Volume 2

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CONCEPTUAL DESIGN OF SOME LONG SPAN SPORT STRUCTURES

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SUMMARY

In the present paper the conceptual design of two new grand stand coverings for football stadiums are illustrated together with a new shell-membrane roofing for a sport hall.

The choice of structural typologies, geometry, materials, and details are consistently described, showing the importance of the preliminary synthetical part of the design phases for the success of the global construction process [1].

1. THE STADIUM OF THE ALPES. THE ROOFING SYSTEM

1.1. Description of the Structural System

The tensile-structural system which has been adopted to cover the new stadium of Torino [2] is mainly formed by:

- a radially oriented set of cable trusses,
- an inner tension ring,
- two cable nets with hyperbolic surfaces,
- an external stayed anchorage system,
- a gravity foundation system.

1.2. Radial Cable Trusses

The cable trusses are formed by two load bearing upper cables, two lower stabilizing cables interconnected, in vertical planes, with hanger cables spaced every 5 m. They are placed in radial direction as to centers C1 and C2 of the polycentric homothetic curves which generate the general geometric scheme of the stadium.

The trusses corresponding to alignments 1 to 6 and symmetrical as to x and y coordinates are generated with a constant angle of 2°.54 at the center. Trusses 7-14 have a generating relative angle of 7°.22.

Depending on the stress-deformation state, the cable structures have been dimensioned differently and collected into two groups. The main geometrical and mechanical characteristics of the system are shown in Fig. 1.

All the cables are spiral zinc coated steel structural strands (class B) and have a locked and/or open section; they have an elementary resistance of the external "Z"-shaped wires greater than 1570 N/mm² and of the internal circular ones greater than 1770 N/mm².

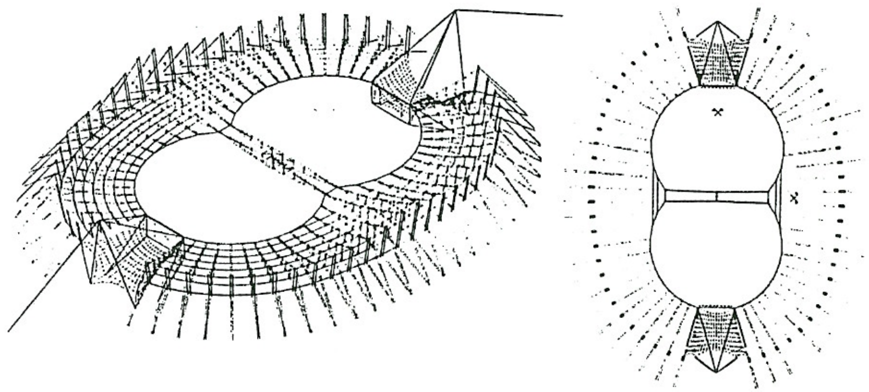

Fig. 1. Perspective view of the structural system.

A secondary transversal structural system is suspended at the stabilizing cable level. The typology adopted for this system is that of a simple supported (hanging) spatial truss with triangular section made of tubular steel elements. The covering system (DECK) which is placed on the extrados of the secondary beams and connected to it, is formed by aluminium corrugated plates, with height of 200 mm and thickness of 12/10 mm, by an insulation layer and by extrados impermeabilization mantle consisting in two aluminum thin plates which are mechanically connected to the intrados plates with anchor bolts.

1.3. Internal Tension Ring

The internal ring whose main function is to balance the horizontal forces, transmitted by the radial oriented cable system, in a local closed system, is geometrically configured on design by four circular arches with radius 56.468 m.

In order to increase the curvature and consequently to reduce the tension forces, it has been necessary to introduce a transversal tie bar characterizing the bilobate polycentric configuration of the inner ring.

The ring is formed by 6 zinc coated, locked section spiral shaped cables with diameter of 84 mm; they are arranged on horizontal planes at a height of +41.00 m, and are vertically spaced in order to allow a functional connection to radial trusses. The cables of the internal tie bar have a 2x6 diam. 66 mm having the same shape of the previous cables.

1.4. Cable Nets

Two cable nets with quadrangular mesh and with negative total curvature surfaces (saddle-shaped) are arranged in the central areas of the North-South curves.

The cable net is anchored to the central ring at +41.21 m height, to the carrying structure of the third level of the grandstands at +31.5148 and at +21.00 m respectively and to the foundation at a level of +8.215 m.

The covering of these areas is linked to the general covering in a sector of the stadium where the third level of grandstands is missing.

