

[54] **LIGHTWEIGHT HYPERBOLIC
PARABOLOID ROOF STRUCTURE**

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[51] Int. Cl. **E04b 1/32**

[58] Field of Search..... 52/80, 81, 86

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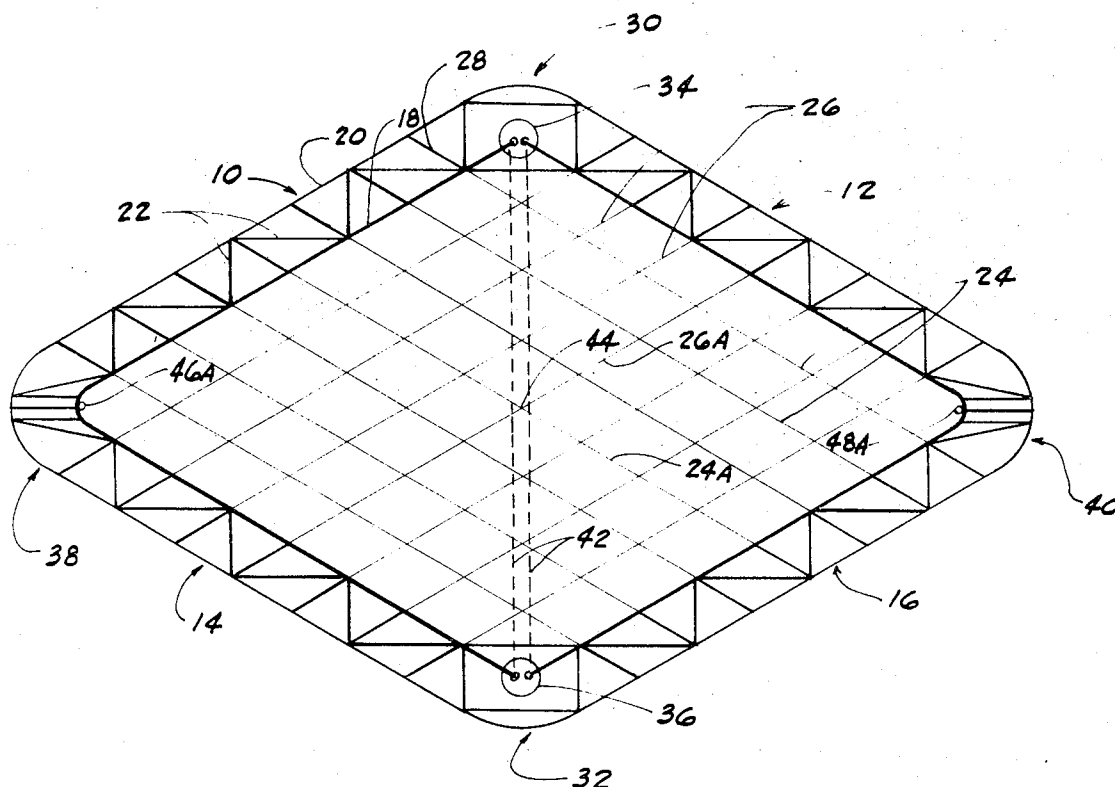
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[57] **ABSTRACT**

The roof structure comprises at least one hyperbolic paraboloid formed by structural tension members stretched between bending stress resistant structural boundary members. The boundary members forming the edge members of the roof comprise thin trusses.

14 Claims, 14 Drawing Figures



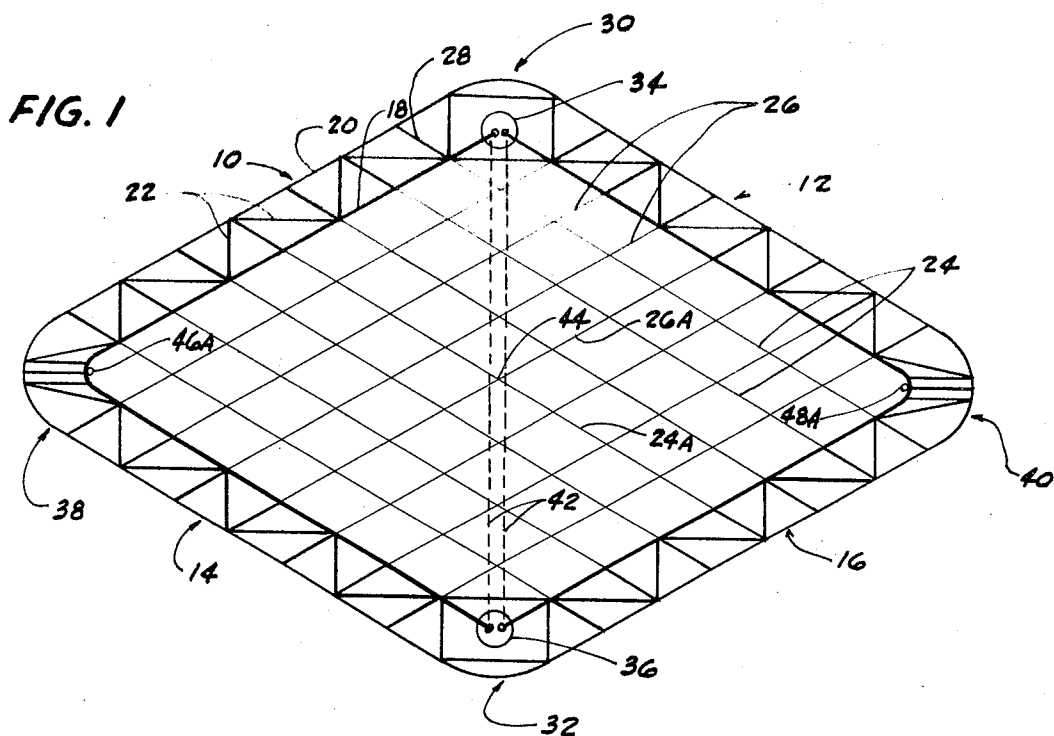
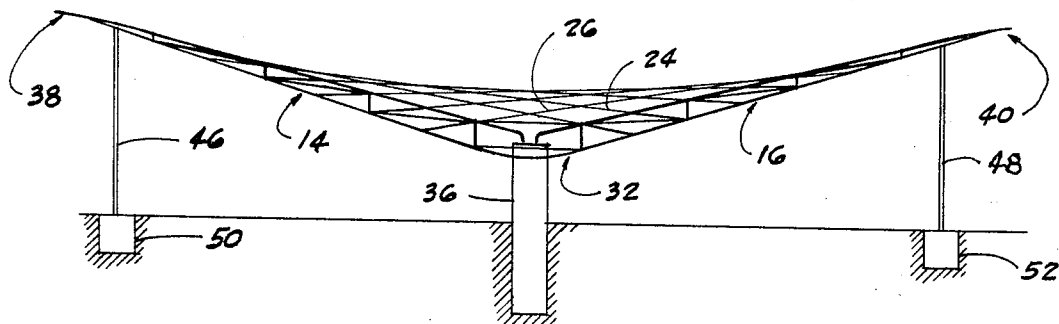


