Mobile and Rapidly Assembled Structures III

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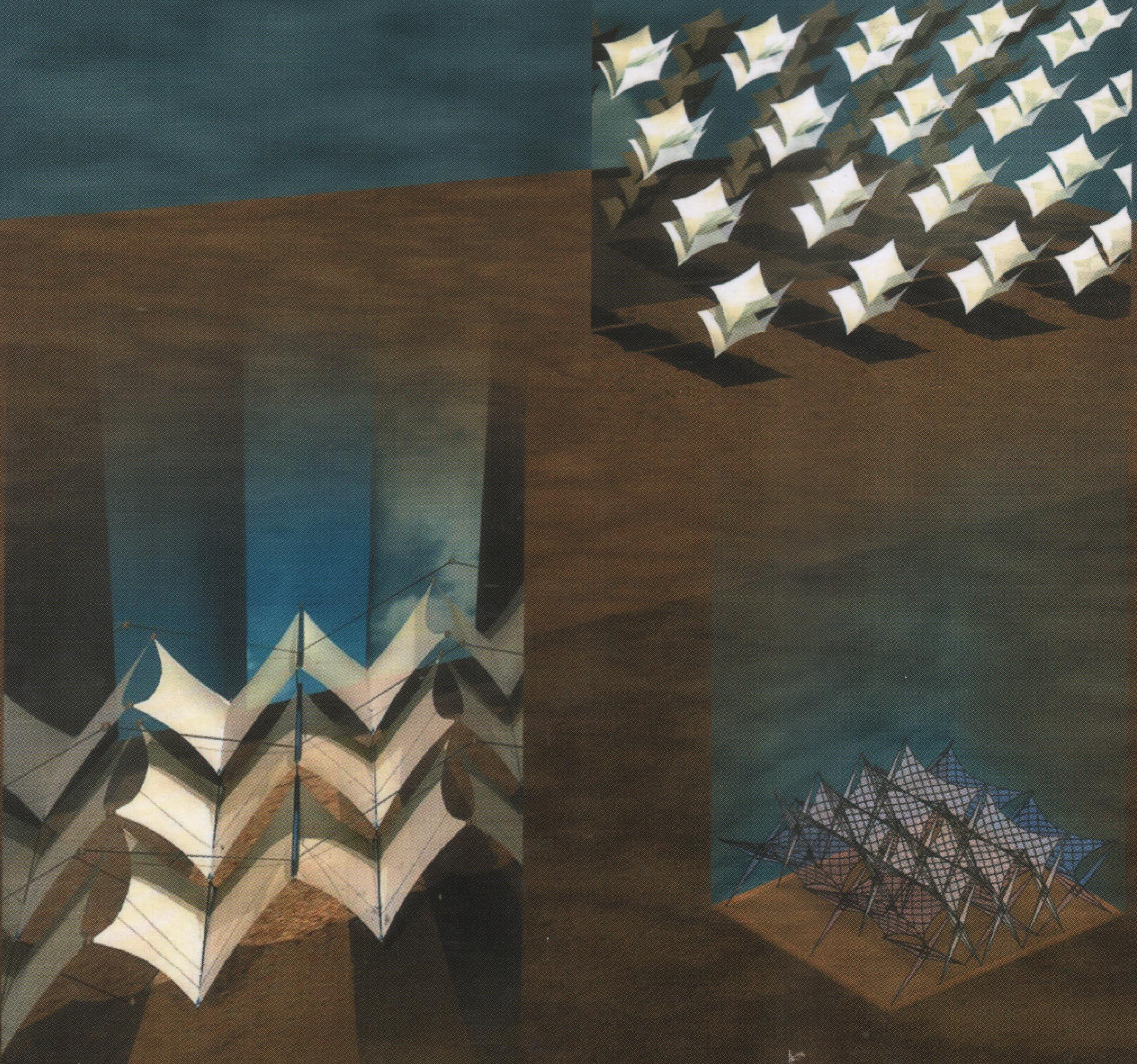

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Development of folding aluminum sheet roofs

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Abstract

This work describes the development of a Folding Aluminum Sheet Roof where the structural component is also the protection membrane. The portable capacity conferred by thin sheets when folded in a certain way is used to comply with the structural commitment. Likewise, the sheet's geometry is used to obtain the roof's sealing, without needing to use sealing compounds or flexible joints. The design consists of an 853 sq.m. roof consisting of six (6) independent modules 24 m. long x 5.56 m. wide. Each module folds from an initial size of 24 m. to a final position of 4.60 m., drawn by a motor-driven system of wire cables. The geometry chosen produces an oscillating movement during the folding and unfolding processes. To counteract this, we developed an pulling system with wires capable of absorbing rotation movements during the sheets' displacement. Two types of mobile joints were also developed: one for the high arrises where a meshing-type continuous hinge is used which in turn produces a joint that is water-tight. There is a second joint for the low arrises, where independent hinges are used and the sealing is obtained through a fold in the sheet which forms a channel that conducts the water out of the joint. The construction and testing of this roof proves the technical feasibility of using thin sheets to construct transformable roofs where the sheet assumes the structural commitments. This relatively simple example is a step towards combining metal roofs with transformable structural systems using bars.

Introduction

When one works with transformable structures using bars, where the resulting structure is a permeable mesh, it is necessary to add a membrane that completes the roof. In most cases, textile membranes are used because they are light and can be folded together with the mesh. For short-use structures this is a very adequate solution. On the other hand, for permanent structures the use of longer-lasting materials in the closing membrane would enlarge the field of application of these structures. Several authors [2] [4] [5] have put forward the idea of incorporating rigid sheets in transformable structural meshes. Among these, we must mention the architect E. Pinero in his development of a «folding hypercubic glazing» a system that combines a transformable structural mesh with glass that fold together, starting out from flat surface and developing into a cubic form. On the other hand, if these rigid membranes are given certain qualities they can perform structural functions and cover spaces without needing additional structural surfaces [1] and at the same time these structural surfaces can be built in such a way that they themselves are transformable structures [3].

Proposal

The starting point is the need for a 853. m. roof to cover the terrace of the pool area of the building that houses the International Center of Education and Development in the Las Esmeraldas Urbanization (Caracas). The roof cannot be permanent because municipal ordinances do now allow this. On the other hand, there is an existing structure consisting of seven steel trusses which should be used as a support. Several proposals involving textile roofs and rigid roofs were presented, with the decision leaning towards the latter because of the durability factor. Fig. 1.

