DESIGN, MANUFACTURING, AND TESTING OF AN AUTOMATED WINDING MACHINE FOR WRAPTOR COMPOSITE TRUSS STRUCTURES

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Keywords: Truss structure, Filament winding, Mechanical testing, Buckling

Abstract

Wrapped Tow Reinforced (WrapToR) trusses are a family of novel, ultra-efficient composite structures. They are produced by wrapping wet fibre tow around longitudinal members to form a continuous, co-bonded truss geometry. This paper details the development of a three degree-of-freedom winding machine for the manufacture of these continuously wound composite truss structures. Automating the winding process allowed faster and more consistent production of truss samples with better control over process variables than achievable by hand winding. Using this machine, test samples were manufactured to investigate the effect of a proposed design improvement: twisting of the carbon fibre tow during winding to create circular shear web members. Testing in three-point bending found this technique to improve stiffness and load carrying capabilities by 8 and 7 % respectively. A comparison with conventional carbon fibre pultruded tubes found the WrapToR truss configuration offered 16 % less mass, over double the load carrying capability and 6.7 times the flexural rigidity.

1. Introduction

High specific strengths and stiffnesses make composites desirable for many weight critical structural applications. However, the structures in which composites really excel are those where there is a dominant stress direction and where that direction is known. In these applications the anisotropic nature of composites can be tailored to maximise material properties in the dominant stress direction by aligning the fibres.

Trusses and space frames are structural configurations that are also desirable for many weight critical applications. They achieve high structural efficiencies through the use of two mechanisms: firstly, by moving material away from the neutral axis they take advantage of favourable non-linear scaling rules of strength and stiffness. Secondly, their geometry encourages a two-force member structure, where each individual element experiences primarily axial loading along its length. This means that within truss structure members a known dominant stress direction is present therefore making the use of fibre reinforced composites an ideal solution. This would then result in an efficient structural configuration constructed of highly efficient members. Despite this, the use of composite trusses to date has been limited. A possible reason for this is related to manufacturing and more specifically with joining of the truss elements. Within traditional metallic truss structures and space frames, elements are typically joined by mechanical fasteners or welds. However, in composite structures, creating reliable joints is notoriously difficult. Considering this in a truss where vast numbers of joints are required, the use of composites then becomes less attractive.

In a study by Schutze[1] CFRP truss structures were assembled from individual members via bonding. To achieve sufficient adhesion between elements, nodal gusset plate connectors made from CFRP were manufactured and used at each joint. While the CFRP truss concept offered a mass reduction of over 50 % compared to an aluminum equivalent, the manufacturing process involved production and assembly of a huge number of composite parts, making it unsuitable for many applications.

Within the literature several composite truss concepts have been investigated which use novel manufacturing techniques to reduce or remove the need for bonding multiple members. This includes truss sandwich core concepts, such as those seen in [2], [3] and composite lattice truss structures which have been produced using both filament winding [4], [5] and fibre braiding [6], [7]. While these lattice structures have displayed impressive structural performance, their unconventional truss geometries all possess members that are either curved or bent. Under loading, internal bending moments will be generated within these members reducing their load carrying capability.

The patented Wrapped Tow Reinforced truss concept (WrapToR) [8], [9] uses an adaptation of the filament winding process to produce beams that more closely resemble traditional trusses than the lattice trusses mentioned previously. The process involves holding longitudinal members, typically premade composite tubes, on a rotating mandrel while wetted fibre tow is wound around them to form a shear web. The process, shown in Figure 1, results in trusses with all the fibres aligned with the member's respective primary loading directions, therefore maximising efficiency. The manufacturing process removes the need to assemble large numbers of parts as by winding wetted tow, shear elements are both created and co-bonded simultaneously. Further detail of the WrapToR truss concept is given in [9] where analysis, testing, and optimisation of the structures was conducted. The previous work demonstrated impressive stiffness to weight ratios of the structures when compared to conventional composite beam structures, such as pultruded or pull-wound tubes. Testing of the trusses in torsion was conducted where failure predominately occurred due to buckling of the shear members. One potential solution for improving the buckling resistance of the shear elements is to twist the fibre tow to form a circular section, which compared to tow wound in its native configuration (which is a thin, wide section) has a larger minimum second moment of area.

