(54) Title: APPARATUS, SYSTEM, AND METHOD FOR FILAMENTARY COMPOSITE LATTICE STRUCTURE MANUFACTURING

(57) Abstract: An apparatus, system, and method are disclosed for the manufacture of composite lattice structures comprising a weaving mechanism 104 configured to position fibers in a lattice structure and a shape retention structure 108 configured to hold the fibers in the lattice structure. The weaving mechanism 104 includes one or more bobbins 304, each of the one or more bobbins 304 configured to carry fiber. The weaving mechanism 104 includes a plurality of horn gears 302 configured to move the one or more bobbins 304 across the face of the weaving mechanism 104 to control the position of the fiber in the lattice structure. Beneficially, such an apparatus, system, and method would automate the process of manufacturing composite lattice structures and reduce the costs associated with the existing methods for manufacturing such structures.

Published: — without international search report and to be republished upon receipt of that report for two letters codes and other abbreviations, refer to the “Guidance Notes on Codes and Abbreviations” appearing at the beginning of each regular issue of the PC Gazette.
APPARATUS, SYSTEM, AND METHOD FOR
FILAMENTARY COMPOSITE LATTICE STRUCTURE MANUFACTURING

CROSS-REFERENCES TO RELATED APPLICATIONS

This application claims the benefit of United States Provisional Patent Application Number 60/708,558 entitled "Apparatus, System, and Method for Filament Wound Lattice Structure Manufacturing" and filed on August 16, 2005 for David W. Jensen, et al., which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

This invention relates to the manufacture of filamentary composite lattice structures and more particularly relates to the automated manufacture of filamentary composite lattice structures using a weaving component, a shape definition component, and a curing component.

DESCRIPTION OF THE RELATED ART

The pursuit of structurally efficient structures in the civil, mechanical, and aerospace arenas is an ongoing quest. An efficient truss structure is one that has a high strength to weight ratio and/or a high stiffness to weight ratio. An efficient truss structure can also be described as one that is relatively inexpensive, easy to fabricate and assemble, and does not waste material.

Advanced composite structures have been used in many types of applications to create structurally efficient structures. Some of these composite structures have been used to create structural members having enhanced load bearing capacity per unit mass and capable of withstanding multiple loadings. An example of these composite structures is a filament composite structure with multiple, straight members attached in a lattice structure, such as the IsoTruss.

These filamentary composite lattice structures can provide excellent weight to performance ratios in multi-planar bending, buckling, axial loading, and combined loading and torsion applications, and are therefore very valuable. The manufacture of these structures using existing methods, however, is labor-intensive, time consuming, and costly.

From the foregoing discussion, it should be apparent that a need exists for an apparatus, system, and method for manufacturing a filamentary composite lattice structure. Beneficially, such an apparatus, system, and method would automate the process of manufacturing filamentary composite lattice structures and reduce the costs associated with the existing methods for manufacturing such structures.
SUMMARY OF THE INVENTION

The present invention has been developed in response to the present state of the art, and in particular, in response to the problems and needs in the art that have not yet been fully solved by currently available methods for manufacturing filamentary composite lattice structures. Accordingly, the present invention has been developed to provide an apparatus, system, and method for manufacturing filamentary composite lattice structures that overcome many or all of the above-discussed shortcomings in the art.

The apparatus to manufacture filamentary composite lattice structures is provided with a plurality of modules configured to functionally execute the necessary steps of weaving a filamentary composite lattice structure, defining the shape of the filamentary composite lattice structure, and transitioning the filamentary composite lattice structure from a weaving mechanism to a shape retention structure. These modules in the described embodiments include a weaving mechanism configured to position fibers in a lattice structure, a shape retention structure configured to hold the fibers in lattice structure, and a transition device configured to transfer fibers from the weaving mechanism to the shape retention structure.

In one embodiment, the apparatus further comprises a curing device configured to cure resin on the fibers held in the shape retention structure. In another embodiment, the apparatus further comprises a resin impregnation device configured to apply a resin to the fibers in the filamentary composite lattice structure. In a further embodiment, the apparatus includes a pulling device configured to apply an axial force to the filamentary composite lattice structure.

The weaving mechanism of the apparatus, in one embodiment, comprises a plurality of horn gears configured to move a bobbin carrying fiber across the face of the weaving mechanism. In a further embodiment, one or more of the plurality of horn gears are driven by a spur gear on an adjacent one or more of the plurality of horn gears such that a motor attached to one of the plurality of horn gears drives the plurality of horn gears. In another embodiment, one or more of the plurality of horn gears are driven by an individual motor.

