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- (54) Benævnelse: **Vævet 3D-fiberforstærket struktur og fremgangsmåde til fremstilling deraf**
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EP-A1- 3 095 901
US-A1- 2012 144 984
US-A1- 2013 216 770

DESCRIPTION

Description

BACKGROUND

1. Field of the disclosure

[0001] The application relates to load bearing structures and methods of making same. In particular, the load bearing structures are made from three-dimensional (3D) woven fabrics.

2. Related Art

[0002] In load bearing structures (automobiles, airplanes, bridges, etc.), oftentimes the load cases and the geometric constraints create a load path that subjects the material to significant shear stresses. For example, an aircraft fuselage will experience torsional flight loads that result in shear stresses in the fuselage skin. As such, it is an important feature for the material used in such structures to have adequate shear stiffness and strength.

[0003] A common structure for improving shear stiffness and strength are laminated composites constructed from unidirectional (uniaxial) or bi-axially woven layers. These layers, which by themselves have weak shear properties, are placed at various angles to create laminates that have shear properties that are dramatically improved. Most commonly, lamina are placed at 0°, 45°, or 90° angles in different proportions to meet structural design requirements, but other angles are also possible.

[0004] Figure 1 illustrates a 3D woven composite that is woven bi-axially. That is, tows and fibers are in warp (0°) and weft directions (90°). Bi-axially woven composites in three dimensions have multiple layers as shown in FIG. 1A. Lack of bias fibers at other angles combined with inherently weak shear properties of the tows leads to weak macroscale shear stiffness and strength that can manifest itself in pure shear loading or when loaded in 45°. The in-plane shear stiffness and strength is a weakness for certain applications. FIG. 1B shows a comparison of tensile strength (stress-strain) for a 3D woven composite with intermediate modulus carbon fiber reinforcement when loaded in the 0° (warp), 45° (bias), and 90° (weft) directions. Where COV is the coefficient of variation and IM7 is intermediate modulus carbon fiber reinforcement. A typical value for in-plane shear modulus (G_{12}) is about 5.5 GPa.

[0005] Some researchers have attempted to solve this in-plane weakness of shear strength and stiffness of 3D bi-axially woven composites by weaving in bias tows at angles other than 0° and 90°, which can significantly increase the complexity of the weaving system and process. See, for example, Labanieh et al, "Conception and characterization of multiaxis 3d woven preform," 2013, TexComp Conference, Leuven, Belgium.

[0006] Documents EP3095901A1, US2013/216770A1 and US 2012/144984A1 disclose 3D woven structures comprising a plurality of first yarns in a particular direction and a plurality of second yarns in another direction interwoven with the plurality of first yarns, wherein at least some second yarns include at least one bias reinforcement yarn.

SUMMARY OF THE DISCLOSURE

[0007] The disclosure is directed to a three-dimensional (3D) woven structure and method of making the structure, as defined in the independent claims. The structure includes a plurality of first yarns in a particular direction and a plurality of second yarns in another direction interwoven with the plurality of first yarns. At least some second yarns include at least one bias reinforcement yarn.

[0008] At least some second yarns are a laminated structure having at least three layers that include at least one second yarn bias layer, each of the at least one second yarn bias layers having fibers at an angle of other than 0° or 90° with respect to fibers in second yarn layers that are not second yarn bias layers.

[0009] The laminated structure includes a second yarn first layer of fibers in a first direction and a second yarn second layer of fibers in a second direction. The at least one second yarn bias layer of fibers is disposed between the second yarn first and second layers and fibers in a second yarn first bias layer are at a first angle with respect to the first direction.

[0010] The laminated structure can also comprise a second yarn second bias layer of fibers disposed between the second yarn first and second layers with n fibers in the second yarn second bias layer at a second angle with respect to the first direction.

[0011] The structure can also include at least some first yarns that are a laminated structure having at least three layers that include at least one first yarn bias layer, each of the at least one first yarn bias layers having fibers at an angle of other than 0° or 90° with respect to fibers in first yarn layers that are not first yarn bias layers. The laminated structure can also include a first yarn first layer of fibers in a third direction and a first yarn second layer of fibers in a fourth direction. The at least one first yarn bias layer of fibers is disposed between the first yarn first and second layers and fibers in a first yarn first bias layer are at another first angle with respect to the first direction.

[0012] In another embodiment at least some of the second yarns are braided tows and can

include at least some of the first yarns being braided tows.

[0013] In yet another embodiment at least some of the second yarns are multiaxial tapes and can include at least some of the first yarns being multiaxial tapes.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The accompanying drawings, which are included to provide a further understanding of the invention, are incorporated in and constitute a part of this specification. The drawings presented herein illustrate different embodiments of the invention and together with the description serve to explain the principles of the invention. In the drawings:

Figure 1A illustrates a ply-to-ply 3D weave of related art.

Figure 1B illustrates a typical tensile stress-strain relationship in a biaxially 3D woven composite with no bias fiber reinforcement.

Figure 2 illustrates a structure of a multi-directional, multi-layer tow.

Figure 3 is a graphical comparison of the elastic constants of three sample structures.

Figure 4 is a photograph of a 3D woven preform constructed with braided yarns containing off-axis fiber reinforcement.

Figures 5 and 6 are photographs of the composite formed from the preform of Figure 4.

Figures 7A-7B illustrate examples of yarns that contain off-axis orientation of fibers.

Figure 8 illustrates a summary of tensile modulus and strength results for a sample comprising a multiaxial tow.

Figure 9 illustrates the in-plane tensile stress-strain performance for a 3D woven composite comprised of multiaxial fiber reinforcement.

Figure 10 illustrates a comparison between the in-plane 45° tensile responses for 3D woven composites comprised of multiaxial reinforcement and uniaxial reinforcement.

