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**United States Patent
King**

**4,038,440
July 26, 1977**

Three dimensional fabric material

Abstract

Three-dimensional impregnated filamentary materials and methods for making the same.

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Assignee: **Avco Corporation** (Wilmington, MA)
Appl. No.: **706849**
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Current U.S. Class:	442/205; 139/408; 156/148; 156/167; 156/296; 428/902; 428/910
Intern'l Class:	D06M 017/00
Field of Search:	156/148,166,167,296 428/221,228,245,257,902,910 139/DIG. 1,408,409,410,411,412,413

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"A Three-Dimensionally Reinforced Material", SPE Journal, May 1968--vol. 24, pp. 33 and 34.

Primary Examiner: Bell; James J.
Attorney, Agent or Firm: Ogman; Abraham

Parent Case Text

This is a division of application Ser. No. 220,510, filed Jan. 24, 1972, now U.S. Pat. No. 4,001,478, issued Jan. 4, 1977, which, in turn, is a continuation of application Ser. No. 675,367, filed Oct. 16, 1967, now abandoned.

Claims

I claim:

1. A method for fabricating three-dimensional material comprising:
 - a. orienting a group of filaments parallel to a given axis,
 - b. weaving into said oriented filaments a second group of filaments arranged in a planar course, said filaments being at an angle to said axis,
 - c. weaving into said oriented filaments a third group arranged in a plane which is contiguous with the plane of said second group of filaments, said third group of filaments also being woven at an angle to said second group filaments,
 - d. said filaments being sized and spaced relative to each other such that the filaments of each group are in close touching contact with the filaments of each other group and,
 - e. alternating such second and third groups of filaments in such manner to form a three-dimensional structure.
2. A method as described in claim 1 where, in addition, the structure is impregnated with a cured plastic matrix substance.
3. A method as defined in claim 1 in which said oriented filaments and said filaments of said second and third groups are mutually orthogonal to one another.
4. A method as defined in claim 1 wherein said structure is compressed until it has a density of at least 30% of the density of the filaments.
5. A method as defined in claim 3 wherein said structure is compressed until it has a density of at least 30% of the density of the filaments.
6. A three-dimensional material comprising:
 - a. a group of filaments oriented parallel to a given axis,
 - b. a second group of filaments arranged in a planar course, said filaments being woven into said oriented filaments at an angle to said axis,

- c. a third group arranged in a plane which overlies and is contiguous with the plane of said second group of filaments, said third group filaments also being woven into said oriented filaments but at an angle to said second group filaments,
- d. all of said filaments being sized and spaced relative to each other such that the filaments of each group are in close touching contact with the filaments of each other group, and
- e. alternating such second and third groups of filaments in said manner to form a three-dimensional structure.
7. A three-dimensional material as described in claim 6 where, in addition, the structure is impregnated with a cured plastic matrix substance.
8. A structure as defined in claim 6 in which said oriented filaments and said filaments of said second and third groups are mutually orthogonal to one another.
9. A structure as defined in claim 6 wherein said structure has a density of at least 30% of the density of the filaments.
10. A structure as defined in claim 8 wherein said structure has a density of at least 30% of the density of the filaments.

Description

This invention relates to new types of three-dimensional materials and new methods for fabricating these materials. More specifically it relates to structures composed of filaments which are woven in three-dimensional shapes and then impregnated with a suitable matrix substance such as plastic, resin or other solutions. After these impregnated structures are hardened by curing, they can then be machined to desired shapes. The filament and impregnating compositions and the weaving orientation of the filaments may be varied to provide the desired characteristics for the composite structure.

According to this invention, a three-dimensional structure is made by weaving filaments in a two-dimensional network on an oriented group of filaments which define a third dimensional reinforcement axis. For convenience, the two-dimensional network will be referred to as being woven in the X-Y axis, and the reinforcement axis as the Z axis. The term "weaving" is used here in a broad general sense to indicate a moving into close adjacency with and overlapping of adjacent filaments rather than requiring an interlacing of these filaments. It also includes the interlacing of these filaments. This weaving must be performed in a way such that the filaments are in close, touching contact with each other. In this way, the woven structure acquires self-supporting three-dimensional integrity because of the inter-yarn friction between adjacent filaments.

After the structure is woven in this manner, it is then impregnated with a suitable plastic, resin, ceramic or metallic or other matrix. The structure is then cured to produce a hard billet of composite material. This billet may then be machined to the desired final dimensions.

Because the structure comprises separate individual filaments in the X, Y and Z axes, a large variety of filaments are available to tailor the composite to the particular characteristics which are desired. For example, the reinforcement density and stiffness in each axis can be varied independently of the other axis by using different filament sizes, densities and filament groupings and also by changing filament compositions. Examples

of suitable filament materials include glass, metallic, ceramic, synthetic, asbestos, *jute* and cotton filaments as well as boron and quartz filaments. Certain of these materials may also be graphitized to vary the electrical characteristics of filaments. In addition, the orientation of these filaments in the woven structure can be varied to control the physical characteristics of the material.

