shear Properties

In general, the displacement of a sandwich beam can be found by superposing the bending and shear deflections. The mid-span deflection of a sandwich beam with identical facings in four-point bending (see Figure 2d) is given as follows [20]:

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

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 the results of testing the same sandwich beam with two different loading configurations (i.e. S=150 and 300 mm), 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:

$$G = \frac{U(h - 2t)}{h - t\ {}^{2}b} \qquad (2)$$

where G = core shear modulus in MPa, h = sandwich thickness in mm, and b = sandwich width in mm, and 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. The configuration #1 was performed using S_1=300 mm (L_1=2S_1/11=54.54 mm) and the configuration #2 was performed using

S_1=150 mm (L_1=2S_1/11=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:

$$D = \frac{33P_1S_1^3\ \ 18048 - \ 161051S_2^2/S_1^2}{247808\Delta_1\ \ 121 - \ 72P_1S_1\Delta_2/P_2S_2\Delta_1} \tag{3}$$

$$U = \frac{11979P_1S_1\ \ 9024S_1^2/S_2^2 - \ 161051}{484\Delta_1\ \ 1299456P_1S_1^3\Delta_2/P_2S_2^3\Delta_1 - \ 19487171} \tag{4}$$

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.

3.3.1. Flexural Stiffness

Figure 6 shows the variation in flexural stiffness (D) of glass/honeycomb and flax/cork sandwich composites calculated using Eq. (3). In the figure, the bars show a standard deviation above and below the average value of five test specimens. Figure 6(a) shows that increasing the honeycomb core thickness from 6 to 25 mm increases the flexural stiffness from about 43 to 617 MN-mm^2. It means the sandwich panel 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 that 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.

3.3.2. 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 to 16 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.

3.3.3. 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

4. ANALYTICAL STUDY

This section present an analytical modeling of the sandwich beams were tested earlier. Consider a sandwich beam with the cross-section as shown in Figure 9. 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 [1]:

$$D = E_f \frac{bt^3}{6} + E_f \frac{\mathrm{btd}^2}{2} + E_c \frac{\mathrm{bc}^3}{12} = D_1 + D_2 + D_3 \qquad (5)$$

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) amounts to less than 1% of the second term when the condition below are applicable [2].

$$\frac{d}{t} > 5.77 \qquad (6)$$

The error introduced by neglecting the first term is therefore nneglegible. Majority of sandwiche composites with thin FRP slins usually satisfy the condition. Table 3 demonstrates that the majority of sandwich specimens tested in this study satisfy the d/t criteria. The flax/cork sandwich specimens had d/t ranging from 6.51 to 21.45. The glass/honeycomb sandwich specimens had d/t ranging from 5.76 to 20.97. The actual thickness of skins were calculated using subtracting the thickness of the core from the total thickness of the sandwich at three sections of each specimen and then the values were averaged. The third term (D_3) amounts to less than 1% of the second term and may be consequently neglected when the condition below are applicable [2].

$$6\frac{E_f}{E_c}\frac{t}{c}{\frac{d}{c}}^{2} > 100 \qquad (7)$$

Table 3 shows that the majority of sandwich specimens tested in this study satisfy the criteria. The flax/cork sandwich specimens had the ratio ranging from 61 to 317 and the glass/honeycomb sandwich specimens had the ratio ranging from 117 to 237. The only sandwich specimen that does not satisfy the criteria is F1-C22 with a ratio of 61. As presented in Table 3, the first and third terms are very small and can be neglected, however they were included in the total flexural stiffness of each sandwich in this study. As shown in the table, the 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 thick cork is recommended for further experimental study to eliminate any slip.

