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Wrapped Tow Reinforced Truss Structures: Progress, Performance, and Prospects

Benjamin K.S. Woods†
* *University of Bristol*
Bristol, BS8 1TR, United Kingdom
ben.k.s.woods@bristol.ac.uk
† Corresponding Author

Abstract
The Wrapped Tow Reinforced (WrapToR) truss manufacturing process allows for low cost, scalable manufacturing of high structural efficiency composite truss structures. The technology, originally developed in 2009, has since been under development at the University of Bristol, where significant progress has been made in the manufacturing of WrapToR trusses, numerical tools for predicting and improving structural performance, and WrapToR based Hierarchical Space Frames (WrapToR-HSFs). The concept has also been expanded into other structural forms with new capabilities. The very high levels of structural performance achieved motivate wider uptake, and key focus areas for future work are identified.

1. The structural advantages of composite truss structures

Before exploring the WrapToR technology, it is useful to first consider the history of trusses in general and composite trusses in particular, and to discuss their advantages and disadvantages, alongside new technologies which have been developed to address some of these shortcomings.

1.1. The history of truss structures

Truss structures have been known in various forms since antiquity, and while their exact origin is unknown, they are at least as old as the early Bronze age – based on archaeological evidence of wooden truss roof supports in central Germany [1]. Trusses then progressively permeated architecture throughout the world as efficient solutions for supporting long spans. There was a very rapid rise in the popularity of this approach during the construction of the first railroad networks across the United States and Europe, with wooden truss bridges being particularly well suited to the rapid expansion of the US network, as locally sourced timber could be made into reasonably easy to manipulate members and assembled via simple methods, as opposed to the slow to build and more craftsman dependent stone piers and arches of traditional bridge building. When iron and then steel became available, an explosion of progress erupted across the globe, with many new truss designs being trialled and iterated before a slow convergence towards simple and efficient designs such as the Warren, Pratt, and Howe trusses. The usage of trusses and space frames (the fully three-dimensional, volume filling version of truss structures) also expanded outside of bridges and buildings to include towers, aircraft wing and fuselage structures, automobile chassis, cranes, and even roller coasters, amongst many others, and they remain very common structural solutions in our modern society.

Trusses became so common because of their very high levels of structural efficiency. This is achieved through three primary exploitations of structural scaling laws. Firstly, using small amounts of material placed far apart gives trusses very large second moments of area for a low mass, which then gives the structure high stiffness and strength. In effect, this approach gives the small members very large moment arms over which to resolve the global bending moments carried by the structure, lowering the forces required to do so. Secondly, by grouping this small amount of material into localised discrete members (as opposed to spreading it thinly into continuous walls), the local second moments of area are increased in a highly non-linear fashion, which allows for a number of stability-driven failure modes (e.g. buckling, crippling, etc.) to be avoided. Finally, and most famously, the arrangement of these straight members into triangular patterns leads to the resolving of applied forces and moments as predominantly axial forces in the members, allowing them to act as stretch-dominated as opposed to bending-dominated structures, which are inherently more efficient. Beautifully, these three tricks can be used recursively, which is to say they have the same positive benefits if

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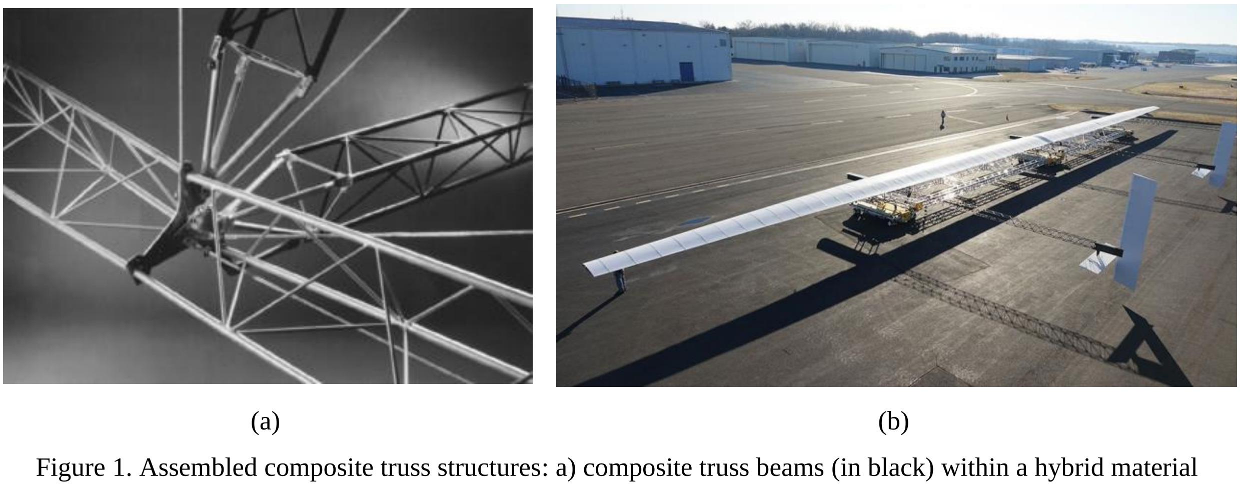
applied to the individual members of a truss as they do for the truss itself. This is why truss and space frame structures are often hierarchical, with the Eiffel tower being a particularly evocative example.

It must be admitted, however, that the first golden age of the truss is perhaps behind us. In large infrastructure projects, assembled truss structures have largely been replaced with monolithic structures, either of precast reinforced concrete or of large steel beam sections. These structures are not inherently more efficient, but because they do not require the very large numbers of parts and tedious assembly processes of trusses, they are often significantly lower cost. Similarly, the truss towers of early wind turbines have been replaced with steel monopoles. Fundamentally, the very clever and efficient usage of material within trusses currently comes at the cost of complex manufacture and assembly processes, because the members are made separately and then combined. If instead truss structures could be made in a more monolithic manner, with the separate members being formed through some continuous process of material placement and joining, then perhaps the second golden era of trusses could begin. We will return to this idea shortly, but we first must consider the benefits that high performance composite materials can bring to trusses.

