ABSTRACT

Preforms for open structured (lattice) composite truss structures manufactured from large prepreg yarns on a conventional maypole braiding machine, and subsequently cured to produce fiber reinforced composites of high strength and light weight.
MINIMAL WEIGHT COMPOSITES USING OPEN STRUCTURE

CROSS-REFERENCE TO RELATED APPLICATION

[0001] The present application claims priority to U.S. provisional application No. 61/624,528, filed on Apr. 16, 2012, and hereby incorporates the subject matter of the provisional application in its entirety.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The field of the invention is fiber reinforced composites having an open-truss or lattice structure and methods for their manufacture.

Brief Description of the Related Art

[0003] Until recently, structures such as frames, trusses, struts, shafts, bridges, etc. were constructed from an assemblage of standard metal elements, mass-produced and commercially available lengths and cross-sectional geometries. The geometries included plates, sheets, angles, channel sections, I-beam shapes, and hollow, circular, square and rectangular tubing (Manual of Steel Construction, 8th Edition, American Institute of Steel Construction, 1987), and are commonly made from steel or aluminum. It is well known that truss structures provide high strength and stiffness while minimizing weight. Metal truss structures are composed of large apex members or beams connected along the length of the beams with smaller connecting elements that are welded or bolted between the beams. The connecting elements are often placed in an X or W configuration along the beams. The advent of high strength fibers has ushered in a new approach to the creation of light weight and strong structural elements.

[0004] When producing composite trusses, welding of the connecting elements is not possible, and bolting is not the most desirable joining method for composite materials because of stress concentrations at the bolt holes, which may lead to failure.

[0005] In composite materials, a reinforcement material is distributed in a second bonding material called the matrix. The application considered here is concerned with the polymer matrix composites (PMC), where the reinforcement materials are fibers of high strength, and the matrix is a thermosetting or thermoplastic polymer. Most often, the reinforcing fibers comprise one or more of the available high performance fibers such as graphitic carbon, glass, para-aramid (such as Kevlar™), LCP (such as Vectran™) and others. PMC’s are known to offer strength and weight advantages over aluminum and steel, but in order to achieve these advantages the structure and elements in the assemblage of the structure must account for the non-isotropic properties and directionality of composite strength. That is, composites achieve their strength if the largest loads and stresses can be directed along the direction of the fibers.

[0006] Despite these differences in materials, and the difficulties of qualifying new materials, there is a need for composite truss structures to minimize the weight of construction elements, since a well-designed composite typically offers equivalent strength at weight savings of 20 to 60% over equivalent metal structures. The question then becomes: how to manufacture a composite truss or other open structure composite structure without the need for bolted joints within the truss.

[0007] Braiding is a method of forming a seamless “fabric” tube and is often used to form shapes useful as composite structures after resin impregnation and curing. Braided sleeves have a unique ability to form polygons, flat plates, angle brackets, I beams, and indeed—any closed geometry having uniform or even variable dimensions along the length. This sort of shape variation accompanied by resin impregnation or resin infusion and curing to stiffen the resin, makes braiding an ideal method for construction of composite reinforcement.

[0008] As mentioned above, a truss structure is the most efficient for strength and stiffness at low weight. The question is can the braided seamless tube be constructed approximating the beams and open lattice structure that comprise a truss. That idea is the subject of this invention. Of course, to be practical, it is necessary that the structure should be efficiently manufactured, preferably on simple machinery already in use. One objective of this invention is to produce a fiber reinforced open structured truss preform on a conventional maypole braider.

[0009] Infusion of large structural elements with resin is difficult, especially when the large structural elements are immediately adjacent to open spaces in a truss structure. Since the beams and cross members of a truss are large, an array of small yarns or tows have been prepregated with resin and arranged in a jacketed parallel bundle to make a large diameter yarn structure. An assembly of small yarns or tows to produce large prepreg yarns is the subject of a pending patent application based on preliminary patent application 61/624,534, filed Apr. 16, 2012, the subject matter of which the present application incorporates by reference in its entirety.