DETAILED DESCRIPTION

[0015] Terms "comprising" and "comprises" in this disclosure can mean "including" and "includes" or can have the meaning commonly given to the term "comprising" or "comprises" in U.S. Patent Law. Terms "consisting essentially of" or "consists essentially of" if used in the claims have the meaning ascribed to them in U.S. Patent Law. Other aspects of the invention

are described in or are obvious from (and within the ambit of the invention) the following disclosure.

[0016] The terms "threads", "fibers", and "yarns" are used interchangeably in the following description. "Threads", "fibers", and "yarns" as used herein can refer to monofilaments, multifilament yarns, twisted yarns, textured yarns, coated yarns, bicomponent yarns, as well as yarns made from stretch broken fibers of any materials known to those of ordinary skill in the art. "Tows" are comprised of multiple fibers and are referred to herein interchangeably as, and include the structures of, tows, multifilament tows, multifiber tows, and braided tows. Fibers can be made of carbon, nylon, rayon, fiberglass, cotton, ceramic, aramid, polyester, metal, polyethylene glass, and/or other materials that exhibit desired physical, thermal, chemical or other properties.

[0017] The term "folded" is broadly used herein to mean "forming", which includes unfolding, bending, and other such terms for manipulating the shape of the woven fabric. The term "bias" is used interchangeably with "off-axis" and means at an angle other than 0° and 90°, with respect to a stated reference.

[0018] For a better understanding of the invention, its advantages and objects attained by its uses, reference is made to the accompanying descriptive matter in which non-limiting embodiments of the invention are illustrated in the accompanying drawings and in which corresponding components are identified by the same reference numerals.

[0019] This invention disclosure describes a product and method of making the product to improve in-plane shear properties for woven structures by using tows that have improved shear properties that can be woven using existing 3D weaving equipment and processes. While, as discussed above, bi-axially woven fabrics can employ laminated bias layers to improve in-plane shear properties, the present disclosure provides improvement in in-plane shear properties by weaving tows that are themselves constructed to have off-axis (bias) reinforcement. That is, the tows contain fiber reinforcement in various directions with respect to the tow axial direction. The tows are multilayered, such as laminated tapes, multiaxial tapes. The tows disclosed herein may be used for some or all of the tows in any or all directions of the fabric. For example, the tows can be used for some or all the tows in either or both the warp and weft directions of the woven fabric. In another example, the tows can be used in some or all of the tows in either the warp or weft direction while uniaxial tows are used in the remaining weft or warp direction. It is contemplated the tows could also be used in a bias layer of a laminated fabric.

[0020] Figure 2 illustrates a sectional view of an embodiment of a multiaxial, multilayer tow 200 having four layers. Fibers in outside layers 202 are oriented in a particular direction, which for purposes of reference will be referred to as 0°. Fibers in a first intermediate layer 204 are oriented at +45° and fibers in a second intermediate layer 206 are oriented at -45°, with respect to the fibers in outside layer 202. While the tows are shown with fibers at +/-45° in the intermediate layers, other angles including +/-30° or +/-60° might be preferred due to other

considerations. Also, the angles shown and discussed for the bias uniaxial layers are for illustration only and can be angled with respect to one another as design necessities require. It should be noted that more or fewer layers can be used depending on design necessities.

[0021] Each of the layers 202, 204, 206 can have multiple layers of fibers in the same orientation to have a desired thickness D. It should be noted that the thickness of each layer may be the same or different from other layers as necessitated by design requirements. An exemplary thickness of each layer is in the range of 0.01" (0.025 cm) to 0.075" (0.190 cm) with 0.0625" (0.159 cm) being a nominal thickness.

[0022] The tow 200 may be fabricated in a desired tape width W or as a sheet and slit into tapes of the desired width W. Multilayer and multi-directional non-crimp fabrics (NCF) can be treated with thermoplastic veils on either or both of the outside surfaces of the first and last layers 202 then slit to tape width W for Automated Tape Layup (ATL) or in this instance 3D weaving applications.

[0023] An exemplary tape width W of the tow is in the range of 0.02" (0.051 cm) to 0.75" (1.905 cm) with 0.25" (0.635 cm) being a nominal width. Regardless, the multi-directional, multi-layer tows constructed as described herein are used to fabricate a 3D bi-axially woven preform of desired configuration.

[0024] 3D bi-axially woven preforms can be woven with multiple bifurcations within the preform to result in a preform with various cross-sectional shapes including Pi, T, H, O, I and other shapes known to those of ordinary skill in addition to a 3D woven sheet with multiple layers. A 3D bi-axially woven preform can subsequently be impregnated with resin to form a composite structure.

[0025] The tows can be used in any known weaving technique including but not limited to Jacquard or dobby weaving with shuttle and rapier looms. Figure 2 illustrates a tow that is a laminate structure. However, additional binder fibers, not shown, may be added to the laminate structure as known to those of ordinary skill.

[0026] Such methods of manufacturing create thin non-crimp fabric (NCF) and/or resin treated material similar to Hi-Tape[®] that can be used directly in laminated composites or in automated tape layup (ATL) manufacturing.

[0027] As illustrated, tow 200 is a laminate having a substantially rectangular cross-sectional shape, which may be referred to as a laminated tape.

[0028] As discussed above, yarns have a laminated tape structure with one or more bias layers. That is, the bias layers are layers produced from fibers that are at an angle of other than 0 degrees or 90 degrees to the layers that are not bias layers. Although in FIG. 2 the outside layers are shown with fibers in the same direction, this is not a restriction. The angular direction of fibers in a bias layer can be the same or different from the angular direction of

fibers in other bias layers. Moreover, fibers in bias layers may be at 0 degrees or 90 degrees with respect to one another.

[0029] FIG. 8 shows a summary of experimental test results of tensile modulus and strength for a sample comprising a 3D fiber reinforced multiaxial tow when loaded in the 0° (warp), 45° (bias), and 90° (weft) directions.

[0030] The test was performed with the following conditions:

Tow type: Toray® T300 carbon fiber

Tow size(s): 1K - number of filaments per tow

Number of tows: 24 - number of tows used to weave the braided reinforcement.