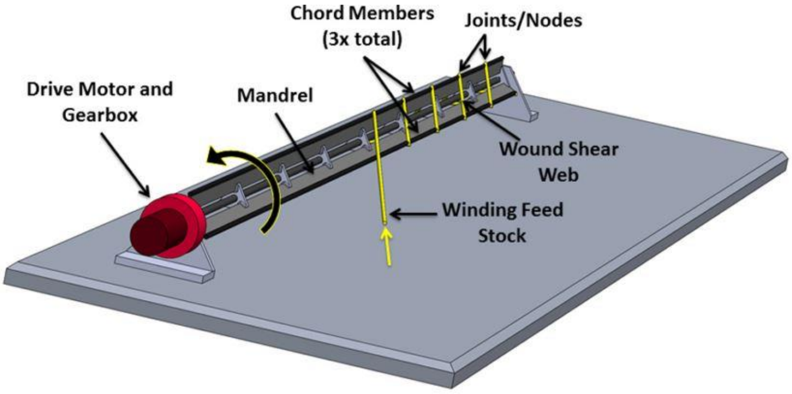

Figure 1. Schematic of winding process. Reproduced from [9].

In previous studies and applications WrapToR trusses were manufactured by hand winding where the mandrel was rotated by a manually controlled electric motor and the fibre tow was guided by hand. To fully exploit the benefits of the WrapToR truss concept, development of an automated machine is necessary to improve both process consistency and throughput while reducing labour requirements and allowing greater control over the process variables.

In this study the design and manufacture of an automated winding machine for the production of WrapToR truss structures is presented. Sample trusses made using the machine are then mechanically tested to investigate the effects of twisting the tow to form circular shear web elements. Finally, the trusses are compared to a conventional composite beam configuration to highlight their benefits.

2. Winding machine design and operation

2.1. Machine overview

For automated, computer-controlled production of WrapToR composite trusses, a three degree-of-freedom (DOF) winding machine was designed and manufactured. A CAD model image showing the layout of the machine with labelling of key components is displayed in Figure 2. The winder is sized for production of trusses with section diameter up to 0.5 m and lengths of up to 2 m however, the design allows easy expansion should larger trusses be required.

