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Ultra-efficient wound composite truss structures

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ABSTRACT

This paper presents the design, analysis, manufacturing, experimental testing, and multiobjective optimization of a new family of ultra-efficient composite truss structures. The continuously wound truss concept introduced here is a versatile, low cost and scalable method of manufacturing truss structures based on a simple winding process. A prototype truss configuration is shown and experimentally characterized under torsion and three point bending loads. A large deformation implementation of the direct stiffness method is shown to provide good prediction of the stiffness properties of the prototype truss. This model is extended to include strength prediction with multiple failure modes. The design space achievable with these truss structures is then explored through multiobjective optimization using the NSGA II genetic algorithm. These continuously wound truss structures have the potential to provide between one and two orders of magnitude increase in structural efficiency compared to existing carbon fiber composite tubes.

1. Background

There is an ever present need in structural design to minimize mass and maximize structural efficiency. This is true in nearly all engineering disciplines, but is especially true in transportation related applications such as the aerospace and automotive industries where any mass associated with a structure brings recurring costs from the need to transport that weight. There are other factors which also motivate weight reduction more generally, including the potential to reduce material and fabrication costs, dynamic and vibration concerns and increased stresses due to self-loading.

Truss structures and space frames have long been preferred solutions to the problem of maximizing structural efficiency, as they allow for very large increases in the flexural rigidity and load carrying capacity achievable from a given amount of material. The primary advantage of a truss over a monolithic or tubular structure is that grouping the material available into discrete local beam members allows for the overall size of a structure built from a given amount of material to be increased to take advantage of the highly non-linear scaling laws governing bending stiffness and strength (as determined by equivalent flexural rigidity) without being overly restricted by the strength limitations inherent in trying to make large, thin walled tubular structures. Another key advantage of truss structures is that they divide the large structure into a number of local members which due to their slenderness, straightness, and attachment methods are able to act in a manner which approaches an ideal two-force member. A two-force member, unlike a beam, experiences only tensile and compressive forces. Structures are considerably stiffer and stronger under axial loading then they are under bending loading, and so the use of trusses allows the material to experience lower stress levels and to be used more efficiently. It is important to note that this only applies if the truss members are straight, as curvature in an element leads to intrinsic coupling of axial and bending loads.

The usefulness of trusses was realized as early as the Ancient Greeks and Romans who used timber frame trusses to support roofs of previously unspanable length [1,2], and to this day the truss and its three dimensional extension the space frame form the basis of a wide range of structures including bridges, towers, building roofs, light aircraft fuselages, and high performance automobile frames. Truss structures and space frames have been created at nearly all size scales, from the micrometer [3] scale all the way up to the 400 m long Ikitsuki truss bridge in Japan (the world's longest) as seen in Fig. 1 and the world's largest indoor theme park, Ferrari World, who's elegant space frame structure encloses an incredible 86,000 m^2.

One of the primary drawbacks of existing truss structures is the difficulty and expense of manufacturing them from separate individual members, often numbering in the dozens, hundreds, or even thousands which must be individually attached together at a series of nodes. This requires first the fabrication of the truss members,

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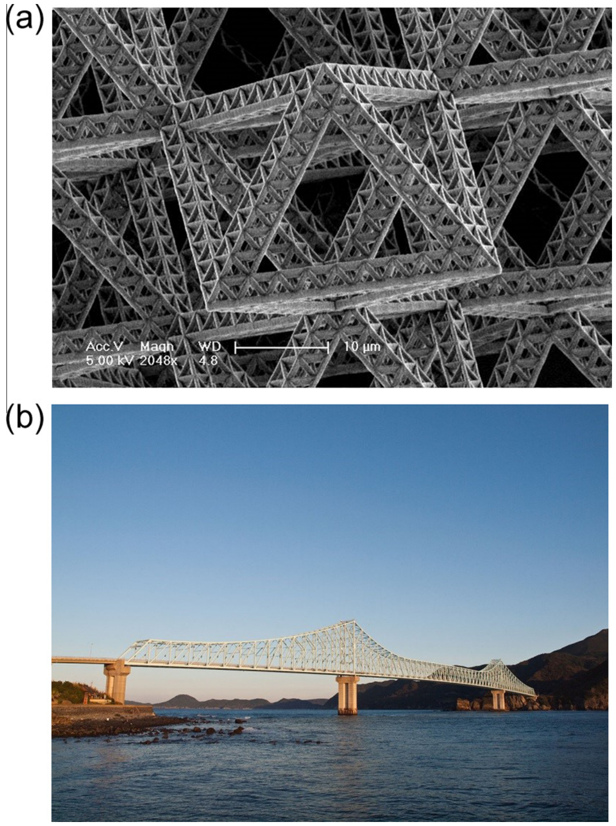

