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Rapidly Assembled Structures

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Deployable Structures

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INTRODUCTION

There are many examples of ideas (concepts) of structural assemblies possessing foldable, extensible, capabilities, so that they may be extended, deployed when desired and folded up to a compact form for storage and or transportation. The common characteristic of foldable structures is tne abilitv these structures, whose points are lying on the surface of revolution, have to assume two different configurations; first the collapsible (compact) one, suitable for storage and transportation, and second the deployed (extended) form allowing the structure to preserve (keep) its shape (usually spherical or cylindrical)(eg. Zalewski [1])

APPLICATIONS OF THE PRINCIPLE OF DEPLOYABILITY TO LARGE SCALE SITUATIONS

Deployable structures are suitable in response to the following needs :

a- A situation in which there is a need to create enclosed or protected space for a short period of time and then move that space to another location for erection or storage. Examples: -Travelling expositions,Fairs, Provisional shelters, Movable Hospitals.

b- Difficult access places, and/or lack of labor. Examples: -Remote retransmissions units , Antenna masts, Meteorological or research stations, Military installations, Emergencies in distant localities, requiring Shelters, Bridges, Hospitals, etc.

c- Special applications equipment and shelters for special equipment which can not be transported in full open size and needs to be erected in a very quick way. Examples: - Portable radars and antennas , Portable hangars , Portable bridges, Protection and camouflage of military equipment.

d- Need to enclose space due to variable weather conditions.Examples: Stadium covers, Cover-plazas.

e- Situations of high risk with elevated labor costs, hostile environments, costly transportation.Examples: Earth exploration, Space exploration, Space stations.

f- Construction aid. Example: Reusable scaffolding for complex forms. One of the problems of building shell structures is the high cost of the forms needed; this has inhibited the use of these efficient structures. Deployable structures can provide a reusable, easy to erect scaffolding, for example inflatable forms are now being used for the construction of concrete domes and vault like structures.

g- As a construction method. The traditional view of building has been one of simple accretion. Stone is put on stone, brick on brick, steel on steel, and so forth until the final form takes shape. In modern construction, accretion is often by larger modules in the form of walls, floors, and even entire rooms.(eg. Zut [2]) A new method consists of bringing the complete structure to the site in some compact configuration and deploying it there for permanent use.

METHODS OF DEPLOYABILITY

There are many mechanisms which fall into the category of deployable structures, but we can group them into two general categories:

A) Struts Structures : scissor-hinged, tensile, and sliding mechanisms, etc.
B) Surface Structures :folded ,inflatable ,telescopic ,etc.

The general characteristic of group A is that these structures are made out of struts which commonly work as compression, tension or bending components connected by joints or hinges. This first category includes:

The Scissor-Hinged Mechanism
(This work will emphasize these mechanisms): The basic element of this system is the deformable truss shown in Fig. 1 which is a set of struts connected by nodes, and scissor-hinges (a rotational degree of freedom about the normal plane defined by two connecting struts). This assembly has the characteristic that by rotation of the struts with respect to one another, the assembly encompasses two forms; the first form is the compact state having theoretically one dimension, and the second form is the deployed state, which is a three-dimensional body.

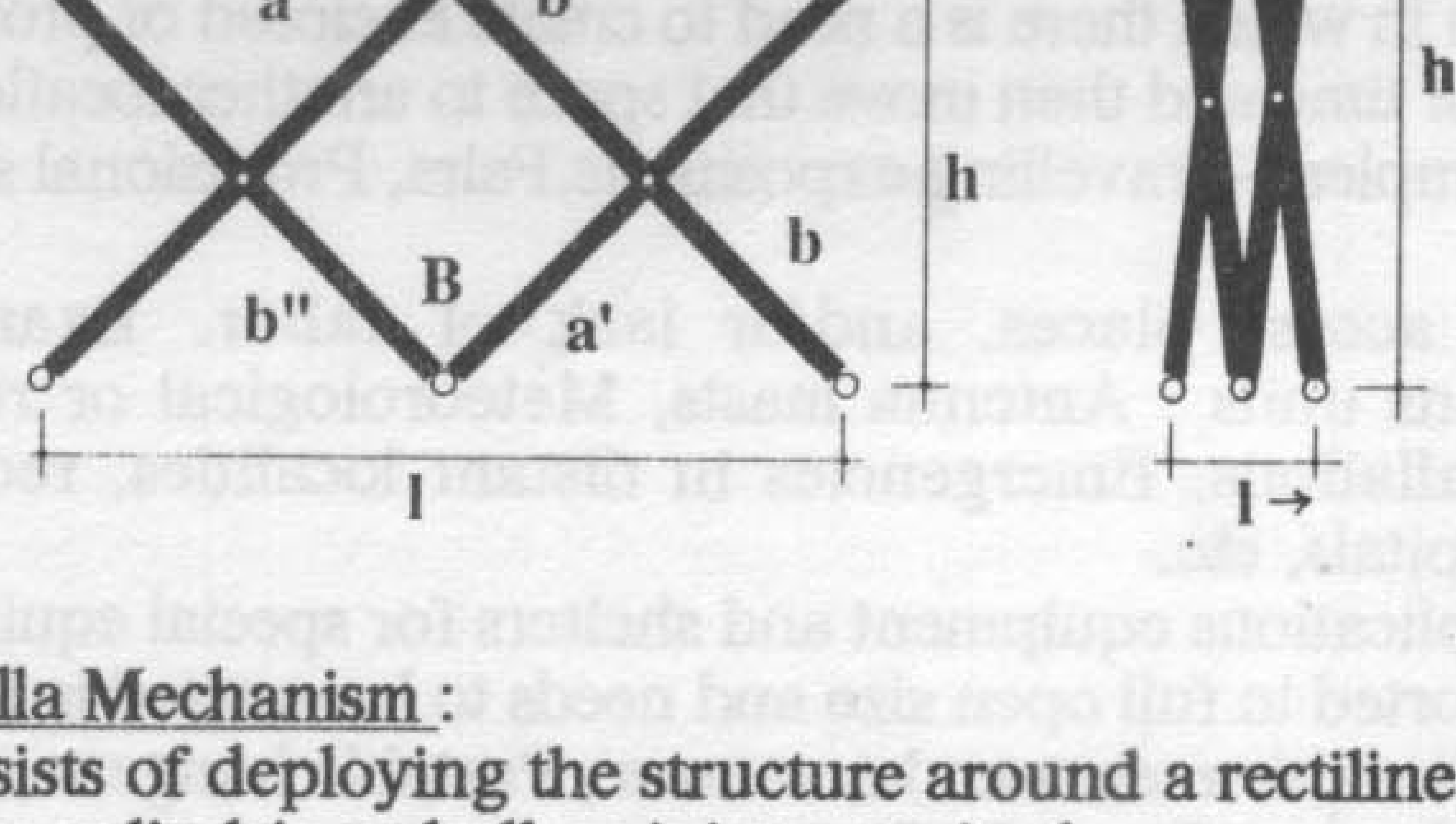


Figure 1

Sliding or Umbrella Mechanism :
This method consists of deploying the structure around a rectilinear support or guide, by sliding a cylindric or hollow joint over it, the more common example is the umbrella.

Hinged-Collapsible-Strut Mechanism :
This is another method of deployability which consists of a set of struts hinged at the ends, that allows the structure to be folded. After reaching the final open configuration the hinged joints are locked and the structure behaves as a single continuous piece.

In Group B stresses are carried by surfaces. In some, cases a continuous surface carries only tension forces like, in pressurized or inflatable construction; other structures are made out of small surfaces or planes joined together by some usually flexible means of forming a continuous structure. In this category, the more important groups are:

Inflatable or Pneumatic Structures:
These are structural forms made of a light, collapsible, very strong membrane, stabilized wholly or mainly by pressure differences of gases, liquids, foam, or material in bulk.

Folded Structures :
Another type of deployable structure can be collapsed and expanded like an accordion; it can be of two types. One made of rigid panels joined by a flexible connection along its edges, and the other is made of a continuous flexible material which allows itself to be folded.

Telescopic Structures:
These structures are based on tubular elements that can enter one inside the other, forming a compact packet which is them telescoped and stabilized to its final configuration.

