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Compression strength of natural fibre composite plates and sections of flax, jute and hemp

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ABSTRACT

Natural fibres such as flax, jute and hemp have been utilised for thousands of years, however have only recently been considered for fibre-resin composites. A major motivation for such an application is their superior sustainability attributes compared with traditional building materials. Population rise continues to place increasing demands for new infrastructure. Meanwhile, public concerns about the environment, climate change, energy consumption and greenhouse gas emissions, place increasing demands for the use of sustainable materials in infrastructure.

While there is a wealth of knowledge in the materials aspects of natural fibre composites, relatively few studies have investigated their potential for structural applications. This paper presents an experimental and analytical study of natural fibre composite plates and channel sections consisting of flax, jute and hemp fibres and subjected to pure compression. The intrinsic mechanical properties are shown to be relatively modest. However, the buckling and post-buckling responses are shown to be stable, the ultimate condition is reached in a stable and predictable manner, and failure ensues in a gradual and ductile process. These characteristics show promise for the use of natural fibre composite sections in light structural applications such as in the residential and light commercial markets. Additionally, the analytical effective width mechanics model shows promise for use as a design technique for estimating their compression strength.

1. Introduction

Natural fibres such as flax, jute and hemp have been used by humans for thousands of years, with early records of textile use of flax dating back at least 7000 years in Egypt [1]. In recent decades, the use of natural fibres in composite materials has gained substantial interest, where these fibres may be combined with thermoset or thermoplastic polymers to create natural fibre composites, which have been particularly identified for their sustainability attributes [2–7]. Favourable sustainability properties of natural fibres such as flax, jute and hemp include: renewable resources that absorb CO_2 whilst retuning O_2 to the environment; short growth cycle times (eg the sow to harvest cycle for flax is 100 days, compared with around 15–20 years for radiata pine); low energy production; recyclable; biodegradable; and low hazard manufacturing and composite handling and working.

Much of the previous research has focused on the materials aspects, including fibre processing techniques, composite fabrication methodologies, matrix materials and their effects on the mechanical properties [8–13]. While applications for natural fibre composites could be similar to carbon and glass fibre composites, research has indicated that composites consisting of natural fibres have comparably low intrinsic mechanical properties compared with their synthetic fibre counterparts [2–13]. As a result, identifying structural applications such as those in civil infrastructure have thus far been limited [14]. Nonetheless, natural fibre composites have intrinsic strength which could potentially be harnessed for structural applications so long as the mechanical behaviour is well understood, reliable and predictable.

Some previous studies have investigated flax fibre composites for use as energy absorbing components in crashworthiness applications [8,15], and semi-structural applications. The latter includes such applications as: flax fibre confinement for concrete columns [16]; flax fibre skin foam core [17], flax fibre skin balsa core [18] and jute fibre skin foam core [19] sandwich panels; flax fibre wind turbine blades [20]; bamboo fibre boat hulls [21]; and wood flour sheet piling [22]. To the authors knowledge no studies have specifically examined flax, jute and hemp fibre composites for use as primary structural components for civil infrastructure applications. For such applications, an important basic load case is compression to resist gravity loads. The aim of this study was to characterise the intrinsic compression behaviour of natural fibre composites. To establish these compression characteristics, the two fundamental components of flat plates and plain channel sections were considered.

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Table 1
Composite plate specimens and test results (subscript P refers to predicted values).

Fibre	Layers	Fibre weight (g/m^2)	Width (mm)	Thickness (mm)	E_C (MPa)	f_{uC} (MPa)	F_{buckle} (N)	$F_{ultimate}$ (N)	λ	$F_{buckleP}$ (N)	$F_{buckle}/F_{buckleP}$
Flax	2	800	152.8	1.6	4199	38.5	306	2294	5.55	435	0.70
Flax	2	800	152.7	1.6	4199	38.5	218	2231	6.57	435	0.50
Flax	3	1200	154.0	2.5	4199	38.5	1300	5275	3.34	1547	0.84
Flax	3	1200	153.2	2.5	4199	38.5	1293	5081	3.34	1556	0.83
Flax	4	1600	153.8	3.4	4199	38.5	2612	8800	2.78	4141	0.63
Flax	4	1600	154.2	3.4	4199	38.5	2906	9181	2.64	4129	0.70
Jute	2	800	153.2	1.6	3523	40.2	175	1825	7.50	364	0.48
Jute	2	800	153.1	1.6	3523	40.2	187	1995	7.26	364	0.51
Jute	3	1200	152.8	2.5	3523	40.2	1081	4238	3.77	1391	0.78
Jute	3	1200	153.0	2.5	3523	40.2	1218	3863	3.55	1389	0.88
Jute	4	1600	152.9	3.5	3523	40.2	3025	9394	2.65	3652	0.83
Jute	4	1600	152.5	3.5	3523	40.2	2975	8656	2.67	3662	0.81
Hemp	3	861	152.4	2.0	2649	33.9	313	3688	5.67	498	0.63
Hemp	3	861	152.7	2.0	2649	33.9	401	3138	5.02	497	0.81
Hemp	4	1148	153.6	2.7	2649	33.9	1031	6319	3.66	1238	0.83
Hemp	4	1148	152.6	2.7	2649	33.9	987	6313	3.73	1247	0.79
Hemp	6	1722	152.7	3.6	2649	33.9	2656	10,400	2.65	3125	0.85
Hemp	6	1722	153.4	3.6	2649	33.9	2962	10,063	2.51	3109	0.95
										Mean:	0.74

