Nov. 22, 1966 N. E. SCHLENKER 3,286,415

REINFORCED SHELL CONSTRUCTION

Filed Aug. 22, 1962 5 Sheets-Sheet 1

Fig. 1.

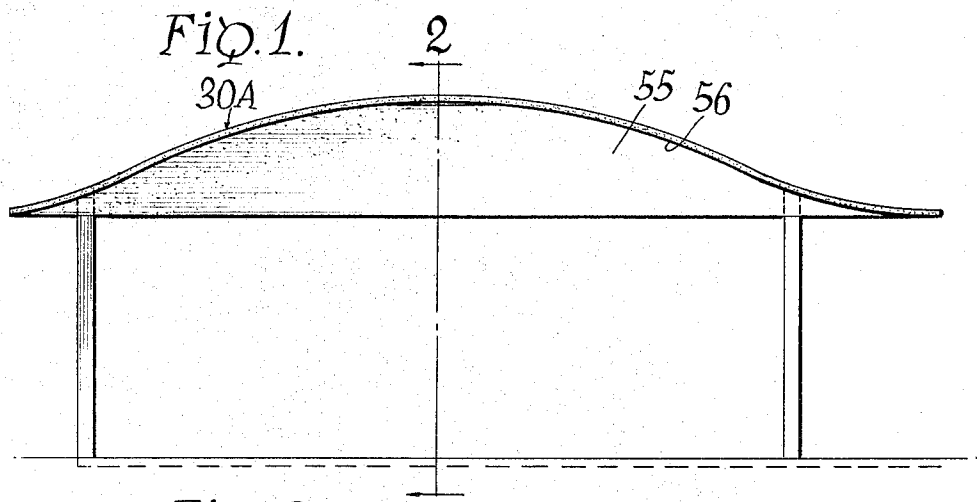


Fig. 2.

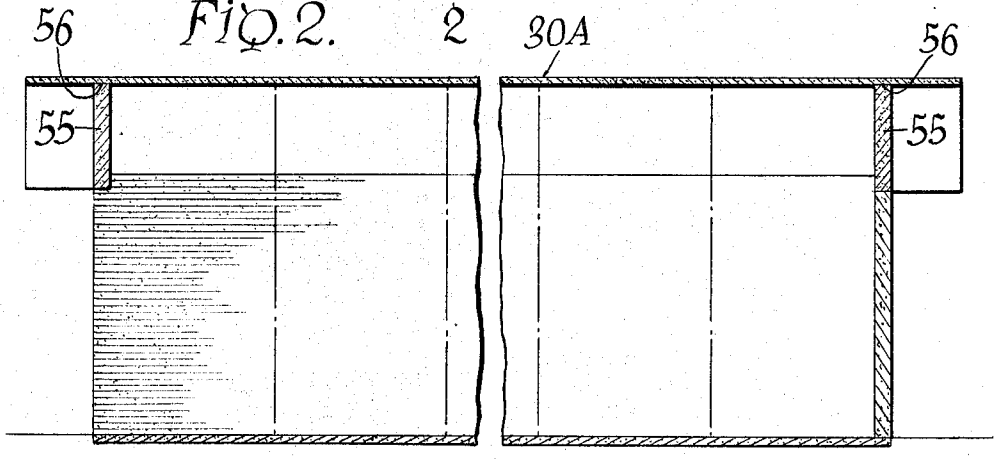
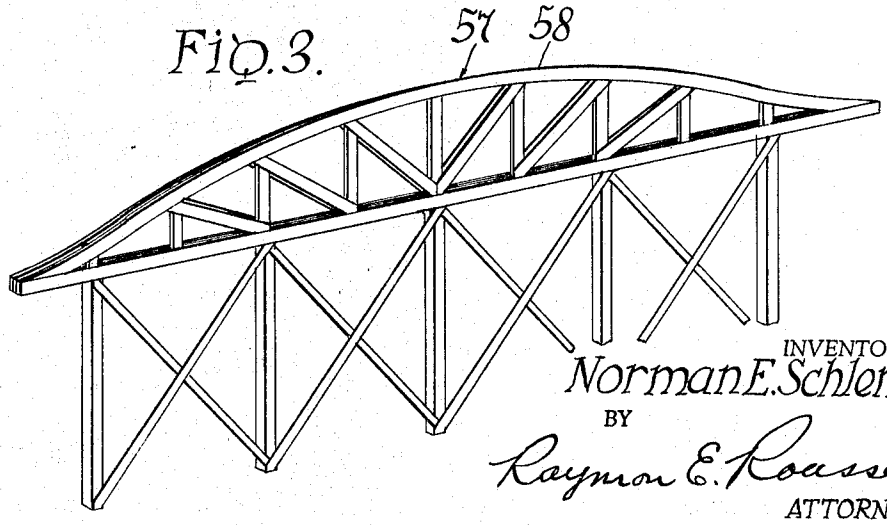


Fig. 3.