Likewise the composition of the matrix can be varied to change the characteristics of the structure. Thus, the properties of the material can be controlled through these variables to provide materials having precisely the characteristics required for the particular application.

In order to better understand this invention, it is helpful to briefly review its general background. The closest known analogous prior art are materials made from two-dimensional fabrics and/or fibres dispersed in a resin or plastic matrix. These materials differ from the invention disclosed herein in that they are basically a plastic or resin structure into which reinforcing fabrics or fibers have been added to enhance the physical properties of the plastic or resin structure. The fabric and fibers have no self-supporting three-dimensional integrity. Nor do they provide significant, if any, inter-yarn friction along the three orthogonal axes.

These prior art reinforced materials have the serious difficulty of lacking sufficient strength between one layer of fabric and its adjacent layers. The reinforcement effectively occurs in one plane only and is greatest within this plane in the two directions parallel to the interwoven yarns. Little or no reinforcement is present in the direction perpendicular to the fabric plane.

In contrast, the woven structure disclosed herein is free-standing, having three-dimensional integrity in all three axes. The matrix material is added for setting the filaments in their preselected orientation, and for enhancing the physical, thermal, ablative, and other properties of the woven filamentary materials. The basic strength of the fabric structure results primarily from inter-yarn friction of the adjacent filaments, where they intersect throughout the material. This friction provides the binding forces which maintain fabric integrity even in the absence of the plastic, resin or other type matrix.

It is therefore a principal object of this invention to provide three-dimensional materials (and methods for making them) which combine the advantages of the prior art reinforced materials without being subject to these materials' deficiencies of interlaminar weakness and susceptibility to planes or axes of weakness.

It is another object of this invention to provide a new class of materials, and a method for making these new materials, which have a composition that can be tailored to satisfy strength, thermal electrical, ablating and other physical property requirements either isotropically or directionally in any of the three orthogonal axes.

This invention will be more fully understood from the following detailed description of specific embodiments thereof when read in conjunction with the accompanying drawings, in which:

FIG. 1 is a pictorial representation of a *loom* for weaving three-dimensional fabric material in accordance with this invention;

FIG. 2 is an enlarged perspective view of a structure fabricated in accordance with this invention on a *loom* of the type shown in FIG. 1; and

FIG. 3 is a cross-sectional elevation of an apparatus for impregnating the structure shown in FIG. 2.

Referring to FIG. 1, base 10 supports four aligned uprights 11 on which are movably mounted upper frame 12 and lower frame 13. Frames 12 and 13 are movably mounted to uprights 11 by conventional collar and set

screw positioning means 14.

A plurality of vertically oriented filaments 15, which in this particular embodiment are rigid rods made of a self-supporting material such as boron, extend in what will be referred to as the Z axis between upper and lower frames 12 and 13. They are positioned in this way by passing through holes (not shown) in upper frame 12 and resting in mating recesses (not shown) in the upper surface of lower frame 13. The holes and recesses in frames 12 and 13 are oriented and spaced in this embodiment in equally spaced perpendicular ranks and rows, thus defining mutually perpendicular axes X and Y. These axes are so indicated in FIG. 1.

While filaments 15 in this particular embodiment are self-supporting boron rods, it should be understood that other filaments made of materials as referred to above, some of which are self-supporting and others of which are not, may also be used. Those which are not self-supporting may be extended between upper and lower frames 12 and 13 by any conventional filament tensioning means. Similarly, filaments 15 could be replaced by hollow tubes extending between frames 12 and 13, which could later be replaced by the desired filaments after the X and Y axis filaments have been woven in the manner to be described below.

Adjacent upper and lower frames 12 and 13 and filaments 15 are two essentially identical filament feed units generally referenced 20 and 20'. Since the structure and operation of these units are essentially identical, this description will be limited to the yarn feed unit 20 for the X axis, it being understood that the yarn feed unit 20' operates in a similar manner on the Y axis.

Supple filament 21 is fed under tension from bobbins (not shown) to each of a plurality of parallel, equally spaced needles 22, which are mounted in needle bar 23 and extend through needle spacer 24. Needle bar 23 is connected to two parallel push rods 25, which are reciprocally journaled in yoke assembly 26. Stop plate 27 limits the forward travel of push rods 25 in yoke assembly 26 in a manner to be described below. Yoke assembly 26 is supported above base 10 by uprights 28.

In operation, lower frame 13 is adjusted to a convenient working height above base 10 by manipulating positioning means 14 on uprights 11. Upper frame 12 is then positioned at a convenient working height relative to lower frame 13 so as to maintain filaments 15 in their vertically aligned, spaced orientation. Filaments 15 are then inserted through the hole of upper frame 12 and into the recesses of lower frame 13. Once filaments 15 are in place, filament 21 can be woven into filaments 15 from filament feed units 20 and 20'.