4.1. Core Shear Strength

For a sandwich beam with weak core that satisfies Eq. 7, the shear stress may be assumed constant over the depth of the core [2]. The constant shear stress in the core is then given by:

$$\tau = \frac{V}{D}\frac{E_f t d}{2} \tag{8}$$

where V is the maximum shear force. If, in addition, the flexural rigidity of the skins about their own separate axes is small (i.e., Eq. 6 is fulfilled), then the first term of Eq. 5 may also neglected as well as the third term. In this case the shear stress τ in the core can be simplified as follows:

$$\tau = \frac{V}{bd} \tag{9}$$

For the cork/flax sandwich specimens with core shear failure, the shear stress of specimens F2-C11-S150, F1-C22-S150, F2-C22-S150, and F2-C22-S300 is calculated as 0.64, 0.33, 0.51, 0.40 MPa; respectively. The average shear strength of the cork used in this study is calculated as 0.47 MPa. This can be compared to tests results by Castro et al. [12] with an average shear strength of 0.16 and 0.87 MPa for commercial and modified cork materials, respectively. The same was performed for honeycomb/glass sandwich specimens and an average shear strength of 0.60 MPa was obtained. It can be concluded that the cork board used in this study is only 22% weaker that the honeycomb boards in shear.

4.2. Skin Normal Stress

For a sandwich beam with weak core that satisfies Eqs. 6 and 7, the skin normal stress σ can be calculated as follows:

$$\sigma = \frac{M}{bdt} \tag{10}$$

where M is the maximum bending moment. The only cork/sandwich specimen with skin buckling was F2-C11-S300. The maximum normal stress in the compressive skin of the specimen was obtained as 27 MPa; which is 13% of the tensile strength of flax FRPs presented in Figure 1(a). This is explains why tensile rupture of skin is not achievable in sandwich structures with identical skins. For all flax/cork and honeycomb/glass specimens, the average normal stress of skin was obtained as 21 and 44 MPa; respectively. It shows that flax and glass FRP skins were loaded to 10 and 5% of their tensile strength; respectively. In the other word, flax FRPs were implemented more effective than glass FRPs.

5. CONCLUSION

In this study, two types of fiber materials, namely glass and flax fibers, as well as two types of core materials, namely polypropylene honeycomb and cork core materials were used to make sandwich panels. A total number of 105 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 were evaluated. Moreover, based on deflections and applied forces from the results of testing the same sandwich beam with two different loading configurations (i.e. 150 and 300 mm spans), the flexural stiffness, the transverse shear rigidity, and the core shear modulus of the sandwich composites were determined from simultaneous solution of deflection equations. An analytical model was also implemented to compute the flexural stiffness, shear strength, and skin normal stress of the sandwich specimens. The following conclusions can be drawn:

- The most common failure mode of the sandwich specimens was the shear failure of the cores. However, the specimens with one layer of flax FRP at each side of the cork core experienced the indentation failure of the skin and core area under the point loads. Adding one more layer of flax FRP at each side of the core switched the failure to the core shear failure.
- 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 and shear strength 44 and 22% less that the honeycomb boards, respectively. The shear strength of the cork core was comparable to the honeycomb core, however it is recommended to explore modification methods to enhance the shear modulus of cork cores.
- The sandwich specimens with flax and glass FRP skins failed averagely at 10 and 5% of their skins tensile strength; respectively. It means flax FRPs were implemented more effective than

glass FRPs. Modifying the quality of the cork core could increase their efficiency, however the buckling of the compressive skin can limit the effectiveness of the modification.

- Overall, sandwich composites made of natural flax fibers and natural cork core materials used in the study showed a comparable structural performance with respect to their counterparts made of synthetic glass fibers and synthetic honeycomb core materials.
- More research with different natural core materials is needed to improve the mechanical properties of bio-based sandwich composites. It is recommended to study skin normal stress and core shear stress using strain gauges in the four-point bending tests in future research.

