FLEXURAL BEHAVIOUR OF THIN-WALLED FLAX FIBRE REINFORCED POLYMER BEAMS WITH FOAM CORES

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ABSTRACT

There is a rapidly growing demand for more environmentally sustainable materials in the construction industry. Natural flax fibre reinforced polymers (FRPs) have potential applications as lightweight skins for utility poles, pedestrian bridge elements, and small wind turbine shafts but the structural behaviour of flax-FRP wrapped foam beams has yet to be investigated. Six beams with various internal foam density and fibre arrangements were constructed and tested. A control beam was made using one glass-FRP (one layer of longitudinal fibres, one transverse) while the remaining used flax-FRP. A fabrication technique for constructing the tubes was developed and presented here. An arrangement using 5 layers of longitudinal flax fibres and 3 hoop flax fibres gives similar strength to the glass-FRP control; 4 longitudinal and 3 hoop flax fibres is expected to give similar stiffness to the glass-FRP control. Flexural strength and stiffness was found to be proportional to the number of longitudinal layers. Increasing the amount of hoop layers shifted the failure mode from compression to tension controlled. Flax-FRP beams that failed in compression gave slightly more warning and higher deflections than those that failed in tension. The results show that flax-FRP skinned foam beams have potential applications in lightweight construction but further testing under environmental and cyclic loading is recommended before these tubes are used in practice.

Keywords: Fibre Reinforced Polymers, Natural Materials, Thin-Walled Structures, Lightweight Construction.

1. INTRODUCTION

Over the past few years, there has been a growing interest in lightweight construction. Though the materials are generally more expensive, the overall construction cost of a lightweight structure is similar to a conventional one due to the reduced amount of material required, lower shipping costs, a reduction in heavy equipment size (e.g. cranes, forklifts), and accelerated construction schedules (Navon, 1995). Fibre reinforced polymer (FRP) structures are commonly used, particularly in the automotive and aerospace industries, for lightweight construction as their strength-to-weight ratio is considerably higher than that of structural steel. FRPs are also resistant to corrosion and have high energy absorbing capability (Yan and Chouw, 2013a) However, FRPs are generally less stiff than steel and are linear-elastic to failure, leading to design often being controlled by serviceability requirements rather than strength (ACI 2015).

There is also more awareness now than ever regarding the environmental effects of construction. Traditional construction materials (e.g. concrete, steel) contain substantial embodied energies. For instance, the production of cement alone is attributed to between 9 and 10% of global CO₂ emissions (Taylor et al. 2006).

These two drivers have increased interest in the use of natural fibres such as flax, coir, and jute in structural applications as they combine lightweight construction with environmental considerations. Flax fibres have a reasonably high tensile strength with reported values ranging between 500-1500 MPa (Ku et al. 2011). However,
they also have considerably lower embodied energy (2.75 MJ/kg) than glass (31.7 MJ/kg) and carbon (355 MJ/kg) fibres (Cicala et al. 2010). Flax-FRP has successfully been used to confine concrete cylinders and gives similar results to glass or carbon-FRP despite having lower strength (Yan and Chouw, 2014). Concrete filled flax-FRP tubes have been shown to perform well relative to steel-reinforced sections in bending (Yan and Chouw, 2013b). A ratio of 3 layers of flax to 1 layer of glass fibres has been shown to give similar structural behaviour to glass-FRP when used in FRP-skinned sandwich panels (Mak et al. 2015). However, natural fibres have been shown to degrade from UV or moisture intake (Yan and Huang, 2015) but chemical treatments have shown promising results in addressing these issues (Loong 2015).

This paper investigates the potential for flax-FRP to be used as the skin element in foam-core tube structures for lightweight construction. Different foam densities and fibre arrangements are considered and the resulting systems are compared with a tube structure constructed with glass-FRP.

2. EXPERIMENTAL PROGRAM

2.1 Description of Test Specimens

A new structural system composed of flax FRP-wrapped soft-core tube structures was considered. This system has potential applications as a utility pole, truss members in pedestrian bridges, and as support structures for small wind turbines. The constructed tubes are 2000 mm long and consist of fibres wrapped around an internal polyisocyanurate foam section 150 mm in diameter. Fibres are aligned either longitudinally (0°) or transversely (90°) along the tube. Longitudinal fibres provide structural strength and stiffness while the transverse (aka hoop) fibres confine the longitudinal fibres under compression to prevent them from buckling. The foam acts both formwork during construction as well as an internal brace to prevent buckling or crushing of the longitudinal compression fibres, similar to the function of the hoop fibres.