FIG. 2



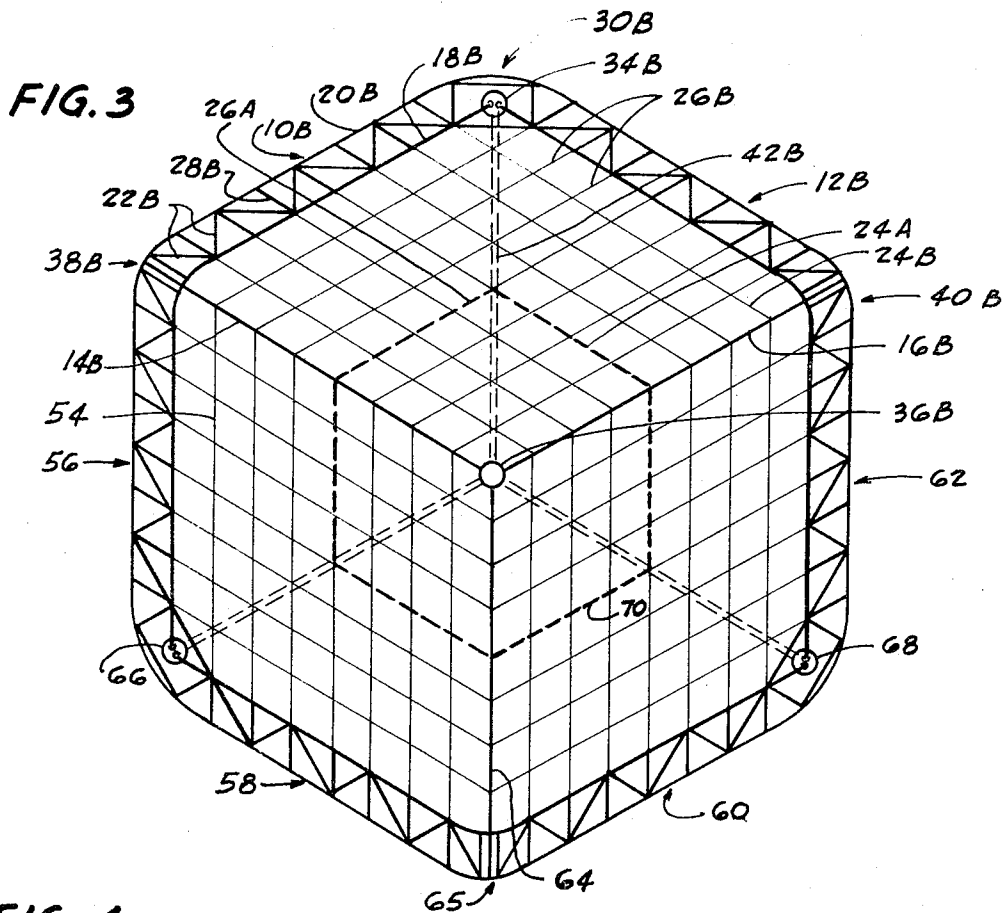


FIG. 4

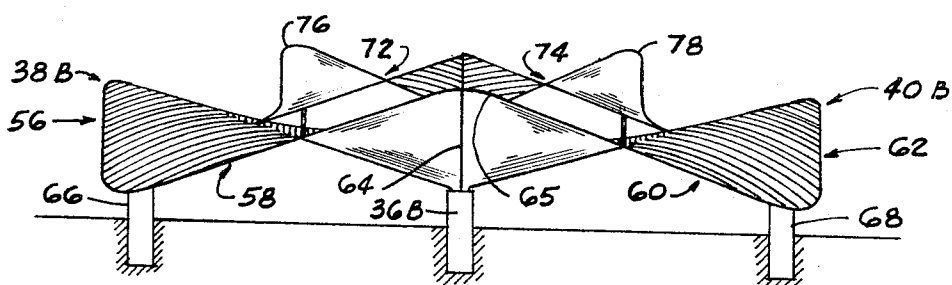


FIG. 5

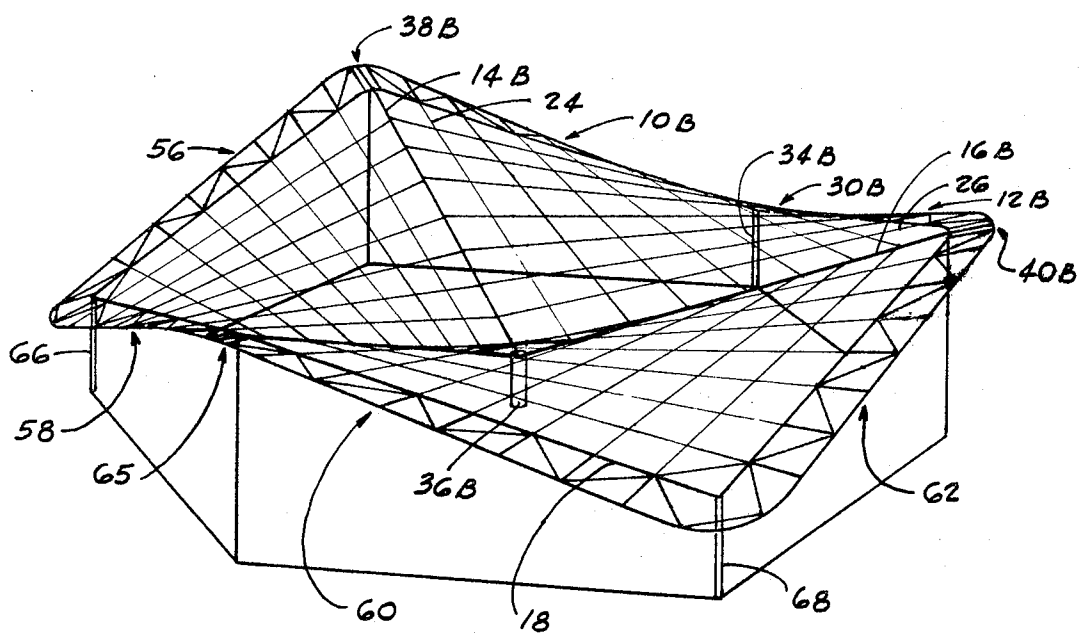


FIG. 6

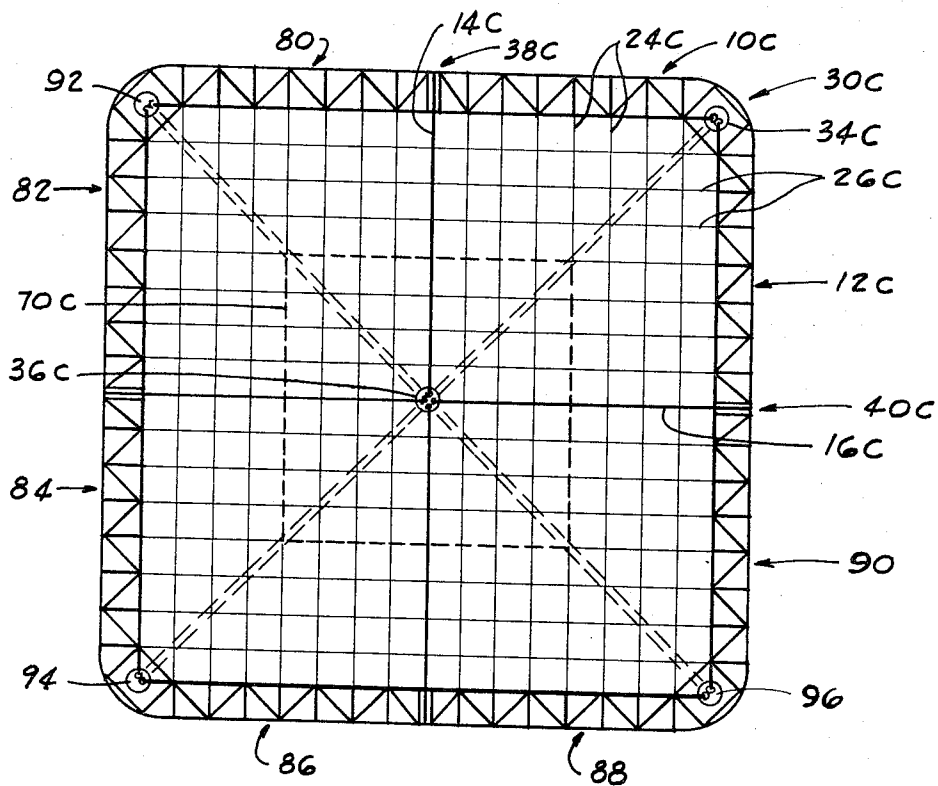


FIG. 7

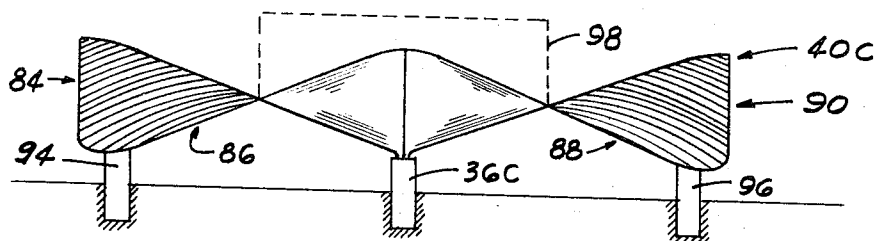


FIG. 8

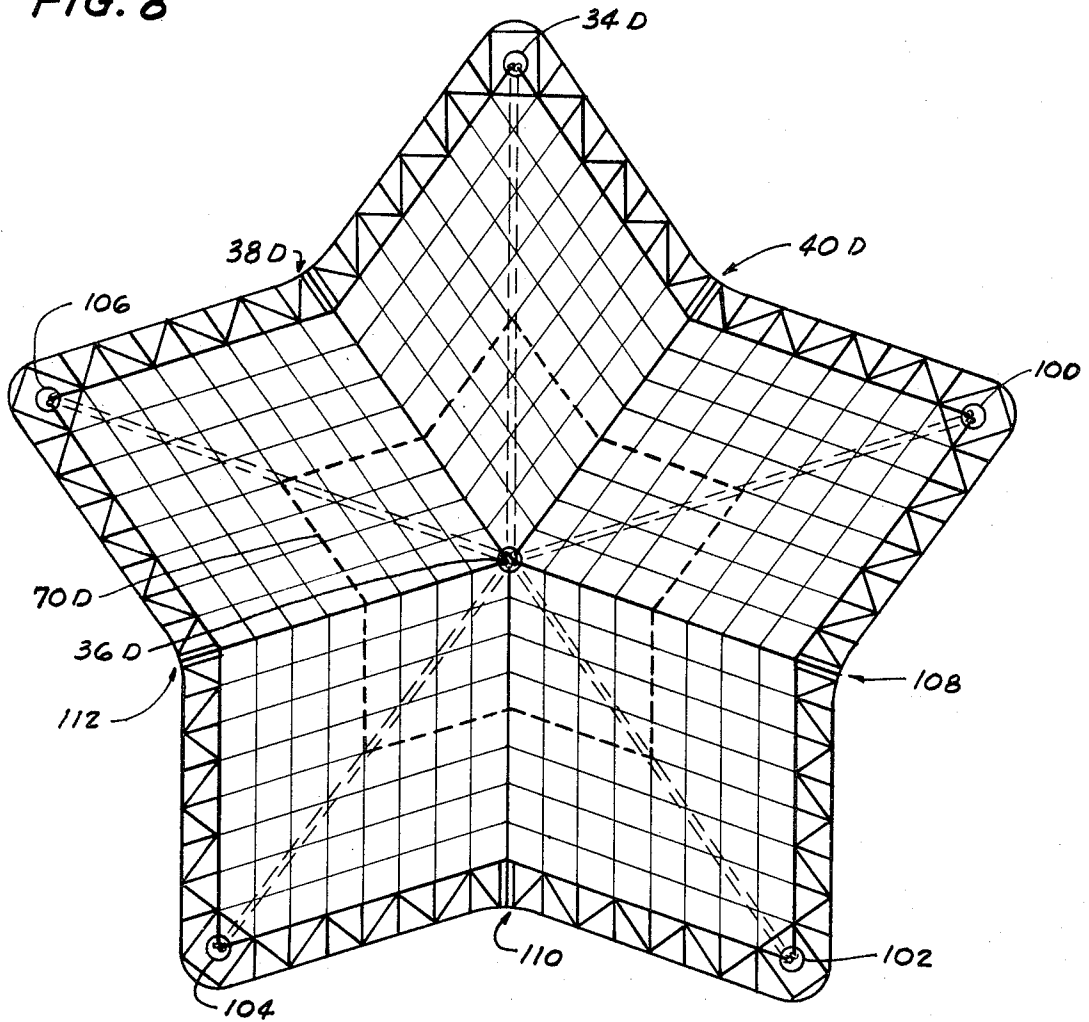


FIG. 9

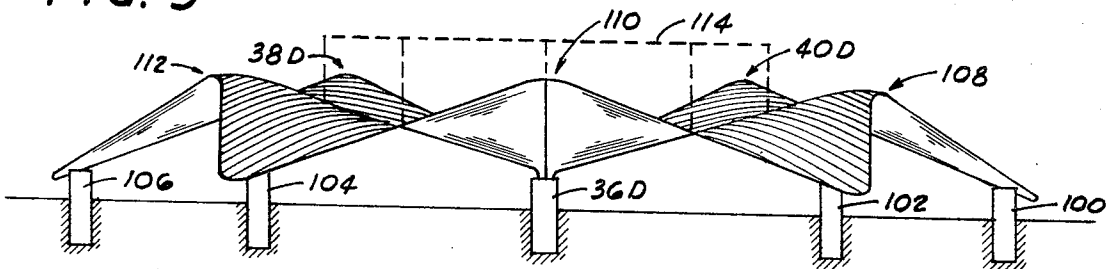


FIG. 10

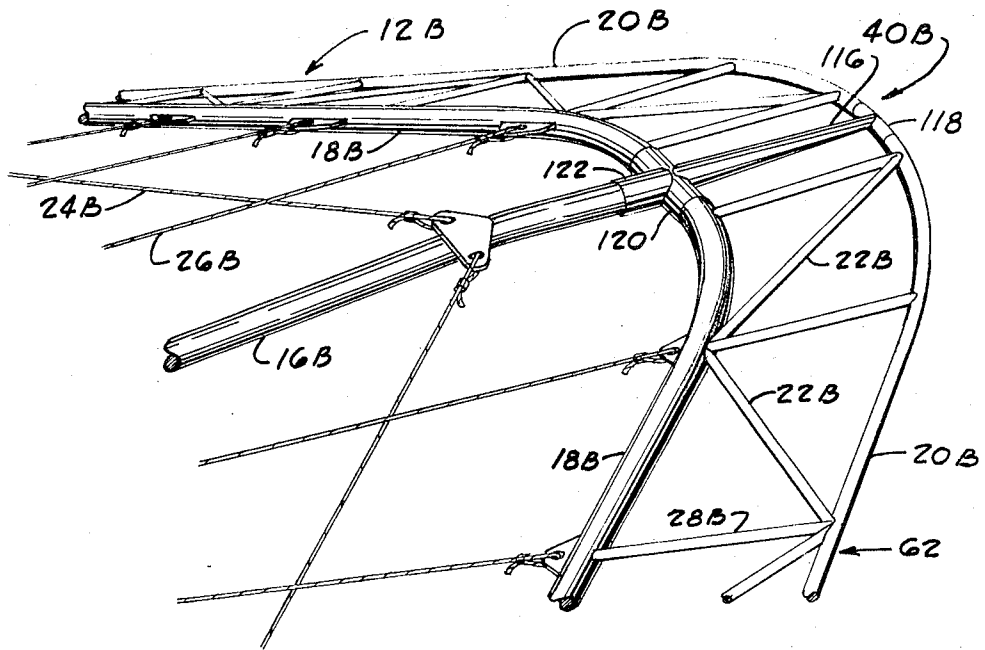


FIG. 11

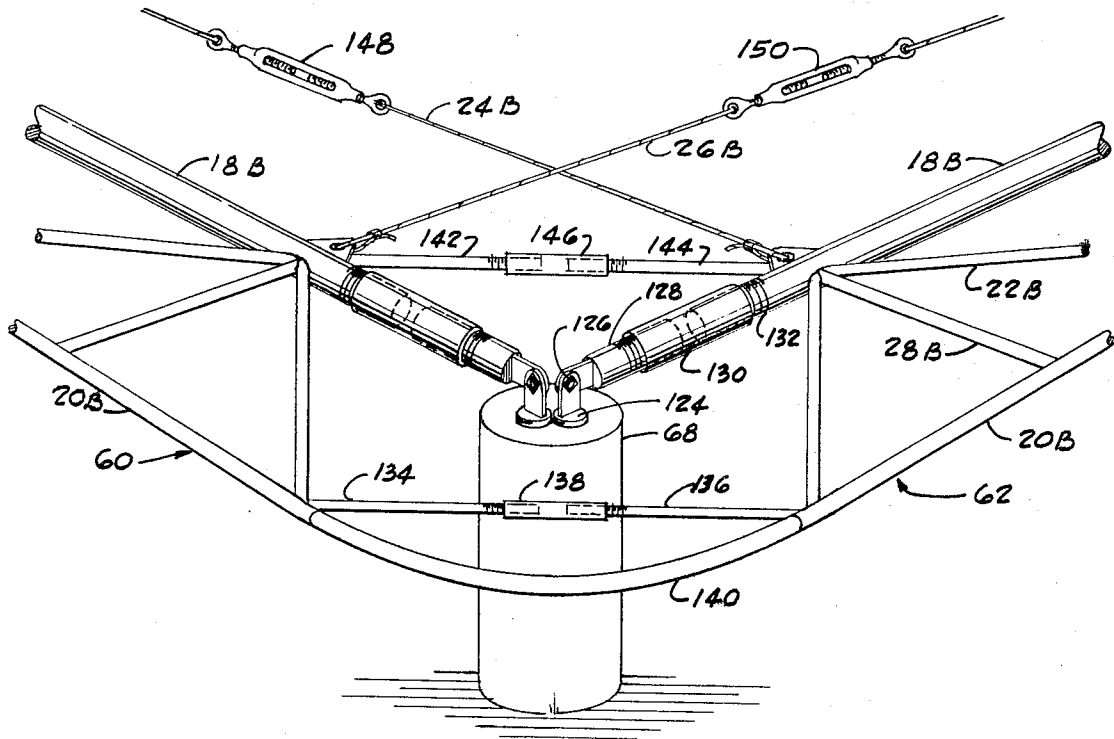


FIG. 12

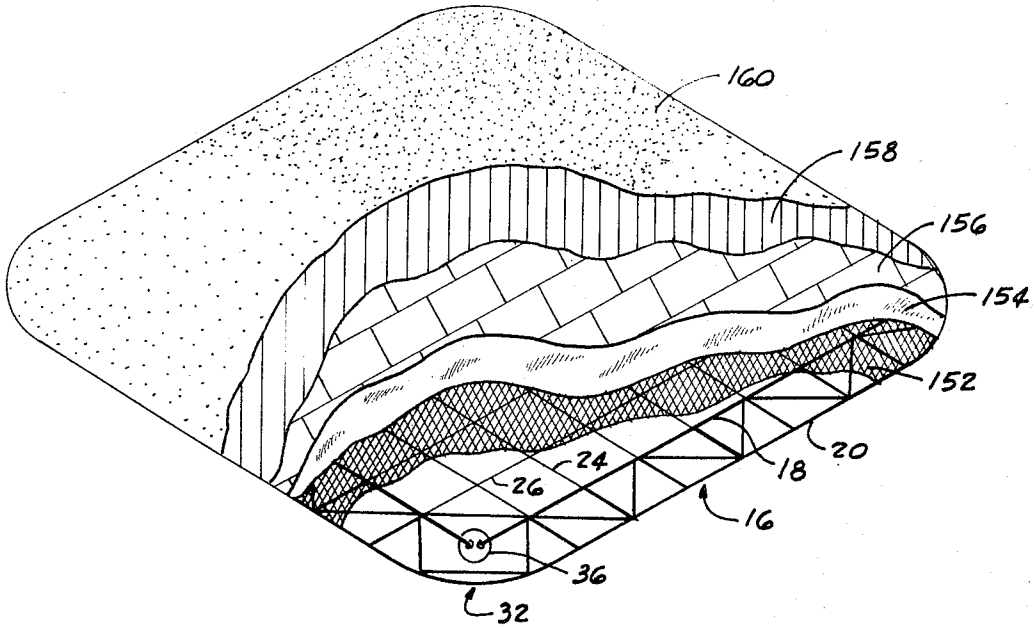


FIG. 13

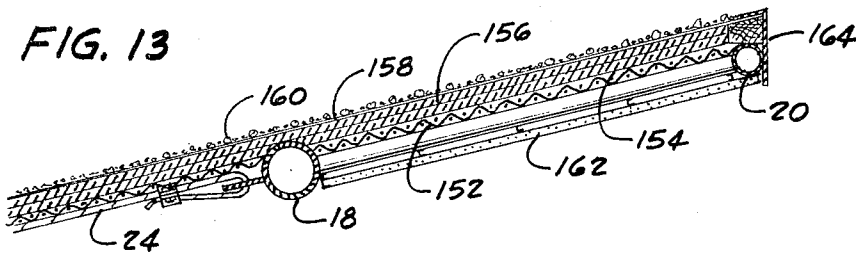
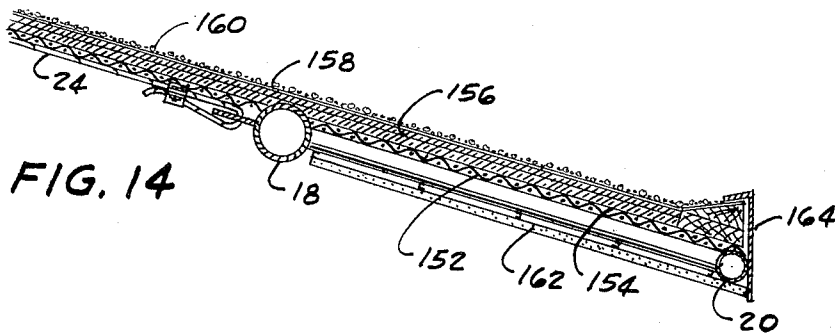


FIG. 14



LIGHTWEIGHT HYPERBOLIC PARABOLOID ROOF STRUCTURE

This invention relates to a hyperbolic paraboloid structure which is particularly adapted for producing lightweight roofs of various sizes.

It has been recognized for some time that the hyperbolic paraboloid provides an ideal configuration for the economical production of architectural structures. This was pointed out, for instance, in a two-part article entitled "Understanding the Hyperbolic Paraboloid" by Felix Candela which appeared in the July and August 1958 issues of *The Architectural Record*. However, consideration of the hyperbolic paraboloid as an architectural structure has usually been directed primarily to construction using a reinforced concrete shell. This requires the expensive procedure of erecting forms for holding the fluid concrete until it hardens. In such a structure, the concrete provides the resistance to compressive stresses, and steel reinforcing rods or cables embedded within the concrete resist the tension stresses. Not only is the construction method expensive, but the construction materials themselves are quite heavy, adding substantially to the static load on the structure.

Various attempts have been made at producing a lightweight hyperbolic paraboloid roof structure using materials having a higher strength to weight ratio than concrete. However, such prior attempts appear to have been generally deficient in failing to provide a truly economical structure at the edges of the hyperbolic paraboloid roof to resist the inwardly directed stresses. Furthermore, the structure at the edges, in such prior attempts, has failed to provide a pleasing appearance which fits in with the general appearance of the hyperbolic paraboloid shape.