To accomplish this, filaments 21 are first threaded into each of needles 22 and then grouped and tightly secured to a typing-off hook (not shown) on the under-surface of lower frame 13. Needles 22 and their threaded filaments 21 are then woven through the spaced rows between filaments 15 along the X axis to extend beyond the opposite side of filaments 15 by advancing the push rods 25 until stop plate 27 reaches the yoke assembly 26. A pin 30 is inserted so as to lie across the top of the filaments 21 just outside the last row of filaments 15, the pin 30 lying in the Y-axis direction. Pin 30 is manipulated downwardly so as to tamp filaments 21 down against the upper surface of lower frame 13. Needles 22 (which are above pin 30) are then retracted from the filaments 15 to their starting position, thus forming a tightly looped first course of X-axis filaments which is restrained by pin 30 at the far outside edge of filaments 15.

Following this, the first course of Y-axis yarn is woven into the filaments 15 by advancing threaded needles 22' in the same manner as previously described, inserting pin 30' on top of filament 21' immediately outside the last row of filaments 15 in the X-axis direction and withdrawing needles 22' to their start position. In this manner, the first course of Y-axis filament (the second course of filaments in the X-Y plane) is laid on top of the X-axis course and packed tightly downwards against the X-axis filament course to maximize the pressure of the close touching contact of X, Y and Z-axis filaments at their points of intersection.

Following this, the filament feed units 20 and 20' are alternately operated in the same manner, until a three-dimensional network of X, Y and Z yarn of the desired height is built up on the Z-axis filaments 15. As the filament layers build up, it will be obvious that the pins 30 and 30' may be removed and inserted in the higher newly formed courses of filament, since they are no longer needed to hold in place the lower courses of the structure. The adjacent layers prevent the courses in the lower part of the structure from being undone. In this manner pins 30 and 30' can be removed and used over again, thus reducing the number of pins required for the operation.

It is important to emphasize that filaments 21 and 21' should be fed under tension and packed tightly against the adjacent filaments in the X, Y and Z-axes to insure maximum inter-yarn friction between adjacent filaments. The strength of the builtup structure depends principally upon this inter-yarn friction; the importance of maximizing it is therefore apparent.

It should also be understood that other filament weaving configurations may be used. For example, the apparatus described above allows a weave pattern where an X-axis filament course is overlapped and sandwiched between by a Y-axis course. This would be done by extending the Y-axis needles 22' through filaments 15, thus weaving a single layer of Y-axis filament 21' into filaments 15, and then extending and retracting the X-axis needles in the above described manner to weave an overlapped double layer of filaments 21 on the X-axis into filaments 15 on top of single layer of filaments 21', and then retracting needles 22' to weave a single layer of filaments 21' on the Y-axis on top of the double layer of filaments 21 on the X-axis.

Similarly, a multiple shuttle-type *loom* could be used whereby single-layer X-axis and Y-axis courses could be laid on top of each other. Such a woven structure is illustrated in FIG. 2. This would require a *loom* having oppositely disposed banks of X-axis and Y-axis needles on either side of the Z-axis filaments, and a suitable filament transfer system on each bank of needles to permit transfer of the filament between the opposite banks as the needles traverse the Z-axis. Still more sophisticated looms have been designed to interlace, rather than simply overlap these filaments.

Also, while the looms thus far considered in detail have only X-axis and Y-axis courses woven on the Z-axis, it should be understood that these courses need not be woven perpendicular to each. Nor is it necessary for the Z-axis filaments to be aligned vertically and parallel to each other. Diverging and converging Z-axis filaments have been successfully used to weave conical shapes. Also, less than or more than the two above-described courses can be woven into the X-Y axes network, e.g. all courses on the X-axis, or more than two courses woven in at 30.degree. , 60.degree. , and/or other angular intervals in the X-Y plane into the Z-axis filaments.

Other *loom* designs are available, and others will become available, which can produce still different weaving configurations. These designs do not, however, depart from the basic principles of the materials and processes which are described herein.

After sufficient layers of filament have been woven in the above-described manner to produce a structure of the desired overall dimensions, it is preferably compressed along the Z-axis. This increases the density and inter-yarn friction of the finished material. Compression may be accomplished in any conventional manner. One suitable method is to employ a compression member having a plurality of parallel slats which are sized and positioned to fit between the rows of Z-axis filaments 15. This member is then applied to the structure as by a conventional tie bolt arrangement to lower frame 13, so as to force the slats downwardly between the adjacent rows of Z-axis filaments 15. The slats in turn force the X-axis and Y-axis filaments downwardly into a far more compact and denser structure.

Another compression technique which has been found suitable is to use a heat shrinkable filament such as

Nylon or Rayon. After the structure is woven with this filament, it is simply heated in order to shrink and thereby compress it.