Number of straight vs. angled 8 vs 16 tows: 8 tows are used in the axial direction. The remaining 16 tows are interlaced via a braiding process.

Intended braid angle: 45° (actual ~55°)

Final panel FV (fiber volume): -55%

[0031] It is contemplated that flattened braided tows may simulate multiaxial tows. Homogenized tow properties are based on the lamina 58% fiber volume, which makes total composite fiber volume 46%. G_{12} of the composite improves using braided tows (~17 GPa versus expected 4-5GPa).

[0032] FIG. 9 shows experimental results for in-plane tensile stress-strain performance for a 3D woven composite comprised of multiaxial braided tow reinforcement. Note the modulus (slope of the lines) of the bias, weft, and warp directions are very similar. This is a result of the incorporation of off-axis fiber reinforcement within the braided tows used during the 3D weaving process.

[0033] As can be seen, the modulus of FIG. 9 is similar with that of the multiaxial reinforcement of FIG. 8, whereas the image shown in related art FIG. 1B has very different responses from the composite when loaded in warp, weft, and bias (45°) directions.

[0034] Figure 10 shows a comparison between the in-plane 45° tensile responses for 3D woven composites comprised of multiaxial reinforcement and uniaxial reinforcement. The modulus associated with multiaxial reinforcement is substantially greater than that of uniaxial reinforcement.

[0035] Figure 4 is a photograph of a 3D woven preform 400 having braided yarns with an off-axis fiber rather than a flat tape. The off-axis fiber in the braided yarns woven in both the warp

and weft directions is the middle section 410 across the width. The top and bottom thirds 420 and 430 are woven with multi-directional braided yarns in the warp direction and standard uniaxial tows in the weft direction. This illustrates that hybrid preforms can be woven mixing standard and multiaxial tows to meet performance requirements. The braided yarn is a multi-directional tow rather than just off-axis fiber. It provides on- and off-axis reinforcement. The braided tow may have on-axis fibers in addition to off-axis fibers.

[0036] Figures 5 and 6 are photographs of the composite of the 3D woven fabric of Figure 4.

[0037] Three configurations of 3D woven composite structure using multi-directional, multi-layer tows of the present invention were compared using micromechanics homogenization capabilities embedded in Albany Engineered Composites' (AEC) 3D Composite Studio™ software:

Example 1:

[0038] A 3D woven composite manufactured with uniaxial tape with fiber content and dimensions similar to Hexcel Hi-Tape®. The tow packing factor is 60% resulting in an overall fiber volume of 50%. The fiber content in 0°, ±45°, and 90° directions in the composite are 50%, 0%, and 50%, respectively. A low-angle interlock fiber architecture was chosen to calculate composite elastic properties.

Example 2:

[0039] A 3D woven composite manufactured with multidirectional tape with fiber content and dimensions similar to Hexcel Hi-Tape® although their construction is more similar to C-Ply™ material. The tow packing factor is 60% resulting in an overall fiber volume of 50%. The fiber content in 0°, ±45° and 90° directions in the composite are 25%, 50%, and 25%, respectively. Each tow has a 50%, 50%, 0% fiber distribution. The same low-angle interlock fiber architecture from example 1 was chosen to calculate composite elastic properties and quantify the changes in mechanical properties.

Example 3:

[0040] Standard quasi-isotropic laminate construction with 50% fiber volume and (25%, 50%, 25%) fiber distribution. This was chosen as a baseline to illustrate the weaker shear properties of standard 3D woven composites (Example 1) and quantify improvements from this invention (Example 2).

[0041] The results comparing the three examples are summarized in Table 1 and Figure 3. Example 2 shows a 3.83X improvement in shear stiffness (G_{xy}) over Example 1 and is within 20% of the shear stiffness of the quasi-isotropic laminate. While axial moduli (E_{xx} and E_{yy}) were significantly reduced by about 33% in Example 2 compared to Example 1, they are within 4% of Example 3.

Table 1 - Comparison of composite properties and elastic constants of the examples. Percent fiber in 0° , $\pm 45^\circ$, and 90° is shown for each configuration. Values for E_{xx} , E_{yy} , and G_{xy} are in GPa

	<i>Example 1</i>	<i>Example 2</i>	<i>Example 3</i>
	3D Woven with Uniaxial Tape (50%, 0%, 50%)	3D Woven with Multidirectional Tape (25%, 50%, 25%)	2D Quasi-Isotropic Laminate (25%, 50%, 25%)
E_{xx}	78.8	52.9	53.1
E_{yy}	75.1	51.2	53.1
G_{xy}	4.2	16.1	20.1
N_{uxy}	0.037	0.209	0.322
FV	50%	50%	50%

[0042] From these results, it can be concluded that by using a multidirectional reinforcement as described in this disclosure, it is possible to manufacture a 3D woven composite with in-plane stiffness properties very similar to the industry standard quasi-isotropic laminate with additional benefits of improved through thickness stiffness and strength, damage tolerance, and energy absorption characteristics.

[0043] The 3D multilayer, multidirectional fabrics can be impregnated with a matrix material. The matrix material includes epoxy, bismaleimide, polyester, vinyl-ester, ceramic, carbon, and other such materials.

[0044] Other embodiments are within the scope of the following claims

REFERENCES CITED IN THE DESCRIPTION

Cited references

This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all liability in this regard.