1.2. Composite trusses and space frames

Composite materials have become well known and increasingly useful throughout modern society due to the tremendous amount of scientific progress that has been made over the last three to four decades in their performance and manufacture, supported by a growing understanding of their complex mechanics. Indeed, high performance composite materials such as carbon fibre reinforced polymer (CFRP) and glass fibre equivalents (GFRP) have become the go-to solution for many demanding applications including aircraft and high performance automobiles (amongst other forms of transit), wind turbines, sports equipment, and increasingly, civilian infrastructure. One inherent feature of fibre reinforced composites that is both an advantage and a potential liability is their highly anisotropic nature, with mechanical performance in the fibre dominated direction generally being significantly higher than in the matrix dominated direction. In structures with clearly defined and focused loading directions, aligning the fibres with the load provides incredible performance. For multi-axial loading conditions, more complex layups can be used which provide fibres in different directions through the stacking of multiple thin plies, although careful attention must be paid to how this is done due to a wide range of micro-mechanical considerations [2]. Ultimately, while composites for complex multi-axial loading conditions are certainly and increasingly useful, the mechanical properties of unidirectional composites are substantially higher.

Considering this, it would seem that using composite materials within truss structures would be an ideal combination – with the incredible structural efficiency of trusses being further enhanced by the superlative material properties of composites. Furthermore, aligning the composite’s fibres to the predominantly axial loads within the truss members would provide a coalescence of form and function, allowing each fibre to perform at its best. In this way, our most effective materials could be used within our most efficient structure in order to realise new heights of structural performance.



(a) (b)

Figure 1. Assembled composite truss structures: a) composite truss beams (in black) within a hybrid material hierarchical space frame on the Zepplin NT [3] and b) truss beams visible in the tail booms of the Aurora Flight Sciences Odysseus high altitude pseudo-satellite [4].

And yet, while composite trusses of various forms have indeed been researched and experimented with over the years, there has not been any widescale adoption of this solution. We will first consider composite trusses which have been made using the traditional approach to truss manufacture: assembly of large numbers of separate components. One of the most well known examples of this approach is the carbon fibre composite truss structures made by Schütze for the

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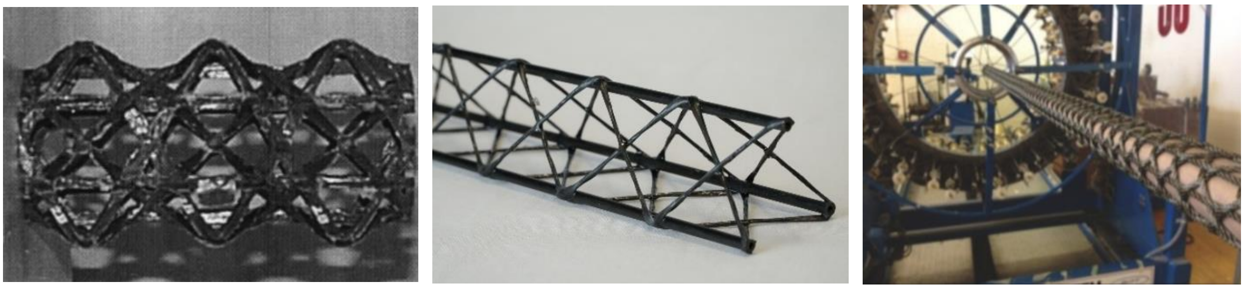
Zeppelin NT airship [3]. In this case premade CFRP tubes were bonded together using CFRP gusset plates to create truss beams, as shown in Figure 1a. These beams were then assembled into a hybrid hierarchical space frame made of both welded aluminium and CFRP truss beams. Another more recent example of assembled composite trusses is the Odysseus high altitude pseudo-satellite designed and manufactured by Aurora Flight Sciences, shown in Figure 1b. This vehicle uses CFRP trusses within its airframe, although the details of its construction are not publicly known. Photos of the aircraft during its development show exposed truss beam tail boom structures which were covered in later images. So while these examples show that it is certainly possible to make composite truss beam structures through assembly, which can then in turn also be assembled into higher order space frames, it could be argued that this approach is far from ideal as it combines the very labour intensive, and therefore expensive, traditional truss assembly process with the perennially difficult problem of joining composite materials. This "worst of both" argument is partially offset by the simplicity of the approach, the ability to use off-the-shelf composite tubes (be they roll wrapped, pultruded, or pull-wound) and indeed the high levels of structural efficiency which the material/structure combination is capable of. Ultimately though, this approach has not been widely adopted, most likely due to cost.

1.3. Continuous truss beam technologies

If composite trusses are to become a more generally successful and useful technology, the assembly and joining processes both need to be cheaper and more robust. We consider here the question of assembly, where an ideal approach to reducing assembly costs of individual truss beams would be to negate the need to assemble entirely. This could be achieved by instead creating the structure through some form of continuous process, where the fibres can run between members without breaks, and the joints between members are created automatically during the manufacturing. There have been several technologies introduced to do exactly this, wherein various forms of winding or braiding are used to create continuous truss beam-like structures. This area of research has been comprehensively reviewed in [5], but it is useful here to consider the three examples shown in Figure 2, namely the IsoTruss, Wrapped Tow Reinforced (WrapToR), and Open-Architecture Composite Structure (O-ACS) technologies, as they are arguably the most relevant and furthest developed. The IsoTruss process was the first to be shown (with references going back to 1996 [6]), and consists of continuous epoxy wetted tows wound around a complex, captive mandrel to create a series of nested radially aligned pyramidal sub-structures interwoven with axially aligned chord members. The WrapToR truss, developed in 2009 but first published in 2011 [7], is significantly simpler in geometry and manufacture, as it consists of three pre-made pultruded tubes connected by a one piece continuously wound shear web. The O-ACS on the other hand, is made using a maypole braiding process, using cordage like preforms built up from multiple tows, and it was first shown in 2015 [8]. Both the IsoTruss and WrapToR have members that are substantially straight, thereby reducing internal bending moments under load, whereas the O-ACS is braided around a cylindrical mandrel such that the helical members are curved, which will affect their strength. Here, we will focus on the progress that has been made with the WrapToR concept in particular.