The weaving mechanism of the apparatus, in one embodiment, further comprises one or more switches configured to transfer the bobbin from one of the plurality of horn gears to an adjacent one of the plurality of horn gears. In another embodiment, one or more of the plurality of horn gears further comprise an aperture configured to allow a fiber to pass through the aperture. In yet another embodiment, one or more of the plurality of horn gears further comprises a gear assembly configured to be individually removed from the weaving mechanism.

A system of the present invention is also presented to manufacture filamentary composite lattice structures. The system may be embodied a weaving mechanism, a shape retention
structure, and a control module. In particular, the system, in one embodiment, includes a weaving mechanism configured to position fibers in a lattice structure, a shape retention structure configured to hold the fibers in a lattice structure using one or more attachment mechanisms, and a control module configured to control the weaving mechanism and direct the positioning of the fibers in the lattice structure.

The one or more attachment mechanisms in the system, in one embodiment, may further include one or more hooks configured to hold the lattice structure in a desired configuration. In another embodiment, the one or more attachment mechanisms include one or more servo mechanisms configured to hold the lattice structure in a desired configuration. In one embodiment, the relative position of the one or more attachment mechanisms is variable such that a bay length in a filamentary composite lattice structure manufactured by the system is adjustable. In another embodiment, the relative position of the one or more attachment mechanisms is variable such that a diameter of a filamentary composite lattice structure manufactured by the system is adjustable.

The system, in one embodiment, includes the one or more attachment mechanisms that move relative to the weaving mechanism as the system manufactures a filamentary composite lattice structure such that the filamentary composite lattice structure is continuously manufactured. In another embodiment, the shape retention structure is curved such that the filamentary composite lattice produced by the system is curved.

A method of the present invention is also presented for manufacturing a filamentary composite lattice structure. The method in the disclosed embodiments substantially includes the steps necessary to carry out the functions presented above with respect to the operation of the described apparatus and system. In one embodiment, the method includes positioning fibers to form a lattice structure with a weaving mechanism, transitioning fibers in assembled lattice structure to a shape retention structure, and constraining the geometry of the assembled lattice structure in the shape definition component.

In a further embodiment, the method includes curing resin in the assembled lattice structure. The method may include, in another embodiment, tensioning the fibers with a pulling device.

Reference throughout this specification to features, advantages, or similar language does not imply that all of the features and advantages that may be realized with the present invention should be or are in any single embodiment of the invention. Rather, language referring to the features and advantages is understood to mean that a specific feature, advantage, or characteristic described in connection with an embodiment is included in at least one embodiment of the
present invention. Thus, discussion of the features and advantages, and similar language, throughout this specification may, but do not necessarily, refer to the same embodiment.

Furthermore, the described features, advantages, and characteristics of the invention may be combined in any suitable manner in one or more embodiments. One skilled in the relevant art will recognize that the invention may be practiced without one or more of the specific features or advantages of a particular embodiment. In other instances, additional features and advantages may be recognized in certain embodiments that may not be present in all embodiments of the invention.

These features and advantages of the present invention will become more fully apparent from the following description and appended claims, or may be learned by the practice of the invention as set forth hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that the advantages of the invention will be readily understood, a more particular description of the invention briefly described above will be rendered by reference to specific embodiments that are illustrated in the appended drawings. Understanding that these drawings depict only typical embodiments of the invention and are not therefore to be considered to be limiting of its scope, the invention will be described and explained with additional specificity and detail through the use of the accompanying drawings, in which:

Figure 1 is a schematic block diagram illustrating one embodiment of a system for manufacturing a filamentary composite lattice structure in accordance with the present invention;

Figure 2 is a side view illustrating one embodiment of an apparatus to manufacture a filamentary composite lattice structure in accordance with the present invention;

Figure 3 is a front view illustrating one embodiment of a weaving mechanism apparatus in accordance with the present invention;

Figure 4 is a front view illustrating one embodiment of a weaving mechanism apparatus in accordance with the present invention;

Figure 5 is a cut away side view illustrating one embodiment of a gear assembly apparatus in accordance with the present invention;

Figure 6 is a side view illustrating one embodiment of a bobbin carrier apparatus in accordance with the present invention;

Figure 7 is a side view illustrating one embodiment of a shape retention structure apparatus in accordance with the present invention;

Figure 8 is a side view illustrating one embodiment of a transition device apparatus in accordance with the present invention; and
Figure 9 is a schematic flow chart diagram illustrating one embodiment of a filamentary composite lattice structure manufacturing method in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Many of the functional units described in this specification have been labeled as modules, in order to more particularly emphasize their implementation independence. For example, a module may be implemented as an assembly of one or more mechanical components, a hardware circuit comprising custom VLSI circuits or gate arrays, off-the-shelf semiconductors such as logic chips, transistors, or other discrete components. A module may also be implemented in programmable hardware devices such as field programmable gate arrays, programmable array logic, programmable logic devices or the like.