Compression is, however, not essential. The structure is sufficiently compact and dense for certain applications without compression. In this regard, it should be noted that the structure can be woven by the above-described method to produce a very compact composite having a density before compression of 30% or greater of the density of the filaments making up the composite structure. For more demanding uses, however, compression of the structure is desirable.

After the structure is compressed, it is removed from the apparatus of FIG. 1 by raising upper frame 12 off the uprights 11 and lifting it off and away from the lower frame 12. The woven structure which will now be referred to as a billet, is then impregnated with a suitable plastic or resin material in order to fix the filaments in their woven orientation in the manner now described.

Referring to FIG. 3, billet 40 rests on support blocks 41 under a liquid resin bath 42 in a conventional pressure cylinder 43. Liner 44 encloses billet 40. A vacuum is drawn by usual means in cylinder 43 through vacuum port 45. At the same time, piston 46 presses resin bath 42 downwardly against billet 40. The combined action of the evacuation of cylinder 43 and pressure from piston 46 causes the resin to thoroughly impregnate billet 40, filling in the interstices between adjacent filaments.

After structure 40 is fully impregnated in this manner, it is then cured so as to form a solid billet which may be machined to the desired shape and dimensions.

The advantages of 3-D materials with planar courses are manifold. It has been shown that where filaments are offset from the direction of stress, such as is found in interwoven configurations, the strength of the composite drops dramatically in that direction. For example, a mere 10.degree. offset results in more than a 50% decrease in strength of composites using high-strength, high-modulus graphite filaments.

Moreover, an offset also exhibits a substantial loss in the composite's thermal stress resistance. Compressive strength and modulus are also less in fabrics that are not fully constructed from planar courses.

Further, in planar structures as described herein containing three mutually orthogonal groups of filaments, the strength of the composite in a direction of 45.degree. offset from any of the orthogonal axes is from 1/3 to 1/4 of the strength of the same composite in the direction of the filament axes. The planar configuration allows the practitioner to adjust the angular orientation of the parallel filaments in the planar courses so as to align such filaments in the anticipated direction of stress.

Additionally, Applicant knows of no interwoven filamentary reinforced structure which is capable of being manufactured with a very large number of layers so that very high (or thick) forms may be produced. The offset required in interwoven fabrics precludes the possibility of constructing three-dimensional materials having heights (or thicknesses) in the order of 8 to 12 inches or greater.

Interwoven fabrics have another limitation, particularly where the filaments cross in a plane perpendicular to the direction in which a 3-D block is to be compressed. The filaments at the cross-over point act as knife edges. The result is a very large deterioration of properties after a block has been compressed due to the filaments being cut or broken at the points in which they cross one another.

The various features and advantages of the invention are thought to be clear from the foregoing description. Various other features and advantages not specifically enumerated will undoubtedly occur to those versed in the

art, as likewise will many variations and modifications of the preferred embodiment illustrated, all of which may be achieved without departing from the spirit and scope of the invention as defined by the following claims:

* * * * *



[54] **THREE DIMENSIONAL FABRIC MATERIAL**

[75] Inventor: **Robert W. King**, Lexington, Mass.

[73] Assignee: **Avco Corporation**, Wilmington, Mass.

[21] Appl. No.: **706,849**

[22] Filed: **July 19, 1976**

Related U.S. Application Data

[60] Division of Ser. No. 220,510, Jan. 24, 1972, Pat. No. 4,001,478, which is a continuation of Ser. No. 675,367, Oct. 16, 1967, abandoned.

[51] Int. Cl.² **D06M 17/00**

[52] U.S. Cl. **428/245; 139/408; 156/148; 156/167; 156/296; 428/257; 428/902; 428/910**

[58] **Field of Search** 156/148, 166, 167, 296; 428/221, 228, 245, 257, 902, 910; 139/DIG. 1, 408, 409, 410, 411, 412, 413

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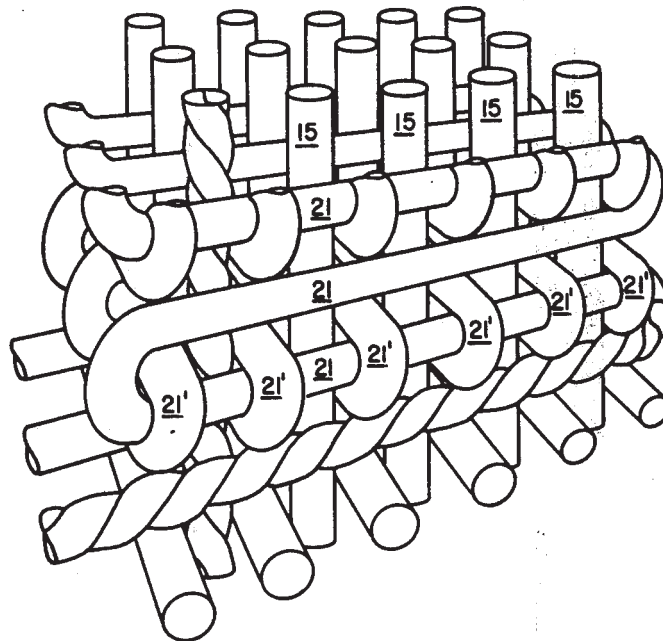
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[57] **ABSTRACT**

Three-dimensional impregnated filamentary materials and methods for making the same.