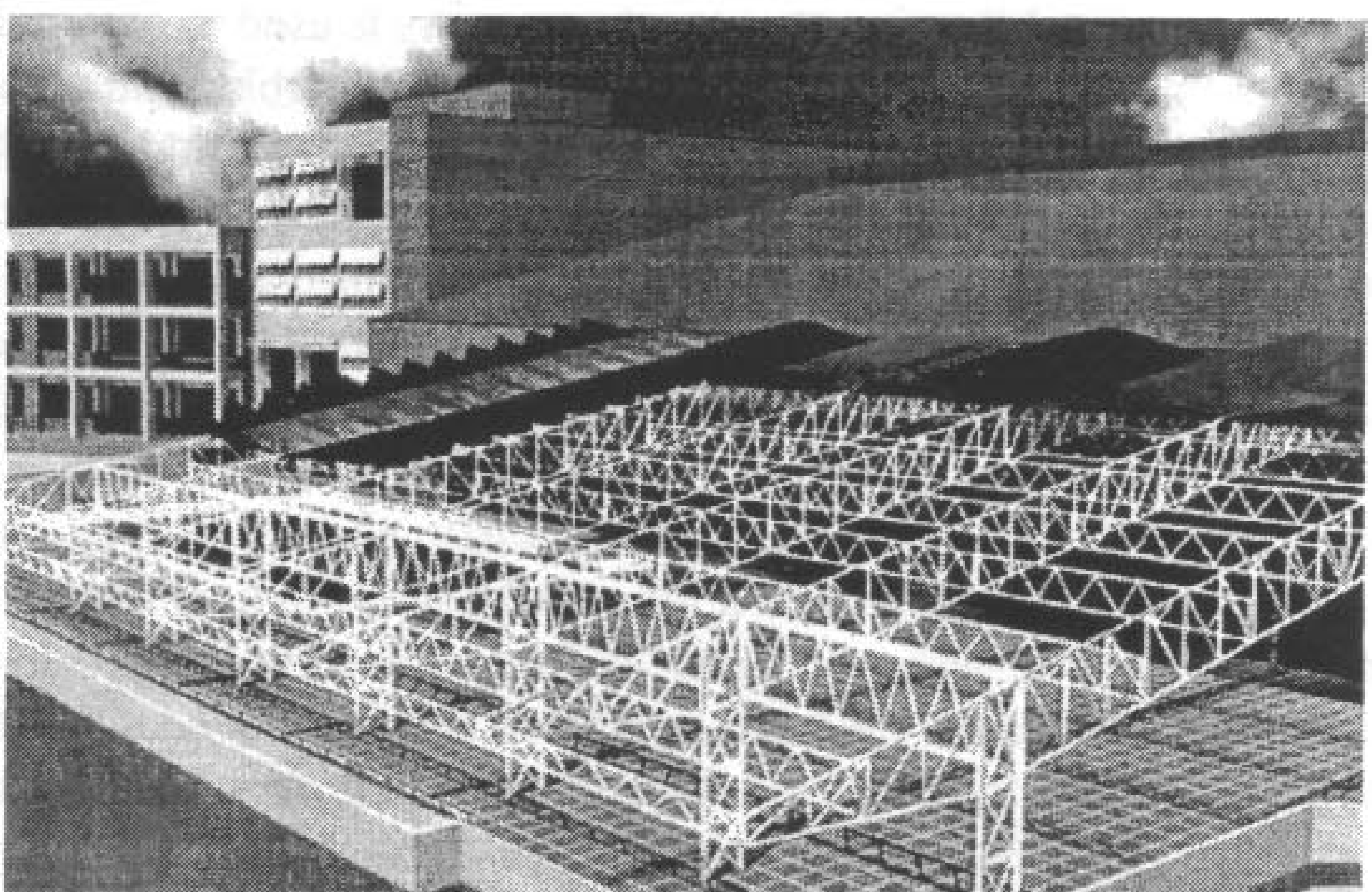


Figure 1: General view of the terrace

The roof designed consisted of six independent modules 24 m. long by 5.56 m. wide that use the existing six steel trusses as a support to which an extension has been added to cover the whole area. Each module consists of thirty three (33) pairs

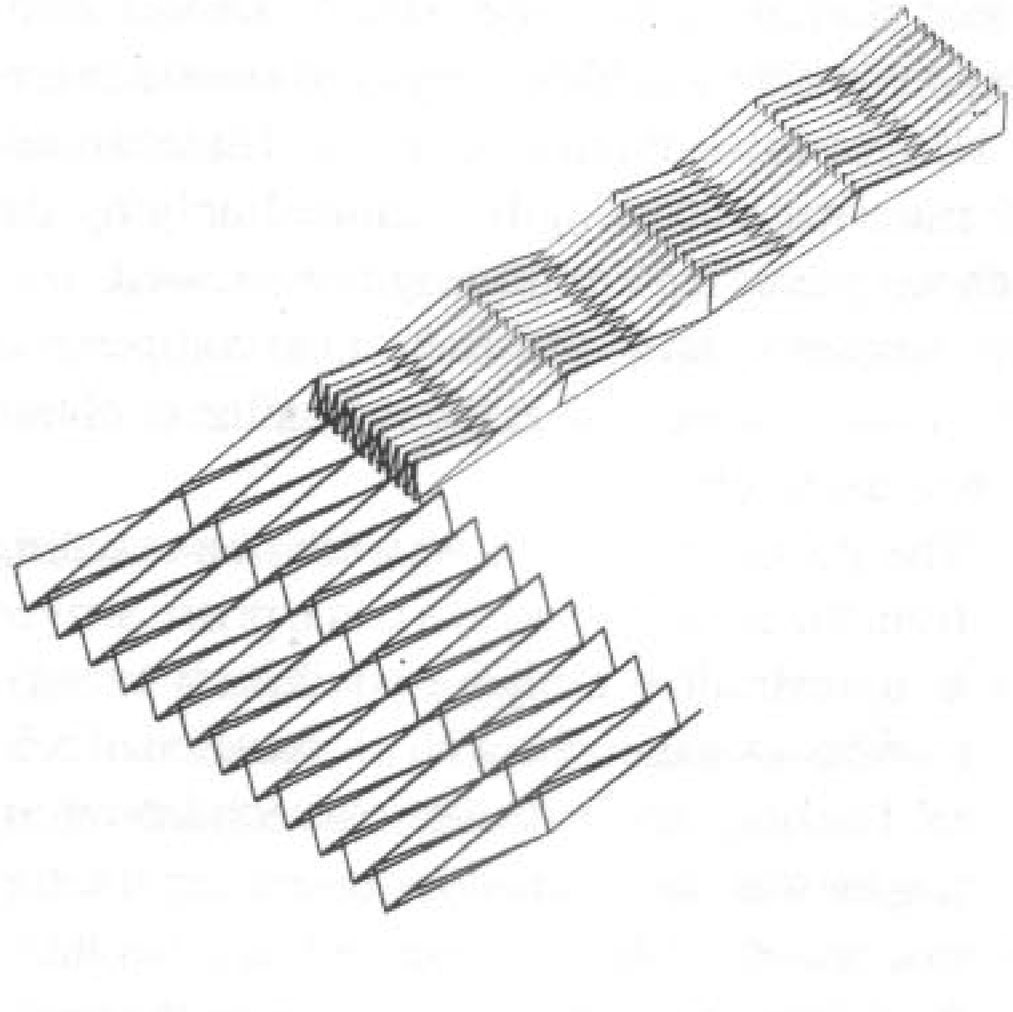


Figure 2: Isometric view

of trapezoidal aluminum sheets which in their unfolded position form conic prisms that are moved to produce a geometric movement in the roof. Fig. 2.

These sets of sheets are folded in such a way to form an accordion from an initial size of 24 m., to a final width of 4.60 m. The sheets are supported by wheels that run on a rail that acts as a channel. A motor-driven system of wire cables is used, which is located behind the decorative screen on the building's facade for the movement of the modules.

Development

The three basic design problems that had to be solved were the following:
1. To give a structural capacity to the roof with very light elements.
2. How to produce the transformation movement
3. Development of the mobile connections that allow the folding of the roof, the transmission of the forces and at the same time the sealing of the roof.
These interrelated problems are summarized below separately in order to simplify their description.

