INNOVATIVE STRUCTURAL SYSTEM FOR LARGE COLUMN FREE AREA OF AN INDOOR STADIUM

Abstract:

Rajkot Municipal Corporation built an indoor stadium, having a play court that complies standards for international sports events. The stadium is having a column free area of 40 m x 40 m, which gives an unobstructed view of the play court from anywhere in the stadium. This large area was to be covered by adopting such a structural system, which can achieve predefined objectives of appealing appearance, cost effectiveness, and ease of construction while using locally available materials, skills and equipments. An innovative structural system was conceived to attain these objectives. This article discusses evolution process of the system, along with key features of its analysis, design and construction.

The Stadium

Racecourse, located in the heart of Rajkot, has gradually emerged as a hub for various sports activities. It was already having a cricket stadium, a swimming pool, and fields for various other sports. Rajkot Municipal Corporation enhanced it, with the addition of a multipurpose indoor stadium. *Fig 1*

FIG 1 EXTERNAL VIEW OF THE STADIUM

The stadium is having total area of approximately 3250 m^2 with viewers capacity of 1500. It is having floors at two major levels. *Fig 2, Fig 3 and Fig 4*

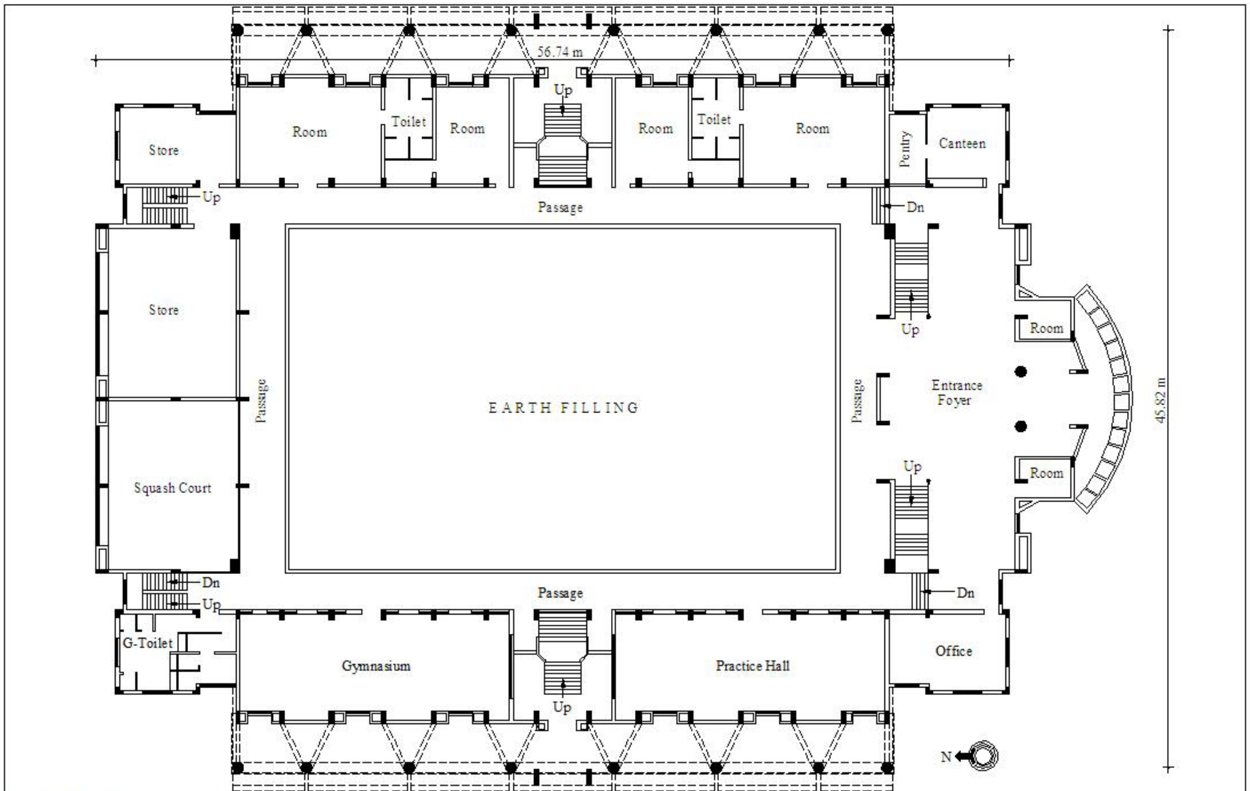

Fig 2 Lower level plan

The lower level entry is from a south side main entrance, which opens into a grand entrance foyer with adjoining office, canteen and pantry facilities. Central portion of the lower level is earth filling, below the upper level play court. A passage around the earth filled portion leads to various utility areas like, a practice hall, a gymnasium, a squash court, rooms for player's stay and a store. On the east and the west, there are two side entrances.