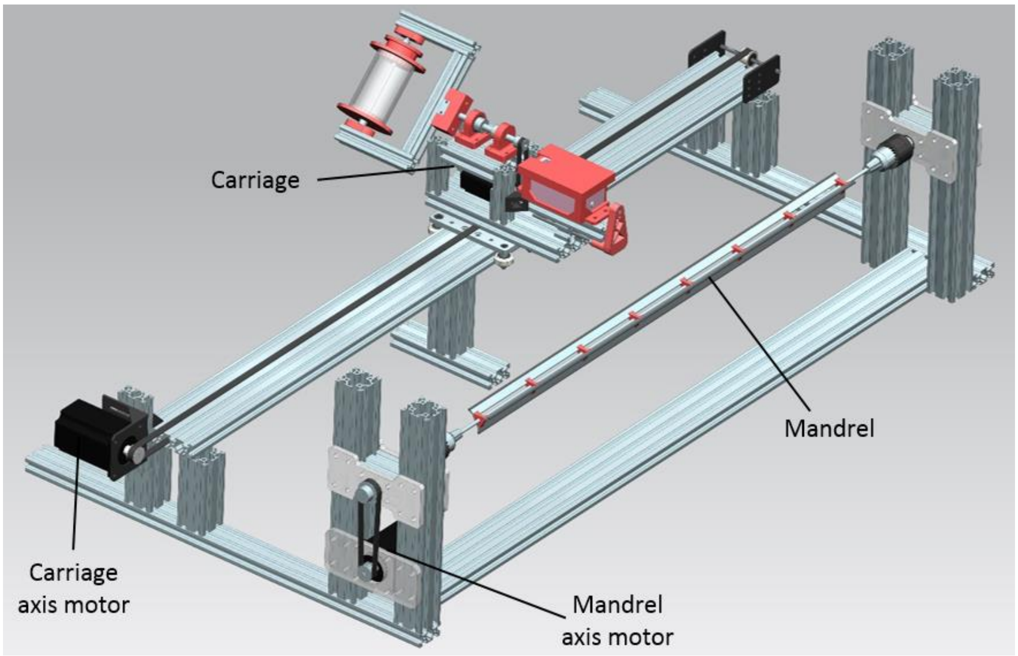

Figure 2. CAD model image of WrapToR truss winding machine.

Two of the machines degrees of freedom are inherent to any filament winding machine: a mandrel rotational axis and a longitudinal carriage axis that translates the tow delivery carriage along the length of the mandrel. The third DOF is required to twist the tow which is achieved by rotating the entire tow spool on the delivery carriage during winding. The carriage is the most intricate part of the winder and is detailed in Section 2.2.

The truss winder layout was initially designed using CAD software before purchase and assembly of the components. Low-cost and ease of modification were key drivers in the machine design. This lead to a design where the supporting structures and linear rail are made from slotted aluminum extrusions, most of the mechanical parts are off-the-self, and where applicable 3D printed, or laser cut plastic components are used.

2.2. Tow delivery carriage

The tow delivery carriage is required to perform a number of key functions whilst being compact and light enough to move along the carriage axis. It is responsible for holding, twisting, tensioning, and impregnating the tow. A photograph of the delivery unit is shown in Figure 3 with key components labelled.

For tow twisting the entire spool is rotated by a motor, belt and pulley system. Whilst being twisted the tow runs off the spool into a silicone resin bath where it is impregnated with resin. The tow then exits the bath, passes through an eyelet and is placed onto the mandrel. Tow tension is controlled by a simple spring and string frictional device which resists the unwinding of the tow.

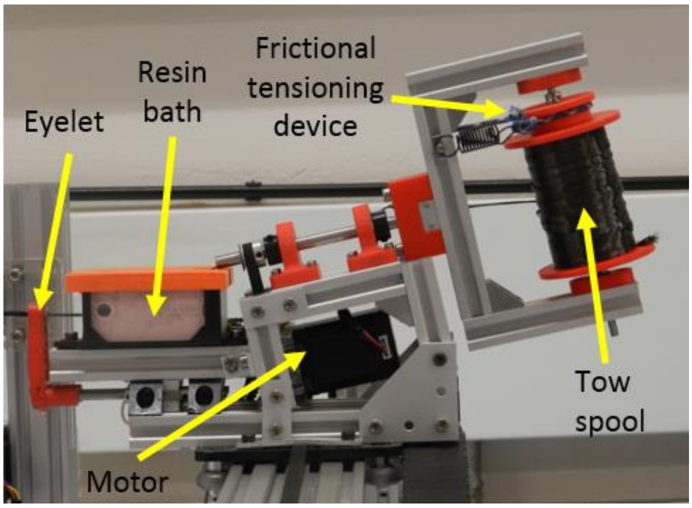

Figure 3. Tow delivery carriage.

