A composite lattice structure formed of one or more face sheets connected with lattice members, where the lattice members are formed of single or multiple contiguous fiber tows, and the lattice members and face sheets are interfused in a matrix.
LIGHTWEIGHT COMPOSITE LATTICE STRUCTURES

BACKGROUND

[0001] Fiber-reinforced composites are integrated into parts for high-strength / low-weight applications, such as aerospace structures, due to their high strength-to-weight ratio. However, composites tend to possess a variety of drawbacks that prevent adoption into all applications for which this ratio is important. Composite beams may be extraordinarily strong in tension, but in compression may be subject to a variety of failure modes such as: matrix splitting, wherein the ends of a composite beam separate along planes between the fibers sheets and the beam splits down the middle; small-scale and large-scale buckling, wherein the individual fibers or the whole beam bends and fractures (respectively); or delamination, wherein the fibers may separate from one another along a shear plane between the fibers. Composite construction tends to be expensive and time-consuming where the geometries of parts are complex. Various parts of the construction process, for example cutting and attaching composite parts, may introduce surface imperfections which significantly diminishing strength. Therefore, in conventional composite manufacturing, increasing complexity may be correlated with ever greater risk of part failure.

BRIEF SUMMARY

[0002] Embodiments disclosed herein relate to, for example, a composite lattice structure formed of one or more face sheets connected with lattice members, where the lattice members are formed of single or multiple contiguous fiber tows in a matrix. In embodiments, fiber tows may abut, weave through, or both abut and weave through parts of the face sheet or sheets to form the lattice structures. The lattice members and face sheets may additionally be formed of and connected to one another by being interfused with the matrix.

[0003] At least some embodiments relate to a method of making composite lattice structures such as those described above by threading one or more fiber tows through bores of a removable pattern in a lattice configuration, covering the pattern and lattice members in one or more face sheets, and interfusing the assembly of pattern, lattice members and face sheets with a matrix. The fluid matrix material is interfused into the face sheets and bores and then cured to form a
rigid matrix. The pattern is then removed from around the matrix. When the pattern is removed, the matrix-filled volume where the bores had been disposed forms a composite lattice structure. Parts may be strengthened by interweaving the fibers of the lattice members with the face sheets.

[0004] As a first aspect of the present invention, there is provided, a composite lattice structure, comprising:

- a superior face sheet;
- an inferior face sheet;
- at least one fiber tow arranged in a plurality of lattice members, the lattice members separating the superior and inferior face sheets and connecting with each of the face sheets at a plurality of points; and
- a polymer matrix interfused throughout the lattice members and the superior and inferior face sheets.

[0005] Preferably, the at least one fiber tow passes through each of the superior and inferior face sheets at a plurality of points, and abuts exterior surfaces of each of the superior and inferior face sheets.

[0006] Preferably, the at least one fiber tow is contiguous between at least two adjacent members of the plurality of lattice members.

[0007] Preferably, the at least one fiber tow is multiply wound among the plurality of lattice members, such that each lattice member comprises a bundle of parallel fiber tows, and such that each lattice member is connected with one or more adjacent lattice members and with the superior and inferior face sheets by at least one fiber tow.

[0008] Preferably, the superior face sheet and inferior face sheet are contiguous with each other about a bend.

[0009] As another aspect of the invention, there is provided a composite lattice structure, comprising:

- a face sheet; and
- one or more lattice members, comprising:
at least one fiber tow; wherein
the at least one fiber tow is configured in a lattice shape and into
contact with the face sheet at a plurality of points on a surface of the face
sheet; and
the at least one fiber tow and the face sheet are fixed in a
contiguous matrix with an interfused matrix material.

[0010] Preferably, the at least one fiber tow comprises a plurality of carbon fiber filaments.

[0011] Preferably, the one or more lattice members further comprise a plurality of parallel
fiber tows.

[0012] Preferably, the matrix material is a low-viscosity thermoset polymer resin.

[0013] Preferably, at least a portion of the at least one fiber tow passes through the face sheet
from an inner surface to an outer surface of the face sheet, runs along the outer surface of the
face sheet, and passes back through the face sheet.

[0014] Preferably, a portion of the at least one fiber tow abuts an inner surface of the face
sheet, and runs along the inner surface of the face sheet.

[0015] Preferably, at least a first portion of the at least one fiber tow passes through the face
sheet from an inner surface to an outer surface of the face sheet, runs along the outer surface of the
face sheet, and passes back through the face sheet; and
at least a second portion of the at least one fiber tow abuts an inner surface of the
face sheet, and runs along the inner surface of the face sheet.

[0016] Preferably, the face sheet comprises a woven fiber sheet, and the at least one fiber tow
is interwoven with at least a portion of the face sheet.

[0017] Preferably, the face sheet comprises a unidirectional carbon fiber sheet.

[0018] Preferably, the face sheet comprises a plurality of sheets arranged in a stack.
Preferably, one or more of the plurality of sheets comprises a unidirectional carbon fiber sheet; and the stack is arranged in a plurality of ply orientations.

Preferably, at least a portion of the at least one fiber tow passes through a subset of the plurality of sheets making up the face sheet, runs along an intermediate surface between at least two of the plurality of sheets, and passes back through the subset of the plurality of sheets.

Preferably, the face sheet is arranged with a bend such that the face sheet partially encloses a volume, the face sheet having at least two opposed interior faces; and the one or more lattice members comprises a plurality of lattice members, arranged such that that plurality of lattice members connects with and separates the opposed interior faces of the face sheet.

As a further aspect of the invention, there is provided a composite lattice structure, comprising:

- a first face sheet;
- a second face sheet; and
- a lattice between the first and second face sheets;

the lattice and the first and second face sheets formed by a method comprising:

- applying the first face sheet to an exterior surface of a first portion of a removable pattern having an exterior surface and one or more bores passing through the pattern;
- threading a fiber tow through at least a portion of the first face sheet and through at least two of the one or more bores;
- interfusing the face sheet and the fiber tow with a resin;
- curing the resin; and
- removing the pattern from the cured resin material, so as to form the lattice from the cured matrix and the fiber tow and the lattice structure from the cured lattice and face sheet.

Preferably, the method further comprises:
applying the second face sheet to a second portion of the exterior surface of the pattern, such that the first and second face sheets are arranged at opposed portions of the exterior surface of the pattern; and

threading the fiber tow through at least a portion of the second face sheet.