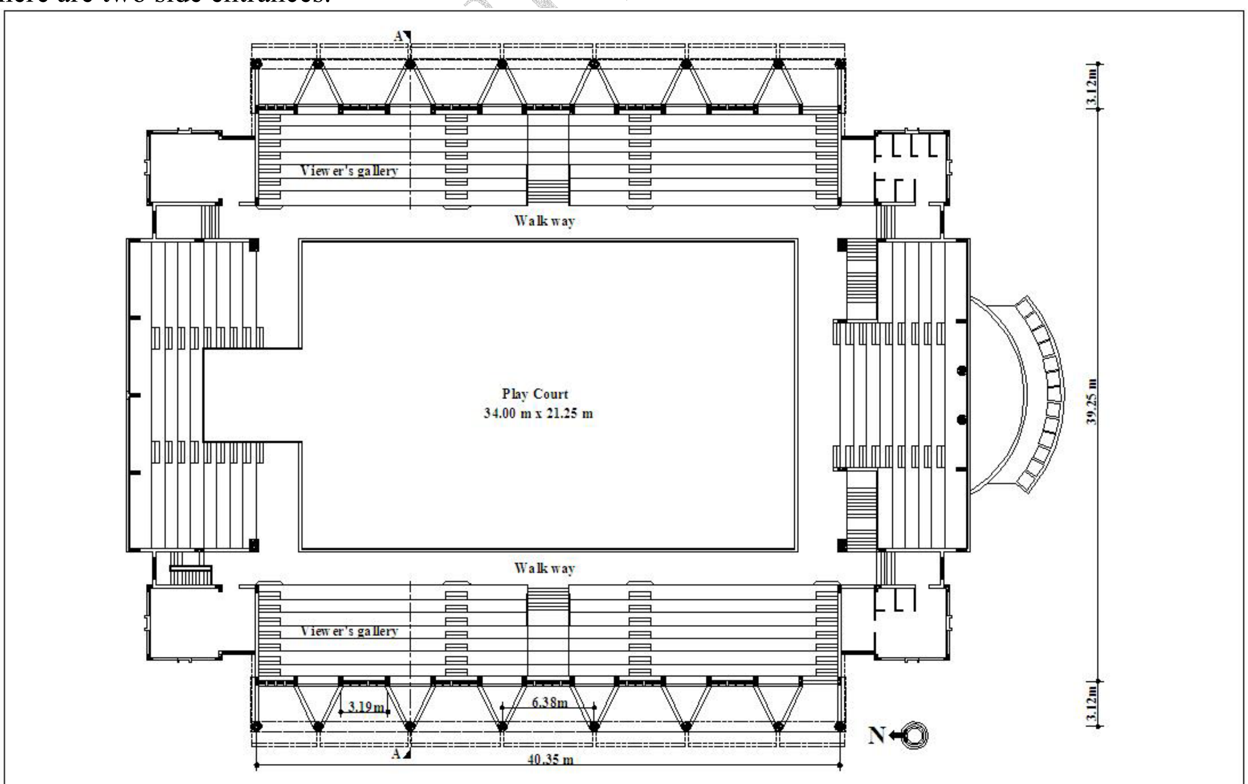

Fig 3 Upper Level Plan

Six stairs, two in the front, two near the side entrances, and two on the rear, lead to the upper level. The upper level is having a play court of the size 34 m x 21.25 m, with a peripheral walkway. Adjacent to the walkway are viewer's gallery on all the four sides of the court. The play court, along with the walkway and viewer's gallery on the east and the west, make the column free area of 40 m x 40 m. Four corner towers accommodate toilet units and machine rooms for future provision of air-cooling plants.