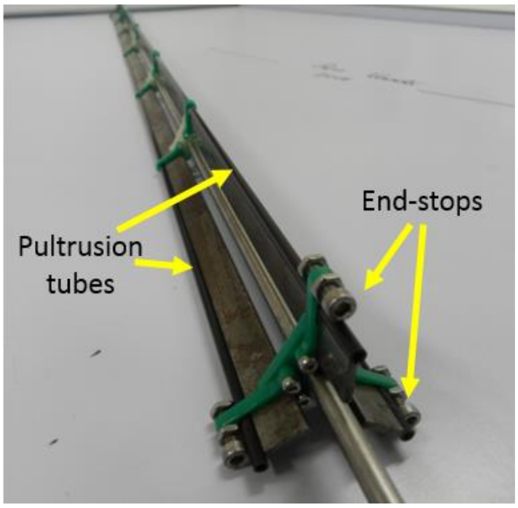

Figure 4. Mandrel.

2.3. Mandrel

A fixed size mandrel was used for manufacture of the samples in this study. The mandrel, displayed in Figure 4, is constructed from three steel flat bars which are attached to a steel rod by several laser-cut acrylic mounts. The carbon pultruded rods that form the chord members of the trusses are then held on the flat bars with acrylic clips. At the truss ends, screws are attached to the clips which act as end stops allowing the tow to change direction once a pass is completed.

2.4. Electronics and controls systems

Each DOF is driven by a stepper motor allowing precise control of absolute positioning without the need for external position feedback. Each motor is driven by a Toshiba TB6600 stepper driver. Limit switches are used on the carriage axis to limit the travel of the tow delivery carriage. Relative motion of the three DOFs is controlled by an Arduino Mega microcontroller and the open source G-code interpreting software: GRBL. This set-up provides a low-cost and easily modifiable control system.

3. Sample manufacture

Truss samples produced for testing had equilateral triangular sections with dimensions detailed in Figure 5 and Table 1. Commercially available unidirectional pultruded carbon-epoxy tubes were used for the longitudinal members. The shear web was formed of Tenax IMS60 24K carbon fibre tow and SuperSap® CLV low viscosity bio-epoxy resin cured at room temperature. Winding speed and linear traverse rates were controlled to create a tow feed-rate of 2000 mm/min.

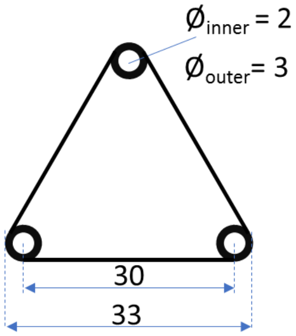

Figure 5. Truss sample cross section (dimensions in mm).

Table 1. Truss sample geometry.

Geometric feature	Value
Winding angle	45 °
Bay length	33 mm
Sample length	495 mm

To investigate the effect of twisting the fibre tow during the creation of the shear web, two truss configurations were produced and tested. The first has an untwisted-flat tow shear web (Figure 6a), the second has a twisted-circular shear web with one twist per shear element (Figure 6b).