Structure and geometry

To obtain a light roof, we started out from the idea of using thin flat sheets that, like «a sheet of paper», are unable to cover a space however small it may be, but which achieve a surprising rigidity when folds are introduced in them. Playing with the height of the fold and the thickness of the material, it is possible to cover different spaces.
If the material is folded in a single direction, perpendicularly to these the resistance is much lower and not very strong, it will tend to fold and this is how we obtain the accordion. There is an infinity of folding combinations that make it possible to obtain very rigid sheets in one direction and to fold them like accordions in the other direction.
In the case of a sheet of paper or carton, the mobile joints are formed by the material itself; in the case of metal sheets mechanical joints are required in each arris.
In our case, we explored a combination with the lowest number of arrises, the maximum fold height and the maximum exploitation of the sheet.
An aluminum sheet was used to reduce the weight of the roof and to obtain minimum maintenance. In earlier experiences, we had worked with galvanized sheets

of 0.6 mm. for similar spaces but because aluminum is a material with a lower module of elasticity than steel and given that the whole would be subject to kinetic deformations and loads, we decided to use 1.6 mm. thick aluminum sheets. The commercial sheets are produced in reels 1.22 mm. wide, the length is limited only by the cutting ands folding machines. Continuous pieces 5.56 m. in length were used.
We studied a combination between the geometry and dimensions of the components to exploit the sheet to the maximum (minimum waste) and at the same time to obtain the maximum height when the whole was assembled.

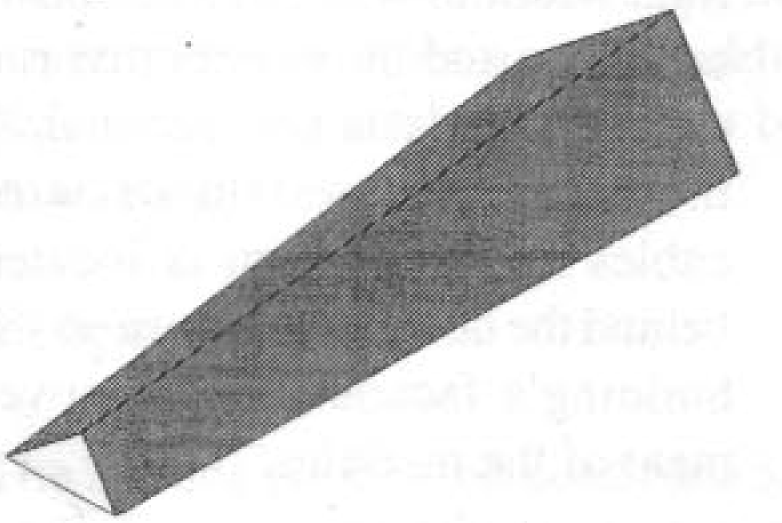


Figure 3: The conic prism

The geometry chosen was the one resulting from the combination of a conic prism arrived at by extruding a bigger equilateral triangle towards a smaller one with a separation of 5.56 m. The height ratio between the equilateral triangles was determined by balancing the formal aspect of the roof, the average height of the fold and the effect of the latter on the roof's kinetics, obtaining a ratio of 2:1. (Fig. 3).
The result of the combination of the conic prisms can be seen in (Fig. 4) the whole which is a series of rhombic sections that move from row to row, an effect which is accentuated by painting half of the prisms blue (the company's color) and the others half of the sheets were anodized with their natural color to obtain a matt silver finishing. Each prism is formed of two types of that are produced by a diagonal cut on the sheet of 1.22 x 5.56 m. (Fig. 5) One of the sheets also receives a «fold» at one end

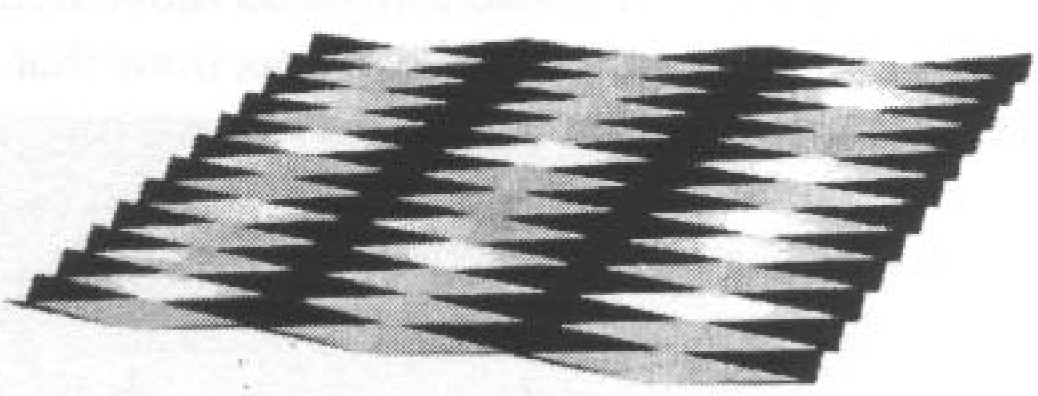


Figure 4: Unfolded roof

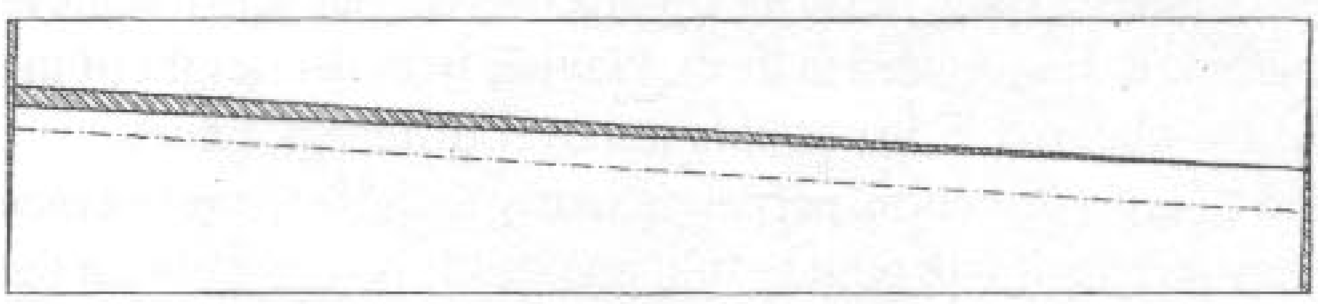


Figure 5: Aluminium sheet cutting patern

which, depending on the sheet's location in the whole, can run to the left or the right (there is an equal number of sheets «folded» in each direction). (Fig. 6)

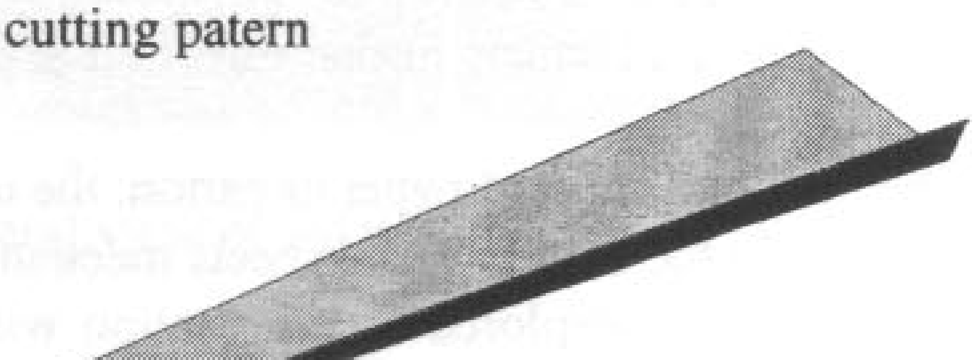


Figure 6: Bended aluminium sheet "folded"

A continuous hinge is fixed to the upper edge of the sheets, formed by two aluminum sections, with 1/8" driven rivets placed every 103 mm. This reinforces the two upper edges of the sheets that are not folded which consequently are easily bent. An aluminum section is fixed at the lower end of the sheet that is not «folded» which runs continuously along the edge of the sheet and 1/4" driven rivets are fixed every 103 mm. for the same purpose as those on the upper edge. Lower hinges are fixed on this reinforcement.