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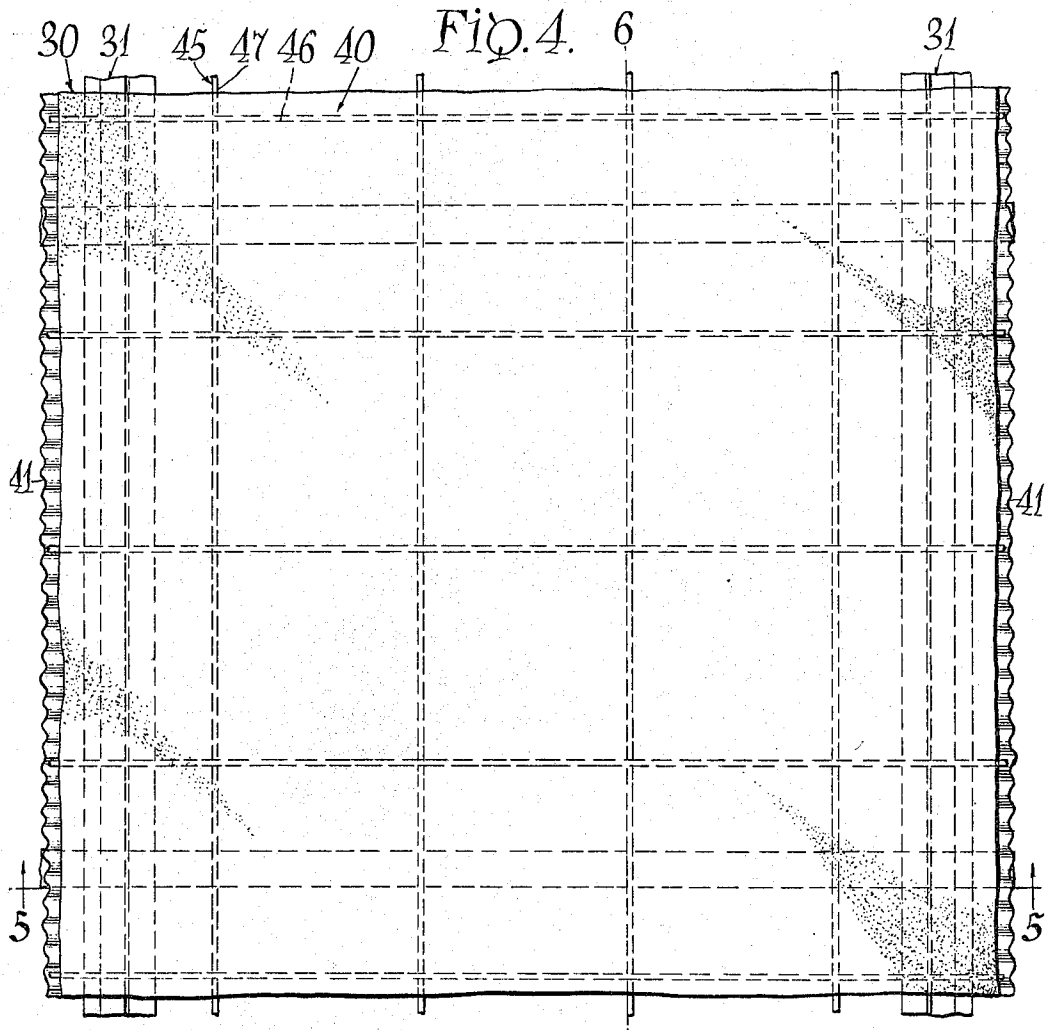


FIG. 4.

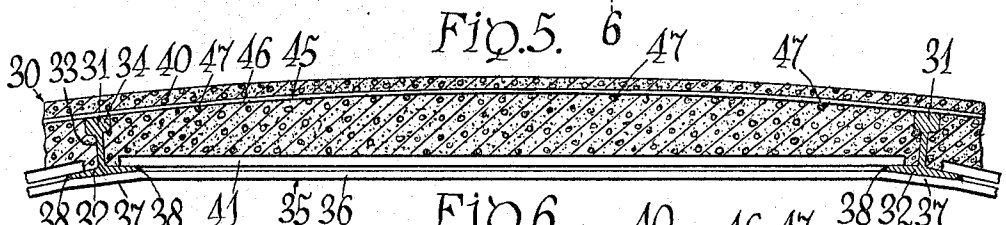


FIG. 5.

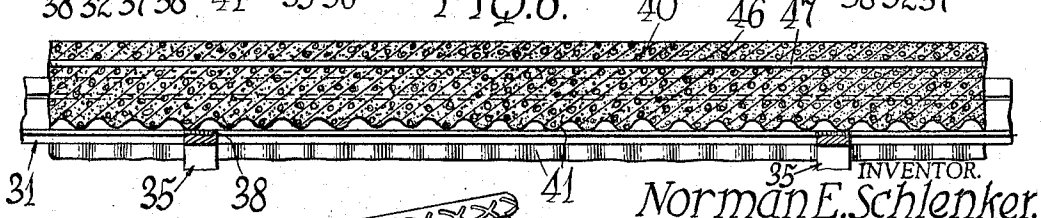


FIG. 6.

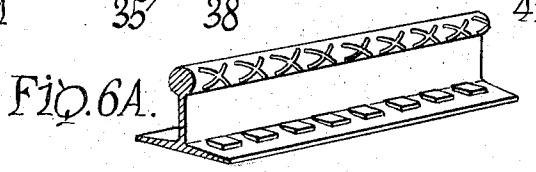


FIG. 6A.

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Fig. 7.

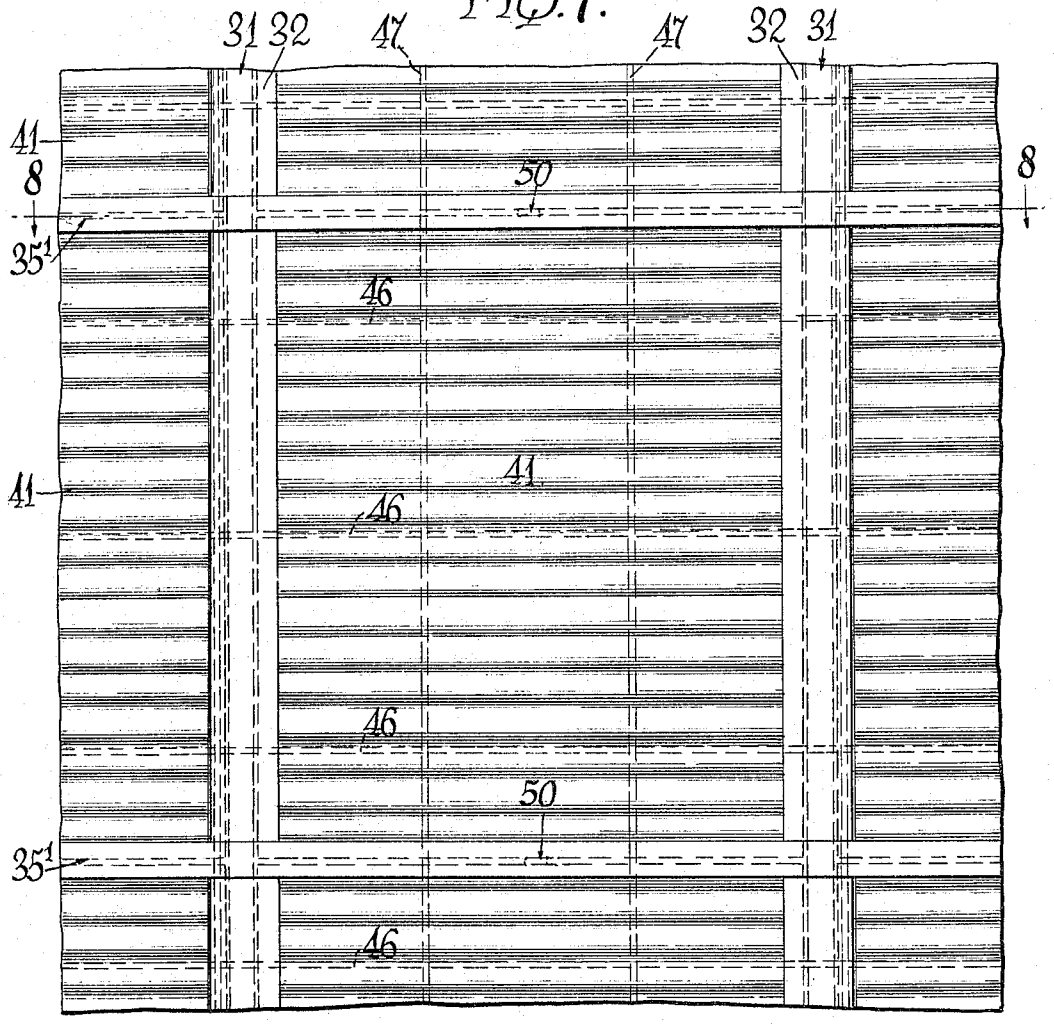


Fig. 8.

