

March 15, 1960

Filed Oct. 16, 1956

E. C. HEINE, JR.
FLEXURAL TENSION FRAMING SYSTEM AND
STRUCTURAL UNIT THEREOF

2,928,360

4 Sheets-Sheet 1

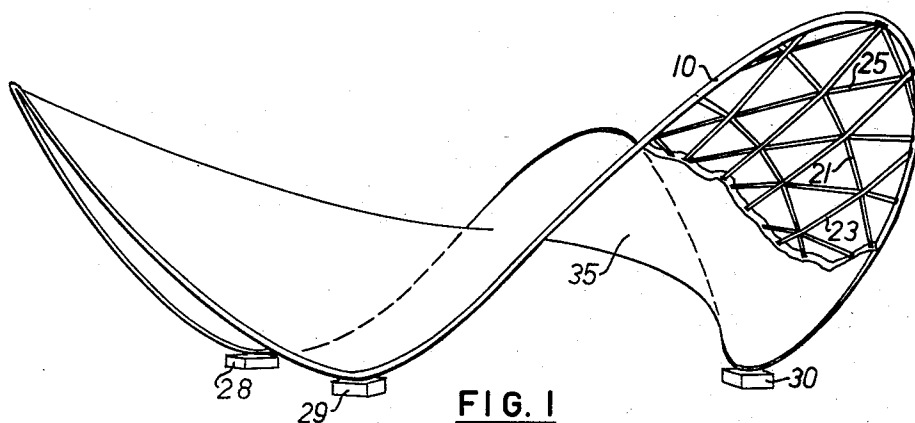


FIG. 1

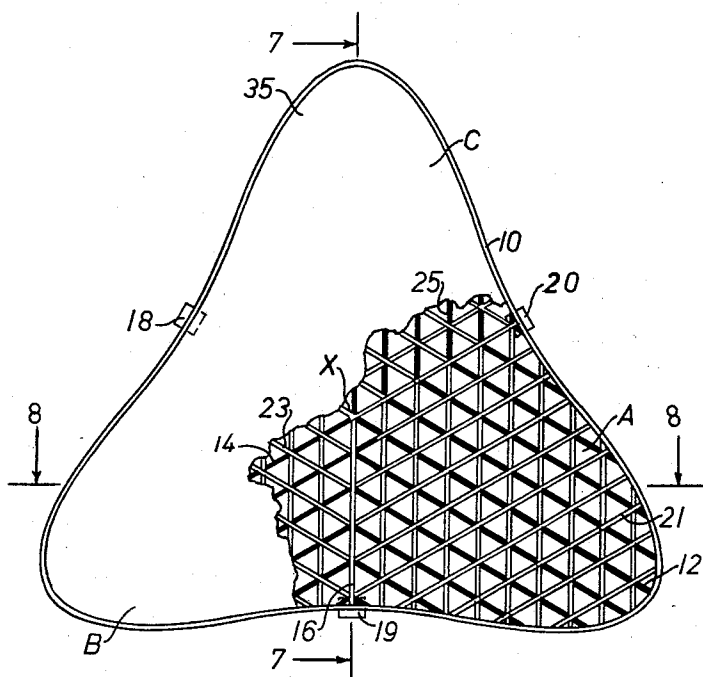


FIG. 2

INVENTOR

Edmund C. Heine Jr.

BY *Thomas, Munro & Russell*

ATTORNEYS

March 15, 1960

E. C. HEINE, JR.
FLEXURAL TENSION FRAMING SYSTEM AND
STRUCTURAL UNIT THEREOF

2,928,360

Filed Oct. 16, 1956

4 Sheets-Sheet 2

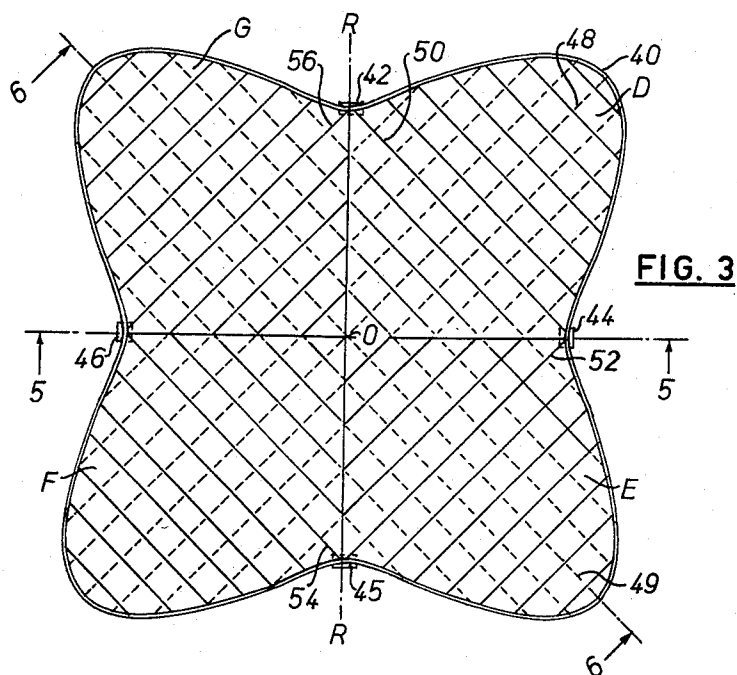


FIG. 3

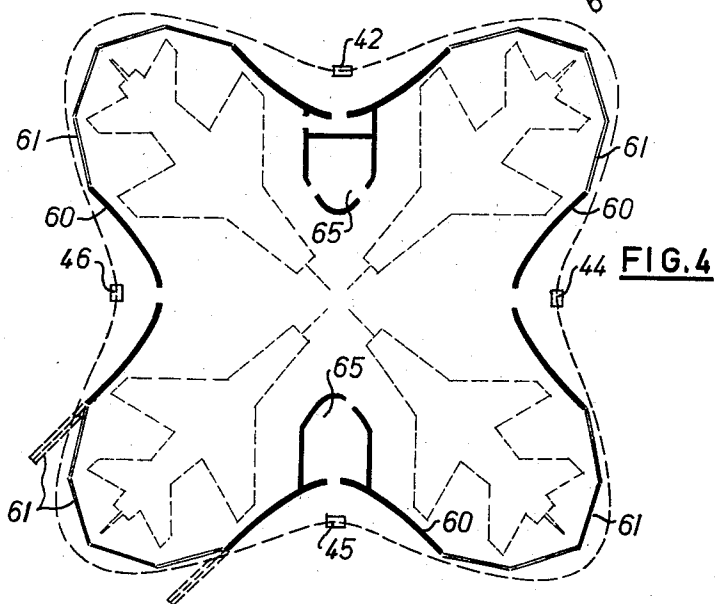


FIG. 4

INVENTOR

Edmund C. Heine Jr.

