

March 5, 1957

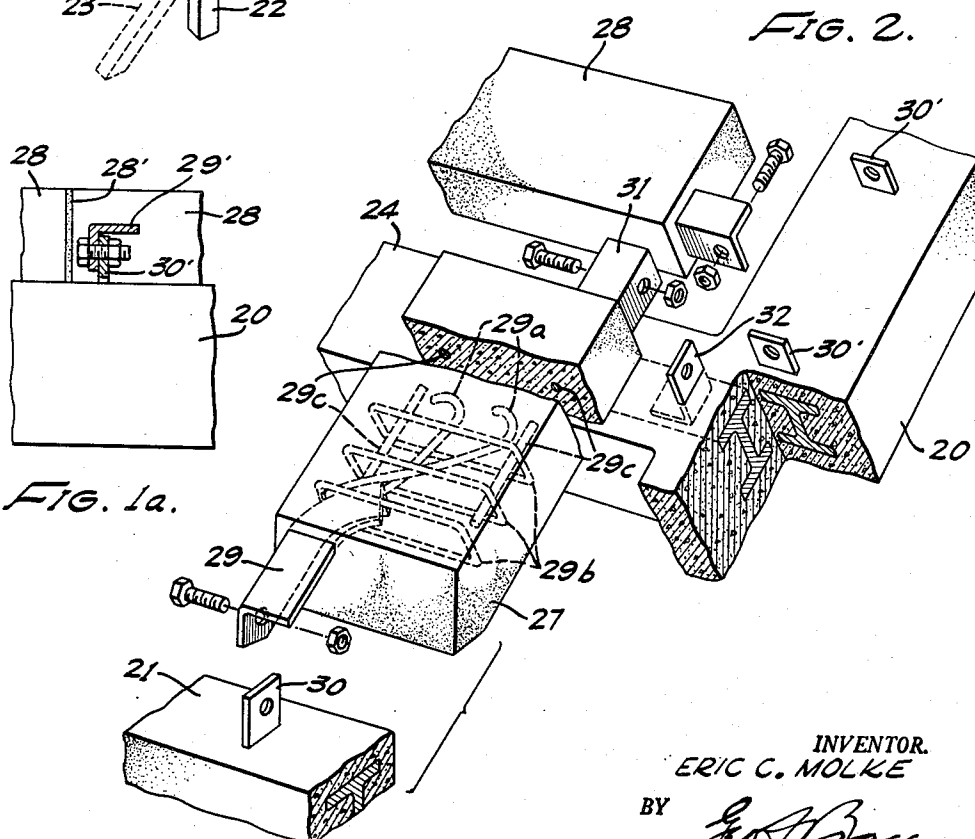
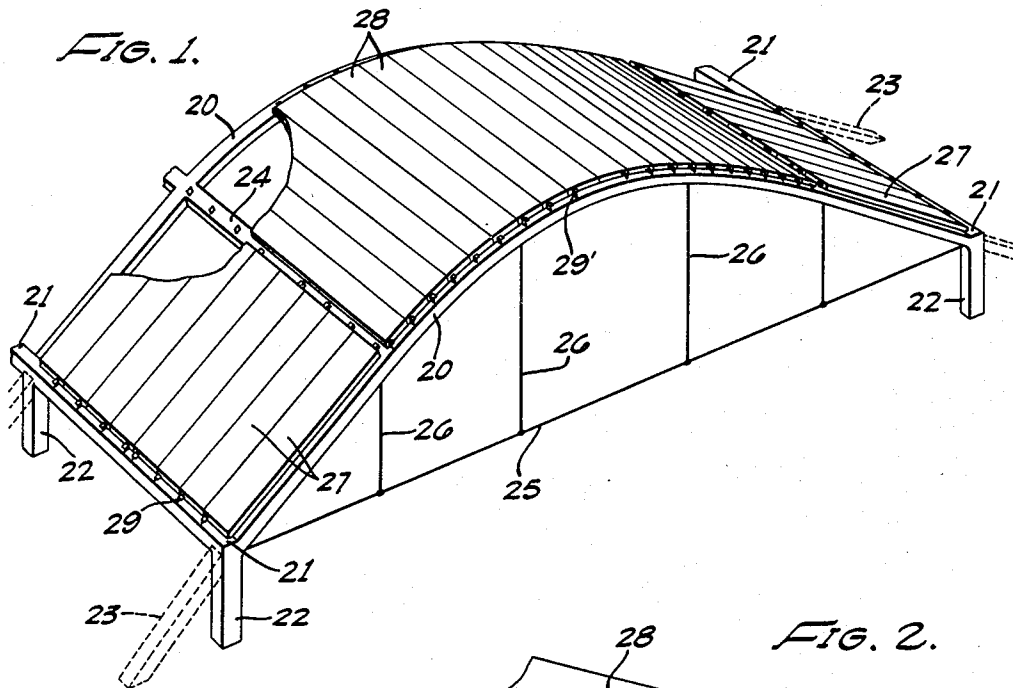
E. C. MOLKE