The covering adopted for the cable nets is a membrane system made with fiber-glass + PTFE with the 60% of translucidity. The membrane is fixed to the net on lines and/or points through mechanical connections.

1.5. Anchorage Systems

The anchorage system of the cable trusses and cable net consists of external stayed frames with tubular columns and stay cables.

As to the rectilinear areas, the anchorage frames are placed on the structures of the third level grandstands at a height which is variable between +35.539 and 35.556 m. The tops of the columns are placed at heights included between +50.868 and +60.834 m. The anchorages of the stays are set at height +21.05 m.

The steel tubular columns have diameters included between 508 and 762 mm and thicknesses between 10 and 14.2 mm. The quality of the material is

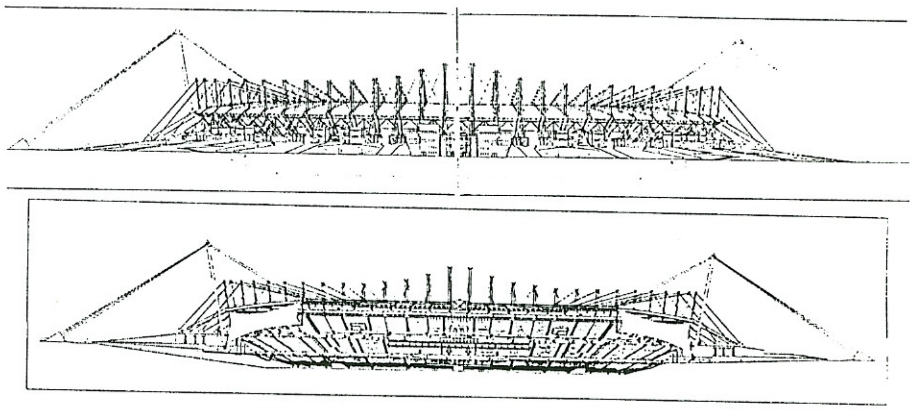

Fig. 2. Section and front view of the Stadium.

Fe 510 C. The upper and lower stays have been realized with the same cables which have been used for the carrying and stabilizing cables.

Also the anchorage system of the cable nets and of the ring in the curve is formed by a frame consisting of tubular columns having a diameter of 1600 mm and a thickness of 28 mm. They are positioned according to an inverse "V"-shape and have an inclination of 10° tooward the outside of the vertical axis. The top of the "V" is placed at the height of 73.5296 m and the base (with width of 35.8 m) is set at the height of 9.90 m. The stays realized with 4 cables having a diameter of 80 mm are anchored along the longitudinal axis of the construction at a distance of 237.5 m from the center of the green field and at the height of +15.00 m from the playground.

1.6. Gravity Foundation System

The foundation system, adopted in order to equilibrate the tension forces transmitted by the cable stay anchorages, are of gravity type. All the adjustable connections provided to introduce the pre-tension forces are placed in the top of the special shaped concrete anchorage blocks.

2. A SUSPENDED ROOF FOR THE OLYMPIC STADIUM IN ROME

2.1. Design Criteria

The cable roofing system, used to cover the new Olympic stadium in Rome [3], is formed mainly of (Fig. 2):
- a radial distribution of cable trusses;
- a polycentric inner tension cable ring;
- an outer anchorage system consisting of a space framed, reticular, polycentric ring.

2. THE RADIAL CABLE-TRUSSES AND INNER TENSION RING

The need to find a structural system that was easy to create, quick to build and assemble, and of the lightest possible form, led to the formation of the cable-truss roofing solution for the Olympic Stadium.

External limitations made it impossible to joint the roof to existing structures and thus was necessary to create a "closed" structural system. The need for a structure not vulnerable to a chain failure mechanism in the event of accidental breakage of tension members, led to the adoption of a ring-like cable-truss system, in a "bicycle wheel" arrangement, with modular tension members made of steel cable which could largely be replaced - even during operation - and would be easy to check, adjust and maintain.

The cable trusses, consisting of load bearing cables, stabilizing cables and a connecting system of vertical, almost parallel cables, are distributed in a radial direction from centres C1 and C2 of the homothetic polycentric curves from which all the geometry of the stadium is generated (Fig. 3).

In Fig. 3 we can see that the cable trusses corresponding to alignements 1-5, symmetrical about x and y, are generated with a constant central angle of approximately 2°.31′. The structures aligned with cables 6-15 have generating angles which vary from 2°.26′ to 6°.87′, while from 15 to 20 the angle is constant at approximately 7°.6′.