(a) (b) (c)

Figure 2. Composite truss beams made via continuous winding or braiding: a) IsoTruss [9], b) WrapToR (author's own photo), and c) O-ACS [8].

A useful ancillary point can be made by considering what trusses, composites, and composite trusses (assembled or continuous) all have in common with regards to when and how they are, or could be, used. They all involve more complexity than alternative "monolithic" solutions (monolithic structures and/or monolithic materials), which brings inherent cost, but due to the tailorability this complexity provides they can also bring compelling performance benefits. This simple balance is of course true for many other types of systems as well, and can perhaps be generalised as "dollar-per-delta" ($/Δ), which represents the generic idea of a performance normalised cost gradient: that is say how much money ($) are designers/customers willing to pay for of a given amount of change (Δ) in some key performance metric – whatever that may be (fuel efficiency, range, speed, energy generated, etc). Historically, high dollar-per-delta applications are the first to adopt complex new technologies (as in the adoption of composites into aviation and automobile racing), and then as technologies are proven and evolved, the price comes down (often accompanied by

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acceptable reductions in performance) and the technology becomes increasingly viable for and present in lower dollar-per-delta applications. In the same way, we can consider the viability of all of the technology areas discussed above and all of the particular technologies shown below not as a yes/no question, but instead as a $/Δ question, where both terms in that ratio can change over time (with effective development), and where the magnitude of that ratio helps determine the application areas that may suite any particular technology at any particular time.

2. WrapToR truss origin

It is in this context that we now consider the history and development of the WrapToR technology, starting with the incredibly challenging, if not necessarily useful, application for which it was invented.

2.1. Invention

The WrapToR truss manufacturing method was invented as part of the development of the Gamera Human Powered Helicopter at the University of Maryland [10]. During design of the main rotor blades, various tubular composite spar configurations were tested but found wanting, and so in 2009 trials began on a modified form of filament winding wherein 6.5m long sections of pultruded CFRP tubes were attached to sacrificial foam tooling that had been hot wire cut into triangular cross-sections, with recesses for the pultrusions. This preform was then rolled by hand along the floor (see Figure 1a) as epoxy wetted carbon fibre tow was wound around it to create a single co-bonded truss beam spar. While perhaps a bit crude, this approach was immediately successful, and was adopted for the first generation vehicle, Gamera I. Smaller versions of these trusses were also manufactured on a small tabletop winding apparatus to replace commercially available CFRP tubes in highly loaded compression members at the base of the four arms of the quad rotor airframe, and likewise proved successful, with the trusses providing an experimentally measured 620% increase in buckling efficiency (defined as EI/mass) compared to the CFRP tubes they replaced [11]. Indeed, the success of these first trials led to near universal adoption of the technology on the improved Gamera II. The vast majority of the airframe, cockpit, rotor spars, and many ancillary components such as drive pulleys were made using this simple truss winding technique, with tremendous effect. The airframe, being a particularly efficient hierarchical space frame of truss beams within large truss arm structures, saw a 39% mass reduction, and the overall vehicle benefitted from a 33% reduction [11]. This weight savings, combined with improved rotor aerodynamics, led to an increase in achievable hover duration from 11 seconds to 95 seconds, which remains the FAI certified world record for Human Powered Helicopter flight duration.

(a) (b) (c) (d)

Figure 3. WrapToR trusses on the Gamera Human Powered Helicopter: a) hand winding process for spars, b) rotor blade spars, c) WrapToR hierarchical space frame airframe and cockpit, and d) rotor drive pulleys

2.2. Assessment of initial technology viability

While the WrapToR technology performed very well on the Gamera helicopter, the manufacturing and assembly of WrapToR truss beams and then hierarchical space frames were both quite *ad hoc* and imprecise processes that required a lot of manual labour. The tooling for the truss beams had mediocre dimensional tolerances, and the winding machine was nothing more than a DC motor to spin the mandrels, with the impregnated carbon fibre tow being wound back and forth by hand using rough guide marks to locate the nodes. For the airframe and cockpit, a very basic hand lashing process was used to connect truss beams within the HSFs, with epoxy wetted carbon fibre tows being wound from truss to truss. This approach was simple, light weight, and very robust to different numbers and orientations of truss beams within the joints, but it was also slow and somewhat inconsistent. In all cases, control of important processing parameters such as fibre volume fraction, winding tension, and cure temperature was rudimentary at best. These structures were not made in controlled, automated laboratory settings, as these solutions were being developed on the fly as part of a fast-paced experimental vehicle design and iteration process. The Gamera team found a lot of practical, workable solutions to the challenges of composite truss manufacture and joining that served very well in the context. Indeed, the performance achieved is perhaps even more remarkable given the aforementioned limitations around

