Green Sandwich Composites Fabricated from Flax FRP Facings and Corrugated Cardboard Cores

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Abstract. Composite sandwich beams and panels made of fiber-reinforced polymer (FRP) and lightweight, low-density core materials have been shown to be effective in reducing weight and increasing strength and stiffness in a variety of structural applications. The FRP skins resist the tensile and compressive stresses as a result of flexure, similar to the action of the flanges on an I-Beam, while the core resists shear stresses, provides insulation and increases the distance between skins resulting in a higher moment of inertia. In this study, sandwich panels made of green materials are studied. Namely, flax fibers and partial bio-based epoxy were used for the FRP skin and three flute varieties of corrugated cardboard with bulk densities of 127, 138 and 170 kg/m^3 were used for the core. A total of 30 small-scale sandwich beam specimens were manufactured across six unique beam varieties with dimensions of 50 mm in width, 25 mm in depth, and 200 and 350 mm in length (150 mm and 300 mm spans) to be tested under four-point bending up to failure. This is an ongoing research and so far, 6 of the sandwich beams have been tested and the results are presented in this paper. The load-deflection behavior, load-strain behavior and moment-curvature behavior as well as the strength and stiffness of the sandwich beam specimens were analyzed. Overall, the flax FRP and cardboard sandwiches displayed promising structural behavior and may be considered as a viable, green option for the fabrication of sandwich composite panels.

Introduction

The abundance of structural sandwich panels is growing as civil engineers look to improve the structural efficiency of building materials. Comprised of two high-strength facesheets to resist tensile and compressive stresses of bending as well as a low-density core, sandwich panels are often favoured due to their light weight and high moment of inertia [1]. In addition to separating the two facesheets, the core provides strength to resist transverse and longitudinal shear stresses and may also provide greatly improved thermal insulation [2]. In order to be more environmentally-conscious, building materials must be revaluated to determine how they can become more sustainable and have a smaller environmental impact during production. This will limit waste and pollution in the process of constructing and maintaining buildings and infrastructure.

Although synthetic fiber-reinforced polymer (FRP) composites, such as glass FRP or carbon FRP, are often used for the facesheets of sandwich beams, the concept of using natural fibers, such as flax or hemp, has also been explored [3][4]. Although the natural fibers have a lower strength than their synthetic counterparts, it has been showed that this may be acceptable since the core strength is what often governs the failure of the beams [5][6]. Additionally, natural fibers have many economic and environmental advantages compared to synthetic fibers [7]. Thus, flax FRP facesheets represent a viable structural option for sandwich beams and are a more environmentally-friendly choice than synthetically produced fibers.

Many different core materials have been explored for use in composite sandwich beams and panels. Core materials that are commonly studied include low-density foam and plastic or metal honeycombs [8][9]. In order to present a more sustainable option, this study will use corrugated cardboard as the core material. According to the Paper and Paperboard Packaging Environmental Council (PPEC), approximately 85% of corrugated cardboard in Canada is recycled and new cardboard is produced with nearly 100% recycled materials [10]. Along with being 100% biodegradable, corrugated cardboard is a very sustainable as it can be repurposed and produces very little waste. Although studies have been conducted on bio-based sandwich composites [11], recycled corrugated cardboard has not been explicitly studied in the context of a sandwich beam with natural fibres and natural epoxy.

In this paper, flax FRP facesheets is combined with corrugated cardboard cores to manufacture sandwich beams. In addition to these materials, the beams were cured using a non-toxic and organic epoxy. As a result, the sandwich beams produced were constructed using entirely green materials. The aim of the study is to analyze and evaluate the structural performance of corrugated cardboard and flax FRP composite sandwich beams. Although flax has previously studied for use in sandwich beams, the combination of flax FRP with cardboard has yet to be analyzed. This combination of materials represents a structural panel that has a minimal impact on the environment as corrugated cardboard is readily available and composed almost entirely of recycled material.