Joints and sealing

One of the basic problems in the design of a transformable rigid roof arises from the fact that the roof surface is formed by a large number of relatively small inter-articulated components. How can the roof be made rigid and at the same time permit the articulation so that it is transformed?
At first, we discussed the possibility of using flexible materials (rubber, textile membranes, silicon rubbers, thin metal sheets, etc.) that allowed the joint to be mobile while at the same time producing a closed joint that water cannot pass through. The problem was that these materials did not adequately transmit the forces between the different components in the roof therefore there is no structural behavior of the whole. On the other hand, this type of joint tends to become fatigued with repeated use and, in the case of the rubbers or plastic materials, the UV radiation breaks the polymeric links and accelerates the material fatigue process even more. This led to the use of rigid hinges, to transmit the forces and perform the movements between sheets. The sealing was obtained by producing folds in the same sheet that generate overlaps and channels when all the sheets are unfolded and also direct water to the collection points. After studying the hinges, we found an ingenious hinge that is produced by two aluminum sections where the edge is the meshing section. The hinge is produced (unlike the majority of hinges) not by rotating the elements on an axis, but by displacing the two meshing sections. This hinge permits a continuous connection between the adjacent edges of the sheets which is very convenient for their structural performance while at the same time, the section that keeps the meshings joined seals the joint. (Fig. 7).
This hinge can only be used in the top joints because in the lower joints dust and accumulated sediments would block the mechanisms and, on the other hand, the inversely-placed joint is not rigid.

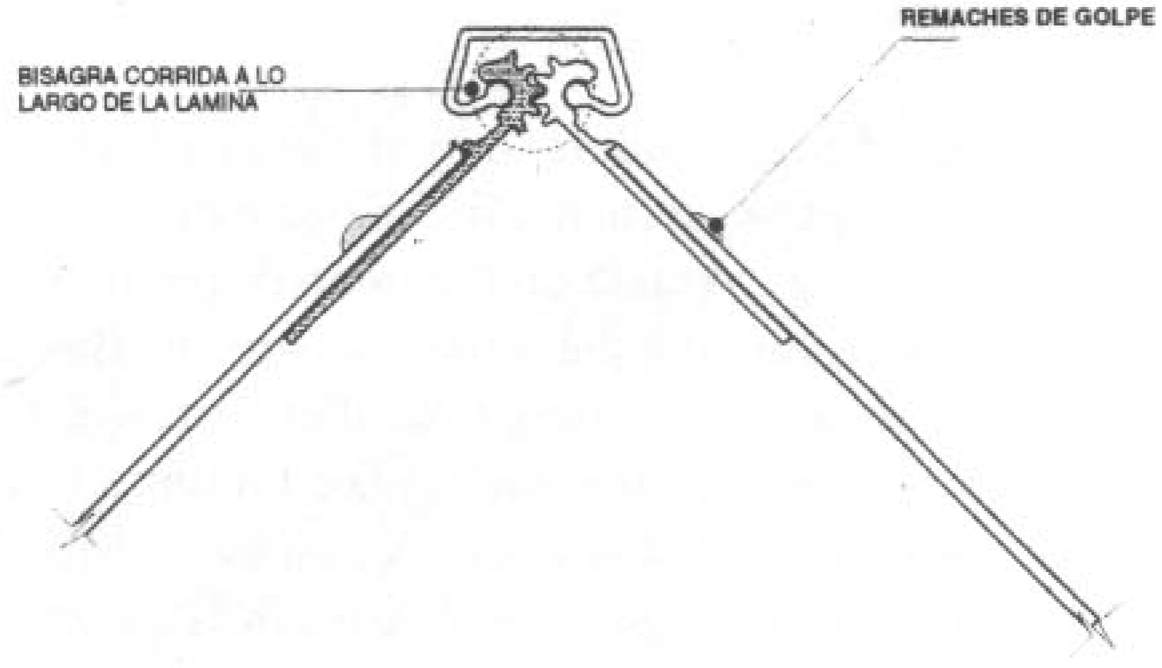


Figure 7: Top hinge

In the lower joints, a 10 cm. fold (fig. 8) in one of the sheets produces a channel in an unfolded position able to collect water from the two adjacent sheets under rainfalls of 400 mm/m2. The hinges are separated from the bottom of the channel by an L-shaped aluminum section to stop dust from entering the hinge mechanism so that it will no impede the exit of water and accumulated sediment.
These lower channels send the water sideways towards a channel that runs perpendicular to the sheets to collect the water and drain it out of the covered area. The lower hinges are made from 60 mm. segments of an aluminum section which are machined to obtain the hinge (fig. 9).
The hinges are joined with a stainless steel pin which is fixed with a catch. Graphited nylon sleeve bearings are placed between the pin and the aluminum hinge to reduce the friction, the wear of the aluminum and the galvanic forces that could form between the steel pin and the aluminum. Likewise, two graphited nylon washers are placed to avoid contact between the faces of the aluminum components.

