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Corrugated cardboard core sandwich beams with bio-based flax fiber composite skins

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ABSTRACT

This paper presents an experimental study on the behavior of sandwich beams made of green materials for both core and skin components. A unidirectional flax fabric and a partial bio-based epoxy were used to make fiber-reinforced polymer (FRP) skins and three flute varieties of corrugated cardboards (known as B, C, and BC flutes) with the bulk densities of 170, 127, and 138 kg/m^3 were used for the core, respectively. 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) and tested under four-point bending up to failure. Two failure modes of transverse indentation for the short specimens and longitudinal crushing of the core and skin for the long specimens were observed. The load-deflection, load-strain, and moment-curvature behaviors were analyzed to evaluate the strength and stiffness of the sandwich beam specimens. C flute with the lowest bulk density and the highest availability in the market amongst all the three flutes exhibited the highest strength and stiffness for sandwich applications. Overall, the corrugated cardboard cores combining with the flax FRP skins may be considered as a viable, green option for the fabrication of large-scale structural sandwich panels for building applications.

1. Introduction

Composite sandwich structures made of fiber-reinforced polymer (FRP) skins and lightweight, low-density core materials have been shown to be very effective in reducing weight and increasing strength and stiffness in a variety of construction and building applications. The FRP skins resist the tensile and compressive stresses under flexure, like the action of the flanges on an I-shaped beam, while the core resists shear stresses, increases the distance between skins resulting in a higher moment of inertia, and provides insulation for the system. The popularity of sandwich structures in the form of wall, cladding, roof, and floor panels is growing as engineers look to improve the structural efficiency and insulation properties of buildings. To be more environmentally-conscious, conventional materials and structures need be re-evaluated to determine how they can become more sustainable and have a smaller environmental impact during manufacturing, installation, and service.

Although FRP composites made of synthetic fibers, such as glass or carbon fibers, are often used for the skins of sandwich panels [1–3], the concept of using plant-based natural fibers, such as flax and hemp fibers, has also been explored [4–6]. Although the natural fibers have a lower strength than their synthetic counterparts, it has been showed that this may be acceptable since the core failure is one of common failure modes in sandwich structures with strong skins [7,8]. However, sandwich structure may experience different failure modes (core shear, indentation, skin crushing/rupture, and skin wrinkling) dependent on the ratio of skin thickness to span length and relative core density [9,10]. Additionally, natural fibers have many economic and environmental advantages compared to synthetic fibers [11–13]. Thus, FRP skins made of natural fibers represent a viable structural option for sandwich structures and are a more environmentally-friendly choice than synthetically produced fibers. In FRPs, the role of polymer resins to impregnate and bond the fibers is critical. Synthetic polymers, such as epoxy and vinyl ester, have been used with natural fibers [14–16]. However, numerous studies have been conducted on the use of fully or partially bio-based resins with natural fibers [17–19].

Beside of skin materials, the core materials of sandwich structures play a major role in the structural (i.e. shear, composite action, and out-of-plane properties) and insulation properties. Many different core materials have been explored for use in sandwich structures. Core materials that are commonly studied include low-density foam and plastic or metal honeycombs [20–22]. To present a more sustainable option, this study considers corrugated cardboard as the core material. According to the Paper and Paperboard Packaging Environmental

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Council (PPEC), approximately 85% of corrugated cardboard in Canada is recycled and new cardboard is produced with nearly 100% recycled materials [25,22]. Along with being 100% biodegradable, corrugated cardboard is a very sustainable as it can be repurposed and produces very little waste. Corrugated cardboard is an orthotropic sandwich with two paper based facings separated by a lightweight corrugated core known as fluting [23]. The system has good thermal insulation properties and high load-carrying capacity by being low-costs and lightweight [24]. Although studies have been conducted on balsa wood and cork cores for sandwich composites [4,5,26,27], corrugated cardboard has not been explicitly studied in the context of a sandwich composites with natural fibers and bio-based resins.

In this study, flax FRP skins were combined with corrugated cardboard cores to manufacture sandwich beam specimens. Unidirectional flax fabrics were impregnated using a resin with almost 30% bio content. As a result, the sandwich beams produced were constructed using almost entirely green materials. The aim of the study is to analyze and evaluate the structural performance of corrugated cardboard and flax FRP sandwich beams as an alternative to conventional construction and building materials. 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 system that has a minimal impact on the environment as corrugated cardboard is readily available and composed almost entirely of recycled and green material.

2. Experimental program

This section presents the details of test matrix, material properties, specimen preparation, test setup, and instrumentation of the test specimens. The experimental program using two loading arrangements was specifically designed to investigate the properties of three corrugated cardboard cores.

2.1. Test matrix

A total of 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 sizes of the corrugated cardboard. Two span lengths of 150 mm and 300 mm as well as three flute sizes of B, C, and BC were tested. More information concerning the flute sizes can be found in the next section. A complete summary of this study's test matrix is shown in Table 1. Note that three identical specimens were manufactured and tested per case. All specimens are identified with a specimen identification (ID) which follows the format X-SY where X identifies the flute size, S stands for span and Y identifies the specimens test span in mm. For example, the specimen 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	Cardboard 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

Three identical specimens per case were prepared and tested.

Table 2
Cardboard flute comparison.

Cardboard flute	Thickness (mm)	Flutes per meter length	Bulk density (kg/m^3)
B	2.8	160	170
C	4.0	120	127
BC	6.6	Mix	138

2.2. Material properties

Three unique cardboard flutes were used in the fabrication of the sandwich beams: B, C and BC flutes. 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 starch-based adhesive used to combine the layers of cardboard.

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. 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 (30% bio content) with a reported tensile strength, modulus and elongation of approximately 53.23 MPa, 2.65 GPa and 6%, respectively. Betts et al. [26] 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 made of the bio-based epoxy used in this study, the average tensile strength and initial modulus were reported to be 198.0 $\pm$ 9.3 MPa and 17.09 $\pm$ 0.63 GPa, respectively (two-layer thickness = 1.97 $\pm$ 0.09 mm). A secondary modulus was reported as 11.93 $\pm$ 0.39 GPa as it was found flax FRPs display an approximately bi-linear mechanical behavior. The rupture strain of flax FRP was reported to be 0.0153 $\pm$ 0.0006 mm/mm.

2.3. Specimen preparation

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 width were cut from larger sheets 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 a vegetable starch-based adhesive known as Tri-Tex Tribond P-1031 adhesive was used. This adhesive was provided by the cardboard manufacturer and is the same used in the manufacturing of corrugated cardboards. 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.

Once the cardboard cores were completed, the flax FRP skins were applied using the standard wet lay-up method. Sheets of flax fabrics 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