CONTINUOUS TENSION, DISCONTINUOUS COMPRESSION STRUCTURES

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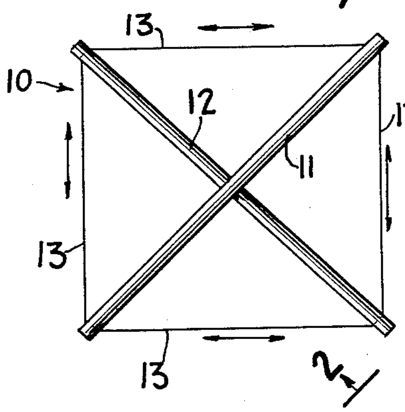
Fig. 1



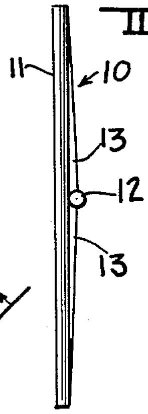


Fig. 2

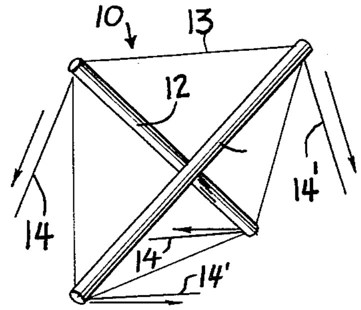


Fig. 3

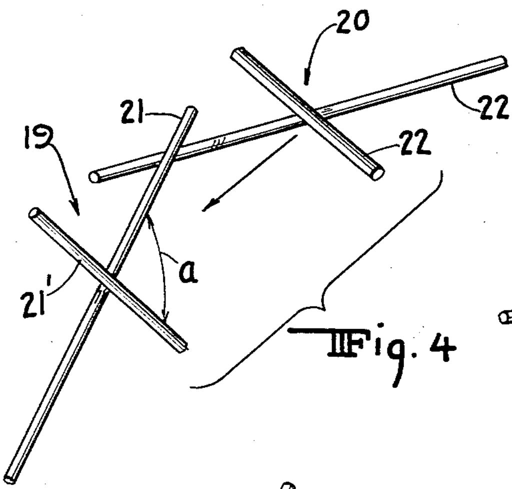


Fig. 4

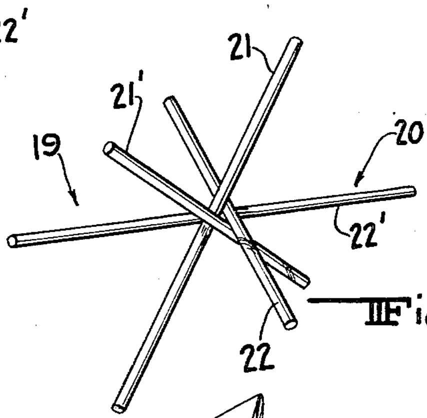


Fig. 5

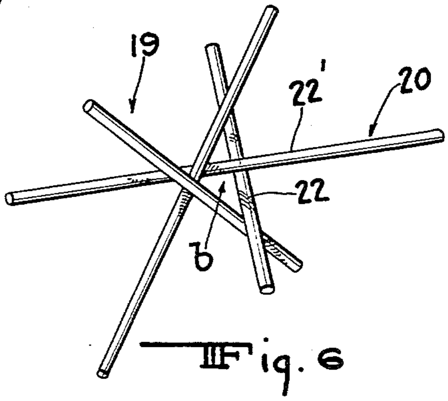


Fig. 6

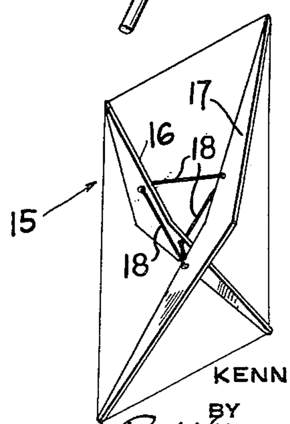


Fig. 3a

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CONTINUOUS TENSION, DISCONTINUOUS COMPRESSION STRUCTURES

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Fig. 7

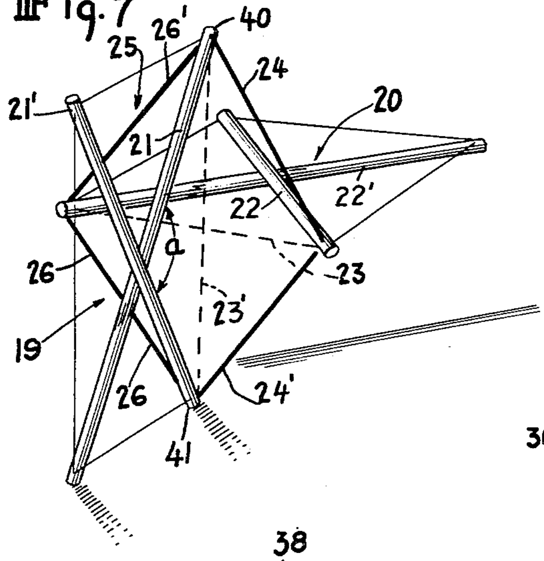
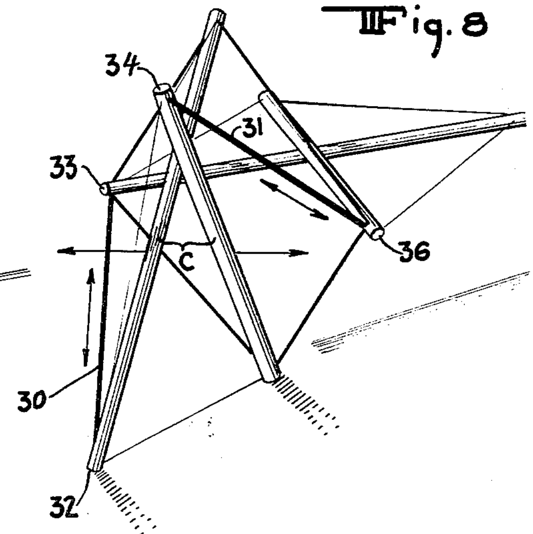