5 [0024] Preferably, removing the pattern from the cured resin material comprises at least one of: melting, dissolving, or mechanical extraction.

[0025] As a further aspect of the invention, there is provided a method of manufacturing a composite lattice, the method comprising:

providing a pattern in a removable material, the pattern having an exterior surface and one or more through-holes passing through the pattern;

threading a fiber tow through at least one of the one or more through-holes;

applying a face sheet to a portion of the exterior surface of the pattern;

interfusing the face sheet and the fiber tow with a matrix material;

curing the matrix material; and

removing the pattern from the cured matrix material, so as to form a lattice formed by the resin-impregnated fiber tows and the face sheet.

[0026] Preferably, the method comprising providing a pattern further comprises:

shaping the pattern to approximate the shape of an internal cavity of a substantially hollow structure.

[0027] Preferably, the method comprising providing a pattern further comprises:

boring a plurality of through-holes in the removable material, the through-holes being arranged in a lattice configuration.

25 [0028] Preferably, boring a plurality of through-holes comprises a boring process performed by a computer-numerically-controlled machine.

[0029] Preferably, at least a subset of the plurality of through-holes have openings that are adjacent to each other at the exterior of the pattern; and further comprising:
where first and second through-holes of the subset have adjacent openings, threading a fiber tow out from the first through-hole and into the second through-hole by way of the adjacent openings.

[0030] Preferably, interfusing the face sheet and the fiber tow with a matrix comprises a single resin-transfer process.

[0031] Preferably, the resin-transfer process further comprises:
sealing the pattern, the fiber tow, and the face sheet within a vacuum bag having one or more inlets and one or more outlets;
generating a vacuum within the vacuum bag; and
placing the one or more inlets into fluid contact with a reservoir containing the matrix material.

[0032] Preferably, the method of manufacturing a composite lattice, the method further comprising:
prior to the permeating act, mixing the resin with a hardening agent.

[0033] Preferably, threading a fiber tow further comprises:
threading the fiber tow through the face sheet from an interior surface of the face sheet to an exterior surface of the face sheet, passing the fiber tow over a section of the exterior surface of the face sheet, and passing the fiber tow back through the face sheet.

[0034] Preferably, the face sheet comprises carbon fiber fabric.

[0035] Preferably, applying a face sheet further comprises:
applying a plurality of unidirectional fiber sheets in two or more ply orientations.

[0036] Preferably, the fiber tow comprises a plurality of parallel carbon fiber filaments.

[0037] Preferably, removing the pattern comprises at least one of the following: melting, dissolving, or mechanical extraction.
[0038] Preferably, a composite lattice formed by the method of claim 1.

[0039] As a further aspect of the invention, there is provided a method of manufacturing a composite lattice, the method comprising:

preparing a removable pattern, the pattern having an exterior surface that approximates an internal cavity of a structure, the removable pattern having a plurality of through-holes therethrough, the through-holes being arranged in the shape of a lattice;

threading a first length of fiber tow through a first subset of the plurality of through-holes; such that the first length passes along and abuts at least one section of the exterior surface of the pattern;

applying a fiber face sheet to the exterior surface of the pattern;

threading a second length of fiber tow through a second subset of the plurality of through-holes and also through the face sheet, such that the second length passes over and abuts at least one section of an exterior surface of the face sheet;

interfusing a resin throughout the first and second lengths of fiber tow and the face sheet;

curing the resin; and

removing the pattern.

[0040] Preferably, the first length of fiber tow and second length of fiber tow are sections of a contiguous carbon fiber filament tow.

[0041] Preferably, the first and second subsets of through holes comprise the same through-holes.

[0042] Preferably, each through-hole is adjacent to one or more additional through-holes; and wherein each of the threading acts further comprises:

passing the first and second lengths of fiber tow out of the pattern by way of a first through hole and back into the pattern by way of an adjacent second through-hole.

[0043] Preferably, interfusing a resin comprises a vacuum-assisted resin transfer molding process.
Preferably, curing the resin further comprises:

prior to the interfusing act, mixing the resin with a hardening agent;

allowing the resin to gel at a room temperature for a first curing time; and

curing the resin at an elevated temperature for a second curing time.

Preferably, a composite lattice formed by the method of claim 15.

BRIEF DESCRIPTION OF THE DRAWINGS

Various embodiments in accordance with the present disclosure will be described with reference to the drawings, in which:

FIG. 1A is a top view of a composite lattice structure formed with fiber reinforced composite lattice members, in accordance with embodiments.

FIG. 1B is a side view of the structure shown in FIG. 1A.

FIG. 1C is a perspective view of the structure shown in FIG. 1A.

FIG 2A is a cutaway side view of an embodiment of a composite lattice structure having fiber reinforced composite lattice members and a face sheet with fibers of the lattice members abutting the face sheet.

FIG. 2B is a cutaway side view of an embodiment of a composite lattice structure having fiber reinforced composite lattice members and a face sheet with fibers of the lattice interwoven with the face sheet.

FIG. 2C is a cutaway side view of an embodiment of a composite lattice structure having fiber reinforced composite lattice members and a face sheet where subsets of the fibers diverge from the lattice members to pass along a surface of the face sheet.

FIGS. 3A through 3G represent stages of a process for forming a fiber-reinforced composite lattice structure in accordance with embodiments, with FIG. 3A being a perspective view of a block of removable pattern material, in accordance with embodiments.
FIG. 3B is perspective view of a removable pattern, formed from the block of removable pattern material of FIG. 3A having a complex set of bores added, in accordance with embodiments.

FIG. 3C is a cutaway side view of a first process of winding a fiber tow through a section of the bores of the pattern of FIG. 3B and encasing the pattern in face sheets, in accordance with embodiments.

FIG. 3D is a cutaway side view of an alternative embodiment of a process of winding a fiber tow through a section of bores in the pattern of FIG. 3B, with the fiber being wound also through the face sheets.

FIG. 3E is a cutaway side view of an embodiment of a vacuum-assisted resin infusion process for permeating the face sheets, bores, and fiber tows with a matrix material.

FIG. 3F is a cutaway side view of an embodiment of a resin curing process being applied to the resin-infused face sheets, bores, and fiber tows of FIG. 3E so as to form a cured lattice structure.