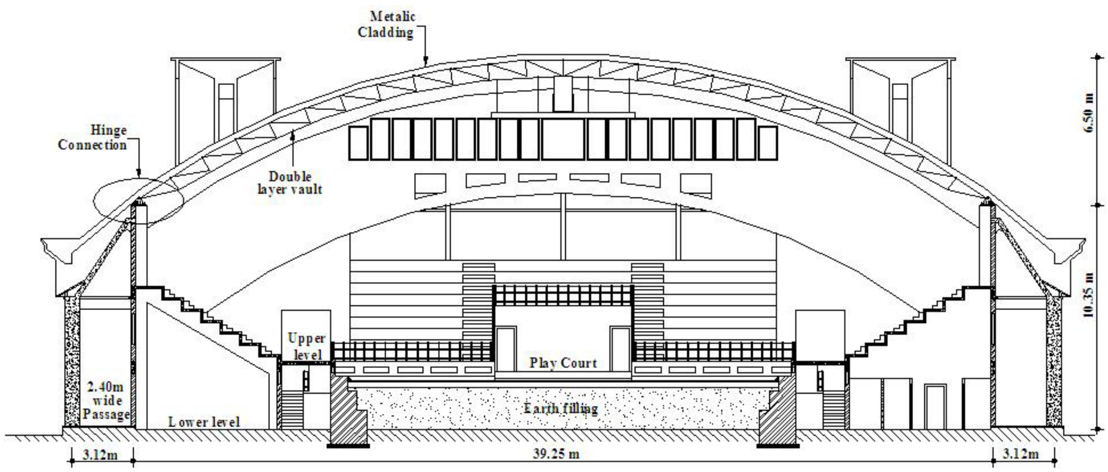

Fig 4 Section "A - A"

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Structural System

The structural system's geometrical form and material had to play a vital role in derivation of architectural character of the stadium. After finalization of basic architectural plans for the two floor levels, the structural system's geometry and materials were decided. The system was derived, first for the roof, and then for the roof supporting structure.

System for the roof

The geometrical forms considered for the roof were,

(1) Flat roof, *Fig 5(a)*

As per the international standards, minimum clear height required above the play court was 14.00 m. Bottom of the flat roof at that level was resulting in a structure that was too high with large volume of unused space above the viewer's gallery. The option was rejected, for the same reason.

(2) Vault (curved) roof, *Fig 5(b)*

The vault form was ideal in context of the height, as it was giving the required height above the play court and gradually reducing height at the springing points, where the same was not required. An immediate implication of the vault roof was to tackle the tremendous outward horizontal thrust at the springing points due to the vault's large span of 40 m.

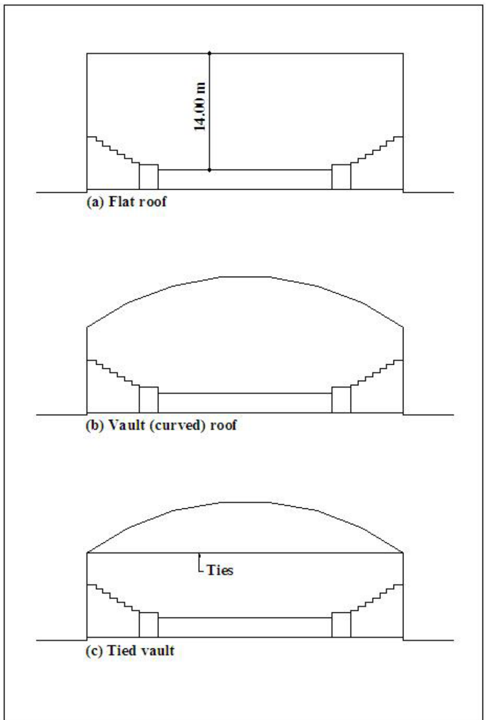

Fig 5 Geometrical Forms for the Roof

(3) Vault roof with ties at springing level, *Fig 5(c)*

A tied vault was also considered to take advantage of the geometrical form of a vault, while the ties at springing point level taking the outward thrust as direct tension. It would have resulted in a very economical structural solution, but again, the height constraint above the court did not permit the ties at springing point level, and option (2) was finalized for the roof with the inevitable outward thrust at the springing points.