2.2 Test Matrix

The test program is shown in Table 1. Each specimen is given a four term identifier. The first term represents the fibre material (F – flax, G – glass) (Figure 1), the second is the number of longitudinal layers, the third is the number of hoop layers, and the fourth is the foam density (L – Light, M – Medium, H – Heavy). A reference glass-FRP beam, G11M, was constructed using 1 layer of longitudinal and hoop fibres. Previous work on flax-skinned sandwich panels using the same materials (properties given in the next section) showed that 3 layers of flax gives similar response to one layer of glass (Mak et al. 2015) and is the reason why the flax beams were constructed with a minimum of 3 longitudinal layers. Three flax beams (F31L, F31M, and F31H) were compared in order to evaluate the contribution of the foam density to structural response. These beams had the fewest hoop layers as it was anticipated that the foam contribution would be more clearly understood in these tests. F33M and F53M investigated the contribution of providing more hoop layers and longitudinal layers respectively on response and failure mode.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Foam Density, kg/m³</th>
<th>Fibre Material</th>
<th># Longitudinal Layers</th>
<th># Hoop Layers</th>
<th>Specimen Weight, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>G11M</td>
<td>58</td>
<td>Glass FRP</td>
<td>1</td>
<td>1</td>
<td>6.29</td>
</tr>
<tr>
<td>F31L</td>
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<td>Flax FRP</td>
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<td>1</td>
<td>4.51</td>
</tr>
<tr>
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<td>1</td>
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<tr>
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<td>1</td>
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<tr>
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<td>Flax FRP</td>
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<td>3</td>
<td>7.13</td>
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<tr>
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<td>58</td>
<td>Flax FRP</td>
<td>5</td>
<td>3</td>
<td>9.09</td>
</tr>
</tbody>
</table>
2.3 Materials

2.3.1 Foam Cylinders

Three densities (33, 58, and 66 kg/m$^3$) of precut rigid closed-cell polyisocyanurate foam cylinders were used. The cylinders had a diameter of 150 mm. Flexural tests on pure foam specimens gave modulii of elasticity of 40, 64, and 79 MPa and flexural strengths of 0.45, 0.79, and 1.14 MPa from the lowest to the highest density respectively.

2.3.2 Flax-FRP

The flax-FRP was comprised of 275 g/m$^2$ fibres (Figure 1) bonded together with a blended epoxy-pine oil resin. Prior material tests on wet-layup coupons using the same fibres and epoxy as that used in this program gave a tensile strength of 135±11.9 MPa and modulus of elasticity of 8.7±1.15 MPa (Mak et al. 2015).

2.3.3 Glass-FRP

The glass-FRP was comprised of 1150 g/m$^2$ fibres (Figure 1) bonded together with a blended epoxy-pine oil resin. Material tests on wet-layup coupons using these fibres and epoxy gave a tensile strength of 481±31.4 MPa and modulus of elasticity of 24.2±1.59 MPa (Mak et al. 2015).

2.4 Fabrication of Test Specimens

The specimens were fabricated as illustrated in Figure 2. First, fibre material was cut to length (2000 mm for longitudinal layers and 550 mm for hoop layers) from a stock sheet. The width of the longitudinal layers was 475 mm (i.e. there is no overlap). An overlap of 75 mm was provided for the hoop layers.

The longitudinal layers were laid on top of each other and saturated (Figure 2 (a)). After the fibres were saturated, the foam was wetted with the resin to encourage bonding between the fibres and foam. The foam was then rolled to wrap it with the longitudinal fibres (Figure 2 (b)). After wrapping, air bubbles and misaligned fibres were worked out by hand and the tube was left to cure for a period of 18 to 24 hours. The curing period allowed the longitudinal fibres to set in place and allow the hoop layers to be added without causing the longitudinal fibres to become misaligned.

Each hoop layer was saturated and wrapped around the longitudinal layers (Figure 2 (c)). For each hoop layer, the overlap was set on the opposite side of the tube from the previous layer; in the first layer, the overlap was placed on the opposite side of the tube from the seam caused by the longitudinal fibres. After all hoop layers were added, potential issues (e.g. air bubbles, misaligned fibres) were worked out by hand and the tube was left to cure for a minimum of 2 weeks prior to testing (Figure 2 (d)).
2.3 Test Setup and Instrumentation

The tubes were tested at in four-point bending using a 50 kN capacity electro-mechanical testing frame (Figure 3). The test span was 1800 mm with the 400 mm apart loading points, giving a shear span of 700 mm on both sides. The beams were loaded in stroke control at 2 mm/min until failure. To ensure even load distribution to the tube, semi-circular steel sections were used at the support and loading points Figure 3 (c). The weight of the spreader beam (7.5 kg) and semi-circular loading points (2.8 kg) is included in the reported loads.