DEPLOYABLE STRUCTURE COMPONENTS

Joints:
The successful behavior, duration, and reliability of a deployable structure will depend on a great way in its joints. The joints are points at which forces converge, and their ability to resist and transmit those forces will determine to an important degree the soundness of the structure the joint should meet the following criteria :

1. Should transmit the forces evenly throughout the components which arrive at that point.2. It should firmly hold all the struts which meet at that point.

3. It should give every strut enough freedom to go from the closed stage to the open one, but avoid holding the struts too loosely.

4. In the cases were reusability is required, the joint has to be designed to stand the stresses created during the erection process, minimizing fatigue in the material.

5. Friction between the moving pieces should be minimized to avoid excessive wearing and to facilitate the erection and dismantling processes.

6. As we are dealing with moving connections (usually pin connections), it is important to take into account, when designing and choosing the material, that the transference of forces between bodies which are not bonded together can occur only by the pressure exerted by one body against another; the values of compressive or tensile stresses increase at the joint. The flow of compressive forces are curving in the vicinity of the joint resulting in the need for an internal pulling action towards the center of the element; such an action always causes transverse tension to develop within the material. As a result, the element may crack and split longitudinally, if measurements are not taken. Thus, it is very important to have tension resisting materials around the connection.

Opening and Closing Mechanism:
Another fundamental aspect to consider when designing a deployable structure is the open-closing mechanism. As size and weight increase opening and closing a deployable structure become a more and more problematic factor in the effective good functioning of the concept. The structures have to be provided with a mechanism to accomplish the erection-dismantling process, these mechanisms

can go from manually driven ones to fully automatic and even remote-controlled ones. But every system will depend on each structure, and in particular, on its size and weight, frequency and conditions of deployment, environmental factors, possibility of energy sources, etc.

Opening and closing mechanisms can be hydraulic systems, motor or manually-driven screws, cables and pulley mechanisms, spring-driven mechanisms, etc. But any mechanism use should provided a even movement of all the parts at a controlled rate. Since the structures usually start the deployment process running horizontally over the erecting surface, for those structures to be erected over surfaces or terrains it is convenient to mount them over wheels in order to reduce friction with the surface,thus reducing the force needed for the erection.

<u>Covers:</u>
There are some situations which require a protected or enclosed space, and the deployable structure has to be designed with an enclosure or cover system. There are many different solutions:

The enclosure system can be attached to the structure or free-standing; the enclosure can be added after the structure is erected, or it can be permanent part of the structure. It can also operate as a structural member, stabilizing member and/or locking member of the open configuration. Enclosures can be made out of light and flexible materials, which can act as tension carries, Such as teflon coated nylon or fiberglass fabrics, etc. Or they can be made out of rigid materials like metals or plastics.

<u>Other Components and Materials:</u>
The structure should be made out of materials which are light (for easier transportation) but at the same time strong enough to stand the stresses and deformations to which the structure is subjected ; in some cases flexibility is a desirable property. Materials like aluminum, laminated steel, steel, plastics, or composite materials like fiber-glass epoxy or graphite-epoxy are commonly used.

For the compression or bending members of the structure, tubular struts are a reasonable solution, due to their weight/resistance relationship and good resistance to bending; for tension components, high resistance steel cables or fabric are used.

STRUCTURAL FORMS SUITABLE FOR TRANSFORMATION.

<u>Structural Requirements:</u>
Clearly an essential structural requirement for all the forms with which we shall be concerned is that they shall stand and not collapse. They should carry their own weight and the live loads to which they will be subjected (wind, snow, other components attached to the structure, etc.), and under normal circumstances they should have adequate margins and stiffness in all structural elements and in their interconnections.

The basic element of the scissor-hinged mechanism, as we saw before, is the deformable truss shown in Fig.1. Due to its one degree of freedom this truss is unstable, and has no structural properties. Although if height "h" is fixed ,the truss will be able to carry loads acting on its plan. As it is not triangulated, its struts are working in flexion. By adding compression and tension members to the system, bending stresses can be reduced and the truss will become a triangulated one, where stresses are mainly transmitted by tension or compression. By using more suitable geometrical forms, and by locking the joints, the structural characteristic of the system can be improved.

The load capacity of a structure can be increased without increasing the amount of material, by choosing an adequate form. This is of special importance when designing deployable structures, because increasing the carried-capacity by adding material will make the movable joints used more expensive than they already are, and will increase the weight of all components, therefore the overall weight of the structure, reducing its efficiency and transportability.

Forms which allow the stress to be transferred mainly by compression or by tension are more efficient. The catenary and the arch are examples of those forms.There are three-dimensional forms which have the same properties of the linear funicular systems, cables and arches. They can be classified as forms with single curvature,(cylindrical or conical) or forms with double curvatures (spheres,ellipsoid, hyperbolic paraboloid, etc.).

The dome is an example of those three-dimensional forms in which, ideally, there is no bending (and therefore no variation in stress through the thickness at any point), and in which internal forces are represented by sets of principal tensions and compressions. One set of principal stresses acts radially from the crown to the base. These stresses are compressive throughout and may be likened directly to the thrusts in a large number of arches into which the shell might be split by cuts on vertical radial planes. The other set of principal stresses in the shell acts horizontally and circumferentially to prevent the upper part of the shell from falling toward the center and the lower parts from bursting outward. These stresses are compressive near the crown but become tensile nearer the base.

By a translation movement of an arch, a vault will be obtained. It works similarly to an arch, when loads acting on each transverse strip are the same. If the transverse shape of the vault is the funicular for a certain load, each strip will develop only compressive stresses in the direction of curvature and no longitudinal stresses between adjacent carried strips. If the cross section is not the funicular of the loads, bending stresses may develop in the arched strips. Other shell forms behave in a more complicated way, but in all of them the stresses are mainly tensions and compressions.