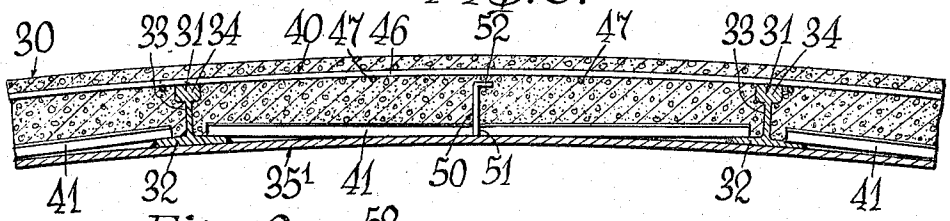
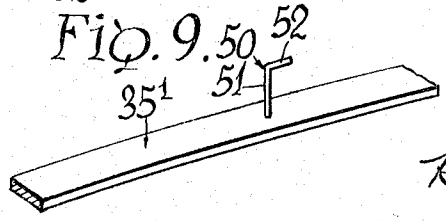


Fig. 9.



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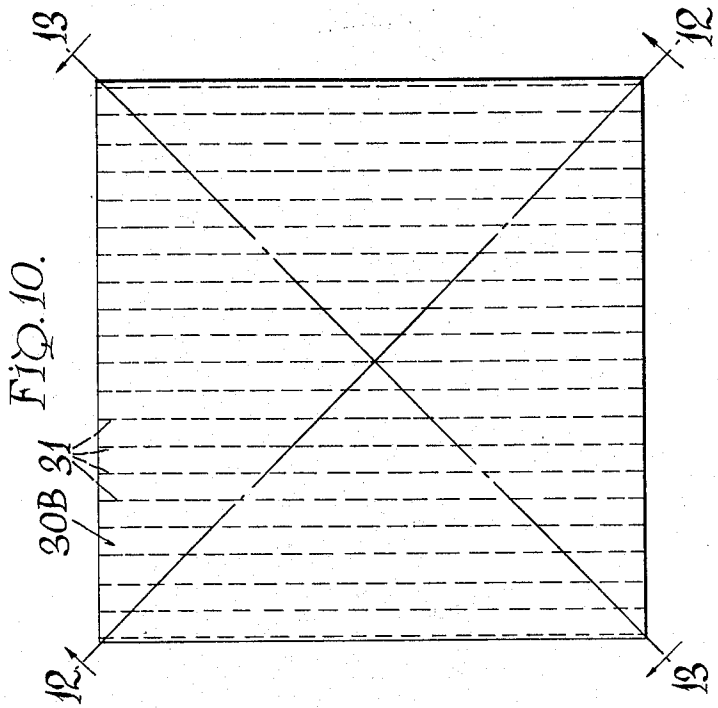


FIG. 10.

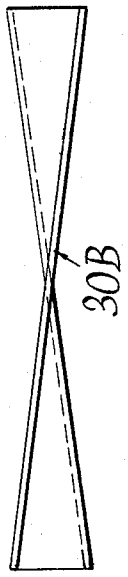


FIG. 11.

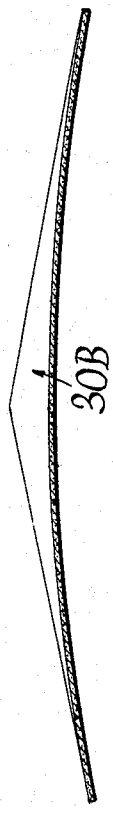


FIG. 12.

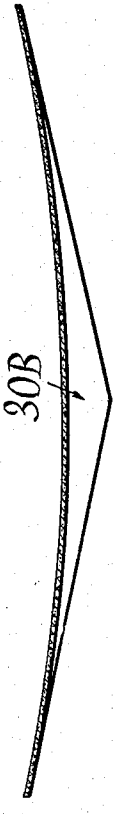


FIG. 13.

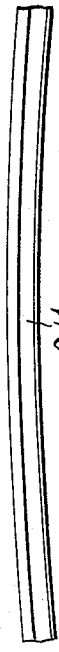


FIG. 14.



FIG. 15.

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REINFORCED SHELL CONSTRUCTION

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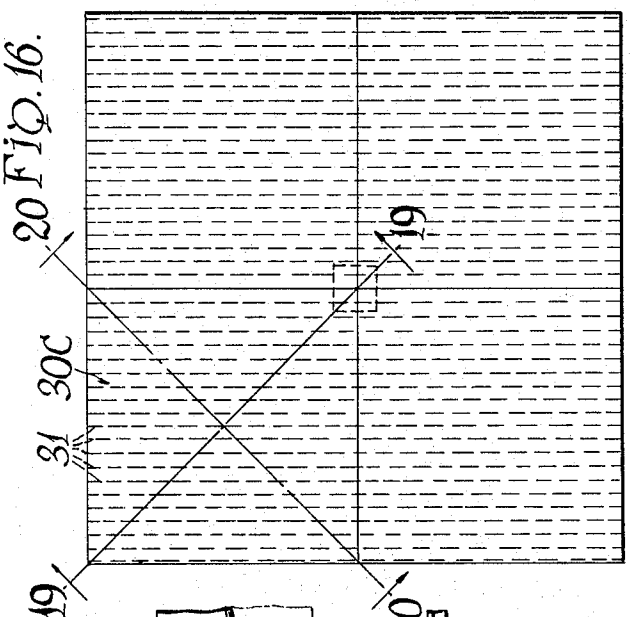


Fig. 16.

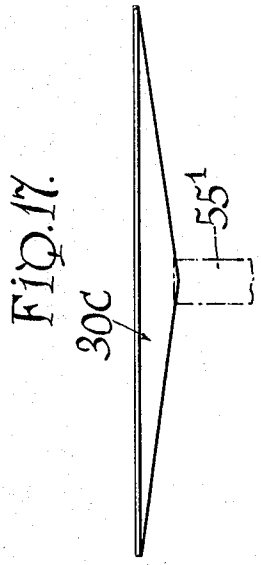


Fig. 17.