FIG. 3G is a cutaway side view showing pattern material being removed from the cured lattice structure of FIG. 3F.

DETAILED DESCRIPTION

In the following description, various embodiments will be described. For purposes of explanation, specific configurations and details are set forth in order to provide a thorough understanding of the embodiments. However, it will also be apparent to one skilled in the art that the embodiments may be practiced without the specific details. Furthermore, well-known features may be omitted or simplified in order not to obscure the embodiment being described.

Various embodiments herein described are directed to lattice structures made of fiber-reinforced composite materials. The lattice structures have one or more face sheets connected with lattice members. One or more fiber tows create two or more lattice members in the lattice structure. Both or either of the lattice members and face sheets are a fiber-reinforced composite material. Some embodiments of the lattice members and face sheets can be formed as a single contiguous piece, and can be formed according to a method that uses a removable pattern.
In embodiments of such a method, the pattern is a removable material and has a complex array of through-holes or bores, such that a fiber tow can be interwoven throughout the bores of the removable pattern and connected with face sheets at an exterior of the pattern. Assembled fiber tows and face sheets can be permeated with a matrix and cured in order to produce a contiguous fiber-reinforced composite lattice structure. The pattern is then removed from the lattice structure, for example by melting the pattern.

**Detailed description of the figures**

FIG. 1A is a top view of a lattice structure 100a formed with fiber reinforced composite lattice members 104a running in a pattern along a length 102 of the structure, in accordance with embodiments. Notably, the spacing, length, and angle of the lattice members may vary along a length or width of a part, depending on the desired geometry of the entire part as well as, for example, part-specific loading and strength requirements, or other desired attributes.

FIG. 1B is a side view of a lattice structure 100b, formed with fiber reinforced lattice members 104b, showing an example of how lattice members may be configured according to at least one embodiment. The lattice members 104b in this example connect with both superior 106 and inferior 108 face sheets in a triangular truss configuration. Each member of the lattice members 104b is a fiber-reinforced composite beam formed of a bundle or tow 110 of substantially parallel fibers. The lattice members 104b and the face sheets 106, 108 are connected with one another at least by a matrix being infused with all parts, forming a composite material. In some embodiments, the lattice members 104b are connected with one another by adjacent members being formed of at least one continuous fiber tow 110, and by meeting at the face sheets 106, 108.

Composite material conventionally means a combination of two or more constituent materials wherein the combination has different properties that one or another of the materials alone. At least some embodiments in the present disclosure include fiber-reinforced composites, for example (but not limited to) carbon fiber suspended in a polymer matrix. Except where indicated otherwise, "composite” in the present disclosure will be defined generally as any fiber-reinforced or fabric-reinforced composite material.
[0066] The fibers in embodiments of the reinforced fiber/polymer composite material may be any fiber which is now or which may in the future become suitable for such a composite, for example, the fiber may be a glass, carbon, cellulose, high-strength polymer such as aramid fiber (or para-aramid fiber such as KEVLAR™), metallic wire, conductive or insulating filaments, any comparable fiber, natural fiber, or a combination of these fibers. In various embodiments, the fibers may be organized relative to one another in a pattern, for example, they may be woven, laid randomly, braided, twisted, or grouped into a tow comprising adjacent parallel fibers. In particular embodiments, the fiber may be carbon fiber filaments arranged in a tow of parallel fibers. In specific embodiments, the reinforcing carbon fiber tows may be CARBON 12K™ (made by Gurit, Inc.), or may be fiber tows extracted from a fiber face sheet (below).

[0067] Fiber face sheets may be used as a structural element in the lattice structure, for example as an outer skin of a sandwich structure, in accordance with embodiments. The fibers within a face sheet may be the same or different from the fibers used in the lattice members. In a specific embodiment, a face sheet may be a uni-directional carbon fiber sheet such as UT-C300™ (made by Gurit, Inc.), or may be a multi-ply sheet formed of multiple layers of face sheets laid across one another in two or more ply orientations. For example, in a stack of sheets having multiple ply orientations, the fibers of multiply layered sheets may run orthogonal to the fibers of a first sheet at 90 degrees, at 45 degrees, at 30 degrees, at 60 degrees, at any other angle, or any combination of angles and in any order. Additional fiber tows may also be used to thicken or reinforce fiber sheets where necessary to enhance the strength of the sheet, for example at points intended for attachment points, or at points intended to be load bearing; and face sheets may additionally be connected with one another by adhesive bonding.

[0068] FIG. 1C is a perspective view of a composite lattice structure 100c, similar to lattice structures 100a and 100b of FIGS. 1A and IB, showing an example of an alternative configuration of lattice members according to at least one embodiment. Shown are superior 106 and inferior 108 face sheets and a partial selection of lattice members 104c. In particular, this view shows how a complex arrangement of lattice members may be positioned in relation to one another and within an arbitrary topology of the face sheets, in accordance with various embodiments, with the lattice members intersecting at a plurality of points between the face sheets.
In structural settings, a lattice generally provides stiffness to a larger structure while allowing it to remain relatively lightweight. In the present disclosure, a lattice refers to any structure that extends between and connects two surfaces or opposed portions of a curved surface, and individual beams within that structure are referred to as lattice members. In embodiments, lattice members may or may not be repeated. One form of lattice is a network of lattice members separating and supporting two or more face sheets in a sandwich-type lattice structure. In some embodiments, the lattice is a regular, repeated arrangement of intersecting members, such as a truss configuration, with repeating diagonal elements and straight members connecting the two face sheets. The supporting elements of the lattice are referred to as lattice members, and the totality of an assembly of face sheets and lattice members are referred to as a lattice structure.

In various embodiments, individual lattice members may cross from one face sheet to the other in a truss configuration along a plane that lays diagonal to the face sheets. In at least one embodiment, the planes on which these lattice members lie may cross proximate to an inner surface of one or the other of the face sheets, such that pairs of lattice members appear to "lean" toward one another, forming, for example, a repeating pyramidal configuration.