BY *Thomas, Macrae & Russell*

ATTORNEYS

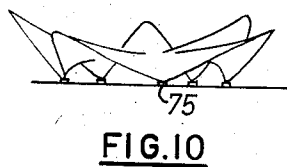
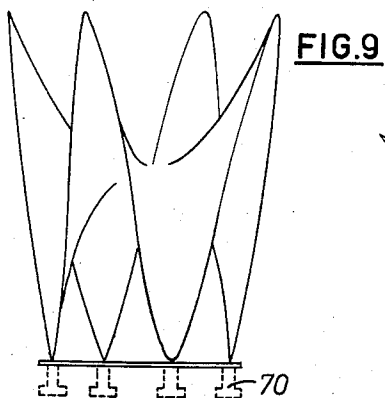
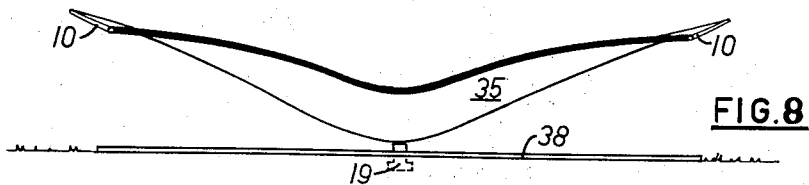
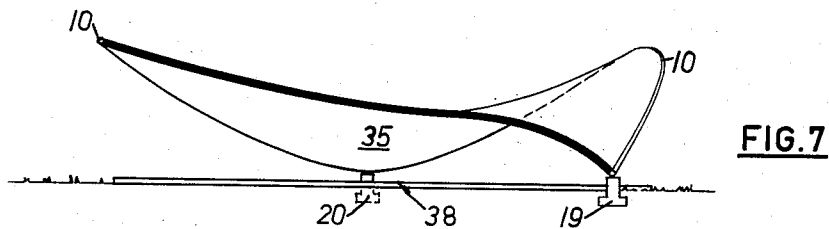
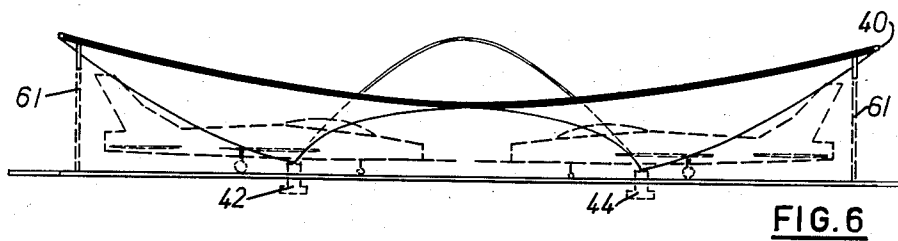
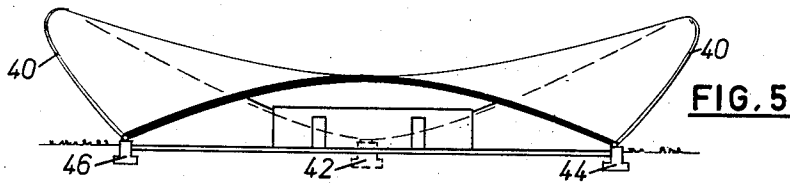
March 15, 1960

E. C. HEINE, JR.
FLEXURAL TENSION FRAMING SYSTEM AND
STRUCTURAL UNIT THEREOF

2,928,360

Filed Oct. 16, 1956

4 Sheets-Sheet 3



INVENTOR

Edmund C. Heine Jr.

BY Thomas, Newman & Russell

ATTORNEYS

March 15, 1960

E. C. HEINE, JR
FLEXURAL TENSION FRAMING SYSTEM AND
STRUCTURAL UNIT THEREOF

2,928,360

Filed Oct. 16, 1956

4 Sheets-Sheet 4

FIG. 11

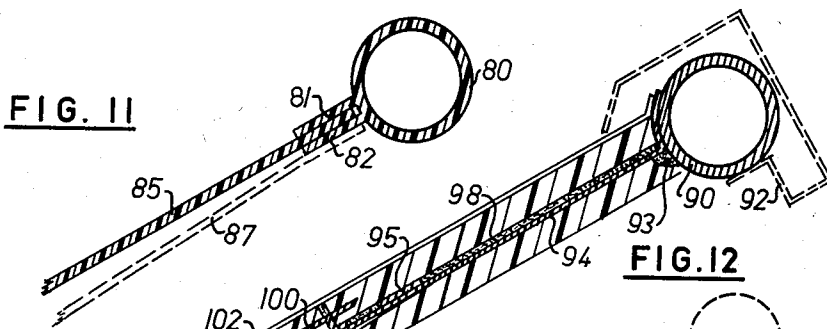


FIG. 12

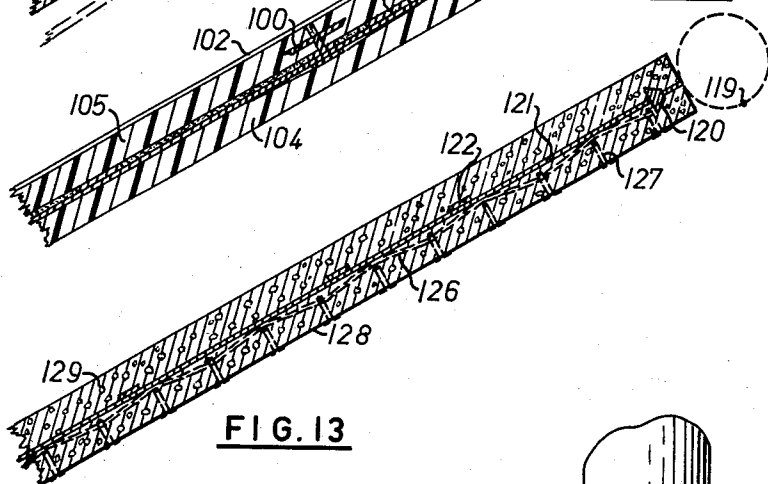


FIG. 13

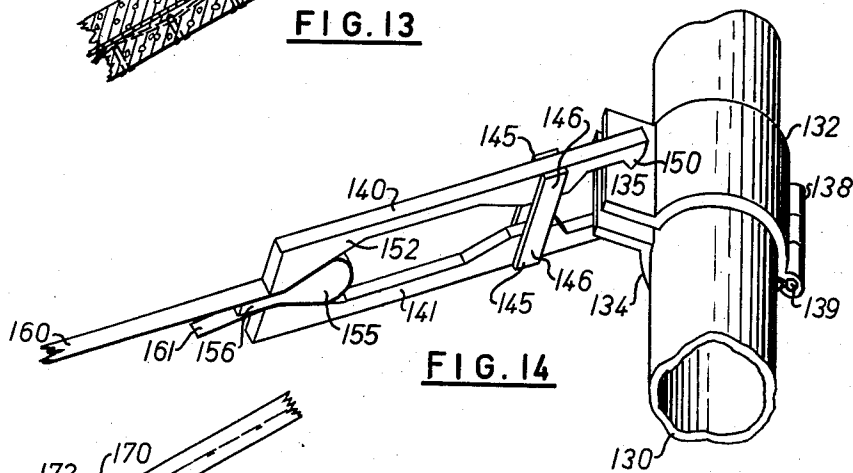


FIG. 14

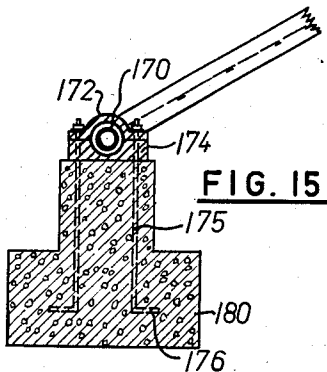


FIG. 15

INVENTOR

Edmund C. Heine Jr.