Description of the Prior Art

[0010] The utility of truss structures is well known, so it is natural that people working in composite structures have attempted to manufacture composite trusses. The fragility of joints in composite structures (if they are made by metal joining procedures) is likewise well known. It is natural that there have been numerous attempts to manufacture a composite truss which does not rely on metallic joining techniques.

[0011] Some of the earliest and indeed the latest attempts have been by the filament winding process (U.S. Pat. Nos. 3,551,237, 4,278,485, 6,050,315, 6,290,799, and 8,313,600). Mostly the efforts in filament wound lattice trusses involve a grooved mandrel to accept and align the helical winding of a flat prepreg tape yarn, although one could envision a yarn winding procedure which infused the resin after winding. The most recent, the Geostrut™, is a tubular lattice structure with fiber tows wound helically and longitudinally and that wrap as multilayers over one another at nodes where they intersect. The tows are laid into rigid channels in a rigid mold (Wilson, Kipp and Ridges, U.S. Pat. No. 8,313,600; Method and system for forming composite geometric support structures, Nov. 12, 2012; http://www.geostrut.net/home/) Perhaps the main difficulty of such structures is that the intersections of tapes thickens the nodes and incorporates voids as the tape transitions from the thick joint to the thinner truss member. These voids create points of incipient delamination of the resin infused tape. The previous art has attempted to minimize
the thickness and voids at the joints by offsetting successive wrapping layers to either side of the joint (U.S. Pat. No. 4,137,354, and U.S. Pat. No. 8,313,600—FIGS. 8 and 9).

[0012] The other major effort at constructing a composite truss is that described in patent literature is one which creates an elegant truss structure which can be produced only by hand (U.S. Pat. No. 5,921,048) or by a slow complicated mechanical device revealed in U.S. Pat. No. 7,132,027, and patent applications 2006/0153661, and 2006/0247866. The IsoTruss is a lattice tubular structure with fiber tows wound helically, counter-helically and longitudinally and that intersect at nodes held by a support frame with engagement members, in association with an advanced form of a 3-D braiding machine. (Jensen, U.S. Pat. No. 7,132,027, Nov. 7, 2006; Jensen, M. J., Jensen, D. W., Howercroft, A. D., Continuous Manufacturing of Cylindrical Composite Lattice Structures, TExCOMP10 Recent Advances in Textile Composites, edited by Christophe Binetruy, Francois Boussu, 2010, p. 80-90).

[0013] The Hoyt tether is a lattice structure for a space tether application with fiber yarns that intersect at nodes, and manufactured on a lace braid. Multiple primary load-bearing lines and normally slack secondary lines are connected together with knotless, slipless interconnections (Hoyt tether: Failure resistant multilink tether U.S. Pat. No. 6,386,484). The lace braiding machine as it currently exists is not suitable for braiding the large yarn assemblies that are needed to make the trusses of this invention.


SUMMARY OF THE INVENTION

[0015] This invention creates an open composite truss structure on a conventional maypole braiding machine. The open composite truss structure has a higher strength to weight ratio than composite structures made from resin infused fabric or from solid filament wound composites, or from other typical construction materials like metal. The invention uses large prepreg yarns which may be derived from the copending patent application, above. These yarns are jacketed yarns with a core assembly of prepreg tows, having upwards of 20,000 filaments and a jacket of braided or wrapped yarns, or a jacket of extruded polymer. These yarns may be used as both axial and helical yarns on a standard maypole braiding machine although axials and helicals are not necessarily the same size. The carrier positions on the maypole braider often are not completely filled by yarn bobbins, but it is generally preferable that the helical yarns be placed symmetrically on the machine and in the structure. Axial yarns may be placed in a manner that provides the most support where it is needed for the load being applied. For ease of maintaining the yarn locations in the final structure, a mandrel is often used with the yarns being pulled tightly to the mandrel surface by the action of the braiding machine. The cross section of the mandrel may be circular, elliptical, polygonal, or of varying shape and diameter. Two speeds, the braiding speed and the mandrel travel speed, are controlled to produce an open structure of yarns on the mandrel, with the yarn placement on the carriers and the two speeds being adjusted to produce the desired opening sizes in the truss. The mandrel with its prepreg yarn in place is then heated to cure and stiffen the resin and produce a fiber reinforced composite. During curing, either resin is exuded from the prepreg yarn or the melting of the thermoplastic jacket causes bonding at the intersections of the various yarns in the composite structure. The strength of the joints and the truss may be increased by