As described above, the lattice members are formed from fiber tow bundles. These fiber tow bundles align along the length of the lattice members. For example, FIG 2A is a cutaway side view of an embodiment of two fiber-reinforced composite lattice members 210a that form part of a lattice structure 200a. The lattice members 210a meet at a surface of a face sheet 212a, with the fibers of the lattice abutting the face sheet at a contact point 214a. In the example schematic as shown, the fibers comprising the lattice members 210a are substantially parallel and straight for a length of a first lattice member, and then curve proximate to the face sheet, and then straighten again as part of a second lattice member. The fibers comprising lattice members may, in various embodiments, curve more or less abruptly than shown where they contact the face sheets; or they may contact a face sheet and then run parallel to that face sheet for a distance before curving to form an additional lattice member; or, one or more fiber tows may originate at and join the collection of fibers forming the lattice member at or proximate to a face sheet.
Specific embodiments of the lattice may have any lattice configuration, such as the square-pyramidal configuration shown, but variations of the embodiments may be any conventional three-dimensional lattice shape, for example: parallel columns; parallel two-dimensional planar trusses having triangular elements; three-dimensional triangular pyramidal (tetrahedral) lattices, combinations of tetrahedral lattices such as a Kagome lattice, three-dimensional square-pyramidal lattices, honeycomb or hexagonal lattice systems incorporating triangular elements; octet lattice structures; lattices incorporating round shapes such as bowed elements or wheel-and-spoke arrangements; and any other three-dimensional shape including both repeating truss-like structures and nonrepeating, arbitrary structures.

FIG. 2B is a cutaway side view of an embodiment of fiber reinforced composite lattice members 210b that form part of a lattice 200b with a face sheet 212b, where the face sheet is at least partially composed of fibers, and at least some of the fibers of the lattice members are interwoven with the fibers of the face sheet 214b. The fibers of the beams may interweave with the fibers of the face sheet once or multiple times, and each fiber may interweave with one or more fibers. In the embodiment shown in FIG. 2B, the fibers of the beam each interweave with a at least one fiber of the face sheet, with some beam fibers interweaving with multiple face sheet fibers. The fibers within the lattice members may curve and depart from the face sheet in a short span; or the fibers may run parallel to or within a section of the face sheet such that the lattice members and face sheet are more tightly interwoven.

FIG. 2C is a cutaway side view of an embodiment of fiber reinforced composite lattice members 210c that form part of a lattice 200c with a face sheet 212c. In this example, some fibers of the lattice members 210c are partially interwoven 214c with fibers of the face sheet 212c. Some fiber tows 216 diverge from the lattice members to run along a section of the face sheet.

Where more than two lattice members join a face sheet proximate to one another, fiber tows may branch at the intersections such that the fibers of multiply joined lattice members may be effectively interwoven with one another at the intersections. However, in certain embodiments, the fiber tows run continuously from one lattice member to one other lattice member, such that when multiple lattice members abut or join a face sheet at a point proximate to one another, the different fiber tows of two intersecting pairs of lattice members may abut one
another without being interwoven. Furthermore, in various embodiments, the lattice members may be connected with the face sheets by one or more of: abutting the face sheets and being joined by the matrix; resting within an indentation or cavity in one or more of the face sheets; being partially interwoven with the abutting face sheets; being fully interwoven with the face sheets; being mechanically connected with the face sheets by a connector such as a pin, rivet, screw, bolt, or other connecting means; or some combination of the above connecting means.

[0076] In alternative embodiments, the fibers forming the composite lattice members may pass through two or more holes formed in a face sheet, rather than being interwoven, or in addition to being interwoven, with the face sheet. In addition, the face sheets may comprise more than one layer or ply of fiber fabric, and the fibers forming a lattice element may pass through one, multiple, or all layers making up said face sheet. The plies may be the same or they may be different materials, or they may be a stack of structural layers of monodirectional carbon fiber sheet laid in varying orientations, and may additionally include one or more woven fiber fabric layers. The fibers forming lattice members may interact with the face sheets in a variety of configurations. For example, a fiber tow making up lattice members may be partially interwoven with sections of one or more inferior layers in a multi-ply face sheet; and may abut without passing through one or more superior layers in the face sheet.

[0077] FIGS. 3A through 3G are representations of examples of process acts for a process 300 of forming a structure with a fiber reinforced composite lattice, in accordance with at least one embodiment. In particular, the process 300 forms a sandwich structure having two opposed face sheets (e.g., the face sheets 106) and a lattice of fiber-reinforced composite beams, but alternative embodiments of the process may be used to produce other structures.

[0078] In embodiments, the process starts with a pattern. The pattern includes bores for forming the beams, and outer faces for receiving the face sheets, if used. FIG. 3A shows a perspective view of an embodiment of a pattern 302 including a superior face 304 and an inferior face 318. The outer faces 304 and 318 correspond to at least parts of an inner surface of a hollow or sandwich structure of the eventual lattice structure to be formed on the pattern; for example, the inner surface of a predominantly hollow airfoil. One or more nonworking portions 306 may correspond to an open edge or port in the outer skin of the desired structure, such as a joining region or end; for example a region where sections of an airfoil may be assembled together. The
pattern may be initially formed inclusive of surface features 308, which may correspond to functional surface features in the desired structure, or may correspond to guides for, or to sections of bores through the material for forming internal structures.

[0079] The pattern may be formed of any removable material suitable for a lost-wax or investment casting technique, including but not limited to: wax blocks, plaster blocks, compressed granular blocks, dissolvable material such as rock salt, ceramic, frozen mercury, a non-wax polymer; or any other suitable removable material which is compatible with any or some combination of carving, machining, drilling and computer-numerically-controlled (CNC) machining. For example, in a specific embodiment, FERRIS® PURPLE FILE-A-WAX® carving and milling wax (made by Freeman Manufacturing and Supply Co.) is used, which has properties including heat resistance and CNC machining compatibility.

[0080] Embodiments of the pattern may be one piece, or may be several pieces or made of multiple patterns configured to be joined together. The pattern may be formed in one or more steps, and may, for example, be cast in a permanent or semi-permanent mold, cast in a temporary mold, or produced entirely by automated machining or by hand. The pattern also need not have a solid core, but in certain embodiments is preferably solid.