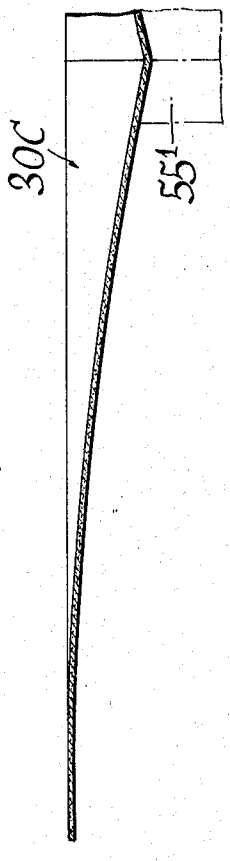


Fig. 19.

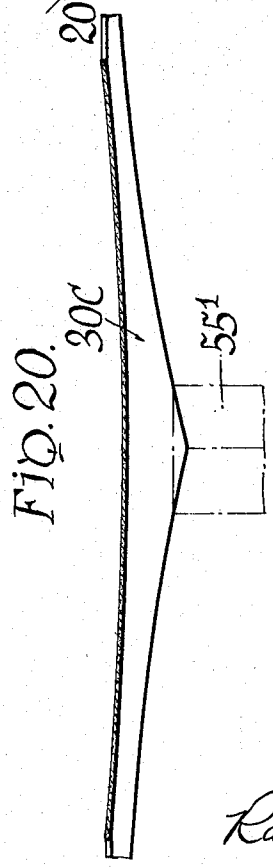


Fig. 20.

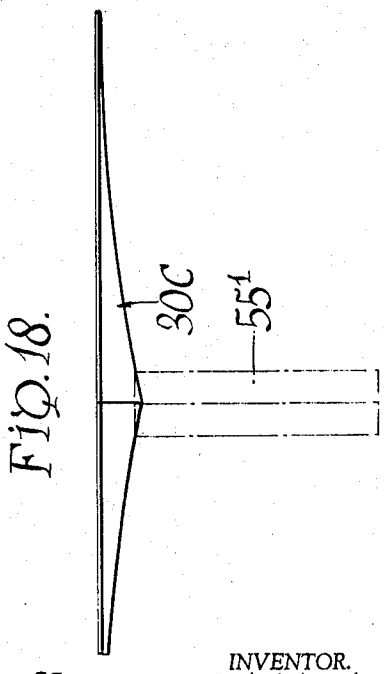


Fig. 18.

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United States Patent Office 3,286,415
Patented Nov. 22, 1966

3,286,415

REINFORCED SHELL CONSTRUCTION

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Filed Aug. 22, 1962, Ser. No. 219,815
1 Claim. (Cl. 52—86)

This invention relates to architectural structures and more particularly to an improved shell construction and to an improved method of fabrication thereof. The present application is a continuation-in-part of application Serial No. 778,878, filed December 8, 1958, now abandoned.

In recent years there has been a trend in architecture toward constructing buildings with curved walls and roofs. If such curved portions of a building are constructed by conventional methods and of conventional materials, their cost is relatively expensive. If such curved structures are fabricated of conventional reinforced concrete, their ratio of material to strength is relatively high, and they are relatively costly. However, in recent years shell types of construction have been widely adopted because, in general, this form of construction provides a low ratio of material to strength and consequently is desirable not only from an economic viewpoint but also because various curved surfaces can be generated in a relatively easy manner. It is with the providing of an improved shell construction that the present invention is concerned.

Shell structures are defined as any structure wherein the thickness is bounded by two curved surfaces and the thickness is small compared to the other dimensions of the structure. Generally, shell structures are formed of concrete-like material reinforced in each of two directions by reinforcing elements, such as reinforcing rods, in such a manner that the strength of the resulting structure is not only attributable to the existence of the reinforcing elements but especially to the curved shape of the concrete-like material which causes direct loads applied thereto to be transmitted into stresses within the shell itself, as membrane stresses, while subjecting the shell to relatively low bending stresses. Shell types of structures, having the thickness thereof bounded by two curved surfaces are always curved in at least one direction, as for example a sector of a cylinder or a sector of a cone, or may be doubly curved, as for example a dome, a hyperboloid, a hyperbolic paraboloid, or other complex curved forms. As noted above, the fundamental characteristic of shell type structures is their ability to carry relatively heavy loads while utilizing relatively small amounts of material because the loads are essentially transmitted to tension, compression, and tangential shearing in the shell without subjecting the shell to significant bending stresses. However, in the past, prior type of shell constructions were required to be relatively thick to carry the loads to which they were to be subjected. Furthermore, prior types of shell constructions required carefully built and expensive forms to produce the desired shell curvature. Such forms were not only cumbersome and difficult to handle, but were also expensive in that they had to be built for each particular configuration of the desired shell structure, that is, if a predetermined curvature was required in a shell, forms had to be made to provide such curvature and these forms were of no use whatsoever in constructing shells of another desired curvature. Furthermore, these forms were relied on entirely to support the shell, consisting essentially of reinforced concrete as noted above, until such time as the shell hardened. Thus the forms had to be relatively massive and were extremely difficult to handle, in addition to being expensive. It is with the overcoming of the foregoing shortcomings incidental to the fabrication of prior art shell constructions that the present invention is concerned.

It is accordingly one of the objects of the present invention to provide an improved shell construction which possesesses a high ratio of strength to both thickness of the concrete-like material and mass of the total shell and therefore permits thin shell structures to be economically fabricated from a cost of materials viewpoint.

It is another important object of the present invention to provide an improved method of constructing shell structures which is extremely economical in that portions of the composite shell construction serve as permanent forms and therefore obviate the necessity for using the massive, cumbersome, and expensive temporary supports of prior types of shell constructions. A related object of the present invention is to provide an improved method of constructing shell structures which utilizes relatively simple, inexpensive, and lightweight temporary supports for supporting the composite shell structure only until it becomes self-sustaining due to the hardening of the concrete-like material used therein.

A further object of the present invention is to provide an improved shell construction having curved surfaces which can be fabricated from reinforcing components having a curvature different from the curved surfaces of the shell, thereby permitting relatively inexpensive conventional curved or uncurved structural elements to be utilized in fabricating a curved shell structure in an economical manner. Other objects and attendant advantages of the present invention will readily be perceived hereafter.