Experimental Program

Test Matrix. In total, 30 flax FRP and corrugated cardboard sandwich beams were fabricated to be tested in four-point bending. All specimens were constructed using one layer of flax FRP skin on either side and a corrugated cardboard core with a thickness of approximately 25 mm. The variables being tested were span length as well as the flute of the corrugated cardboard. Two span lengths, 150 mm and 300 mm, as well as three cardboard flutes, B, C and BC, were tested. More information concerning the flutes can be found in the following section, *Material Properties.* A complete summary of this study's test matrix is shown in Table 1. Note that five identical specimens were manufactured and tested per case. All specimens are identified with a specimen ID which follows the format X-SY where X identifies the cardboard flute, S stands for span and Y identifies the specimens test span in mm. For example, the specimen ID B-S150 designates a flax FRP and cardboard sandwich beam constructed using B flute cardboard with a test span length of 150 mm.

Table 1: Test Matrix

Case #	Specimen ID	Flute	Span (mm)
1	B-S150	B	150
2	B-S300	B	300
3	C-S150	C	150
4	C-S300	C	300
5	BC-S150	BC	150
6	BC-S300	BC	300

Material Properties. As previously mentioned, three unique flutes were used in the fabrication of the sandwich beams: B, C and BC. Cardboard flutes are standard in international packing and are identified with a single capital letter. Each flute has a different nominal thickness and density. Table 2 compares the approximate measured dimensions of each flute in this study. The density measurements were taken after the flute layers had been combined into a core for the specimens. Thus, this density reflects the actual density of the core, including the small amount of adhesive used to combine the layers of cardboard.

Table 2: Flute Comparison

Flute	Thickness (mm)	Flutes per Meter	Density (kg/m^3)
B	2.8	160	170
C	4.0	120	127
BC	6.6	Mix	138

Fig. 1 shows a visual comparison between the flutes with both a photo of the flutes as a part of a core as well as a 2D side-view schematic.

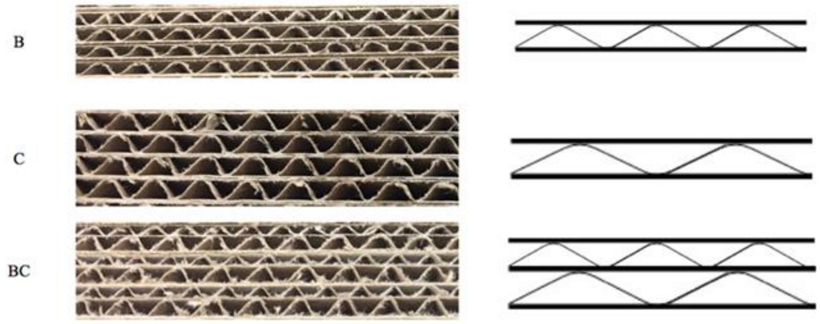

Fig. 1: Visual Flute Comparison

For the flax FRP skins, a unidirectional flax fabric with a reported aerial weight of 275 g/m^2 (gsm) was used. In terms of epoxy, Super Sap ONE was used, which is a bio-based epoxy with a reported tensile strength, modulus and elongation of approximately 53.23 MPa, 2.65 GPa and 6 %, respectively. Betts et al. [12] conducted a study on the tensile properties of flax FRP composites manufactured using the same unidirectional flax fabric and three different epoxies. For the flax FRP samples tested with the bio-based Super Sap ONE epoxy, the average tensile strength and initial modulus were reported to be 198.0 ± 9.3 MPa and 17.09 ± 0.63 GPa, respectively. A secondary modulus was reported as 11.93 ± 0.39 GPa as it was found flax FRPs display an approximately bi-linear mechanical behavior.

The first step in the fabrication of the sandwich beams was to construct the cardboard cores. To do this, strips of cardboard (manufacturer: Maritime Paper, Dartmouth, NS, Canada) approximately 25 mm in with were cut from larger panels using a straight edge and a sharp blade. The two span lengths being tested were 150 and 300 mm, thus strips were cut to lengths of 200 and 350 mm to provide an overhang of approximately 25 mm on each end of the specimen. To bond the strips together, a small amount of Tri-Tex Tribond P-1031 adhesive was used. This adhesive was provided by Maritime Paper and is the same used in the manufacturing of corrugated cardboard. The number of strips in the core varied per flute as all cores were manufactured to have an approximate width of 50 mm. Fig. 2 shows the fabrication process of the cardboard cores.