All of the cables are of a full-lock and/or open spiral type and are galvanized (class B). The main wires have an elementary strength of 1600 N/mm².

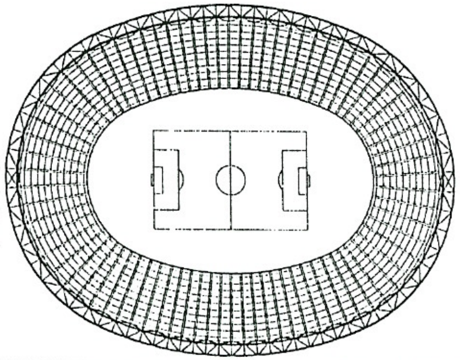

Fig. 3.

Plan view of the structural axes layout with indication of the parameters from which the geometry of the whole structural system is generated.

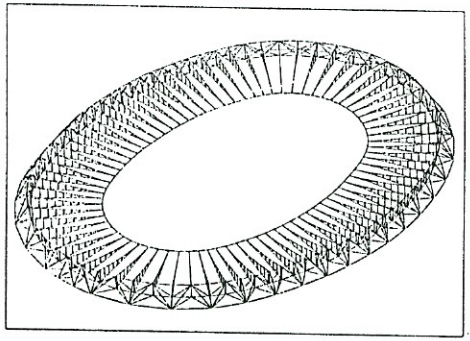

Fig. 4.

Axonometric view of the geometric-mathematical model used for static and dynamic analysis of the roof's structural system.

The radial cable truss is combined with a secondary frame which supports the roof covering: girdes supported by a simple bearing system are suspended at the same level as the stabilizing cables, forming a reticular truss.

2.3. Polycentric Inner Ring.

The inner ring, whose main function is to balance horizontals stresses transmitted by the radial trusses within a closed local system, is geometrically shown on the plan as two arcs with radii of 165.89 and 52.69 m, respectively.

The ring consists of 12 spiral, galvanized, full-lock coil cables, Ø 87 mm, arranged on horizontal plane at a height of + 29 m, and positioned so that, if viewed in cross-section, their barycentre points form a circle with an approximately 1 m diameter. The aim of the structure is to allow for practical connection with the radial cable trusses.

2.4. Outer Anchorage Ring.

The load-bearing and stabilizing cables are anchored around the outside to a space framed reticular ring, appearing as a polycentric circle on the plan with maximum external dimensions of 307.94 m for the larger diameter, and 237.28 m for the smaller one.

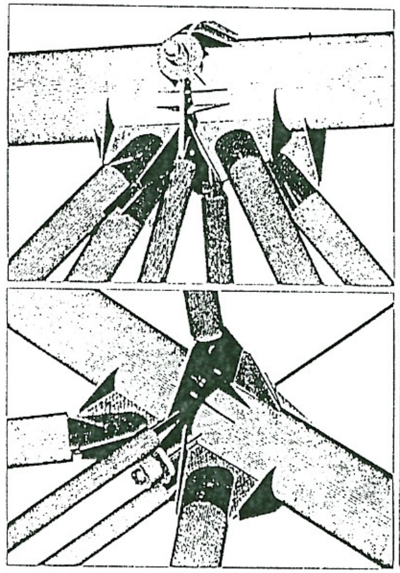

Fig. 5
CAD of ring joints

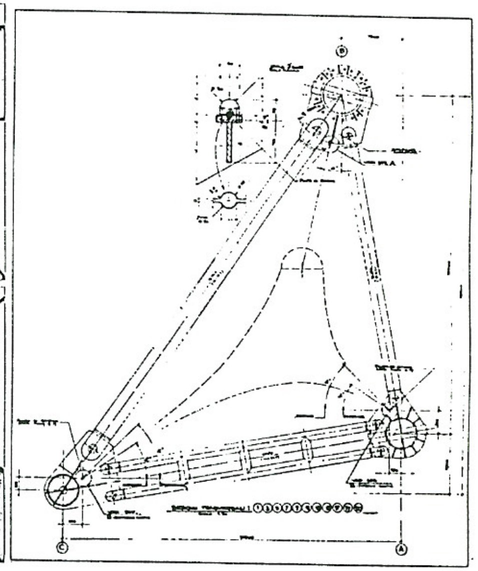

Fig. 6. Cross-section of the external reticular ring and internal positioning of the cone-shaped PTFE membrane element.