During each test, midspan deflections were recorded using two 100 mm linear potentiometers (LPs) attached to brackets mounted at midheight of each side of the tube (Figure 3 (b)). Strains at midspan were measured using three 5 mm strain gauges: one at the bottom of the tube (longitudinal tensile strain), and the other two at the top of the tube (longitudinal compression strain and transverse tensile hoop strain).

Figure 2: Tube fabrication process (a) Saturating longitudinal fibres (b) Rolling tube to wrap longitudinal fibres (c) Wrapping hoop fibres 18-24 hours after longitudinal layers wrapped (d) completed tube
3. EXPERIMENTAL RESULTS

3.1 Response up to Failure

The load deflection relationships for the tests are shown in Figure 4 with the results summarized in Table 2. At loads up to service (taken as span/360, common for beam elements) the response of the beams is linear-elastic. The beam stiffness, particularly for the flax-FRP wrapped tubes, decreased as loading increased beyond this point. The effective stiffness, $EI$, of the system was evaluated using Equation 1 which back-calculates the stiffness based on the expected deflections under four-point bending.

$$EI = \frac{Pa}{12\delta_{cl}}(3l^2 - 4a^2)$$

Where $P$ is the total applied load, $a$ is the shear span length, $l$ is the span length, and $\delta_{cl}$ is the centreline deflection (measured from LPs). The value for $EI$ in service (span/360 = 5 mm) is given in Table 2 while $EI$ over the course of each test is given in Figure 5. The load-strain relationships for each beam (Figure 6) showed similar relationships to the load-deflection curves, as expected but also show that the hoop fibres are under non-negligible strains, indicating that the longitudinal compression fibres were being confined during loading. The effect of the various parameters on the beam response is discussed later. Failure of the specimens occurred at deflections considerably higher (between 7.3 and 12.6 times) the service deflection of 5 mm, indicating that design of these sections is governed by serviceability rather than strength.
Figure 4: Load-deflection curves for all tested beams. Service limit of span/360 is highlighted for reference.

Table 2: Test Results

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Peak Load, kN</th>
<th>Deflection at Peak, mm</th>
<th>Effective Stiffness, Nmm²×10⁹</th>
<th>Compressive Strain at Peak, με</th>
<th>Tensile Strain at Peak, με</th>
<th>Hoop Strain at Peak, με</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>G11M</td>
<td>18.0</td>
<td>36.4</td>
<td>165</td>
<td>-8517</td>
<td>+7431</td>
<td>+978</td>
<td>Fibre Crushing</td>
</tr>
<tr>
<td>F31L</td>
<td>10.8</td>
<td>44.6</td>
<td>112</td>
<td>-8062</td>
<td>+8850</td>
<td>+1312</td>
<td>Hoop Rupture</td>
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<tr>
<td>F31M</td>
<td>12.7</td>
<td>62.9</td>
<td>115</td>
<td>-11770</td>
<td>--</td>
<td>+5444</td>
<td>Hoop Rupture</td>
</tr>
<tr>
<td>F31H</td>
<td>11.4</td>
<td>58.6</td>
<td>104</td>
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<td>+11830</td>
<td>+2925</td>
<td>Hoop Rupture</td>
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<tr>
<td>F33M</td>
<td>12.8</td>
<td>40.4</td>
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<td>-9356</td>
<td>+8459</td>
<td>+2529</td>
<td>Fibre Rupture</td>
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<td>39.9</td>
<td>201</td>
<td>-8248</td>
<td>+6717</td>
<td>+1665</td>
<td>Fibre Rupture</td>
</tr>
</tbody>
</table>

a – effective stiffness evaluated with Equation 1 at span/360., b – gauge failed prior to peak (reading > 15000με)

Figure 5: Flexural stiffness, EI, over the course of each test.
3.2 Failure Modes

Three distinctive failure modes were observed in the tests and shown in Figure 7. The first, crushing of the longitudinal fibres (Figure 7 (a)), was observed in the glass-FRP tube (G11M). There were no clear indications that failure was imminent from the load-deflection or strain readings but there were sounds of distress (i.e. pops indicating fibre failure) close to failure. It was observed that the fibres crushed into the foam; this is attributed to the foam having a considerably lower stiffness than the hoop layer.