In accordance with one aspect of the present invention the composite shell construction, which may be used for roofs, walls, or floors, has first and second external curved surfaces and includes a plurality of spaced first reinforcing elements having first and second sides. The first reinforcing elements may be of any desired conventional configuration, but are specifically oriented to define the general curvature of the shell, which may be different from the curvature of the first reinforcing elements. A plurality of spaced second reinforcing elements extend transversely of and are rigidly secured to the first sides of said first reinforcing elements and are supported thereby. A plurality of permanent forms are supported by the above-mentioned first reinforcing elements and span the spaces therebetween. Because the first reinforcing elements are relatively close to each other, the permanent forms which are located between adjacent first reinforcing elements, may be substantially planar, and when all of the permanent forms are considered together, define the first external curved surface of the shell. A plurality of third reinforcing elements extend transversely of and are contiguous to the above-mentioned second sides of said first reinforcing elements. A concrete-like material embeds the first and third reinforcing materials and has a first surface following the contour provided by the permanent forms and its opposite surface shaped to any desired curvature. The above-mentioned second reinforcing elements are preferably located on the opposite sides of said permanent form means from the concrete-like material and are therefore external thereof. Thus the first reinforcing elements provide resistance of said shell against internal tension or compression or flexure or shear forces or combinations of certain of said internal forces when they are bonded to the concrete-like material in said composite shell structure. The second reinforcing members, also enhance the strength of said shell against the above-described compression and tension and flexural forces notwithstanding that they are located externally to the concrete-like material of said composite shell structure. In resisting such forces the second reinforcing elements act substantially only in tension or compression. Since said second reinforcing elements are external of the concrete-like materials, they permit the

minimizing of the thickness of the concrete-like portion of the shell. In short, the above-described composite shell construction has a relatively high ratio of strength to both thickness of concrete and mass and is therefore extremely economical from a cost of materials viewpoint. The cost of the material is also relatively low because standard reinforcing elements may be utilized, and such elements need not be precurved, at an additional expense, to provide the desired overall curvature of the composite shell structure. It is the orientation of the standard reinforcing elements relative to each other, and not their shape, which provides the desired curvature of the shell.

Another aspect of the present invention resides in the improved method of fabricating the above-described improved shell structure which has first and second curved surfaces. This method comprises the steps of orienting a plurality of first reinforcing elements in spaced relationship to define the general curvature of said shell; rigidly securing second reinforcing elements to portions of first sides of said first reinforcing elements in transverse relation thereto to cause said first reinforcing elements to support said second reinforcing elements; placing permanent forms between said first reinforcing elements in an orientation to provide said first curved surface and causing said first reinforcing elements to support said permanent forms; placing third reinforcing elements in contiguous relationship with second sides of said first reinforcing elements; placing a concrete-like material on to said permanent forms and over said first and third reinforcing elements to thereby embed said first and third reinforcing elements; and shaping the top of said concrete-like material to provide said second curved surface. By practicing the above-described method, the improved shell structure of the present invention may be economically fabricated. In the practice of the above-described method it is also contemplated that the additional steps of placing a plurality of temporary supports under the framework of the above described composite shell structure may be performed under certain circumstances to provide temporary strength to the framework during the step of placing the concrete-like material. After the concrete-like material hardens and the composite shell structure becomes self-sustaining, the temporary supports are removed. It will be appreciated that the above described steps need not necessarily be performed in the sequence described but may be modified to meet any particular situation. Also considered inherent in the above described method is the basic concept of taking a plurality of first reinforcing elements of a first predetermined configuration and orienting these first reinforcing elements relative to each other in such a manner as to provide a curvature for a composite shell structure having a second predetermined configuration which is different from said first predetermined configuration. By the foregoing procedure standard conventional reinforcing members may be utilized to generate any desired shape to a shell structure, thereby obviating the necessity for using specialized shapes of reinforcing members at added expense.

Both the improved shell construction and the improved method of fabrication thereof will be more fully understood when the following portions of the specification are read in conjunction with the accompanying drawings wherein:

FIGURE 1 is a front elevational view schematically showing a building provided with one form of a shell-type roof constructed in accordance with the principles of the present invention;

FIGURE 2 is a fragmentary vertical section view taken on the line **2—2** of FIGURE 1;

FIGURE 3 is a perspective view schematically showing one of a number of spaced temporary supports shaped to support the roof (shown in FIGURES 1 and 2) during its construction;

FIGURE 4 is an enlarged plan view showing a portion of a shell-type roof which is adapted to roof large areas and which embodies and typifies the principles of the present invention;

FIGURES 5 and 6 are vertical cross-sectional views taken respectively on the lines **5—5** and **6—6** of FIGURE 4 and show how the straight main supporting structural T bar elements of the improved roof construction may be formed, spaced, arranged and secured in a predetermined relation one to the other by spaced transverse tie-bars to directly support reinforcing elements within the concrete-like shell and to support sheets of material which support a plastic mass of concrete-like material while it sets and hardens;

FIGURE 6A is fragmentary perspective view of a modified form of main supporting bar;

FIGURE 7 is an enlarged bottom plan view of a portion of a modified form of shell-type roof wherein the transverse tie-bars are curved to substantially follow the curvature of the roof and carry one or more anchoring devices which, being bonded to the shell prevent deflection of the tie bars;

FIGURE 8 is a vertical cross-sectional view taken on the line **8—8** of FIGURE 7;

FIGURE 9 is a perspective view showing a portion of a curved tie bar provided with one of the anchoring devices;

FIGURE 10 is a top plan view schematically showing another form of shell-type roof wherein the straight and parallel structural T elements, indicated by broken lines, each have their opposite ends arranged at predetermined elevations, to thereby provide the roof with light and strong convex and concave portions;

FIGURE 11 is a front elevational view of the roof shown in FIGURE 10 and shows one diagonally opposite pair of its corners located at a predetermined elevation different from the elevation of its other diagonally opposite corners to provide desired convex and concave portions;

FIGURE 12 is a vertical cross-sectional view taken on the line **12—12** of FIGURE 10 and showing the resultant convexity of the roof between its diagonally opposite lowermost corners;

FIGURE 13 is a vertical cross-sectional view taken on the line **13—13** of FIGURE 10 and showing the resultant concavity of the roof between its diagonally opposite uppermost pair of corners;

FIGURES 14 and 15 are fragmentary side elevational views respectively showing an upwardly bowed and a downwardly bowed structural T element which may be used alone or in combinations, and in combination with straight T elements to provide other roof shapes;

FIGURE 16 is a top plan view of another form of shell-type roof, wherein the straight parallel structural T elements, indicated by broken lines in each of the four sections of the roof, have their opposite ends arranged at predetermined elevations to provide the desired convex and concave portions of the roof;

FIGURE 17 is a front elevational view of the roof shown in FIGURE 16;

FIGURE 18 is an elevational view of the roof in FIGURE 16 as viewed from one of its corners;

FIGURE 19 is an enlarged vertical cross-sectional view taken on the line **19—19** of FIGURE 16 to show the convex portion of that section of the roof; and

FIGURE 20 is an enlarged vertical cross-sectional view taken on the line **20—20** of FIGURE 16 to show a concave portion of the same section of the roof.