BY *Thomas, Newman & Russell*

ATTORNEYS

1

2,928,360

FLEXURAL TENSION FRAMING SYSTEM AND STRUCTURAL UNIT THEREOF

Edmund C. Heine, Jr., Arlington, Va.

Application October 16, 1956, Serial No. 616,228

10 Claims. (Cl. 108—1)

This invention relates to an architectural or structural system for providing anticlastically curved thin shell roofs and compoundly curved walls and surfaces. The types of tensioned structural units contemplated by the invention are entirely self-contained, in stable equilibrium and adapted to a wide variety of uses in the general building industry.

More particularly identified, the system involves the primary concept of initially placing a generally curved peripheral member under tension, thus subjecting it to its inherent forces of expansion, in such manner that the entire unit may be described as substantially a tension system throughout. Such results in the formation of a unit, when viewed either in section, in elevation or in plan, as one comprised of a multitude of contiguous, parabolic, or nearly parabolic, curvatures. As further broadly descriptive of my invention and prior to a more detailed disclosure thereof, the novel system might be defined as follows: firstly, one made up of a continuous peripheral member so curved in the flat plane as to circumscribe given area requirements by a series of parabolic curves. This peripheral member is so deformed or deflected normal to, or approximately normal to, such flat plane and in such varying degrees as to obtain a second group of parabolic curves.

Secondly, the deformation of the peripheral member is attained by a network of metal tapes, cables or similar tensionable materials which are primarily and initially secured from a point at or near the respective high points of such peripheral member to a point near or at an opposite point on such periphery. Such tension means, as, for example, steel tapes, thus deflect successive points of the peripheral member in opposite directions roughly normal to a flat plane. They are so crossed with respect to each other as to exert relative compressive forces against each other at their points of contact, or their crossing points. By this system of development of successive parabolic curves in the peripheral member and throughout its intermediate area, the plane developed will be one approaching various contiguous saddle shaped planes. The depths of these are actually functions of the lengths of the various tape or cable components or, stated differently, are the functions of the amount of tension placed upon the various tension members running from one part of the circumference of the peripheral member to another part thereof. At any rate, the completed unit is one in a permanent state of stress due to the bending and compressive forces referred to above.

This structural system is unique over known architectural and engineering forms in that the periphery is under tension, the shape-retaining elements are under tension, and the only forces of compression which are at work are those resulting from the opposed forces exerted at the intersections of the various framework or tension members. The foregoing statement is subject to the qualification that the system of this invention is a tension system in its entirety when lighter weight materials, such as plastic, etc., are used, or, in any case, where the ten-

2

sion developed in the various components of the system is greater than the reaction caused by dead loads within the system. By this is meant loads imposed upon a structure when concrete or some equally heavy material is used as a filler to create the membrane. When this is done, the dead load or weight of such fill overcomes the purely tensional aspect of the peripheral member, or its tendency to expand outwardly. Thus, when heavy materials are employed, this member becomes one existing in compression, the tension developed in the tapes, rods, etc. being resisted by the mass of concrete, thus opposing the tensions in these tapes by the natural resistance or compression of the surrounding mass. What is accomplished, in effect, is a freezing of the outward thrust of the original peripheral member into the filler of the surface itself. At any rate, the so-called load-weight ratio is not substantially reduced or impaired.

The system is thus one based upon a theory diametrically opposed to the usual engineering practices as they are found represented in such building structures or units as the cantilever, the dome, arches, roof trusses, etc. Generally speaking, all of these usual types of supporting structures are predicated upon the principle of compression of the individual elements thereof. As a prime example would be either the dome or arch, both of which usually comprise a series of interfitted parts, compressed with respect to each other, with maximum compressive force exerted downwardly upon whatever base is provided. In the instant case, and subject to the above qualification having reference to the use of materials such as concrete, the only compressive force in this direction is the mere weight of the unit itself; the supporting structure, having a periphery which is under tension throughout, is self-supporting and independent of any forces of compression around that periphery.

It is here to be observed that, in speaking of common forms of structures such as the truss, cantilever, dome, etc., it is true that in each of same there are certain forces of both tension and compression at work; however, the important thing is that these forces are not utilized to the greatest advantage. For example, in a given factory shed, a large number of trusses may be used but, at the same time, stresses developed within each individual truss are not utilized in conjunction with the forces of tension and compression employed throughout the remaining structure. Such is not true of structures of the instant invention.

In known architectural devices utilized as basic frameworks in roofs, bridges and building structures generally, reliance upon compression forces has imposed a definite limitation upon the maximum load-bearing capacity which is obtainable as compared with or in ratio to the weight of such units. As an aspect of the instant invention, it is estimated that the load-weight of unit ratio is far in excess of that heretofore obtainable. The phrase "load-weight ratio" is here to be understood as being the ratio between the load-bearing capacity of the system and the weight of the system itself. It is estimated in this aspect of the invention that certain units following this system will support loads of up to one hundred times the actual weight of the unit. This is due to the fact that the peripheral member, restrained by tension, exerts an outward thrust which is caused by the stress within it, and which resists the bending, gravity and compression reactions resultant from the dead load of substances comprising the membrane supported by such peripheral member.

Structural units as they are generally employed in the architectural field are designed for more or less specific uses and purposes. The instant invention presents a system and structural unit which is almost universal in its application and subject to fabrication out of almost

any type of ordinary building material, including metals, concrete, plastics and even fabrics. Whatever may be the basic material that is utilized, the ultimate completed structure with its warped, parabolic surfaces, is one that is self-contained, stable, self-supporting and free of secondary reactions. Although heretofore considered structurally impossible without secondary bracing or re-inforcing, by the practice of my invention, it is possible to achieve almost limitless variations of useful surfaces and shapes. The system completely eliminates the need for a built-up formwork of any kind, a factor that has heretofore been a principal deterrent to the execution of any but the simplest types of shell structures, particularly those of concrete form, due to cost consideration.

It is, accordingly, a primary object of this invention to provide a self-supporting and self-contained structural unit and a system or method of fabricating such unit that is predicated upon the principle of maintaining a closed periphery under constant stress, either tensional or compressional.