The ring has a triangular section, comprising an upper chord made of tubular steel Fe 510 C with a 1400 mm diameter and thickness of 70-60 mm, positioned at a height of +34.49 m, and of two lower joists at +23.99 m and 25.89 m, made of tubular steel with a 1000 mm diameter and thickness of 16-18 mm. The overall dimensions of the triangle, measured along the axes, are 10.50 m along the base and 12.50 m, in height.

The faces of the ring are reticulated by shafts (uprights and diagonal braces). The braces and uprights are made of tubes with a 609.6-409.8 mm diameter and thickness of 10 and 8 mm, respectively.

The generating radii on the plan are:

$$R_1 = 212 \text{ m}, \quad R_2 = 222.60 \text{ m},$$
$$R_3 = 98.90 \text{ m}, \quad R_4 = 109.40 \text{ m}.$$

Table 1. List of dimensions of the cable system

Position	Ø mm	A (cm²)	Cable L (m)	No. pieces	p (wt) (KN/m)	$P_{tot\ wt}$ (KN)	Cable terminal
L-bearing							
1÷10	64	27.50	55.20	38	0.23	48.2	F+R
11÷20	87	52.11	55.20	40	0.43	96.0	F+R
L-Stab.							
1÷10	47	14.77	52.80	38	0.12	24.7	F+R
11÷20	74	37.91	52.80	40	0.31	67.1	F+R
Ring	N*12-87	625	116.50	4	522	243.2	F+R
Hangers	2019	3.94	mean 4.00	1248	4	19.9	F+R

F = Fixed; R = Adjustable; P_{tot} = 5000 KN

2.5. The Membrane Covering

As prime importance was given to the need to create a covering structure which would have a minimal effect on the environment, also from the spectator's viewpoint, and would therefore preferably be horizontal with a radial distribution - guiding the spectator's attention towards the centre of the playing area - the designers were obliged to propose a covering made of a light, synthetic membrane which would not deteriorate through time and whose deformations would be compatible with those of the cable-truss system.

Technical requirements were equally important, demanding a covering which would be quick and easy to assemble and which would last through time.

Rather than creating a single membrane, it was decided to divide the covering up into independent radial panels in order to limit breakages due to isolated occurrences to the single panel affected and allow for easy replacement while avoiding detrimental effects on the adjacent panels.

The choice of Teflon for the membrane covering, and prefabrication of the radial wedges in the workshop, meant that the roof was light, easy to assemble, translucent and of exceptional durability through time. Teflon's intrinsic characteristics actually make it completely weatherproof with a low friction coefficient. It is also self-cleaning, and has a minimum estimated life of 30 years without maintenance.

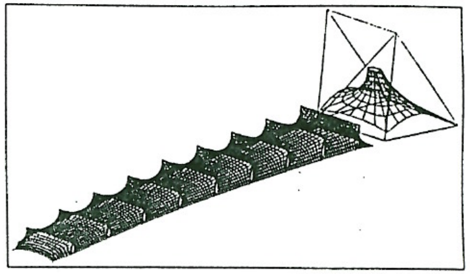

Fig. 7.
Computer simulation and form finding a typical membrane panel.

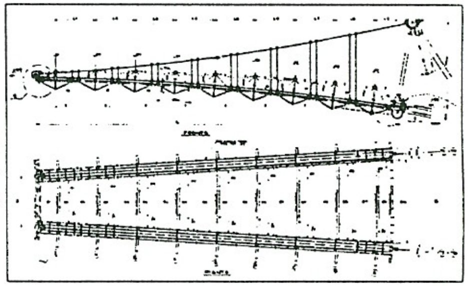

Fig. 8.
Plan and section view of a typical radial cable truss and of the radial and parallel framework of the secondary tubular structures supporting the membrane covering.

3. ARTS AND SPORT HALL IN RAVENNA

The roof structure can be defined as a double layer space frame with an average geometrical surface of global elliptical curvature.

The inner and outer layers are omothetic circular cylindrical surfaces of 54.602 m and 56.102 m, respectively. Those surfaces are disposed in a square plan of 54.06 m side, 25.09 m high with a ribbed connection along the diagonals.

A standard mesh of 3.90x3.90 m in correspondence of the outer surface define the base of the tetrahedral unit of the space frame lay-out.

In the top of the vault a 7.80 m square grid, electrically movable permits the natural ventilation of the vault.