[0081] FIG. 3B shows a perspective view of a bored pattern 302 produced from a blank such as the blank pattern 302 of FIG. 3A, with bores 310 formed through the body of the pattern 302 in accordance with embodiments. The bores 310 may be formed by a variety of techniques, and may be formed after the pattern 302 is cast or at the same time. For example, in some embodiments of the process 300, a blank pattern 302 is formed in a mold and then a complex lattice network of bores is formed in the pattern by a series of drilling operations. The bores 310 connect between opposing faces 304 and 318 of the pattern 302 through openings 312 and 314 in, for example, the superior 304 and inferior 318 face of the pattern. The size of bores may be determined by choice of drill bit size, or if a CNC machine is used, bores sizes and shapes may be determined by the selection of a tool path. In embodiments, additional finishing, boring, or smoothing operations may be conducted on the pattern by machine or by hand after the bores 310 are formed.

[0082] FIG. 3C shows a cutaway side view of a first example of a fiber threading process 332 in accordance with the process 300 of forming a structure with fiber reinforced composite lattice
members. In the fiber threading process 332, at least one continuous fiber tow 324 is threaded from an opening 312 in the superior surface 304 and passes through a bore 310 to pass out of an opening 314 in the inferior surface 318. The fiber may be threaded sequentially through multiple bores 310, passing in and out of the pattern 302. The fiber may be threaded manually, for example, using a needle 326 to pull fiber from a source such as a spool 328 and through the bores; or the threading process may be automated. Following the threading process, one or more face sheets 320 and 330 may be added to the working surfaces 304 and 318 of the pattern, such that the face sheet or sheets come into contact with, or into proximity with, at least some of the fiber tows where they encounter the surface of the pattern. This process can result in a fiber pattern such as is shown in FIG. 2A.

[0083] In alternative embodiments, more than two face sheets may be used, or a single face sheet may wrap about the pattern forming both superior and inferior faces. A portion of a fiber tow 324 may be threaded through a portion of one or more of the face sheets 320 and 330. The fiber tow 324 may be a single tow that substantially fills the path formed by the bores 310; the fiber tow 324 may be wound multiply through the bores to substantially fill the bores; or multiple fiber tows may be wound in parallel. Additionally, a combination of the above configurations may be used, and particularly for embodiments having bores of multiple sizes. For example, where a sandwich-type lattice structure has faces that are not equidistant at all points, it may be desirable to adjust the thickness of the lattice members according to the distance between the faces. Thus, some shorter bores may be filled with a number of parallel fiber tows; and some longer bores may contain a larger number of parallel fiber tows. The number of fiber tows may vary according to a formula based on, for instance, any or all of the distance of separation of the surface sheets, the relative density of lattice members in that section, or design-specific concerns related to the desired use of the part being fabricated, such as loading points.

[0084] The face sheet or sheets may be formed of a variety of materials, for example, they may be any one of, or a combination of multiple of: carbon fiber woven sheets, fiberglass woven sheets, unidirectional sheets, fabric sheets, paper sheets, nonwoven fiber mats, metal sheets that may be flexible or may be rigid and preformed, or other comparable material layers. In at least one embodiment, the face sheet or sheets are predominantly carbon fiber, and may be stacked unidirectional sheets, cross-stacked unidirectional sheets, woven sheets, randomly matted sheets,
or a combination of any of the above; and any of said sheets may, in some embodiments, contain composite elements such as additional fibers, which may be for example: Kevlar™, Twaron™, metal fibers (such as, but not limited to, aluminum or steel), glass fibers, or high-strength plastic fibers. In a specific embodiment, fiber sheets may be one or more layers of a uni-directional carbon fiber sheet such as UT-C300™ (made by Gurit, Inc.); and more specifically, embodiments of a face sheet may be four or more layers of the carbon fiber sheet. Generally, face sheets will be assembled with the pattern as one or more dry layers absent any pre-impregnation or infusion with any matrix materials, in embodiments. Prior to matrix infusion, the face sheets are typically pliable and can be shaped according to an arbitrary surface topology of the removable pattern. The face sheets become stiff with the addition and curing of the matrix material in subsequent process steps. However, in some embodiments, face sheets may be either partially or fully pre-impregnated with a matrix material.

[0085] FIG. 3D shows a cutaway side view of a second embodiment of a fiber threading process 334, comparable to the process 332 shown in FIG. 3D, in accordance with embodiments of a composite lattice manufacturing process. In the threading process 334, the one or more face sheets 320 and 330 may be added about a pattern 304 first. Then the fiber tow or tows 324 pass through the openings 312 and 314 in the bores 310 in the threading process. During the threading process, a subset of the fiber tow or tows may be threaded through the one or more face sheets 320 and 330, such as was described with FIGS. 2B and 2C. In embodiments of the process 334, the fiber tow or tows are threaded through the face sheet or sheets 320 and 330 through either or both of through holes punched in the face sheets and through voids formed in the face sheets by the weave of the sheets. Where a fiber tow is threaded through a face sheet, if the face sheet is formed of one or more layers of a fabric (for example, woven carbon fibers), then the fiber tow may be directly interwoven with a portion of the face sheet, or through the entire face sheet. If the face sheet is a contiguous material, the fiber tow may be passed through a set of holes prepared in the face sheet. Furthermore, in accordance with some embodiments, some fiber tows may run in parallel for certain lattice members and diverge or merge at a surface 304 or 318 with other fiber tows.

[0086] In some embodiments, a fiber threading process includes elements of both of the above-described threading processes 332 and 334. A portion of the fibers may be threaded through a
series of bores in the pattern, as in process 332 (FIG. 3C), prior to the addition of any face sheets. Then, following the addition of face sheets about the pattern, additional fiber tows may be threaded through the bores and also the face sheets, as in process 334 (FIG. 3D).

[0087] In some embodiments, the openings 312 and 314 of individual bores 310 may be proximate to, or overlapping with, other individual bores 310 such that a complex path for a fiber tow is formed, whereby fibers passing out of one bore may pass over part of an superior or inferior surface 304 or 318 and pass down a different bore. In some embodiments, three or four (or more, for example, five in a square triangular truss arrangement with a center beam) bores may emerge from the pattern at a shared opening, or with openings proximate to one another at the surface. In this example, the bores are situated predominantly in a square-pyramidal configuration, however, a wide variety of configurations are attainable with these methods.

[0088] In at least some embodiments, individual fiber tows generally connect adjacent or proximal lattice members; however, in truss configurations where there exist multiple adjacent lattice members for each lattice member, the individual fiber tows generally connect lattice members in a pattern designed to optimize balance, symmetry, and the resilience of the lattice joints. For example, in embodiments having a pyramidal configuration, at least some fiber tows from each lattice member will turn and join a directly adjacent, abutting lattice member. Where more than two lattice members join at a single peak, fibers from one lattice member may diverge and join with fibers forming two or more other lattice members. Additionally, fiber tows may be periodically tied to the face sheets, or may be tied at the ends, to create additional mechanical stiffness.