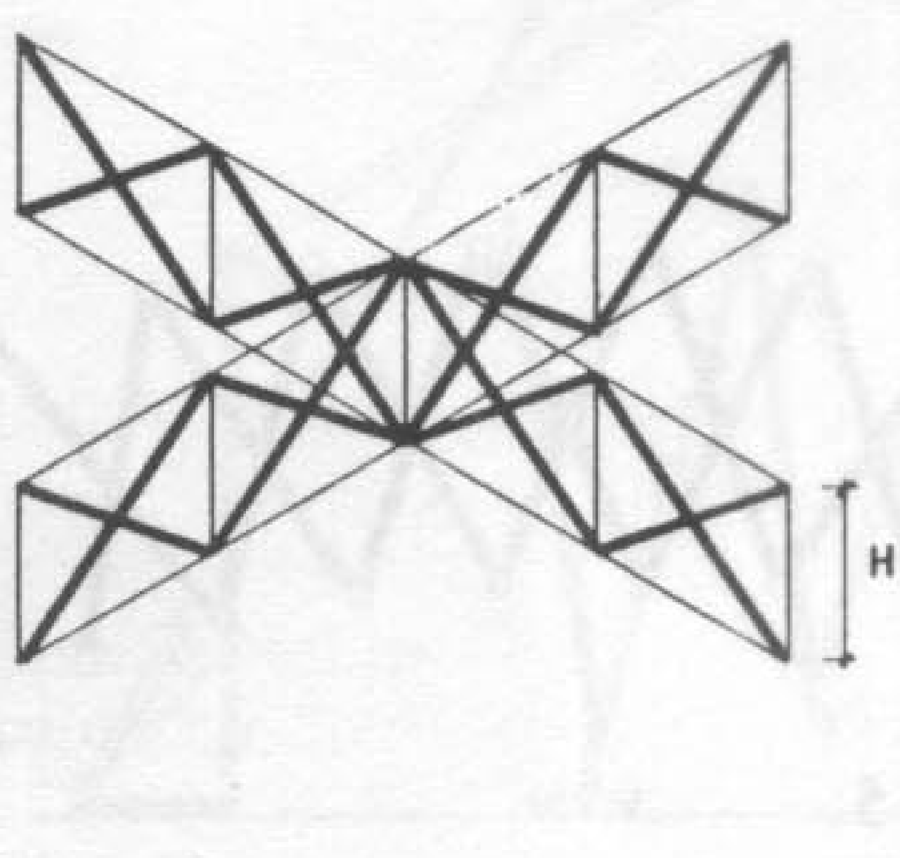


Figure 2

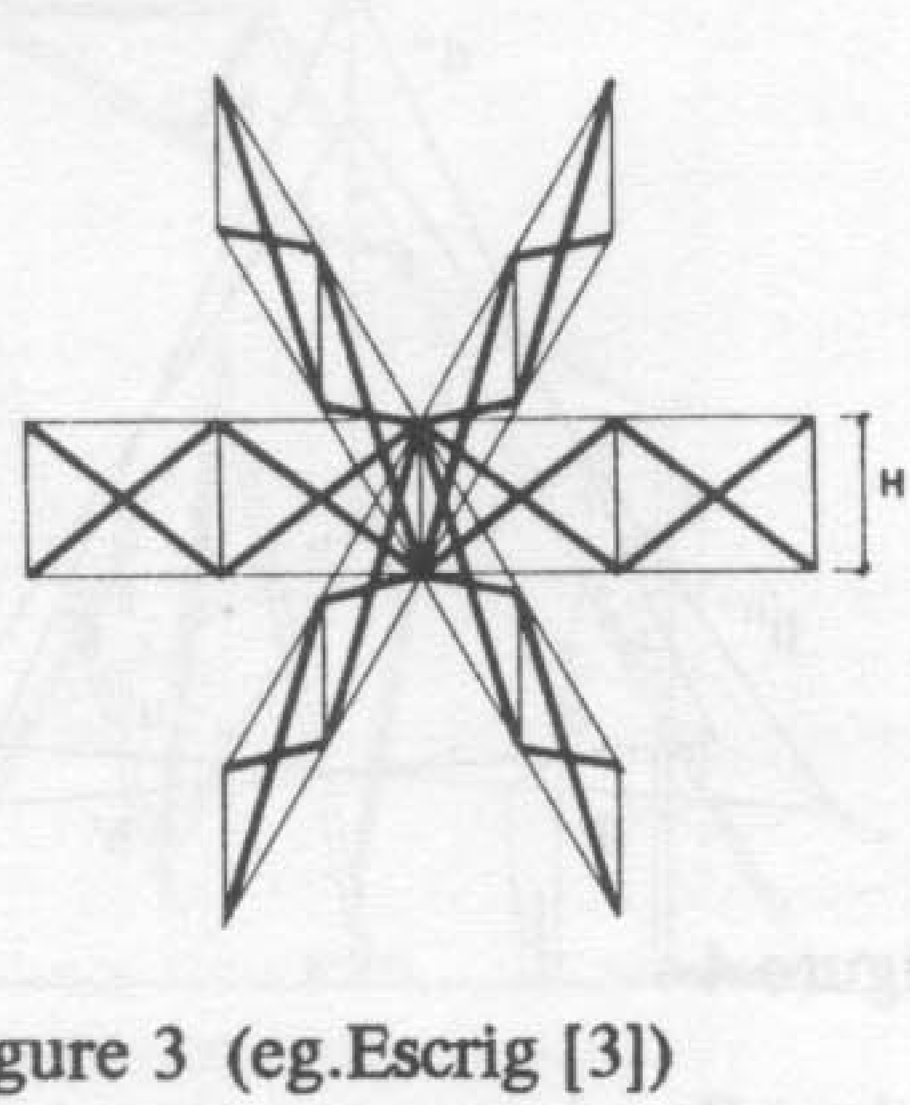


Figure 3 (eg.Escrig [3])

Kinetic Requirements:

Returning to our basic truss (Fig.1). If height "h" is modify by any mechanical mean, the "l" dimension will change with any variation of "h" according with the number of crosses and the length of the trusts. When "h" is equal to b+a the system is in its close configuration, and when "h" approach 0 height, the system will theoretical approach a straight line and "l" will be maxima.

For the system to obtain its closed configuration the only relation that have to be kept is, that around any pair of nodes A,B (a'+ b'= a"+ b"). Keeping that relationship, new combinations, with our basic system, are possible.

Until now we have only deal with flat elements, but three-dimensional combinations are possible too, and the system will closed if the same relationship used for the flat configuration is kept. By crossing two flat element perpendicular, a three-dimensional group of families is created (Fig.2); by intersecting three planes we obtain another three-dimensional configuration (Fig.3), in which the basic element is a triscissor (eg.Clarke [4]). It is a mobile assembly, of six struts, six nodes, and three scissor hinges, in which all the struts lie in one plane for a given value of the angle ß (Fig.4). The required action of a triscissor is such that, as ß increases the assembly folds rigidly out of the plane, passing through a three dimensional form and reaching a limiting one dimensional state for ß = 180 degrees. This action places constraints on the relative values of a, b, c, d. It is a necessary and sufficient condition for the mobility of a triscissor that the six struts in the plane are tangent to a circle. The triscissor is an important basic unit for some tridimensional forms like domes.

Until now we have dealt only with flat structures in which a= a' and b=b' but what happens if the center of rotation is moved out of the center ?. By making a'> a and b'< b , the basic truss starts to bend (Fig.5). The bigger the difference between a',a and b', b the smaller the radius of the curve. The radius of the curve and the number of crosses will define the length of a+a' and b+b'.

With the scissor-hinged deployable system it is possible to make flat structures, and structures with a single or double curvature, positive or negative, following the method described above.

By repeating an arch, a simple vault structure will be obtained-by rotating it, a dome, etc. The same type of geometrical forms can be obtained, by using as a basic unit the triscissor described before.