10 Claims, 3 Drawing Figures



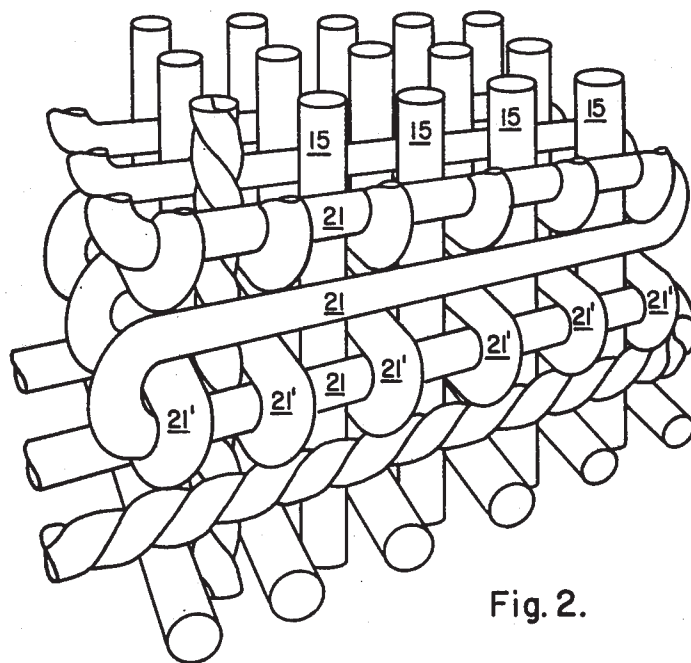
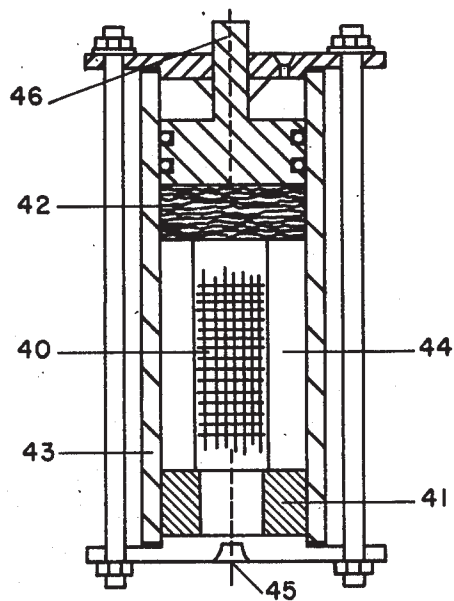


Fig. 2.

Fig. 3.



THREE DIMENSIONAL FABRIC MATERIAL

This is a division of application Ser. No. 220,510, filed Jan. 24, 1972, now U.S. Pat. No. 4,001,478, issued Jan. 4, 1977, which, in turn, is a continuation of application Ser. No. 675,367, filed Oct. 16, 1967, now abandoned.

This invention relates to new type of three-dimensional materials and new methods for fabricating these materials. More specifically it relates to structures composed of filaments which are woven in three-dimensional shapes and then impregnated with a suitable matrix substance such as plastic, resin or other solutions. After these impregnated structures are hardened by curing, they can then be machined to desired shapes. The filament and impregnating compositions and the weaving orientation of the filaments may be varied to provide the desired characteristics for the composite structure.

According to this invention, a three-dimensional structure is made by weaving filaments in a two-dimensional network on an oriented group of filaments which define a third dimensional reinforcement axis. For convenience, the two-dimensional network will be referred to as being woven in the X-Y axis, and the reinforcement axis as the Z axis. The term "weaving" is used here in a broad general sense to indicate a moving into close adjacency with and overlapping of adjacent filaments rather than requiring an interlacing of these filaments. It also includes the interlacing of these filaments. This weaving must be performed in a way such that the filaments are in close, touching contact with each other. In this way, the woven structure acquires self-supporting three-dimensional integrity because of the inter-yarn friction between adjacent filaments.

After the structure is woven in this manner, it is then impregnated with a suitable plastic, resin, ceramic or metallic or other matrix. The structure is then cured to produce a hard billet of composite material. This billet may then be machined to the desired final dimensions.

Because the structure comprises separate individual filaments in the X, Y and Z axes, a large variety of filaments are available to tailor the composite to the particular characteristics which are desired. For example, the reinforcement density and stiffness in each axis can be varied independently of the other axis by using different filament sizes, densities and filament groupings and also by changing filament compositions. Examples of suitable filament materials include glass, metallic, ceramic, synthetic, asbestos, jute and cotton filaments as well as boron and quartz filaments. Certain of these materials may also be graphitized to vary the electrical characteristics of filaments. In addition, the orientation of these filaments in the woven structure can be varied to control the physical characteristics of the material.