2,783,721

WIDE SPAN STRUCTURES

Filed Sept. 9, 1950

3 Sheets-Sheet 1



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March 5, 1957

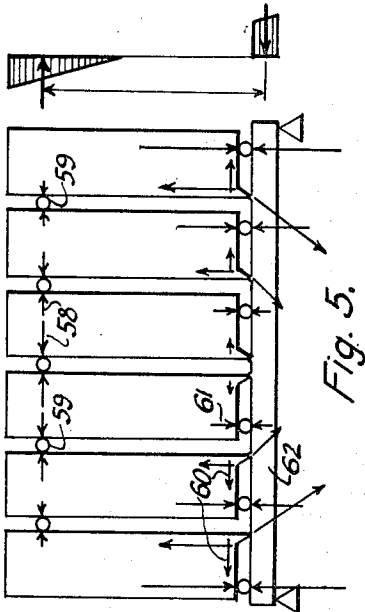
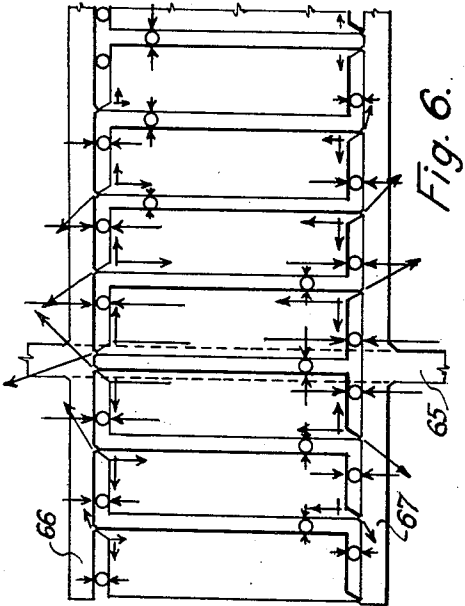
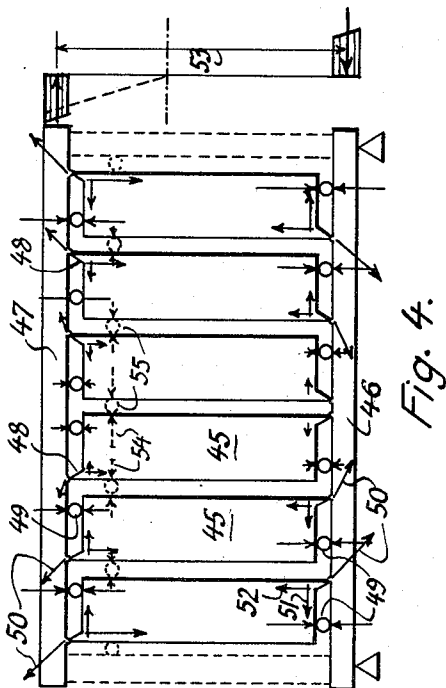
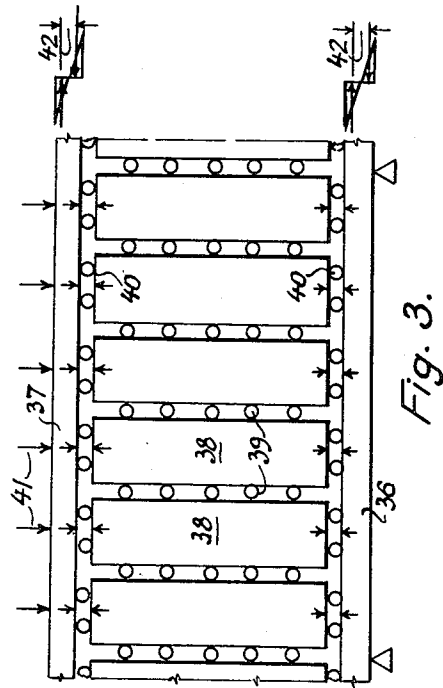
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WIDE SPAN STRUCTURES

Filed Sept. 9, 1950

3 Sheets-Sheet 2



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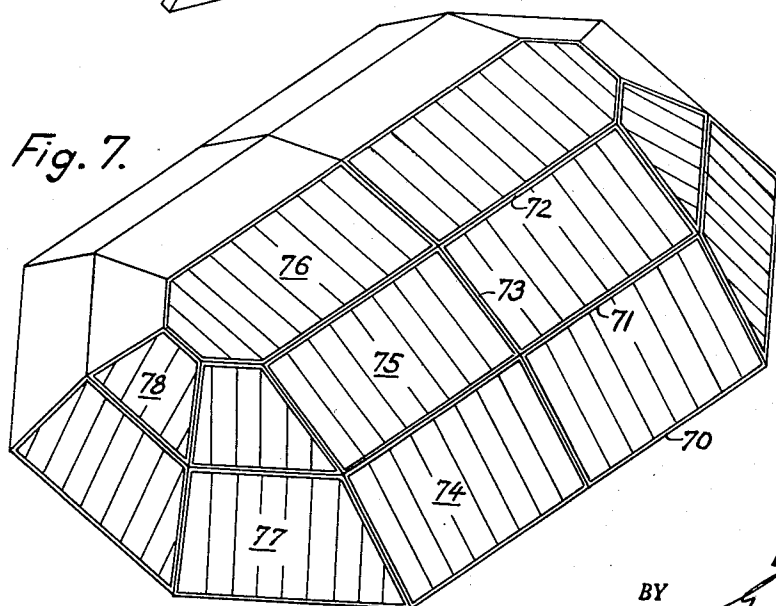
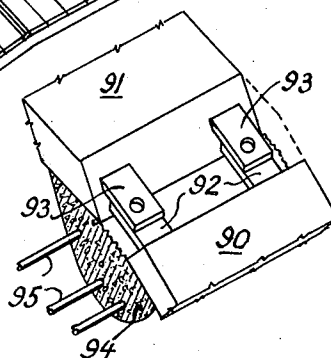
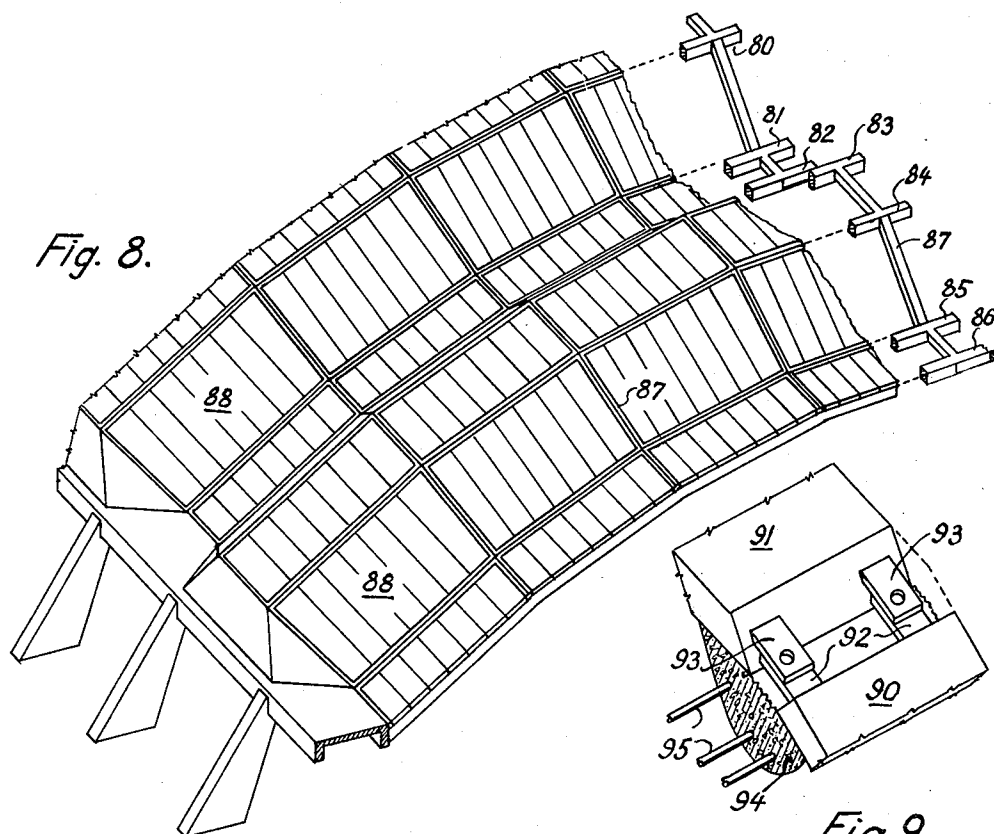
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E. C. MOLKE
WIDE SPAN STRUCTURES