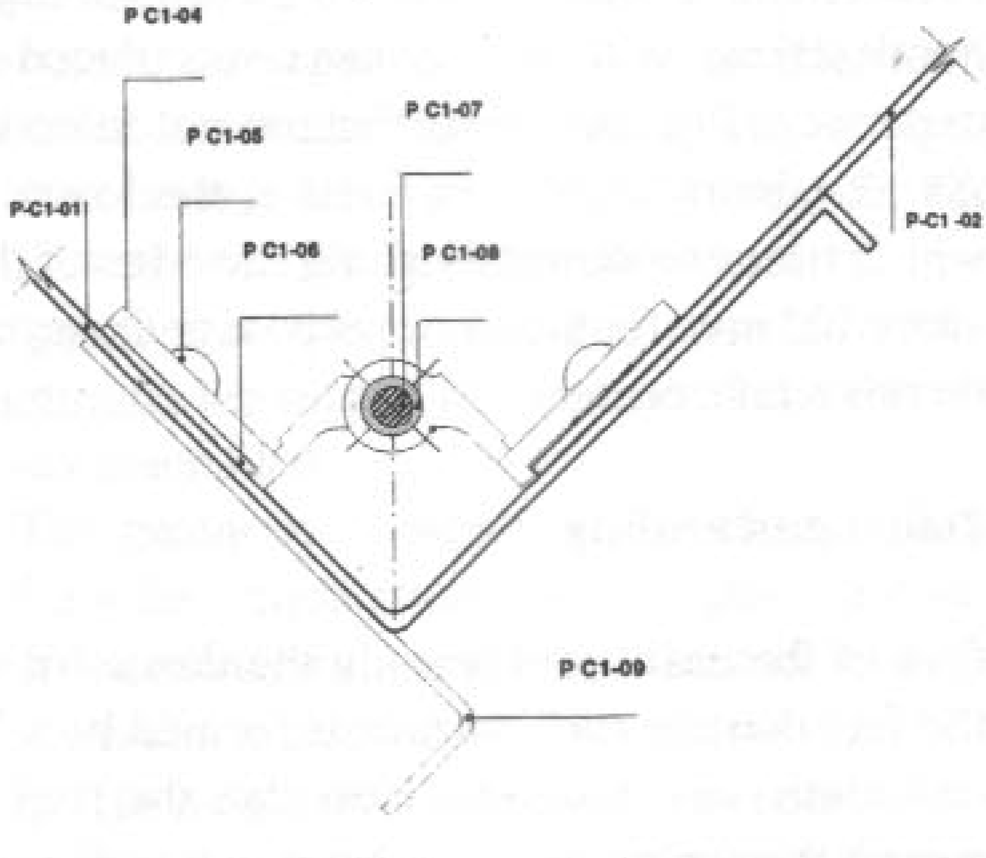


Figure 8: Lower hinge

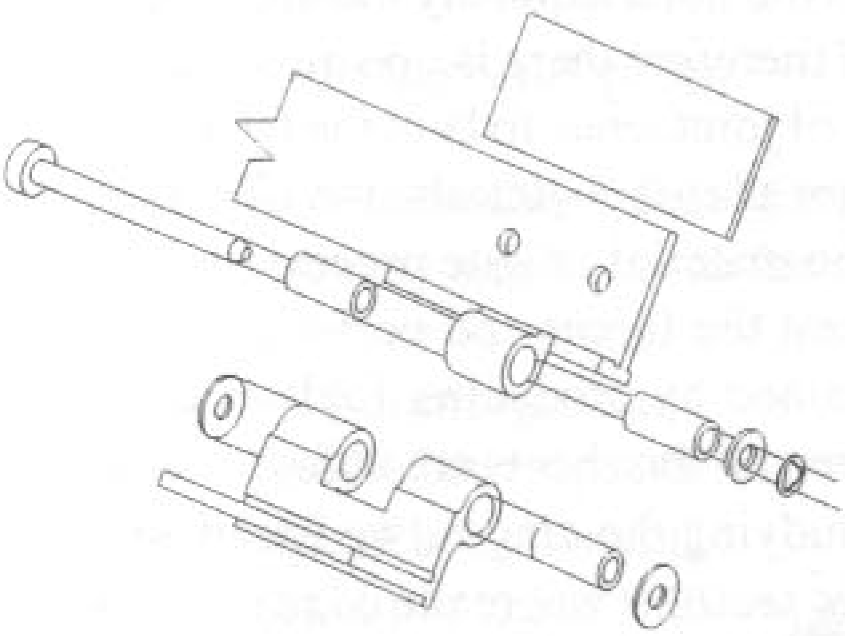


Figure 9: Lower hinge detail

The movement

With a system of conic folding, only the roof's high arrises are parallel. The low arrises form an angle with each other to cause the movement, during the process of folding or unfolding to rotate on the intersection point of the imaginary axes that are obtained by prolonging the arrises outside the sheets; this means that the nearest end to the rotation axis runs a smaller distance than the farthest end. These different running lengths alternate in the folding of the following pair of sheets where the rotation point changes direction so that the end which ran the smaller distance now runs the longer one. The result is an oscillation movement (fig. 10) (fig. 11) where there are lateral movements on the supports which the guide channel has to absorb. The changes of speed at the opposite ends of each pair of sheets has to be absorbed by the pulling mechanism.