Likewise the composition of the matrix can be varied to change the characteristics of the structure. Thus, the properties of the material can be controlled through these variables to provide materials having precisely the characteristics required for the particular application.

In order to better understand this invention, it is helpful to briefly review its general background. The closest known analogous prior art are materials made from two-dimensional fabrics and/or fibres dispersed in a resin or plastic matrix. These materials differ from the invention disclosed herein in that they are basically a plastic or resin structure into which reinforcing fabrics or fibers have been added to enhance the physical properties of the plastic or resin structure. The fabric and fibers he no

self-supporting three-dimensional integrity. Nor do they provide significant, if any, inter-yarn friction along the three orthogonal axes.

These prior art reinforced materials have the serious difficulty of lacking sufficient strength between one layer of fabric and its adjacent layers. The reinforcement effectively occurs in one plane only and is greatest within this plane in the two directions parallel to the interwoven yarns. Little or no reinforcement is present in the direction perpendicular to the fabric plane.

In contrast, the woven structure disclosed herein is free-standing, having three-dimensional integrity in all three axes. The matrix material is added for setting the filaments in their preselected orientation, and for enhancing the physical, thermal, ablative, and other properties of the woven filamentary materials. The basic strength of the fabric structure results primarily from interyarn friction of the adjacent filaments, where they intersect throughout the material. This friction provides the binding forces which maintain fabric integrity even in the absence of the plastic, resin or other type matrix.

It is therefore a principal object of this invention to provide three-dimensional materials (and methods for making them) which combine the advantages of the prior art reinforced materials without being subject to these materials' deficiencies of interlaminar weakness and susceptibility to planes or axes of weakness.

It is another object of this invention to provide a new class of materials, and a method for making these new materials, which have a composition that can be tailored to satisfy strength, thermal electrical, ablating and other physical property requirements either isotropically or directionally in any of the three orthogonal axes.

This invention will be more fully understood from the following detailed description of specific embodiments thereof when read in conjunction with the accompanying drawings, in which:

FIG. 1 is a pictorial representation of a loom for weaving three-dimensional fabric material in accordance with this invention;

FIG. 2 is an enlarged perspective view of a structure fabricated in accordance with this invention on a loom of the type shown in FIG. 1; and

FIG. 3 is a cross-sectional elevation of an apparatus for impregnating the structure shown in FIG. 2.

Referring to FIG. 1, base 10 supports four aligned uprights 11 on which are movably mounted upper frame 12 and lower frame 13. Frames 12 and 13 are movably mounted to uprights 11 by conventional collar and set screw positioning means 14.

A plurality of vertically oriented filaments 15, which in this particular embodiment are rigid rods made of a self-supporting material such as boron, extend in what will be referred to as the Z axis between upper and lower frames 12 and 13. They are positioned in this way by passing through holes (not shown) in upper frame 12 and resting in mating recesses (not shown) in the upper surface of lower frame 13. The holes and recesses in frames 12 and 13 are oriented and spaced in this embodiment in equally spaced perpendicular ranks and rows, thus defining mutually perpendicular axes X and Y. These axes are so indicated in FIG. 1.

While filaments 15 in this particular embodiment are self-supporting boron rods, it should be understood that other filaments made of materials as referred to above, some of which are self-supporting and others of which are not, may also be used. Those which are not self-sup-

porting may be extended between upper and lower frames 12 and 13 by any conventional filament tensioning means. Similarly, filaments 15 could be replaced by hollow tubes extending between frames 12 and 13, which could later be replaced by the desired filaments after the X and Y axis filaments have been woven in the manner to be described below.

Adjacent upper and lower frames 12 and 13 and filaments 15 are two essentially identical filament feed units generally referenced 20 and 20'. Since the structure and operation of these units are essentially identical, this description will be limited to the yarn feed unit 20 for the X axis, it being understood that the yarn feed unit 20' operates in a similar manner on the Y axis.

Supple filament 21 is fed under tension from bobbins (not shown) to each of a plurality of parallel, equally spaced needles 22, which are mounted in needle bar 23 and extend through needle spacer 24. Needle bar 23 is connected to two parallel push rods 25, which are reciprocally journaled in yoke assembly 26. Stop plate 27 limits the forward travel of push rods 25 in yoke assembly 26 in a manner to be described below. Yoke assembly 26 is supported above base 10 by uprights 28.

In operation, lower frame 13 is adjusted to a convenient working height above base 10 by manipulating positioning means 14 on uprights 11. Upper frame 12 is then positioned at a convenient working height relative to lower frame 12 so as to maintain filaments 15 in their vertically aligned, spaced orientation. Filaments 15 are then inserted through the hole of upper frame 12 and into the recesses of lower frame 13. Once filaments 15 are in place, filament 21 can be woven into filaments 15 from filament feed units 20 and 20'.