Patent documents cited in the description

- [EP3095901A1](#) [0006]
- [US2013216770A1](#) [0006]
- [US2012144984A1](#) [0006]

Non-patent literature cited in the description

- **LABANIEH et al.** Conception and characterization of multiaxis 3d woven preformTexComp Conference, Leuven, Belgium, 2013, [\[0005\]](#)

P a t e n t k r a v

1. Tredimensionel (3D) vævet struktur, der omfatter:

en flerhed af første garner i en bestemt retning;

5 en flerhed af andre garner i en anden retning og sammenvævet med flerheden af første garner,

kendetegnet ved, at mindst nogle andre garner er en lamineret struktur (200) med mindst tre lag (202, 204, 206), som omfatter

et første fiberlag (202) af andre garner med fibre i en første retning,

10 et andet fiberlag (202) af andre garner med fibre i en første eller anden retning, og

mindst et skrålag (204, 206) af andre garner, hvor ethvert af det mindst ene skrålag (204, 206) af andre garner har fibre i en vinkel på andet end 0° eller

15 90° i forhold til fibre i lag af andre garner, der ikke er skrålag af andre garner, og det mindst ene skrålag (204, 206) af andre garner er anbragt mellem det første og andet lag (202) af andre garner,

hvor fibre i et første skrålag (204) af andre garner er i en første vinkel i forhold til den første retning.

20 2. Vævet struktur ifølge krav 1, omfattende:

et andet fiberskrålag (206) af andre garner, der er anbragt mellem første og andet lag (202) af andre garner,

hvor fibre i det andet skrålag (206) af andre garner er i en anden vinkel i forhold til den første retning.

25

3. Vævet struktur ifølge krav 2, hvor den første vinkel er mellem 30 og 60 grader, og den anden vinkel er mellem -30 og -60 grader.

30 4. Vævet struktur ifølge krav 3, hvor den første vinkel er 45 grader og den anden vinkel er -45 grader.

5. Vævet struktur ifølge krav 3, hvor den første vinkel er 30 grader og den anden vinkel er -60 grader.

5 **6. Vævet struktur ifølge krav 1, hvor de i det mindste nogle andre garner omfatter et første slør af andre garner på en udvendig overflade af det første lag (202) af andre garner og et andet slør af andre garner på en udvendig overflade af det andet lag (202) af andre garner.**

10 **7. Vævet struktur ifølge krav 1, hvor i det mindste nogle første garner er en lamineret struktur (200) med mindst tre lag, der indbefatter mindst et skrålag (204, 206) af første garner, hvor ethvert af det mindst ene skrålag (204, 206) af første garner har fibre i en vinkel på andet end 0° eller 90° i forhold til fibre i første garnlag, der ikke er skrålag (204, 206) af første garner.**

15 **8. Vævet struktur ifølge krav 7, hvor den laminerede struktur (200) omfatter:**
et første fiberlag (202) af første garner i en tredje retning;
et andet fiberlag (202) af første garner i en tredje eller fjerde retning; og
hvor det mindst ene fiberskrålag (204, 206) af første garner er anbragt mellem
det første og andet lag (202) af garner,
20 hvor fibre i et første fiber skrålag (204) af første garner er i en anden første vinkel i forhold til den første retning.

25 **9. Vævet struktur ifølge krav 8, hvor den 3D-vævede struktur er formet til en præform med en tværsnitsform, der er valgt fra gruppen bestående af Pi, H, T, O og I.**

10. Vævet struktur ifølge krav 1, hvor i det mindste nogle af de andre garner er multiaksiale bånd.

30 **11. Vævet struktur ifølge krav 10, hvor i det mindste nogle af de første garner er multiaksiale bånd.**

12. Fremgangsmåde til at danne en tredimensionel (3D) vævet struktur omfattende:

vævning af en flerhed af første garner i en bestemt retning med en flerhed af andre garner i en anden retning og sammenvævet med flerheden af første garner,

kendetegnet ved, at i det mindste nogle andre garner er en lamineret struktur (200) med mindst tre lag (202, 204, 206), der omfatter mindst et andet skrålag (204, 206) af andre garner, et første fiberlag (202) af andre garner med fibre i en første retning og et andet fiberlag (202) af andre garner med fibre i en første eller anden retning, hvor ethvert af det mindst ene skrålag (204, 206) af andre garner har fibre i en vinkel på andet end 0° eller 90° med hensyn til fibre i lag af andre garner, som ikke er skrålag af andre garner, og det mindst ene skrålag (204, 206) af andre garner er anbragt mellem det første og andet skrålag (202) af andre garner, hvor fibre i et første skrålag (204) af andre garner er i en første vinkel i forhold til den første retning.

13. Fremgangsmåde ifølge krav 12, omfattende:

anbringelse af et andet fiberskrålag (206) af andre garner mellem det første og andet lag (202) af andre garner, hvor fibre i det andet skrålag (206) af andre garner er i en anden vinkel i forhold til den første retning.

14. Fremgangsmåde ifølge krav 13, hvor den første vinkel er mellem 30 og 60 grader, og den anden vinkel er mellem -30 og -60 grader.

15. Fremgangsmåde ifølge krav 12, hvor de mindst nogle andre garner omfatter et første slør af andre garner på en udvendig overflade af det første lag (202) af andre garner og et andet slør af andre garner på en udvendig overflade af det andet lag (202) af andre garner

5 **16.** Fremgangsmåde ifølge krav 12, hvor i det mindste nogle første garner er en lamineret struktur (200) med mindst tre lag, der indbefatter mindst et skrålag (204, 206) med første garner, hvor ethvert af det mindst ene skrålag (204, 206) af første garner har fibre i en vinkel på andet end 0° eller 90° i forhold til fibre i lag af første garner, som ikke er skrålag (204, 206) af første garner.

10 **17.** Fremgangsmåde ifølge krav 16, hvor den laminerede struktur (200) omfatter:
et første fiberlag (202) af første garner i en tredje retning;
et andet fiberlag (202) af første garner i en fjerde retning;
hvor det mindst ene fiberskrålag (204, 206) af første garner er anbragt mellem det første og andet lag (202) af første garner; og
fibre i et første skrålag (204) af første garner er i en anden første vinkel i forhold til den første retning.