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3 Sheets-Sheet 3



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2,783,721

WIDE SPAN STRUCTURES

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Application September 9, 1950, Serial No. 187,113

18 Claims. (Cl. 108—1)

This invention relates to a unique low-cost, lightweight, high-strength structure for spanning areas without the use of vertical supports inside the perimeter of the span and which is particularly applicable to roofs, bridges and the like.

Prior designers have resorted to a great profusion of structural arrangements to span wide areas without using intervening columns. The more successful designs have as their objective the shaping of the structure to coincide with the funicular curve of the principal loads applied. Such roofs are commonly known as thin-walled, monolithic arch roofs. These structures are usually made of intricately reinforced concrete, having few and preferably no joints throughout the span. Although such designs have achieved some degree of acceptance, they are subject to numerous disadvantages and limitations.

For example, if the cost of prior designs is to be kept within acceptable standards, the roof shape must be cylindrical in order that the elaborate staging required for the forms can be built for one arch section and then moved laterally to provide forms for other sections in succession. This impediment, imposed by cost considerations, involves a second and serious limitation on the design of monolithic arch roofs; namely, that the span can be arched only cross-wise of its axis and not also lengthwise thereof as would be desirable to obtain greater strength and economy in the use of materials. When one bears in mind that heavy and costly movable staging is required for the full width of the span, that accurate forms must be constructed on top of the staging and that intricate and carefully designed reinforcing must be laid therein, it will be readily appreciated that highly skilled labor is essential and that the cost and time considerations involved in constructing this type of roof are exorbitant, if not prohibitive.

By the use of my invention it is possible to utilize the recognized advantages of the monolithic arch design and yet avoid its numerous inherent disadvantages. Thus, my invention contemplates the construction of a wide area span, comprising a simple, rigid skeleton and a covering layer of prefabricated, light-weight easily handled slabs, which are rigidly connected to the skeleton in a new and ingenious manner. The slabs are assembled individually and provide a working platform for the erecting crew, thereby eliminating the need for staging.

Particularly noteworthy is the fact that, by my design and arrangement for interconnecting the slabs and the skeleton, the resultant stress actions are confined between the upper and lower faces of the slabs. Only compressive forces are transmitted from slab to slab and all shearing stresses are transmitted to the skeleton.

Accordingly, a principal object of my invention is to provide a novel and highly efficient area spanning structure having characteristics and advantages not heretofore known or obtainable.

Another object is the provision of a wide spanning structure erectable element by element and in which the

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principal action is by direct stresses acting between the surfaces of the component elements.

Still another object is the provision of an area spanning structure comprising, essentially, a high strength skeleton and a high stress transmitting covering of prefabricated slabs.

Another object is the provision of a novel wide area roof construction which is arched both crosswise and lengthwise in such a manner that the two arching systems supplement one another and mutually cooperate in carrying the load.

Yet another object is the provision of a spanning structure in which major stresses acting on the component slabs are transmitted to the supporting skeleton by the individual slabs.

It is a further object to provide a spanning structure comprising individually erected slabs, arranged edge to edge and so connected to a supporting skeleton that shearing stresses acting on individual slabs are transmitted directly to the skeleton rather than to the bonding agent between adjoining slabs.

Still another object of the invention is to provide a new high-strength, light-weight panel construction comprising a pair of rigid load bearing elements interconnected by a plurality of pre-fabricated elements which cooperate with and supplement the rigid elements in carrying compressive stresses acting within the panel.

It is another object of the invention to provide a spanning structure constructed principally of beams comprising panels of pre-fabricated slabs arranged in different planes and rigidly interconnected to one another.

Other objects include the provision of a unique spanning structure presenting unusual flexibility and latitude to the designer in the arrangement of parts, as well as one featuring great strength, low cost components, speedy, low cost, assembly by unskilled labor, high efficiency in the utilization of material strengths and which is unusually efficient in the use of space.

Numerous other objects and advantages of my invention will become readily apparent from the following detailed description of illustrative embodiments of the invention and the accompanying drawings, in which:

Figure 1 is an isometric view of an arched shell roof incorporating the invention, showing part only of two consecutive arch girders and the mode of arranging the covering slabs thereon;

Fig. 1a is a fragmentary end elevation view of a pair of crown slabs for an arched roof showing tie means for rigidly interconnecting the same together.

Figure 2 is an enlarged isometric view of one of the slabs extending in the same direction as the arch girders and the means for rigidly connecting it to the arch skeleton;

Figure 3 is a stress diagram of a prior art roof panel formed of a plurality of slabs having their opposite ends resting on a pair of beams supported at their ends;

Figure 4 is a stress diagram of a roof panel according to this invention and wherein both ends of the slabs are rigidly connected to the skeleton members.

Figure 5 is a stress diagram of a roof panel according to this invention in which only the lower ends of the slabs are rigidly connected to a skeleton member;

Figure 6 is a stress diagram of a roof panel having skeleton members rigidly connected to the opposite ends of the slabs and wherein one end of the panel is supported as a cantilever;

Figure 7 is an isometric view of a dome-like roof span formed in accordance with this invention.