It is a further object of the invention to provide a unit of the described type wherein structural strength, flexibility of design and ease of fabrication and erection all flow from the basic concept that if a continuous curved periphery is subjected to forces that place it out of plane and compel the formation of contiguous parabolic curves in both plan and section, the result will be a self-contained and self-supporting unit of a strength and adaptability far superior to building units and designs heretofore known.

Another object of the invention is the provision of a building structure which is not only of esthetically pleasing appearance but is also readily adaptable to mass production techniques by panelization procedures, and having particular reference to size or volume requirements, these being accomplished without any encroachment on freedom of planning.

It is an additional object of the invention to provide a structure wherein the outward forces, or forces of expansion of a deformed continuous peripheral member is utilized to sustain and stabilize a warped, parabolic surface for which the peripheral member is the boundary.

A further object of the invention is the provision of a building unit which eliminates the requirement of additional framework when the erection thereof involves certain building materials such as concrete, perlite, gypsum, or similar aggregate mixes. In this connection, the tension members which have been referred to, be they wires, tapes, cables or rods, can be utilized as the reinforcing and supporting means for the positioning of panels, fabrics, paper-backing or many variant types of lathing. It follows that these inner component members of the membrane will be suitable for any type of plastic or synthetic sheets or films which may be provided as decking, or for protective or insulative purposes.

Another objective of the invention is the provision of a structural unit that utilizes every component element thereof in at least two ways to the exclusion of secondary bracing or external supporting members, resulting in a design that is self-contained, self-supporting and extremely flexible in the sense that it is subject to practically limitless variations of useful architectural surfaces and shapes. Along this line it is to be further noted that such unit provides complete freedom from obstructive vertical supports of any type whatsoever.

A final objective of the invention is to provide a structural unit that, because of its adaptability and flexibility to the numerous shapes as hereinbefore referred to, may be applied to a multitude of different uses on the one hand and, on the other, may be fabricated of almost any type of material having in mind, of course, such relative size, space requirements, purpose of use and other practical limiting factors as are applicable.

Reference will now be made to the drawings wherein

a more specific description of the invention will be found and wherein:

Figure 1 presents a side elevation view, partially in section, of one embodiment of the invention;

Figure 2 is a plan view, similar to Figure 1 and also partially in section;

Figure 3 is a plan view showing another modification of the invention and illustrating the manner of interweaving the tension members in a four-pointed, approximately square configuration, this view depicting the open lattice-work of the tension members as being filled with a suitable building material;

Figure 4 is a plan view, similar to Figure 3, but showing the roof broken away and the application of this embodiment of the invention to practical use—that of an airplane hangar;

Figure 5 is a section view taken on the line 5—5 of Figure 3;

Figure 6 is a section view taken on the line 6—6 of Figure 3;

Figure 7 is a section view taken on the line 7—7 of Figure 2;

Figure 8 is a section view taken on the line 8—8 of Figure 2;

Figure 9 is an elevation view illustrating another embodiment of the invention adapted, architecturally, for such esthetic building structures as cathedral towers;

Figure 10 is an elevation view of a further embodiment of the invention having five so-called high points with complementary parabolic or near parabolic arches and illustrating the use of the invention for a structure of considerable size;

Figure 11 is a detailed section view of one manner of interconnecting synthetic or plastic tension members to a peripheral member of like material;

Figure 12 is a section view illustrating in detail a manner and means of interconnecting metallic tension members to a peripheral member of like material;

Figure 13, similar to Figures 11 and 12, shows, in section, a tension means which is imbedded in concrete and terminates in a periphery of like material;

Figure 14 is an enlarged detail and perspective view of a means for rapidly interconnecting a given type of tension member to the peripheral framework; and

Figure 15 is a detailed view, in section, showing one form of base support for interconnection with the so-called low points of a given structural unit and with consequent overall support of the entire unit.

Having now more particular reference to Figures 1 and 2 of these drawings, it is seen that the form of the invention here shown is one which in plan is approximately triangular in configuration. Reference is here made to the outline of Figure 2 bordered continuously about its periphery by the peripheral member 10. As seen in section in Figure 1, it is to be appreciated that the contiguous curves here shown are each parabolic in form, the low points representing the ground contact points and the high points representing the peak of what would be, in the usual case, a roof structure.

The materials of fabrication involved in the representation in Figure 10 are intended to be commensurate with a structural size of perhaps 50' laterally from high point to high point. In a structure of this size, the peripheral member would preferably be of a metal such as steel or steel tubing of relatively high tensile strength and having a natural inherent flexibility or springiness—at least sufficiently so to exert a constant outward thrust after being placed under tension by the crossed or interwoven framework. In fabrication of a structure of this type, the contour, before placing the unit under tension and stress, would be somewhat different from that shown in Figure 2, if the amount of curvature necessary is predetermined to be in excess of the elastic limits of the material used. That is, in plan and viewing the peripheral configuration from above, the metal, in such a case, is preferably

5

prebent or prashed so that the periphery at the so-called low points would extend outward to a greater degree as shown in Figure 2, or at least to that degree which would place the periphery under sufficient stress after the tensioning thereof. At any rate, such periphery, placed under stress, provides support for the membrane (of whatever material), the latter effectively locating all points thereof upon or near corresponding points of an imaginary warped plane which yields the minimum possible area within such deflected peripheral member.

As shown in certain of these figures, it is contemplated that the formwork consisting of the many intersecting tension braces or tapes together with the peripheral member, would be suitably filled with concrete, or like material, in a manner to be further referred to hereinafter, resulting in a structure that is actually steel reinforced.

Prior to this, however, the procedure followed in erecting such a unit would be of this order: the formwork 19 is initially prashed to the desired extent, if this be necessary, and subjected to the tensional stress placed upon it by three initial tapes or tension members, namely members 12, 14 and 16. Each of these run from high point to low point of the structure, respectively, and intersect at the center, here indicated at X. They may be subsequently joined together by any suitable media at this point.

By placing a predetermined amount of tension upon these three crossing elements, it is seen that the ultimate high points of the structure are each lifted in this manner, and, having reference to the opposed portion of the approximate triangle or that portion directly opposite each high point, the low points thereof are bowed. These three tension members, 12, 14 and 16, divide the shape of Figure 2 into three different sectors, this feature being mentioned in order to clarify the manner in which the tapes or tension members in each sector overlies or underlies each other, respectively. These three sectors would be as follows: that divided by tape 16, point X, tape 14 and periphery 10 extending between the peripheral points 19 and 20; that circumscribed by tape 16, point X, tape 12 and the periphery 10 extending between the peripheral points 18 and 19; and that bounded by tape 12, point X, tape 14 and the periphery 10 extending between the peripheral points 18 and 20. The three described sectors, for purposes of illustration, are generally indicated at A, B and C, respectively. Each of the initial three tapes or tension members 12, 14 and 16 are maintained in position at the periphery by some appropriate form of securing means, here but diagrammatically indicated at the three points 18, 19 and 20.