15 **18.** Fremgangsmåde til at danne en tredimensionel vævet komposit omfattende:
dannelse af en tredimensionel vævet struktur ifølge krav 12 eller 17; og
imprægnering af den tredimensionelle vævede struktur med et matrixmateriale.
20

DRAWINGS

Drawing

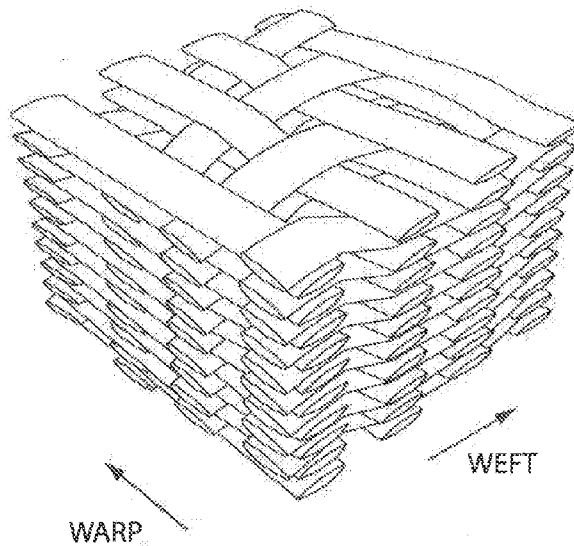


FIG. 1A
(RELATED ART)

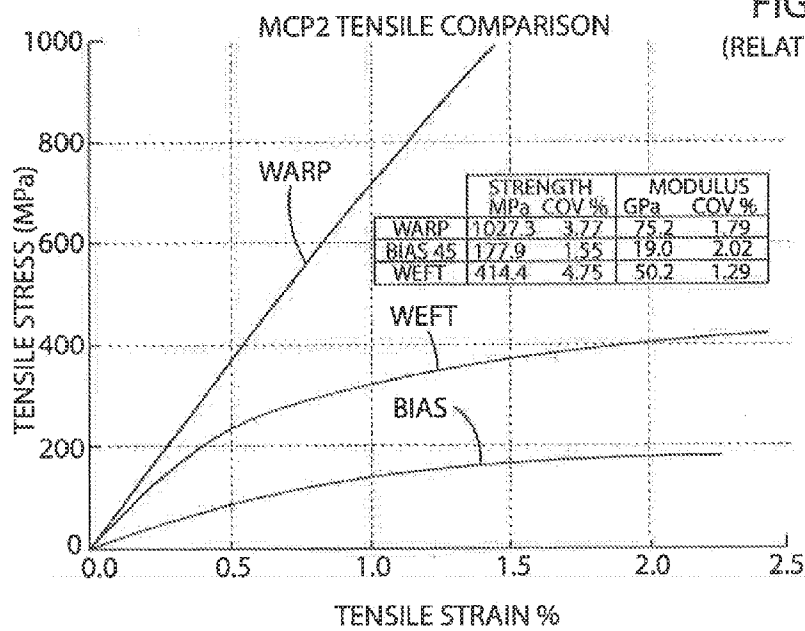


FIG. 1B
(RELATED ART)