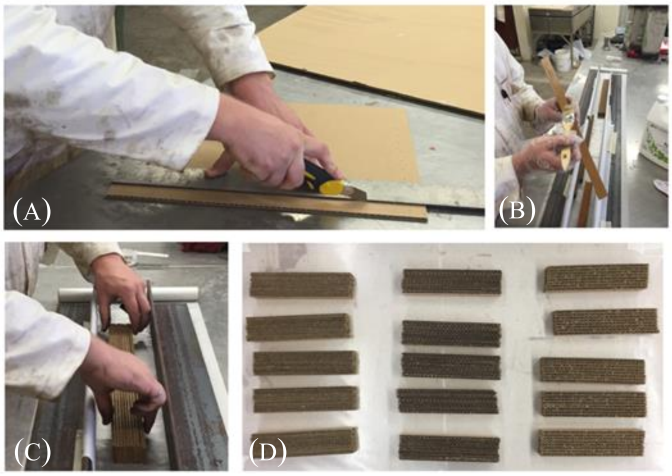

Fig. 2: Cardboard Core Fabrication: (a) Cutting; (b) Applying adhesive; (c) Combining into one core; and (d) Completed cores for 150 mm span.

Once the cardboard cores were completed, the flax FRP skins were applied using the standard wet lay-up method. Sheets of flax fabric approximately 300 mm in width and either 200 or 350 mm in length were pre-cut before the mixing of the epoxy. A sheet of parchment paper was put on the bottom surface and a layer of epoxy was applied. Next, a sheet of flax fabric was applied to the epoxy, then the top side of the fabric was saturated with another layer of epoxy. Each of the five cores per case was placed on the saturated sheet of flax. A piece of particle board was placed on top of the cores while the bottom layer of flax FRP cured. Once the first side of had cured, this process was repeated for applying the flax FRP skin to the other side of the cores. This method allowed for the curing FRP to always be below the cardboard core to help ensure that unwanted resin did not seep down into the cardboard. Fig. 3 shows the application process of the second side of flax FRP.

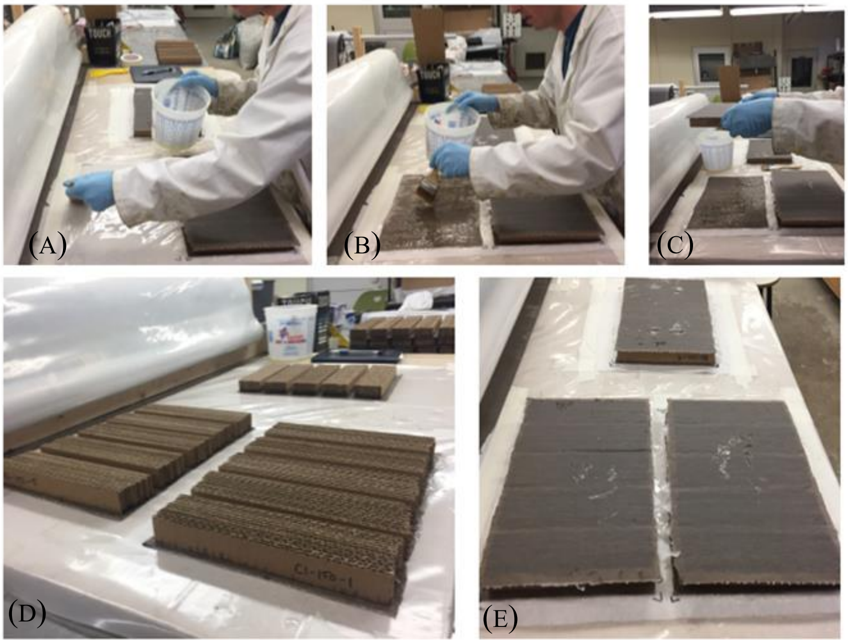

Fig. 3: Fabrication: (a) Applying epoxy; (b) saturating flax fabric; (c) placing cardboard cores on saturated fabric; (d) First side complete; And (e) Both sides complete.