The tapes or tension elements within each of the three sectors, A, B and C, do follow a definite pattern, as will be demonstrated, in order that their function of placing the peripheral member in tension and the further necessary function of asserting compressive forces against each other to attain the desired parabola in section, is achieved. Accordingly, having reference to sector or area A, the diagonal tapes 21 appear to be parallel to the initial high to low point tension member 14. Actually, and as seen in Figure 1, the relationship, because of the bowed effect, is asymptotic. In any event, such diagonal tapes lie, in this sector, on top with the other crossing tapes underneath. However, when these tapes 21 meet the boundary line of an adjacent sector, or sector B, it is seen that they then go underneath tape 16 and are placed underneath or, optionally, in between the other intermediate tapes found in that sector. Similarly, and having reference to area B of this triangular configuration, it is seen that the intermediate tapes, here shown as 23, all having an approximately asymptotic relationship to each other and to the initial high to low point tape or tension member 12. These also lie on top of the remaining tapes in this sector until these tension members 23 reach the dividing line of the sector represented by tension member 16. They then underlie the respective tapes found in sector A.

6

Following through with this procedure, the third series of diagonal tapes, with the same relationship to each other and to the initial high to low point tension member 16 and having particular reference to sector A, may be positioned largely on top of or surmounting the remaining tapes in that third sector until meeting the boundary lines defined by the respective tension members 12 and 14. At this point, these can underlie or be intermediate the other two series of tapes as represented by those shown at 21 and 23 at the crossing points found in sectors A and B.

The result of this rather interwoven assembly of tension members is to permit the high points to rise in the manner graphically illustrated in Figure 1 but, because of the intersecting compressive force of the intermediate tapes, to bow these high points, as shown in this figure, to a configuration that is either parabolic or near parabolic in both section as well as in plan.

Illustrated in these two figures (Figures 1 and 2) is a covering for the tapes, as generally indicated at 35. This may be of such material as concrete and poured into a skin or covering which is affixed to the underneath side of the entire assembly, connected to the peripheral member at its outer edges and following the contour of the lacework represented by the relatively large number of crossing tension members. When set, this concrete form will be the full counterpart of the tension system herein described and, taking the form of reinforced concrete due to the imbedded tension members, will exhibit greater, or at least the same, relative strength as the initial steel or metal formwork.

The sectional views of the embodiment of the invention shown in Figures 1 and 2, and here represented in Figures 7 and 8, further illustrate the simplified form which this invention may take when industrially applied as a building structure. Referring to Figures 7 and 8, it is seen that, even in section, the continuous parabolic curve is preserved throughout the section or, in the alternative, an approximate series of parabolas are formed, the latter perhaps also approaching concoidal, curved formations. These figures further illustrate with great clarity the simplicity of ground anchoring of structures of this type, with only three ground loci necessary to rigidly maintain the unit in place upon an appropriate flooring 38.

The use of the parabolic form (having reference to the curvature assumed by the periphery or the curves found in section from any direction) permits the form to reach a height above ground level that is appreciable and fully adequate for any normal clearances. If it be assumed, as suggested above, that the largest diameter of the structure, in plan, is 50', then the average height of the outermost peripheries illustrated in Figures 7 and 8 will approximate 8'. Of course, as will be seen, the type of parabolic form employed is determinative of the height of these elevated points. Since geometrically a parabola may be defined as the intersection of a cone with a plane parallel to its side, the height of the structures herein contemplated is easily varied, within the knowledge of those skilled in the art, by calculations derived from the alternate use of the primary structure, the cone—the more narrow or pointed the cone, the more extended and narrower the resulting parabolas, with consequent elevation of the high points of the tensional system which is herein described.

The basic principle of the invention can be varied to find application to innumerable forms, all tensioned, however, in approximately the same manner. Generally speaking, the triangular formation of Figures 1 and 2, by its very nature, necessitates for proper performance at least three sets of tension members. However, by reference to Figure 3, it is seen that a quadrangle, roughly square, or four-pointed configuration in plan, is shown.

In the construction of the unit of Figure 3, there being an even number of high points and an even number of low points (in contrast to the modification of Figures 1 and 2), the initial stressing by way of tension is accom-

plished by but two sets of tension members, the individual elements of each set being right-angularly disposed with respect to each other. In this instance, also, having reference to the initial stress placed upon the peripheral member, the resilience or spring-back quality of the peripheral member can be prejudged by those skilled in the art and such may be prebent to that degree sufficient to exert the desired degree of outward thrust after the complete formwork has been placed under tension. Here, the initial stresses are obtained by the two longest of the several tension elements, namely elements 49 and 43 which, respectively, run from high point to high point of the peripheral member, here shown at 40, and which intersect at the center of the unit or at the point generally indicated at O.

As with respect to the modification of Figures 1 and 2, and having reference to the interlacing or positioning of the series of tension elements, it is seen that in this case the total area in plan may be divided into quadrants represented by the four areas generally indicated at D, E, F and G. For purposes of explanation, Figure 3 has been bisected by two dividing lines 5-5 and R-R. The quadrant D is thus found to define an area bounded by R-R, point O, 5-5 and with, of course, an outer boundary or peripheral member 40 which extends between the peripheral points 42 and 44. Likewise, quadrant E is an area within the peripheral member defined by 5-5, point O, R-R, and the outer boundary which extends between the peripheral points 44 and 45. The quadrant F lies within the area defined by the line R-R, point O, the line 5-5, with an outer boundary between the peripheral points 45 and 46. The quadrant G, as will be seen referring to Figure 3, lies within the lines 5-5, point O, the line R-R, and the peripheral points 46 and 42. The quadrants F and G are, respectively, within R-R, point O and 5-5, on the one hand, and 5-5, point O and R-R, on the other.

All of the intermediate tension members (although in the plan view appearing parallel to either the central tension tape 48 or its counterpart 49) are actually in approximately asymptotic relationship to each other. Within a given and particular quadrant, such tensional members running across points of elevation to a central point O are on top of the crossing tapes. For example, and having reference to quadrant D of Figure 3, it is seen that the tension member of whatever type and here designated at 50 (as here viewed) approximately runs parallel to the tension member 49 and between the two low points on each side of the quadrant, both located at the supporting positions 42 and 44. In normal practice, the tension members between these two low points, or from ground point to ground point, would first be added with the other overlying tension tapes, within a given quadrant, being added simultaneously or in sequence. Again, having reference to quadrant D, it is seen that the tapes adjacent to tension member 50 and progressing towards the center O of this quadrant, all lie on the top of the tapes running normal thereto. However, as they meet the dividing line 5-5 or the dividing line R-R of this quadrant, these tapes then progress underneath the adjacent tapes which are normal thereto.

This system is followed throughout quadrants E, F and G, where a similar statement is applicable with respect to tension members 52, 54 and 56, respectively.