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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

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	Core tensile rupture
F1-C11-S150	501.58	57.38	132.88	9.14	7.58	1.40	Indentation
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	Core 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	Indentation
F2-C11-S300	583.53	17.78	64.25	0.72	20.75	0.90	Skin buckling
F1-C22-S300	437.70	19.86	73.13	4.14	9.85	0.73	Indentation
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

Table 3. Comparison of modeling and test results

Specimen	Model: Flexural Stiffness Components (MN-mm2)			Flexural Stiffness D, ($MN\text{-}mm^2$)		Modeling Error (%)	d/t	$6\frac{E_f}{E_c}\frac{t}{c}\ \frac{d}{c}^{2}$
	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

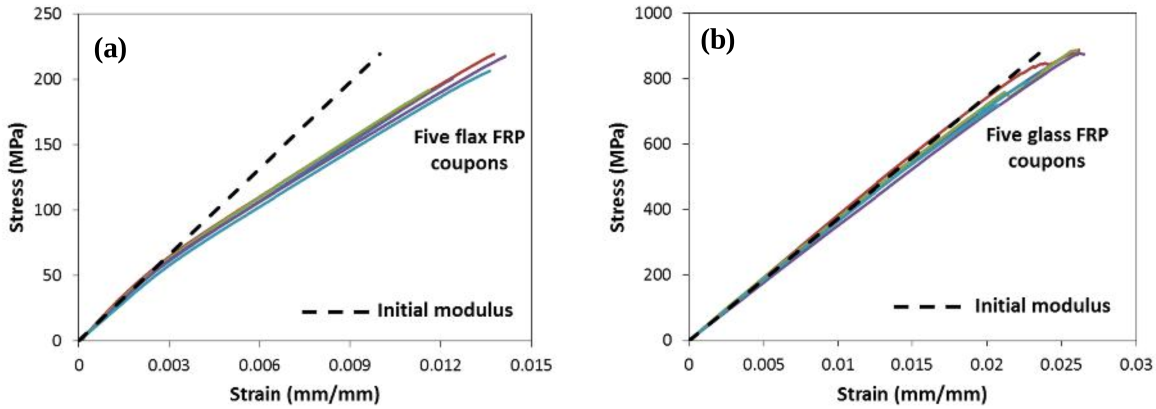

Figure 1. Tensile properties of (a) flax and (b) glass FRPs

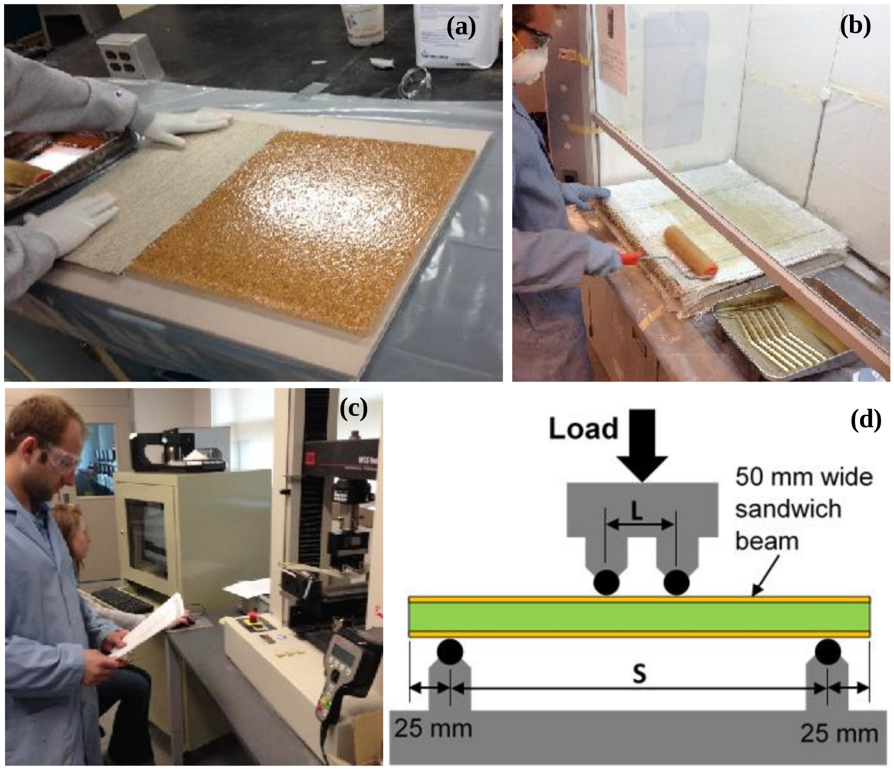

Figure 2. Specimen preparation and test set-up: (a) applying flax fabric on cork; (b) applying glass fabric on honeycomb; (c) test set-up; and (d) four-point bending configuration.

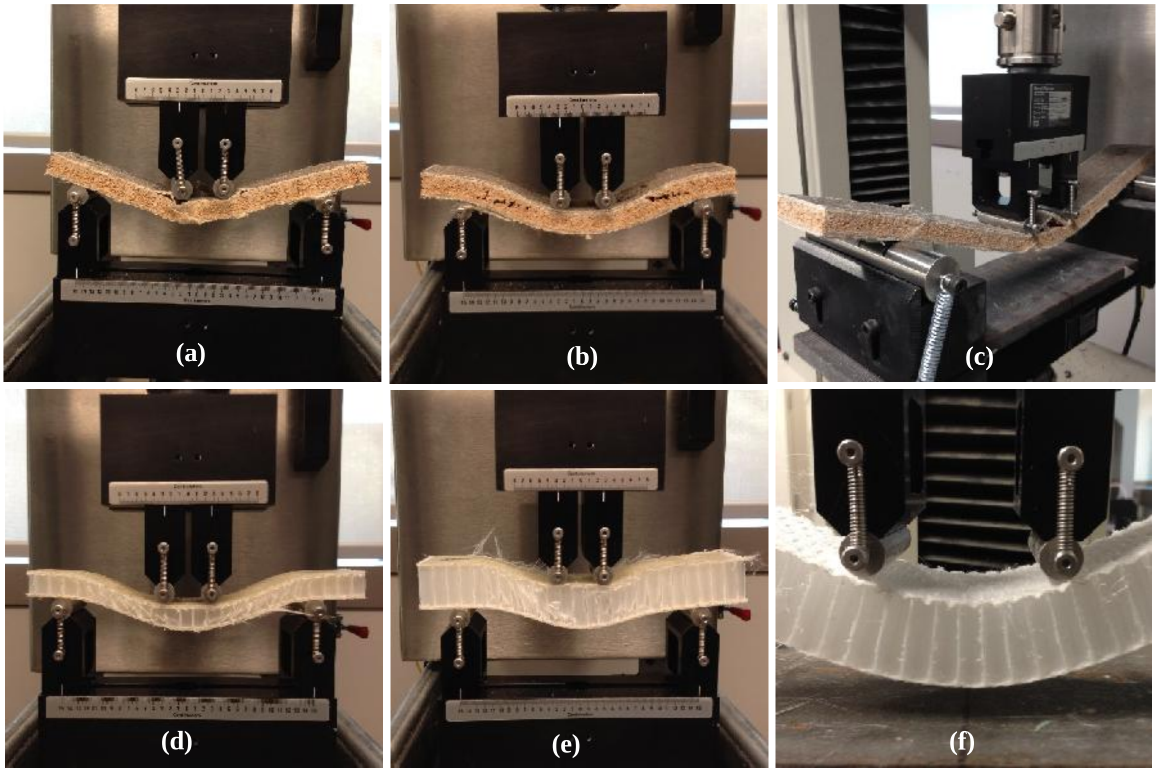

Figure 3. Failure modes: (a) skin indentation; (b) cork core shear failure; (c) skin buckling; (d) core shear; (e) core shear/buckling; and (f) core crushing.