The shell is supported, at 7.40 m from the play ground, by a reinforced concrete framed structure which takes the vertical components and the global drag forces due to wind an seismic action. The horizontal components due to arch behaviour is eliminated by a hybrid cable system

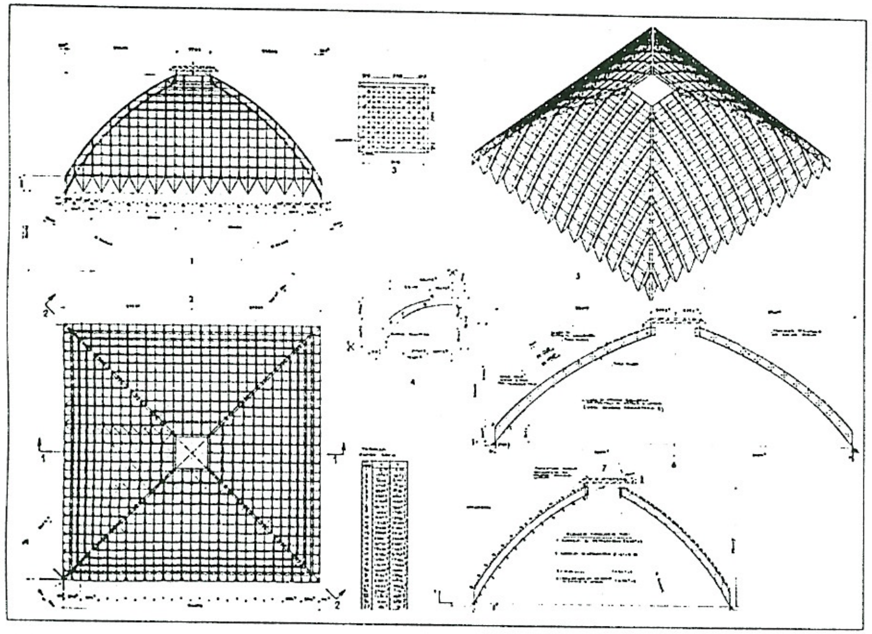

Fig. 9. Double layer space frame cylindrical units interconnected by diagonal elliptical arches.

placed horizontally at the level of supports. The cable is pre-stressed for dead load components.

The structural elements are tube profiles between Ø 76.1/3.2 to Ø 127/4 diameter and thickness of Fe 510 C steel. The elliptical diagonal arches have rectangular section formed by welded steel plates of 10 to 15 mm thickness.

The space frame, in order to facilitate the erection procedure has been produced by initial independent triangular section meridian arches, then connected by steel tube bars in the inner surface in order to complete the frame-work. According to this fabrication system, was possible to optimize the assembling in the work-shop and the procedure of erection.

On the outer surface, corresponding to meridian lines, were placed neoprene pads for the linear contact of the covering pre-stressed membrane system realized with teflon coated fiber glass.

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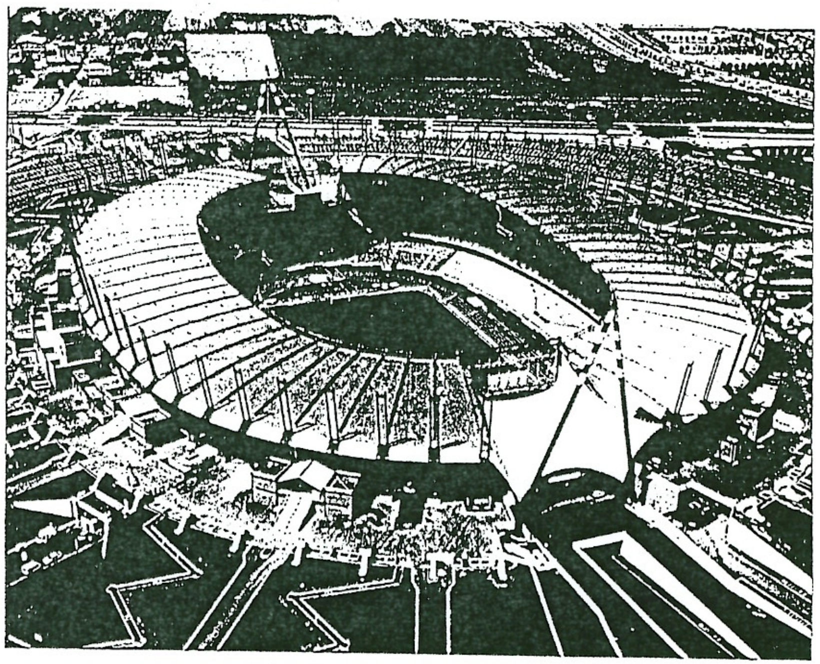

Fig. 10. Aerial view of the Stadium of the Alpes.