Next, material for the roof was finalized. Reinforced concrete and structural steel were the options considered.

Calculation of life costing for the two options (including initial and maintenance cost), with specified design life of 60 years, was carried out. According to which, the steel roof was proving cheaper than the concrete roof. Secondly, in view of the fact that the construction was to be carried out in a time bound schedule while adopting locally available materials, skills and equipments, steel roof had advantages over the concrete roof in terms of construction time period and ease of construction. Considering all these, it was decided to adopt structural steel for the roof with coated metallic sheets as roof cladding.

For the roof vault in steel, braced barrel vault was adopted due to its aesthetics and economy in material consumption. For ease of fabrication and erection, the vault was idealized as a series of two hinged arches, laterally braced by horizontal and diagonal bracings, *Fig 6 and Fig 7*

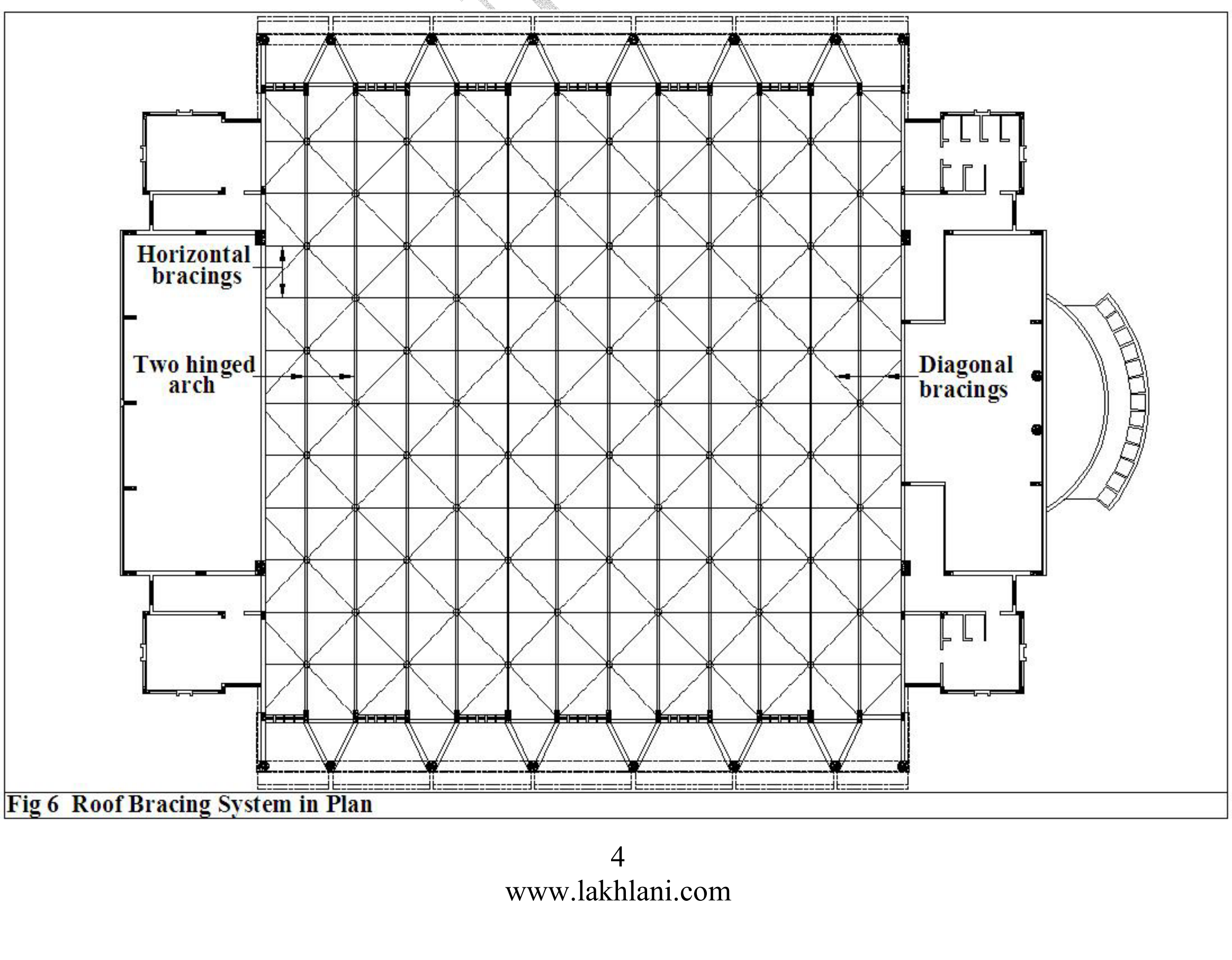

Fig 6 Roof Bracing System in Plan

A braced barrel vault can be constructed in a single layer or double layers[1]. Preliminary analysis for the single layer vault show that the deflections were excessive; hence a double layer vault was considered for final design, *Fig 4 and Fig 7*

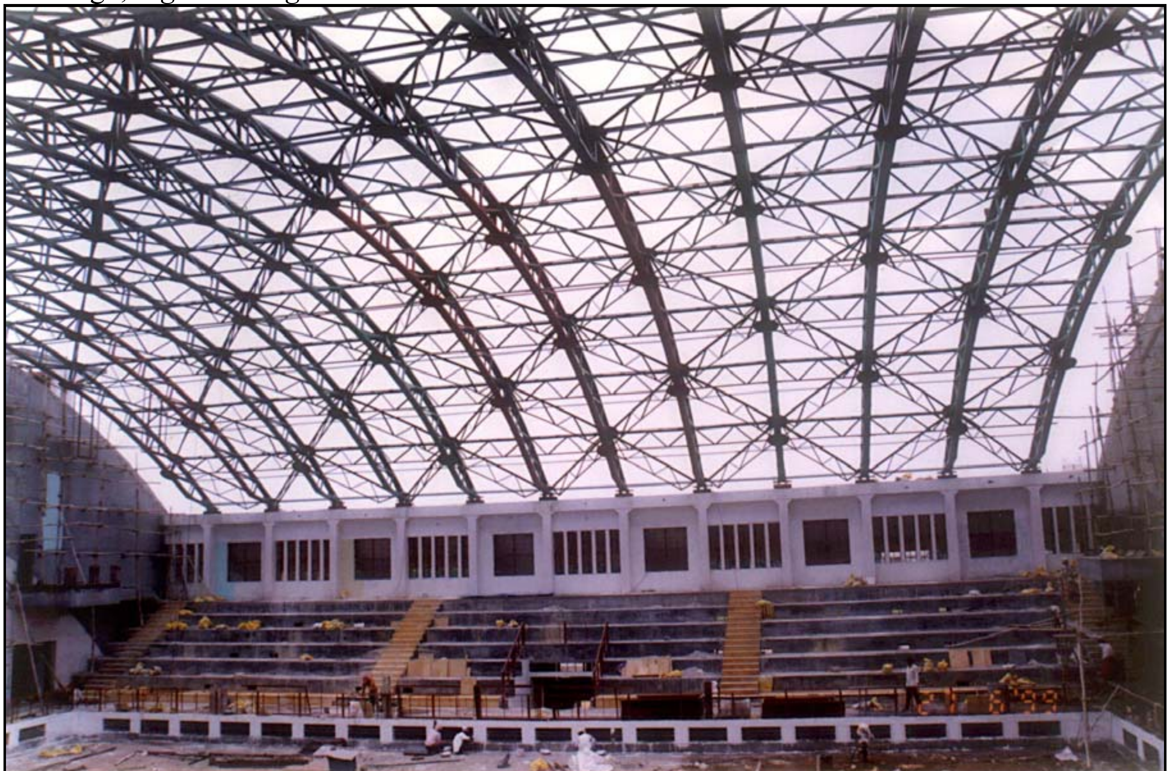

FIG 7 DOUBLE LAYERED BRACED BARREL VAULT

Table – 1 shows salient geometrical properties of the vault.

Table 1 : Geometrical properties of the vault

Geometrical property	Dimension
Span of the vault	39.25 m
Central rise	6.50 m
Radius	32.88 m
Semi central angle	36.65º
Thickness of the double layer vault	0.75 m
No. of segments along the circumference of the vault	24
Spacing of two hinged arches	3.19 m

System for the roof supporting structure

For this, the prime requirement was an efficient path to transmit the thrust from the roof to the ground. Three geometrical forms were considered.