Applying larger sheets of flax fabric allowed for a quicker fabrication process. Once both sides had fully cured, a band saw was used to cut the beams to their approximate width of 50 mm and a rotary sander was used to smooth the edges of the flax composite and ensure it was in line with the sides of the core. A completed sandwich beam is shown in Fig. 4.

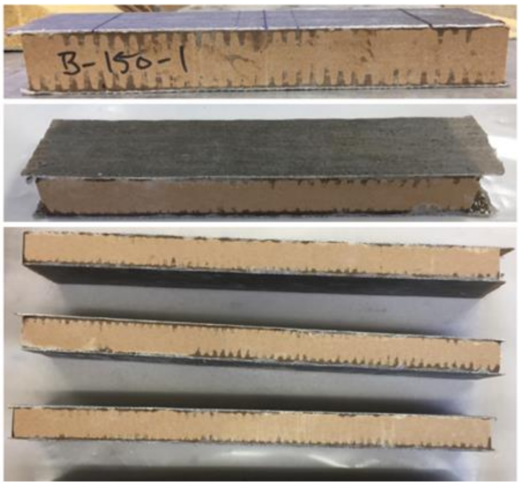

Fig. 4: Completed Beams.

Test Setup. All specimens were tested under four-point bending with a loading span proportional to the supporting spans of 150 and 300 mm. As per ASTM D7249 [13] and D7250 [14], the loading span (L) was to be equal to (2/11) of the supporting span (S). A schematic of the four-point bending set up is shown in Fig. 5 where S is the supporting span, L is the loading span and P is the applied load.

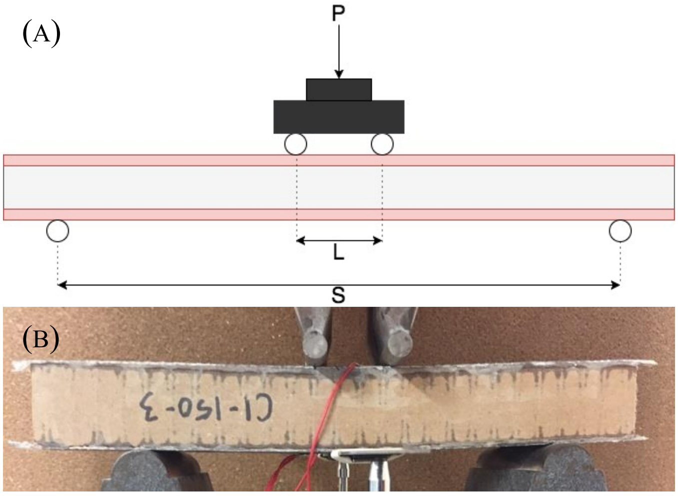

Fig. 5: (a) Four-point bending schematic; and (b) Specimen ready for testing.

In terms of instrumentation, a strain gauge was applied on either side of the sandwich beam, centered in the longitudinal direction to measure he tensile and compressive strains. Additionally, two linear potentiometers were setup in the middle of the beam's span to measure an average mid-span deflection. These values, along with the applied load, measured every 0.1 seconds, were collected for data processing. All tests were completed using a 100 kN universal testing machine and were displacement controlled using a fixed rate of 2 mm/min. Fig. 6 shows photos of the sandwich beams before and after testing.

Results and Discussion

A summary of the test results as well as the modes of failure for the C-S150 and C-S300 specimens is shown below in Table 3.

Table 3: Test Results

ID	Peak Load (N)		Initial Stiffness (N/mm)		Deflection at peak (mm)		Peak moment (N-m)		Curvature at peak (1/km)		Failure Mode
	AVG	**SD**	**AVG**	**SD**	**AVG**	**SD**	**AVG**	**SD**	**AVG**	**SD**	
C-S150	3985	297	2209	144	3.37	0.25	122.3	9.1	953	188	Vertical crushing
C-S300	1715	201	387	27	9.73	1.05	105.2	12.4	1168	208	Longitudinal crushing