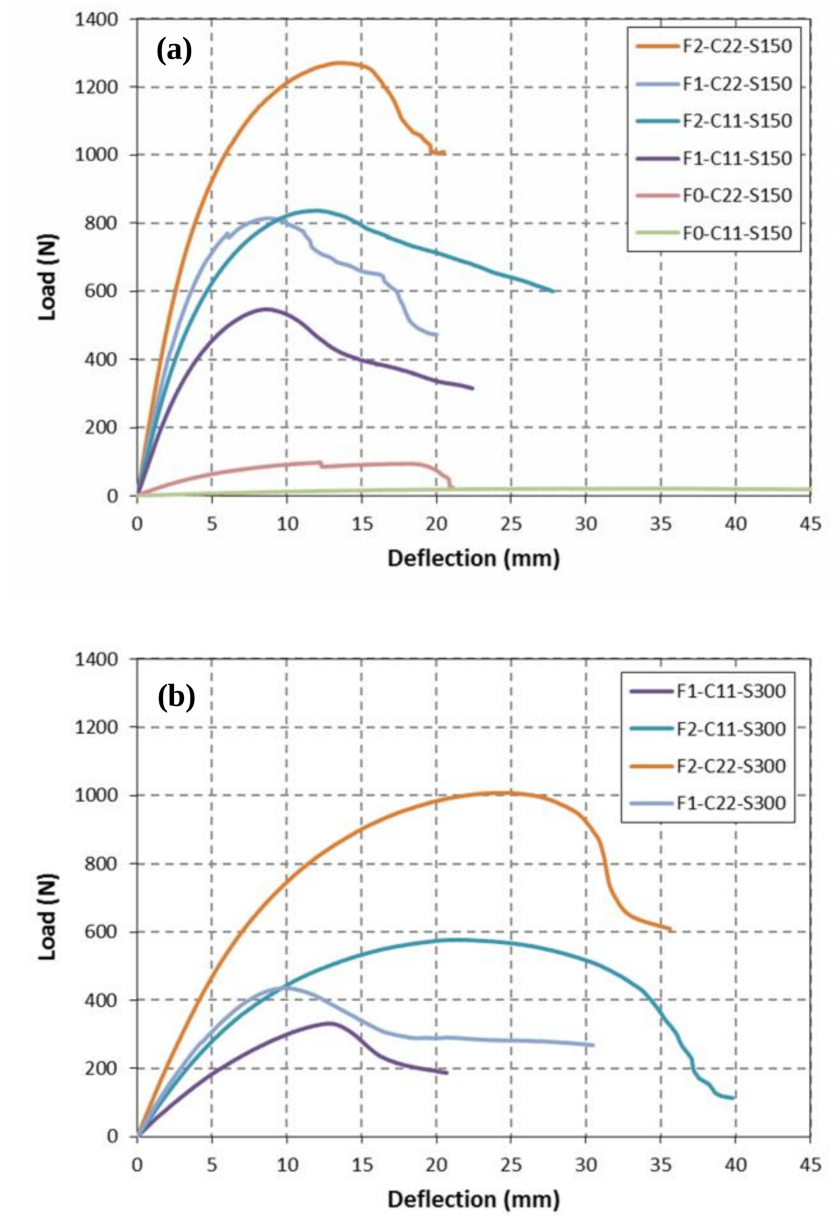

Figure 4. Load-deflection response of flax/cork sandwich composites: (a) S=150 mm; (b) S=300 mm