Figure 8 is an isometric view of a roof span having a covering of prefabricated flat slabs so arranged that the roof is arched lengthwise as well as cross-wise thereof; and

Figure 9 is a fragmentary isometric view showing a

modified mode of joining and supporting the ends of the slabs in adjacent roof panels.

One particularly practical embodiment of the invention is illustrated in Figures 1 and 2. For purposes of clarity, only half of the spanning arch has been shown and the length has been limited to two consecutive girders. It will be understood that the other half of the arched shell is of the same construction and that any desired roof length may be obtained by erecting the required number of parallel arch girders, covering slabs and supporting columns.

As shown, the supporting skeleton comprises rigid spanning arches 20, 20 the ends of which are rigidly connected to rigid, continuous beams 21 extending the full length of the area to be covered. Generally, it is desirable to support the arch above the ground in which event columns 22 are located beneath beams 21 opposite the ends of arches 20. The thrust load of the arches is carried in any suitable manner as by props or buttresses 23, 23. The skeleton also includes a plurality of rigid cross beams or chords 24 interconnecting the arches at spaced points there along. In reality, those chords in end to end alignment are also continuous beams and differ from those at the perimeter of the roof primarily in design strength.

Each of the above mentioned elements of the skeleton may be formed of conventional construction materials such as structural steel, timber, reinforced concrete and the like. As shown in Figure 1, the ends of arch members 20 are connected by tie rods 25. Vertical struts 26, 26 also connect intermediate portions of arch 20 and tie rod 25. Both the tie rods and the struts may be omitted from the skeleton if desired, and if certain design adjustments are made to take over the load carried by the rods.

The covering of the skeleton comprises pre-fabricated slab elements, which are individually and rigidly assembled to the skeleton in such manner as to supplement one another as well as the skeleton in supporting the loads imposed on the structure. One row of slabs is indicated at 27, while a second row of slabs 28 is shown arranged at right angles to slabs 27. The slabs may be fabricated of suitable materials and of a size which can be conveniently handled by the erecting crew and for transportation to the building site. In practice, it has been found feasible and economical to construct the slabs of re-inforced concrete. Other common building materials such as wood and metal, as well as combinations of these in a great variety of designs are also satisfactory.

As will be noted in Figures 1 and 2 rather heavy, high strength tie members 29, 31 extend from the ends of each slab at opposite corners thereof. As shown, these ties are right angle steel members which extend for a considerable distance longitudinally of the slabs and are suitably tied into the body thereof as by rods 29a, 29a so as to distribute and transmit stresses. Tie 29 is bolted, riveted or welded to a mating tie 30 projecting upwardly from marginal beam 21, while the upper tie 31 is similarly secured to a tie 32 secured to rigid chord 24. Manifestly, the ties need not be right angular members, but may be of any desired shape and design. Likewise, these ties may be connected directly to the skeletal members thereby avoiding the use of mating tie members 30 and 32.

Slabs 28 are constructed in the same general way as slabs 27 but have their ends mounted upon arch members 20, 20 as illustrated in Figure 1. Cooperating rigid tie members 29', 30' similar to ties 29, 30, 31 and 32 are employed to secure slabs 28 to the arch members. All slabs are laid edge to edge with sufficient intervening space to receive a filler such as concrete grout 28'. This same material is also employed to fill in around the ties and between the ends of slabs in adjoining panels to provide a roof having a continuous upper surface.

The above described ties between the slab and the

skeleton constitute an important feature of my invention, as they permit certain stresses and more particularly certain shear stresses, to be transmitted by the individual slabs directly to the skeletal members, which is highly advantageous. It will be understood that the slabs may be suitably reinforced for the transmission of the shear and the other stresses such as by reinforcing loops 29b adjacent the slab ends and by longitudinally extending rods 29c. Of equal or greater importance is the fact that the slabs themselves carry a considerable portion of the load which, except for the ties, would be carried by the skeleton. Thus, it will be appreciated that the slabs, together with the rigid skeleton members to which their upper and lower ends are connected, in reality, cooperate to form a composite beam. This highly significant aspect of the invention will be best understood by reference to the stress diagrams illustrated in Figures 3 to 6. Before discussing these figures in detail, however, let it be understood that each represents the major forces acting upon a roof panel constructed of prefabricated slabs and supporting skeletal members, but differing from one another in respects which will be noted below.

For example, Figure 3 represents a conventional prior art slab roof construction comprising the usual rectilinearly arranged skeleton including rigid horizontal beams 36 and 37 and a covering of slabs 38, 38. For purpose of analysis, the grout which normally completely fills the gaps between the slabs has been replaced by rollers 39, 39. Likewise the ends of the slabs are shown terminating short of the beams and rollers 40, 40 have been substituted for the grout. Justification for this substitution is that sound design practice treats a grouted joint as having zero strength for both tensile and shearing forces, but good strength in compression. A roller will transmit compression forces, but will not transmit tension or shear stresses. In this connection it may be noted that a grouted joint under tension tends to open. Hence any tendency that the rough mating surfaces of the grout and slab might have to absorb shear, must be disregarded by the designer. Therefore, the use of rollers in place of the grout is not only proper but assists one in gaining a better understanding of the forces acting within the assembly.

Now, let us assume that a uniform load, indicated by arrows 41, 41 is applied along upper beam 37, such as would be imposed on chords 24 of Figure 1 by the arch thrust of slabs 28. Obviously, this load is transmitted to slabs 38, 38 and to the lower beam 36 through compressive forces acting through the upper and lower rows of rollers 40, 40. One half of the total load is absorbed by beam 36 and the other half by beam 37. As is true of all beams, a load places the lower half of a beam under tension and the upper half under compression. This is graphically illustrated by the familiar stress diagram opposite the right hand end of beams 36 and 37. The vertical distance between the resultant tensile and compressive forces in each beam is indicated at 42, and in general this distance is two thirds of the beam depth. Note that there are no shearing forces acting between adjacent slabs 38, 38—nor can there be any shearing forces because of the presence of rollers 39. For a like reason, there are no horizontal stresses, either of a tensile or compressive nature, acting on the vertical rows of rollers 39.

Due to the presence of rollers 40, 40 between the slab and beams 36 and 37, it will be readily recognized that neither shearing nor tensile stresses can be transmitted between the slabs and the beams. It follows that there are no tensile or compressive stresses acting between the slabs through rollers 39.