[0089] FIG. 3E shows a cutaway side view of resin-transfer infusion process 336, in accordance with at least one embodiment. A membrane layer 346 is applied about an assembly of the pattern 302, face sheets 320 and 330, and threaded fibers 324. Following emplacement of the membrane layer 346, a fluid (uncured) matrix material 338 is fed into the enclosed pattern, and the air is removed 340, such that the matrix material fully inundates and penetrates the fiber tows 324 in the bores 310 as well as the face sheets 320 and 330. The lattice members and face sheet may be attached to one another at least in part by coextensive permeation with the matrix material, and may have other attachment means applied in addition to the matrix.
[0090] In at least one embodiment, the resin transfer process may be a vacuum-assisted resin transfer molding (VARTM) process. In this process, a vacuum is generated within the membrane layer, and the air pressure difference draws the matrix material to fill voids throughout the dry fibers. In some embodiments, the vacuum is generated within the membrane before the matrix material is fed in order to minimize the possibility of bubbles occurring within the composite; or the vacuum may be generated concurrently with the addition of matrix material. The vacuum process may be conducted at one or at multiple points at an end of the membrane layer 346 distal from the point or points where matrix material 338 is fed, such that the vacuum process causes matrix material to seep from the inlet ports to the outlet ports. The seal of the membrane layer may be enhanced or secured by means of tape or additional material, such as a secondary membrane, applied externally to the membrane layer. The precise number, placement, and means of reinforcement of the inlet and outlet ports of the membrane will vary depending on the geometry of the part, the viscosity of the matrix material, and the specific infusion process selected.

[0091] In alternative embodiments having pre-impregnated matrix material in one or more of the face sheets, the resin-transfer infusion process 336 may include a pre-treatment step for softening the pre-impregnated matrix material or causing it to flow fully or partially into the adjacent lattice members. The pre-treatment may include softening by means of applying a chemical solvent or applying heat, or any other suitable means of softening a matrix material.

[0092] In some embodiments of a vacuum-assisted resin transfer infusion process, the flow of matrix material is enhanced by the provision of a distribution medium or flow medium. Generally, a distribution medium or flow medium is a course fabric through which a matrix material can quickly spread; but for purposes of this disclosure, distribution medium means any material having similar properties. In at least one embodiment, a peel-ply or release-fabric layer is applied directly to the fiber sheets that will form the part, the distribution medium is positioned outside the peel-ply layer, and the membrane is placed about the entire assembly. The distribution medium provides channels for the fluid matrix material to spread across a broad surface area of the peel-ply layer. The peel-ply layer is porous, or alternatively may be perforated, such that matrix material can pass through the peel-ply layer and into the part over a broad surface area of the part, which enables more thorough and more rapid penetration of the
part by the matrix material. The peel ply layer can be removed from the final part, which also removes the distribution medium. In at least one specific embodiment, the distribution medium is KNITFLOW 40™ (made by Gunt, Inc.).

[0093] The matrix material in the reinforced fiber/polymer composite may be formed any substance that may be substantially interfused with a fiber network or a fiber tow (or bundle of fiber tows) to lend macro-scale structure or rigidity to the fibers, in accordance with embodiments. As an example, a matrix may be formed from a low viscosity thermoset polymer resin. As specific examples, the matrix material may be one or more of: Epoxy, Vinylester, Polyester, or shape-memory polymer (SMP) such as acrylate-based resins. In certain embodiments, the matrix material may be an epoxy such as, for example, PRIME™ 20LV (made by Gurit Inc.). Alternative embodiments may be formed of thermoplastic polymer resin. The matrix material may be configured to harden by chemical process, heat-induced curing, ultraviolet light or other energy cured process, a combination of one or more of these processes, or other means. For example, in certain embodiments the matrix may be mixed with a hardening agent, such as PRIME™ HARDENER (made by Gurit, Inc.), which provides for an approximate gel time of 30 minutes for the mixture; and may be subsequently hardened by a heat-curing process.

[0094] In some embodiments, the resin is allowed to partially cure at room temperature within the membrane layer; and in some specific embodiments, the resin is allowed to cure at room temperature for approximately 12 hours.

[0095] FIG. 3F shows a cutaway side view of an example of a curing process 342 using heat 344 from heating elements 348, such as in an oven, to harden the matrix material. In various embodiments, the matrix may be subjected to one or more procedures for curing. For example, the matrix material may contain a mixture of a matrix material and a chemical curing agent (or hardening agent), such that the matrix material and chemical curing agent are mixed prior to infusion, infused into the pattern as described above, and then allowed to cure at or near room temperature for an initial cure. Following initial curing, the part may undergo a second curing process, or a hardening cure, at an elevated temperature. In at least one embodiment, the resin is cured within the membrane layer, or prior to the removal of the membrane layer; but in alternative embodiments, the membrane layer may be removed prior to a curing process. In at
least one embodiment, the matrix material may be an epoxy such as epoxy PRIME™ 20LV with a hardening agent such as PRIME™ 20 Fast Hardener (both as supplied by Gurit, Inc.). In a specific embodiment, the hardening cure may be at 65 degrees Celsius; however, the temperature of the hardening cure may vary depending on the particular matrix material and hardening agent selected; or depending on the temperature tolerance of the removable pattern. For example, the hardening cure may be conducted at or above 65 degrees Celsius, or more than 50 degrees Celsius, or another temperature depending on the particular matrix material and pattern material selected. In various embodiments, the time selected for the first and second curing processes may vary. For example, in one specific embodiment, the hardening cure process may include elevating the ambient temperature to approximately 65 degrees Celsius for approximately 7 hours. The hardening cure may include high temperature, high pressure, or (as shown) heat transfer 344 from one or more heating elements 348.