NOTE: AVG = AVERAGE; SD = STANDARD DEVIATION

Failure Modes. As expected, the failure of the core was the initial source of failure in both the 150 and 300 mm span sandwich beams. Due to their higher stiffness, the 150 mm span specimens did not flex very much, only deflecting and average of 3.37 mm at peak load. All three tested 150 mm specimens failed by vertical crushing of the core due to transverse shear stresses. This was followed by indentation of the top layer of flax. However, the 300 mm span samples reached a significantly lower peak load and failed by longitudinal crushing of the core due to bending and longitudinal shear stresses. Once the corrugated cardboard had begun crushing longitudinally, this created a noticeable increase in compressional strain on the top of the beam, which caused the flax FRP to rupture after the peak load. This result is somewhat expected, as corrugated cardboard is designed to have strength in the vertical direction to resist crushing. Images of these two failure modes can be seen in Fig. 7.

Fig. 7: Failure Comparison: (a) Vertical crushing; (b) Longitudinal Crushing; and (c) Detail of compressional rupture.

Load-Strain Behavior. As previously mentioned, the 300 mm span samples experienced much larger compressive strain compared to tensile strain. This was caused by the longitudinal crushing of the cardboard near the top facesheet of the sandwich. The 150 mm span samples experienced comparable tensile and compressive strains until the vertical crushing of the cardboard core. Graphs comparing the load-strain behavior of the C-S150 and C-S300 specimens is shown in Fig. 8.

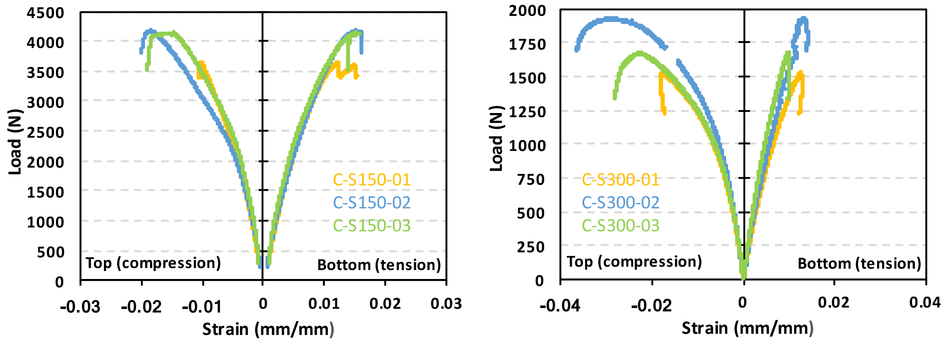

Fig. 8: Load-strain graphs: (a) C-S150; and (b) C-S300.

Moment-Curvature Behavior. As expected, the moment curvature behavior was similar between the two spans that were compared. Graphs comparing the moment-curvature behavior of the C-S150 and C-S300 specimens is shown in Fig. 9. Initial flexural stiffness and the shear rigidity of the core will be discussed further in a following section.

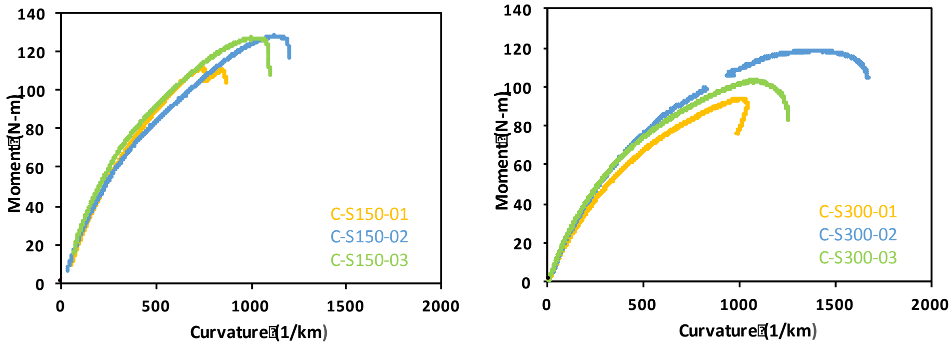

Fig. 9: Moment-curvature graphs: (a) C-S150; and (b) C-S300.