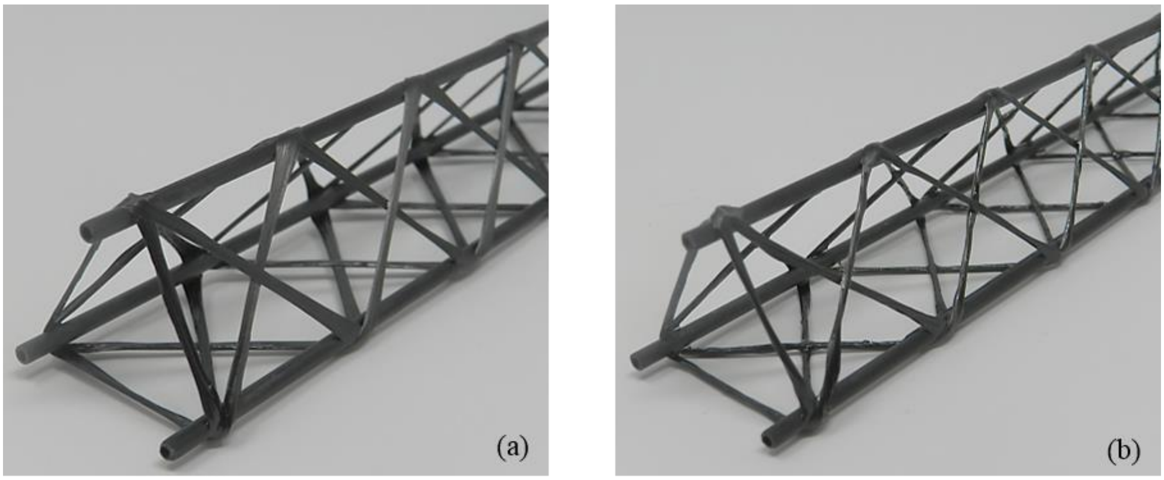

Figure 6. Shear web configurations: a) Flat; b) Twisted.

For comparison to a conventional composite structural configuration, two sizes of unidirectional carbon fibre pultrusion tube were investigated under the same test conditions. 7 and 8 mm external diameter tubes both with 1 mm wall thicknesses were chosen as they have similar mass per unit lengths to the truss samples. Averaged masses of the truss and pultrusion samples are displayed in Table 2.

4. Testing method

For comparison of the truss configurations and pultrusion tubes, samples were loaded to failure in a three-point bending test using the custom-built support rig seen in Figure 7. Displacement of the test specimens at the central load-point was measured using two laser sensors and displacement of the supports was measured using potentiometers. A 396 mm span, corresponding to twelve truss units, was chosen for the test. This span was selected to purposely create high loading in the shear members as this would aid comparison of the shear web configurations. Testing was conducted on an Instron 8872 test machine at a displacement rate of 4 mm/min using a 5kN load cell.

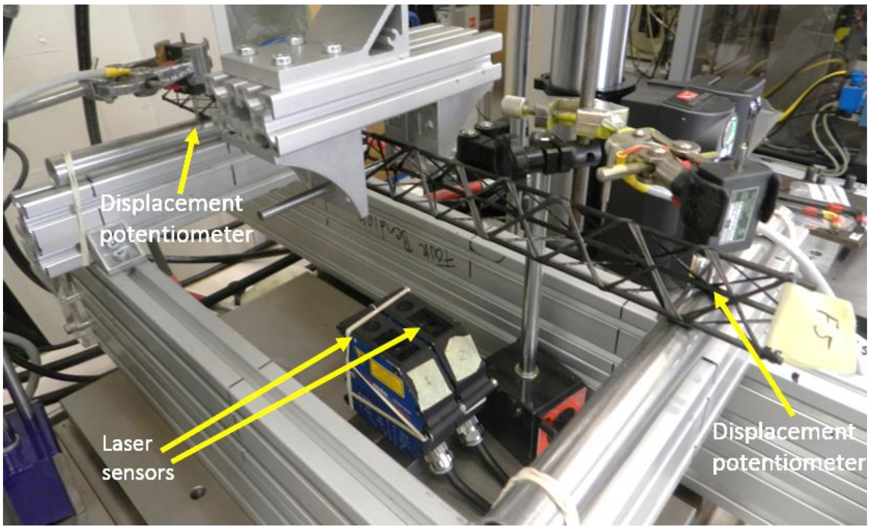

Figure 7. Three-point bend test set-up.

Table 2. Test samples mass per unit length.

Configuration	Number of samples	Mass per unit length (g/m)	
		Average	Standard deviation
Flat	6	33.8	0.8
Twisted	6	34.5	0.6
7 mm carbon tube	4	32.1	0.2
8 mm carbon tube	4	38.0	0.1

5. Results and discussion

Load-displacement responses of representative samples from each test configuration are plotted in Figure 8. These representative samples displayed the minimum variation from the configurations average failure load and flexural rigidity. The responses are compared to predictions from Direct Stiffness Method analysis (DSM) which is detailed in [9]. Note here the DSM data does not include prediction of failure and therefore is only used for stiffness response. From this plot the benefits of the WrapToR truss over conventional carbon tubes are clearly visible. The pultrusion tubes show much larger displacements at a given load and are seen to fail at significantly lower loads.