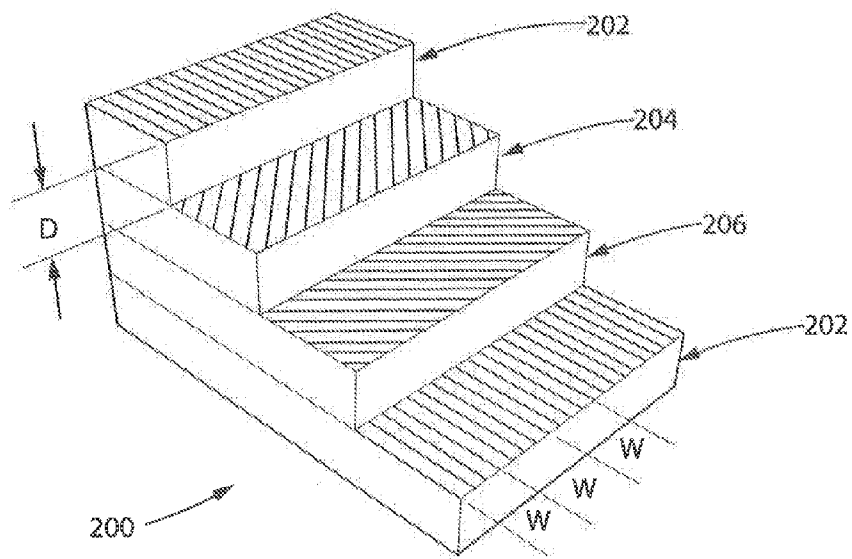


FIG. 2

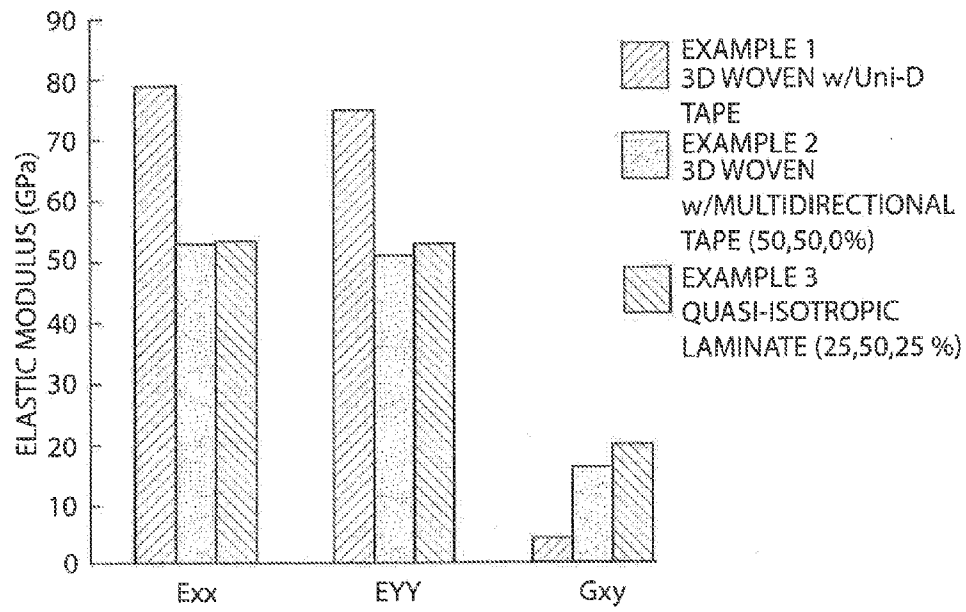


FIG. 3

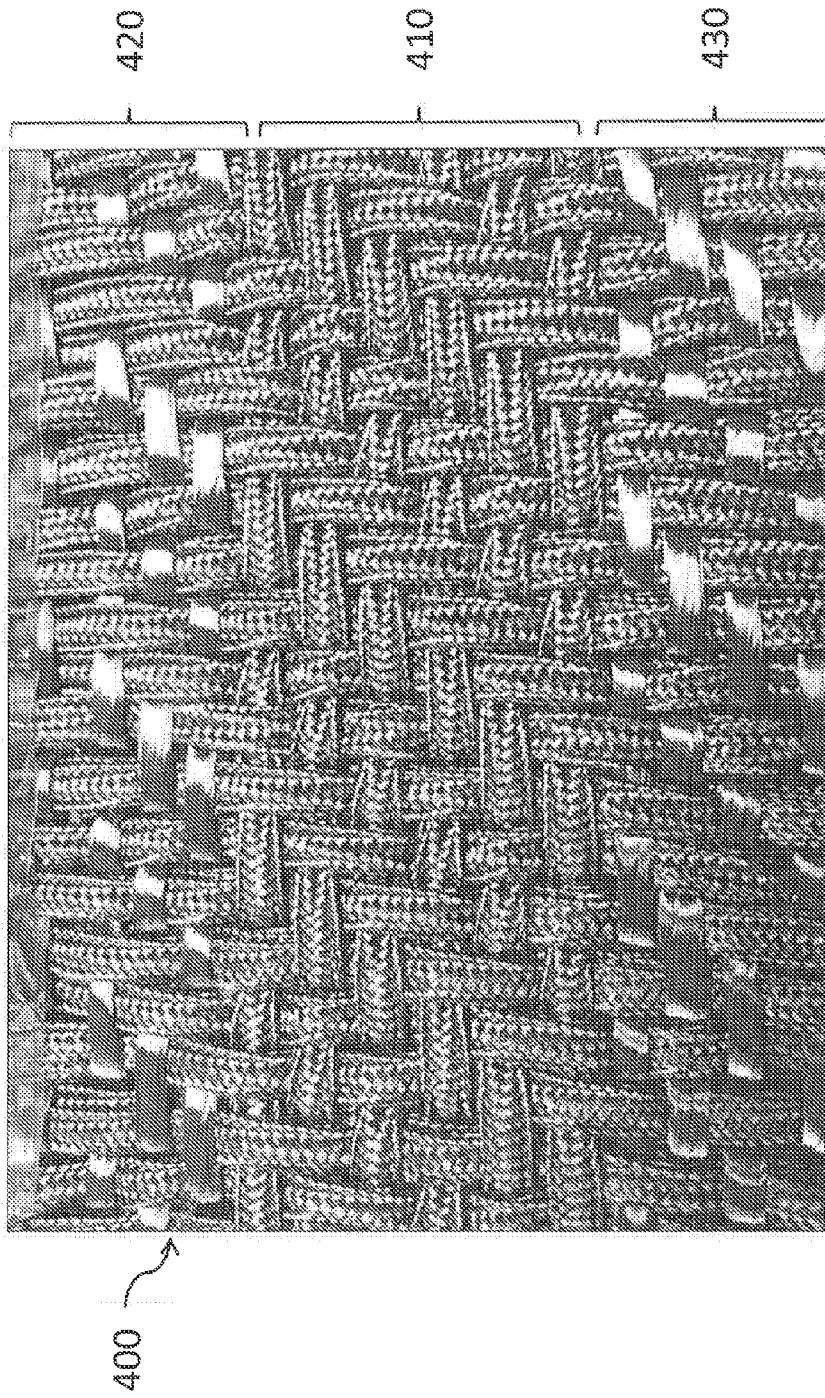


FIG. 4

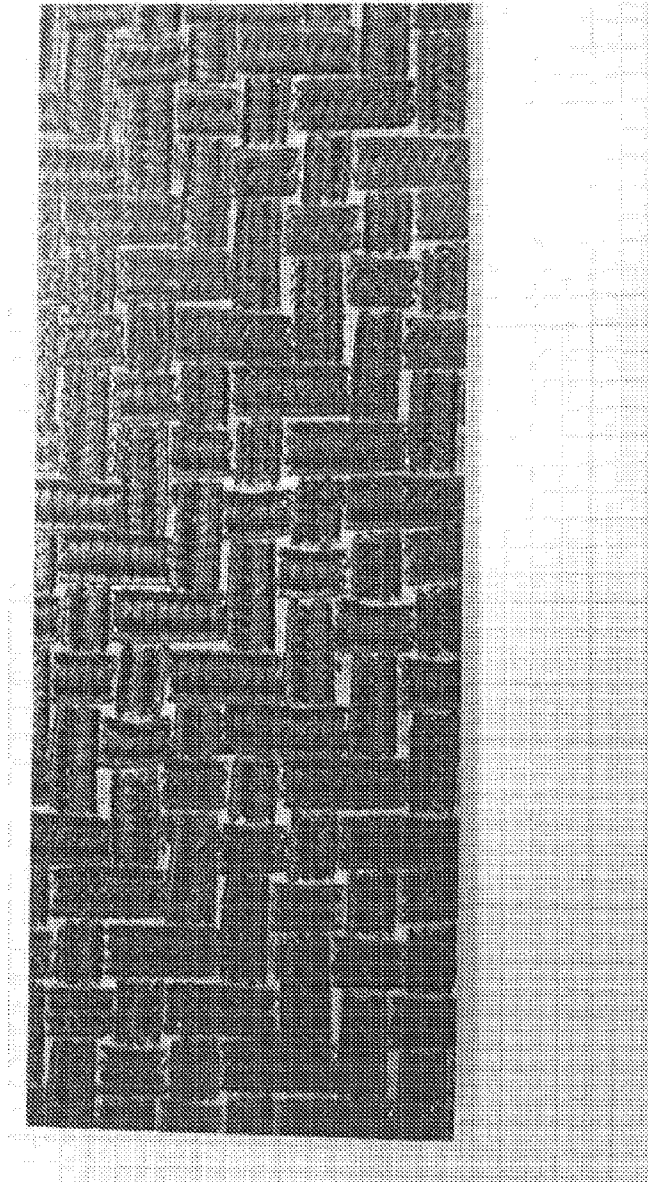