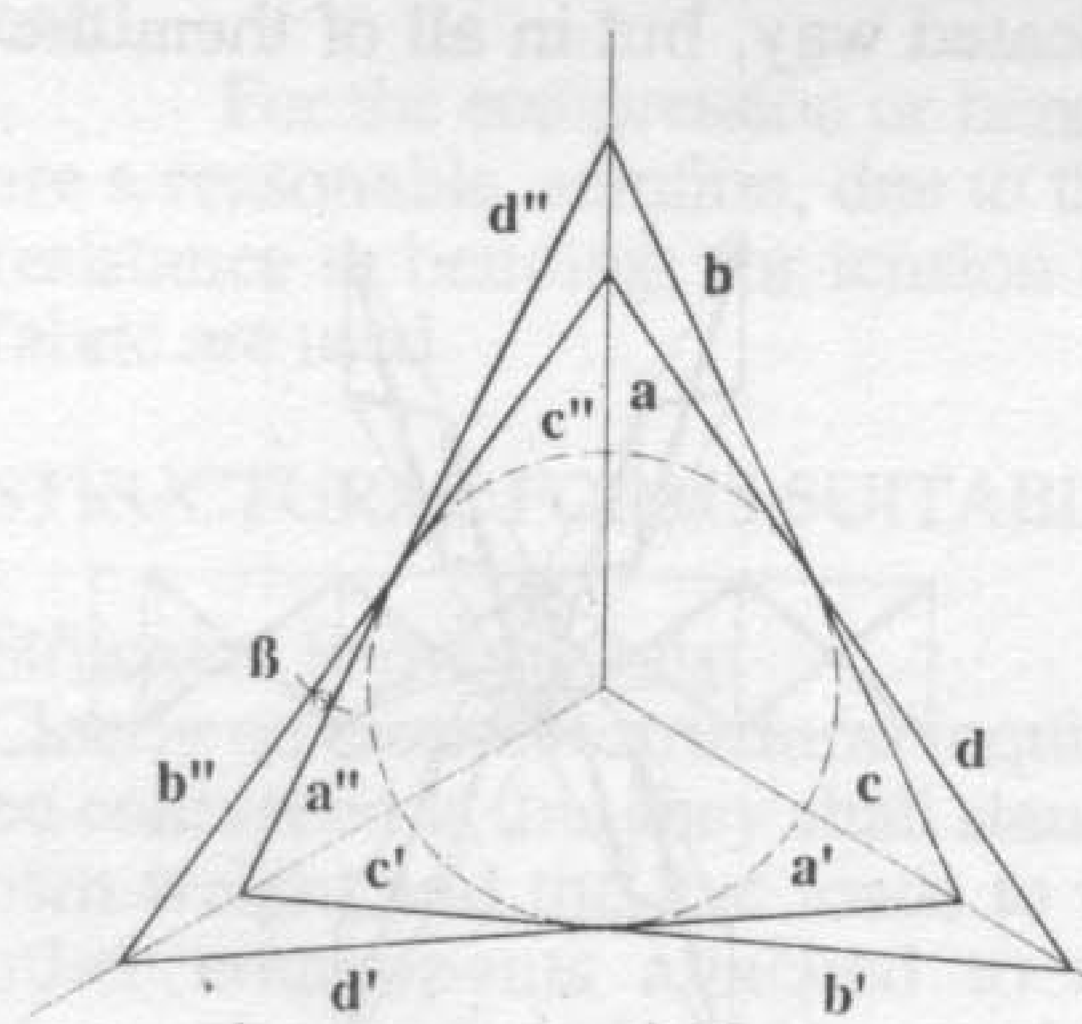


Figure 4

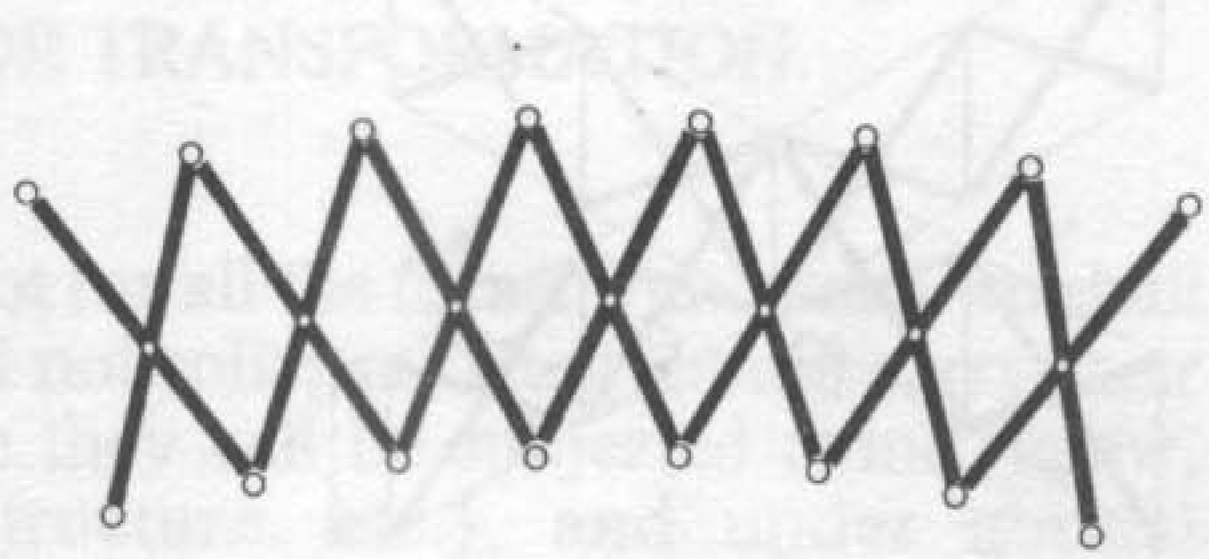


Figure 5

Others Requirements:

It is not only important to has a structural soundness, and the correct geometrical relationship between the parts, which allow the structure to be transform and to acquired the desire shape, but it also has to be reliable and buildable . A deployable structure has any advance, if it can not be opened, closed, or reused. As it was mention before joints are a crucial point, but the right dimensioning and positioning of all part are as important. In many of the models we have built problems during the transformation process were generally due to small mistakes in the dimension of some parts. To avoid mistakes in the dimension and position of parts, the variety of these should be as small as possible, at the same time this will facilitate the production of part, the assembly, and reduce the cost of the structure.

ESTRAN 1

Estran 1 is the result of years developing deployable structures in paper and models. It is our first scale 1/1 prototype.It was developed to be used as transportable hangar for small airplanes and it was and opportunity to test many ideas we have developed in the past years. Estran 1 is a deployable (scissor-hinged) vault structure, built by three parallel arches joined together by fourteen connections or arms and triangulated by wires in its upper plane. starting from a packet of 1x1x4.20 mts the structure deploys in two directions to an hangar of 14 mts wide, 8 mts long and 7 mts of radius.

The deployment process starts by transporting the structure horizontally as a compact packet which weight 500 Kg. after it had been stood up by a small crane (Fig.6 & Fig.7A) the deployment begin by pulling the four corners of the packet manually diagonally (Fig.7B), the structure expands over the ground surface (Fig.7C & Fig.7D) and then it begin to rise until it reaches its final position (Fig.7E - Fig.7G) The total process takes about 5 minutes to accomplish. The deployment sequence can also be achieved without a crane, by using skates, placed under the packet, to ease the expanding movement of the structure over the deployment surface, and by small winches placed between two opposite nodes in order to force the structure to arrive to its final or open configuration.Once this configuration has been reached, the structure is secured with pins and bars of reinforcement and fixed to the site where it is going to stay.

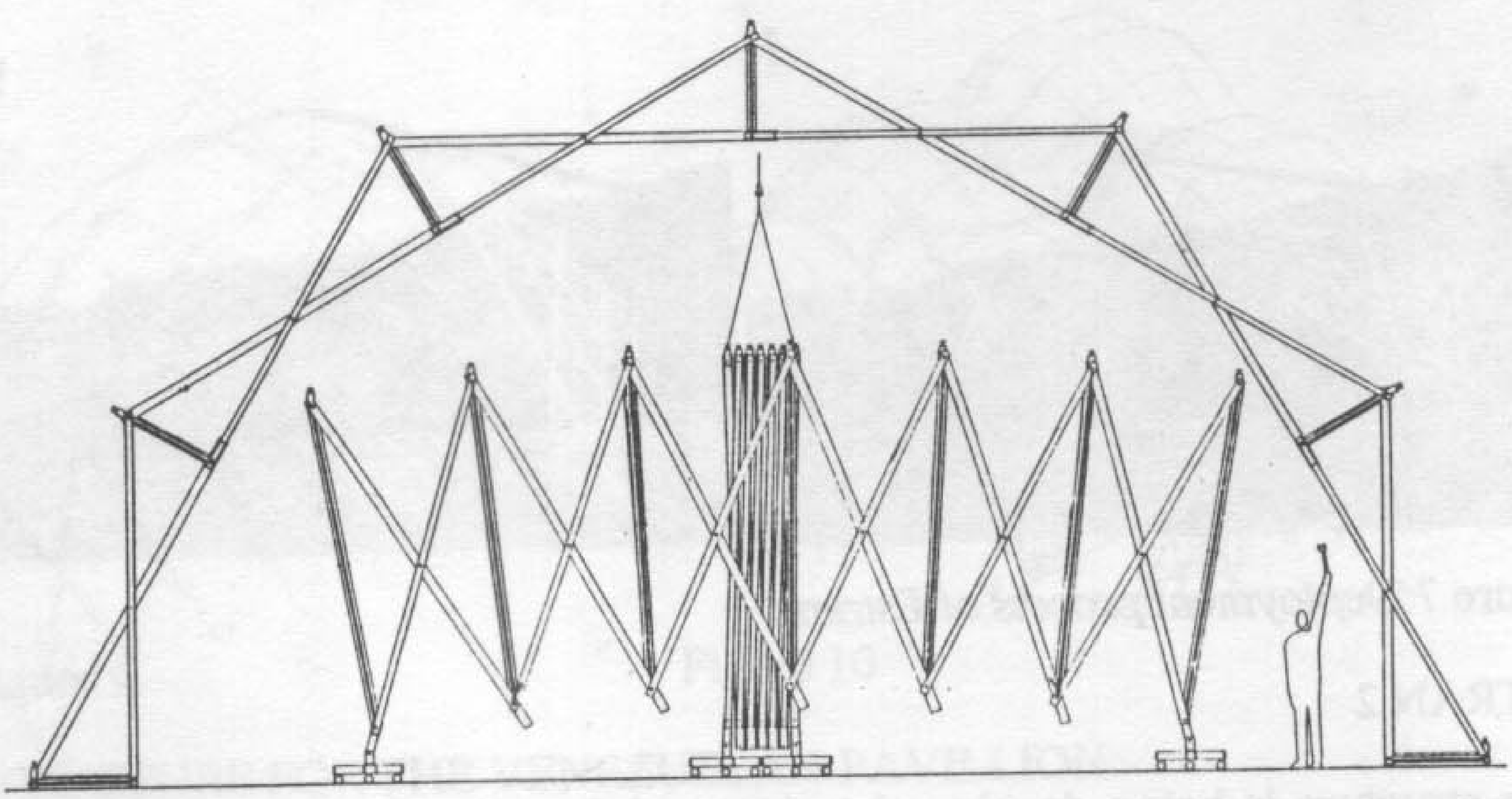


Figure 6 *Deployment process scheme for Estran 1*

The cover made out of PVC coated Nylon fabric its hanged from the structure.(weigh: 50 gr/m2, resistance:90 Kg) the cover is placed during the "erection" process, when the structure starts to rise, then when it has been fully deployed and fixed the fabric is stretched in order to reach its final form.