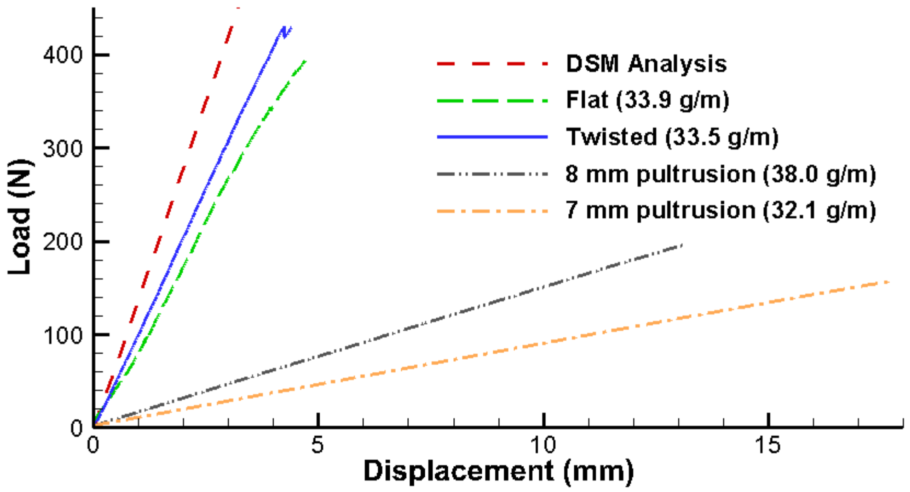

Figure 8. Load-displacement of representative test samples with comparison to DSM analysis.

Using the slopes of the load-displacement graphs the equivalent flexural rigidity, EI, was calculated for each sample from the following Euler-Bernoulli beam equation for a simply supported beam with span L:

$$EI = \frac{PL^3}{48w} \tag{1}$$

Average flexural rigidity values for each configuration are plotted in Figure 9 and are compared to predictions from the DSM analysis. Here it is seen that the experimentally determined flexural rigidities were around 30 % less than the analysis predicted. The analysis method used here is of low fidelity and assumes full two-force member behaviour in which each member of the truss only experiences axial loading. In reality the members will also experience bending moments which may cause larger displacements. The analysis method also only models strains within the truss members and therefore does not look at strains within the joints. For the WrapToR configuration, where the truss members are fibre reinforced and the joints are not, strains at the joints may create a significant contribution to the overall displacement. It should also be noted here due to the high stiffness of the trusses, the differences in deflections between the experimental results and analysis are only around 1 mm at failure load meaning that small experimental errors could cause significant variation.

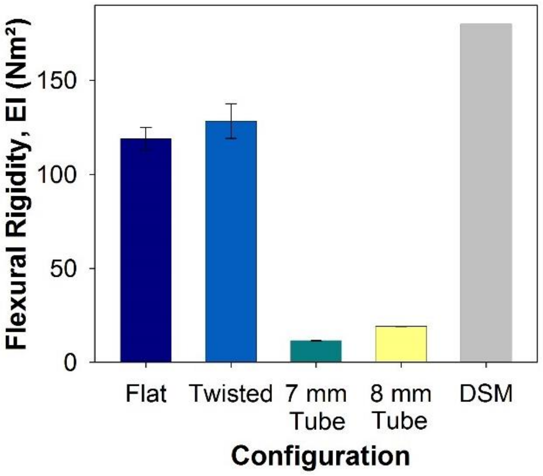

Figure 9. Average flexural rigidity for each configuration with comparison to DSM analysis. Error bars denote 1 standard deviation.