In summary and in addition to the foregoing, it should be noted that the overall height of the structure is many times the length of the effective lever arms 42, 42. Another important fact is that the slabs serve solely to transmit vertical compressive loads and do not cooperate

with one another or assist the beams in any degree in carrying the load.

Figure 4 is a stress diagram similar to Figure 3, showing the marked changes in stress distribution accomplished by the use of rigid ties between the slabs and the supporting beams. Thus, pre-fabricated slabs 45, 45 have their ends connected to lower beam 46 and upper beam 47 by means of rigid, high strength ties 48, 48. The gaps between the beams and the slab ends would of course be grouted. However, this grout has been replaced by roller 49 for purposes of analysis for reasons explained in connection with Figure 3. For present purposes, it will be assumed that no grout is employed between the vertical edges of the slabs.

Arrows similar to arrows 41 in Figure 3 indicating a uniformly distributed load on beam 47 have been omitted to avoid confusion with the other arrows. It will now be shown that, in sharp contrast with the Figure 3 arrangement, beam 46 is in tension throughout its cross sectional area as graphically indicated by the stress diagram at the right hand end of Figure 4. This follows essentially from the fact that the rigid ties between the beams and the slabs convert the structure into a truss capable of effectively transmitting shear stresses between the top and bottom chords or beams, as well as from one slab to another by way of the beams. It is of course axiomatic that the top chord of a truss acts in compression while the bottom chord acts in tension. Likewise, the compressive and tensile stresses in the two chords of a uniformly loaded single span truss are a maximum in their centers and zero at their ends. The progressive reduction of these stresses along the chords is made possible by the web action of the slabs interconnecting the chords. Arrows 50, 50 represent the resultants of horizontal and vertical stresses reacting on each of the ties 48, 48. The varying lengths of these arrows graphically represent the relative intensities of the stresses from slab to slab along the span. The horizontal and vertical components of these resultants, as well as their relative magnitude are represented by the series of arrows 51 and 52, respectively.

Attention is called to the fact that arrows 51 also represent the stresses transferred from one chord to the other by way of my rigid slab and tie design. By the same token, vertical arrows 52 represent the transfer of vertical shear stresses between the slabs by way of the chords. Note that ties 48, 48 are located at the opposite corners of a given slab and that diagonal lines through the ties of slabs at the opposite ends of the panel would be inclined to one another.

It follows from the foregoing that the effective lever arm of the composite panel structure represented by Figure 4 is the distance 53 between the resultants of the stresses acting within chords 46 and 47. This distance is obviously many times greater than lever arms 42, 42 of the Figure 3 panel arrangement.

Let us now consider the slightly changed conditions effected by filling the vertical spaces between the slabs in the Figure 4 arrangement with grout. The composite panel will now approximate a solid beam with a cracked tensile zone (that is, a tensile zone traversed by grouted joints incapable of transmitting tensile stresses) and a neutral axis indicated by the dot and dash line to the right of Figure 4. It will at once be apparent that the grouting permits the utilization of the portion of the slabs above the neutral axis of the panel for the absorption of compressive forces and this fact is represented by the dotted stress triangle at the right of Figure 4. This dotted portion of the stress diagram portrays the transferral and distribution of compressive stresses previously carried by the top chord 47 to the top portions of the slabs located above the neutral axis. The effective line of action of these transferred stresses and their relative magnitudes is represented by dotted arrows 54. Dotted rollers 55 indicate that grout is present but that

it is not relied upon to carry vertical shearing forces, which, as previously noted, are transmitted through ties 48 into chords 46 and 47.

Figure 5 represents a composite panel but differs from Figure 4 basically in the omission of the upper chord. Consequently the horizontal compressive stresses which would have been carried by the upper chord are now carried in the upper section of the slabs as indicated by the stress diagram to the right of Figure 5. This fact is further indicated by arrows 58, acting on rollers 59 representing the usual grout between slabs. It will be understood that horizontal arrows 60 and vertical arrows 61 correspond in nature and action to arrows 51 and 52, respectively, discussed above in connection with Figure 4. Thus, the horizontal arrows 60 of differing magnitudes represent the transfer of increments of chord stress through the slabs to the compression zone in the upper portions of the slabs. Likewise, the vertical arrows 61 represent the transfer of vertical shear stresses between slabs by way of lower chord 62 and the rigid ties and grout between the chord and the slab ends.

Comparing Figures 4 and 5, it will be observed that the shearing stresses are divided between chords 46 and 47 in the Figure 4 arrangement. In Figure 5, on the other hand, there is only the single chord 62 to take the shearing stresses. Accordingly, it will be clear that, under similar loading conditions, chords 62 will carry double the shearing stresses carried by either chord 46 or 47.

Figure 6 is similar to the other stress diagrams discussed above except that it depicts the forces acting in a cantilever panel in combination with a panel of the type illustrated in Figure 4. The normal panel is shown to the right of the rigid skeleton member 65, while the cantilever panel is shown to the left of member 65. As is true of all cantilever beam trusses, a downward load places upper chord 66 under tension and lower chord 67 under compression. Since these chords are also extensions of a continuous chord, the tension in chord 66 will continue in diminishing degree to the right of rigid member 65 to an inflection point beyond which the chord will be under compression, as is well understood by structural designers. A reverse condition of course exists in lower chord 67. Similar conditions and stresses will be understood as applicable to continuous beam and panel constructions.

From these facts and the analysis made above, the other arrows appearing on the diagram will be readily understood. In summary it may be pointed out that the arrangement of the slabs together with the rigid ties between the component slabs and the chords results in the transferral of horizontal stresses between tensile and compressive zones, as well as the transferral of vertical shear stresses between adjacent slabs. Note that the lower portions of the slabs in the cantilever panel, together with the slabs immediately to the right of rigid member 65, assist lower chord 67 in carrying the compression load. Likewise the upper portions of the remaining slabs appearing in the diagram are similarly under compression loads.

As indicated by dotted lines in Figure 4 and by reference 65 in Figure 6, horizontal chords are preferably interconnected by cross members for several practical reasons. Such members can be employed to advantage in reducing bending action in the chords as well as in adjoining slab elements when these are grouted to the cross members.