Modules may also be implemented in software for execution by various types of processors. An identified module of executable code may, for instance, comprise one or more physical or logical blocks of computer instructions which may, for instance, be organized as an object, procedure, or function. Nevertheless, the executables of an identified module need not be physically located together, but may comprise disparate instructions stored in different locations which, when joined logically together, comprise the module and achieve the stated purpose for the module.

Indeed, a module of executable code may be a single instruction, or many instructions, and may even be distributed over several different code segments, among different programs, and across several memory devices. Similarly, operational data may be identified and illustrated herein within modules, and may be embodied in any suitable form and organized within any suitable type of data structure. The operational data may be collected as a single data set, or may be distributed over different locations including over different storage devices, and may exist, at least partially, merely as electronic signals on a system or network.

Reference throughout this specification to "one embodiment," "an embodiment," or similar language means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, appearances of the phrases "in one embodiment," "in an embodiment," and similar language throughout this specification may, but do not necessarily, all refer to the same embodiment.

Reference to a signal bearing medium may take any form capable of generating a signal, causing a signal to be generated, or causing execution of a program of machine-readable instructions on a digital processing apparatus. A signal bearing medium may be embodied by a transmission line, a compact disk, digital-video disk, a magnetic tape, a Bernoulli drive, a
magnetic disk, a punch card, flash memory, integrated circuits, or other digital processing apparatus memory device.

Furthermore, the described features, structures, or characteristics of the invention may be combined in any suitable manner in one or more embodiments. In the following description, numerous specific details are provided, such as examples of programming, software modules, user selections, network transactions, database queries, database structures, hardware modules, hardware circuits, hardware chips, etc., to provide a thorough understanding of embodiments of the invention. One skilled in the relevant art will recognize, however, that the invention may be practiced without one or more of the specific details, or with other methods, components, materials, and so forth. In other instances, well-known structures, materials, or operations are not shown or described in detail to avoid obscuring aspects of the invention.

Some basic features of the manufacture of a complex composite structure are described in U.S. Pat. Publication No. US2004/0247866A1, published Dec. 9, 2004, which is herein incorporated by reference into this document.

Figure 1 illustrates a system 100 for manufacturing a lattice structure. The system 100, in one embodiment, may comprise a lattice structure manufacturing device 102, a weaving mechanism 104, a transition device 106, a shape retention structure 108, a resin impregnation device 110, a curing device 112, a pulling device 114, and a control module 116. The system 100 manufactures a lattice structure from fibers.

The lattice structure manufacturing device 102, in one embodiment comprises a weaving mechanism 104, a transition device 106, a shape retention structure 108, a resin impregnation device 110, a curing device 112, and a pulling device 114. The weaving mechanism 104 directs the relative position of a plurality of fibers that make up the lattice structure. In one embodiment, the weaving mechanism 104 may weave a plurality of fibers. In another embodiment, the weaving mechanism 104 may braid a plurality of fibers. In yet another embodiment, the weaving mechanism 104 may wrap one or more fibers around one or more fibers.

As will be appreciated by one skilled in the art, a variety of configurations of the weaving mechanism 104 should be considered to fall within the scope of the invention. For example, in one embodiment, the weaving mechanism 104 may interweave fibers at the joints of a lattice structure that may be stronger and more durable than non-interwoven joints. In another embodiment, the weaving mechanism 104 may wrap fibers around the straight elements of the lattice structure to aid in consolidation of fibers. In yet another embodiment, the weaving
mechanism 104 may be capable of arranging fibers into multiple lattice configurations, such as IsoTrusses, rectangular lattice structure trusses, flat lattice structure panels, and the like.

In one embodiment, the transition device 106 guides fibers from the weaving mechanism 104 onto the shape retention structure 108. The transition device 106 may comprise hooks, clasps, guides, or the like. The transition device 106 acts to ensure proper transition of the fibers into a correct geometry.

The shape retention structure 108, in one embodiment, receives fibers from the transition device 106 and holds the fibers in the proper shape for the lattice structure. The shape retention structure 108 constrains the geometry of the lattice structure and maintains the geometry during curing of the structure. The shape retention structure 108 may be configured to operate continuously as a lattice structure is formed, releasing portions of the structure that have been cured, and accepting additional uncured portions of the lattice structure from the transition device 106. In one embodiment, the shape retention structure 108 may comprise hooks, clasps, grips, or the like that are held in a frame and attach to the lattice structure.