After nearly 50 deployment the behavior of the structure has been very satisfactory, it has not shown problems or deterioration of its parts, it has demonstrated that structures of this size and weight are easy to handled manually or with light weight equipment. It has shown the feasibility of deploying nearly instant structures from compact packets easy to transport, storage and handled.(Fig.8)

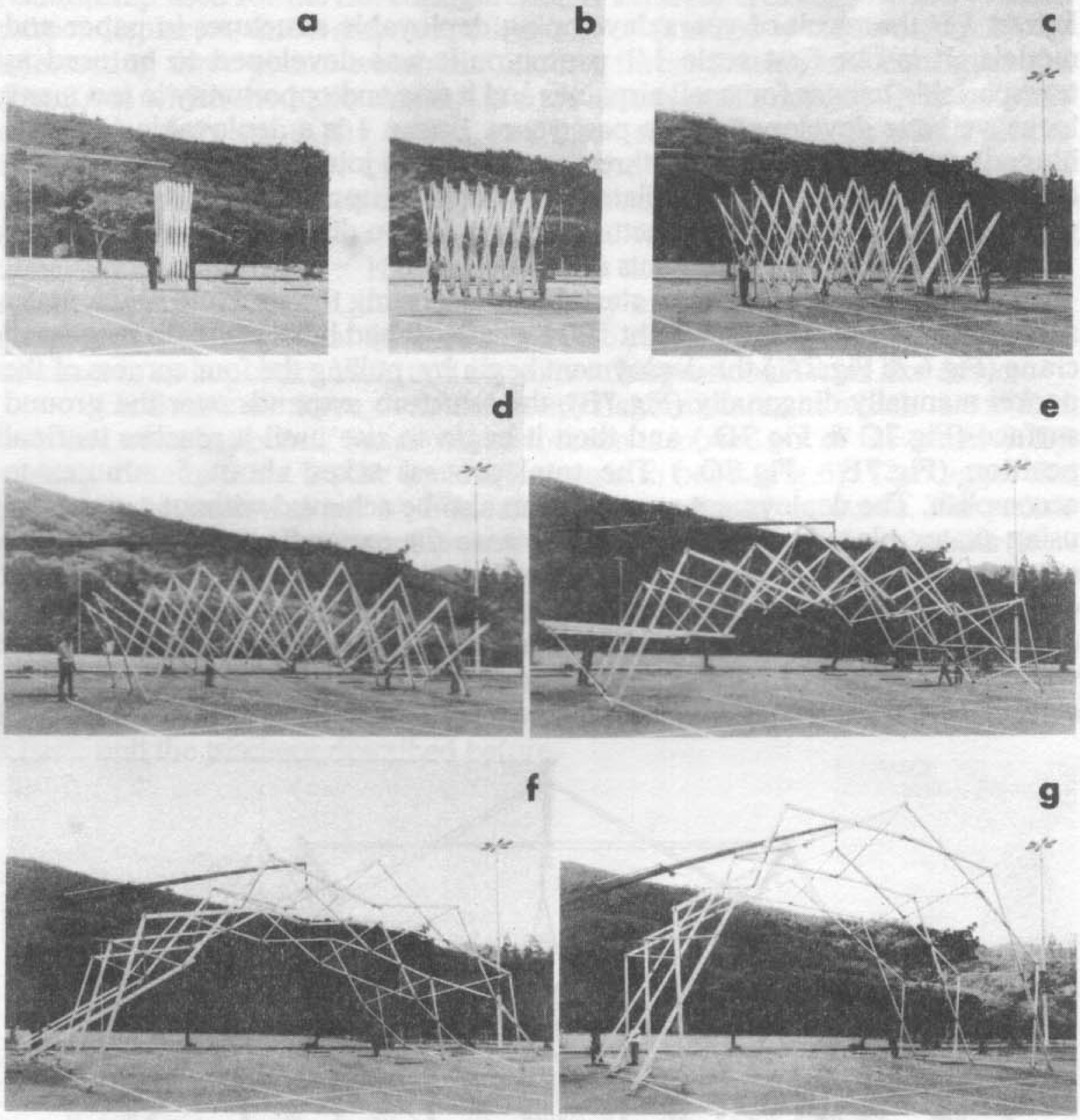


Figure 7 *Deployment process of Estran 1*

ESTRAN 2

This structure is being developed to be used for exposition and temporary events. Estran 2 is a double curvature structure formed by two series of parallel arches, (Fig.9) perpendicular between each other. The structure is supported in four corners and has a projection on the horizontal plane of 14 by 14 mts. each face has a maximum height of three meters, and the structure center is six meters high.

