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Geometric optimisation and compression design of natural fibre composite structural channel sections

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ABSTRACT

Public concerns about the environment, climate change, energy consumption and greenhouse gas emissions have placed increasing demands for the use of sustainable materials in the built environment. Natural fibres such as flax, jute and hemp have recently been considered for fibre-resin composites, with a major motivation for their implementation being their notable sustainability attributes. However, many studies have noted the relatively modest mechanical properties of natural fibre composites. Despite this, a recent paper by the author demonstrated that the compression strength of flat plates and plain channel sections may be suitable for light structural applications. This paper presents the geometric optimisation of channel sections via the inclusion of complex web, flange-edge and flange-interior stiffeners. It is demonstrated that the inclusion of geometric stiffeners restricts the development of local buckling, creating less slender channel sections with greater compression strength. Compression strengths are compared with steel and timber wall stud strengths and shown to be suitable for residential building applications. The combined plain channel and stiffened channel experimental data covers a broad range of section slenderness values, and design models are developed to predict their compression strength.

1. Introduction

Recent decades have seen substantial interest in the use of natural fibres in composite materials, 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. Favourable sustainability properties of natural fibres such as flax, jute and hemp include: renewable resource; carbon sink; short growth cycle time (eg the sow to harvest cycle for flax is 100 days); low herbicide requirements due to rapid growth; low energy production; recyclable; biodegradable; and low hazard manufacturing and composite handling and working [1–7].

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]. Most studies have demonstrated that natural fibre composites have comparably low intrinsic mechanical properties [2–13], and as a result, applications have thus far been limited to semi-structural or non-structural applications [14–22]. In a previous study, the author undertook an experimental program to characterise the intrinsic structural compression behaviour of natural fibre composites [23]. To establish the basic characteristics, the two fundamental components of flat plates and plain channel sections were considered, wherein a plain channel section consists of flat plate elements (web and flanges). These experiments demonstrated that the buckling and post-buckling responses were stable, the ultimate condition was reached in a stable and predictable manner, and failure ensued in a gradual and ductile process; characteristics that show promise for the use of natural fibre composite sections in light structural applications.

Many decades of research on thin-walled structures consisting of metals and plastics have demonstrated that compression buckling may be delayed with the use of discrete stiffeners placed in the zones of local buckling susceptibility. In this paper, the utility of complex stiffeners in natural fibre channel sections is studied, with the aim of optimising their compression strength. The stiffener design draws on the implementation of complex stiffeners in thin steel channel sections, particularly those used in the residential stud wall market. The overall dimensions of the channels also reflect such application, with a particular research question of the study being: could load bearing residential stud walls be manufactured from natural fibre composites? The results of the previous [23] and present study are used to develop a design procedure capable of predicting their compressive strength with reasonable accuracy.

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2. Methods

2.1. 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 50GPa, and for the jute were; 1.46 g/cm^3, 400 MPa and 40GPa. 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 H126 (fast) hardener was used for all composite fabrications, with density 1.1 g/cm^3 and measured (neat) compression ultimate stress of 105.3 MPa, tension ultimate stress of 33.1 MPa and tension ultimate strain of 0.8% [23]. The channels 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 over a mandrel and held under a full vacuum during a cure time of a minimum of 5 h in a constant temperature room at 23 °C. Fibre volume fractions were calculated using the mass of fabric prior to fabrication, the mass of composite after fabrication, and the constituent densities.

2.2. Channel specimens

Flax, jute and hemp fibre-resin composite channels were fabricated with nominal geometries of web depth 100 mm, flange width 50 mm and 300 mm length. A length of three times the web depth was chosen since webs (stiffened elements) are known to nominally buckle in square half-wavelengths, and having three half-wavelengths of buckle minimises end effects. The channel lengths were short enough so as to preclude column member lateral-torsional buckling, such that the pure section capacity was established. The preclusion of column member lateral-torsional buckling was observed from the previous channel tests of length 300 m [23], and confirmed by the results observed in the present tests. Two different channel thicknesses were fabricated for each of the different fibre types; 4 and 6 fibre layers for the flax and jute channels, and 6 and 9 fibre layers for the hemp channels (in order to create hemp sections with similar fibre content to the flax and jute sections).