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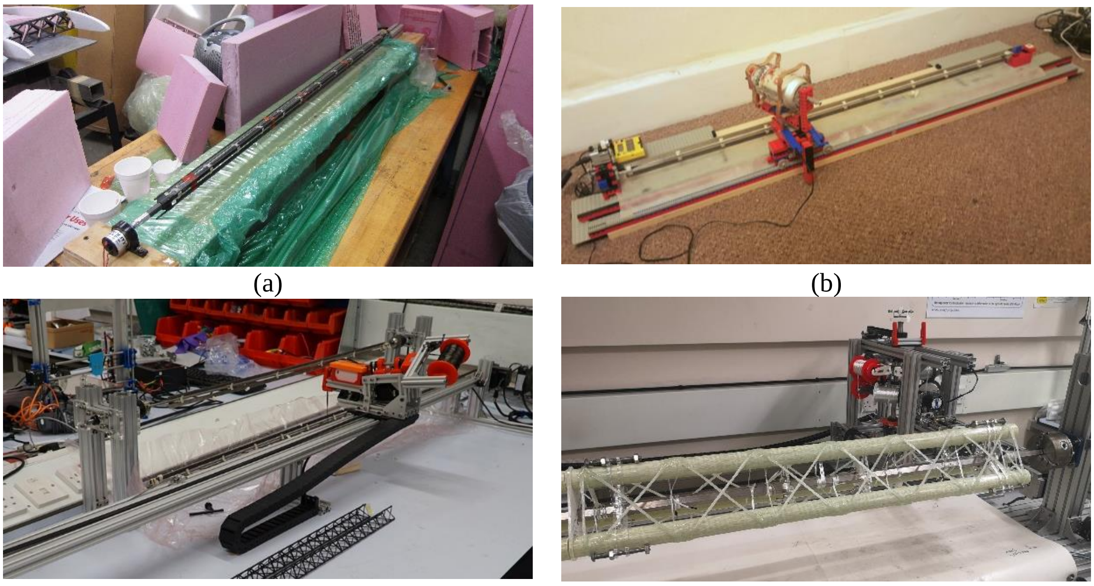
process control and consistency. In the end though, even if the techniques implemented left some room for improvement, Gamera clearly showed the basic viability of the WrapToR concept, for both truss beams and HSFs. As a final swan song, Gamera II was modified with electric motors and solar panels in 2016 to become the first manned solar powered helicopter in history to successfully hover [12]. Meanwhile, work on the WrapToR concept continued, first at Swansea University [13] and now at the University of Bristol.

3. WrapToR truss beam manufacturing

The first focus of WrapToR research post Gamera was on automating the manufacturing process by building a series of what are essentially modified filament winders. Improvements along the way allowed for higher strength, additional design freedom, and the use of alternative fibre materials. Parallel development started later on an inverted version of the process known as Trusstrusion, which turns a one-at-a-time batch process into a continuous process, something akin to extrusion and pultrusion, but for trusses.

3.1. Automated winding

In order to provide more accuracy and consistency to the winding process, automation was required. The first attempt at an automated WrapToR winding machine, shown in Figure 4b, was actually made from Lego Technic, and driven by an RCX 1.0 computer coded Lego control board, with the machine incorporating motors and sensors run by a closed loop feedback control system that drove mandrel rotation (with angle sensor feedback), winding carriage traverse (with end stop sensors) and a new degree of freedom: tow twisting. By twisting the tow before it is impregnated and wound, a more uniform circular cross section is achieved, which has more consistent second moment of area around its long axis (compared to the thin rectangular native shape of the tow) and therefore higher buckling loads, as discussed later. The various aspects of this machine worked, but the low refresh rate of the control electronics led to accumulating position errors and the system was not able to reliably automatically wind trusses, although it did work well as an augmented hand winding rig.



(a) (b) (c) (d)

Figure 4. The evolution of WrapToR truss beam winding: a) hand winder with DC motor, b) Lego winder, c) WrapToR 1.0 and d) WrapToR 2.0

The first successful automated winding machine, WrapToR 1.0, was developed in 2017 at the University of Bristol [14]. This machine used off-the-shelf motion control components (stepper motors, drive belts, contact sensors, drive board, etc) and was built using modular aluminium slotted framing, which allowed for design improvements and added functionality over time, including the development of a multi-spool holder which allows for four separate tows to be twisted together to form thicker shear webs. The quality of the trusses produced on this machine was substantially higher than hand winding, with consistent part masses and stiffnesses [14]. Experimental three-point bend testing of 33 mm wide, 33.5 g/m trusses made with this machine showed much better performance than the closest available unidirectional pultruded tubes, with a 637% increase in bending rigidity and a 133% increase in failure load compared to 8 mm diameter pultruded tubes, despite the truss weighing 9% less. Further comparative testing also showed that the tow twisting led to significantly higher strength for configurations which are susceptible to buckling of the shear

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web members, with a 51% increase in strength for the case of a 66 mm wide truss. Alternative truss configurations have also been made on this machine, including lengthwise tapered and hexagonal cross-sections.

A second generation WrapToR 2.0 machine was built in order to expand the size of trusses that could be made, and is capable of winding trusses up to 2.5 m in length and 500 mm in width. It can hold up to eight tow spools, and also features an additional degree of freedom to control the distance between the tow guiding eye and the mandrel, which increases positioning accuracy when there are large variations in truss width and allows for more complex winding patterns. This machine was used to wind large fibreglass truss beams for wind turbine applications, for example a 1 m long, 240 mm wide truss made with 38 mm diameter fibreglass pullwound tubular chord members (shown in Figure 4d) designed for the shear web of a large wind turbine blade, which was experimentally and numerically shown to be able to support 136 kN in direct compression (more than the weight of a double decker bus), despite a mass of only 1.5 kg and the use of lower performance glass fibres.