To accomplish this, filaments 21 are first threaded into each of needles 22 and then grouped and tightly secured to a typing-off hook (not shown) on the under-surface of lower frame 13. Needles 22 and their threaded filaments 21 are then woven through the spaced rows between filaments 15 along the X axis to extend beyond the opposite side of filaments 15 by advancing the push rods 25 until stop plate 27 reaches the yoke assembly 26. A pin 30 is inserted so as to lie across the top of the filaments 21 just outside the last row of filaments 15, the pin 30 lying in the Y-axis direction. Pin 30 is manipulated downwardly so as to tamp filaments 21 down against the upper surface of lower frame 13. Needles 22 (which are above pin 30) are then retracted from the filaments 15 to their starting position, thus forming a tightly looped first course of X-axis filaments which is restrained by pin 30 at the far outside edge of filaments 15.

Following this, the first course of Y-axis yarn is woven into the filaments 15 by advancing threaded needles 22' in the same manner as previously described, inserting pin 30' on top of filament 21' immediately outside the last row of filaments 15 in the X-axis direction and withdrawing needles 22' to their start position. In this manner, the first course of Y-axis filament (the second course of filaments in the X-Y plane) is laid on top of the X-axis course and packed tightly downwards against the X-axis filament course to maximize the pressure of the close touching contact of X, Y and Z-axis filaments at their points of intersection.

Following this, the filament feed units 20 and 20' are alternately operated in the same manner, until a three-dimensional network of X, Y and Z yarn of the desired height is built up on the Z-axis filaments 15. As the filament layers build up, it will be obvious that the pins

30 and 30' may be removed and inserted in the higher newly formed courses of filament, since they are no longer needed to hold in place the lower courses of the structure. The adjacent layers prevent the courses in the lower part of the structure from being undone. In this manner pins 30 and 30' can be removed and used over again, thus reducing the number of pins required for the operation.

It is important to emphasize that filaments 21 and 21' should be fed under tension and packed tightly against the adjacent filaments in the X, Y and Z-axes to insure maximum inter-yarn friction between adjacent filaments. The strength of the builtup structure depends principally upon this inter-yarn friction; the importance of maximizing it is therefore apparent.

It should also be understood that other filament weaving configurations may be used. For example, the apparatus described above allows a weave pattern where an X-axis filament course is overlapped and sandwiched between by a Y-axis course. This would be done by extending the Y-axis needles 22' through filaments 15, thus weaving a single layer of Y-axis filament 21' into filaments 15, and then extending and retracting the X-axis needles in the above described manner to weave an overlapped double layer of filaments 21 on the X-axis into filaments 15 on top of single layer of filaments 21', and then retracting needles 22' to weave a single layer of filaments 21' on the Y-axis on top of the double layer of filaments 21 on the X-axis.

Similarly, a multiple shuttle-type loom could be used whereby single-layer X-axis and Y-axis courses could be laid on top of each other. Such a woven structure is illustrated in FIG. 2. This would require a loom having oppositely disposed banks of X-axis and Y-axis needles on either side of the Z-axis filaments, and a suitable filament transfer system on each bank of needles to permit transfer of the filament between the opposite banks as the needles traverse the Z-axis. Still more sophisticated looms have been designed to interlace, rather than simply overlap these filaments.

Also, while the looms thus far considered in detail have only X-axis and Y-axis courses woven on the Z-axis, it should be understood that these courses need not be woven perpendicular to each. Nor is it necessary for the Z-axis filaments to be aligned vertically and parallel to each other. Diverging and converging Z-axis filaments have been successfully used to weave conical shapes. Also, less than or more than the two above-described courses can be woven into the X-Y axes network, e.g. all courses on the X-axis, or more than two courses woven in at 30°, 60°, and/or other angular intervals in the X-Y plane into the Z-axis filaments.

Other loom designs are available, and others will become available, which can produce still different weaving configurations. These designs do not, however, depart from the basic principles of the materials and processes which are described herein.

After sufficient layers of filament have been woven in the above-described manner to produce a structure of the desired overall dimensions, it is preferably compressed along the Z-axis. This increases the density and inter-yarn friction of the finished material. Compression may be accomplished in any conventional manner. One suitable method is to employ a compression member having a plurality of parallel slats which are sized and positioned to fit between the rows of Z-axis filaments 15. This member is then applied to the structure as by a conventional tie bolt arrangement to lower frame 13, so

as to force the slats downwardly between the adjacent rows of Z-axis filaments 15. The slats in turn force the X-axis and Y-axis filaments downwardly into a far more compact and denser structure.

Another compression technique which has been found suitable is to use a heat shrinkable filament such as Nylon or Rayon. After the structure is woven with this filament, it is simply heated in order to shrink and thereby compress it.

Compression is, however, not essential. The structure is sufficiently compact and dense for certain applications without compression. In this regard, it should be noted that the structure can be woven by the above-described method to produce a very compact composite having a density before compression of 30% or greater of the density of the filaments making up the composite structure. For more demanding uses, however, compression of the structure is desirable.