One skilled in the art will recognize that a variety of configurations of shape retention structure 108 should be considered to be within the scope of the invention. For example, in one embodiment, the shape retention structure 108 may comprise a mandrel. In another embodiment, the shape retention structure 108 may include an integral transition device 106. In another embodiment, the shape retention structure 108 may comprise robotic arms that constrain the geometry of the lattice structure. In yet another embodiment, the shape retention structure 108 may comprise a frame that has a variable geometry such that the lattice structure can be curved.

The resin impregnation device 110 applies resin to the fibers in the lattice structure. The resin is later cured and acts as a matrix to hold the fibers in position. In one embodiment, the resin impregnation device 110 sprays resin onto fibers held in the shape retention structure 108.

In another embodiment, the resin impregnation device 110 applies resin to fibers in the weaving mechanism 104. In yet another embodiment, the resin impregnation device applies resin to fibers in the transition device 106. In another embodiment, the fibers are pre-impregnated with resin (pre-preg) and the resin impregnation device 110 is not included.

The curing device 112, in one embodiment, cures the resin in the lattice structure held by the shape retention structure 108. The curing device 112 may continuously cure the resin in the lattice structure as the lattice structure is assembled. In one embodiment, the curing device 112 may comprise a heat curing apparatus.

As will be appreciated by one skilled in the art, a variety of types and configurations of curing device 112 may be implemented without departing from the scope and spirit of the
present invention. For example, in one embodiment, the curing device 112 may use a microwave curing apparatus. In another embodiment, the curing device 112 may use an ultraviolet light (UV) curing apparatus. In yet another embodiment, the curing device 112 may completely cure the resin in the lattice structure. In another embodiment, the curing device 112 may cure the outer layer of the lattice structure to maintain the geometry of the structure.

The pulling device 114, in one embodiment, applies an axial force to the lattice structure. The axial force may be translated through the lattice structure to the fibers in the weaving mechanism 104. The axial force generated by the pulling device 114 pulls the lattice structure from the lattice structure manufacturing device 102 as the structure is progressively assembled, and maintains the correct tension in the fibers as the lattice structure is assembled. In one embodiment, the pulling device 114 comprises a motorized winch with a cable attached to the lattice structure.

One skilled in the art will appreciate that a variety of types and configurations of pulling device 112 may be implemented without departing from the scope and spirit of the invention. For example, in one embodiment, the pulling device 112 comprises a weight attached to a cable attached to the lattice structure. In another embodiment, the pulling device 112 comprises tension applied by the shape retention structure 108 applied to the lattice structure.

The control module 116, in one embodiment, provides control over the various components of the lattice structure manufacturing device 102. The control module 116 may comprise a computing device configured within software code to control the movement and actions of the weaving mechanism 104, the transition device 106, the shape retention structure 108, the resin impregnation device 110, the curing device 112, and/or the pulling device 114. In one embodiment, the control module 116 may be configured to allow a user to select or design the geometry of a lattice structure, adjust the components of the lattice structure manufacturing device 102 to create that structure, and control the action of the components of the lattice structure manufacturing device 102 as the desired structure is created.

Figure 2 illustrates one embodiment of a side view of an apparatus 200 to manufacture a filamentary composite lattice structure. The apparatus 200 may comprise a weaving mechanism 104, a transition device 106, a shape retention structure 108, a curing device 112, and a pulling device 114. Also illustrated are a plurality of fibers 202 and a lattice structure 204. The apparatus 200 manufactures a lattice structure from fibers. The weaving mechanism 104, the transition device 106, the shape retention structure 108, the curing device 112, and the pulling device 114 are similar in function to like numbered elements discussed above in relation to Figure 1.
The plurality of fibers 202, in one embodiment, comprises fibers that are formed by the apparatus 200 into a lattice structure. The fibers 202 may be any fiber used to make composite structures, such as carbon, aramid, fiberglass, or the like. In one embodiment, the fibers 202 are impregnated with resin before entering the apparatus 200. In another embodiment, the fibers 202 are not impregnated with resin before entering the apparatus 200.

The lattice structure 204 is formed from the plurality of fibers 202 by the apparatus 200. In one embodiment, the lattice structure 204 may be an IsoTruss structure. In another embodiment, the lattice structure 204 may be a lattice structure truss with a rectangular cross-section. In yet another embodiment, the lattice structure 204 may be a flat lattice structure panel. In another embodiment, the lattice structure 204 may be a curved lattice structure. In another embodiment, the lattice structure 204 may be a tapered lattice structure.

Figure 3 illustrates a front view of one embodiment of a weaving mechanism 300. The weaving mechanism 300 comprises a plurality of horn gears 302, and one or more bobbin carriers 304. The weaving mechanism 300 transports the one or more bobbin carriers 304 on a path across the face of the weaving mechanism 300 to position fibers in a lattice structure.