Crushing of the longitudinal fibres and rupture of the hoop layers were seen in the flax-FRP beams with a single hoop layer (F31L, F31M, and F31H). This failure is distinctive from the crushing seen in G11M as the failure happened outward from the foam) and was accompanied by rupture of the hoop layer. This failure was also pre-empted by slight decreases in load and rapidly changing strains immediately before failure, giving more warning than G11M. After failure, it was noticed that the ruptured fibre sections had foam attached to them, indicating that the foam was well bonded to the tube and failure happened within the foam rather than at the fibre-foam interface.

The third failure mode was by fibre rupture (Figure 7 (c)), seen in the flax-FRP beams with 3 hoop layers (F33M, F53M). There were no clear indications that failure was imminent from the experimental data. Failure was sudden and the abrupt energy transfer caused both of these tubes to break completely in half.

Figure 6: Load-strain relationships for the each beam.

Figure 7: Tube failure mechanisms (a) Crushing of longitudinal fibres (G11M), (b) Crushing of longitudinal fibres and rupture of hoop layer (F31M), (c) Rupture of longitudinal fibres (F33M).
4. DISCUSSION

4.1 Effect of Foam Density

Foam density’s effect was investigated by comparing F31L, F31M, and F31H. The foam has a similar function to the hoop fibres (i.e. it prevents buckling of the longitudinal fibres in compression). Higher density foam is expected to perform better as it has higher stiffness and strength. All three tests had similar load-deflection relationships, indicating that changing the foam density has little effect on flexural stiffness, especially compared to the other investigated parameters. However, F31L was weaker and failed at lower deflections than F31M and F31H. This is attributed to the weaker foam rupturing in tension (which then caused the skin to expand outward and rupture the hoop fibres). The other two beams had the same failure mode but this occurred at higher loads as the higher densities of foam have higher strength.

4.2 Effect of Adding Hoop Fibres

Adding two hoop layers (F31M vs. F33M) caused two noticeable effects. Firstly, the failure mode of the beam changed from being compression-controlled to tension-controlled. This is attributed to the hoop layers adding more confinement to the compression fibres and preventing them from buckling outwards. This allowed the fibres to reach their tensile capacity in F33M. The second effect was that stiffness was higher (by 13%) in F33M. Though the additional fibres were added in the hoop direction (i.e. not expected to add to flexural stiffness), the contribution of the resin to resistance is not negligible. Interestingly, the strengths of the two beams were almost identical (~1% different); it is believed, based on the recorded strains, that with slightly more confinement from the hoop fibers that F31M would have failed in tension.

4.3 Effect of Adding Longitudinal Fibres

The effect of varying longitudinal fibres is investigated by comparing F53M and F33M. The two additional longitudinal flax layers increased the tube peak load and stiffness considerably (by 55% and 54% respectively) especially relative to the 27% increase in specimen weight. The failure modes of the two tubes were the same, showing that 3 layers of hoop fibres are enough to confine even 5 layers of longitudinal flax and develop the full tube capacity.

4.4 Effect of Fibre Material

One of the goals of the test program was to compare flax-FRP wrapped tubes to ones wrapped with glass-FRP. For F33M and G11M, which abide by the 3:1 ratio presented for sandwich structures by Mak et al (2015), the two specimens had similar weights but G11M was considerably stronger (by 41%) and stiffer (by 27%). The reason the 3:1 ratio does not apply to this case is that sandwich structures have non-negligible shear deformations which cause them to behave differently than beam structures whose deformation is dominated by flexure.

Specimen F53M is stronger (by 10%) and stiffer (by 22%) than G11M. This indicates that a ratio of 5 longitudinal flax layers is comparable in strength to 1 layer of glass, provided that adequate hoop confinement is provided. This capacity comes at the cost of increased weight (4.55 kg/m for F53M and 3.15 kg/m for G11M). The average stiffness of F33M and F53M is 166 Nmm²×10⁶ so it is suspected that 4 longitudinal layers of flax would provide equivalent stiffness to 1 layer of glass (stiffness of 165 Nmm²×10⁶). Additional testing or modelling is recommended in order to confirm this.