3.2. Trusstrusion

A completely different approach to making WrapToR trusses, known as Trusstrusion, has recently been demonstrated, wherein the standard filament winding based process is essentially inverted. Instead of a linearly traversing carriage winding around a rotating mandrel, this system uses a pair of contra-rotating winding heads which spin around a non-rotating mandrel, over which the pultruded chord members are advanced. Each of the winding heads has three separate tow supply/guide systems at 120 degree spacing, such that all six of the different shear web members are wound simultaneously. In this way, the chord members are able to pass continuously through the winding apparatus, such that there is no longer the need to wind back and forth as in the basic batch manufacturing WrapToR process. This provides the ability to continuously create trusses in a manner analogous to pultrusion, which if scaled up could lead to significantly higher production rates and therefore lower per part costs. A first generation prototype, seen in Figure 5, has been built and tested, and the quality of the trusses produced speaks to the basic viability of the concept, although further development is required to achieve the high production rates desired.

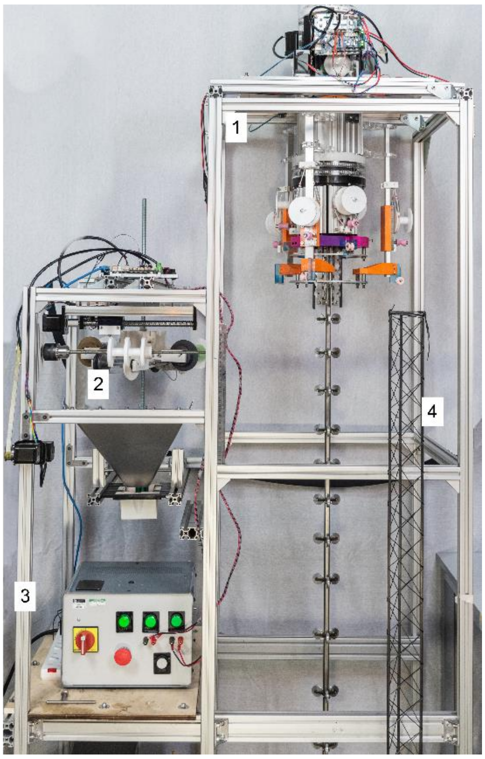

Figure 5. Trusstrusion machine: 1) contra-rotating winding drums and chord member feed units, 2) tow impregnation spooling station, 3) control electronics, and 4) Trusstruded WrapToR truss beam

4. Analysis and optimisation

In order to utilise any structural technology well, it is critical to be able to predict and understand its mechanical performance. Accordingly, significant research effort has gone into the numerical modelling and optimisation of

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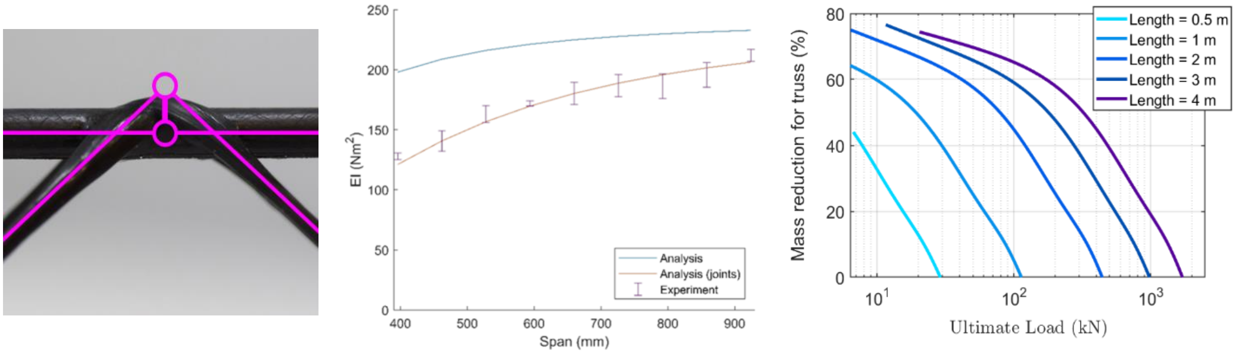
WrapToR truss beams and WrapToR-HSFs. As a result, effective methods have been identified that provide very useful levels of fidelity and accuracy at low to moderate computational cost.

4.1. Truss beam analysis and optimisation

Simple beam element finite element (FE) codes have been used to predict the performance of WrapToR truss beams from the early days of their development. Good predictive accuracy for a bespoke developed direct stiffness method FE code was shown in [13] for a 33 mm wide, 1 m long truss under both cantilevered bending and torsional loading, with a deflection prediction error of 2.9% and 6.4% respectively. Later work [15] showed the importance in capturing the shear deformations which occur at the bonded nodes, especially for shorter and wider trusses that experience higher relative levels of shear loading. In order to capture this, an additional short shear beam element was added into the geometry rationalisation, as seen in Figure 6a. This significantly improved accuracy across a wide range of width to length ratios. Figure 6b shows this, with the upper line being the FE without shear elements, and the lower line, in close agreement to experiments, is with it included. This figure also shows the reduction in effective bending rigidity that occurs in shorter trusses due to the effect of nodal shear compliance.

Recent work [16] has undertaken a comprehensive analysis and optimisation effort in order to more fully compare the performance of trusses against tubes. This analysis included established models for a wide range of stress and stability driven failure modes in order to more accurately capture the complex stability driven failure modes of thin walled tubes under compression, such as crippling and buckling. The tubes and trusses were made as similar as possible, with equivalent beam lengths and material properties, and were optimised separately but with the same method. The tubes were also fully unidirectional in order to maximise their potential. The results of this study are shown in Figure 6c, where the percentage of mass saved by using a truss instead of a tube is plotted against the compressive load the truss and tube are able to withstand. Different lengths of truss/tube are plotted as separate lines, and it can be seen that very useful mass savings can be achieved up to quite considerably large load levels, especially as the length of the beams increases. For example, a 1m truss is 60% lighter under 10 kN of compression, and doesn’t break even with the tube until 113 kN, while a 3 m long truss carrying 300 kN is still 37.5% lighter than the best possible CFRP tube.