Load-Deflection Behavior. Graphs comparing the load-deflection behavior of the C-S150 and C-S300 specimens is shown in Fig. 10. Typical failure for the 150 mm specimens was transverse shear failure of the core. Considering the 300 mm specimens, typical failure was longitudinal crushing of the core under compressive normal stress which was followed by crushing of the top facesheet.

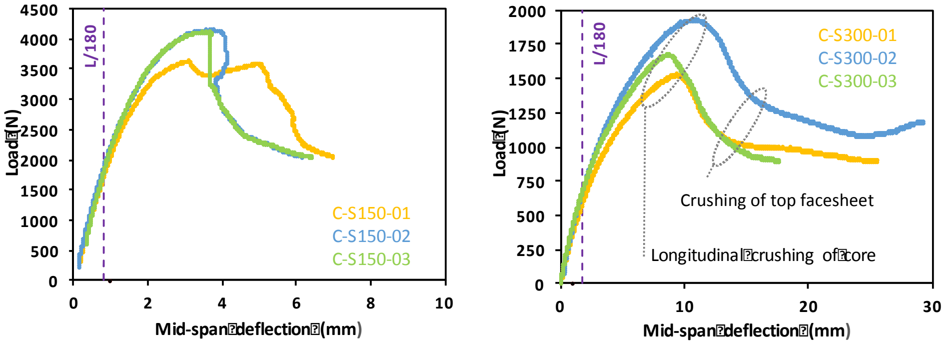

Fig. 10: Load-Deflection graphs: (a) C-S150; and (b) C-S300.

Flexural Stiffness. Flexural stiffness (D) of the sandwich beams was calculated based on moment-curvature behaviour. Additionally, by comparing the initial stiffness of two span lengths, flexural stiffness (D) and transverse shear rigidity (U) can be calculated using Eq. 1 where K is initial stiffness in N/mm, S is the span length in mm and L is the loading span in mm [6] [14] as follows:

$$K_i \frac{(2S_i^3 - 3SL_i^2 + L_i^3)}{96D} + K_i \frac{(S_\mathrm{i} - L_i)}{4U} = 1. \tag{1}$$

where i = 1 denotes the parameters to the short-span specimens, and i = 2 to the long-span specimens. The first term in the equation is related to flexural deformation and the second term to shear deformation. Combining the equations for each span length and simplifying gives:

$$D = \frac{\alpha_2 - \frac{\alpha_1 \delta_2}{\delta_1}}{96(\frac{1}{K_2} - \frac{\delta_2}{\delta_1 K_1})}. \tag{2}$$

$$U = \frac{\delta_2 - \frac{\alpha_2 \delta_1}{\alpha_1}}{4\left(\frac{1}{K_2} - \frac{\alpha_2}{\alpha_1 K_1}\right)}. \tag{3}$$

where

$$\alpha_i = 2S_i^3 - 3S_i L_i^2 + L_i^3. \tag{4}$$

$$\delta_i = S_i - L_i. \tag{5}$$

Table 4 shows the calculated values for D and U as well as an experimental value of D based on moment-curvature behavior. As the tests move forward this table will be complete. The results will be also compared with similar sandwich beams with alternative synthetic materials.

Table 4: Flexural Properties

Flute	D (N-m^2) [Calculated]	D (N-m^2) [Average based on curvature]	U (kN)
C	239.19	225.13	178.0

Conclusion

In this study, flax FRP facesheets and three different flutes of corrugated cardboard cores, namely B, C and BC, were used to manufacture composite sandwich beams with two different span lengths of 150 and 300 mm. This is an ongoing research and currently only the sandwich beams containing the C-flute core have been tested under four-point bending. Compared to the 300 mm span samples which failed at an average load of 1715 N, the 150 mm span samples failed at an average load of 3985 N. Corrugated cardboard displayed impressive strength against transverse shear, however it was not as strong under compressive normal stress in the longitudinal direction. Once the remainder of specimens are tested, a more comprehensive understanding of how corrugated cardboard performs as a core will be developed. Although more research must be conducted, the all-natural flax FRP and corrugated cardboard sandwich beams displayed encouraging structural behaviour and may prove to be a sustainable and structurally efficient building material.

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