Fig. 8



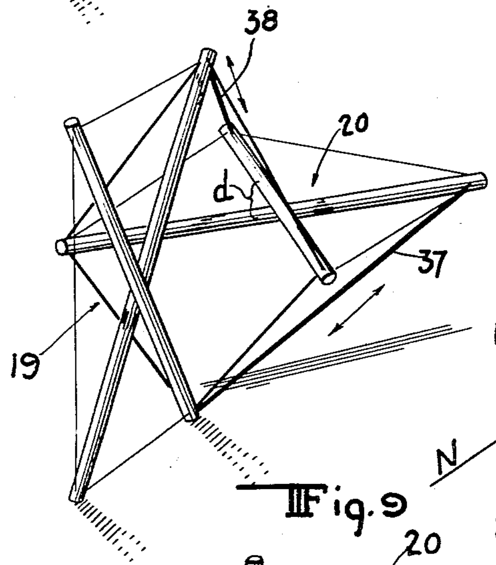


Fig. 9

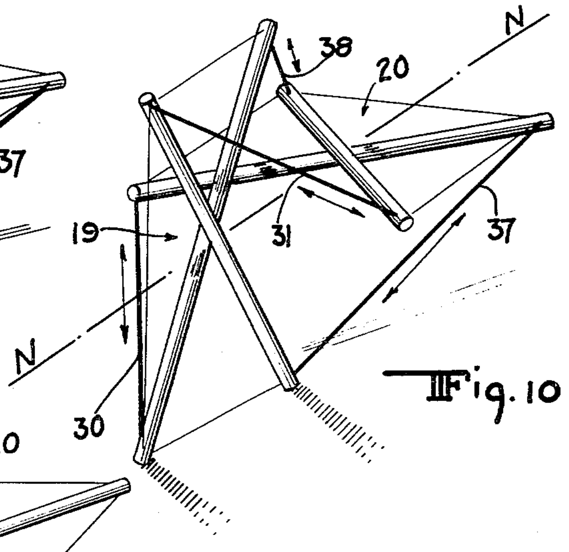


Fig. 10

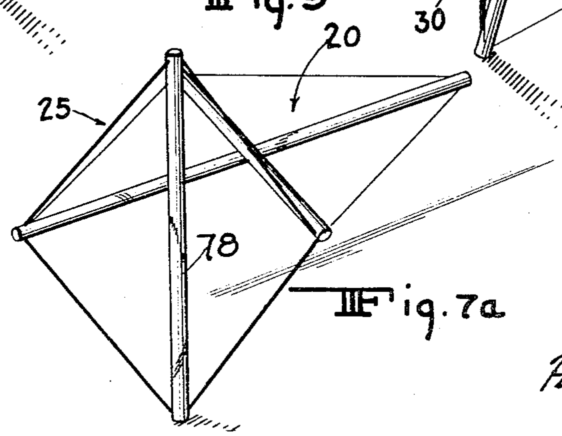


Fig. 7a

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CONTINUOUS TENSION, DISCONTINUOUS COMPRESSION STRUCTURES

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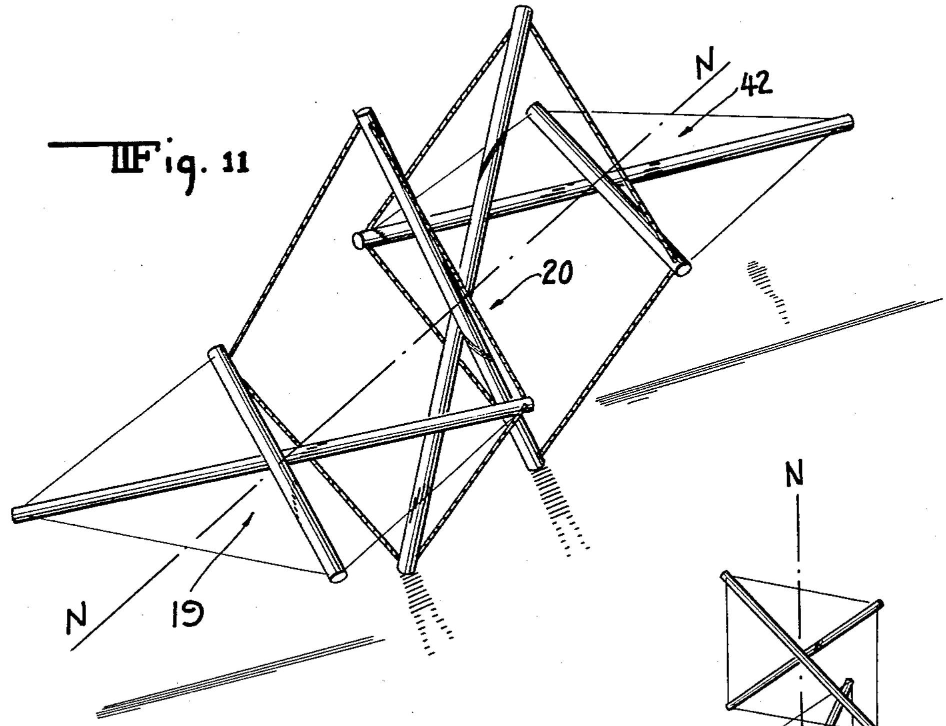

Fig. 11

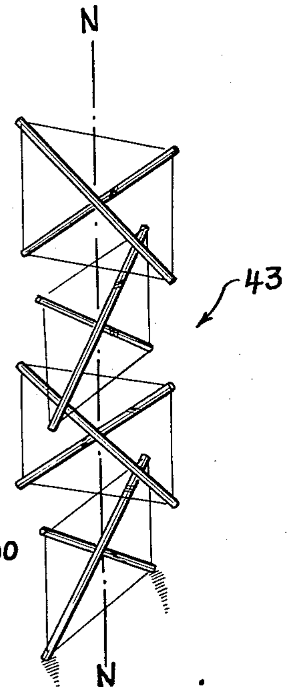

Fig 12

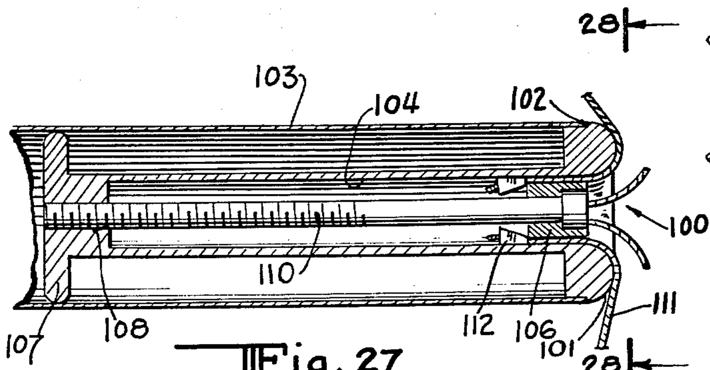

Fig. 27

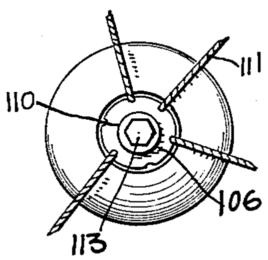

Fig. 28

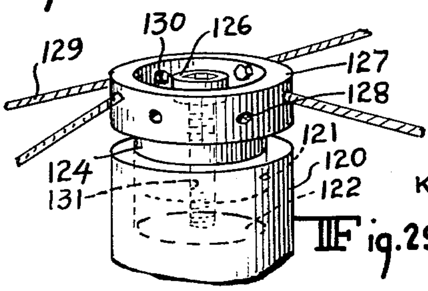

Fig. 29

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CONTINUOUS TENSION, DISCONTINUOUS COMPRESSION STRUCTURES

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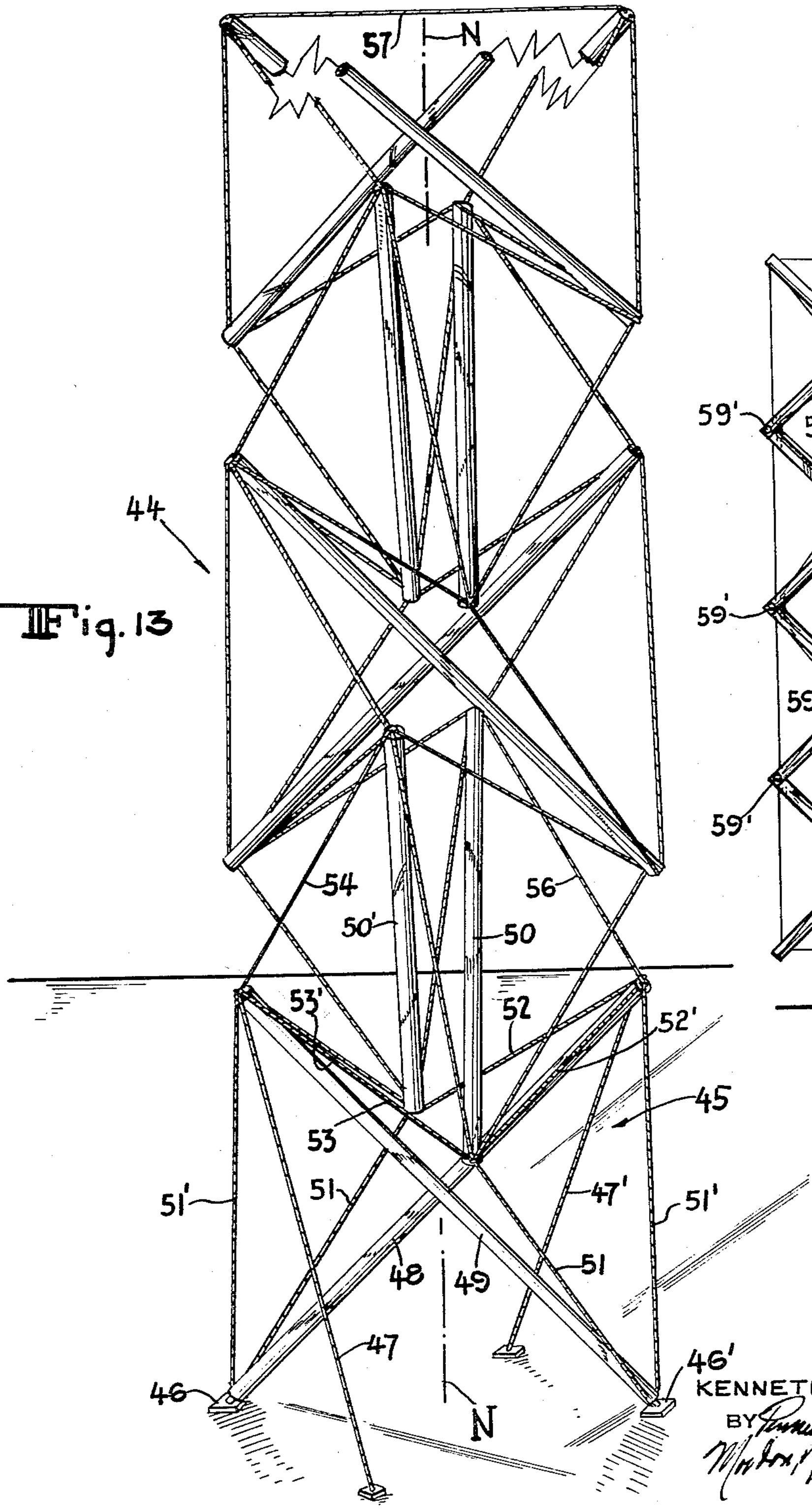