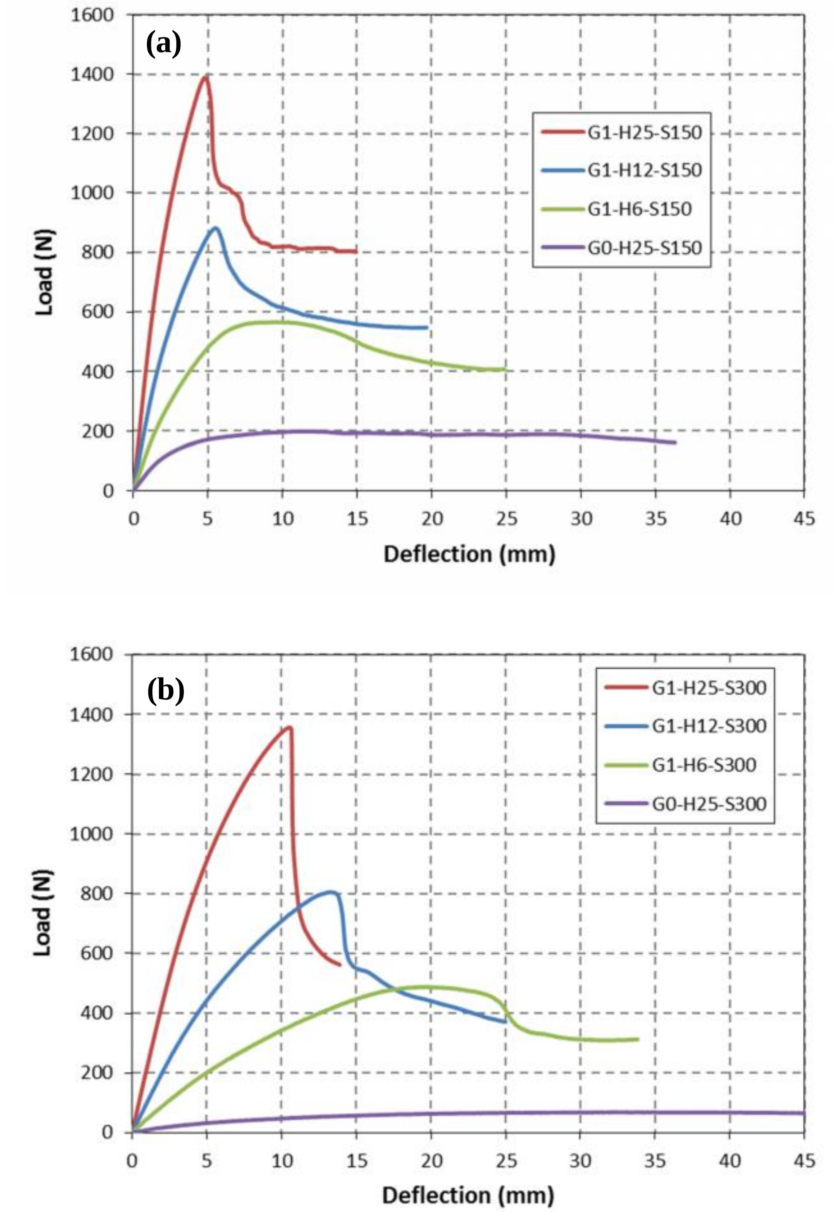

Figure 5. Load-deflection response of glass/honeycomb sandwich composites: (a) S=150 mm; (b) S=300 mm

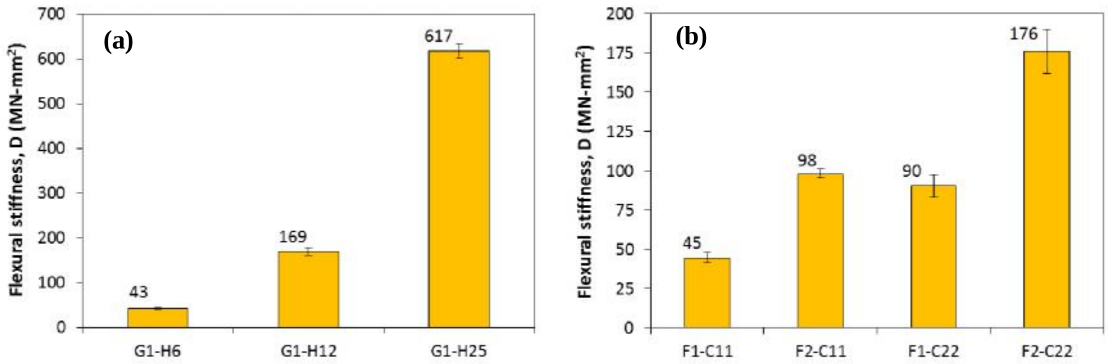

Figure 6. Variation in flexural stiffness of (a) glass/honeycomb and (b) flax/cork sandwich composites.