In the previous study [23] plain channel sections were tested, consisting of flat web and flange elements (Fig. 1a). Optimisation of the channel section geometry was considered by adding flange edge stiffeners, and additionally; one intermediate web stiffener (Fig. 1b and c), two intermediate web stiffeners (Fig. 1d and e), and two intermediate web stiffeners with one intermediate flange stiffener (Fig. 1f and g). For each web/flange stiffener arrangement, two different sized flange edge stiffeners were used. For all configurations (Fig. 1b–g) the smaller thickness was tested (4 layers of flax and jute and 6 layers of hemp), and for the configuration of two intermediate web stiffeners with one intermediate flange stiffener (Fig. 1f and g) the larger thickness was additionally tested (6 layers of flax and jute and 9 layers of hemp). The different stiffener configurations were fabricated by fixing 12 mm diameter half-rounds to the mandrel at specific locations, the mandrel being two 50 mm × 50 mm steel square hollow (SHS) sections with external corner radius of 6 mm. An example mandrel and resulting channel section is exemplified in Fig. 2. A split mandrel was required to facilitate extraction of the mandrel after curing. It is noted that 2 mm shim was placed between the SHS mandrel members to assist extraction, thus the nominal channel internal web depth was 102 mm. For the specimens with two intermediate web stiffeners, the rounded corners of the SHS resulted in a small central stiffener, as some fabric and epoxy was drawn into this space (Fig. 2a). This was an unintended artefact of the use of a split mandrel. The stiffeners were centrally located for all elements with one stiffener, and located at the quarter points for elements with two stiffeners (Fig. 2b). The channels were fabricated with approximate length 650 mm, then following curing were trimmed and cut into two 300 mm specimens using a standard powered circular drop saw with a timber cutting blade. The flange edge stiffeners were fabricated with approximate length of 40 mm, then following curing were trimmed to nominal dimensions of 20 mm or 30 mm using a high speed rotary tool (Dremel brand), with a carbide cutting wheel. The measured channel geometries are tabulated in Table 1. Exemplar channel specimens are shown in Fig. 3.

2.3. Channel section tests

The channels were tested in pure compression between fixed load platens. In order to reduce possible end effects such as eccentric loading or stress concentrations resulting from the channel ends not being completely flat and/or parallel, prior to testing 2 mm thick steel end plates were bonded to both ends of the channels using fast cure Araldite K219 epoxy. This resulted in the channel ends being essentially fixed ended, since end rotations were precluded. This method has been used and validated previously by the author [23,24]. Additionally, the channels were seated on a spherical bearing which when unlocked allowed free rotations in all directions. The test procedure involved placing the channel on the unlocked spherical bearing and applying a small load, then locking the spherical bearing such that rotations were then restrained. The restraint condition was thereby fixed end restraints. Four displacement transducers were located around the channels to measure the out-of-plane buckling deformations, including two on the web at the mid-length and quarter length, and one on each flange at the mid-length. The channels were loaded in displacement control at a speed of 0.5 mm/min.

In the previous tests [23], compression and tension material tests of the neat epoxy resin and fabricated fibre-resin materials were undertaken in accordance with ISO 604 [25] and ISO 527 [26], respectively. As the same constituent materials and fabrication procedures were used in the present study, these material values are nominally valid for the present channels also.

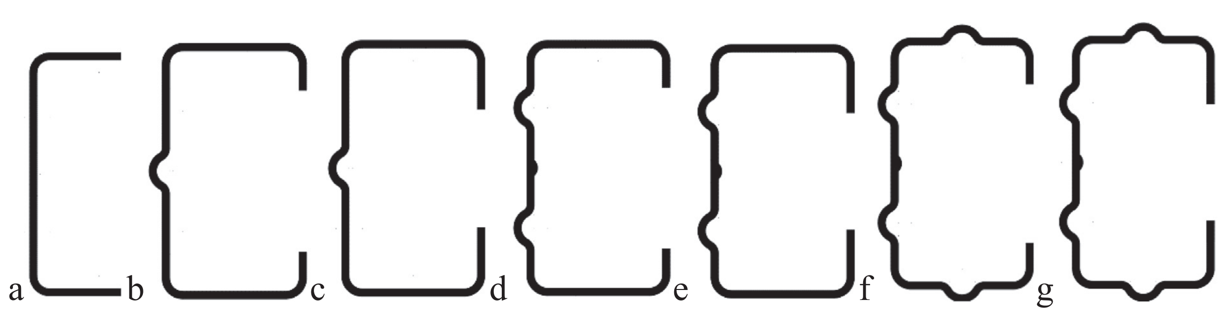

Fig. 1. Channel section geometries; a) plain (unstiffened) from [23], b) to g) stiffened (present study).