Fig. 13

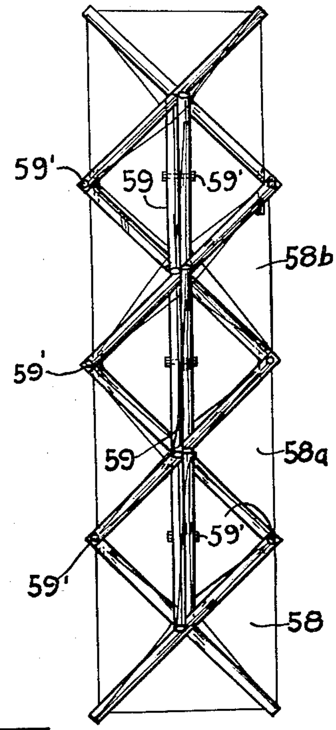

Fig. 14

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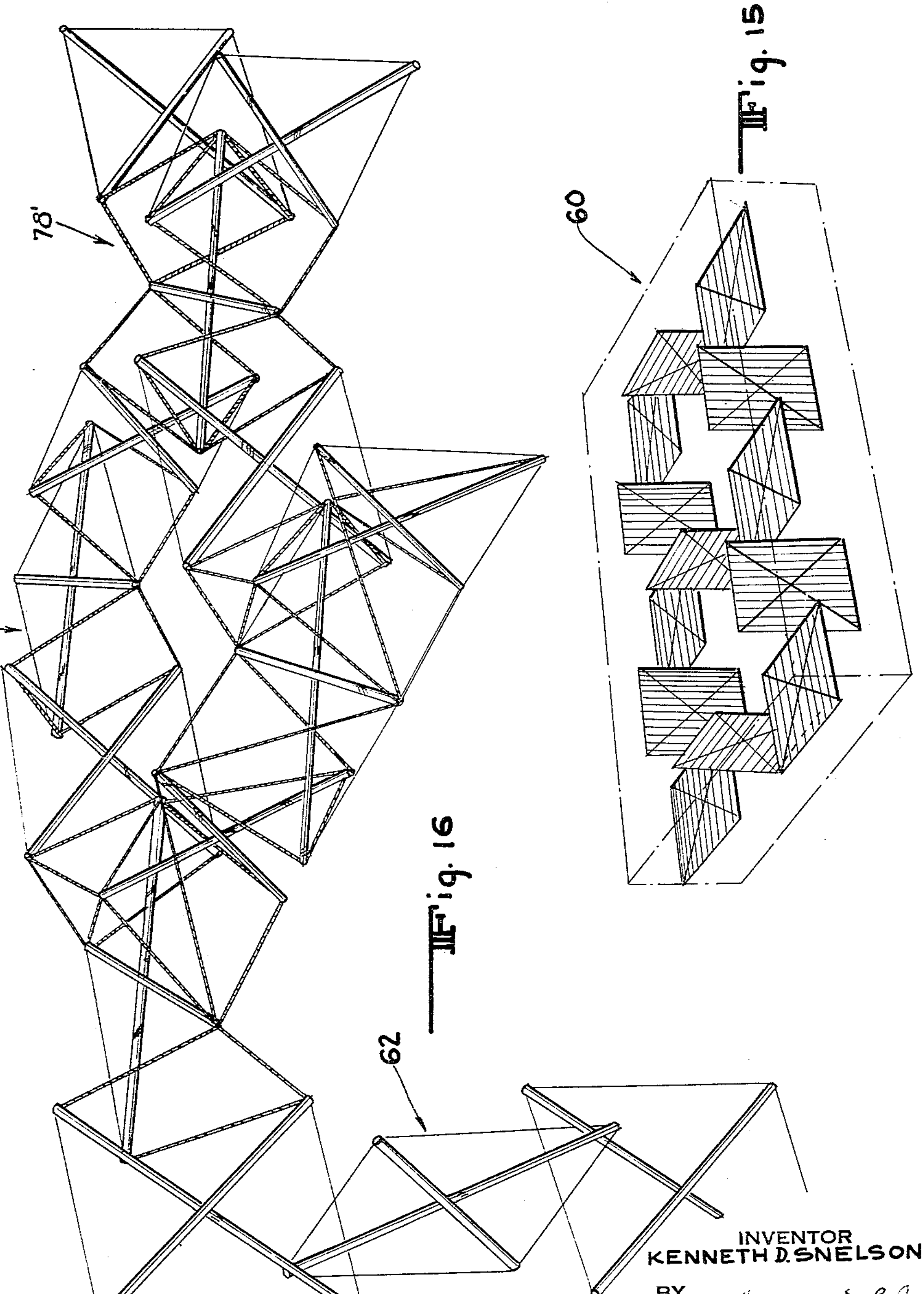

Fig. 15

Fig. 16

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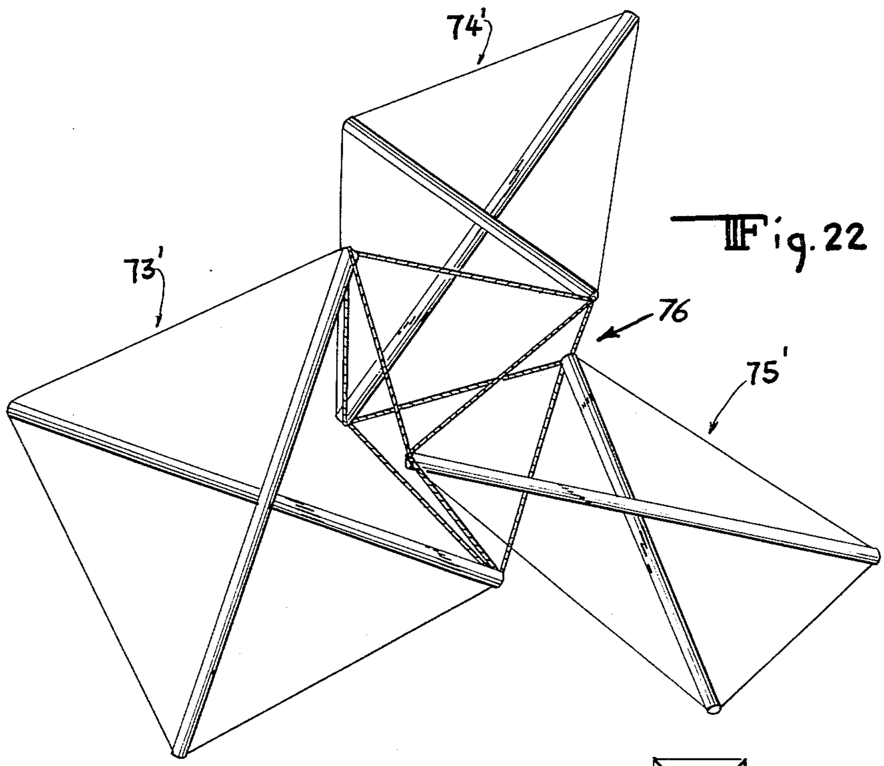

Fig. 22

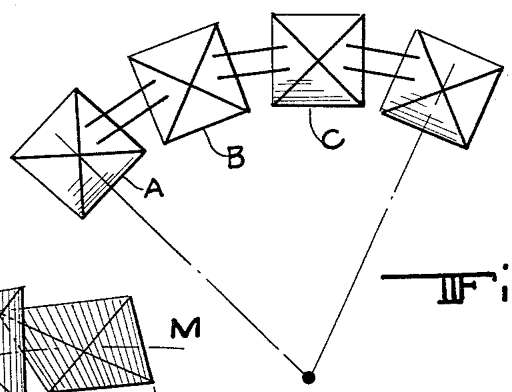

Fig. 18

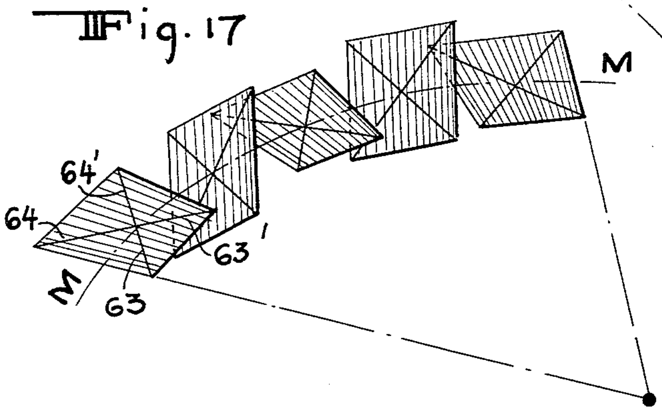

Fig. 17

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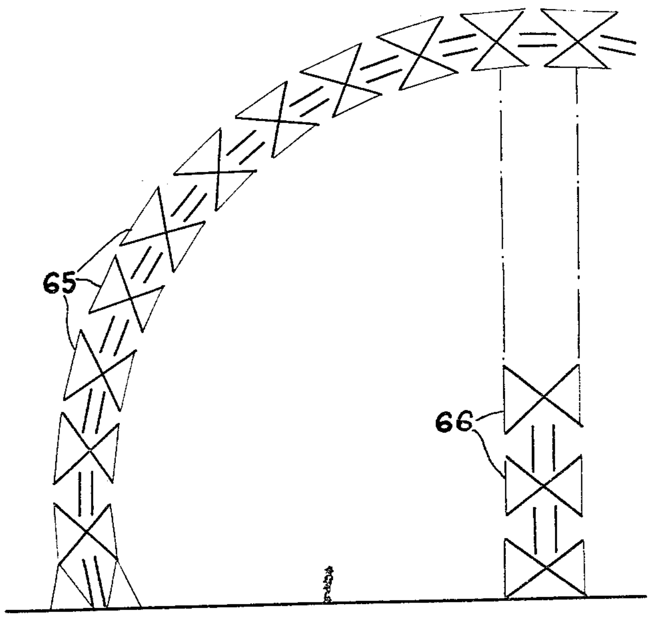