Fig. 1. The incredible scale range of engineered truss structures (a). Micrometer scale structures created with Two Photon Lithography Direct Laser Writing [3] and (b). The Ikitsuki Bridge, the longest continuous span truss bridge in the world at 400 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

which are often different sizes and lengths and then attaching them with a large number of bolted or welded joints. Additional gusset plates are often required to strengthen these joints, further adding to the part count and labor requirements. While the structural advantages of trusses outweigh these added manufacturing costs for many larger structures, there appears to be a real world lower limit on the size of truss structures. It is relatively uncommon to see built up truss structures with individual member lengths smaller than roughly 10 cm or overall structural lengths less than a few meters. Since the strength and stiffness advantages of trusses exist at all engineering length scales, it must be the case that the reason for this practical lower limit is not physical but economical. In this size region, traditional built up truss structures are more difficult and therefore more expensive to make (due to the small size of individual members). On the other hand, it is exactly in this size range that tubular and monolithic structural members (extruded metal profiles for example) are most often made and so they benefit from massive economies of scale in their production. This gap in the implementation of truss structures unfortunately exists exactly in the size range of our most common daily interactions with our engineered world, which results in many of the structures which we encounter in our day-to-day lives which would benefit from the structural efficiency of trusses do not employ them; with furniture being one relevant example.

Several research groups have investigated ways of manufacturing composite truss structures at this “missing” length scale. Shütze presented the development and implementation of composite truss beams of equilateral triangle cross section which were manufactured using traditional methods of attaching individual members together with bonded joints and reinforcing gusset plates [4]. These truss beams were designed for use within the structural frame of a rigid airship. Weaver and Jensen introduced a complex truss beam structure manufactured with a braiding machine [5]. This concept is known as the IsoTruss® and is currently under commercial development. The IsoTruss® concept has the advantage of being made from continuous elements and therefore not requiring the manufacture of separate individual members which are then connected together. Instead, as seen in Fig. 2, a braiding machine is used in conjunction with a multi-point node supporting apparatus to allow for the individual members to be created by winding various tow elements together. The geometry of these truss structures is complex, with eight to twelve nodes around the perimeter of the truss forming a star shaped, non-continuous cross section with the fiber running in straight segments between nodes. This creates a fully three dimensional structure of overlapped and interlaced tetrahedron elements. In the process shown in Fig. 2, there is no mandrel around which the truss is braided, which therefore requires the use of individual hook type supports for every single node. These supports must be able to translate along the length of the truss as it is wound, and must remain there until the polymer matrix bonding the tows together is fully cured. Other work by the same research group and others has used internal mandrels to make the same basic structure [6–8], and have considered winding based methodologies instead of braiding, but in this case the non-continuous cross section, visible in Fig. 2, and the need to support the material at each node creates captive mandrel geometries, which requires the use of complex multi-component mandrel solutions that can be disassembled, collapsed, or dissolved for removal after the composite has cured. Other researchers have considered modified forms of braided truss structures that greatly simplify the geometry, but they do so using a circular cross section mandrel which creates curved segments [9]. These curved sections are inherently less stiff and weaker than straight elements between nodes because they will act as beams under combined axial and bending loading instead of as two-force members. While these

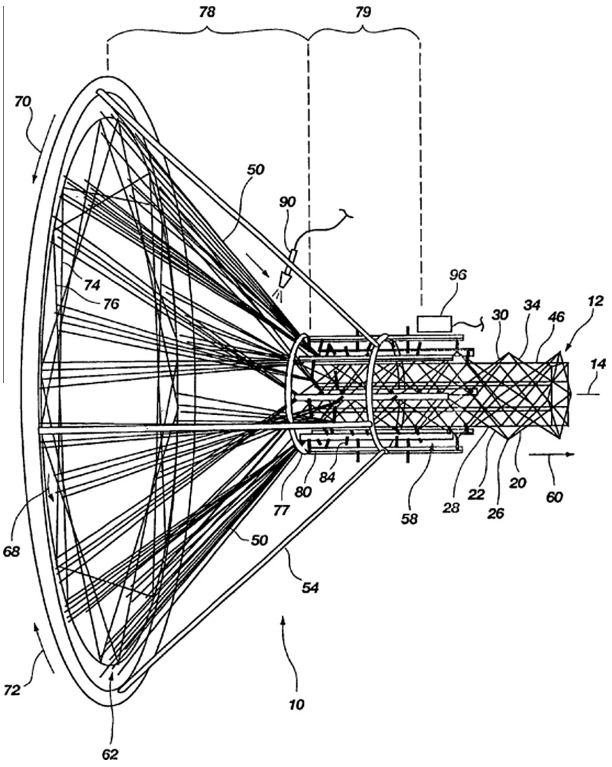

Fig. 2. Schematic of braiding process for IsoTruss® structures [26].