As will be appreciated by one skilled in the art, variations of the weaving mechanism 300 that comprise any number of horn gears 302 and are arranged in any shape should be considered to be within the scope and spirit of the invention. Figure 1 illustrates a weaving mechanism 300 containing 16 horn gears 302 arranged in a square panel. In another embodiment, the weaving mechanism 300 may contain hundreds of horn gears 302. In another embodiment, the horn gears 302 may be arranged in a circle across the face of the weaving mechanism 300.

The plurality of horn gears 302, in one embodiment, each comprises one or more notches 306, an aperture 308, and an axis of rotation 310. Each horn gear 302 rotates around its axis of rotation 310 and may carry a bobbin carrier 304 in a notch 306. A horn gear 302 may transfer a bobbin carrier 304 to an adjacent horn gear 302. Transfer of a bobbin carrier 304 may occur in response to both horn gears 302 having aligned notches 306 and the direction of a switch (not shown). Through these transfers, a bobbin carrier 304 may follow a path across the surface of the weaving mechanism 300.

The plurality of horn gears 302 may be gear driven such that each horn gear 302 rotates at the same rate as each adjacent horn gear 302, but in the opposite direction. In another embodiment, the rotation of each horn gear 302 is independently controlled. The plurality of horn gears 302 may be driven by one or more motors.

The plurality of horn gears 302 may each include an aperture 308 at the axis of rotation 310. One or more fibers may pass through the aperture 308 and be incorporated into the lattice structure.
structure. In one embodiment, the fibers that pass through an aperture 308 form the longitudinal members of the lattice structure. The fibers that pass through an aperture 308 may be drawn through the aperture 308 by the progression of the lattice structure.

The one or more bobbin carriers 304, in one embodiment, may each carry a bobbin of fiber as they traverse the weaving mechanism 300. Fiber may be drawn from the bobbins and arranged into a lattice structure by the motion of the bobbin carriers 304 and the progression of the lattice structure. As the bobbin carriers 304 move across the weaving mechanism 300, fibers may be braided, woven, and/or wrapped around one another.

Figure 4 illustrates a front view of one embodiment of a weaving mechanism 400. The weaving mechanism 400 comprises a plurality of horn gears 302, one or more bobbin carriers 304, and one or more switches 402. The weaving mechanism 400 transports the one or more bobbin carriers 304 on a path across the face of the weaving mechanism 400 to position fibers in a lattice structure.

In one embodiment, the plurality of horn gears 302 and the one or more bobbin carriers 304 are preferably configured in a manner similar to like numbered components described above in relation to Figure 3. The one or more switches 402 direct the transfer of the bobbin carriers 304 between horn gears 302. In one embodiment, the switches 402 are located at the interface between horn gears 302.

In one embodiment, the one or more switches 402 comprise a variable-geometry guide that switches between a transfer state and a continue state. A bobbin carrier 304 traversing a switch 402 in the transfer state is transferred to the adjacent horn gear 302. A bobbin carrier 304 traversing a switch 402 in the continue state continues to travel on its current horn gear 302.

The one or more switches 402 may be switched between a transfer state and a continue state by a solenoid. In another embodiment, the one or more switches 402 may be switched by a motor. In another embodiment, the one or more switches 402 may be switched pneumatically.

Figure 5 illustrates a side view cross section of one embodiment of a gear assembly 500. The gear assembly 500 comprises a horn gear 302, a weaving mechanism surface 502, an axle 504, and a drive gear 506. The gear assembly 500 controls the rotation of the horn gear 302 in a weaving mechanism.

In one embodiment, the horn gear 302 includes an aperture 308 and an axis of rotation 310. The horn gear 302, aperture 308 and axis of rotation 310 are preferably configured in a manner similar to like numbered components described above in relation to Figure 3. The horn gear 302 rotates around the axis of rotation 310 and may carry one or more bobbin carriers 304 across the weaving mechanism 300.
The weaving mechanism surface 502, in one embodiment, provides a surface for the bobbin carrier to slide. In one embodiment, the weaving mechanism surface 502 is sectioned such that each gear assembly 500 may be removed from the weaving mechanism for maintenance and repair. The gear assembly 500 may slide toward the horn gear 302 for removal. In another embodiment, the gear assembly 500 may slide toward the drive gear 506 for removal. In yet another embodiment, the segmented weaving mechanism surface 502 may be removably attached to adjacent weaving mechanism surfaces 502 by a fastener.

The axle 504, in one embodiment, may be attached to the horn gear 302 and share a common axis of rotation 310 with the horn gear 302. The axle 504 translates motion from the drive gear 506 to the horn gear 302. In another embodiment, the axle 504 is hollow and provides an aperture 308. Fiber used to form a lattice structure may pass through the aperture 308. The axle 504 may be made from any material strong and stiff enough to transfer force from the drive gear 506 to the horn gear 302, such as steel, aluminum, alloys, plastic, composites, or the like.