Fig. 19

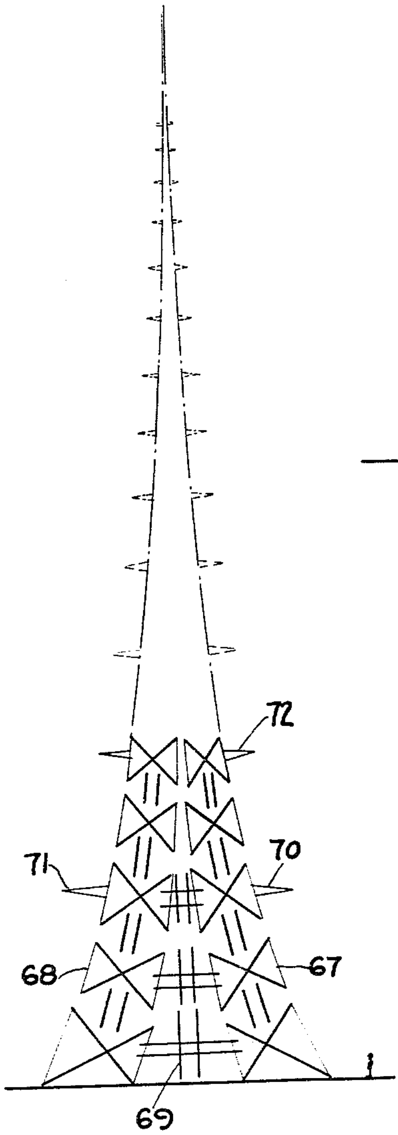

Fig. 20

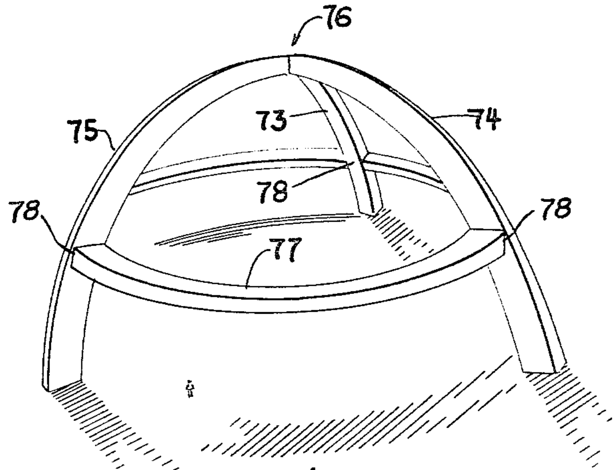

Fig. 21

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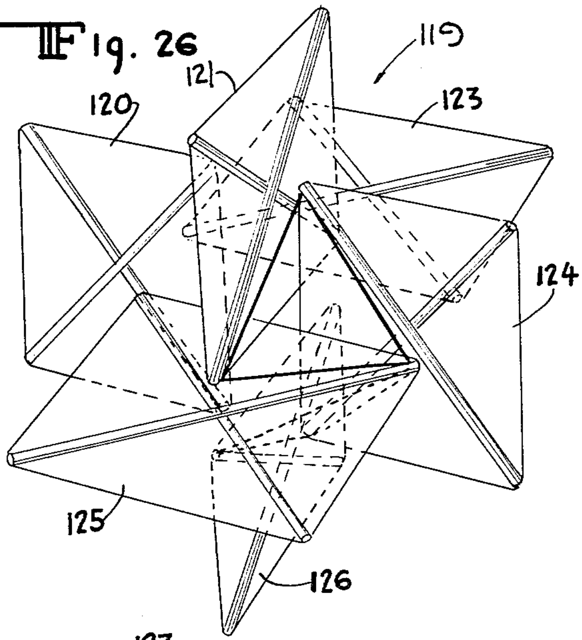
Fig. 26



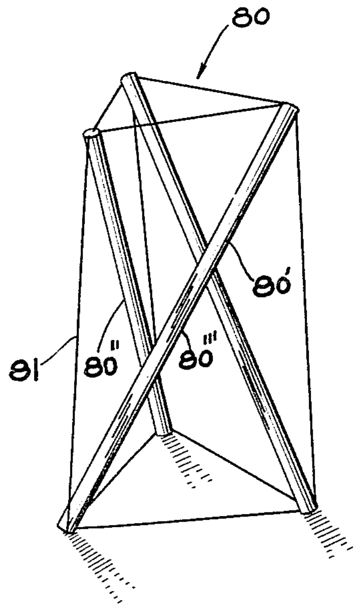


Fig. 22b

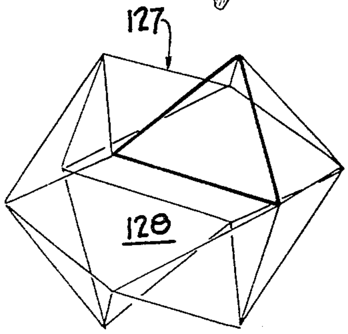


Fig. 26b

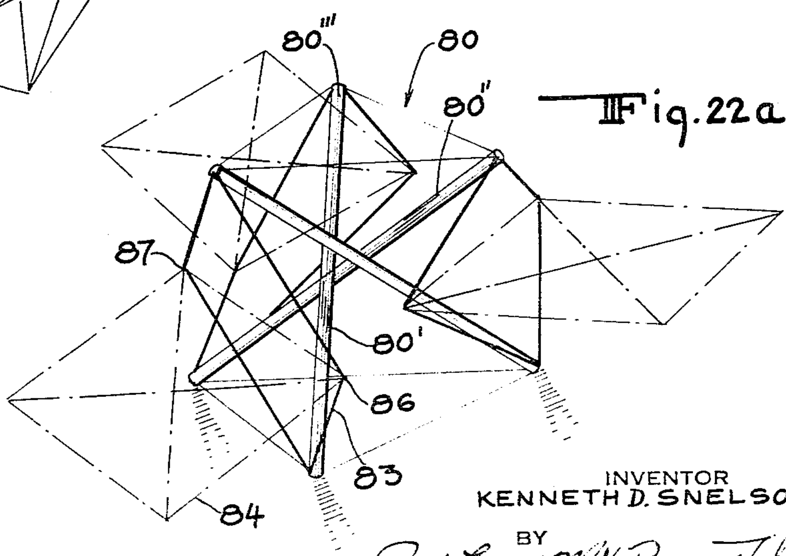


Fig. 22a

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CONTINUOUS TENSION, DISCONTINUOUS COMPRESSION STRUCTURES

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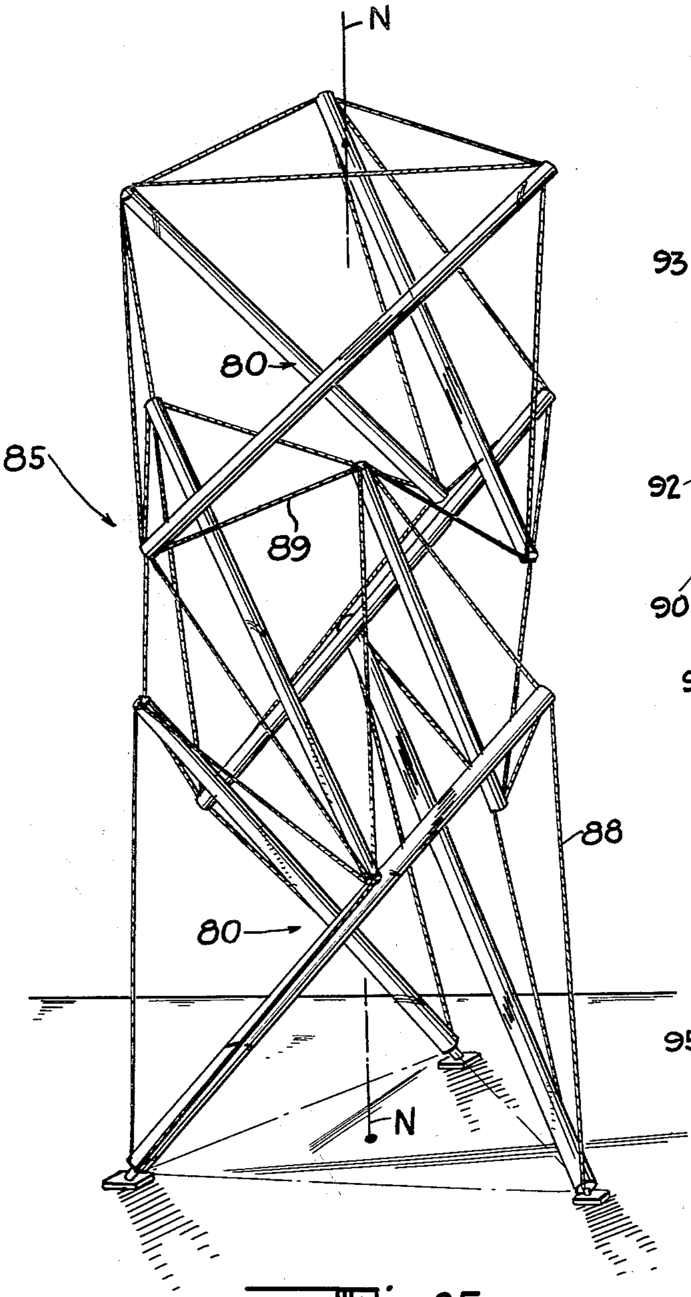