(a) (b) (c)

Figure 6. WrapToR truss beam modelling: a) geometry conceptualisation showing added shear element to model nodal joint deformations, b) validation of effective beam rigidity in 3-point bending against experiment showing good prediction accuracy and the increased impact of shear deformations on shorter trusses [15] and c) comparison between optimised truss beams and unidirectional tubes under compression showing substantial mass savings for trusses up to high load levels [16].

4.2. Hierarchical Space Frame Analysis

Analysis methods for optimising Hierarchical Space Frames are in the first instance very similar to those for truss beams, as the same beam element FE methods can be used. To handle the substantially more complex geometries, automated, parametrically driven geometry and mesh generation codes have been written, both during the Gamera work and separately later at Bristol. The computational cost for HSFs is considerably higher, but the low cost of linear static analysis using beam element FE means that reasonably complex 2nd order HSFs (e.g. dozens of truss beams in a larger space frame) can still be solved quickly with every member of every truss beam being fully resolved and meshed. For analysing structures that are larger still, or for optimisation work requiring many hundreds if not thousands of evaluations, it can be useful to consider replacing fully meshed lower level truss beams with equivalent beam elements. An example of this can be seen in Figure 7, where equivalent beams were used to analysis a WrapToR-HSF shear web on the DTU 10 MW reference wind turbine blade [17], as seen in Figure 7a. As can be seen in Figure 7b, replacing the fully resolved truss beams with beam elements of equivalent rigidity produces similar global deflections of the entire

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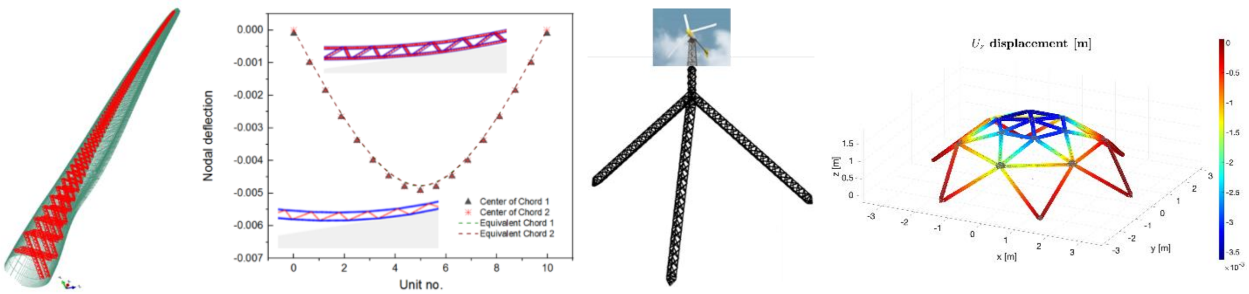
HSF, but at much reduced computational cost. It should be noted however, that finding equivalent properties is not trivial for these structures, especially considering the changing effective rigidity with length that comes from a changing balance between bending and shear – as shown previously in Figure 6b. Much work remains to be done to establish and demonstrate robust, efficient methods for that approach.

The finite analysis tool has been used to optimise various HSF configurations for mass reduction (using in all cases fully resolved truss beams and not equivalent beams). In the aforementioned 10 MW wind turbine blade study, a GFRP HSF shear web was found to weigh 50% less than the existing GFRP sandwich solution, although it is important to note that this did not include the mass of any truss joints, which in this case were not designed. Figure 7c shows an 18m tall tetrahedral WrapToR-HSF 10 kW wind turbine tower designed with bamboo chord members and jute/epoxy shear webs which was likewise optimised, but with the mass of the joint included. In this case, despite the significantly lower properties of the natural materials used, the optimal tower was still 60% lighter than commercially available steel towers [18]. Finally, Figure 7d shows a recent result for a mass optimised WrapToR-HSF dome [16] as an example of the level of structural complexity than can currently be optimised with fully resolved members (14,800 members, 42,800 mesh elements) on a single workstation. For problems larger than this one, it will be increasingly useful to explore equivalent beam methods.



(a) (b) (c) (d)

Figure 7. WrapToR-HSF analysis: a) HSF shear web on the DTU 10MW reference blade, b) result showing that equivalent beams (dashed lines) are able to match fully resolved (symbols) HSF models with a useful level of accuracy, c) an optimised natural fibre 10 kW wind turbine tower design which weighs 60% less than commercially available steel towers [18], and d) an optimised WrapToR-HSF dome structure [16]

5. Joints

As discussed previously, the joints are a critical aspect of all truss and space frame structures, and joining is also a key driving question in the usage of composite materials in general. As such, they have been the focus of a significant amount of research for the WrapToR concept, although this work only proceeded in earnest after automation of truss beam manufacturing. As mentioned earlier, Gamera saw extensive use of WrapToR-HSFs within its structures, and a simple, robust hand-lashing method was developed there to join adjacent truss beams, often using simple wooden tooling to hold components in place during joining, as in Figure 8a. This is still a viable solution for certain applications, especially at the lower end of the $/Δ scale.

Recent work at Bristol [19] has focused on the development of a winding-based approach to making three dimensional WrapToR truss joints with premade fittings wound in to accept the chord members of WrapToR truss beams, as seen in Figure 8b. This approach can be adapted to any arbitrary truss joint configuration (including the number of truss beams and their orientation, within reasonable limits), and by varying the number of winding passes between any two nodes, additional material can be built up in the more highly stressed edges, allowing for complete tailoring of the joint's stiffness and strength. Work is currently underway on building a comprehensive, manufacturing informed, joint design tool by wrapping a multi-objective optimiser around the WrapToR FE code and additional algorithms which assess the manufacturability of these variably stiffened wound truss joints. In assessing manufacturability, a complex multi-layer graph theory problem needs to be solved to ensure that any particular combination of number of passes for each edge in any arbitrary joint can indeed be continuously wound. The winding paths are also naturally much more complex then those of WrapToR beams, and so additional machine degrees of freedom would be needed to automate this currently manual 3D winding process.