Thus it is seen that within each quadrant the tapes or tension members exerting compression forces on the crossing tapes are overlying to that point delineating the particular involved quadrant; beyond that boundary they progress underneath adjacent tapes of the adjacent quadrants which run at right angles thereto.

The result is to pull the four corners of the structure represented in Figures 3 and 4 to equal points of maximum height; the further result of this method of interlacing the tapes in this assembly is to bow these elevated points, by the crossing tension members, to pro-

vide contiguous curves approaching the parabolic in form and in shape.

As a practical exemplification of the structure of Figure 3, reference is made to Figure 4 wherein this design, here indicated as being of considerable size, is utilized as a self-supporting roof structure for airplanes. This structure can be enclosed by side walls 60 following the curved contour of the roof, fitted with door 61 and other compartments, as generally indicated at 65, to meet the requirements of any given housing problem of this type. The shape is peculiarly adaptable to airplane storage as indicated by the graphic illustrations of planes, one of which is located in each of the four corners of this quadrantal structure.

This embodiment of the invention is further represented in Figures 5 and 6 which are section views taken on the section lines of Figure 3. The practicality of this variation of the invention is at once apparent from a consideration of such sections where it is seen that despite the relative simplicity of fabrication and erection of a unit of considerable size, there is ample height and surface coverage to accomplish the purposes of this type of building structure. In addition, the all-important factor is still present that with the quadrangular type of unit, only four anchoring points are necessary; extraneous of these, the shelter or housing construction is entirely self-sufficient, eliminating the need of any further buttressing elements or other supporting members.

Further illustrative of the wide variety of structural shapes and configurations that can be obtained with the system comprising this invention are the graphic representations found in Figures 9 and 10 hereof, definitive of the extremes which may be reached in practicing this architectural system. In Figure 9, the continuous parabolic configuration is geometrically and theoretically based upon a cone of acute angularity with respect to the apex; in Figure 10, the opposite is true—the parabolas and concoidal curves there represented are based upon the geometric planes cutting through the surfaces of cones having sides of relatively obtuse angularity with respect to the apex. In each instance, the ground securing medium, here represented at 70 and 75, respectively, is attached to the so-called low point of such curved structure. In the representation of Figure 9 is found a more decorative architectural unit, applicable particularly to cathedral construction. The structure of Figure 10, although "flatter" in overall dimension, is somewhat similar to the embodiment of the invention found in Figures 3 and 4 but here representing a five-pointed construction or one having five high points and the same number of corresponding low points.

It is to be understood that the systems of the types herein referred to may be developed which are asymmetrical in formation, e.g., one elevation of the structure may be higher than the rest in the series, or with respect to a view in plan, one raised point may occupy a greater area, or be projected further, than the others of the series. In any event, the same system, described above, of creating the required curve in section and in plan would be followed.

As stated, not only does the system of the instant invention lend itself to variation in size and application of uses but, most significantly, it is of the type that permits utilization of practically any material for its construction. In Figures 11 to 15, inclusive, are illustrated certain details of construction, particularly with reference to the manner of affixation of the tension members to the peripheral element where the involved problem of use of different construction material is disclosed.

For example, in Figure 11, it is contemplated that an entire unit could be fabricated of plastic or equivalent synthetic materials. Here, the hollow tube 80 is representative of a plastic peripheral member which, either by being inflated or filled or because of its inherent structural strength, exhibits the property of resilience or nec-

essary outward thrust after the application of tension thereto. Tension is applied by constructing the member 80 with interior flanges 81 and 82 which may be either continuous along the inner side of the member 80 or spaced to appropriately receive the spaced tension members. At any rate, the space between these two extensions or flanges 81 and 82 is adapted to receive the end of a tension membrane 85, here shown as also being of plastic. Such synthetics are easily bonded together and, in actual construction of this type of unit, after the member 80 has been brought into its desired flexed position, the tension means 85 is placed in between the flanges 81 and 82 and bonded thereto in a well-known manner. A plastic web or membrane of desired curvature is thus obtained. Similarly, the plastic sheeting 85 can be replaced by fabric, which will function in the same manner.

This plastic form of interconnection has high utility in another respect: if the inner rings 81 and 82 are continuous, then by application of an additional plastic sheet, indicated at 87 in dotted line, a double-walled membrane is formed. Obviously such a double wall provides a dead air space, effective as insulation and effective also as a sound-proofing construction.

Figure 12 is representative of a unit fabricated of high quality metal such as structural steel where the periphery or flexed member 90 may be tubular in formation. If desired, and after stressing of the entire unit in the manner described, this peripheral member can be corniced in any usual manner as by means of the angular enclosure 92, shown in this figure. Steel tapes 94, running from high point to high point, as described, are affixed to the peripheral steel tubing 90 by butt welding, as at 93. These tapes are, of course, crossed by and interwoven with, in the described manner, tapes 95.

In this form of the invention it is contemplated that plastic sheets could be used to form the entire web or membrane, when appropriately affixed to the tension members. Accordingly, as indicated in Figure 12, such tension members can be bonded as by a cement 98 to synthetic sheets 104, 105 located on each side of the elements 94 and 95. Furthermore, and interspersed throughout the web, a usual type of clip 100 may be employed to additionally secure adjacent sheets of this material together. The resulting plastic membrane is then surmounted by any form of suitable sheeting or covering 102, to prevent deterioration of the membrane structure. It is to be here observed that a continuous film of plastic or fabric will achieve the same effect as a series of tension members. Such constitutes, in effect, an infinite number of tension elements, and will function in the same way so long as the film follows the same planes developed by the system of tapes herein described.

At any rate, upon completion of the stressing operation to place the entire structure under tension, and with respect to the interlaced tension members, the upper surface may be covered with any additional suitable material 102. This latter can be in the form of a sheathing, employed for the obvious protective purpose of shielding the underneath tape and plastic structure from the elements.

As another alternative type of construction and one deemed to be most practical in the fabrication of particularly large units, the concrete example of Figure 13 is referred to. Here, the original, supporting peripheral member is but generally and diagrammatically indicated in dotted line at 119. Initial stress is placed upon the periphery in a manner heretofore explained. However, since the structure in its final form is one essentially of reinforced concrete, the tapes or tension members 121 are firmly held in position at their ends by the use of an inverted wedge-shaped lug 120.

The metallic lug 120 is thus, after setting, imbedded in concrete as are the rest of the interlaced tension elements. The shape of such metal lugs 120 (that of a

wedge) is inverted as shown in this figure, so that after the unit has been set in concrete, each wedge-shaped lug (in cross section) resists the forces of tension placed upon it by the corresponding tension members.