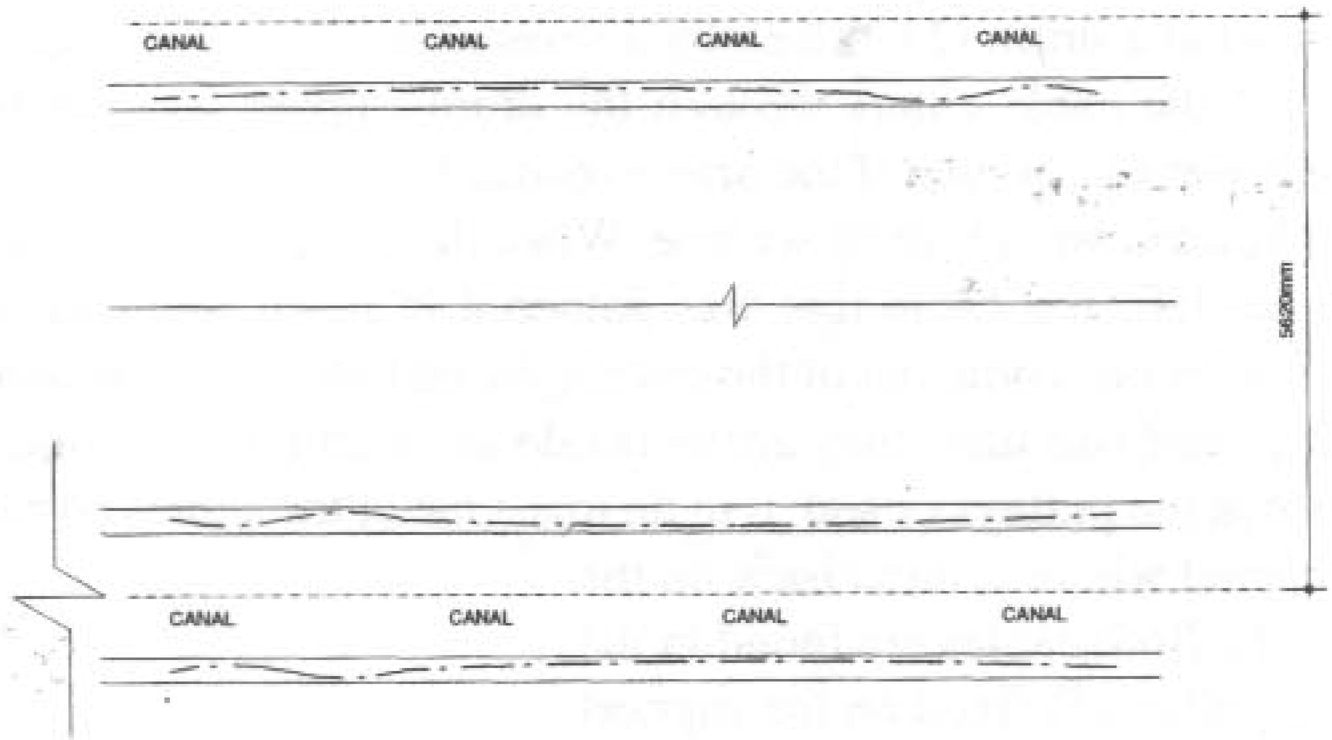


Figure 10: Horizontal movement

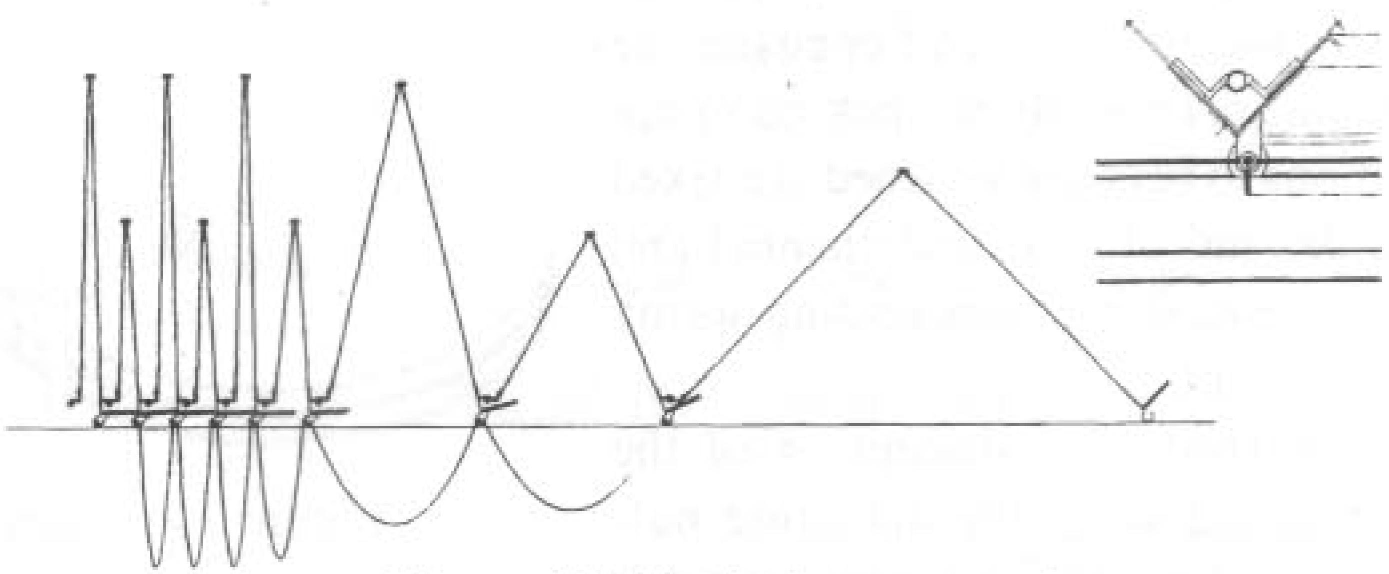


Figure 11: Vertical movement

The movement of the sheets is carried out using a system of two cables which move alternately in the opposite direction to pull or push the first pair of sheets of each set and these in turn pull the other sheets using the perimeter restriction cables, or they push using the stops (fig. 12) placed on the lower edge of the sheets' channel.

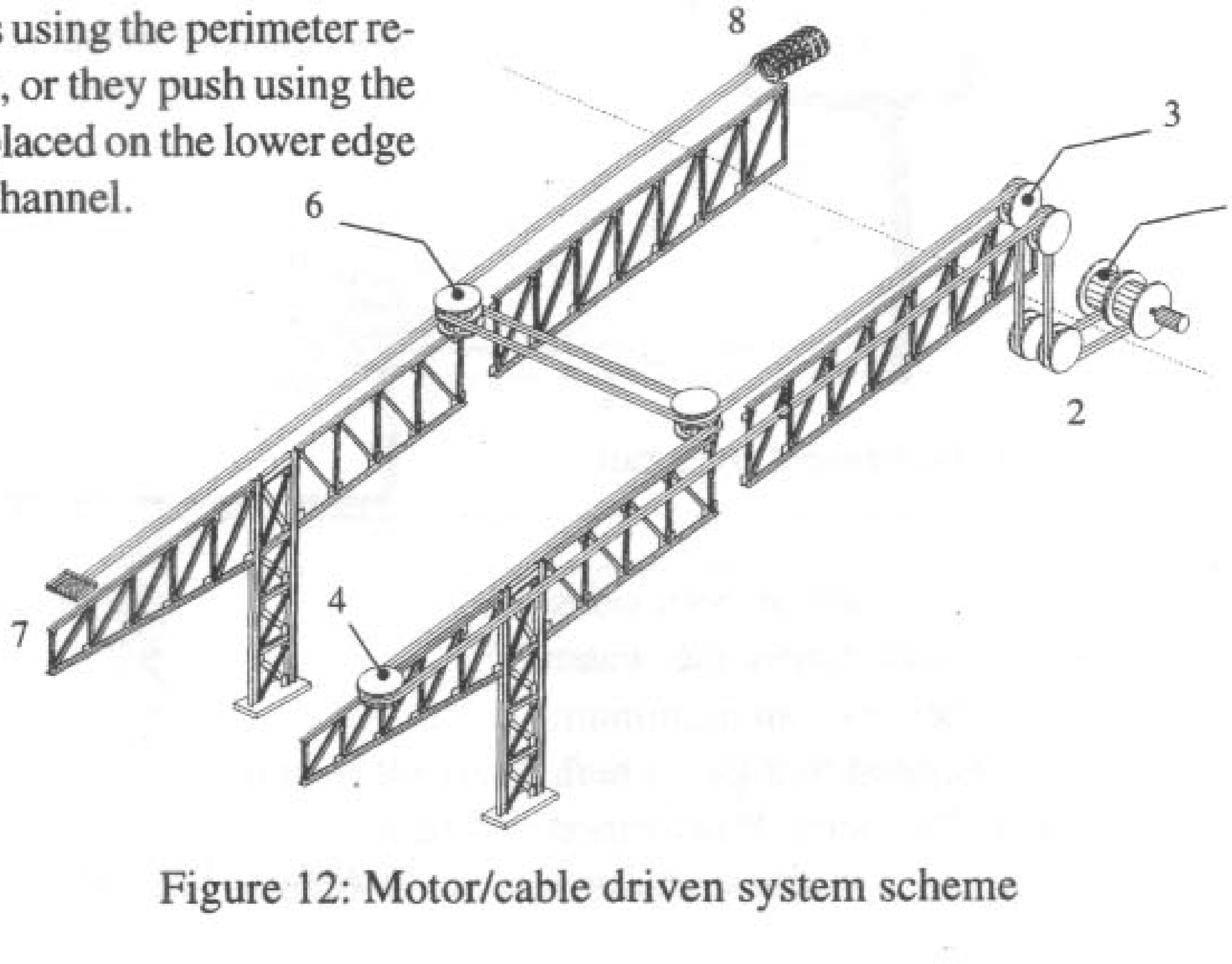


Figure 12: Motor/cable driven system scheme

Both cables start at a drum (1), driven by a reversible DC motor with a reduction gearbox; one of the cable enters through the drum's upper face while the other leaves by the lower one so that if the motor rotates to the right one of them will be gathered in while the other will be set free. When the motor rotates in the opposite direction, to the left, the cable that was gathered in is set free and the other is gathered in. The cables come out of the drum (placed behind the decorative facade of the building) and rise until they arrive inside the aluminum channel, changing direction twice in the pulleys (2 and 3) to do this. One of the cables continues to the end of the channel where it turns back on the return pulley (4). Both cables are found in the first actuating pulley (5) fixed on the support of the first pair of sheets; they change direction and go towards the of the second actuating pulley (6) placed at the end opposite the first pair of sheets. From there, they go in opposite directions to become attached at a fixed point (7) at the end of a second channel and the other runs towards a compensating spring (8) fixed to the wall.