By reference to Figures 4 to 6 it will be observed that the rigid ties between the slabs and the skeletal members are arranged in a certain pattern. In general, these ties are at opposed corners of the slabs, and the diagonal lines through the ties of the slabs at one end of the panel are inclined oppositely to the corresponding lines at the other end of the panel. In a sense these lines may be viewed as the inclined connecting members of a truss.

Accordingly, it may be stated that the ties and slabs should be so arranged in a panel that the inclined lines passing through the ties of a given slab point toward the support carrying the slab load. Naturally, conditions will be encountered where the direction in which the slab load is carried toward a support will reverse under changing loading conditions. Under such conditions, it will be of advantage to provide ties at all four corners of the slab. In fact, design situations may exist where it is desirable to locate the ties at other than corners of the slabs.

In connection with the location of the ties it should also be pointed out that it is important to employ some means of counteracting the tensile loads transmitted by the ties at the other corners of the slabs. Of course, this counteracting means must be one which can transmit a compression load. Concrete grouting is ideal and is the means preferably employed for this purpose, as has been discussed above in connection with rollers 49 in Figure 4.

In some designs it may be desirable to make the individual slabs in several units or subassemblies for more convenient handling. In this event, any of several well known expedients could be utilized to lock the units together to form a unitary slab having the above mentioned ties distributed as desired for the particular design application of the slabs.

The foregoing discussion has dealt with the distribution of loads applied normal to and along the edge of the panel. In more complex structural arrangements, such as in the prismoidal roof structure illustrated in Figure 7, it becomes necessary to consider the manner in which loads applied at the hipped joints are distributed.

The prismoidal structure diagrammatically represented in Figure 7 comprises a plurality of endless, high strength chords 70, 71 and 72, formed of straight sections joined at their adjacent ends. These chords are arranged in super-imposed planes and are interconnected at their joints by inclined rib members, such as those forming the arched rib 73, extending from one side to the other of chords 70, 71 and 72. The straight sections of the horizontal chords cooperate with the vertical ribs to form flat panels similar to those discussed above. Each panel is covered by pre-fabricated slabs having rigid ties between their ends and on the underlying chords or ribs, as the case may be as, for example, ties 29, 30, 31 and 32 illustrated in Figure 2. For example, such panels are indicated by reference characters 74, 75, 76, 77 and 78. Note that most of these panels lie in planes inclined to one another. The line of juncture between connected, inclined planes is known as the hip line or hip joint.

Let us now consider the forces acting within and between representative panels such as panels 74, 75 and 76 of Figure 7. At the outset, it may be said that panels 74 and 75 do not act independently to carry the roof loads, since they are rigidly connected at chord 71. Because of this connection these two panels really act as a single panel having much greater aggregate strength than do the component panels when acting alone.

There are two principal reasons for this greater strength. In the first place, the lever arm of the interior forces for the two rigidly connected panels acting together and corresponding to the lever arm 53 in Figure 4 is much greater. Secondly, loads on slabs abutting at chord 71 will first be carried by simple beam action to the chord and the beam reactions will be split into two stress components acting parallel to the plane of the respective panels. Due to the rigidity of panels 74 and 75, these two components will act within and parallel to the plane of these panels.

It has already been pointed out that, due to the connections at chord 71, panels 74 and 75 will act as a single panel. It follows that the upper panel will act in compression and the lower panel will act in tension. The forces acting within combined panels 74 and 75 will be generally comparable to those already discussed in con-

nection with Figure 4. Chord 71 will lie in or near the neutral axis of the combined panels. Its principal function is to prevent relative longitudinal movement between the component slabs in each panel. This permits the transferral of horizontal shearing forces from the tensile zone in panel 74 to the compression zone in panel 75.

In concluding the discussion of Figure 7, it might be observed that any two panels in the entire structure located in different planes and joined along a rib member will assist one another in carrying their individual load components as explained above in connection with panels 74 and 75.

Yet another interesting example of my arched shell prismoidal structure constructed in accordance with this invention is diagrammatically illustrated in Figure 8. Basically, it consists of a plurality of arched chords spanning the area to be covered. In the fragmentary showing in Figure 8 will be seen a succession of such arches. Note that arches 81, 82, 85, and 86 are arranged at a lower level than arches 80, 83 and 84. It will also be understood that, like arch 73 in Figure 7, each of the arches in Figure 8 consists of straight beams, joined end to end and lying in the funicular curve for which the structure is designed. Preferably, but not necessarily, the joints between beam ends are interconnected by ribs 87, 87 thereby dividing the entire structure into polygonal sections or panels as previously discussed and as herein represented at 88, 88. If the arches all have the same radius of curvature, juxtaposed straight sections of adjacent arches will be parallel to one another so that slabs of equal length can be used to form panels therewith.

Particular attention is called to the fact that Figure 8, as well as Figure 7, illustrates a roof having a curvature in two directions at angles to one another. In Figure 8 the two curvatures are at right angles to one another, although this is not essential as evidenced by the Figure 7 construction. Compound arching is of importance because of the much greater strength imparted to the structure and the economies in the use of materials which follows therefrom.

It will of course be understood that the ends of the arches are rigidly secured to any of the usual supporting beams, buttresses and columns in accordance with standard practice and as generally indicated by way of example in Figure 8.

The skeletal network just described is overlaid with pre-fabricated slabs of the type discussed above and in the general arrangement illustrated. Rigid ties, not shown, project from the slab ends and are rigidly connected to mating ties mounted on the arches. The intervening space between slabs is preferably filled with grouting as before.

To appreciate fully the significance of the foregoing design it is essential that one bear in mind what has been said above in connection with the stress analysis of Figures 3 to 6 and in particular, what has been said with respect to a plurality of composite panels rigidly joined together in a hipped arrangement. For example, it has been shown that a composite panel having rigid chords on its opposite sides and inclined to the horizontal acts as a beam of very considerable rigidity and load carrying ability. Furthermore, when inclined panel 88 has its longer sides rigidly connected to the panels on either side thereof, the three panels inter-act as a beam or as a truss. That is to say, the middle panel acts as the connecting web between the other two panels which are equivalent to the chords of conventional trusses. Carrying the analogy further, it will be apparent that the three rows of these same panels extending in rigidly interconnected relation across the arch span form an arched beam or truss in which the middle, inclined series of panels form the web of the truss. In fact, the entire roof shown in Figure 8 comprises a plurality of interconnected arched trusses. The rigidity of the individual arched trusses is dependent upon the width and the inclination of the panels acting as webs between the panels acting as chords.