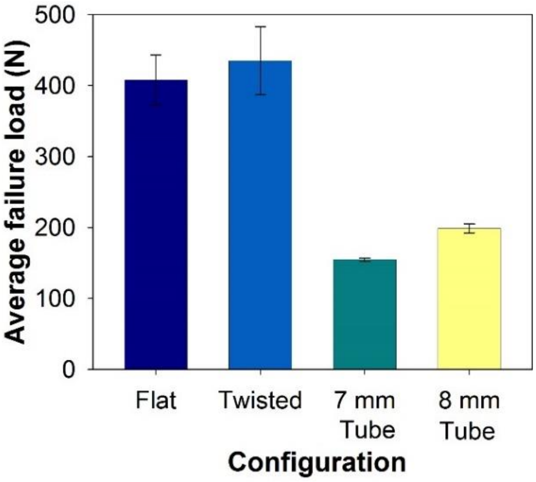

Figure 10. Average failure loads for each configuration. Error bars denote 1 standard deviation.

When comparing the two truss configurations in Figure 9, the average flexural rigidity is 8 % larger in the twisted samples. One possible reason for this relates to the higher mass of the twisted samples seen in Table 2. This increased mass corresponds to more resin within the structure which stiffens the elements and potentially results in stiffer joints. Another possible reason for this difference in stiffness could be due to bowing of the shear member under compression. If this phenomenon were to occur the flat samples would be more susceptible as their shear webs have a lower minimum second moment of area. Furthermore, a gradual and progressive bending of the flatter shear web would help to explain the gradual softening non-linearity in the response of the flat samples that can be seen in Figure 8. This phenomenon may also contribute to the variation from analytical predictions as the DSM method does not account for it.

When compared to the 7 and 8 mm pultruded tubes, the twisted shear web trusses provided a 570 % and 1010 % increase in flexural rigidity respectively. As both the tubes and the trusses use unidirectional carbon fibre epoxy, this impressive increase in stiffness demonstrates how the WrapToR configuration uses geometry to improve structural performance.

Average failure loads of the test configurations are compared in Figure 10. Here the twisted shear web truss again offers a slight increase in performance over the flat configuration with an increase in average failure load of 7 %. The trusses are again seen to outperform the carbon tubes with the twisted configuration giving a 118 % and 181 % increase in load carrying capability compared to the 7 and 8 mm tube respectively.

Figure 11. Tested sample showing debonding and failure of compression longitudinal member.

The primary failure mechanism for both truss configurations was debonding of the shear web and longitudinal members. Failure of the upper compression longitudinal member was also common, particularly in the twisted samples. A sample displaying both these failure mechanisms is displayed in Figure 11. Buckling of the shear members was also witnessed in a quarter of the samples.

6. Conclusions

This study demonstrates the ability to automate the manufacturing process of Wrapped Tow Reinforced (WrapToR) trusses via the design and manufacture of a low-cost three degree of freedom winding machine. Automating the process increased throughput and reduced labour requirements allowing consistent production of carbon-fibre epoxy truss samples for testing. The machine was designed with the capability to twist the shear web tow to improve shear member buckling resistance. To investigate the benefits of this technique, samples with twisted-circular and untwisted-flat shear webs were compared in a three-point bend test. For comparison to a conventional structural configuration two sizes of pultruded carbon tubes with similar mass per unit lengths were also tested.

Results of truss testing showed that twisting the tow when creating shear web members improved the performance of the trusses in terms of both strength and stiffness. A mismatch between experimental results and low-fidelity stiffness analysis was observed, likely caused by inaccurate assumptions in the analysis. This prompts the need for the development of higher fidelity analysis. Investigation of the truss failure mechanisms showed that bonding of the shear and longitudinal components of the truss is critical in this test configuration. Comparison with the carbon tubes showed the incredible increases in structural performance that the WrapToR trusses offer.

Data Statement

The supporting information is available on request from chris.hunt@bristol.ac.uk.

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