After prestressing these tension members 121 to the desired extent, or to that extent to force the unit into its desired parabolic shape, as discussed above, cross tension elements 122 are fixed in the position indicated. It may then be desirable to create a form to receive the poured concrete mix and, to this end, a latticework or expanded type of metal 126 is positioned against the tension members 121 and 122 and affixed thereto in any desirable manner. This last-named metallic lathing 126, or similar type of means, provides support for a number of retaining members 127, such being adapted to hold an underlying covering 128 of paper, cardboard, plywood, etc., or any material that acts as a closure for the underneath side of the completed unit. The concrete 129 may then be poured into the frame and built-up to the extent indicated to provide relatively smooth, curved surfaces on each side of the structure. Upon setting of the mix, it is apparent that the entire unit becomes one of reinforced concrete, the tension members extending from high to low points and, as well, those interlaced with the former, contacting the metallic reinforcing elements.

The peripheral member, diagrammatically indicated at 119, to which the tension members 121 are initially attached for the exertion of stress upon the periphery of the unit, may ultimately be detached and disposed of as salvage or otherwise, when the concrete has set. Since the wedge-shaped lugs 120 are then firmly filled in the concrete periphery and the entire structure is rigid and, in effect, reinforced concrete, the peripheral member 119 is no longer needed to preserve the structural strength of the unit.

Means have been provided for simplifying the manner of interconnection of such tension members, as metal tapes, to the continuous peripheral element, as it has been identified above. In Figure 14, this latter element, here shown at 130, may consist of a steel tubular element, prebent to a predetermined extent so that it will, as stated aforesaid, exert only the desired amount of outward thrust or resilience. The several referred to tapes can be easily attached by the mechanism depicted in this figure. Here, two elements 132 and 134, semi-circular in configuration and having an interior concave shape complementary to the shape of the peripheral member, are hinged together by means of a hinge 138, fitted with the usual hinge pin 139. Each of these members 132, 134 terminate, opposite the hinge point, in extensions 135 which, when disposed in the position shown in this figure, are parallel or approximately parallel to each other.

A clamping means to engage these two flanges 135 takes the form of two bars 140 and 141, shaped approximately as shown in Figure 14, and disposed, when in locked position, in approximately parallel relationship. Each of these bars 140, 141 are hinged near the end adjacent the peripheral member by means of oppositely positioned hinge plates 145, perforated at either end to receive pivot pins 146, the latter pivotally interconnecting these two bars together. At the end near the tubular element 130, each of the bars is provided with a relatively sharp right-angular projection 150, the latter being adapted, under adequate pressure, to tightly engage with or bite into the metal of the flanges 135. It is obvious that suitable depressions may be created in these flanges for the reception of such projections 150 to further assure permanent fixation of the same.

The opposite end of these parallel, hinged bars 140, 141, and with respect to the inner or facing edges of same, is angled as at 152, these edges thus approaching each other with the same angular deflection. A tape holding wedge 155, having the sides thereof angled complementary to the angle formed between the adjacent

angled edges of bars 140, 141, when approximately parallel to each other, terminates interiorly in an extension 156, the latter, as shown, having parallel sides. Reference to Figure 14 should make clear the construction of the inner sides of these bars 140, 141, and the complementary shape of the wedge 155. In operation of this system, the tape 160 can be placed completely around the wedge 155, as shown. With the exertion of tension upon the tape 160, the same is drawn tightly, by the wedge, against the inner sides of these parallel bars. By reason of the hinged relationship of the latter, the opposite ends of these bars, due to the wedge action, are brought together. Hence, the greater the amount of tension applied, the greater the "bite" upon the flanges 135 and the more tightly the tape is held within the connecting assembly represented by these two parallel bars 140, 141. It is thus seen that this interconnection is of the utmost simplicity and once in place, the amount of tension can be carefully regulated by pulling through the tape end 161 to the desired extent. Such type of interconnection is, of course, applicable to almost any variant of this invention and equally appropriate for use with plastic peripheral members and plastic tapes or tension members when utilization of the same is indicated.

Reference has been made to the fact that the number of ground supports necessary are few in number: actually, ground contact points are of a number equalling the number of the so-called low points of the system. It follows that the number of ground contact points are the same as the number of high points of the system. At any rate, one means of ground interconnection with the all-important membrane supporting peripheral member is found in Figure 15. Here, such peripheral member is indicated at 170. It is encased in what might be termed a bearing block, i.e., a two-part element consisting of a top semi-circular cover 172 and a base member 174 of complementary shape, both being provided with interior, concave surfaces to approximately match the external circumference of the peripheral member 170.

This so-called bearing member is affixed in a concrete block 180 by means of two or more bolts 175 that terminate in lateral flanges 176. The latter will assure retention of the bolts 175 and, hence, the accompanying clamping structure in the block 180 after setting of the mix. This structure in one sense is actually a bearing member because, if desired, the tolerances can be such that the holding or retention power is maximum while the peripheral member is permitted to twist and even move longitudinally somewhat to accommodate possible changes in the length or size of the tubular element due, for instance, to temperature fluctuations and resultant contraction or expansion of the metal.

In summary of the description of the invention, as rendered above, it is the essence of this concept that the structural components of the system described will develop warped surfaces that are self-contained, stable, self-supporting and free of secondary reactions. As indicated, use of this system permits achievement of limitless variations of useful surfaces and shapes hitherto deemed structurally impossible without some form of secondary bracing or reinforcement. The system of this invention completely eliminates the need for a built-up formwork of any kind, it being generally recognized that such constitutes the principal deterrent to the execution of any but the simplest types of shell structures in concrete due to cost consideration.

Having particular reference to the execution of the system in concrete wherein a network of rods, cables, etc. is employed, it will further be clear that the peripheral member may be detached, salvaged or disposed of if the ends of the rods or cables are provided with lugs which become imbedded in the concrete (e.g., see Figure 13). The remaining concrete shell will then represent an achievement in negatively curved architectural surfaces, somewhat akin to the positively curved surfaces

of a dome structure. The main difference from the dome type configuration is that the perimeter of the dome develops a tension which is restrained by buttresses, cables, tie rods, etc., while the surface of the dome itself is in compression. The perimeter of the new negatively curved surfaces, represented by this invention, is in compression, acting like an endless succession of edges restrained by the opposed tension in the surface proper and achieving alignment by the continuous, unbroken, successive curvatures of the perimeter.

As inferred above and again having reference to the wide variety of applications of the principles here set forth, the use of plastic in the execution of the system presents the art with an inexpensive, light-weight, yet extremely durable form of structural unit. Such, in fact, can be realized by employing either a plastic or textile film for the membrane. These would constitute units of low weight when used together with a peripheral member of relatively thin-walled plastic tubing. When suitably patterned prior to the stressing thereof, the membrane will assume a predetermined warped shape when the peripheral member is filled with compressed air or with plastic materials under pressure which may or may not harden once injected. Conductive to manufacture in rather small sizes, such plastic units can be provided with side curtains following the periphery of the high points, thus providing light weight shelters, useful as tents, which can be very compactly packaged and erected in a minimum of time. For such shelters requiring rather higher degrees of insulation, the area within the peripheral member may be covered by a second membrane 86 (as referred to in the explanation with reference to Figure 11), thus providing a dead air space (or space to receive insulation) between the inner and outer skin thereof.