Another important characteristic of the arrangement is that the entire arched structure, including the slabs and the arched chords, is acting in compression. Accordingly, the designer makes use of the strength of the slab covering or decking to carry the major load of the structure. This leads to the conclusion that the skeleton members in certain skeletal arrangements are primarily useful during assembly of the slabs and not as the principal load carrying members. Indeed it is quite feasible to forego the use of chords for shear transmission when erecting hipped panels, as indicated by the fragmentary showing in Figure 9. Thus, the adjacent ends of slabs 90 and 91 can be directly joined to one another by means of rigid ties 92 and 93. Their opposite ends are connected to rigid beams. Since the two slabs are in different planes, they mutually cooperate with one another and with the rigid beams to form a rigid load carrying structure. Increased strength, particularly for compressive and tensile forces in the direction of the rib, is achieved by filling the gap between and beneath the slab ends by grouting 94, reinforced by steel rods 95. This type of construction is particularly useful at the ridges of roofs and at such locations as chord 72 in Figure 7.

The foregoing description of several embodiments of the invention is indicative of the great flexibility of designs which can be utilized in practising the principles thereof. Obviously, there are many other possible arrangements falling within this inventive concept and it is understood that the scope of the invention encompasses these as well as the particular embodiments described.

I claim:

1. A roof structure comprising a plurality of spaced arched chords arranged parallel to one another and spanning an area to be covered, some of said chords being at higher elevations than others, rows of pre-fabricated slab units laid edge to edge and spanning the space between said chords to form an arched covering for said roof, rigid ties interconnecting said slab units to said chords, the arched row of slabs on one side of a given chord being inclined to the arched row of slabs on the other side thereof whereby said arched rows of slabs mutually assist one another to carry the load.

2. A roof structure as defined in claim 1 wherein all of said arched chords have the same radius of curvature whereby the shortest distance between adjoining chords is substantially constant throughout the arch span.

3. A roof structure comprising a plurality of spaced, arched chords arranged parallel to one another and spanning an area to be covered, means supporting one pair of said chords at a higher elevation than an adjacent pair of chords, rows of pre-fabricated slabs arranged edge to edge cross-wise of said arched roof structure with the slabs in each row spanning the distance between adjacent chords, rigid ties interconnecting the ends of the slabs in each row to the ends of the slabs in the adjacent row by way of the arched chord underlying said slab ends, one arched row of slabs being inclined to the row of slabs on either side thereof and cooperating with said last mentioned rows to transmit stresses therebetween by way of said rigid ties and to increase the load carrying ability of each of said rows over and above the load carrying ability of each row if acting independently of the other rows.

4. A roof structure as defined in claim 3 wherein the shortest distance between adjoining arched chords is substantially constant throughout the arch span whereby slabs of uniform length can be employed to span said adjoining chords to form a covering therefor.

5. A roof structure comprising spaced arched chords extending over a space to be covered, a plurality of panels supported on said arched chords, each of said panels comprising a plurality of pre-fabricated slabs arranged edge to edge and having concrete grouting filling the space therebetween, rigid means interconnecting slabs in one panel with slabs in an adjacent panel to transmit

stresses between said panels, and rigid means including said arched chords for supporting one panel at an angle to an adjacent panel whereby the load carrying ability of said angularly arranged panels is increased over and above the load carrying ability of one of said panels if acting independently of the other.

6. A composite, high strength cantilever beam comprising rigid, vertically spaced generally parallel upper and lower beam members, means supporting the adjacent ends at one end only of said beam members, a plurality of rectangular rigid web elements arranged in closely spaced relation between said upper and lower beam members and extending substantially from end to end thereof, and rigid ties connecting one corner of each end of each of said webs to said beam members, the rigid ties connected to said upper beam member being at the web corners near said supporting means for said upper member and the ties connected to said lower beam member being at the web corners remote from said supporting means to provide a composite cantilever beam having a neutral axis traversing said web element intermediate the ends thereof as well as a composite cantilever beam wherein the imposition of a load on the upper of said beam members acts to place the area of said web element below said neutral axis under compression acting transversely of said web.

7. A roof structure arched in two different directions comprising rigid skeleton members connected to form relatively long arches and relatively shorter arches at right angles to said long arches, a rigid covering for said structure comprising elongated pre-fabricated concrete slabs separately assembled to said skeleton in edge to edge relation and bridging the gap between adjacent skeleton members, and rigid ties interconnecting the adjacent ends of slabs located on the opposite sides of one of said skeleton members, at least some of the slabs so interconnected lying in planes at an angle to one another.

8. An area spanning structure comprising a high strength load bearing skeleton having a perimeter co-extensive with the spanned area, said skeleton including interconnecting rigid members arranged to form two or more polygons in planes inclined to a horizontal plane, a covering for said polygons comprising pre-fabricated slabs arranged in closely spaced edge to edge relation, grouting filling the spaces between said slabs for transmitting compressive stresses from one to the other between said facing edges, high strength rigid ties connecting said slabs at their opposite ends to said skeleton to transfer loads imposed on one skeleton member to another by way of said ties and said slabs and from the slabs in one polygon to the slabs in an adjacent polygon and whereby the skeleton members and slabs in a given polygon act as a deep beam having a neutral axis traversing said slabs between the opposite ends thereof.

9. An area spanning structure comprising a high strength load bearing skeleton having a perimeter arranged in a horizontal plane and composed of members supported to carry high tensile loads, at least some members being rigid to support shearing loads, rigid members connected to the perimeter of said skeleton and arranged to form a plurality of polygons therewith in planes above the plane of said perimeter, a rigid covering for said polygons comprising pre-fabricated concrete slab elements arranged edge to edge so as to transmit compressive stresses between the facing edges of said elements, said slab elements having their ends supported by said rigid skeleton members, and disconnectable rigid means interconnecting the ends of said slab elements and said skeleton members for transmitting compressive and shearing stresses between said skeleton members through said slabs and for placing the portions of the slabs near one of said skeleton members under compressive stresses acting transversely across the width and between the upper and lower surfaces thereof.