Because of the extremely small scale necessary to illustrate the roofs shown in FIGURES 1, 2 and 10–20 no attempt, except for the broken line indication of the structural T elements thereof, was made to show the roof construction in detail, but it should be understood that the roof constructions detailed in FIGURES 4–6 and in FIGURES 7–9 and modifications thereof are adapted for use in the forms of roofs shown and in other roof forms. It

will also be appreciated that while the portions of the following description refer specifically to roofs, the principles of the present invention may also be applied to the construction of walls and floors.

Generally stated, the present invention resides in providing improved shell-type constructions for roofs, or the like, and an improved method of fabricating shell-type constructions which are capable of providing many different shapes and forms having large areas and which require less material, no accessories, no expensive forms and simple inexpensive temporary supports, so that the cost per square foot of area of roofs and other types of shell constructions constructed in accordance with the principles of the present invention is considerably less than the cost per square foot of area of prior shell-type constructions.

For the reason that either of the improved shell-type roof constructions illustrated in FIGURES 4–6 and FIGURES 7–9 and modifications thereof are adapted for use in the differently shaped forms of shell-type roofs depicted in FIGURES 1, 2, 10–20 and in other possible shapes and forms of such roofs, it is deemed advisable to specifically describe these roof constructions and the method of fabricating them before describing the different roof shapes and forms.

Referring now to the drawings, FIGURES 4–6 illustrate a form of my improved shell-type of roof construction generally indicated by the numeral **30**. In this construction a number of main structural elements, or first reinforcing elements, may have any suitable cross-sectional shape, but which are preferably formed as rail shaped bars **31**, known as bulb T's. These first reinforcing elements, or bars or T's **31**, **32** are formed with a base portion **32**, an upright web portion **33** located, midway between the sides of the base portion **32** and a head portion **34** centered upon the web portion **33**. The T bars **31** are straight and of a length to span the area to be roofed and are located, suported and secured in a spaced substantially parallel predetermined relation one to the other, in a manner to be described, with their web portions **33** normal to the predetermined curvature of the roof. The bars **31** are rigidly maintained in this relation by a number of suitably spaced strap-like tie bars **35**, or second reinforcing elements. The second reinforcing elements or bars **35** extend transversely across and beneath the T's **31** and are preferably formed between the straight portions **36** with the portions **37** upon each of which the base portions **32** of each of the T's **31** is rigidly secured as by the welding **38**. It is to be especially noted that first reinforcing elements, or T's **31**, thus support the second reinforcing elements or tie bars **35**.

The space between adjacent pairs of the tie bars **35** is spanned and closed by permanent forms, such as sheets or panels **41**, which may be substantially planar, formed of any suitable sheet material which form a first curved surface of the shell. These sheets **41**, being installed and supported between the T bars **31**, provide a simple and inexpensive permanent form to support the plastic mass of concrete-like material, such as ordinary concrete, after it is placed or deposited thereon, then worked, finished and allowed to harden to form the shell portions **40** of the roof **30**. The upper shaped surface of the concrete forms the second curved surface of the shell. The sheets **41** also serve as supports for the workmen fabricating and finishing the roof so that the necessity of providing elaborate, massive, and expensive temporary forms for supporting the concrete-like material and the workmen is obviated. As noted above, once the concrete-like material is hardened it causes the composite shell structure to be self-sustaining. However, in order to support the structure after the concrete-like material is placed but before it hardens, simple inexpensive temporary supports **57**, FIG. 3, are strategically positioned relative to the shell, such supports being removed after the concrete-like material hardens, as described in detail hereafter.

It is to be especially noted that sheets or panels **41** are in essence permanent forms for the concrete-like material, and, as such, form an integral part of the composite shell structure. It is also to be noted that the planar permanent forms **41**, when taken all together define the lower curved surface of the shell. Even if the adjacent T bars **31** are oriented in skewed relationship, as shown in FIGS. 10–20, the originally planar permanent forms **41**, by resting on bases **32**, present a warped surface which follows the desired curvature as determined by the orientation of T bars **31** relative to each other.

When the appearance of the interior surface of the roof is not considered important the sheets **41** may be advantageously formed as thin rigidized metal sheets, such as the corrugated sheets shown in the drawings, and the opposite corrugated ends of these sheets may be conveniently supported upon the adjacent base portions **32** of adjacent pairs of the T bars **31** independently of other supporting means. Sheets **41** are substantially planar in the sense that the mean plane thereof is flat and not curved. While the drawings show corrugated sheets, it will be understood that flat sheets may also be used. However, should the appearance of the interior surface of the roof be considered important, the sheets may be formed to not only perform their above stated functions, but may also have their inner surface prefinished, at a slight additional cost, to provide the desired appearance without appreciably increasing the cost of installing the sheets. Furthermore, the inner surface of the sheets **41** may be suitably formed to provide a desired accoustical effect at a cost very low in comparison to present methods of providing a comparable accoustical effect. The sheets **41** may also be formed to provide a desired insulating effect.

The concrete-like shell portions **40**, being externally reinforced in one direction by the base portions **32** of the T bars or first reinforcing elements **31**, and in a transverse direction by the tie-bars or second reinforcing elements **35**, are also internally reinforced in the direction of the latter by reinforcing bars or rods or third reinforcing elements **46**. The rods **46** are arranged to transversely span and cross the head portions **34** and are directly carried thereupon and at selected points of contact with the heads **34** are welded or otherwise secured in place thereon. The rods **46** at their points of securement to the heads **34** act as shear lugs which provide additional resistance against longitudinal movement of the bars **31** with respect to the concrete-like portion **40** of the composite shell. If desired, third reinforcing elements or rods **46**, may merely be laid across heads **34** and need not necessarily be secured thereto at any points of contact.