After the structure is compressed, it is removed from the apparatus of FIG. 1 by raising upper frame 12 off the uprights 11 and lifting it off and away from the lower frame 12. The woven structure which will now be referred to as a billet, is then impregnated with a suitable plastic or resin material in order to fix the filaments in their woven orientation in the manner now described.

Referring to FIG. 3, billet 40 rests on support blocks 41 under a liquid resin bath 42 in a conventional pressure cylinder 43. Liner 44 encloses billet 40. A vacuum is drawn by usual means in cylinder 43 through vacuum port 45. At the same time, piston 46 presses resin bath 42 downwardly against billet 40. The combined action of the evacuation of cylinder 43 and pressure from piston 46 causes the resin to thoroughly impregnate billet 40, filling in the interstices between adjacent filaments.

After structure 40 is fully impregnated in this manner, it is then cured so as to form a solid billet which may be machined to the desired shape and dimensions.

The advantages of 3-D materials with planar courses are manifold. It has been shown that where filaments are offset from the direction of stress, such as is found in interwoven configurations, the strength of the composite drops dramatically in that direction. For example, a mere 10° offset results in more than a 50% decrease in strength of composites using high-strength, high-modulus graphite filaments.

Moreover, an offset also exhibits a substantial loss in the composite's thermal stress resistance. Compressive strength and modulus are also less in fabrics that are not fully constructed from planar courses.

Further, in planar structures as described herein containing three mutually orthogonal groups of filaments, the strength of the composite in a direction of 45° offset from any of the orthogonal axes is from $\frac{1}{2}$ to $\frac{1}{4}$ of the strength of the same composite in the direction of the filament axes. The planar configuration allows the practitioner to adjust the angular orientation of the parallel filaments in the planar courses so as to align such filaments in the anticipated direction of stress.

Additionally, Applicant knows of no interwoven filamentary reinforced structure which is capable of being manufactured with a very large number of layers so that very high (or thick) forms may be produced. The offset required in interwoven fabrics precludes the possibility of constructing three-dimensional materials having heights (or thicknesses) in the order of 8 to 12 inches or greater.

Interwoven fabrics have another limitation, particularly where the filaments cross in a plane perpendicular to the direction in which a 3-D block is to be compressed. The filaments at the cross-over point act as knife edges. The result is a very large deterioration of properties after a block has been compressed due to the filaments being cut or broken at the points in which they cross one another.

The various features and advantages of the invention are thought to be clear from the foregoing description. Various other features and advantages not specifically enumerated will undoubtedly occur to those versed in the art, as likewise will many variations and modifications of the preferred embodiment illustrated, all of which may be achieved without departing from the spirit and scope of the invention as defined by the following claims:

I claim:

1. A method for fabricating three-dimensional material comprising:
 - a. orienting a group of filaments parallel to a given axis,
 - b. weaving into said oriented filaments a second group of filaments arranged in a planar course, said filaments being at an angle to said axis,
 - c. weaving into said oriented filaments a third group arranged in a plane which is contiguous with the plane of said second group of filaments, said third group of filaments also being woven at an angle to said second group filaments,
 - d. said filaments being sized and spaced relative to each other such that the filaments of each group are in close touching contact with the filaments of each other group and,
 - e. alternating such second and third groups of filaments in such manner to form a three-dimensional structure.
2. A method as described in claim 1 where, in addition, the structure is impregnated with a cured plastic matrix substance.
3. A method as defined in claim 1 in which said oriented filaments and said filaments of said second and third groups are mutually orthogonal to one another.
4. A method as defined in claim 1 wherein said structure is compressed until it has a density of at least 30% of the density of the filaments.
5. A method as defined in claim 3 wherein said structure is compressed until it has a density of at least 30% of the density of the filaments.
6. A three-dimensional material comprising:
 - a. a group of filaments oriented parallel to a given axis,
 - b. a second group of filaments arranged in a planar course, said filaments being woven into said oriented filaments at an angle to said axis,
 - c. a third group arranged in a plane which overlies and is contiguous with the plane of said second group of filaments, said third group filaments also being woven into said oriented filaments but at an angle to said second group filaments,
 - d. all of said filaments being sized and spaced relative to each other such that the filaments of each group are in close touching contact with the filaments of each other group, and
 - e. alternating such second and third groups of filaments in said manner to form a three-dimensional structure.

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7. A three-dimensional material as described in claim 6 where, in addition, the structure is impregnated with a cured plastic matrix substance.

8. A structure as defined in claim 6 in which said oriented filaments and said filaments of said second and third groups are mutually orthogonal to one another.

9. A structure as defined in claim 6 wherein said struc-

ture has a density of at least 30% of the density of the filaments.

10. A structure as defined in claim 8 wherein said structure has a density of at least 30% of the density of the filaments.

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