The drive gear 506, in one embodiment, may be attached to the axle 504 and share a common axis of rotation with the axle 504 and the horn gear 302. The drive gear 506 may be a spur gear that meshes with adjacent drive gears 506 in adjacent gear assemblies 500. The drive gear 506 may be driven by an adjacent drive gear 506. The drive gear 506 may drive an adjacent drive gear 506. The drive gear 506 transfers rotational motion to the axle 504 to drive the horn gear 302. The drive gear 506 may be made from any material sufficiently strong, stiff, and durable enough to transfer rotational motion, such as steel, aluminum, alloys, plastic, composites, or the like.

As will be appreciated by one skilled in the art, a variety of configurations of drive gear 506 may be employed without departing from the scope or spirit of the invention. For example, in one embodiment, the drive gear 506 may be independently driven by a motor. In another embodiment, the drive gear 506 may be driven by a belt.

Figure 6 illustrates one embodiment of a side view of a bobbin carrier 600. The bobbin carrier 600 comprises a bobbin 602, a horn gear interface 604, and a track guide 606. The bobbin carrier 600 is transported by a horn gear 302 across a weaving mechanism surface 502 and carries a bobbin of fiber as fiber is drawn from the bobbin 602 to make a lattice structure.

In one embodiment, the bobbin 602 is wrapped with a single strand of fiber that is drawn from the bobbin 402. The bobbin 602 may be removable from the bobbin carrier 600. In another embodiment, the bobbin 602 is integral with the bobbin carrier 600. In another embodiment, the bobbin 602 carries more than one strand of fiber.
The horn gear interface 604, in one embodiment, has a shape that matches the notches on a horn gear 302 in a weaving mechanism. The horn gear interface 604 allows the bobbin carrier 300 to securely rest in a rotating horn gear 302 as the bobbin carrier 300 moves. In one embodiment, the horn gear interface 604 may have a circular cross section, allowing for any rotational orientation within a notch of a horn gear 302. In another embodiment, the horn gear interface 604 may have a shaped cross section, allowing specific rotational orientations within a notch of a horn gear 302.

The track guide 606, in one embodiment, interfaces with a track on the weaving mechanism surface 502 and guides the motion of the bobbin carrier 600. The track guide 606 may interact with a switch to control transfer of the bobbin carrier between horn gears. Figure 7 illustrates one embodiment of a shape retention structure 700. The shape retention structure 700 comprises a frame 702 and one or more attachment mechanisms 704. The shape retention structure 700 constrains the geometry of a curing lattice structure 706.

In one embodiment, the frame 702 may provide a base for the one or more attachment mechanisms 704. The frame 702 may remain stationary as the lattice structure 706 is assembled and allow the one or more attachment mechanisms 704 to travel with the lattice structure 706. In an alternate embodiment, the frame 702 may travel with the lattice structure 706 as it is assembled. In one embodiment, the frame 702 may comprise one or more rails arranged around the lattice structure 706.

As will be appreciated by one skilled in the art, a variety of types and configurations of frame 702 may be implemented without departing from the scope or spirit of the invention. For example, in one embodiment, the frame 702 may comprise one or more rings that encircle the lattice structure 706. In another embodiment, the frame 702 may comprise one or more tracks arranged around the lattice structure 706. In another embodiment, the frame 702 may comprise a base on which actuators for controlling the one or more attachment mechanisms 704 are mounted.

In one embodiment, the frame 702 is adjustable such that a diameter 708 of the lattice structure 706 may be varied. In another embodiment, the frame 702 is adjustable such that a bay length 710 of the lattice structure 706 may be varied. In another embodiment, the diameter 708 and/or bay length 710 may be varied during the process of assembling a lattice structure 706.

In another embodiment, the frame 702 may be adjustable such that the lattice structure 706 may be held in a bent or curved position. The frame 702 may, in another embodiment, be configured to hold a lattice structure 706 in an iso-truss configuration. In another embodiment, the frame 702 may be configured to hold a lattice structure 706 in a flat panel configuration. In
another embodiment, the frame 702 may be configured to hold a lattice structure 706 in a rectangular cross-section configuration.

The one or more attachment mechanisms 704 attach to the lattice structure 706 and constrain the geometry of the lattice structure 706. The lattice structure 706 is held in shape during curing. In one embodiment, the one or more attachment mechanisms 704 are hooks connected to the frame 702.