[0016] 1. Addition of additional resin at the joint,
[0017] 2. Lacing of prepreg yarns around the joints and across the center of the formed truss,
[0018] 3. Inclusion of a braided composite sleeve inside, outside or on both sides of the truss members created during braiding.
[0019] 4. Filling the spaces between the large truss members with small yarns, which occupy some or all of the carrier positions that were not used for the large truss members. The small yarns may either be prepreg yarns or they may be yarns which are resin infused after braiding and prior to curing. This resin infusion may be by hand, spray or vacuum infusion within a bag.
[0020] The objectives realized by this invention are:
[0021] 1. Use of conventional technology and equipment for manufacture of open composite lattice trusses,
[0022] 2. Avoidance of mechanical attachment hardware within the strut or truss,
[0023] 3. Production of structure without the surface irregularity of the IsoTruss™ geometry,
[0024] 4. Production of truss structure with adequate joint strength at element intersections,
[0025] 5. Use of a simple mandrel that does not require extensive machining or a complicated removal mechanism,
[0026] 6. Formation of a structure with significant weight advantage over metal or solid (not open) composite structures, and
[0027] 7. Formation of an open structured composite truss that is scalable depending on the number and size of carriers and bobbins on a particular braiding machine.

[0028] The advantages of the currently described invention include: that it is made by a simple process on a conventional Maypole braiding machine. The manufacturing process is fast (greater than 1 m per minute). It may be produced on a mandrel that is an elongate polygon or cylindrical. Removal of the mandrel after curing is much easier than from the grooved mandrel of the prior art. One can even envision an inflatable mandrel which could be removed by simple deflation and pulling the deflated member out the end or through one of the openings in the truss.

BRIEF DESCRIPTION OF FIGURES

[0029] Figure:
[0030] 1. Drawing of a maypole braiding machine
[0031] 2. Side view of open structure truss with circular cross section and z direction interlaced strengthened joints
[0032] 3. Cross section of open structure truss with circular cross section and z direction interlaced strengthened joints
[0033] 4. Perspective drawing of open structure truss with z direction interlaced strengthened joints
[0034] 5. Open structure truss produced having a true triaxial braid structure
6. 3-D space frame used for human powered vehicle, "moonbuggy". Multiple open truss structure assembled into a much larger truss structure

7. Triangular and hexagonal cross section truss and triangular truss in perspective view—produced by strategic placement of axial yarns, possibly on a triangular or hexagonal mandrel

8. Formation zone of open structured truss on a maypole braiding machine

9. Open structured truss with small yarn stabilization of joints in perspective and cross sectional view

10. Open structured truss with small yarn stabilization of joints in side view and enlarged side view.

DETAILED DESCRIPTION OF INVENTION

The structures of this invention are tubular structures (101) produced on a maypole braiding machine (103) utilizing very large prepreg yarns (102) with filament counts from 20,000 (20K) up to 100,000 (100K) or more. The prepreg yarns are jacketed by braiding, yarn wrapping or extrusion of a thermoplastic sheath. Fig. 1 is a diagram of a typical maypole braiding machine (103), although it will be appreciated by one skilled in the art that such braiding machines are available in a variety of sizes—both physically and in the number of carriers on the machine. Typical carrier numbers on a machine range from 4 up to 1000. Bobbins (104) for the carriers range from 3 inches up to 3 feet and more. So the structures (101) that can be made using this invention can be scaled up in size from the examples produced to illustrate this patent. The structures (101) in the following reduction to practice are all produced on a 32-carrier or 64-carrier Wardwell maypole horizontal braiding machine (103).