Another concept for joining WrapToR truss beams that has been trialled is the use of 3D printed metallic joint structures, as seen in Figure 8c. In this case, a sweep of topology optimisation (TO) studies were run using the TO toolbox within the Abaqus finite element analysis software in order to minimise the compliance and mass of a T-joint structure joining three truss beams [20]. The resulting joint was then 3D printed from titanium and bonded to truss segments before being successfully tested to its design load under a mixed bending/torsion load case.

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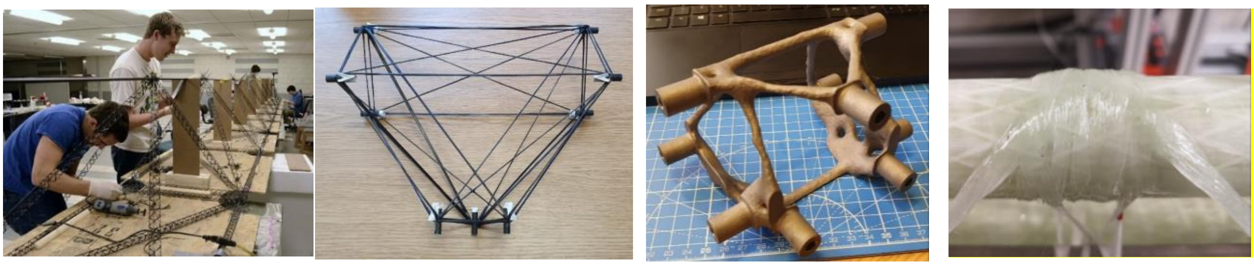
In addition to the joints between truss beams, the joints within a WrapToR beam, that is the bonded connections between the chord members and the shear web elements (which are referred to as nodes), are also critical to the strength of the resulting structure. As these nodes are purely adhesively connected, the thickness, bond area, and strength of the resin between shear and chord members are all key drivers to node stiffness and strength. One simple approach to increasing strength is to add more resin – either by using a higher resin content in the all of the wound tow (increasing local bond area but also weight everywhere), or through locally added additional resin. Beyond that, it is desirable to have direct local fibre reinforcement of the nodes to more efficiently transfer the shear loads and to resist peel. Simply overwrapping additional tow locally around the joint in the manner shown in Figure 8d is a very effective solution. Fatigue testing of a CFRP WrapToR beam under 3-point bending initially show early fatigue failure after roughly 7000 cycles due to node bond failure. This same failed specimen then had its nodes overwrapped with epoxy wetted tow and retested, with no failure or loss of stiffness when testing was stopped after 1.1 million cycles. Due to this success, work has begun on automated approaches to creating these reinforced nodes, with a particular focus on methods that could be used during the truss beam manufacturing winding process, be it filament winding based or Trusstrusion.



(a) (b) (c) (d)

Figure 8. WrapToR joining methods: a) direct tow lashing, b) continuously wound WrapToR truss T-joint, c) 3D printed topology optimised titanium T-joint, and d) nodal overwrapping on a GFRP WrapToR beam

6. Novel WrapToR configurations

In addition to WrapToR beams and HSFs, other structural configurations which use the same basic idea of continuous winding have been explored, including truss reinforced skin panels and geodesic wound fuselage and wing structures.

6.1. WrapToR Shells

While truss beams and space frames can be adapted to a wide range of applications, there are many structures which require smooth, continuous outer surfaces, for example those used in aerodynamic or hydrodynamic applications. To this end, the WrapToR technology has been adapted to create truss grid stiffened shell structures, known as WrapToR Shells [21]. In this concept, WrapToR trusses with one single chord member are wound and cured, before being bonded to traditional CFRP skin structures, with the single chord member being orientated away from the skin surface, as seen in Figure 9a. In this way, the chord member provides a vastly increased local second moment of area to the skin, with the web transferring the shear forces and also serving as the bonding interface between truss and panel. Experimental testing has shown the advantage of the concept, with an originally very compliant 2 mm thick, 600 mm square CFRP panel being able to support over 1000 N in three point bending due to the addition of truss reinforcement, with only a 19% increase in mass [21]. Furthermore, comparison of these experimentally realised results against idealised, best case performance for a wide range of traditional sandwich panel configurations and core materials (ignoring for example minimum thickness requirements and all of the failure modes typical of sandwich structures) shows enormous potential. As seen in Figure 9b, the WrapToR Shell tested has an 83% smaller displacement (and therefore 83% higher stiffness) under a nominal load than any sandwich configuration of the same mass. What's more, if the sandwich panels are limited to being no thicker than the truss reinforced panel, then the WrapToR Shell provides well over an order of magnitude increase in stiffness at equivalent mass. This concept is still in the early stages of exploration, and work is ongoing to quantify the achievable design space, with manufacturing techniques also being developed to allow the WrapToR stiffeners to adapt to skin panel curvature, as many of the intended applications are singly, if not doubly, curved.