[0096] FIG. 3G shows a cutaway side view of an example of a pattern-removal process 350 of the pattern 304 being removed from the cured composite structure, in accordance with at least one embodiment. In this example, the pattern material is removed by melting 352 at a high temperature. The pattern material may be removed mechanically, chemically by addition of a solvent, may be melted, or some combination of the above. In some embodiments, all of the pattern material may be removed; or alternatively, a portion of the pattern material may be left behind. Following removal of the pattern material, a structure remains formed of face sheets 320 and 330 and a complex lattice of composite fiber tows 324 in a cured matrix.

[0097] The bore size, spacing, and positions may vary in embodiments according to the structure desired. The bores may be drilled at almost any angle, which permits the creation of lattice structures at levels of complexity that have heretofore been impossible to produce using conventional means. In an alternative embodiment of the process 300, a mold has features supporting removable beams such that the mold and beams may be used simultaneously to form a portion or all of the bores about the removable beams.

[0098] In embodiments of the method of manufacturing a lattice structure such as the process 300 shown in FIGS. 3A-3G, various process steps may be performed in different orders. For example, fiber winding processes 332 and 334 may be performed in either order, singly or together, in accordance with embodiments. In some embodiments, a fiber tow 324 may be
wound through the pattern 302 prior to the addition of any face sheets; and then one or more face sheets 320 may be added thereto. In some other embodiments, one or more intermediate face sheets 320 may be added, a fiber tow 324 wound through portions of the face sheet or sheets, and then one or more additional face sheets added on top of the intermediate face sheet or sheets and fiber tow. Other embodiments may include aspects of both: a fiber tow may be wound through the pattern prior to the addition of any face sheets, subsequently interwoven with one or more intermediate face sheets, and then one or more additional face sheets may be added. Alternative embodiments may be assembled using a variety of comparable fiber tow winding and face sheet layering orders.

[00099] Embodiments of these methods may be applied in part or in whole to form a broad array of complex lattice structures, with or without an outer skin or skins. In accordance with several embodiments, these methods are ideally suited to producing hollow or sandwich-type structures with two opposed outer surfaces and a supporting lattice within. An airfoil is one example of a structure for which these techniques may be well-suited. Other structures which may be beneficially made by these methods include: wind-turbine blade members; sections of concentric tubular structural members such as an aircraft body; prefabricated sections for building construction; lightweight structural elements for sports equipment such as bicycle frames, surfboards, racing vessels, and vehicles, or insulating sections of vehicles or buildings; among others.

[00100] Embodiments of the methods herein described are also suited to produce lattice structures having a wide range of arbitrary geometries, depending on the specific size, shape, strength, weight, and other desired characteristics of the desired structure. Therefore, while specific lattice structures may be shown or described herein, embodiments may encompass a wide variety of structures not explicitly described. The lattice members may or may not be configured as straight beams, and may or may not cross or join at vertices. At least some embodiments are directed to a complex three-dimensional lattice separating at least two separated face sheets in a sandwich configuration. At least some other embodiments include structures having a continuous face sheet. Such embodiments may include, for example, cylindrical, wheel-shaped, or tubular structures; or structures having a single face sheet with a prominent bend, such as an airfoil or turbine blade.
Other variations are within the spirit of the present disclosure. Thus, while the disclosed techniques are susceptible to various modifications and alternative constructions, certain illustrated embodiments thereof are shown in the drawings and have been described above in detail. It should be understood, however, that there is no intention to limit the invention to the specific form or forms disclosed, but on the contrary, the intention is to cover all modifications, alternative constructions and equivalents falling within the spirit and scope of the invention, as defined in the appended claims.

The use of the terms "a" and "an" and "the" and similar referents in the context of describing the disclosed embodiments (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. The terms "comprising," "having," "including," and "containing" are to be construed as open-ended terms (i.e., meaning "including, but not limited to," unless otherwise noted. The term "connected" is to be construed as partly or wholly contained within, attached to, or joined together, even if there is something intervening.

Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., "such as") provided herein, is intended merely to better illuminate embodiments of the invention and does not pose a limitation on the scope of the invention unless otherwise claimed. No language in the specification should be construed as indicating any non_claimed element as essential to the practice of the invention.

Preferred embodiments of this disclosure are described herein, including the best mode known to the inventors for carrying out the invention. Variations of those preferred embodiments may become apparent to those of ordinary skill in the art upon reading the foregoing description. The inventors expect skilled artisans to employ such variations as appropriate and the inventors intend for the invention to be practiced otherwise than as specifically described herein. Accordingly, this invention includes all modifications and equivalents of the subject matter recited in the claims appended hereto as permitted by applicable
law. Moreover, any combination of the above-described elements in all possible variations thereof is encompassed by the invention unless otherwise indicated herein or otherwise clearly contradicted by context.

[00104] All references, including publications, patent applications and patents, cited herein are hereby incorporated by reference to the same extent as if each reference were individually and specifically indicated to be incorporated by reference and were set forth in its entirety herein.
WHAT IS CLAIMED IS:

1. A composite lattice structure, comprising:
   a superior face sheet;
   an inferior face sheet;
   at least one fiber tow arranged in a plurality of lattice members, the lattice
   members separating the superior and inferior face sheets and connecting with each of the face
   sheets at a plurality of points; and
   a polymer matrix interfused throughout the lattice members and the superior and
   inferior face sheets.

2. The composite lattice of claim 1 wherein
   the at least one fiber tow passes through each of the superior and inferior face
   sheets at a plurality of points, and abuts exterior surfaces of each of the superior and inferior face
   sheets.

3. The composite lattice of claim 2 wherein
   the at least one fiber tow is contiguous between at least two adjacent members of
   the plurality of lattice members.

4. The composite lattice of claim 3 wherein
   the at least one fiber tow is multiply wound among the plurality of lattice
   members, such that each lattice member comprises a bundle of parallel fiber tows, and such that
   each lattice member is connected with one or more adjacent lattice members and with the
   superior and inferior face sheets by at least one fiber tow.

5. The composite lattice of claim 1 wherein
   the superior face sheet and inferior face sheet are contiguous with each other
   about a bend.
6. A composite lattice structure, comprising:
   a face sheet; and
   one or more lattice members, comprising:
      at least one fiber tow; wherein
      the at least one fiber tow is configured in a lattice shape and into
      contact with the face sheet at a plurality of points on a surface of the face
      sheet; and
      the at least one fiber tow and the face sheet are fixed in a
      contiguous matrix with an interfused matrix material.

7. The composite lattice of claim 6 wherein the at least one fiber tow
   comprises a plurality of carbon fiber filaments.