The decrease in stiffness over the course of each test was lower for G11M than it was for the flax-FRP tubes (Figure 5). Comparing the final stiffness to the stiffness at a service deflection of 5 mm shows that G11M reduces in stiffness by 10%. Tension controlled flax-FRP beams (F53M and F33M) see an average decrease of 42% and compression controlled is even higher (averaging 78%) the decrease in stiffness appears to be proportional to deflection and is believed to be due to the flax-FRP itself being non-linear due to mechanisms such as microbuckling of fibres in compression, slip of fibres against the matrix in tension, or non-linearity of the resin material being more apparent with the lower modulus of the flax fibres.

The hoop strains in the flax-FRP beams were higher than those of the glass-FRP beams, showing that the fibres are contributing more to confinement in the flax-FRP beams. Unlike in the flax-FRP beams, fibre buckled inwards in
G11M, showing that the foam failed before the hoop layer ruptured. This is attributed to the higher stiffness and strength of the glass hoop layer relative to flax (and the foam as well) causing failure to occur into the foam as the foam is softer and less able to resist buckling than the glass-FRP hoop layer. In the flax-FRP beams, the hoop layer was either too weak (encouraging buckling to occur outward from the foam) or too strong (buckling in either direction is prevented and failure is governed by tension).

4.5 Strength and Stiffness relative to Weight

Strength-weight and stiffness-weight values are presented for each beam in Figure 8. G11M has both the highest strength (2.86 kN/kg) and stiffness (26.2×10^9 Nmm^2/kg) to weight ratios. Of the flax-FRP beams, F31L had the highest ratios (2.39 kN/kg and 24.8×10^9 Nmm^2/kg) followed by F53M (2.18 kN/kg and 22.1×10^9 Nmm^2/kg). F33M had the lowest strength and stiffness to weight ratios (1.80 kN/kg and 18.2×10^9 Nmm^2/kg).

Overall, the flax beams had between 59 and 82% the strength and between 69 and 95% of the stiffness-to-weight ratios of G11M. Though lower than G11M, these values are much higher than the ratio of flax to glass-FRP’s strength (0.28) and stiffness (0.36) from material tests. F33M’s low ratio relative to the other flax-FRP beams is attributed to the added hoop layers having reduced effectiveness as the full tensile capacity of the tube was developed and the stiffness increase from adding hoop fibres is less effective than from adding longitudinal fibres (such as in F53M). Reducing foam density and increasing longitudinal fibre layers increased the strength and stiffness to weight ratios; future investigations should build upon these findings to determine the ideal foam density and fibre arrangement to maximize both ratios.

5. CONCLUSIONS AND RECOMMENDATIONS

Six tests were run on FRP-wrapped foam structures using glass and flax-FRP in order to investigate the validity of this structural system. The tubes were loaded statically in four-point bending until failure. The following was concluded from this experimental program:

1. A method of successfully fabricating the tubes using wet lay-up was developed. It is suggested that if this system is to be used on a larger scale that a different technique (i.e. filament winding) is used. For filament winding, the foam cylinder could function as a stay in place structural form.

2. For the tested flax-FRP beams, adding hoop layers caused the failure mode to transition from compression controlled (buckling of the fibres and rupture of the hoop layers) to tension controlled (rupture of the fibres). Additional hoop layers also increased the specimen stiffness slightly, due primarily to the increased thickness of resin.

3. For the tested arrangement, it was found that 5 longitudinal and 3 hoop layers of flax gives similar strength to a system with 1 longitudinal and 1 layer of hoop glass fibres. Based on interpolating the results from beams with
3 and 5 longitudinal layers of flax-FRP, it is suspected that a beam with 4 longitudinal layers of flax will give similar stiffness to a beam with 1 layer of glass-FRP.

4. Lower density foam caused premature failure in the flax-FRP beams as the foam’s lower tensile capacity allows fibres to buckle outward under lower loads. Varying foam density did not appear to affect its stiffness.

5. The load-deflection response of the flax beams was non-linear and showed a consistent decrease in stiffness as load increased (the decrease ranging between 42 and 78% that of service at ultimate). The decrease in stiffness was higher for flax-FRP beams that failed in compression (and at higher deflections). The glass-FRP beam had a considerably smaller decrease in stiffness of 10%.

6. Of the investigated parameters, lowering foam density and increasing the number of longitudinal layers gave the highest increases in strength to-weight and stiffness to-weight ratios.

Future work should investigate the response of these tubes to axial and cyclic loading simulating wind loads on utility structures along with further characterization of the long-term performance of flax under environmental effects, creep, and cyclic loads. The authors are now in the process of conducting additional flexural tests that will be compared to an analytical model to ensure reliability in the reported test results.

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