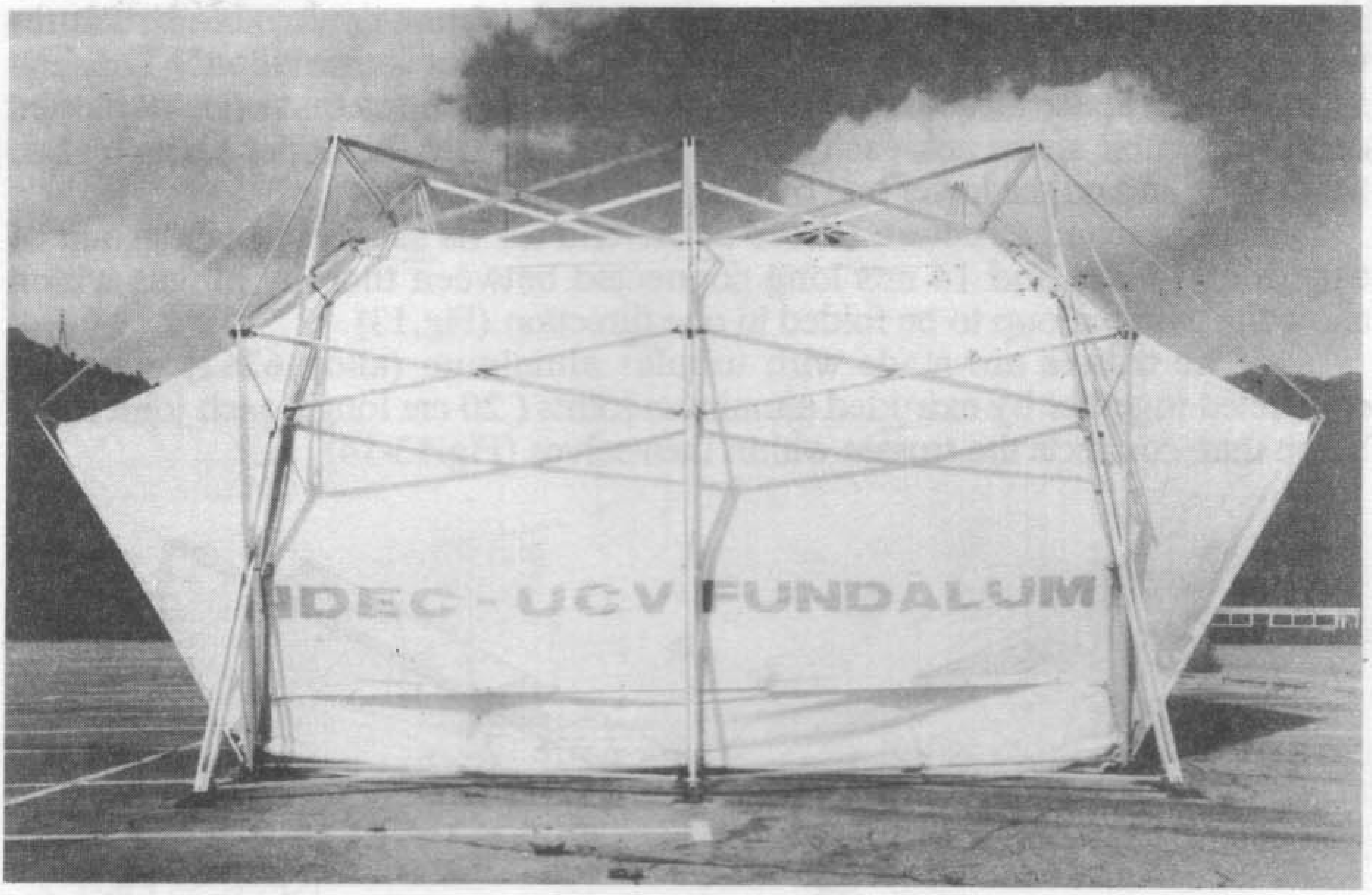
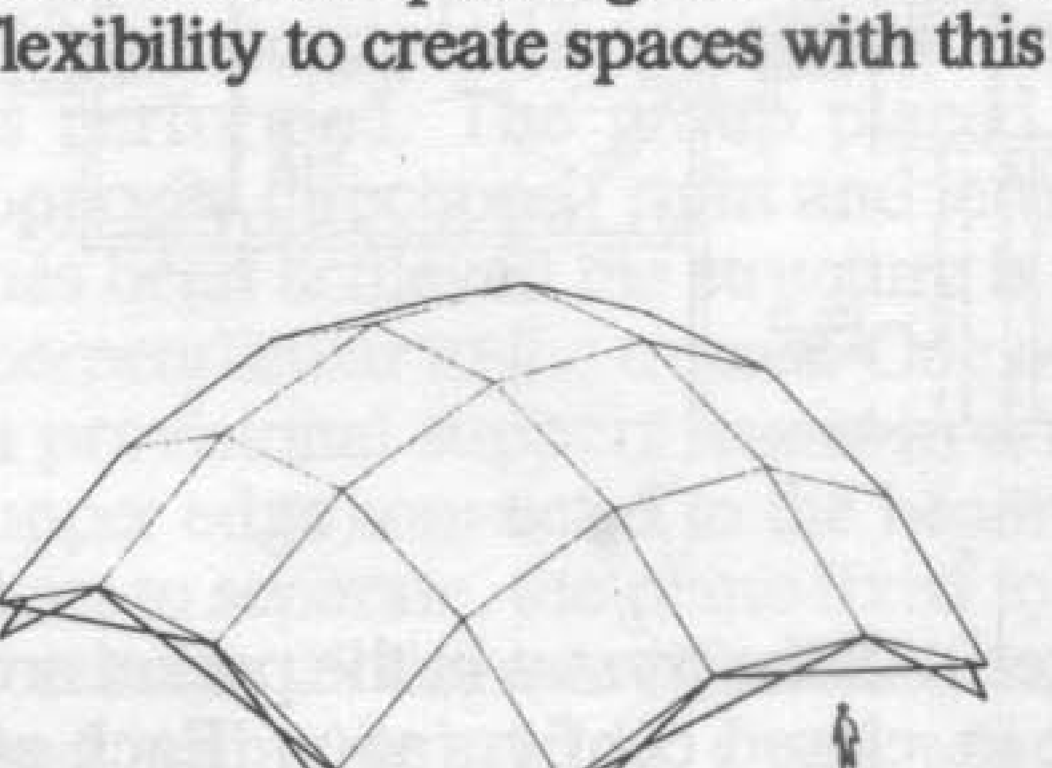


Figure 8

The deployment process is similar to the one in Estran 1 . Once the structure is in its open configuration, a rigid element triangulate each of the four corners and gives stability to the whole system, then a PVC coated Nylon fabric is hung from the structure as a cover.

The basic structural unit of 14x14 mts can be combined with other similar units placing them face to face, this gives a lot of possibilities and flexibility to create spaces with this deployable structure.(Fig.10)



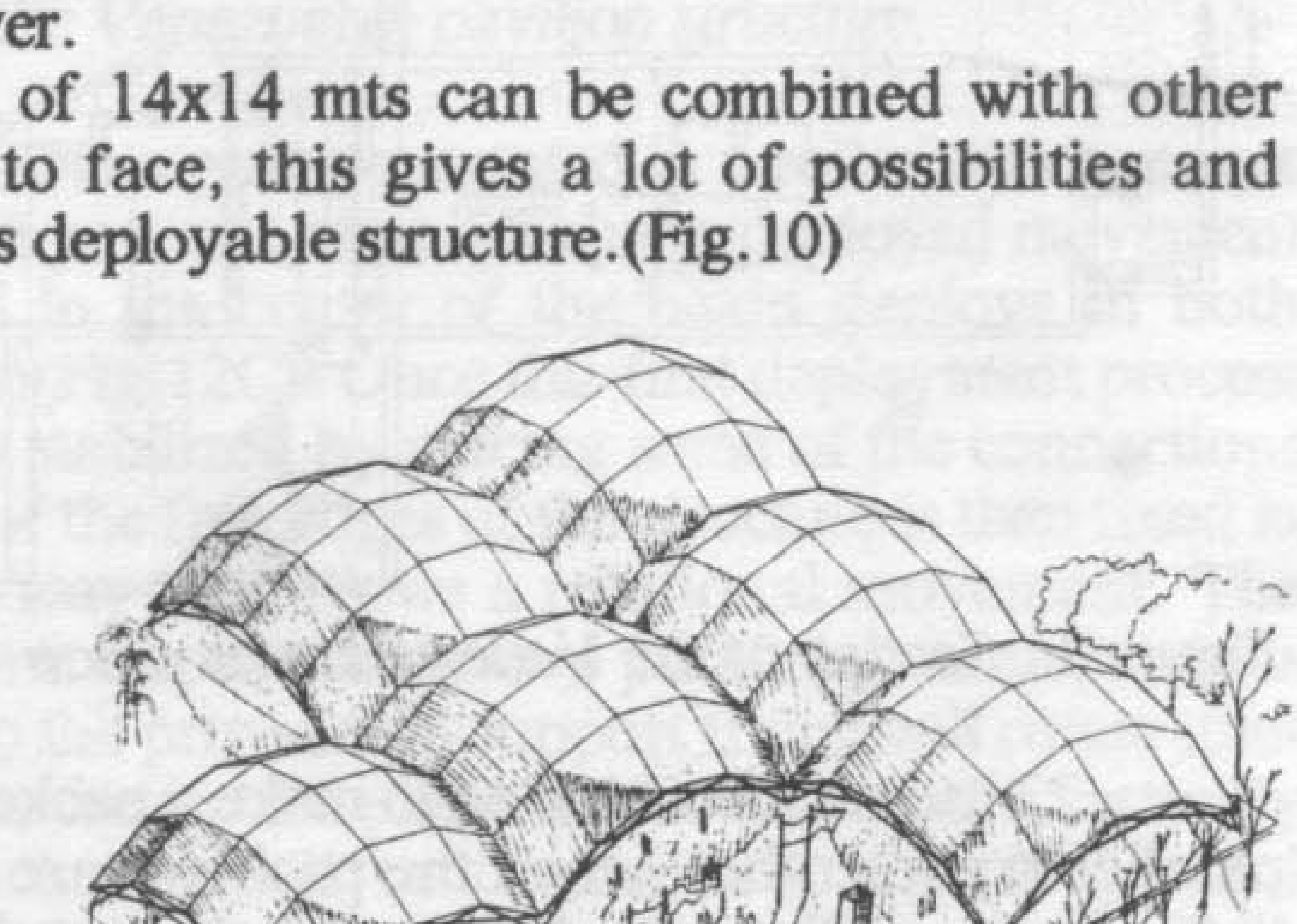


Figure 9 Figure 10

STRUCTURE FOR THE VENEZUELAN PAVILLION

The Venezuelan pavilion at the world fair in Servile (Fig.11), will be constructed under time limitations; transport, and labor cost. The structure is going to be built in Venezuela (building cost is many times much higher in Spain), transported to Servile , erected there, used for six months and then sent it back to Venezuela to be re-erected .