10. A roof structure comprising a pair of rigid beam

members, means for supporting said beam members horizontally at different elevations, and means for placing the upper beam under compression and the lower beam under tension comprising a plurality of elongated pre-fabricated reinforced concrete slabs arranged in edge to edge relation and spanning the distance between said beam members throughout the length thereof, said slabs being arranged in a single layer and extending substantially at right angles to said rigid beam members, and rigid tie means connected between the ends of said pre-fabricated slabs and the adjacent beam members for transmitting stresses from one beam to the other by way of said slabs and to transmit shearing stresses between adjacent slabs through those portions of the beam members located between the ties on adjacent slabs.

11. An arched spanning structure comprising a plurality of parallel arched beams extending crosswise of said structure, rigid means supporting the opposite ends of said beams, each of said beams comprising a plurality of flat panels arranged edge to edge in angular relation to one another lengthwise of said beam, at least certain of said panels including a plurality of elongated pre-fabricated slabs having their longer sides arranged edge to edge with said edges extending at right angles to the curved edge of said structure and being grouted together to provide a continuous high strength arched shell, rigid means at the shorter ends of said slabs rigidly interconnecting said slabs, and the panels in one beam row being inclined to the panels in the adjacent beam to provide a spanning structure arched crosswise and lengthwise thereof.

12. A high strength, thin-walled, arched shell structure comprising a plurality of flat, polygonal panels arranged edge to edge and in hipped relation to one another to form a continuous arched covering for the area to be spanned, means at two opposite sides of said shell structure for supporting the thrust loads acting downwardly from the crown portion thereof, said panels being formed by a plurality of pre-fabricated reinforced elongated concrete slabs having their longer sides arranged in edge to edge relation and grouted together so as to be capable of transmitting high compressive stresses between facing edges, and high strength rigid means extending across the shorter ends of said slabs and along the adjacent edges of said panels and connected to said slabs and to said panels for transmitting stresses from one panel to another by way of said slabs and for transferring stresses acting within an upper panel to an adjacent lower panel along the upper edge thereof whereby said transferred stresses act to place the upper half of the lower panel under compressive stresses acting transversely of the grouted joints between the longer edges of its component slabs.

13. A high strength, thin-walled arched shell structure having a crown at a higher elevation than the opposite lower sides thereof, said arched shell structure comprising a plurality of spaced apart arched rigid skeleton members extending from side to side thereof and including rigid horizontally extending cross ties interconnecting said arched members, elongated reinforced concrete slabs arranged in side by side relation and forming a covering for said skeleton from one side of said arched structure to the other with the ends of said slabs terminating at said arched skeleton members, high strength rigid tie means connecting the ends of said slabs to said skeleton members, means underlying and rigidly supporting the opposite lower sides of said arched shell structure, grouting between the adjacent sides and ends of said slabs and cooperating therewith to transmit compressive stresses from slab to slab, the arrangement of said slabs and of said high strength rigid means interconnecting said slabs and said skeleton members being such that said slabs and the skeleton members extending across said arched structure are acting primarily in compression and tension rather than in bending.

14. That improvement in constructing wide-spanned arched shell structures which comprises, erecting a rigid arched skeleton having a crown at a higher elevation than the horizontal perimeter thereof, said skeleton including rigid arched members and horizontally arranged rigid connecting tie members, covering said skeleton with elongated reinforced pre-fabricated concrete slabs arranged in side by side relation and with the ends thereof terminating at said rigid skeleton members, connecting the ends of said slabs to said skeleton members by rigid ties having a strength greatly in excess of that required to hold the slabs in place on said skeleton and of sufficient strength to transmit the major load of said structure to said slabs as compressive stresses acting in a plane between the upper and lower surfaces of said slabs, and filling the space between the sides and ends of adjacent slabs with material capable of transmitting high compressive forces.

15. That improvement in constructing wide-spanned, arched shell structures in which the major direct stresses act in compression between the upper and lower surfaces of the covering for the structure which comprises, erecting rigid arched members in vertical parallel planes, interconnecting the opposite lower ends of each arched member with high tensile strength members, interconnecting the lower ends of adjacent arched members with rigid members capable of resisting high bending stresses, covering said structure with elongated and relatively wide but thin pre-fabricated reinforced concrete slabs laid edge to edge from one side of said arched structure to the other with only sufficient space therebetween to receive grouting, rigidly connecting the ends of said slabs to said arched members by high strength ties capable of transmitting major stresses between said slabs and said arched members, and grouting the spaces between edges of adjacent slabs whereby the predominate major direct stresses within both said slabs and said arched members act in compression rather than in tension to provide an arched shell structure in which said slab covering cooperates with said arched members in carrying a major portion of both the dead and live loads imposed on said structure.

16. A composite high strength deep beam comprising, a pair of long rigid members arranged in parallel vertically spaced relation, a plurality of pre-fabricated high strength concrete slabs arranged in closely spaced edge to edge relation between said rigid members, said slabs being arranged in a single layer and extending substantially at right angles to said long rigid members, rigid tie means having portions thereof embedded in said slabs and interconnecting the ends of said slabs and the adjacent portions of said rigid members to form an integral rigidly interconnected structure, and high compressive strength grouting filling the space between the adjacent edges of said slabs to provide a composite beam having a neutral axis extending crosswise through said slabs intermediate the ends thereof whereby a load imposed upon the upper of said rigid members is absorbed in part by compressive forces acting on said slabs between the surfaces thereof and above said neutral axis in a direction generally parallel to said neutral axis and whereby another portion of said load is transmitted to the lower of said rigid members by way of said slabs.

17. A composite high strength deep beam as defined in claim 16 wherein the rigid ties on the ends of each of said slabs project from diagonally opposed corners and wherein the slabs in said composite beam are so arranged that diagonal lines through the ties of the individual slabs at the opposite end halves of the beam diverge from one another in a direction toward the upper of said rigid members.

18. A composite, high strength beam comprising rigid vertically spaced generally parallel members, means supporting said members intermediate their ends, a plurality of rigid web elements arranged in closely spaced edge

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to edge relation between said rigid members and extending substantially from end to end thereof, grouting filling the space between the adjacent edges of said web elements and rigid ties interconnecting one corner of each end of said webs to the rigid members adjacent thereto, the rigid ties at one end of said webs being located at the web corners nearest said supporting means and the ties at the other ends of said webs being located at the web corners remote from said supporting means.

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