FIG. 5

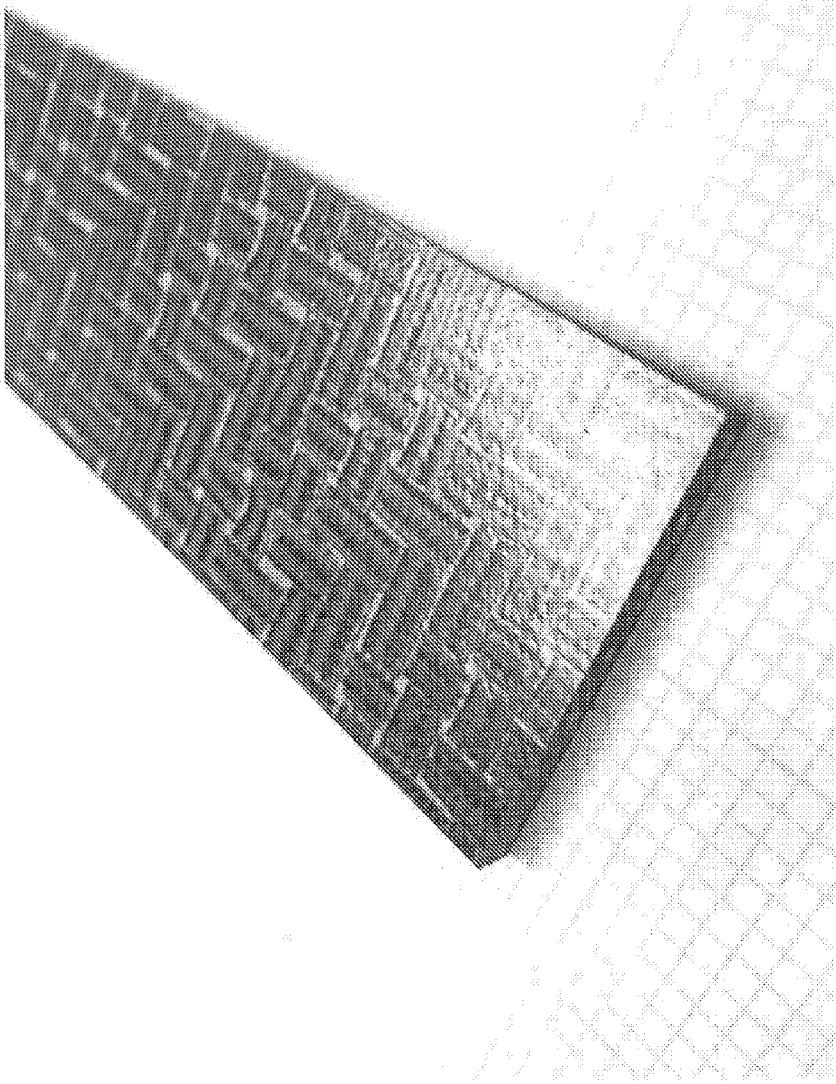


FIG. 6

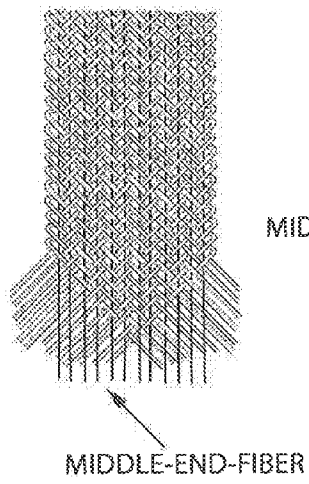


FIG. 7A

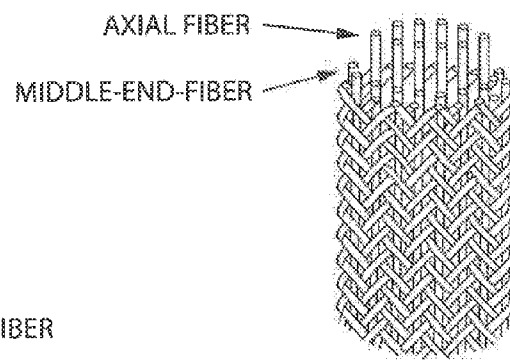
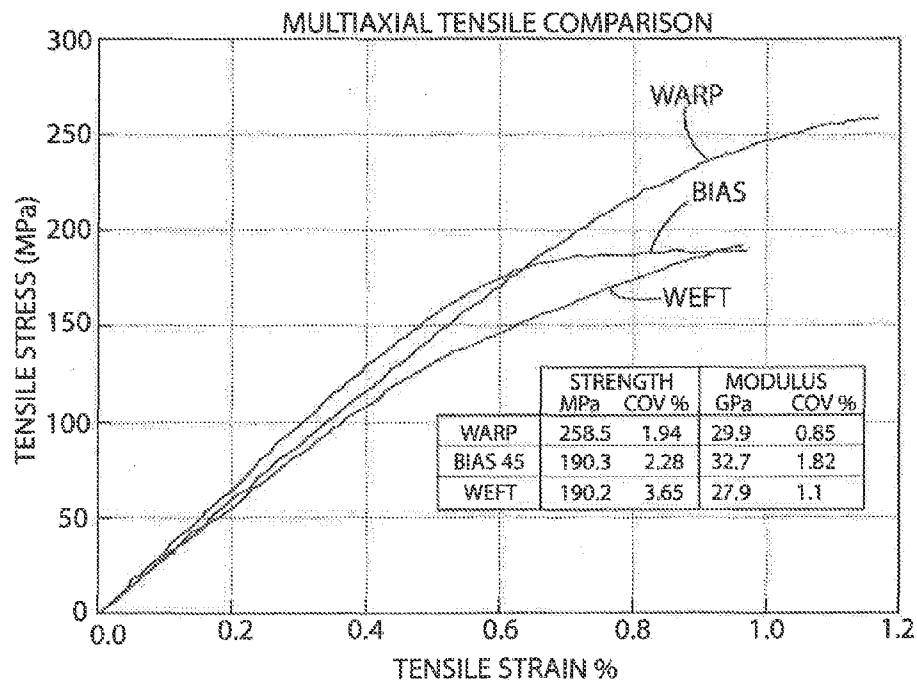