Accordingly, it is one object of the present invention to provide an improved hyperbolic paraboloid roof structure which provides greater efficiency in the use of lightweight materials.

Another object of the invention is to provide a hyperbolic paraboloid roof structure which is more economical than prior structures because of the efficiency in use of materials.

Another object of the invention is to provide a lightweight hyperbolic paraboloid roof structure which is particularly pleasing in appearance.

Another object of the invention is to provide an improved hyperbolic paraboloid roof structure in which the components are easily prefabricated and easily erected.

Because of the prior common modes of fabrication of hyperbolic paraboloids, they have been generally thought of for architectural structures exclusively in the commercial and institutional fields.

It is another object of the invention to provide hyperbolic paraboloid roof structures which are so economical that they provide a maximization of strength and utility versus weight and cost, making them suitable for private housing construction to relieve the ever increasing housing demands.

Further objects and advantages of the invention will be apparent from the following description and the accompanying drawings.

In the accompanying drawings:

FIG. 1 is a plan view of a hyperbolic paraboloid roof structure in accordance with the present invention, and

showing the roof structure before the addition of final roof surfacing material.

FIG. 2 is an elevation view of the roof structure of FIG. 1.

FIG. 3 is a plan view, corresponding to FIG. 1, and illustrating a modification of the invention employing a combination of three hyperbolic paraboloids.

FIG. 4 is an elevation view of the embodiment of FIG. 3, with roofing materials added, and showing an added second level.

FIG. 5 is a perspective view of the embodiment of FIG. 3 and illustrating how walls may be fitted beneath the roof to form a complete building.

FIG. 6 is a plan view, corresponding to FIG. 1, showing another modification of the invention employing four interconnected hyperbolic paraboloids forming a single roof structure.

FIG. 7 is an elevation view of the embodiment of FIG. 6 showing roofing materials added.

FIG. 8 is a plan view corresponding to FIG. 1 illustrating another modification of the invention in which five hyperbolic paraboloids are combined in a single roof structure.

FIG. 9 is an elevation view of the embodiment of FIG. 8 with roofing materials added. FIG. 10 is a detail view of one of the high corners of the structure of the embodiment of FIG. 3.

FIG. 11 is a detail view of one of the low corners of the embodiment of FIG. 3.

FIG. 12 is a plan view of a roof structure in accordance with the present invention, and showing the preferred arrangement of layers of structure and roof finishing materials.

FIGS. 13 and 14 are enlarged sectional views taken through edge portions of the finished roof.

In carrying out the invention there is provided a hyperbolic paraboloid roof structure comprising at least one hyperbolic paraboloid bounded by bending stress resistant structural boundary members. Said boundary members are arranged substantially in a parallelogram configuration when vertically projected onto a horizontal plane. The boundary members forming the edge members of said roof structure are comprised of thin trusses arranged with the thickness dimensions thereof substantially in the vertical direction. The inner portions of each hyperbolic paraboloid comprise a plurality of structural tension members arranged in a criss-cross pattern, the vertical projections of each of said tension members being substantially parallel to the vertical projections of one pair of said boundary members, and each of said tension members being connected between the boundary members of the other pair of said boundary members.

Referring more particularly to FIG. 1, there is illustrated a plan view of a hyperbolic paraboloid roof structure in accordance with the present invention, but omitting the roof finishing materials, and showing the exposed structural framework members to illustrate important features of the invention. This is a single hyperbolic paraboloid structure in which the boundary members also form the edge members of the roof structure and consist of thin trusses 10, 12, 14, and 16. Each of the trusses, such as truss 10, includes a main inner rail 18, an outer rail 20, which is substantially parallel to the inner rail 18, and a series of diagonally arranged truss braces 22 forming a criss-cross pattern between the two rails.

Connected between the inner rails 18 of opposite trusses there are preferably evenly spaced structural tension members 24, and 26. The tension members 24 extend between trusses 10 and 16, and the tension members 26 extend between the trusses 12 and 14. Each truss is preferably provided with a separate cross-tie member, as indicated at 28 in truss 10, which extends from the point on the inner rail 18 where the associated structural tension member is attached, to the outer rail 20. These cross-tie members 28 are each preferably arranged at substantially the same angle as the associated structural tension member so as to effectively form an extension of the structural tension member to help distribute the bending load from the inner rail 18 to the outer rail 20. The diagonal cross braces are preferably connected between the rails so as to intersect with the rails at the points of attachment of the cross connectors 28. Thus, the diagonal cross braces 22 serve to reinforce the truss at the very points where tension forces are applied to the truss so that the maximum resistance to bending is available. The trusses may be composed of various materials, but an ideal material has been found to be steel tubing fabricated by fastening the individual elements together by welding. It will be understood that other structural shapes such as "I" beams and "T" beams may be used for this purpose, but circular tubing is much preferred. The structural tension members 24 and 26 may be composed of stranded steel wire.

The corners of the structure illustrated at 30 and 32 at the top and bottom of FIG. 1 are the lowermost corners and are supported at equal horizontal levels on concrete piers indicated at 34 and 36. The highest corners of the structure, which are also at equal horizontal levels, are indicated at 38 and 40. The piers 34 and 36 are preferably tied together below grade by a tension member, or members, as schematically indicated by the dotted lines at 42.

The nature of the structure of FIG. 1 is more fully illustrated in the elevation view of FIG. 2. A unique feature of the hyperbolic paraboloid is that despite the fact that it has a double curvature, it can be defined by so-called "generator" lines which are perfectly straight lines. The tension cables 24 and 26 are effectively generator lines. It is another feature of the hyperbolic paraboloid of the present invention that in a vertical projection of the structure onto a horizontal plane, which corresponds to the representation of the structure illustrated in FIG. 1, the projections of opposite pairs of the boundary members are parallel. In particular, the inner rails 18 of the opposite trusses 10 and 16 are parallel to one another. Similarly, the projections of the inner rails 18 of the opposite trusses 12 and 14 are parallel to one another. The vertical projections of the tension members 26 are mutually parallel to one another and are also parallel to the inner rails of the boundary members represented by the trusses 10 and 16, and the vertical projections of the tension members 24 are parallel to the vertical projections of the inner rails of the trusses 12 and 14. With the diagonal corners 30 and 32 at the same elevation, and with the diagonal corners 38 and 40 at the same elevation, the center generator lines are in a common horizontal plane. Thus, the tension cables 24A and 26A, which intersect at the center 44 of the structure, are in a horizontal plane. Furthermore, the cables 24 which are spaced between the center point 44 and the truss 14 all lie in parallel vertical

planes, in successively rotated positions, rotated about the point of intersection with the center cable 26A, with the ends terminating at truss 16 being lower, and the ends terminating at truss 18 being higher. Similarly, all of the cables 26 are positioned within mutually parallel vertical planes, rotated about the respective points of intersection with the center cable 24A. Since the cables 24 and 26 lie within two sets of mutually parallel vertical planes, they necessarily fulfill the previously stated principle that when vertically projected onto a horizontal plane, the resultant projections of the members of each set are mutually parallel.