(1) Direct force system, *Fig 8(a)*

In this system, thrust from the roof shall be directly transferred to the ground through the curved members, which shall be carrying axial force as the predominant design force. This would have been a very cost effective solution from material utilization point of view.

But it could not be viable, as it demanded large additional spaces on the east and west sides of the stadium. Surroundings of the proposed site did not permit provision of these large spaces on the sides.

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To reduce the requirement of spaces on the sides, an option of lowering the stadium into the ground, by making the lower floor under ground, was also considered. But the excavation cost (due to very hard, rocky strata), and the cost of making the whole lower level watertight, did not permit to adopt the option.

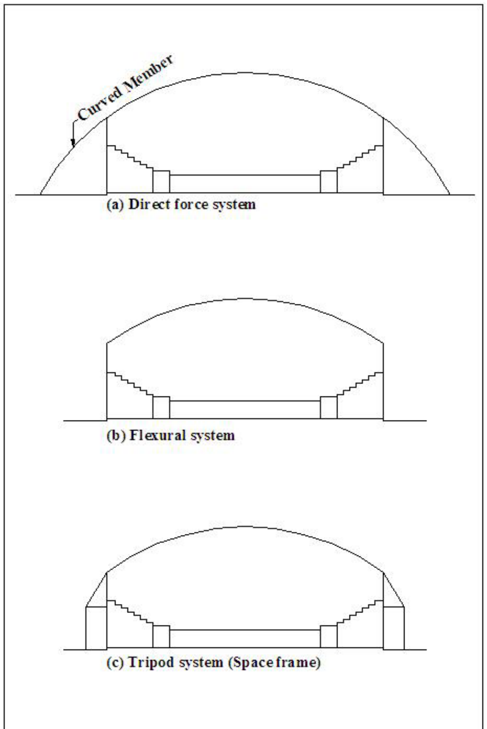

Fig 8 Geometrical Forms for Roof Supporting Structure

(2) Flexural system, *Fig 8(b)*

In this system, the column, which supports the roof arch, behaves as a vertical cantilever, carrying the thrust from the roof at its top. This system transfers the thrust, to the ground, by behaving as a flexural system.

In depth analysis was carried out for this system. The analysis results show that the magnitude of moment in various elements was very high. The element dimensions required for such large moments were neither practicable nor in proportion to other architectural elements. As the material utilization was not proving to be the optimum, this option was also ruled out.

(3) Tripod system, *Fig 8(c) , Fig 9 and Fig 10*

From the above two options, it was clear that a judicious combination of the two was required to get the system, which will eliminate disadvantages of both the options.

An innovative tripod system was conceived by introducing a column between the two roof supporting columns, at a clear distance of 2.4 m on the outward side, forming a triangle in plan. The system of an inclined triangle of elements at top, and horizontal triangles at two different levels, joining the three columns, transmit the thrust to the ground by acting as a tripod shaped space frame. Each frame supports two roof arches. Analysis of the system show that all the elements were having moderate magnitude of direct and bending forces. Thus, material strength utilization was proving to be the optimum for this system.

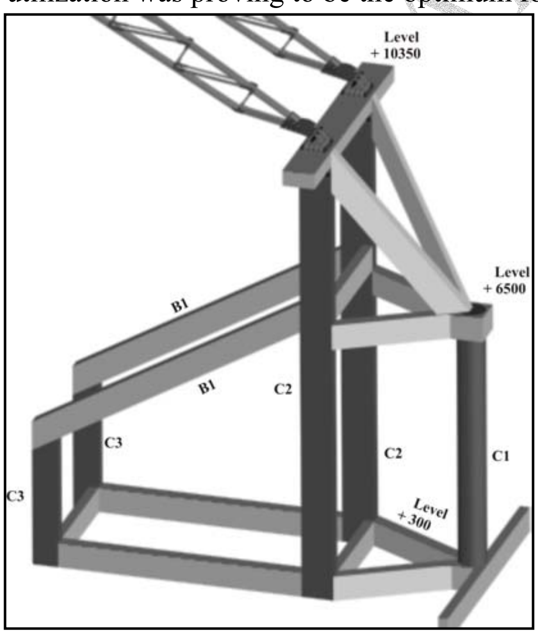

FIG 9 3D VIEW OF THE TRIPOD SHAPED SPACE FRAME

FIG 10 EXTERNAL VIEW OF THE TRIPOD SYSTEM

Reinforced concrete was decided to be used for the system. The complicated geometry of the system and the ease of constructing the same using concrete was the factor in favor of concrete.