As a response to those constraints two aluminum deployable structures were proposed as the main structure of the Venezuelan pavilion . The first structure is a space structure deployable in two directions that once deployed conform a cubic space net, each cube is triangulated on the upper plane by two turnbuckle and on the lower one by a rigid roof panel.

The second structure (chose at the end for its simplicity) is a group of trusses of 18 mts and 14 mts long connected between then by hinges which allow the whole group to be folded in one direction.(Fig.13)

The trusses are made with tubular aluminum (alloy 6261) elements connected together by extruded aluminum joints (20 cm long), each joint has a hinge that connects the trusses within themselves.(Fig.13-14)

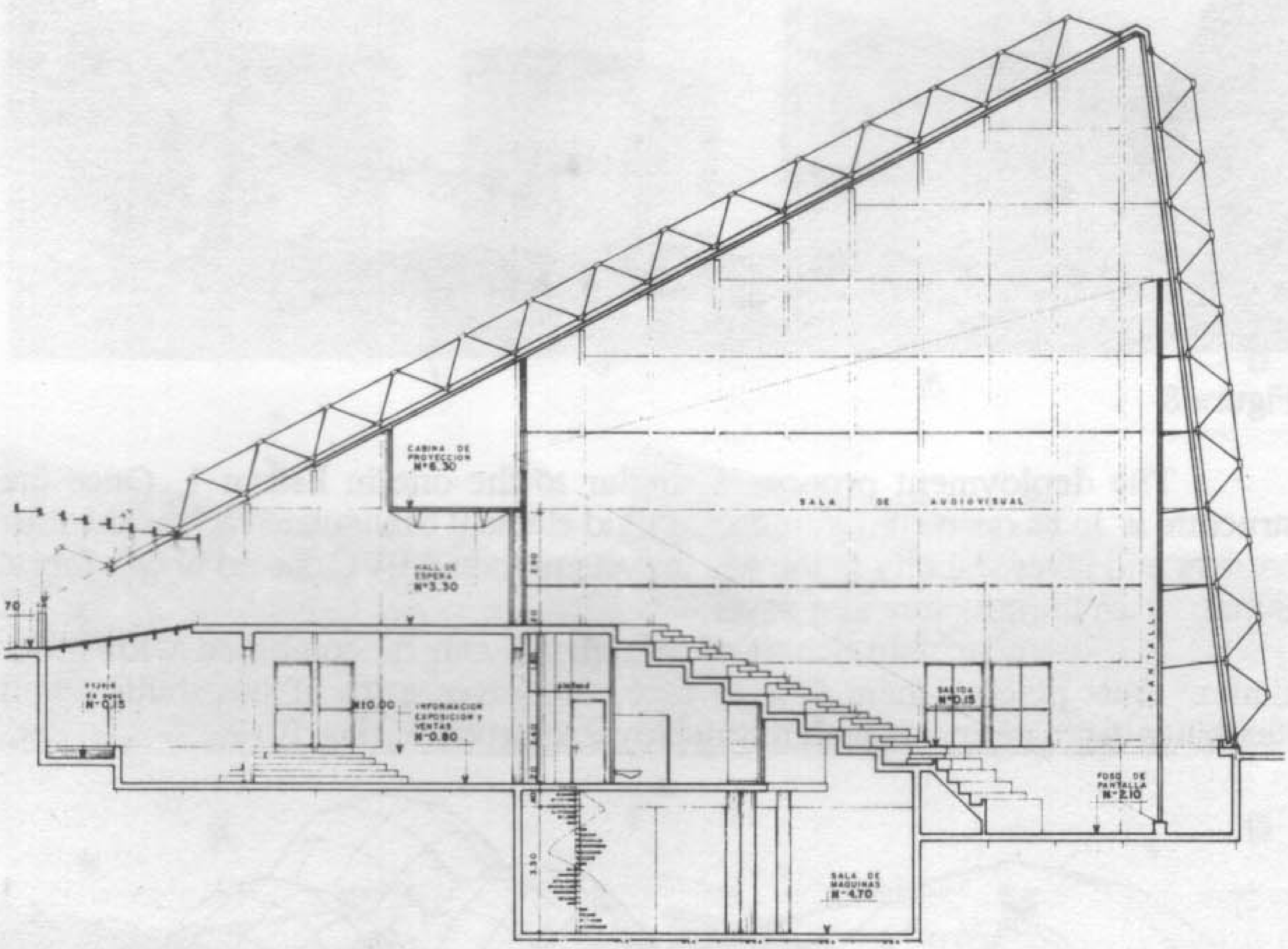


Figure 11 *Section of the Venezuelan pavillion*

22 trusses are conected to make a packet . All the trusses in the packet are parallel to each other, when the packet is are in closed configuration. Each of these trusses will rotate 45 degrees during the deployment process,and as a result an accordion- like structure is obtained. This structure works in one direction. To stand lateral winds forces that will be transmitted by vertical trusses and the envelop to the structure some perpendicular connections to the trusses are needed to give the assemblage rigidity.

The pavilion structure is going to be built out of two group of trusses. The first one is a packet of 22 trusses 14 mts long that once deployed will cover an area of 308 m2. The second group is formed by two packets of 22 trusses each of 18 mts long, one over the other,(Fig. 12A) and joined together in one extreme. In close configuration this group will be 3 mts high, 3 mts wide and 18.80 mts long (including packing) and will weight 8 Ton. The whole group will be lifted by a crane through the joined end (Fig.12B) and deploy in the air like a foldable door or curtain (both parallel packets at the same time)(Fig.12C). The end of each truss is connected with a mechanism which make a hinged connection with the opposite truss in the second packet and at the same time allowing 45º of rotation.