The stability and integrity of the structure depend upon a balance of tension forces applied by the cables 24 between the boundary members 10 and 16, and the tension forces applied by the cables 26 between the boundary members 12 and 14, and the resistance to those tension forces provided by the boundary members. In the most common hyperbolic paraboloid prior art roof structures, the body of the structure is composed of a concrete shell, and the compressive strength of the concrete is relied upon to resist the tension forces of reinforcing tension members embedded within the concrete. However, in the present invention, concrete is not employed, and accordingly, the truss structures of the boundary members 10-16 withstand the tension forces of the cables 24 and 26, acting as trussed beams to resist bending in response to those forces. Despite the high strength of these trusses, they are relatively thin. For instance, they are preferably formed of steel tubular members, welded together in an assembly which is preferably only a single tube thick. Furthermore, as illustrated in FIG. 2, the trusses are preferably twisted or warped so that each lateral portion of each truss has an effective center line which substantially coincides with the line which represents an extension of an adjacent cable 24 or 26. Stated another way, the cross connectors 28 are preferably all in substantially perfect alignment with the associated tension cables 24 or 26. Accordingly, in appearance, the thin edge truss essentially forms an extension of the edge of the hyperbolic paraboloid and thus serves to enhance the appearance of thinness and lightness. This feature of the trusses complements the beauty of the shape of the hyperbolic paraboloid, in addition to providing the very most effective resistance to bending forces from cables 24 and 26.

As described more fully below in connection with FIG. 12, the hyperbolic paraboloid roof may be built up with membrane materials supported upon the cables 24 and 26 and upon the upper sides of the trusses. These materials may be relatively light in weight, and do not require the erection of forms, or other elaborate preparations which are usually required in the production of concrete hyperbolic paraboloid roofs.

As further illustrated in FIG. 2, the hyperbolic paraboloid roof structure must be stabilized in position such as by tension members 46 and 48, extending from the upper corners 38 and 40 to footings 50 and 52. The tension members 46 and 48 may consist of steel cables, or of more rigid steel rods or structural sections. These elements are not required to resist downward compression forces to support the roof, since the roof is entirely supported upon the piers 34 and 36. The tension members 46 and 48 are preferably attached at the meeting point of the inner rails of the edge trusses, as indicated respectively at 46A and 48A in FIG. 1. When vertical

walls are used with the building, the outer walls are preferably erected directly beneath the inner rails 18 of the edge trusses 10-16. Thus, the portions of the roof supported directly upon the tops of the edge trusses form a roof eave to protect the side wall and associated windows from the sun and from precipitation. Since the roof is entirely supported upon the piers 34 and 36, and is stabilized by the structural tension members 46 and 48, the walls need not support any roof weight. Accordingly, many windows may be provided in the side walls without the necessity for construction of heavy window frames to support vertical loads above the windows.

As shown in FIG. 1, at the corners 30, 32, 38, and 40 of the structure, the edge truss members 10, 12, 14, and 16 are joined together by corner structures in which both the inner and the outer rails are preferably curved to provide a pleasing and softly curved outer periphery. The details of these corner structures are more fully shown in FIGS. 10 and 11 and described below in connection with those figures.

Because of the inherent characteristics of the hyperbolic paraboloid structure, the stresses caused by the weight of the structure upon the piers 34 and 36 are inclined to cause an increase in the separation between those piers. Accordingly, it is preferred that the piers be securely anchored in the ground to prevent any such increase in separation. It is for this reason that the piers are shown to be much deeper than the footings 50 and 52 in FIG. 2. Also, in the preferred embodiment of the invention, tension members 42 are provided which are fastened below grade to interconnect the two piers to limit any separation movement. The tension members 42 may be steel cables, or tie-rods, or other similar structures.

The FIG. 1-FIG. 2 embodiment of the invention employs only a single hyperbolic paraboloid. FIGS. 3 through 9 are concerned with embodiments employing more than one hyperbolic paraboloid. The embodiment shown in FIGS. 3, 4, and 5 employs three hyperbolic paraboloids which are fitted together to form a single structure. The parts of the hyperbolic paraboloid shown at the top of FIG. 3 are lettered with identification numbers corresponding to the comparable parts of the embodiment of FIG. 1, but with the letter B added to each number. At the lower boundaries of this hyperbolic paraboloid, bending stress resistant structural boundary members 14B and 16B are provided instead of the thin trusses 14 and 16 of FIG. 1.

These internal boundary members 14B and 16B need not be quite so resistant to bending stresses as is required at the edges of the roof structure, because the bending stresses imposed by the tension cables are largely offset by opposite tension stresses imposed by corresponding tension cables on an adjacent hyperbolic paraboloid. Thus, the bending stresses applied to the boundary member 14B by the tension of the tension cables 26B, are largely offset by oppositely directed tension stresses applied by similar tension cables 54 which comprise a part of a second hyperbolic paraboloid including edge trusses 56 and 58. Accordingly, the structural boundary member 14B may be composed of a single steel tube of suitable size, which may be reinforced to withstand bending and compressive stresses by being filled with concrete. Member 14B not only serves as a structural boundary member for the hyperbolic paraboloid including the edge trusses 10B and 12B, but it also serves in common as a structural

boundary member for the second hyperbolic paraboloid including edge trusses 56 and 58.

The structure is completed by a third hyperbolic paraboloid partially bounded by edge trusses 60 and 62. The member 16B serves as a common structural boundary member for the third hyperbolic paraboloid and the first hyperbolic paraboloid including edge trusses 10B and 12B. Similarly, a third interior structural boundary member is shown at 64 which serves in common for the 56-58 and 60-62 hyperbolic paraboloids and extends to the edge at a third high corner of the structure at 65. Other features of the two added hyperbolic paraboloids are substantially the same as described above in connection with FIG. 1. The pier 36B constitutes a center pier which is a common support pier for all three hyperbolic paraboloids. Individual support piers are provided at 66 and 68 for the outer edge portions of the 56-58 and 60-62 hyperbolic paraboloids. Because of the edge attachments of the three paraboloids, the combined structure is basically stable, being supported upon four different points. Accordingly, no stabilization cables such as the cables 46 and 48 of FIG. 2 are necessary in this embodiment, or in any of the other multiple hyperbolic paraboloid embodiments.

As explained above in connection with FIG. 1, the center tension members 24A and 26A both lie in a common horizontal plane. This principle may be used in the embodiment of FIG. 3 to provide a level peripheral outline position for a second story, or "penthouse" which may be erected on top of the multiple hyperbolic paraboloid roof. This outline is shown as a dotted hexagon 70 in FIG. 3.

FIG. 4 is an elevational view of the embodiment of FIG. 3, but showing the roof with the roofing materials applied, including final layers of roofing felt, and also showing a penthouse roof structure added above the primary structure described in connection with FIG. 3. The penthouse structure consists of another multiple hyperbolic paraboloid roof of correspondingly reduced dimensions, including two hyperbolic paraboloids 72 and 74 which are clearly visible in the drawing, and a third hyperbolic paraboloid which is behind the other two and substantially hidden by the other two. The hyperbolic paraboloids of the penthouse roof are reversed with respect to those of the main roof so that the high points at the outer edges indicated at 76 and 78 are in substantial angular alignment, if viewed from above, with corresponding low points at the piers 66 and 68 respectively of the main roof. The penthouse is primarily supported upon a center post structure (not shown) which constitutes a vertical extension of the center pier 36B. The floor of the penthouse constitutes a level platform which is preferably supported upon the center pier 36B by means of triangular cross section trusses placed beneath the floor. The structure of the penthouse is not primarily supported by the primary or lower roof, but is stabilized by the lower roof, and fits pleasingly into the combined structure. A stairway or elevator shaft from the first level to the second level may be provided, although it is not shown. Such a stairway or other vertical passage extends through the normal openings between adjacent tension members 24 and 26 described above in connection with FIG. 3. Thus, the vertical passage opening does not impair the structural integrity of the roof in any way.

FIG. 5 is a perspective view of the structure of FIG. 3, showing the addition of side walls to the structure to indicate how the building would appear in basic outline. As shown in this drawing, the side walls intersect with the outside support piers 34B, 66, and 68, and they are preferably arranged directly beneath the inner rails 18B of the edge trusses. Thus, the portion of the roof represented by the width of the edge trusses constitutes an overhang of the roof over the edges of the side walls of the building.