Fig. 2 shows a side view of an open structured truss (101) in cylindrical form having eight axial yarns (105) and eight helical braided yarns (106), four in each direction. The structure (101) was braided on a cylindrical mandrel (108) and after curing was removed prior to insertion of four "z" prepreg reinforcing yarns (107), also commonly referred as cross yarns, strut yarns, or through-the-thickness yarns, which were subsequently cured in place. Fig. 3 shows a cross section of the structure (101) in Fig. 2. Fig. 4 is a perspective drawing of the same structure.

Fig. 5 shows a picture of the prepreg yarns (102) as they transition from the carrier yarn packages to the braid consolidation point (fell point) of the structure. One skilled in the art will immediately understand that the size and shape of the braid openings as well as the diameter of the structure are determined by the number of yarns, the speed of the braiding head, the speed of the take up, and the size of any mandrel (108) inserted into the center of the forming structure (101). It will also be understood that the mandrel cross section can be any polygon shape (Fig. 6) or any convex curved elongate shape. The mandrel may also vary in cross sectional size along its length.

Example 1

An open structured cylinder (101) was made according to the teaching of this invention, but similar in size and weight per unit length to an energy drink can and similar in size and weight to a prepreg braided sleeve constructed of carbon fiber and epoxy resin. The structure was made from a 36k assembled prepreg carbon yarn (102) (from TCR Composites) core with eight helical yarns in the jacket. The jacket yarns were 200 denier Vectran yarns which were braided around the 32 prepreg tow carrier jacket. The jacket consists of eight helical yarns and eight axial yarns arranged in a true triaxial configuration. The open structured composite (101) was made on a 32-carrier maypole braider (103) with four helical yarns (106) and four axial yarns (105) in the true triaxial structure (as shown in Fig. 7). In the true triaxial structure, the axial yarns (105) interface with the helical yarns. The crossover joints in this structure (101) were reinforced with addition epoxy resin. Both the aluminum can and the cured prepreg could be easily crushed by hand, but the cured open truss structure (101) could not be crushed by hand.

Example 2

Open structured cylinders (101) similar to that disclosed in Example 1 may be assembled into larger structures like that shown in Fig. 6. Fig. 6 is a drawing of a framework for a human powered vehicle for a student "moonbuggy" competition at NASA's Marshall Space Flight Center. The framework was constructed of cylindrical open structured trusses (101) produced in accordance with the teachings of this invention using the z direction reinforcement (107) of yarn intersection joints shown in FIGS. 2, 3, and 4.

Example 3

An open truss structure was constructed using jacketed 36k carbon prepreg yarns (102)—namely, three axial (105) and eight helical (106) prepreg yarns—in a true triaxial configuration. A mandrel (108) of triangular cross section was used. Each helical prepreg yarn (106) was flanked by 2 Kevlar™ 1000 denier yarns. The structure was cured on the mandrel (108) to set the shape and then the smaller Kevlar™ flanker yarns (109) and the joints were coated with resin before curing again. The Kevlar™ yarns (109) were on either side of the cured yarns (102). The flanking yarns (109) helped to stabilize the joints. The geometry of the structure (101) is shown in Fig. 9 and in enlarged view (Fig. 10).

Example 4

An open truss structure (101) was constructed using 8 axial (105) and 8 helical (106) jacketed 36k prepreg carbon tows on a maypole braiding machine (103) set up for true triaxial braiding. The mandrel (108) was a 1.5 inch diameter pipe with a 1.5 inch diameter sleeve of braided fiberglass covering the pipe. The open structured tube (101) and sleeve was painted with liquid resin and then cured. The structure had significantly greater strength than the same structure (101) without the added sleeve.