As will be appreciated by one skilled in the art, a variety of types and configurations of one or more attachment mechanisms 704 may be employed without departing from the scope and spirit of the invention. For example, in one embodiment, the one or more attachment mechanisms 704 may comprise a grip mechanism. In another embodiment, the one or more attachment mechanisms 704 may comprise a variable geometry mechanism that allows the constraint and release of the lattice structure 706. In another embodiment, the one or more attachment mechanisms 704 may comprise one or more robotic arms with controllable servo mechanisms.

In another embodiment, the one or more attachment mechanisms 704 may be adjustable such that the diameter 708 of the lattice structure 706 may be varied. In another embodiment, the one or more attachment mechanisms 704 may be adjustable such that the bay length 710 of the lattice structure 706 may be varied. In another embodiment, the diameter 708 and/or bay length 710 may be varied during the process of assembling a lattice structure 706.

In one embodiment, the shape retention structure 700 may act as a pulling device. The shape retention structure 700 may provide tension in the fibers for the manufacturing process. The shape retention structure 700 may also draw fiber from bobbins and move the lattice structure 706 away from the weaving mechanism as the lattice structure 706 is assembled.

Figure 8 illustrates one embodiment of a side view of a transition device 800. The transition device 800 comprises one or more transition wheels 802. The transition device 800 guides fibers from the weaving mechanism 104 to onto the shape retention structure 108. The one or more transition wheels 802 may each include a hub 804 and one or more hooks 806. The hub 802, in one embodiment, rotates, and provides an attachment for the one or more hooks 806. The one or more hooks 806, in one embodiment, engage fibers from the weaving mechanism 104 as the hub 804 rotates. The one or more hooks 806 may carry the fiber in a predetermined orientation to the shape retention structure 108. In one embodiment, the one or more hooks 806 may release the fibers in response to the engagement of the shape retention structure 108 with the fibers.
As will be appreciated by one skilled in the art, a variety of types and configurations of transition devices 800 may be utilized without departing from the scope and spirit of the present invention. For example, the transition device 800, in one embodiment, may comprise one or more servo-driven actuators configured to engage fibers and deliver them to the shape retention structure 108. In another embodiment, the transition device 800 may include a four-bar linkage configured to carry the fibers on a pre-determined path from the weaving mechanism 104 to the shape retention structure 108.

The schematic flow chart diagrams that follow are generally set forth as logical flow chart diagrams. As such, the depicted order and labeled steps are indicative of one embodiment of the presented method. Other steps and methods may be conceived that are equivalent in function, logic, or effect to one or more steps, or portions thereof, of the illustrated method. Additionally, the format and symbols employed are provided to explain the logical steps of the method and are understood not to limit the scope of the method. Although various arrow types and line types may be employed in the flow chart diagrams, they are understood not to limit the scope of the corresponding method. Indeed, some arrows or other connectors may be used to indicate only the logical flow of the method. For instance, an arrow may indicate a waiting or monitoring period of unspecified duration between enumerated steps of the depicted method. Additionally, the order in which a particular method occurs may or may not strictly adhere to the order of the corresponding steps shown.

Figure 9 illustrates a method 900 for manufacturing a lattice structure. Initially, fiber tows are arranged 902 in the manufacturing apparatus. In selected embodiments, fibers may be threaded through an aperture 308 in a horn gear 302, or be placed on a bobbin 602 on a bobbin carrier 304. The desired arrangement of the fibers may be determined by the lattice structure to be created.

Next, the fibers are attached 904 to the pulling device. The fibers may be tied to the pulling device. In another embodiment, fibers are attached to the pulling device by fasteners. Next, the fibers are tensioned 906 by the pulling device. The tension applied by the pulling device holds the fibers in position. The tension may also draw fibers through the apparatus. In another embodiment, the tension draws the assembled lattice structure through the apparatus.

Next, the fibers are positioned 908 by the weaving mechanism. Fibers may be arranged side by side, wrapped around other fibers, woven together, and/or braided together by the weaving mechanism. The positioning of the fibers may be controlled by the weaving mechanism to arrange the fibers in the desired configuration to form a lattice structure.
Next, the assembled lattice structure is transitioned 910 onto a shape retention structure. The lattice structure may be placed on guides and/or attachment mechanisms 704.

Next, the geometry of the lattice structure is constrained 912 by the shape retention structure. The shape retention structure holds the lattice structure in the desired shape and configuration while the structure is flexible. The shape retention structure may also tension the fibers.

Next, the resin in the lattice structure is cured 914. The flexible structure held in the shape retention structure is made rigid by the curing process. The resin may be cured by a heat process, a microwave process, an ultraviolet process, or the like. In one embodiment, the resin may be fully cured in the shape retention structure. In another embodiment, the resin may be partially cured in the shape retention structure.

Next, the lattice structure is released 916 from the shape retention structure. The structure may be released through the action of one or more variable geometry attachment mechanisms 704. In another embodiment, the structure may be released releasing tension on one or more attachment mechanisms 704.