Fig. 25

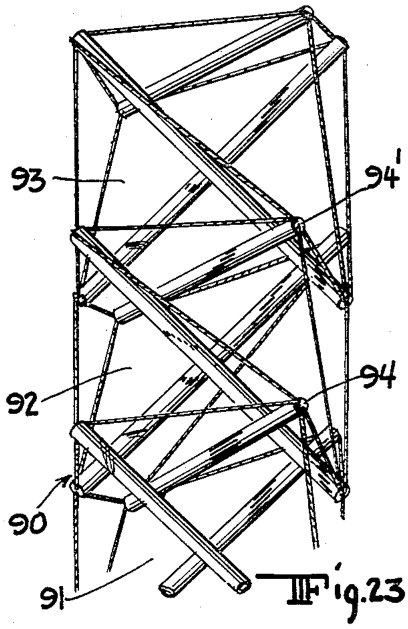

Fig. 23

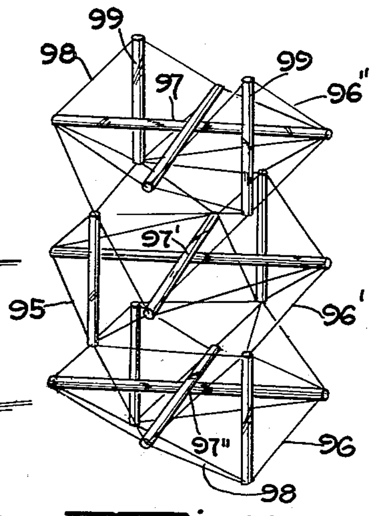

Fig. 24

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3,169,611
CONTINUOUS TENSION, DISCONTINUOUS COMPRESSION STRUCTURES

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(P.O. Box 404, Sagaponack, Long Island, N.Y.)

Filed Mar. 14, 1960, Ser. No. 14,491
6 Claims. (Cl. 189—34)

The present invention relates to structural framework and more particularly, to a novel and improved structure of elongate members which are separately placed either in tension or in compression to form a lattice, the compression members being separated from each other and the tension members being interconnected to form a continuous tension network.

The present invention forms a part of a recently developed class of structures possessing, what may be termed discontinuous compression, continuous tension characteristics. This type of structure is an outgrowth of much earlier forms such as, for example, the wire or tension spoked wheel in which use of tension members has been made to support external compressive loads. Significant weight/strength ratios have been achieved in structures of this type by eliminating heavier compression members and supplanting them with lighter tension members wherever possible. It has been found that materials may be selected which, for a given weight, have tensile strengths several times greater than their ability to withstand compression loads. In fact, most advances in strengths of materials have seen an increase in tensile strengths while compression strength has remained relatively static.

It has been discovered that structures containing elongate compression members such as, for example, rigid tubular struts, might be supported in space and be separated entirely from each other by a network of tension members anchored to and pulling from the ends of adjacent compression members. This arrangement, in common with the wire spoked wheel possesses the advantage of absorbing external loads by a rather unique cooperation between the elements of a compression-tension network. In systems of this type, it has been found that less material, and consequently, less weight of material is required to absorb a given load than where use is made solely of compression members. Compression members are still necessary to complement the tension network; however, the respective lengths thereof may be made quite short thus enabling these members to withstand high loading more efficiently than is possible by the longer compression members ordinarily used in conventional structures. This weight saving factor has always been important structurally, especially in the design of vehicles such as aircraft, missiles, etc. In stationary building structures, the approach has largely been to neglect weight saving considerations as girder rises upon girder, brick upon brick, until the completed building is an immensely heavy structure.

Several different discontinuous compression, continuous tension structures are presently known which form the basic modules or "building blocks" for making more complicated structures such as domes, spheres and the like. A module, it will be understood, is an arrangement of compression members acting as the "bones" or skeleton of the module which are held in relatively rigid relationship to each other by a network of tension members to form a self-supporting unit. A single module may possess the characteristics of having all of the compression members therein isolated from each other by the tension network or alternatively, the compression members may only become completely separated when aditional tension is applied, such as when two or more modules are linked together. Prior art modules often resemble polyhedrons of various orders of magnitude, the number of "sides" being determined by the number of planes defined generally by the ends of the elongated compression members throughout the structure.

It is a basic objective in utilizing the foregoing principles to produce an ultimate structure (such as a dome, sphere, etc.) which can absorb large loads relative to the amount of a given material used. Practically, this requires the greatest use of tension members and the least possible use of members in compression, since the former may be made considerably lighter to withstand tensional forces than the latter to withstand compressional forces. In the evolution or development of new modules there has thus been a constant attempt to develop simpler forms, i.e., units or modules which contain fewer and fewer compression members. To date, the simplest known structure resembles a 3-legged collapsible chair, wherein three elongate compression members are held by a continuous tension network to be self-supporting. The three compression members cross in a spiral intermediate their ends to make this structure resemble the familiar tripod spiral of a sling seated 3-legged collapsible chair.

It is a basic purpose of the present invention to disclose the simplest modular form thought to be possible for a structure of this type. Because of its basic simplicity, the module of the invention lends itself naturally to many applications for use as a basic building block in constructing more complicated structures. Consequently, this structure utilizes tension more efficiently than before possible with the more complicated module forms, to thus bring about a corresponding decreased weight/load ratio.

The basic module disclosed by the invention utilizes only two elongate compression members and an associated tension network, to form a self-supporting structure. The compression members cross each other at some point intermediate their ends in an X-shape or a modified form thereof. The outer ends of the compression members are pulled toward adjacent ends by tension members comprising a continuous tension network. This arrangement forms a self-supporting unit. Means are provided, either in the construction or shape of the compression members themselves, or in the use of additional tension members, for separating the compression members at the points where they cross each other.

As a further aspect of the invention, various composite structures are disclosed which utilize the basic module of the invention as outlined above. In these forms of the invention, the additional tension members for separating various crossed compression members of an individual module, are supplied by interconnecting tension members between the modules. Due to the simplicity of the module, it may be used as a basic building block for almost any composite geometrical figure. To illustrate its utility, the module has been shown as forming a column or tower, an arch, a partial dome or hemisphere and a wall membrane. Included are novel arrangements of modules where they intersect and the joining of the modules of the invention with prior art forms.

It is a further aspect of the invention that individual modules composed of the crossed compression members possess certain left and right-handed characteristics in responding to external forces. This fact may be utilized, if desired, to neutralize the distortion of a structure composed of two or more modules by such forces.

Additionally disclosed herein is a novel joint, which may be connected to the ends of elongate compression members for attaching and adjusting a tension network thereto. A method of utilizing the joint in the prefabrication of a continuous tension, discontinuous compression lattice is described.