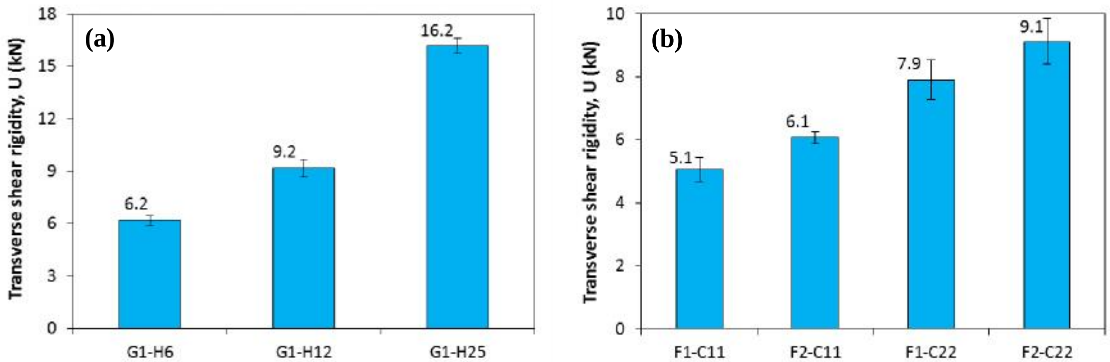

Figure 7. Variation in transverse shear rigidity of (a) glass/honeycomb and (b) flax/cork sandwich composites.

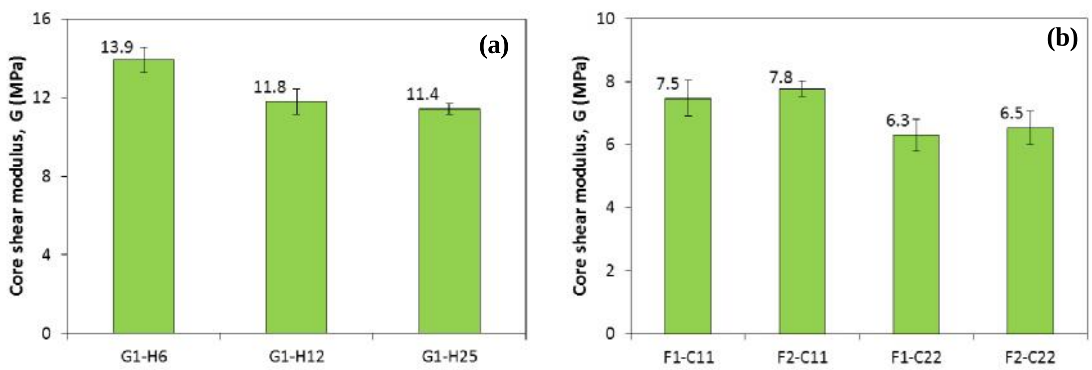

Figure 8. Variation in core shear modulus of (a) glass/honeycomb and (b) flax/cork sandwich composites.

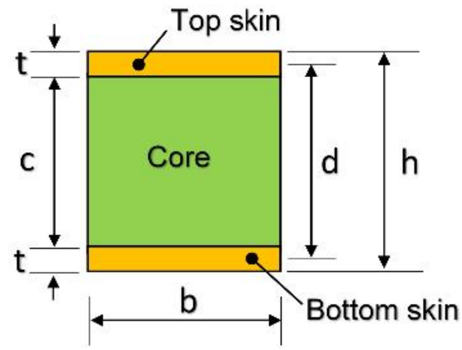

Figure 9. Sandwich beam cross-section