The present invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is, therefore, indicated by the appended claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.
CLAIMS

1. An apparatus to manufacture filamentary composite lattice structures, the apparatus comprising:
   a weaving mechanism configured to position fibers in a lattice structure, the weaving mechanism comprising:
   one or more bobbins, each of the one or more bobbins configured to carry fiber; and
   a plurality of horn gears configured to move the one or more bobbins across the face of the weaving mechanism to control the position of the fiber carried by the one or more bobbins in the lattice structure; and
   a shape retention structure configured to hold the fibers in lattice structure until the lattice structure is cured to a rigid state.

2. The apparatus of Claim 1, further comprising a curing device configured to cure resin on the fibers held in the shape retention structure.

3. The apparatus of Claim 1, further comprising a resin impregnation device configured to apply a resin to the fibers in the filamentary composite lattice structure.

4. The apparatus of Claim 1, further comprising a pulling device configured to apply an axial force to the filamentary composite lattice structure.

5. The apparatus of Claim 1 wherein one or more of the plurality of horn gears are driven by a spur gear on an adjacent one or more of the plurality of horn gears such that a motor attached to one of the plurality of horn gears drives the plurality of horn gears.

6. The apparatus of Claim 1 wherein one or more of the plurality of horn gears are driven by an individual motor.

7. The apparatus of Claim 1 wherein the weaving mechanism further comprises one or more switches configured to transfer the bobbin from one of the plurality of horn gears to an adjacent one of the plurality of horn gears.

8. The apparatus of Claim 1 wherein one or more of the plurality of horn gears further comprise an aperture configured to allow a fiber to pass through the aperture.
9. The apparatus of Claim 1 wherein one or more of the plurality of horn gears further comprises a gear assembly configured to be individually removed from the weaving mechanism.

10. The apparatus of Claim 1, further comprising a transition device configured to transfer fibers from the weaving mechanism to the shape retention structure.

11. A system to manufacture filamentary composite lattice structures, the system comprising: a weaving mechanism configured to position fibers in a lattice structure, the weaving mechanism comprising:

   one or more bobbins, each one or more bobbin configured to carry fiber; and
   a plurality of horn gears configured to move the one or more bobbins across the face of the weaving mechanism to control the position of the fiber carried by the one or more bobbins in the lattice structure;

   a shape retention structure configured to hold the fibers in a lattice structure using one or more attachment mechanisms; and
   a control module configured to control the weaving mechanism and direct the positioning of the fibers in the lattice structure.

12. The system of Claim 11 wherein the one or more attachment mechanisms comprise one or more hooks configured to hold the lattice structure in a desired configuration.

13. The system of Claim 11 wherein the one or more attachment mechanisms comprise one or more servo mechanisms configured to hold the lattice structure in a desired configuration.

14. The system of Claim 11 wherein the relative position of the one or more attachment mechanisms is variable such that a bay length in a filamentary composite lattice structure manufactured by the system is adjustable.

15. The system of Claim 11 wherein the relative position of the one or more attachment mechanisms is variable such that a diameter of a filamentary composite lattice structure manufactured by the system is adjustable.
16. The system of Claim 11 wherein the one or more attachment mechanisms move relative to the weaving mechanism as the system manufactures a filamentary composite lattice structure such that the filamentary composite lattice structure is continuously manufactured.

17. The system of Claim 11 wherein the shape retention structure is curved such that the filamentary composite lattice produced by the system is curved.

18. A method for manufacturing a filamentary composite lattice structure, the method comprising:
   positioning fibers to form a lattice structure with a weaving mechanism configured to position fibers in a lattice structure, the weaving mechanism comprising:
   one or more bobbins, each one or more bobbin configured to carry fiber; and
   a plurality of horn gears configured to move the one or more bobbins across the face of the weaving mechanism to control the position of the fiber carried by the one or more bobbins in the lattice structure; and
   constraining the geometry of the assembled lattice structure in the shape definition component.

19. The method of Claim 17, wherein the method further comprises curing resin in the assembled lattice structure.

20. The method of Claim 17, further comprising tensioning the fibers with a pulling device.
Lattice Structure Manufacturing Device

- Weaving Mechanism 104
- Transition Device 106
- Shape Retention Structure 108
- Resin Impregnation Device 110
- Curing Device 112
- Pulling Device 114

Control Module 116

FIG. 1
FIG. 4
900

902  Arrange fibers

904  Attach fibers to pulling device

906  Tension fibers with pulling device

908  Position fibers with weaving mechanism

910  Transition assembled lattice structure to shape retention structure

912  Constrain geometry with shape retention structure

914  Cure resin

916  Release lattice structure from shape retention structure

FIG. 9