This system permits the absorption of the variations in speed when the actuating pulleys move along the cables adjusting the differences in the run between each end. (Fig. 13)

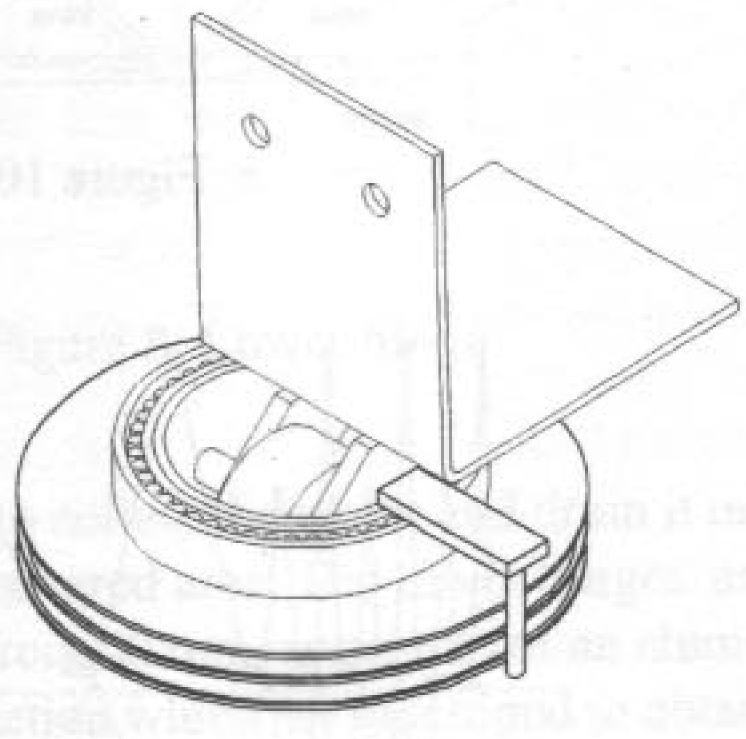


Figure 13: Pulley

The sheets' displacement and support guide should permit the horizontal movements that are produced during the folding and unfolding of the whole. For this, we chose an open channel as a guide on which the wheels that support the roof move. (Fig. 14)

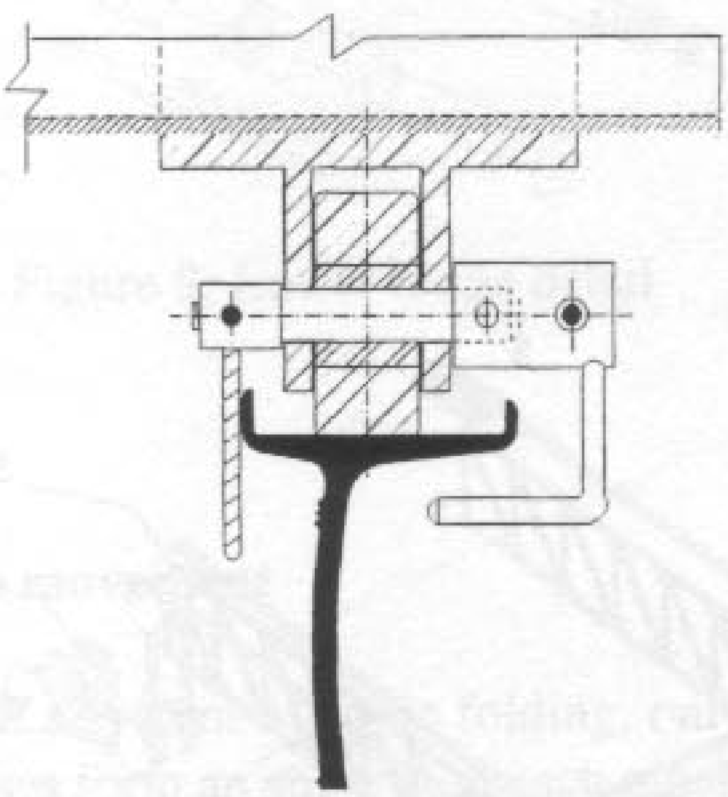


Figure 14: movement over rail

These guides are found at both sides of the channel that drains the water from the roof, therefore an aluminum section was designed that plays both roles (fig. 15). This section is formed by a central channel for the water and