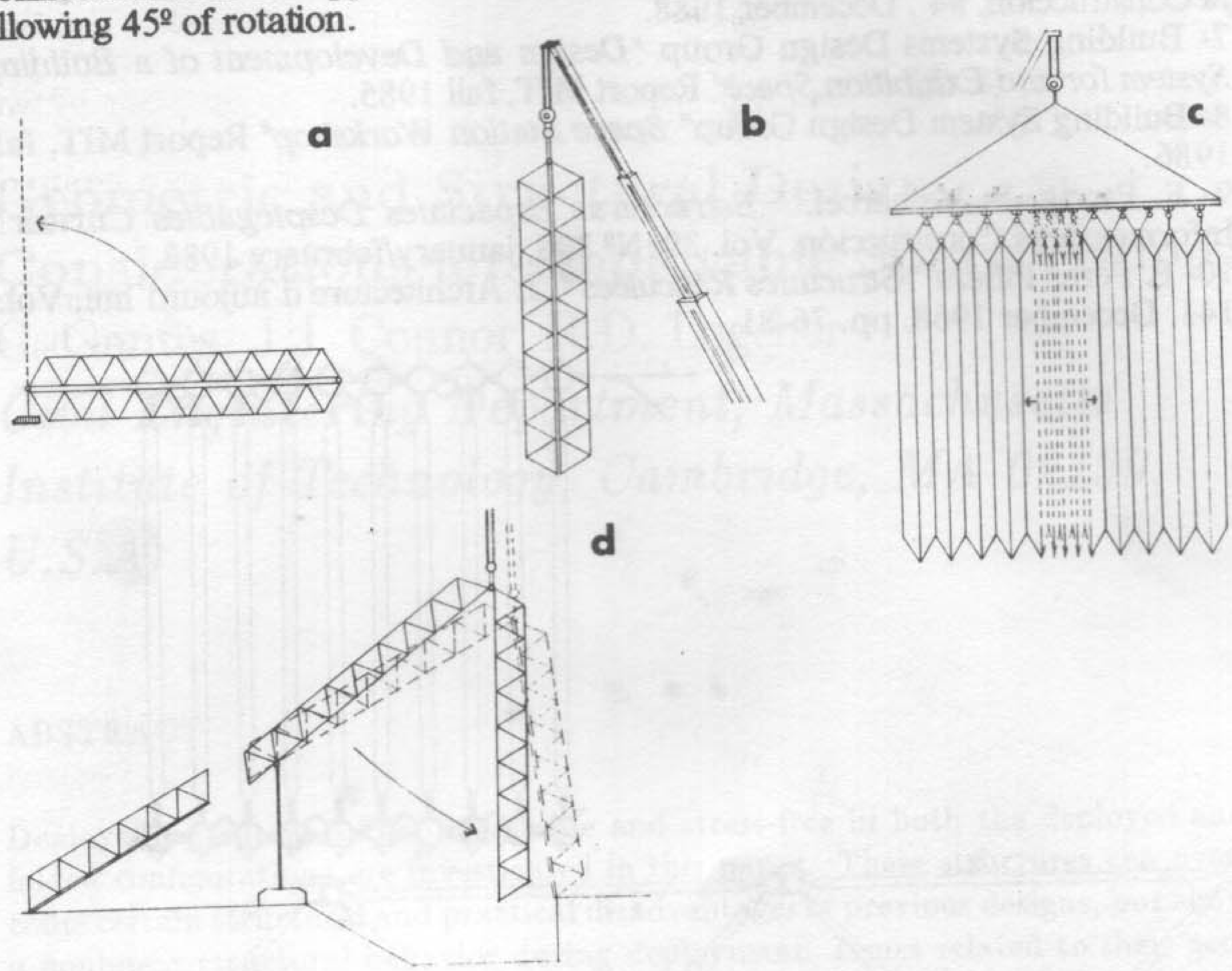


Figure 12 *Deployment process of the Venezuelan pavilion structure.*

Each of these mechanisms hangs from a pulley mounted in a roller which moves along a horizontal beam that works as a rail, over which the deployed movement is performed. The group placed in the center of the beam deploys in both opposite directions (right and left)(Fig.12C). Once this first deployment process has been achieved the structure is stabilized by placing some of the connections perpendicular to the trusses. One of the free edges of the structure is then fixed to a provisional support frame in a way that allows a rotational movement. The upper edge connected to the beam is displaced, the two parallel planes of trusses start to separate, the plane fixed to the provisional support frame will rotate until it reaches 27 degrees of inclination, the second plane will be a this point vertically and with the help of small winches it will be forced to reach the ground connections (Fig.12D) and then will be fixed. the first group of trusses, will be connected to the second group and the whole structure will have stability.

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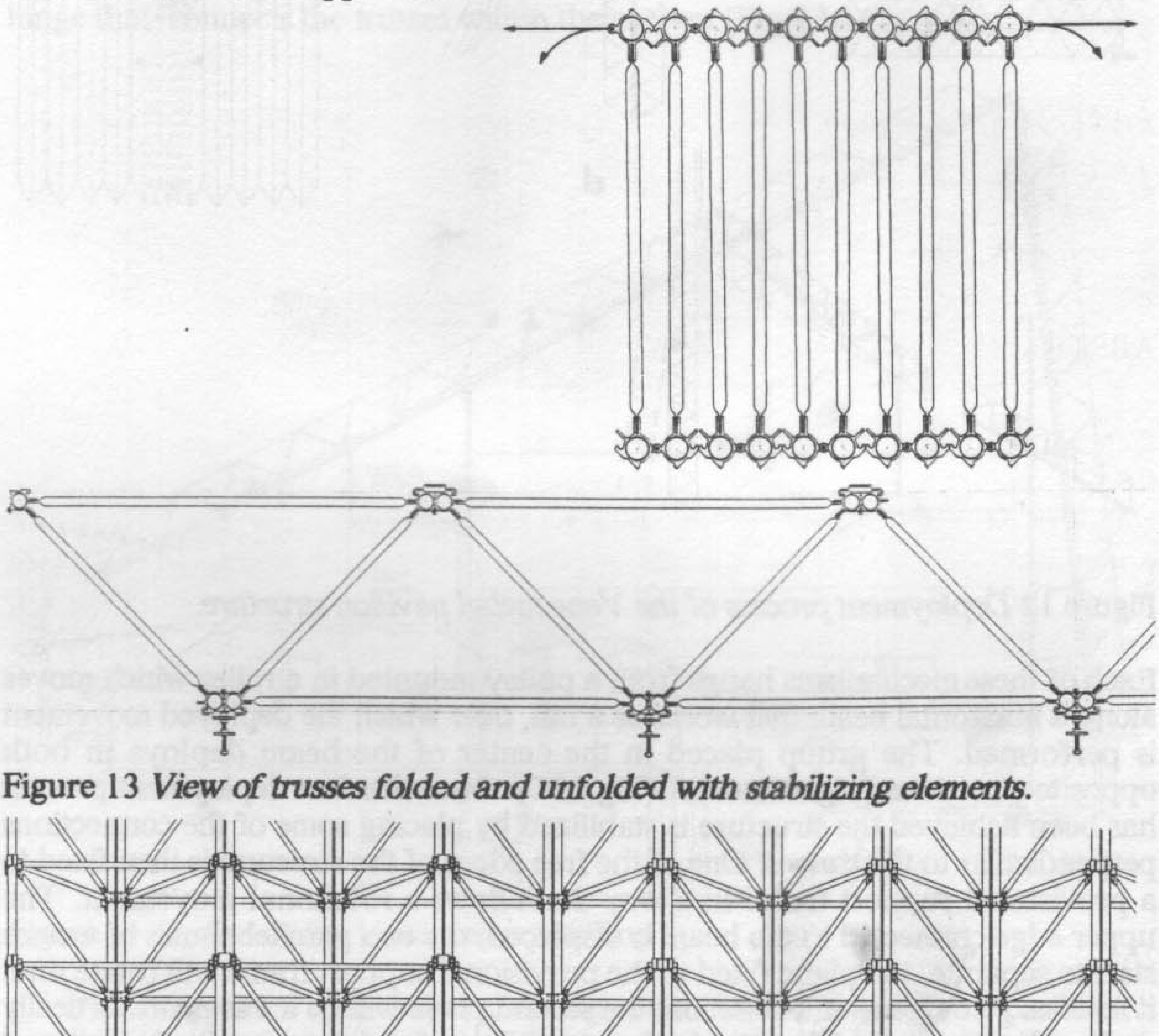

Figure 13 *View of trusses folded and unfolded with stabilizing elements.*

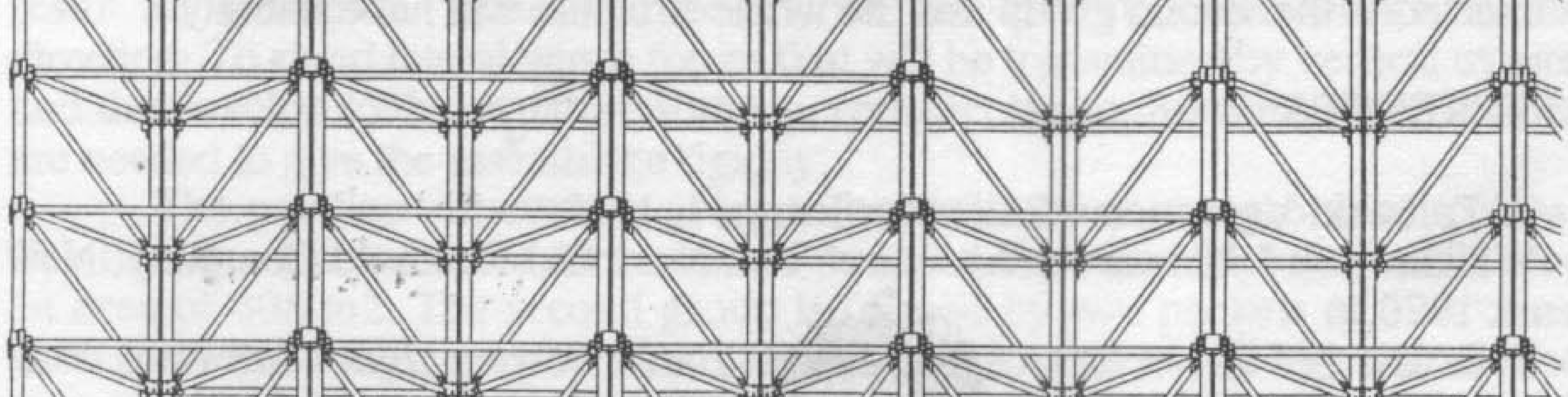

Figure 14 *Front view of part of the pavillion structure*