When additional reinforcement of the shell is required in the other direction, that is to say in the direction of the bars or third reinforcing elements **31**, a plurality of spaced reinforcing bars or rods **47** are arranged in crossing relation to the bars **46** and at selected points of contact are secured thereto. If desired rods **47** may merely be laid across rods **46** without being secured thereto at any points of contact. The rods **45** and **47** thus cooperate with the T-bars **31** and the tie-bars **35** in resisting whatever stresses that may occur in the composite shell structure **30**. In instances where the use of a structural reinforcing mesh is practical the reinforcing rods **46** and **47** may be the elements of the mesh **45** which is shown in the drawings and which at selected points may be welded, otherwise secured to the heads **34**, or merely be laid across said heads. Whether rods **46** are secured to heads **34** at all points of contact, selected points of contact, or are merely laid across heads **34** without being secured thereto, they are in contiguous relationship with heads **34**, and may either be in direct contact therewith or slightly spaced therefrom. In any event, the terminology "contiguous relationship" is intended to describe all of the foregoing variations.

The bars or rods **46**, being bowed into contact with

and secured to the heads 34, naturally assume and remain bowed to a curvature determined by the predetermined relation of the bars 31, independently of "high-chairs" or other supporting accessories which are otherwise used during construction. Therefore the rods 46, when used alone, or when used in combination with the rods 47, or when used as an element of the mesh 45, cannot be displaced, during the operation of depositing upon the sheets 41 a mass of plastic concrete-like material, such as ordinary concrete, which is sufficient to entirely encase the portions 33 and 34 of the bars 31 and the reinforcing bars 46, and the bars 47 when used, and which when worked has its top surface finished to the curvature determined by the predetermined relation of the bars 31 to provide the reinforced shell 40. Thus completed and hardened, the concrete 30 is intimately bonded to and internally reinforced by the portions 33 and 34 and the bars 46 and 47.

The tie bars 35 not only act to maintain the T bars 31 in place but their portions 36, being straight, act in either tension or compression to resist forces applied to and tending to change the transverse curvature of the shell. The use of tie bars 35 permits the composite shell to be made relatively thin and therefore at relatively low cost.

Summarizing the foregoing construction, first reinforcing elements or T bars 31 provide resistance against tension, compression or flexure of the composite shell structure, when reinforcing elements 31 are bonded to the concrete. It is the bonding of the reinforcing elements 31 to the concrete which prevents them from working independently and causes them to work as integral portions of the shell. Reinforcing elements 31 act as a reinforcement in tension and therefore act independently of the concrete, which has a relatively low tensile strength. Furthermore, elements 31 act in compression with the concrete. Tangential shearing stresses, whenever they occur, are resisted by elements of reinforcements which are put in tension by such stresses and by the concrete and reinforcements which are placed in compression by such stresses. It is to be especially noted that reinforcing elements 31 do not act in the nature of beams except during construction and before the concrete-like material hardens. In the foregoing situation first reinforcing elements or T bars 31 act as beams between the temporary supports which are spacedly positioned thereunder. It is to be especially noted that since the temporary supports such as 57 of FIGURE 3 are not required to extend under the entire surface of the structure but are placed only at select spaced apart locations, the cost of construction is decreased.

Insofar as second reinforcing elements or tie bars 35 are concerned it is to be noted that they do not support the load of first reinforcing elements 31 but are in fact themselves supported thereby. Second reinforcing elements 35 act substantially only in tension or compression but not in bending regardless of the type of loading the composite shell is subjected to. Elements 35 do not act as beams. Thus second reinforcing elements, or tie bars 35, are external reinforcing members for providing resistance to compression, tension, flexural or tangential shearing forces exerted on the shell structure. Because second reinforcing elements 35 are external to the concrete, they provide substantial stiffness and flexural strength to the shell structure while minimizing the amount of concrete-like material required.

Third reinforcing elements 46, as noted above, need not necessarily be secured to first reinforcing elements 31. These reinforcing elements 46 have no function during the fabrication of the composite shell structure, but merely act as normal reinforcing elements of reinforced concrete to increase the strength of the composite shell structure in tension. In other words reinforcing elements 40 act in tension to provide membrane action and perform a function which is complementary to second reinforcing elements or tie bars 35.

It is to be especially noted that when the various individual elements 31, 46, 41, 46 and 40 of the composite shell structure are considered as an integral composite shell structure, their action provides a relatively thin shell having a relatively high strength.

The modified form of shell-type roof construction shown in FIGURES 7–9 is essentially the same as that shown in FIGURES 4–6 with the following exception. The tie bars 35′ may be somewhat thinner than the tie bars 35 and, being bowed between their points of attachment to the T bars 31 to a curvature substantially concentric to the curvature of the outer surface of the slab 40, allow the inner surface of the roof to be finished smoothly.

In the event the curvature of the tie bars 35′ is very slight they may have substantially the same action as the straight tie bars 35, however when their curvature is such that they may not resist tension forces tending to straighten them, or compression forces tending to further bow them, they are each provided with one or more anchoring devices such as the anchors 50. The anchors 50 may be formed of L-shaped sections of suitable rod preferably having one leg 51, normal and rigidly secured to the top side of the tie bar 35′, midway between its side edges, and another leg 52 extending from the upper end of the leg 51 and along the medial plane of the bar 35′. The anchors 50, being thus formed and located, extend into and are bonded to the slab 40 thereby serving to maintain the predetermined curvature of the tie bars 35′.

In this modified construction the sides of the sheets 41 may be placed in abutting relation by simply providing suitable notches to receive the legs 51 of the anchors 50, but because it is less expensive to abut the sides of the sheets 41 against the sides of the legs 51 and because the small gap left between the sheets in unimportant, this manner of placing the sheets 41 is considered preferable.

An important advantage of these improved shell-type roof constructions over prior constructions is that the internal and external two-way reinforcing described above permits the construction of roof shells which are thinner, lighter and less expensive than prior roof shells and which, notwithstanding the lightness of their reinforcing elements, have a resistance to bending comparable to that of the thicker, heavier and more expensive prior roof constructions.

Generally stated, the method of fabricating the above described improved roof structures to provide a number of differently curved forms of shell-type roofs, for example the roof forms shown in FIGURES 1–2, and 10–13, and 16–20 comprises the steps of supporting and securing a plurality of the straight main supporting bar or first reinforcing elements 31 in spaced parallel relation and in a predetermined arrangement or orientation relative to each other to provide the desired roof shape; the step of rigidly securing a plurality of spaced tie bars or seconds reinforcing elements to and in transverse relation to the lower sides of the main bar elements to maintain their predetermined arrangement; the step of placing and supporting a plurality of sheets or permanent forms transversely upon said first reinforcing elements to close the space between each adjacent pairs thereof and to provide support for the workmen and support for a plastic mass of concrete-like material deposited thereupon; the step of placing third reinforcing elements upon the top sides of the main bar elements and, if desired, securing said third reinforcing elements to said first reinforcing elements; and the step of depositing upon the sheets a mass of plastic concrete-like material which is sufficient to completely embrace the upper portion of the main bar elements and the reinforcing mesh and which when worked, finished and permitted to harden provides

the internally and externally reinforced shell-type roofs of the present invention.