These and other aspects of the invention will become more readily apparent upon an examination of the following detailed description of particular embodiments and of the accompanying drawings in which:

FIGS. 1–3 illustrate the construction of an X-shaped module according to the invention;

FIG. 3*a* is a modification of the module according to the invention;

FIGS. 4–6 illustrate the compression members of a module which may be arranged in nesting or non-nesting relationship;

FIGS. 7–10 shows the progressive interconnection of two modules by means of a tension network;

FIG. 11 is an extension of X-shaped modules along a nesting axis;

FIG. 12 is a diagrammatic representation of a column which may be formed by attaching modules together along a single nesting axis;

FIG. 13 is a perspective view of a column similar to that shown in FIG. 12;

FIG. 14 is a column constructed according to the principles outlined in FIGS. 7–13; wherein the tension network permits the compression members to contact each other at the ends thereof and at their individual points of crossing;

FIG. 15 is a diagrammatic representation of a generally uniplanar membrane constructed by using the module of the invention;

FIG. 16 is a perspective view of a membrane structure similar to that shown in FIG. 15 and also showing the interconnection of the membrane with a supporting column;

FIGS. 17 and 18 are diagrammatic representations of variations which may be made to the colums of FIGS. 12 and 13 wherein the successive modules are so arranged as to form a curve or arch;

FIG. 19 shows the initial construction of a dome employing arches constructed according to the arrangement of FIG. 17;

FIG. 20 is a tower constructed according to the invention;

FIG. 21 is a simplified sketch showing interconnected upright arches and their connection with a horizontal curved beam or arch;

FIG. 22 is a three-way intersection of X-shaped modules;

FIG. 22*a* is a three-way intersection of X-shaped modules wherein the structure of FIG. 22*b* has been employed as a nucleus;

FIG. 22*b* is an arrangement of three compression members crossing intermediate the ends thereof and held together by a tension network;

FIGS. 23 and 24 are modifications of the column according to FIGS. 12 and 13 employing X-shaped modules;

FIG. 25 is a column constructed by arranging successively the 3-legged structures of FIG. 22*b* in the form of a column;

FIGS. 26 and 26*a* show a six-way intersection of X-shaped modules;

FIG. 27 is a joint which may be used to interconnect compression members to form a lattice;

FIG. 28 is an end view of the joint of FIG. 27; and

FIG. 29 is a modified joint according to the invention for interconnecting the ends of compression members in a compression-tension lattice.

Referring now to the drawings and specifically to FIGS. 1, 2 and 3, a module **10** has been illustrated which has been constructed according to the invention. The module **10** has two members **11** and **12** which cross intermediate the ends thereof, in a generally X-shaped fashion. The members **11** and **12** cross more or less at their midpoints; however, this is by no means essention as will appear hereinafter. The members **11** and **12** are compression members and as such are fairly rigid and may for example, be constructed of aluminum tubing or of any suitable material adapted to withstand compression loads. The members **11** and **12** are attached to each other by means of a tension network comprising four tension members **13**, such as wires, rods, cables or the like. The tension members **13** are secured to each of the compression members **11** and **12** generally at the ends thereof and pull adjacent ends of the members **11** and **12** toward each other. This has the effect of maintaining the members **11** and **12** in rigid relationship relative to each other and makes the module **10** self-supporting in the initial stages thereof as shown in FIGS. 1 and 2. Another effect is that since all tension forces within the network are equal and are imposed at the ends of the compression members as shown, there is a resultant inward component of forces which causes the members **11**, **12** to be placed into compression. Furthermore, in the illustrated stage of partial completion of the module **10** (FIGS. 1 and 2), the tension members **13** pull each of the members **11**, **12** against each other where they cross, i.e., in a direction perpendicular to the plane in which, generally speaking, the compression members **11**, **12** lie. This imposes a bending load upon the members **11**, **12** which may be relieved as will be described by separating the members **11**, **12** as shown in FIG. 3 by means of outwardly pulling tension members **14**, **14'**. Until this is done, the module **10** as such, is not complete since the compression members thereof, when in contact with each other at the point of crossing, are not properly discontinuous or separated from each other.

In an alternative form shown in FIG. 3*a*, a module **15** has been shown, which is similar in all respects to the module **10**, except that the compression members **16**, **17** thereof are curved or bent in order to initially be separated as they cross. Members **16**, **17** are subject to bending loads induced by their curvature, as a result of any compression forces upon them. These forces are initially a product of the force exerted by the tension network holding the module **15** together and the weight of the module. The compression members may be placed additionally into compression by the application of external loads upon the structure. The tendency for the curving members **16**, **17** to bend may be offset to an extent by attaching the members together where they cross by tension members or catenaries **18**. The module **15** may find its application as a substitute for the module **10**. The module serves to illustrate also that the compression members thereof may cross without interfering. Additional alternate constructions are possible such as where two or more compression members may be interconnected by a tension network to operate as a single compression unit. These compression units may be crossed intermediate their ends to form, in effect, a single module according to the invention. However, it has been found advantageous to use a module having straight compression members to form more complicated structures. When the compression members thereof are separated, as by pulling outwardly on their ends (see FIG. 3) bending loads upon the members initially caused by binding them together by the tension network (FIGS. 1 and 2) may be relieved and the members may be placed more nearly into pure compression. However, because of the curvature of the members **16**, **17** of module **15**, the tendency of the members to bend when placed into compression is inherent and necessarily impairs weight/strength ratios relative to capacity for withstanding compression loads.

In respect to the combining of two or more of the X-shaped modules **10** or **15**, it has been discovered that each module possesses a degree of what might be termed left-handedness or right-handedness which is associated with the manner in which the two compression members thereof cross each other. This factor has been illustrated more specifically in FIGS. 4–6 wherein, for the sake of illustration, two sets **19** and **20** of crossed compression members have been shown without an attending tension network. The compression members 21, 21′ in set 19 have been arranged in a plane generally perpendicular to the plane in which the compression members 22, 22′ in set 20 lie. If the compression members of set 20 are moved toward the members of set 19 in the direction of arrow so that the plane in which set 20 lies, generally bisects the angle *a* formed by the crossed members in set 19, it will be observed that the sets 19, 20 nest closely within each other as illustrated in FIG. 5. This is shown by the absence of a gap between them where they rest against each other. However, if the compression members of set 20 were to have the member 22 crossing beneath the member 22′ and the sets 19, 20 were then brought into a position corresponding to that illustrated in FIG. 5, the relative under and over crossings of the two sets would tend to interfere, and as shown in FIG. 6, a gap *b* would appear between the two sets. The significance of the nesting or non-nesting feature will be explained in greater detail hereinafter.

FIGS. 7 through 10 are an exposition of what may occur when two modules are connected together by a tension network. It will be observed that the plane in which the set 20 lies bisects the angle *a* formed by the crossing of the compression members in set 19. In attaching the modules together, the tension members 23 and 23′ (indicated in dotted lines) are removed and supplanted by the sling or girth 25 (indicated in heavy lines). The tension members 24, 24′, 26, 26′ which form the sling 25 pull adjacent ends of the compression members in the sets 19 and 20 toward each other thereby accomplishing the same result formerly provided by tension members 23, 23′ while also causing the adjacent ends of the compression members in each set 19, 20 to be attached together by a tension network.

The sling 25 actually permits universal movement of the compression members in each of the sets 19 and 20 relative to the other. Therefore, in order to fix the sets in space relative to each, it is necessary to add additional tension members. Furthermore, it is desirable to separate the individual compression members from each other at the points where they cross to make each compression member discontinuous from any other, and to remove bending loads which contact between the members produces. Accordingly, in order to separate the compression members in set 19, two additional tension members 30, 31 have been illustrated in FIG. 8 as having been attached between the ends 32, 33 and 34, 36 of the respective compression members in the sets 19, 20. This has the effect of separating the two compression members in set 19 so that they are separated by a distance *c* as indicated. Similarly, in FIG. 9, additional tension members 37 and 38 are attached to outwardly adjacent ends of the compression members in set 19 to pull them apart a distance *d*. Thus, as shown in FIG. 10 both sets 19 and 20 are separated from each other by the tension network and fixed in space relative to each other and the individual compression members in each of the sets, are also separated by the additional tension members provided.

The combination of two X-shaped modules as shown in FIG. 10 possesses certain characteristics, one of which is related to the previously described left-handedness and right-handedness of the individual modules constructed by selective crossing the compression members thereof. It has been discovered that where the individual sets have been arranged such that the crossed compression members thereof would nest if brought together as heretofore shown in FIGS. 4 and 5, even though separated by the tension network as in FIG. 10, that any external loads imposed upon the structure along an axis N—N lying in the nesting direction, will cause the sets of compression members to spiral slightly (to the extent permitted by the elasticity of the tension network) about the axis. Moreover, the spiralling effect in one set will be counter to the spiralling effect in the next adjacent module. This produces the result that loads directed along the nesting axis are absorbed by all of the modules more or less in equal amounts, by the spiralling of the compression members about the axis in cooperation with the elasticity of the tension network; but the spiralling or torquing within each module tends to be canceled out by the counter-torquing which takes place in the next adjacent module. If, however, the adjacent modules be arranged so that the respective crossed sets of compression members are placed in a non-nesting position (as in FIG. 6) loads directed upon the structure along the nesting axis will cause spiralling to take place in each of the respective modules in the same direction. The effect is therefore cumulative and is similar to the reaction of a helical spring when it is compressed. The relative amount of spiralling that takes place in any given instance will be a function of the rigidity of the structure as a whole and the external loads imposed thereupon.