8. The composite lattice of claim 6 wherein the one or more lattice members
   further comprise a plurality of parallel fiber tows.

9. The composite lattice of claim 6 wherein the matrix material is a low-
   viscosity thermoset polymer resin.

10. The composite lattice of claim 6 wherein at least a portion of the at least
    one fiber tow passes through the face sheet from an inner surface to an outer surface of the face
    sheet, runs along the outer surface of the face sheet, and passes back through the face sheet.

11. The composite lattice of claim 6 wherein at least a portion of the at least
    one fiber tow abuts an inner surface of the face sheet, and runs along the inner surface of the face
    sheet.

12. The composite lattice of claim 6 wherein at least a first portion of the at
    least one fiber tow passes through the face sheet from an inner surface to an outer surface of the
    face sheet, runs along the outer surface of the face sheet, and passes back through the face sheet;
    and
    at least a second portion of the at least one fiber tow abuts an inner surface of the
    face sheet, and runs along the inner surface of the face sheet.
13. The composite lattice of claim 6 wherein the face sheet comprises a woven fiber sheet, and the at least one fiber tow is interwoven with at least a portion of the face sheet.

14. The composite lattice of claim 6 wherein the face sheet comprises a unidirectional carbon fiber sheet.

15. The composite lattice of claim 6 wherein the face sheet comprises a plurality of sheets arranged in a stack.

16. The composite lattice of claim 15 wherein one or more of the plurality of sheets comprises a unidirectional carbon fiber sheet; and the stack is arranged in a plurality of ply orientations.

17. The composite lattice of claim 15 wherein at least a portion of the at least one fiber tow passes through a subset of the plurality of sheets making up the face sheet, runs along an intermediate surface between at least two of the plurality of sheets, and passes back through the subset of the plurality of sheets.

18. The composite lattice of claim 6 wherein the face sheet is arranged with a bend such that the face sheet partially encloses a volume, the face sheet having at least two opposed interior faces; and the one or more lattice members comprises a plurality of lattice members, arranged such that that plurality of lattice members connects with and separates the opposed interior faces of the face sheet.
19. A composite lattice structure, comprising:

a first face sheet;

a second face sheet; and

a lattice between the first and second face sheets;

the lattice and the first and second face sheets formed by a method comprising:

applying the first face sheet to an exterior surface of a first portion of a

removable pattern having an exterior surface and one or more bores passing through the

pattern;

threading a fiber tow through at least a portion of the first face sheet and

through at least two of the one or more bores;

interfusing the face sheet and the fiber tow with a resin;

curing the resin; and

removing the pattern from the cured resin material, so as to form the

lattice from the cured matrix and the fiber tow and the lattice structure from the cured

lattice and face sheet.

20. The composite lattice structure of claim 19, wherein the method further

comprises:

applying the second face sheet to a second portion of the exterior surface of the

pattern, such that the first and second face sheets are arranged at opposed portions of the exterior

surface of the pattern; and

threading the fiber tow through at least a portion of the second face sheet.

21. The composite lattice structure of claim 19, wherein removing the pattern

from the cured resin material comprises at least one of: melting, dissolving, or mechanical

extraction.
A. CLASSIFICATION OF SUBJECT MATTER

IPC: B32B3/12 (2006.01); B32B7/08 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC.

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

B32B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database consulted during the international search (name of database and, where practicable, search terms used)

WPPIPODOC, Depatisnet

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
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<td>US 2008145592 A1 (JOHNSON DAVID W) 19 June 2008 (19.06.2008)</td>
<td>1 - 8, 10 - 18</td>
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<td>EP 1538406 B1 (HEXCEL COMPOSITES LIMITED) 18 November 2009 (18.11.2009)</td>
<td>1 - 8, 10 - 18</td>
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<td>[0088], [0095] - [0099], claims 1 - 20, 28, 31 - 37.</td>
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<td>US 2009193961 A1 (JENSEN DAVID W, DAVIS KEITH, GUNNELL BOYD KIMBER, LARSON GREGORY JAMES, BLUNCK DAVID L, EVANS TYLER, HANSEN STEVE, ROGERS SARITA, BOYCE JENNIFER, PATE EVE, AYERS III JAMES T) 06 August 2009</td>
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<td>[0055], [0056], [0096] - [0098], claims 1, 18 - 20.</td>
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<td>DE 0237634 A1 (WIRTZ, MARKUS M, WIRTZ, CHRISTIAN) 12 August 2004 (12.08.2004)</td>
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<td>[0007], [0011], [0020] - [0023]. claims 1, 10, 13 - 15; figures 1, 2.</td>
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[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search
24 June 2016 (24.06.2016)

Date of mailing of the international search report
30 June 2016 (30.06.2016)

Name and mailing address of the ISA/AT

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Form PCT/IS A/210 (second sheet) (July 2009)
# INTERNATIONAL SEARCH REPORT

## C. (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
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| A        | US 4086378 A (KAM, CLIFFORD Y, FREEMAN, VERNON L., PENTON, ALLEN P)  
25 April 1978 (25.04.1978)  
Figures, column 5. lines 36 - 57. | 1 - 8, 10 - 18 |

Form PCT/ISA/210 (continuation of second sheet) (July 2009)
**INTERNATIONAL SEARCH REPORT**

**Box No. II**  
Observations where certain claims were found searchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:  
   because they relate to subject matter not required to be searched by this Authority, namely:

2. ☑ Claims Nos.: 9  
   because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

   The term "low-viscosity thermosei polymer resin" is not clearly defined and therefore not acceptable. There is neither given a range for the viscosity nor for the temperature.

3. ☐ Claims Nos.:  
   because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

**Box No. III**  
Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This international Searching Authority found multiple inventions in this international application, as follows:

Invention I (claims 1 - 5, a composite lattice structure comprising a superior face sheet and an inferior face sheet, fiber tow and lattice members), invention II (claims 6 - 8, 10 - 18, a composite lattice structure comprising only a face sheet and one or more lattice members, fiber tow), invention III (claims 19 - 21, product by process claims covering a first face sheet, a second face sheet, lattice and fiber tow). Invention I to III have no novel or inventive item in common.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☑ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:  

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:  

**Remark on Protest**

1. ☑ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

2. ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

3. ☑ No protest accompanied the payment of additional search fees.
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