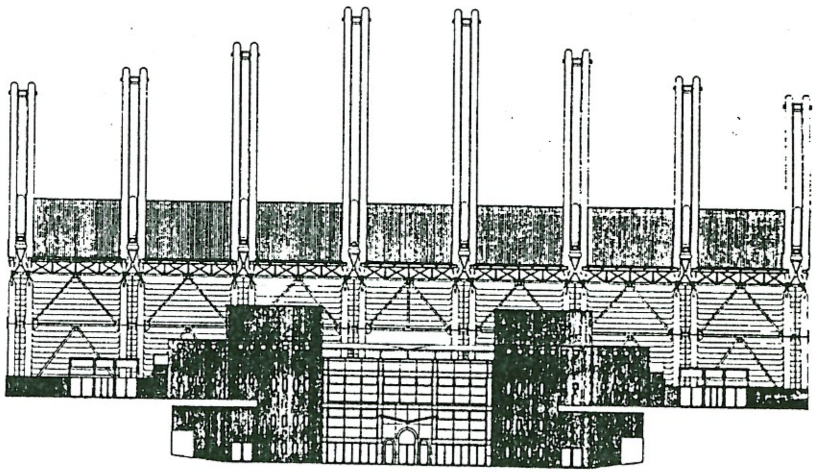

Fig. 10b. Partial front view of the main entrance

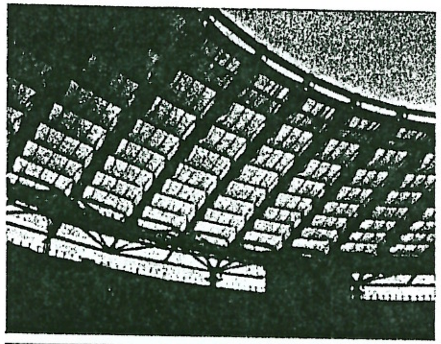

Fig. 11. Internal view of the Olympic Stadium.

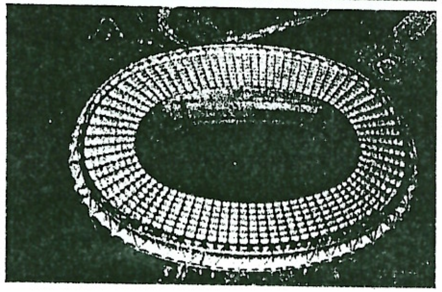

Fig. 12. Aerial view of the covering system of the Olympic Stadium in in Rome.

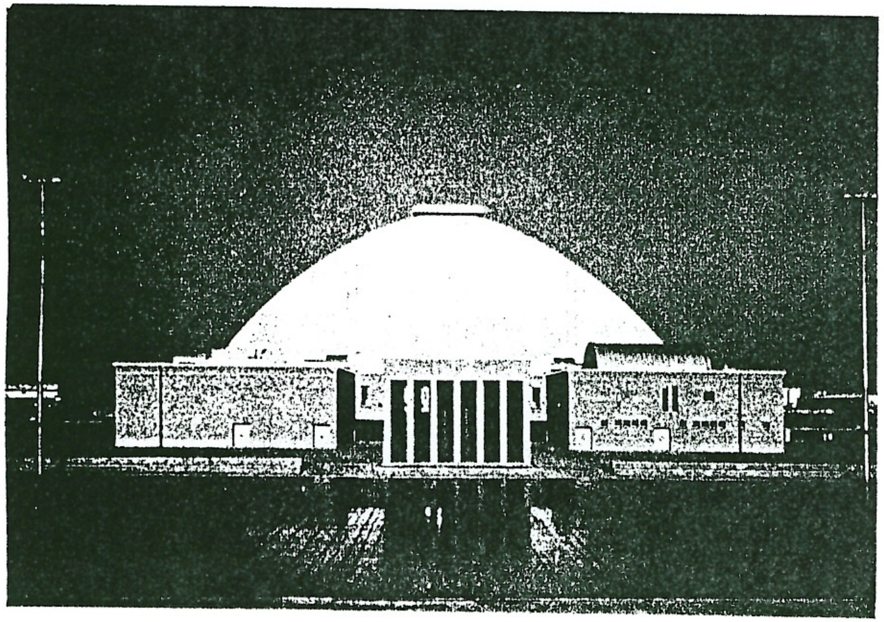

Fig. 13. View of the Sport Hall in Ravenna with PTFE covering

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