FIG. 11 discloses a further extension of X-shaped modules along a nesting axis, N—N. The structure of FIG. 11 is similar to that of FIG. 10 except that a third module 42 has been combined with two others. A further combination of modules along the nesting axis has been shown schematically in FIG. 12, to form an upright column 43. In FIG. 13, this arrangement is shown in perspective as a discontinuous compression, continuous tension column 44. The bottom module is shown with the lower ends thereof resting upon base supports 46, 46′. Tension members 51 pull or separate the crossed compression members 48, 49 of the bottom module. Members 47, 47′ serve as guys and as such also serve to assist in separating compression members 48, 49. Similarly, the next ascending module has crossed compression members 50, 50′ which are attached to the lower module by a sling consisting of the tension members 52, 52′ and 53, 53′. In addition, the compression members 50, 50′ are pulled outwardly by tension members 54 and 56 which separate the compression members 50 and 50′ while also imparting lateral stability to the connection between the two modules. Thus, the construction of the column 44 agrees in all particulars with the description heretofore given with respect to FIGS. 7 through 11. It will be apparent that the connection of additional ascending modules may be made in a similar manner and that the structure may be extended almost indefinitely.

One other feature of the arrangement of FIG. 13 should be mentioned here. It will be found that the location of the compression members of each ascending module is about a nesting axis N—N as heretofore described. Moreover, the axis N—N actually will be intermediate the individual compression members so that the gap separating each of these members within each module forms a continuous passageway when viewed from above or below the column, sighting along the axis N—N. As illustrated in FIG. 13, the uppermost module may be provided with a horizontal cross-beam 57 which intercepts the axis N—N. Although it has not been illustrated, the passageway formed by the crossed compression members which follows the axis N—N might, under certain circumstances (where large scale towers are constructed) serve as a central shaft for the passage of an elevator suspended by cables from the horizontal beam 57.

In a further variation of the column shown in FIG. 13 (see FIG. 14), the arrangement may be such that intermediate each ascending module 58, 58*a*, 58*b* etc. in one plane, the X-shaped modules in the plane perpendicular thereto may have the compression members so arranged as to bring the ends of the compression members in both planes into engagement as at 59. If, in addition, the tension network is so arranged as to permit the individual compression members as they cross, to touch (while introducing no bending loads thereupon), the points of crossing may be held together by some means such as a tension bolt 59′. The nearly abutting ends of the X-shaped members in the first plane may also be bolted together. This described arrangement possesses considerable rigidity since the compression members form a continuous network rather than being entirely separated from one another. However, the use of a supporting, interconnecting tension network is retained with its commensurate advantages, and of course, the bolts 59' function largely as tension members.

From what has been described, it will be apparent that the X-shaped module of the present invention is capable of being used to form many different structures having various shapes. As illustrated in FIG. 15 schematically and in FIG. 16 in perspective a generally uniplanar or membrane structure 60 may be constructed by joining together a series of columns in side-by-side relationship (such as just discussed in connection with FIG. 13) by means of a tension network. As will be understood, some of the tension network has been omitted for ease of illustration. One corner of the membrane 60 (FIG. 16) has been shown connected perpendicularly to a column of X-shaped modules 62 which serves as a support therefore. In a practical building structure, the column 62 would be analogous to a wall column and the membrane 60 might correspond to a floor. The membrane 60 would also find application as a vertical wall structure while the column 62 then functions in a horizontal position as a beam.

With reference to FIG. 17, there has been illustrated a variation of the columns shown in FIGS. 12 and 13, as oriented in a generally horizontal position. The attachment or extension of adjacent X-shaped modules shown in FIG. 17 will be essentially the same as the attachment of adjacent modules as shown and described in connection with FIG. 13. However, although the extension is along a single axis M—M, the axis is made to curve incrementally from one module to the next adjacent module. This is done by varying the lengths of the adjacent legs 63, 63' on one side of the crossing of the two compression members of the module as compared with the legs 64, 64' on the other side of the crossing. The manner in which the axis along which the modules are extended is made to curve is by making the legs 63, 63' shorter than the legs 64, 64'. In other words each of the modules whose compression members lie generally in the plane which includes the arc of curvature will be modified as described while interconnecting modules in a plane generally at right angles to the plane of curvature will be unmodified. Actually, since the individual compression members themselves remain the same length, and points of crossing are caused to be unsymmetrical by changing the lengths of the tension members associated therewith to cause the compression members to cross as illustrated. In FIG. 18, this concept is again illustrated where the points of crossing of the individual compression members in the modules A, B, C, for example, are symmetrical, but where a tension network interconnecting the modules A, B, C is arranged to cause the modules to assume incrementally a path of curvature.

The use of the above principle has been shown in FIG. 19 wherein two arches 65, 66 are joined together to form a partial dome. Of course, the principles described in connection with FIGS. 15 and 16 in forming the membrane structure illustrated therein, may be applied to extend the arches 65 and 66 laterally. By this means a membrane of adjacent arches may be formed to completely enclose the area between the arches 65 and 66, thus forming an enclosed hemispherical structure (not shown).

FIG. 20 is a further modification of the invention in which a tapered tower has been constructed. At the base of the tower two columns 67, 68 have been constructed to curve toward each other (according to the method of FIG. 17) and are interconnected at the lower portions of the tower by connecting modules 69. As the columns 67, 68 become joined, the connecting modules 69 are eliminated. The columns 67, 68 have the X-shaped modules thereof arranged with the struts of the upper portions of each module shorter than the struts of the lower portions of each module so that as the structure increases in height, it tapers toward a pinnacle. It will be understood that the uppermost portions of the tower will be of single column construction. Additional modules 70, 71, 72, etc. are attached laterally (as with beginnings of forming a membrane) at intervals to selected modules within the main body of the tower. These modules 70–72, etc. have the respective compression members thereof crossing adjacent the outer ends to simulate a point or spire. These extensions provide additional effective crosssection for greater strength throughout the structure.

FIG. 21 illustrates a structure which may be built by joining a series of arches. Three upright arches 73, 74, 75 are joined together at the apex of a partial dome as indicated by reference numeral 76. An additional horizontal arch or curved beam 77 forms a circle and interconnects the upright arches 73–75. The three points of intersection between the three vertical arches and one horizontal arch has been designated by reference numeral 78. The method of intersecting the horizontal arch 77 with the upright arches 73–75 may be found by an examination of the membrane structure of FIG. 16 wherein a four-way intersection of modules has been indicated at 78'.

The three-way intersection at 76 of the arches 73–75 of FIG. 21 has been illustrated more specifically in FIG. 22. In FIG. 22, the ends of the three arches have been shown having modules 73', 74', 75' to correspond with the respective legs or arches 73–74 of FIG. 21. The particular manner in which the adjacent ends of the modules 73', 74', 75' are joined will be described after a brief discussion of yet another characteristic of the X-shaped module of the invention. With reference again to FIG. 7, the sling 25 thereof, is in one sense, a rectangular or diamond-shaped tension system, the four corners of which are defined by the adjacent ends of the compression members in the two sets 19, 20. It will be observed that the sling 25 could also be formed substantially as shown if, for example (see FIG. 7*a*), the two ends 40, 41 of the crossed compression members in set 19 were to be supplanted by a single compression member 78 extending between the corners of the sling 25 and forming a diagonal thereof. This establishes a singular characteristic of the X-shaped module, viz. that any two adjacent opposing ends of the crossed compression members may be replaced in a structure made up of two or more of the modules, by a single rigid elongate compression member. Conversely, and more important, any two adjacent ends of any X-shaped module may be substituted for a single elongate compression member in any known structure using the compression-tension lattice. What this means in effect, is that in any of the existing forms wherein elongate compression members are now in use, the present X-shaped module lends itself to combining therewith merely by substituting the adjacent ends of an X-shaped module for a single compression member of the more complicated forms. The X-shaped module possesses in itself the rigidity necessary to make this substitution and to have adjacent ends of compression members thereof eliminate a compression member. Since the ends of the X-shaped module are separated by open space, the described substitution succeeds in eliminating a compression member wherever the module of the present invention is combined with other forms.

Referring now to FIG. 22*a*, a three-way intersection of modules has been shown which may be considered to be a prototype of the intersection 76 shown in FIG. 22. In FIG. 22*a*, a structure 80, known in the prior art, which resembles a 3-legged collapsible chair has been used as a center or focal point. This module is shown more particularly in FIG. 22*b*. Any two of the three legs 80', 80'', 80''' of the module 80 forms a tension sling together with the ends of an X-shaped module. One of the slings has been indicated at 83. An X-shaped module 84 associated therewith has the two ends 86, 87 of its crossed compression members attached to diagonally opposite ends of the sling. From what has been described in connection with the substitution of X-shaped modules for single rigid compression members, it will be seen therefore that the final intersection 76 of FIG. 22 has been constructed by appropriately substituting the ends of the three X-shaped modules 73′, 74′ and 75′ for the three compression members 80′, 80″, 80‴ of FIG. 22*a*. The respective ends of the modules 73′, 74′ and 75′ are, of course, attached to each other by the tension network to maintain them in their relative positions. Of course, it will be understood that the basic principle just described may be applied where the center of a given intersection may initially comprise more than three crossed compression members, simply by arranging as radii from the center thereof, linear extensions, of X-shaped modules.