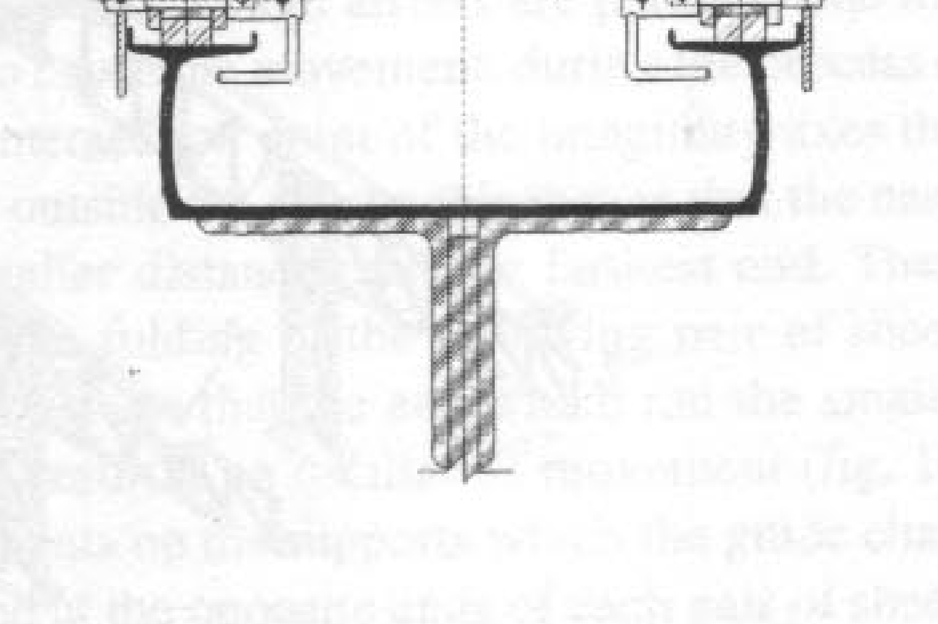


Figure 15: Channel/rail detail

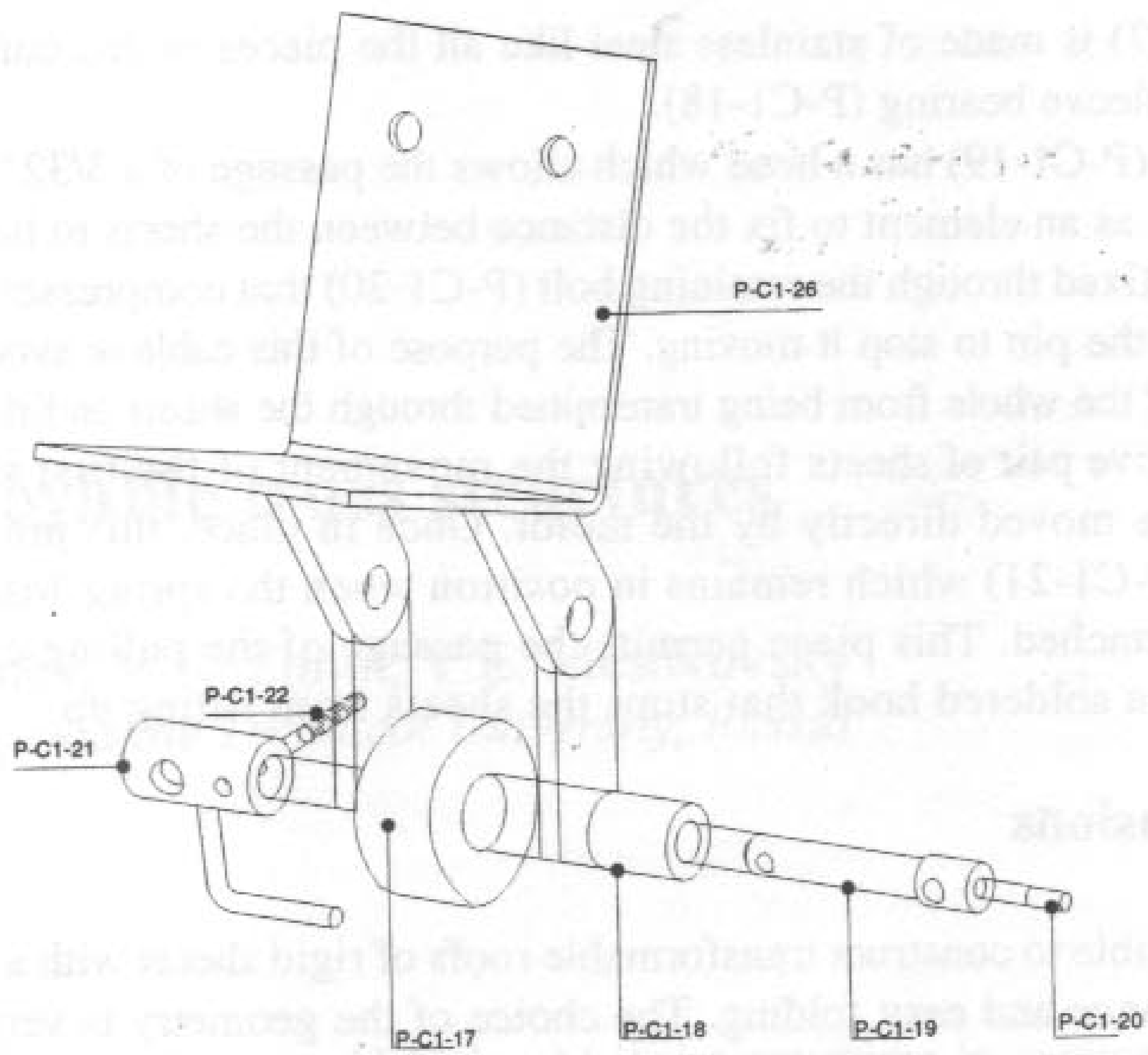
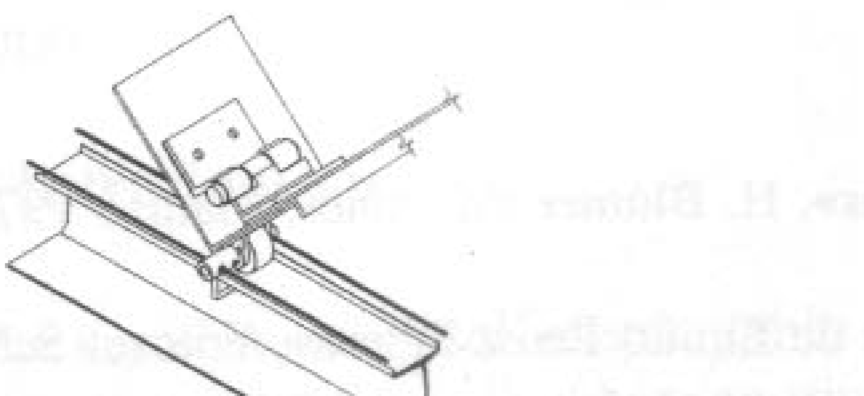


Figure 16: Support component

two high lateral channels for the sheets' support guide. This section is fixed to the upper cordon of the trusses that serve as the base structure of the roof. The support of the sheets on the rail/ channel is produced through the component Fig. 16 and Fig. 17 which in addition acts as a rolling and restriction element to stop the sheets from rising up when there is suction or a push from below caused by the wind. This component consists of a piece that serves as a base, which is fixed under the hinges at each end of the sheets. On one side it uses the rivets that fix the hinge and on the other side it is fixed to the sheet by conic head rivets so that they are level with the sheet and do not block the movement of the second sheet when it unfolds. The wheel



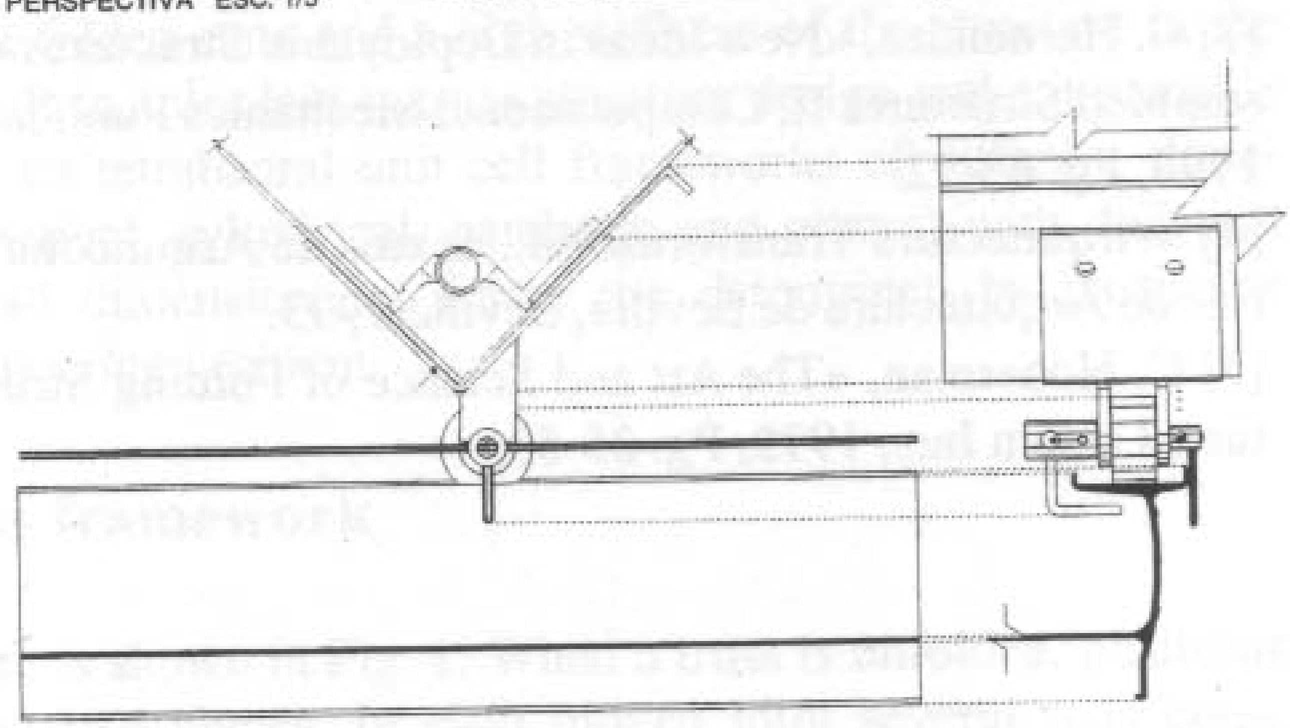


Figure 17: Support detail

(P-C1-17) is made of stainless steel like all the pieces in this component, with a bronze sleeve bearing (P-C1-18).

The pin (P-C1-19) has a head which allows the passage of a 3/32" wire (P-C1-24) that acts as an element to fix the distance between the sheets to be unfolded. This cable is fixed through the retaining bolt (P-C1-20) that compresses the cable in the head of the pin to stop it moving. The purpose of this cable is avoid the deploying forces of the whole from being transmitted through the sheets and it has to pull each consecutive pair of sheets following the movement of the first sheet that is the only one moved directly by the motor. Once in place, this pin is fixed to the piece (P-C1-21) which remains in position when the spring-loaded pin (P-C1-22) is attached. This piece permits the passage of the pulling cable (P-C1-25) and has a soldered hook that stops the sheets from lifting up.

Conclusions

It is possible to construct transformable roofs of rigid sheets with a good structural performance and easy folding. The choice of the geometry is very important for both the structure's kinetic and structural performance. The problem of sealing the joints can be solved by the geometry of the sheet itself or by ingenious mechanical unions. The structural and kinetic performance of the whole depends to a large extent on the solution of the mobile joints.

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