6.1. Geodesic aircraft structures

Inspired by Barnes Wallis's design for the 1930's Vickers Wellington bomber, another use of the WrapToR technology is the creation of complex, three-dimensional, non-prismatic open lattice shell structures, such as the airliner model shown in Figure 10. This particular demonstrator was hand wound with bamboo and willow poles for the chord members (i.e. fuselage longerons and wing stringers/spars) and epoxy wetted jute and hemp for the shear windings,

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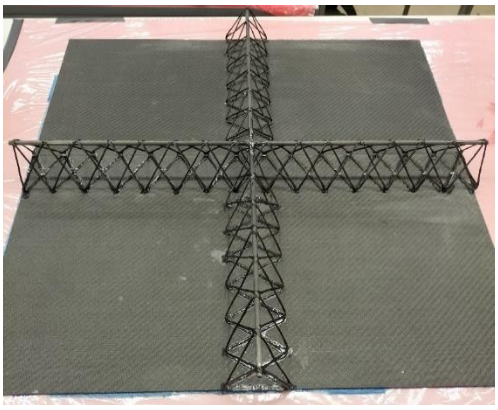
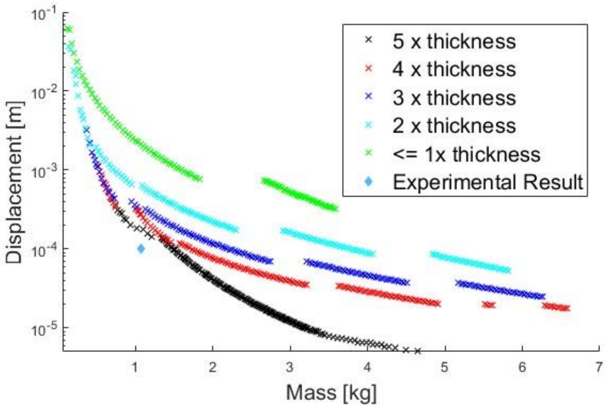
but of course the choice of material is quite open. This version of the concept isn't fundamentally different from the basic WrapToR winding process, and indeed is once again essentially a lattice version of filament winding (with perhaps the exception of the embedded chord members). It does however, show the adaptability of the winding approach to more complex geometries.



(a)



(b)

Figure 9. WrapToR Shells: a) prototype truss reinforced skin panel and b) comparison of experimentally measured WrapToR Shell performance (blue diamond) against idealised sandwich panels (x's), showing a minimum of 83% increase in stiffness at equivalent mass.

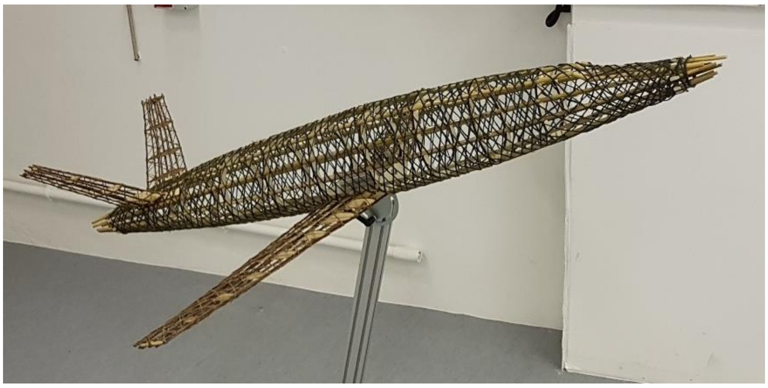


Figure 10. Natural material composite geodesic WrapToR airliner demonstrator

7. Future research directions

The research work and results overviewed above have hopefully helped shown the progress and promise of the WrapToR concept, but its future prospects are still highly dependent on the right effort being put into answering the right questions. For the truss beams, the furthest developed aspect of the technology, the questions remaining have to do with long term robustness (e.g. fatigue testing and damage tolerance) and scalability (e.g. how big can we go, how quickly can we make them). Automating the reinforcement of the nodes between chord members and shear webs is a clear way forward for improving fatigue life. The use of thermoplastic matrices is a parallel line of inquiry ripe for exploration which has been only preliminarily explored at Bristol. For WrapToR-HSFs, the key question remains the junctions between truss beams. The initial work into wound joints is so far quite promising, but the same questions asked of the beams apply here as well – in particular with regards to the interfaces between the beam chord members and the joint windings, although many design options/solutions are available. For the WrapToR Shells, the manufacturing methods need further development to get to the point where grids of complex curved truss stiffeners can be wound and attached to skin panels (either through co-curing or post-cure bonding) with a reasonable level of cost and complexity, although the potential usefulness of this concept in high $/Δ applications such as rocket bodies, aircraft, and high performance automobiles means that there is perhaps room for initial success with less automated, more manual processes.

As an overarching future research direction, and as a means of affecting maximum change, the WrapToR technology is well suited to being developed into a hierarchy of solutions for applications in different tiers of $/Δ – from ultra-high performance, one-off deployable space structures robotically assembled from WrapToR beams and wound joints

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made *in situ*, to commercial airliners clad in thermoplastic CFRP WrapToR Shells, to fully modular, high volume Trusstruded fibreglass WrapToR-HSF infrastructure framing, all the way to hand wound WrapToR wind turbine towers and solar panel mounts made from locally sourced natural fibres for low cost hyper-local energy networks. Considering different technology approaches in terms of $/Δ is thus a useful framing for further consideration of research directions.

8. Conclusions

This paper has sought to motivate the use of composite truss structures in general, and WrapToR trusses in particular, by explaining the inherent structural benefits they provide, considered in the context of the difficulties associated with their realisation. After establishing the historical underpinnings of WrapToR trusses, advancements in the manufacturing methods employed to make them were overviewed, with current methods allowing for rapid, low cost batch processing of truss beam structures in a wide range of sizes, form factors, and materials. New, more continuous methods were also shown which promise to reduce costs at scale. Improvements in our ability to predict and understand the mechanics of WrapToR truss beams and Hierarchical Space Frames were then presented, establishing a robust set of capabilities. Special attention is then paid to the joints inside and between WrapToR trusses, which are not as fully developed as the truss beams themselves, but for which there still exist promising solutions. Finally, alternative embodiments of the concept are shown, including shell structures and geodesics which broaden the applicability of the concept. Quantitative assessments of structural performance, both relative and absolute as available, are provided throughout the paper and compellingly show what can happen when we combine our highest performing materials with our most efficient structural configuration. Finally, the most pertinent and promising future research directions for the WrapToR technology are identified.

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