2. Methods

2.1. General

Plate tests consisted of flat plates simply supported on all four sides, subjected to uni-directional compression. Section tests consisted of plain channel sections, being a simple combination of flat stiffened (web) and unstiffened (flange) plate elements, subjected to pure compression. Thin plate buckling involves the development of membrane strains in the two principle orthogonal directions, longitudinal and transverse, thus at a minimum fibres are required in these two principle directions. In this study the simplest fibre orientation appropriate for such load consisting of multiple layers of biaxial [0/90] woven fabric was chosen. A standard bulk commercial laminating epoxy resin with a room temperature cure was selected, and the hand layup technique with vacuum bag curing was used for fabrication. This study therefore attempted to characterise the compression strength of natural fibre composite structures in their simplest form, and no attempt was made to optimise these basic characteristics, such as could be achieved with; complex fibre layouts, different matrix types, automated fibre layups, autoclave fabrication, complex plate element stiffener arrangements, etc.

2.2. Materials

Three different natural fibres were investigated in the present study; flax, jute and hemp. The flax and jute fabrics were commercially produced for fibre-resin composite fabrications by Composites Evolution; Biotex Flax 400 g/m^2 2 × 2 Twill weave and Biotex Jute 400 g/m^2 2 × 2 Twill weave. Nominal density, tensile strength and modulus values for the flax were; 1.5 g/cm^3, 500 MPa and 50 GPa, and for the jute were; 1.46 g/cm^3, 400 MPa and 40 GPa. The hemp fabric was not produced specifically for fibre-resin composite applications, however was recommended as the most appropriate fabric for working with resins by the manufacturer, and was a plain weave 287 g/m^2 pure unbleached hemp fabric with density 1.48 g/cm^3. The commercial bulk laminating epoxy resin Kinetix R240 with H160 (medium) hardener was used for all composite fabrications, with density 1.1 g/cm^3. Compression and tension material tests of the neat epoxy resin and fabricated fibre-resin composites were undertaken in accordance with ISO 604 [23] and ISO 527 [24], respectively. The fibre-resin composite material specimens were cut from the fabricated plate specimens. Fibre volume fractions were calculated using the mass of fabric prior to fabrication, the mass of composite after fabrication, and the constituent densities.

2.3. Plate specimens

Flax, jute and hemp fibre-resin composite plates were fabricated with nominal geometries of 150 mm width and 450 mm length. A length of three times the width was chosen since stiffened plates are known to nominally buckle in square half-wavelengths, and having three half-wavelengths of buckle minimises end effects in plate tests [25]. Three different plate thicknesses were fabricated for each of the different fibre types; for the flax and jute composites 2, 3 and 4 fibre layers were fabricated. Since the hemp fabric had a lower aerial mass, and in order to create hemp composites with approximately the same mass of fibre as the flax and jute composites for comparison purposes, the hemp plates were fabricated with 3, 4 and 6 layers.

The plates were fabricated with a hand layup technique whereby each layer of fabric was wetted out with resin using a paint brush and roller. The fabrics were laid flat and a full vacuum (approximately 100kPa) was then set over the plate and held during a cure time of a minimum of 15 h in a constant temperature room at 23 °C. The plates were fabricated with approximate dimensions of 250 mm width and 1200 mm length, then following curing were trimmed to size and cut into two specimens using a guillotine. The measured plate geometries are summarised in Table 1. Exemplar plate specimens are shown in Fig. 1.

2.4. Plate test rig

The plates were tested with simple supports on all four sides (stiffened plates). The ends of the plates were seated in circular steel rods with a 6 mm groove to accommodate plates up to 6 mm in thickness. Shim plates were used to firmly seat the plates with thickness less than 6 mm. The grooved plate-seat rod was housed in a split needle bearing, allowing the rod to rotate freely in the solid steel bearing block (Fig. 2). Each bearing block was 60 mm in width, and each grooved plate-seat rod was 20 mm in width, allowing differential rotation across the plate width. The upper bearings were fixed to the loading platen of the test machine, and the lower bearings were fixed to the rigid base of the machine. The plate end bearings have been used and validated previously by the author, and further details are provided in [26]. Simple supports along the plate longitudinal edges were achieved with Teflon half-rounds that were lightly clamped to each side of the plate edge