The roof structure illustrated in FIGS. 1 through 5 have all been composed of hyperbolic paraboloids which represent a configuration which may be characterized as non-rectilinear parallelograms, when viewed from above. However, it is obvious that rectilinear parallelogram hyperbolic paraboloids can also be used in structures of this type. FIGS. 6 and 7 illustrate such a structure.

FIGS. 6 and 7 illustrate another embodiment of the invention employing four hyperbolic paraboloids, each of which is rectilinear in shape, and which are joined together to form a structure having a vertical projection which is substantially in the shape of a square. The hyperbolic paraboloid forming the upper right quadrant of this figure (referring to FIG. 6) has been identified by lettering applied to the major components corresponding to the lettering applied to the hyperbolic paraboloid shown in the upper third of FIG. 3, but substituting the suffix letter C instead of the suffix letter B. Thus, this hyperbolic paraboloid is defined by the edge beams 10C and 12C, and the inside bending stress resistant structural boundary members 14C and 16C. Three other substantially identical rectilinear hyperbolic paraboloids are provided in this structure, and are respectively identified by edge beams 80-90. Outside support piers are provided at each of the corners, at 92, 94, and 96.

As in the embodiment of FIG. 3, there are uniform elevation lines at the center chords of the hyperbolic paraboloids which are parallel to the peripheral edges of the roof structure and which can be combined to be represented by the dotted square 70C. This dotted square can be used as the locus for the erection of the sidewalls of a penthouse structure above the main roof similar to the penthouse discussed above in connection with FIG. 4.

FIG. 7 is an elevational view of the roof structure embodiment of FIG. 6, but showing roofing materials added, including final layers of roofing felt. In FIG. 7, the location of the penthouse is only schematically indicated by a dotted outline at 98.

While the embodiment of FIGS. 6 and 7 illustrates the use of four hyperbolic paraboloids, it is obvious that a similar structure can be created using only two hyperbolic paraboloids, omitting the right half, for instance, of the structure of FIG. 6, and adding edge beams in place of the stress resistant structural boundary member 14C and its counterpart on the lower center line of the figure. In such a structure, only three piers 92, 94, and 36C are required, and the two remaining hyperbolic paraboloids sufficiently stabilize one another so that no additional stabilization elements are required, such as the cables 46 and 48 of FIG. 2.

Many different hyperbolic paraboloid configurations are possible employing the principles of the present invention. For instance, five and six-pointed star configurations

may be constructed, respectively employing five and six hyperbolic paraboloids.

FIGS. 8 and 9 illustrate still another embodiment of the invention in which the vertical projection of the roof, as shown in FIG. 8, is in the form of a five-pointed star. This structure corresponds generally with the embodiment of FIG. 6, except that it is composed of five hyperbolic paraboloids instead of four, and presents five outer corners instead of four. As in the embodiment of FIG. 6, all of the hyperbolic paraboloids employ a common center pier 36D, and each has its own outer pier, as indicated at 34D and 100-106. Just as there are five low points in the periphery of the structure, at 34D and 100-106, there are also five high points in the peripheral edges of the roof structure as generally indicated at 38D, 40D, 108, 110, and 112.

FIG. 9 corresponds generally to FIG. 7 in showing an elevation of the embodiment of FIG. 8 with roofing materials added. Again, the position of a penthouse which can be added to the structure is illustrated in a dotted outline 70D in FIG. 8 and in a phantom outline 114 in FIG. 9.

In all of the embodiments of FIGS. 3-5, FIGS. 6-7, and FIGS. 8-9, the positions of the high points and the low points of the hyperbolic paraboloids can be reversed to produce a useful result which is within the scope of this invention. Another way of expressing this idea is that the structures can be erected upside down from the way they are illustrated in these figures. With such a change in the structure of FIG. 3, for instance, support piers are placed at what were formerly the high points 38B, 40B, and 65. All of the locations previously identified with piers, including the edge piers 34B, 68, and 66, and the center pier 36B, now become high points of the hyperbolic paraboloids. For some purposes, this form of the structure is more useful because the required number of piers is reduced, and the center of the structure is completely unobstructed by any piers, with a maximum ceiling height at the center. Thus, this form of construction is particularly useful for public meeting halls and houses of worship, where an unobstructed central area of maximum ceiling height is greatly desired. In these modifications, the number of piers is reduced to three in FIG. 3, four in FIG. 6, and five in FIG. 8. Furthermore, the support piers are always located only at the edges of the roof structure, leaving the entire interior space completely unobstructed. Exactly the same principles are applied for this modification of the structure of FIGS. 6-7, utilizing only four piers at the outside edges, and eliminating the piers at the center and at the four corners. In similar fashion, the five-pointed star embodiment of FIGS. 8-9 may be modified to provide five piers at the positions 38D, 40D, 108, 110, and 112 previously designated as high points of the structure. Again, the center of the structure is a common high point for the five hyperbolic paraboloids forming the structure.

FIGS. 10 and 11 are enlarged scale fragmentary views showing details of the construction of the framework of the roof structures in accordance with the present invention.

Referring particularly to FIG. 10, there is shown a detail of the high outside corner 40B of the structure of FIG. 3, showing how the edge trusses 12B and 62 are connected together at the corner, and showing how the cables 24B and 26B are attached to the edge trusses 12B and 62, and to the internal boundary member 16B.

As shown in this drawing, the inner rail 18B is much larger and heavier than the outer rail 20B. The trusses are preferably prefabricated off the erection site. The diagonally arranged truss braces 22B and the cross-tie members 28B are securely welded to the inner and outer rails 18B and 20B. The trusses 12B and 62 are then shipped to the erection site and attached together at the corner 40B by means of a double T-fitting 116 having an outer cross-tube 118 and an inner cross-tube 120. These cross-tubes 118 and 120 are preferably somewhat larger in diameter than the respective outer rails 20B and the inner rails 18B. Therefore, the inner and outer rails of the two trusses 12B and 62 can be slipped into the cross-tubes for the purpose of securing them together. After such assembly, the rails are preferably welded in place in the cross-tubes. The double T-fitting 116 also includes a tube extension 122 which provides a sliding fit socket for the end of the internal boundary member 16B. This connection is preferably established after the edge beams 12B and 62 have been connected together and the resultant corner 40B of the structure raised to its intended height. The internal boundary member 16B is then inserted into the tube extension 122 and welded in place.

FIG. 11 is a fragmentary detail view exemplifying the structures of the present invention by showing the lower corner of the structure of FIG. 3 at the pier 68. In the assembly of this corner of the structure, the prefabricated trusses 60 and 62 are first attached to the pier 68 by means of connections to the inner rails 18B of the trusses including, for each truss, a freely rotatable vertical plug member 124 having machine threads and engaging cooperating machine threads in a mating socket member within the pier 68. At the upper end of the plug member 124 there is provided a bracket with a central hole to accommodate a pivot pin 126, which may be in the form of a heavy threaded steel bolt. A similar threaded plug 128 is connected to the pivot pin 126 and is engaged by a threaded sleeve 130 which also engages the threaded end 132 of the inner rail 18B. The machine threads at 132 are in an opposite sense to the machine threads upon the plug 128 so that rotation of the sleeve 130 by a tool, such as a pipe wrench, causes an effective increase or decrease in the length of the inner rail 18B for adjustment of the structure.