Example 5

The structure (101) of example 4 was taken before painting with resin and was covered with a 1.5 inch diameter braided fiberglass sleeve. The mandrel (108) with its 3 layers was vacuum bagged and vacuum infused with liquid epoxy resin before curing. The composite structure (101) was very strong and supported a 200 pound person standing and jumping on the side of the structure (101). In this configuration, as in Example 4, the lattice truss (101) with a sleeve can be viewed as rib stiffened cylindrical structure which on larger scale might be useful as a pipe, tank or rocket motor.
Example 6

[0048] An open structured truss structure (101) was constructed using jacketed prepreg carbon yarns (102) on a maypole braiding machine (103). The structure used 4-36k axials (105) and 16-helicals (106) (8-36k and 8-72k). The helical yarns (106) were arranged in sets of 4 with the smaller two in the center and the larger 2 flanking either side. The yarns (102) were braided on a 2.5 inch diameter mandrel (108). The joints were strengthened and reinforced by painting with additional epoxy resin before curing. The product was used as a drive shaft by a student team in a formula style race car for intercollegiate competition. The axials (105) and helicals (106) were interlaced into a titanium gear to transmit the power. The structure had a 75% weight saving over the metal drive shaft it replaced.

REFERENCES

[0056] http://www.geostrut.net/home/
[0057] US PATENT DOCUMENTS
[0058] US PATENT DOCUMENTS
[0067] U.S. Pat. No. 6,386,484, Hoyer et. al.

What is claimed is:
1. A process for manufacture of an open structured composite truss or strut using a conventional Maypole braiding machine:
   a. Wherein the braiding yarns or structural elements of the truss comprise very large jacketed assemblies of smaller prepreg tows, ranging from about 20000 to upwards of 80000 filaments (total),
   b. Wherein the structure of the braid is any one of several weave geometries that are normally produced on a Maypole braiding machine including diamond, twill, hercules, triaxial, or true triaxial,
   c. Wherein the structure is subsequently cured and rigidized by heating,
   d. Wherein bonding between the yarns at crossover points is created by resin exuded from the yarns during curing, or by melting of the yarn or polymer in the jacket, and
   e. Wherein the bonding between the yarns at crossover points may be augmented by, addition of resin, interfac- ing of one or more prepreg yarns from one side of the structure to the other, addition of a infused and cured fabric (or braided sleeve) inside, outside or on both sides of the open truss structure.
2. A tubular, open, lattice truss structure composite produced by the process of claim 1.
3. The structure of claim 2 wherein the joints at the crossover points are strengthened by addition of resin at the crossover points followed by curing of that resin.
4. The structure of claim 2 wherein the joints at the crossover points are strengthened by lacing of a prepreg yarn through the structure at periodic intervals.
5. The structure of claim 2 wherein the joints at the crossover points are strengthened by inclusion of a braided sleeve inside, outside or both inside and outside the open structure, followed by impregnation and curing of the braided sleeve(s).
6. The structure of claim 2 wherein the joints at the crossover points are strengthened by inclusion of a prepreg sleeve inside, outside or both inside and outside of the open structure followed by curing of the structure.
7. The structure of claim 2 wherein the joints at the crossover points are strengthened by inclusion of a braided prepreg sleeve inside, outside or both inside and outside the open structure.
8. The structure of claim 2 wherein the joints at the crossover points are strengthened by multiple wraps of prepreg fabric either inside, outside, or on both sided of the open structured truss.
9. The structure of claim 2 wherein the joints at the crossover points are strengthened by the inclusion of smaller yarns in the braided structure adjacent to the large prepreg yarns.
10. The structure of claim 9 wherein the smaller yarns are painted or infused with liquid resin and subsequently cured.