FIG. 7B

MULTIAXIAL TOW 3D WOVEN COMPOSITE TEST SUMMARY



TEST TYPE	TEST ORIENTATION	STRENGTH		MODULUS	
		MPa	COV %	GPa	COV %
TENSION	0°	285.5	1.94	29.9	0.85
	45°	190.3	2.28	32.7	1.82
	90°	190.2	3.65	27.9	1.1
SHEAR	0°	158.8	1.78	13.7	6.18
COMPRESSION	0°	244.6	3.33	30.8	6.23
	45°	276.3	1.44	34.5	2.18
	90°	240.2	3.12	29.9	3.82

FIG. 8

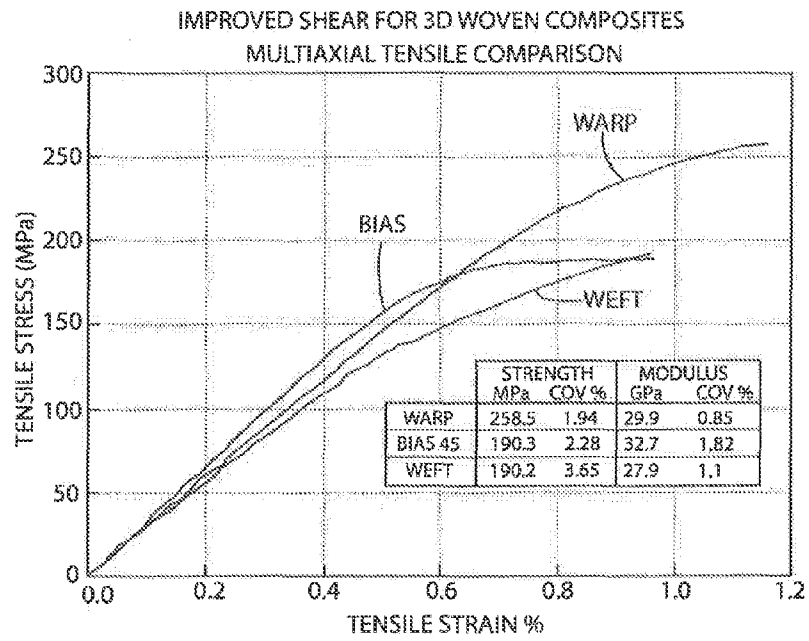


FIG. 9

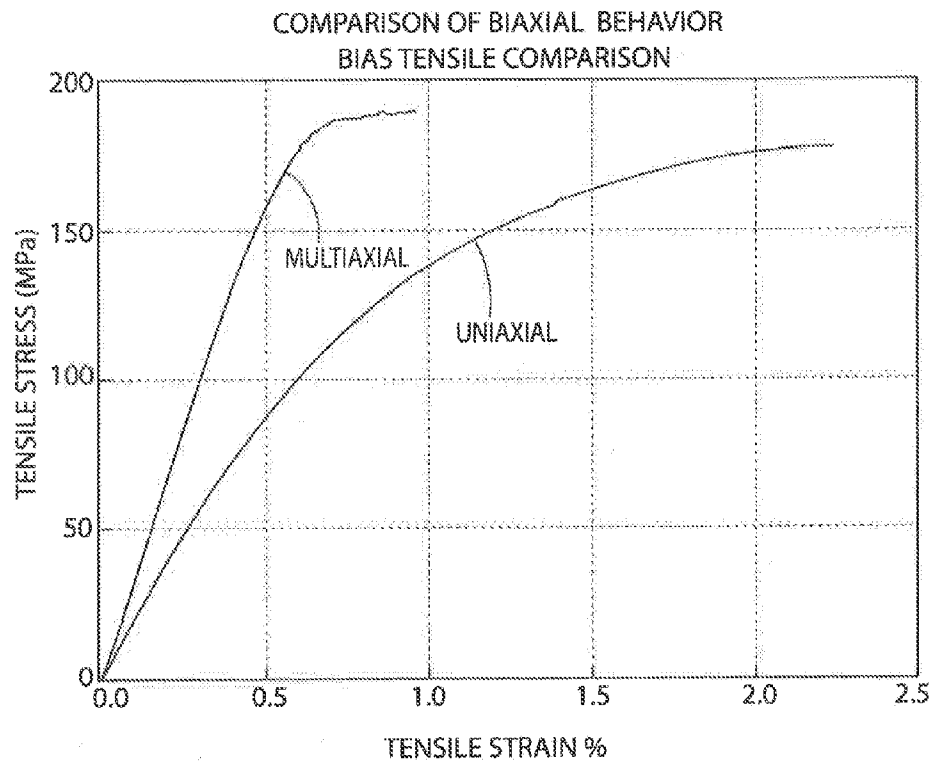


FIG. 10