In fabricating a shell-type roof such as that schematically shown in FIGURES 1 and 2 and generally indicated by the numeral **30A**, my improved method also includes the step of providing the suitably spaced permanent supports **55** which, being formed with a surface **56** having a predetermined curvature, support end portions of the spaced main straight bars **31** thereupon and determine the curvature of the roof; the step of providing and placing a plurality of temporary supports, such as the supports **57** shown in FIGURE 3 which supports, being formed with a curved surface **58**, shaped like the curved surfaces **56**, are spaced as indicated by the dot and dash lines in FIGURE 2 and thus serve to support and prevent bending and movement of the bars **31** from their predetermined position while the roof structure is completed and the roof forming material hardens; and the step of removing the temporary supports **57**, since they are no longer required. It is to be again noted that the temporary supports, such as **57** of FIG. 3, are intended to be used with all modifications of the present invention. It is only in certain isolated instances where temporary supports need not be used. It will also be appreciated that the above enumerated steps need not necessarily be performed in the recited sequence.

It will be apparent that shell-type roofs such as that schematically shown in FIGURES 1 and 2 can be designed and fabricated in accordance with the principles herein described to provide lighter, wider and longer roof spans at less expense per square foot of area than has heretofore been considered practical because massive expensive temporary supports are not needed and because less material is needed because of the unique manner in which the frame of the shell, namely, the various reinforcing elements and the permanent forms are integrated.

The method of fabricating shell-type roofs, such as that schematically shown in FIGURES 10–13 and generally indicated by the numeral **30B**, is essentially the same as that used to fabricate the roof shown in FIGURES 1 and 2. However while the straight bar elements **31**, indicated by broken lines in FIGURE 10 are spaced and in substantially parallel vertical planes, they are supported in a predetermined arrangement or orientation different from that of FIGURES 1 and 2 by spaced supports (not shown) which may be of the permanent or temporary types discussed above, and which are each formed with a straight surface formed and arranged to support the bars **31** in a predetermined arrangement. In this arrangement of the straight bars **31** the opposite sides of the roof **30B** are skewed and equally inclined in opposite directions as shown in FIGURE 11 and, notwithstanding that the bars **31** are straight, the roof between its diagonally opposite lowermost corners has the convex portion shown in FIGURE 12 and between its diagonally opposite uppermost corners has the concave portion shown in FIGURE 13. The roof **30B** is an example of a light and strong doubly curved roof structure.

The modified form of shell-type roof **30C** schematically shown in FIGURES 16–20, comprises four similar sections in each of which the straight, spaced and substantially parallel bars **31**, indicated by broken lines, have a predetermined arrangement different from that in the other forms of roofs. Bars **31** lie in parallel vertical planes but not in the same horizontal plane and are therefore skewed. In this arrangement the outer side bars **31** and the outer ends of the bars **31** of each section are all supported to lie in a single horizontal plane and the inner ends of the bars of each section are supported to lie in a plane which extends downwardly and inwardly from said outer single plane, so that the innermost corners of the sections meet at a point located below said plane. This arrangement of the straight bars **31** produces a roof wherein each of its four sections diagonally between its outermost and innermost corners, i.e., in the plane of the section line **19—19**, is convexly curved as shown in FIG. 19, and diagonally between its other corners, i.e., in the plane of section line **20—20**, is concavely curved as shown in FIGURE 20. The roof **30C** is another example of a light and strong doubly curved roof structure.

The method of forming the roof **30C** is essentially that practiced in forming the other roofs except that a suitably formed single permanent support **55'**, indicated by broken lines, is erected to permanently support its center portion and a plurality of temporary supports, not shown, but each having a suitably arranged straight top surface, are arranged in spaced parallel relation to each other and in transverse relation to the plane of the bars **31** to support said bars in their predetermined relation until the roof is completed, whereupon the temporary supports are removed and the roof is supported by its permanent support and may have its peripheral edge portion supported by suitable walls.

In the event it is desired to provide a roof shape which cannot be made by the straight bars **31**, and assuming that the additional costs of fabricating such a roof shape is not the determining factor, the desired roof shape may be fabricated of the upwardly bowed bars **31'** shown in FIGURE 14, the downwardly bowed bars **31''** shown in FIGURE 15, combinations of these bars or combinations of either or both of the bowed bars **31'**, and **31''** with the straight bars **31**.

It should be understood that the illustrated forms of roof construction are intended to exemplify the principles of the present invention, that while these forms are adaptable to provide the several differently shaped curved roofs depicted, they are also adaptable to many other curved roof shapes, and that various modifications in the form and arrangement of the component elements of the roof structure and the method of fabricating it may be made. Furthermore, while the preceding description has primarily referred to composite shell roof structures, it will be appreciated that the principles of the present invention are equally applicable in the fabrication of composite shell wall and floor structures.

While preferred embodiments of the present invention have been disclosed, it will readily be appreciated that the present invention is not limited thereto but may otherwise be embodied within the scope of the following claims.

I claim:

A composite shell construction having first and second external curved surfaces, comprising a plurality of spaced first reinforcing elements having first and second sides, said first reinforcing elements being oriented to define the general curvature of the shell, permanent support means for said first reinforcing elements, a plurality of spaced second reinforcing elements extending transversely of and being rigidly secured to and being supported by said first sides of said first reinforcing elements and therefore following the general curvature of said shell as determined by the orientation of said first reinforcing elements, said second reinforcing elements aiding in maintaining said first reinforcing elements in predetermined relation relative to each other by virtue of being secured thereto, third reinforcing elements extending transversely of and contiguous to said second sides of said first reinforcing elements, permanent form means spanning the spaces between and being supported by said first reinforcing elements and generally following the curvature of said shell as determined by the orientation of said first reinforcing elements relative to each other to thereby define said first external curved surface, and concrete-like material having first and second sides with said first side resting on said permanent form means, said concrete-like material being bonded to and embedding said first reinforcing elements and said third reinforcing elements, said second side of said concrete-like material being curved to provide said second external curved surface, said second reinforcing elements being located on the opposite side of said permanent form means form said concrete-like material,

whereby said first reinforcing elements provide resistance to said shell against tension or compression or flexure forces when bonded to said concrete-like material in said composite shell structure, and whereby said forces applied to said composite shell structure are resisted in compression or tension by said second reinforcing elements, said second reinforcing elements thereby enhancing the strength and stiffness of said shell while permitting the minimizing of thickness of the concrete-like portion thereof.

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