Analysis

Due to very low ratio of mass to area for the roof, out of wind and earthquake forces, the wind forces governed the design. Design wind speed considered was 200 Kmph. In the analysis, wind effects were considered in addition to the gravitational forces. Different cases of wind loads, as per IS : 875, were considered in combination with the gravitational loads[3].

Thermal stresses in the steel roof structure were taken care of by allowing free expansion and contraction of the arched roof. This was achieved by providing a specifically conceived, designed and detailed, perfect hinge connection between the roof and the supporting structure. *Fig 11*

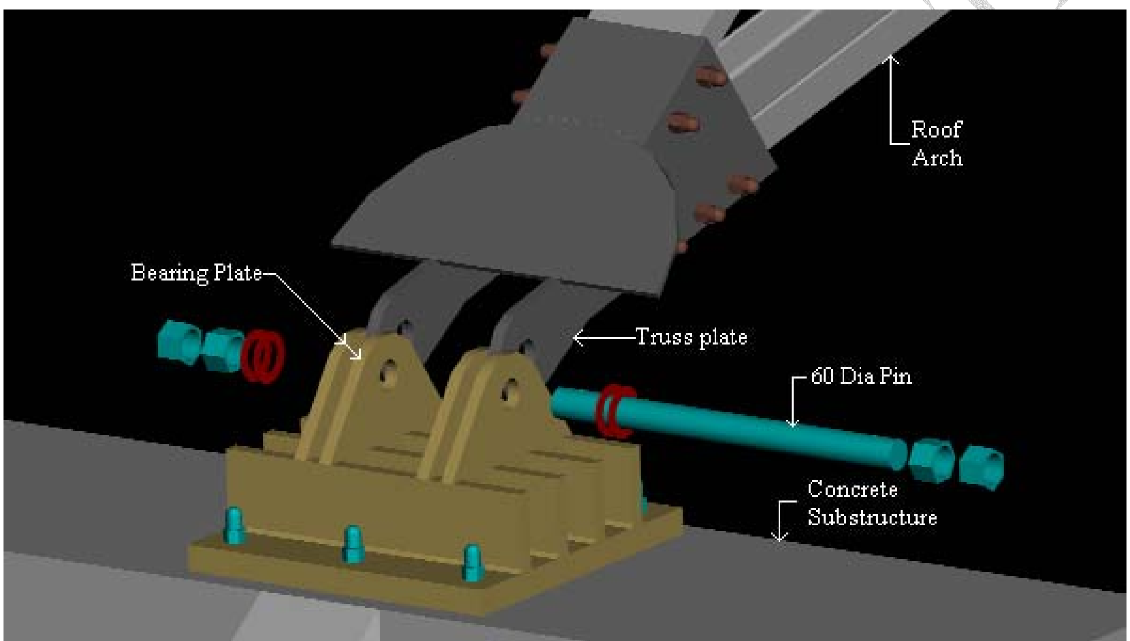

FIG 11 HINGED CONNECTION AT JUNCTION OF THE ROOF AND THE SUPPORTING STRUCTURE

For preliminary analysis, to finalize dimensions for the structural elements, the roof vault was analyzed independently, with hinge supports. The support reactions were applied as loads to the supporting system and a separate analysis was carried out for the same.

Final analysis was carried out for the complete space structure. This consisted of the roof vault in steel and the roof supporting system in concrete, with an internal hinge connection at the junction of the two.

The system was analyzed as a rigid jointed space structure. The arches were idealized as composed of 24 equal segments along the circumference. Analysis was carried out by an in house developed computer program STASS and the results were proof checked using STAAD[2].

The analysis results are shown in Table – 2.