After attachment of the edge trusses to the support piers by means of the pivot pins 126, the intended high points of the edge trusses are fastened together by means of the fittings 116 as described above in connection with FIG. 10. The trusses are then hoisted up into the air, the lower end of each truss pivoting about the pivot 126. The cables 24B and 26B may then be installed in order to tie the structure together. The outer rails 20B of the two trusses 60 and 62 are then attached together by means of tension bars 134 and 136 which are interconnected by an adjustable turnbuckle sleeve 138. The tension bars 134 and 136 are preferably welded to the lower tips of the outer rails 20B. In order to provide a more pleasing appearance, and also to further strengthen the outer rail structure, a curved rail connector 140 is attached between the ends of the outer rails 20B by welding. The inner rails are also preferably interconnected by tension bars 142 and 144 and a turnbuckle sleeve 146.

After erection of the trusses, careful final adjustment of the dimensions and the height levels of all of the edge trusses may be accomplished by adjustment of the

threaded sleeves 130 on the truss inner rails 18B. After all of the cables 24B and 26B have been assembled, the tensions in the individual cables are preferably adjusted so that the stresses on the cables are substantially uniform. For this purpose, a tension adjustment means is preferably provided in each cable, such as the turnbuckles 148 and 150 illustrated for the cables 24B and 26B in FIG. 11.

While the hyperbolic paraboloid frame structures illustrated in the plan views of FIGS. 1, 3, 6, and 8 can be filled in to provide a finished roof by means of various materials and combinations of materials, FIG. 12 illustrates a preferred combination of roof structure layers to be applied to such frames.

FIG. 12 illustrates a preferred arrangement of the layered materials for building up the hyperbolic paraboloid roof structures in accordance with the present invention. The different material layers are cut away in order to more clearly illustrate the arrangement. The first layer 152 over the bare framework preferably consists of chain link fencing. While, so far as the applicant knows, chain link fencing has not been used for this purpose in the past, it is excellent for this non-fence purpose in the roof structures of this invention. The edges of individual widths of the fencing are attached together with short lengths of heavy fencing wire, or with clips or tension bands. The next layer 154 is a heavy polyethylene film which serves as a moisture barrier, and also serves to prevent damage to the next layer of material by reason of abrasion with the chain link fence material 152.

The next layer 156 preferably consists of a commonly available semi-rigid insulation material in panel form, such as dense fiberglass with surface layers of asphalt impregnated fibreboard. While not illustrated as such in the drawing, the panel layer 156 is preferably a double layer with the panels of the second layer carefully positioned to avoid having the joints coincide with those of the first layer. By using two thin layers 156 of the insulation board the board is more pliable so as to obtain a better conformity to the compound curvatures of the roof. The next layer 158 consists of strips of asphalt impregnated roofing felt which are applied with an overlap from one strip to the next, and are applied with roofing compound. Thus, liquid roofing compound is first applied to the portion of the panels 156 to which the next roll of roofing felt is to be applied, the roofing felt is then laid down, and another application of roofing compound is applied for the next row of roofing felt, including the overlap area for that roofing felt so that all roofing felts are securely fastened to the structure by the roofing compound. Finally, a heavy layer of roofing compound is applied to the top surfaces of the roofing felts together with gravel, indicated as the last layer 160 to form a wearing surface. The roofing felt layers 158 are depicted in FIGS. 4, 7, and 9, prior to application of the gravel.

FIGS. 13 and 14 illustrate fragmentary cross-section views of the finished roof at the edge trusses. All of the layers of FIG. 12 are identified. In addition, beneath the edge truss, there is preferably constructed a soffit 162, which may be of conventional cement plaster on wire lathe. The edge of the roof may be finished off, preferably, by means of a metal fascia 164. FIG. 13 illustrates the roof construction near a high corner, while FIG. 14 illustrates the roof structure near a low corner. However, the fascia is constructed differently depending

upon the elevation and the angle of the roof so that the facia 164 outer surface is preferably substantially vertical for all of the roof edges.

While this invention has been shown and described in connection with particular embodiments, various alterations and modifications will occur to those skilled in the art. Accordingly, the following claims are intended to define the valid scope of this invention over the prior art and to cover all changes and modifications falling within the true spirit and valid scope of this invention. 10

I claim:

1. A hyperbolic paraboloid roof structure comprising at least one hyperbolic paraboloid bounded by bending stress resistant structural boundary members, said boundary members being arranged substantially in a parallelogram configuration when viewed as vertically projected onto a horizontal plane, the boundary members forming the edge members of said roof structure comprising thin trusses arranged with the thickness dimensions thereof substantially in the vertical direction, the inner portions of each hyperbolic paraboloid comprising a plurality of structural tension members arranged in a criss-cross pattern, each of said tension members being substantially parallel to one pair of said boundary members when said tension members and said boundary members are viewed as vertically projected onto a horizontal plane, each of said tension members being connected between the members of the other pair of said boundary members, said tension members being subjected substantially exclusively to tension stress. 15
2. A roof structure as claimed in claim 1 comprising a plurality of hyperbolic paraboloids joined in at least one common boundary, the structural boundary members at said common boundary being combined in a single structural boundary member. 20
3. A roof structure as claimed in claim 1 wherein each of said trusses is positioned so that at least the central portion thereof is in substantial alignment with the adjacent edge portion of the hyperbolic paraboloid bounded by said truss so that said central portion of said truss effectively forms an extension of the adjacent edge portion of the hyperbolic paraboloid. 25
4. A roof structure as claimed in claim 3 wherein each of said trusses is twisted so that each portion thereof is in substantial alignment with the adjacent edge portion of the hyperbolic paraboloid bounded by said truss and so that each portion of each truss effectively forms an extension of the adjacent edge portion of the hyperbolic paraboloid. 30
5. A roof structure as claimed in claim 1 wherein each of said trusses comprises an inner rail and an outer rail and a plurality of diagonally arranged truss braces attached between said inner and outer rails. 35
6. A roof structure as claimed in claim 5 wherein the boundary line corresponding to the boundary of the hyperbolic paraboloid at each edge truss is sub-

stantially coincident with said inner rail of said edge truss.

7. A roof structure as claimed in claim 5 wherein said tension members connected to said boundary members comprised by said trusses are connected to each of said trusses at said inner rail member thereof. 40
8. A roof structure as claimed in claim 7 wherein each truss includes a separate cross-tie member extending from the point of attachment of each tension member at said inner rail to said outer rail, each said cross-tie member being substantially in alignment with the direction of the associated tension member. 45
9. A roof structure as claimed in claim 5 wherein said rails and said diagonal braces are comprised of metal tubes. 50
10. A roof structure as claimed in claim 9 wherein said tubes consist of steel, and said tubes are attached together by welds to form said truss. 55
11. A roof structure as claimed in claim 5 in combination in a building wherein there is provided a side wall arranged substantially directly beneath said inner rail of at least one of said trusses so that the portion of the roof formed by the width of said truss between said inner rail and said outer rail provides a roof overhang for said wall. 60
12. A roof structure as claimed in claim 1 including at least one layer of chain link fence material arranged and supported upon said tension members and said boundary members to fill in the openings therebetween to form a substantially continuous roof structure for the application of roofing materials. 65
13. A roof structure as claimed in claim 2 wherein there are provided at least three hyperbolic paraboloids joined together with at least three common boundaries, the low corners of all of said hyperbolic paraboloids being at substantially the same level, and the high corners of all of said hyperbolic paraboloids being at substantially the same level. 70
14. A roof structure as claimed in claim 13 wherein a support pier is provided for support of said roof structure at said low corners of each of said hyperbolic paraboloids, a common low point and a common support pier for all of said hyperbolic paraboloids being provided at the center of said roof structure, and a penthouse arranged above said roof structure, said penthouse being centered above said roof structure and being supported substantially completely upon said center pier, said penthouse having an outline shape which is substantially identical to the outline shape of said roof structure and having basic dimensions which are exactly one-half of each of the corresponding dimensions of said roof structure so that the periphery of said penthouse is positioned above the central chords of said hyperbolic paraboloids which define a common horizontal plane. 75

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