An additional illustration of this principle has been disclosed in connection with FIG. 23. In that figure, a column 90 has been constructed of X-shaped modules 91, 92, 93 by generally orienting the individual crossed compression members of each module in the same plane. As a substitute for the crossed compression members of adjacent modules in a plane perpendicular thereto, there has been substituted horizontal compression struts 94, 94′. As in FIG. 7*a*, the individual compression struts 94, 94′ take the place of the two ends of the compression members in what otherwise might be an adjacent X-shaped module. To carry this principle one step further in FIG. 24, a column 95 has been constructed of three successive layers 96, 96′, 96″ wherein individually crossed sets of compression members 97, 97′, 97″ have been arranged to lie in a generally horizontal plane. Adjacent the outer ends of each of the sets 97, 97′, 97″, a sling 98 similar to the sling 25 of FIGS. 7 and 7*a* has been constructed simply by inserting the upright compression struts 99 as illustrated, the successive layers of crossed compression members in sets 97, 97′, 97″ with their added vertical strut 99 are held together by an interconnected tension network to form a column 95.

Each of the compression members of FIG. 13 may be advantageously constructed of aluminum or other light metals to save weight. In making the connection of the tension network to the several compression members as has been illustrated throughout, the tension members are advantageously secured to the ends of the tubing. This is to assure that the compression members will be substantially placed only into compression. Of course, other arrangemnets are entirely permissible. These will not be described in detail. However, for example, the use of catenaries between individual compression members may in some instances be desirable to enable the structure to withstand loads from certain directions. It is entirely possible for example, that the column shown in FIG. 13 may serve as a horizontal beam. In this case, additional tension members may be required to stiffen the structure against loads transverse to the main axis of the column when it is placed in a horizontal position.

Before leaving a discussion of column structures, such as the column 44 shown in FIG. 13, it should be mentioned that as described, the column of FIG. 13 is a natural evolution of attaching adjacent X-shaped modules together along a single axis. Moreover, while it is not absolutely necessary within the context of the present invention to arrange the successive ascending X-shaped modules with the compression members of each module lying in a plane generally perpendicular to the plane in which the next adjacent module lies, it has been found advantageous as heretofore described to control the arrangement to produce correlative spiralling or spiral-counterspiral between successive modules along a nesting axis. This principle of erecting columns to produce spiral or counterspiraling effects is thought to be wholly novel and may be applied to the association of more complex structures, such as shown in FIG. 22*b*, in a column 85 as shown in FIG. 25.

This is accomplished by arranging the 3 legs or struts of one of the structures or units 80 with the struts canted in an opposite direction to that in which the next ascending group of three compression struts is oriented. As with the column 44 of FIG. 13 which employs X-shaped modules, the column 85 has a sling interconnection between adjacent modules as indicated by the reference numeral 89. Also, as with the X-shaped modules when arranged along a single axis, it is possible to observe the effects of spiral-counterspiral of the individual compression members within each ascending module as the structure as a whole absorbs external loads. The arrangement of the 3-legged compression members may be such as to spiral alternately clockwise-counterclockwise in order to neutralize the cumulative spiralling effect.

In the illustrated arrangement, the effect of a load along the nesting axis N—N will be to cause the individual sets within each structure 80 to spiral in an opposite direction to that of the next adjacent 3-legged structure 80, thus tending to neutralize or cancel out the spiralling effect of the next adjacent unit 80. If, however, the arrangement is such (not shown) that the sets of compression members in each ascending structure are canted in the same direction to resemble an ascending spiral staircase, the effect of a compression load along the nesting axis will be to produce cumulative spiralling about the axis.

With reference to FIG. 26, a unique arrangement of X-shaped modules has been illustrated somewhat diagrammatically in what may be termed a six-way intersection 119. Each of the modules respectively 120–126, is arranged so that the crossed-compression members thereof are substantially in planes perpendicular to the planes in which the next adjacent modules are situated. The internal adjacent ends of the crossed-compression members of the respective modules 120–126 will be held rigidly in the relationship shown by means of a tension network, the arrangement being such that the internal portion of the intersection 119 as defined by the six modules comprises a basic geometric approach to a spherical shell. In FIG. 26*b* the internal tension network 127 of the intersection 119 has been illustrated. The various planes defining an interior hollow portion 128 as outlined by the tension network forms a twenty-sided figure or icosohedron. It will be appreciated by persons interested in the art of building complex lattices using an elongate compression-tension system that the intersection 119 illustrated in FIG. 26 may possess certain unique advantages in that each of the modules 120–126 may be extended in one of six directions and may further be extended laterally as with the membrane of FIGS. 15 and 16, to substantially fill all space.

As illustrated in FIGS. 27 and 28, the ends of individual tension members within a tension network may be connected to the ends of the individual compression members by means of a novel joint 100 having an annular arcuate lip 101 and a shoulder 102 cut into the radially outer periphery of the lip. The shoulder 102 will be seated upon the upper edge of a compression member 103. No threading of the joint 100 into the tube 103 is required since the tension members pull inwardly or toward the center of the compression member 103 and thus hold the joint 100 in the end of member 103.

The joint 100 defines an axial bore 104 adapted to receive a slidable insert 106. The base 107 of the joint 100 defines a tapped hole 108 which may threadably engage with bolt 110, the opposite end of which engages the insert 106. As shown in FIG. 28, the insert 106 has a series of grooves 110 cut into the periphery thereof. An equal number of tension members 111, the ends of which have been fixed to grommets 112 as by swaging, are adapted to be retained within the bore 104 by the insert 106. The bolt 110 has a recessed head 113 which is shaped to receive an insert wrench to be turned thereby so that the bolt may translate inwardly or outwardly of the bore 104. Such translation of bolt 110 will cause the insert 105 to slide within the bore. Thus, when it is desired to apply tension to the members 111, the bolt 110 will be threaded into the tapped hole in the base 107. This will produce a turnbuckle effect upon the tension members 111 which have the ends thereof seated in the grooves within the insert 66 and will draw the ends of the tension members into the compression member 103. As illustrated in FIG. 27, the travel of the bolt and insert into the end of the tube 103 may be considerable, thus, it would be possible to arrange a series of joints 100 with the individual ends of several members 111 attached thereto such that the joints and the tension members comprise a complete tension network. As one method of assembling a structure, for example, a column similar to that shown in FIG. 13, the individual compression members thereof might be placed generally in their correct relative positions while the plurality of the joints 100 and the attending tension network is slipped into the ends thereof. Sufficient slack would be permitted in the tension network for assembly purposes in the lengths of the several individual tension members 111. When the related parts are attached in this manner, each of the individual bolts 110 of the joints 100 would be tightened to draw the attached tension members taut to form a completed structure.

FIG. 29 illustrates a modification of the joint 100 according to the invention. In this form, a plug 120 may be attached or otherwise fitted into the end of a compression member. The plug 120 has a bore 121 and a base thereof 122. Fitted within the bore 121 is a slidable insert member 124. The insert 124 has been provided with a rim 127 having a plurality of radially drilled holes 128. The ends of cable or rod members 129 may be received through the holes 128 and fastened inside thereof by means of nuts 130 and the like. A threaded bolt 126 is received in a correspondingly tapped hole 131 in the insert, and abuts at its lower end, the base 122 of the plug 120. Unlike the joint 100, the individual tension members 129 may be drawn into increasing tension by rotating the bolt 126 so that the insert 124 will be forced to slide outwardly of the plug 122. This form of joint has certain applications where the tension members may comprise heavy cables or substantially rigid rods which would not easily bend about a radius.

It will be understood that the foregoing specific description is merely representative. In order to fully appreciate the spirit and scope of the present invention, reference should be made to the appended claims in which I claim:

1. A continuous tension, discontinuous compression lattice comprising a first set of only two generally elongate compression members crossing intermediate the ends thereof, the compression members of said first set being arranged generally in a first plane, a second set of only two generally elongate compression members crossing intermediate the ends thereof positioned adjacent said first set and lying generally in a second plane, a network of tension members attached generally to the ends of each of said compression members in both sets and pulling adjacent ends toward each other to form a self-supporting structure, said tension members being attached selectively to separate said compression members in a given set.

2. A continuous tension, discontinuous compression lattice according to claim 1 in which said second plane is generally perpendicular to said first plane.

3. A continuous tension, discontinuous compression lattice according to claim 2 in which the individual members in said first and second sets are so arranged that said first and second sets would nest, if brought together along a nesting axis whereby loads directed inwardly of said structure along said axis will cause said first and second sets respectively to spiral and counterspiral relative to each other and about said axis.

4. A continuous tension, discontinuous compression lattice according to claim 2 in which a plurality of first and second sets of compression members are attached together by a tension network, each adjacent set being in a plane generally perpendicular to the next adjacent set, the extension of said plurality of sets continuing in a generally uniplanar direction.

5. A continuous tension, discontinuous compression lattice according to claim 2 in which said extension is along a single axis to form a column.

6. A continuous tension, discontinuous compression lattice according to claim 1, in which each of said compression members comprises a hollow tube, a joint adapted to slidably fit into the end of one of said tubes, means in said joint for connection to individual tension members in said tension network, said means being adjustable to increase the tension in said members connected thereto.

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