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Table 2 : Analysis results and member dimensions

(a) Maximum Displacement

Displacement point	Value
Maximum vertical deflection at vault crown	65 mm
Maximum horizontal deflection at hinged connection	23 mm

(b) Roof design forces and member sections

Member	Max. Axial force, kN		Bending Moment, kN-m	Shear Force, kN	Section
	Compression	Tension			
Arch top and bottom chord	289.50	41.39	2.66	6.08	ISMC 250
Arch Radial and diagonal members	62.00	32.81	-	-	ISA 50x50x6
Horizontal and diagonal bracings	16.15	21.58	-	-	ISA 50x50x6
Pin for hinged connection	-	-	3.10	165.40	60 Dia.

(c) Roof supporting structure design forces and member dimensions (*Fig 9*)

Member	Axial compressive force, kN	Moment, kN-m		Shear, kN	Dimensions, mm x mm
		Muy	Muz		
Circular column, C1	1351.00	20.64	530.00	166.40	675 Dia.
Roof supporting column, C2	-246.64	8.63	258.34	94.92	300 x 750
Internal column, C3	44.58	23.17	337.32	152.90	300 x 600
Beams for sitting gallery, B1	-291.67	12.48	379.08	197.91	300 x 600
Sloping beams connecting C1 & C2	490.94	75.39	121.08	40.55	260 x 600
Beams connecting C1 & C2 at level +6500	-157.19	3.24	172.39	80.63	260 x 600
Beams connecting C2 & C3 at level +300	133.81	2.22	246.90	70.33	300 x 600
Beams connecting C1 & C2 at level +300	7.11	-	286.62	146.13	260 x 600

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Design

Design of steel sections for the roof was carried out as per IS : 800 for service loads[5]. Standard MS rolled channel and angle sections were used. As shown in Table-2, shear force governs the design of the pin for hinge connection. The pin was designed to bear this shear force and effectively transmit it to the bearing plates.

The concrete sections were designed by Limit State method as per IS : 456 using SP : 16[4,6]. Dimensions for various structural elements are shown in Table – 2. Concrete grade M-20 and HYSD bars of grade Fe-415 were used.

Footing for the columns C2 and C3 (*Fig 9*) were designed to be anchored into the rock below, as analysis show upward reaction (upliftment) for these footings.

Construction

The total construction was carried out using locally available materials, labours and construction equipments. No specialized construction machinery, not even a crane, was employed.

The arches and bracings for roof were fabricated on ground and then erected in place. Erection of the steel vault needed special care and attention. The vault was to be erected after total completion of the concrete work for the viewer's gallery below. Any accident during the vault erection could have done heavy damage to the gallery.

Guyed single masts with chain pulley block were used for erection, *Fig 12*. The arches were erected in two equal parts. Each part was lifted and fixed at the hinged connection by insertion of the pin. The two halves then lowered to meet at the crown, bolted and welded at place at the height of 17.50 m.

FIG 12 GUYED SINGLE MAST SYSTEM FOR VAULT ERECTION

After completion of the vault fabrication, an independent agency was assigned the job of complete onsite inspection for the vault with a report for each and every joint, for quality of bolting and welding.

For the roof-supporting frame in concrete, to achieve its intricate geometry, a full-scale model in wood was fabricated on the ground and after its approval, the same was repeated for the formwork of that particular portion.

Conclusion

The braced barrel vault system gives a pleasant appearance to the stadium from inside. It also proved to be a cost effective one with the steel consumption of approximately 45 kg/m^2.

The unique tripod system made it possible to have the concrete elements with the dimensions perfectly matching the scale of the building. This also proved to be a cost effective system as its configuration resulted in a harmonious blend of elements, and due to this, the design forces in all the elements were such that their optimum material capacity was utilized. The passage, created on the outer sides due to the tripod system, gave a distinctive architectural character to the stadium, and did not become a left over space.

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Credits

Client: Rajkot Municipal Corporation
Architect : Vinod Makhesana
Proof checking for the system : Ashok Dani
Technical team (Rajkot Muni. Corp.): P K Tank, N H Vaghela, J V Herma, S N Chauhan, and P Sampat
Contractor: Dhanabhai Rambhai & Co.

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Mr. Jayant Lakhlani obtained his postgraduate degree in computer aided structural analysis and design from Gujarat University in 1991. He is having vast experience for design and commissioning of various types of structures and currently working as a consulting engineer at Rajkot. His fields of interest include development of unconventional structural systems and innovative use of structural materials.

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