As a basic premise for this entire system, it is thus to be noted that the invention provides a structural unit wherein an exceptionally high degree of use is made out of every one of the several components that enter into it. This sharply distinguishes this system and the structural units derived from it from architectural projects heretofore known where exterior supporting or reinforcing elements are necessary in order to obtain the required load-bearing capacities.

It is obvious that this invention may be varied in many ways and other expedients employed to accomplish the purposes thereof; however, it is to be understood that the scope of this invention is to be limited only by the scope of the appended claims.

I claim:

1. In a structural unit, a closed and curved, continuous, peripheral element of resilient material, said element exerting constant outward thrust, said element being prebent to prevent fracture due to application of stress beyond the elastic limit thereof, means to place said periphery under tensional stress, said means comprising tension members interconnecting one side of said periphery to an opposite side thereof, a second series of tension members positioned angularly to said first tension means and also connecting opposed portions of said peripheral element, said peripheral element being under suspended tension by said series of tension means said element having successive high and low points and having a shape approximating contiguous parabolic curves both in section and in plan.

2. In a structural unit, a closed, curved, continuous, peripheral element of material of inherent elasticity, said element being present to exert constant outward thrust, said element being prebent in the direction of interiorly directed tensional forces to prevent fracture upon the application of tensional stress beyond the elastic limit thereof, means to place said periphery under tensional stress, said means comprising tension members interconnecting one side of said periphery to an opposite side thereof, a second series of tension members positioned angularly to said first tension means and also connect-

ing opposed portions of said peripheral element, both of said series of tension means placing said peripheral element under tension, said element having successive high and low points and having an approximate parabolic curve both in section and in plan, said high and low points comprising sectors of a corresponding number, the tension members on top in any given sector running underneath other tension members in any other sector.

3. In a structural unit, a closed, continuous, peripheral element of elastic material having the property of exerting thrust outwardly when placed under tensional stress directed towards the center thereof, said element being prebent in the direction of interiorly directed tensional forces to prevent fracture upon the application of tensional stress beyond the elastic limit of the element, said element defining in plan an area approximately triangular in configuration, means to place said element under tensional stress, said means comprising three tension tapes extending from each corner of said triangular configuration to the opposed side thereof, said tapes comprising three sectors of equal dimension, additional tension members parallel to each of said tension tapes, the tension tapes and members on top in each sector running underneath angularly inclined tension members and tapes in any other of said sectors, said tension tapes and tension means placing said peripheral element under tension said element having successive high corner and low intermediate points, said element and the area defined thereby comprising contiguous and approximately parabolic curves throughout both in plan and in section.

4. In a structural unit, a closed, continuous, peripheral element of inherent elasticity, said element being prebent to prevent fracture upon the application of tensional stress beyond the elastic limit thereof, said element being prestressed to exert constant, outward thrust, said element defining an approximately square configuration in plan, means to place said element under tensional stress, said means comprising tension tapes extending from corner to corner of said square configuration, said tapes defining four sectors of equal dimension, additional tension members in each of said corners disposed normal to the plane of said tension tapes, the tension tapes and tension members lying on top in any sector being disposed underneath the tension tapes and tension members of any adjacent sector, said tension tapes and members placing said peripheral element under tensional stress, said element having adjacent high and low points respectively, said element comprising, in both plan and section, a structure having a series of contiguous parabolic curves.

5. In a structural system, the method of fabrication of a unit which is under stress throughout the periphery and the area circumscribed thereby, comprising forming an endless curved periphery having inherent elasticity causing it to exert outward thrust throughout when placed under stress, submitting said member to tensional stress by interconnecting opposite sides of said periphery and drawing said opposite sides together by interior tension members, thereby creating interiorly directed forces to form successive low and high points in said periphery, said circumscribed area forming a plurality of sectors equal in number to the number of said low and high points, interconnecting said tension members so that said tension members in any one of said sectors which overlie the others of said tension members, underlie the others of said tension members in any other of said sectors, said forces creating a series of contiguous, approximately parabolic curves in section and in plan throughout said periphery and throughout the area defined thereby.

6. In a structural unit, a closed peripheral element, said element being prestressed to exert an outwardly directed, constant thrust, means to place said element under tensional stress to form contiguous, approximately parabolic curves in both plan and section, said means com-

prising a membrane within said element exerting interiorly directed forces thereupon, said peripheral element having at least two low points and a corresponding number of high points are formed in said peripheral element.

7. In a structural unit, a closed peripheral element, said element being prestressed to exert an outwardly directed, constant thrust, means to place said element under tensional stress, said means having contiguous parabolic curves in both plan and section, said means comprising a membrane within said element exerting interiorly directed forces thereupon, said element and said membrane forming a compoundly curved shell structure, said peripheral element having at least two contiguous low and high points.

8. In a structural unit, a continuous, spring-loaded peripheral element of resilient material, said element exerting outward thrust throughout, means to place said element under stress in a direction opposite the direction of said thrust, said means comprising a membrane interconnecting opposed sides of said peripheral element, said membrane placing said peripheral element under restrictive tension, said element having successive high and low points, said element having curves of approximately parabolic configuration in both longitudinal and lateral section.

9. In a structural unit, a spring-loaded peripheral element of resilient material defining a closed area, said element being adapted to exert thrust outwardly in a direction away from the center of said area, means to place said element under stress, said means comprising a membrane interconnecting opposed sides of said periphery, said membrane extending throughout said area and placing said peripheral element under restraint, said peripheral element having successive high and low points, said membrane comprising an anticlastic formation having approximately parabolic curvatures in one direction and having additional approximately parabolic curvatures in a direction approximately normal to said one direction.

10. In a structural unit, a spring-loaded peripheral element of resilient material defining a closed area, said element being adapted to exert thrust outwardly in a direction away from the center of said area, means to place said element under stress, said means comprising a membrane interconnecting opposed sides of said peripheral element, said membrane consisting of at least two series of tapes interconnecting opposed points on said element, one of said series of said tapes being positioned in a direction approximately normal to another of said series, said membrane extending throughout said area and placing said peripheral element under restraint, said element having successive high and low points, said membrane having an anticlastic shape consisting of approximately parabolic curvatures in one direction and consisting of additional approximately parabolic curvatures in a direction approximately normal to said one direction.

References Cited in the file of this patent

UNITED STATES PATENTS

2,545,556 Pont ----- Mar. 20, 1951

FOREIGN PATENTS

1,120,195 France ----- Apr. 16, 1956

OTHER REFERENCES

Engineering News Record, December 1954, page 36.
Journal of the American Concrete Institute, January 1955, pp. 397-415.
Progressive Architecture, March 1955, pp. 130-131.
House and Home, August 1955, pp. 95-96.
Progressive Architecture, September 1955, pp. 82-83.
Civil Engineering, May 1956, pp. 64-65.
House and Home, September 1956, pp. 134-135.