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DESIGN OF UNCONVENTIONAL STEEL ROOF STRUCTURES

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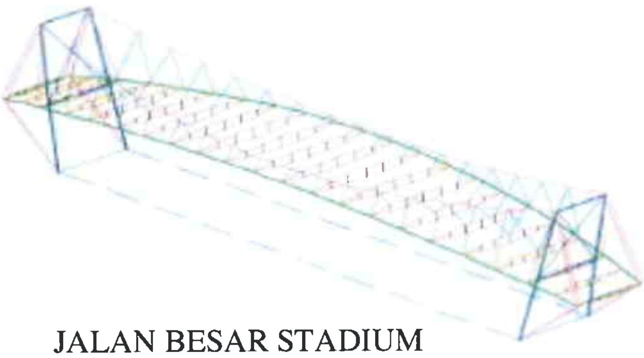
Albert Loh is a consulting engineer practicing in Singapore. He is a registered Professional Engineer in both civil and mechanical engineering in Singapore and California. His firm has designed many unusual roof structures, including the Bishan Stadium, Jalan Besar Stadium and Singapore Sports School.

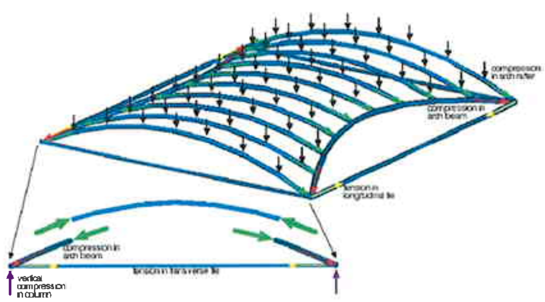
ABSTRACT

Conventional roof structures often cannot provide a good solution to particular site conditions. In particular, conventional steel trusses do little to enhance the aesthetics of a building. In many cases, the structural form also determines the shape of the roof. Therefore, it is sometimes necessary to go beyond the normal textbook structures and venture into the unconventional in order to deliver the best engineering solution

The Jalan Besar Stadium and Singapore Sports School are two recently completed steel roof structures that employ highly unconventional structural concepts. This paper presents the structural concepts and some of the lessons learned on these two projects.



JALAN BESAR STADIUM
MAIN GRANDSTAND ROOF



SINGAPORE SPORTS SCHOOL
SWIMMING POOL ROOF

JALAN BESAR STADIUM

An Unusual Structure

The main grandstand roof of the Jalan Besar Stadium is a unique steel structure, which is a combination of cable suspension, compression arch, and portal frame structure. A revolutionary new structural development is the use of prestressed cables tying the column bases together to eliminate reduce the horizontal loads on the foundations. The result is an elegant lightweight structure, which floats above the grandstand, and requires the minimum footprint to suit a narrow site.

Site Constraints

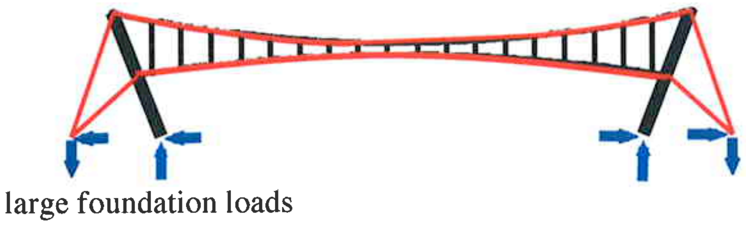
The site for the stadium is extremely restricted, and therefore, space for the structure supports was limited. To achieve a clear line of vision, the enclosed area had to be column free.

Architect's Concept

Given the site constraints, the architect envisaged a massive steel truss spanning the length of the grandstand between two staircase blocks on either end of the structure.

Engineer's Solution

In order to reduce the weight of the structure, the structural engineer proposed a cable suspended roof, which would be curved in both plan and elevation. A curved bottom cable was added to carry the roof as well as to give rigidity to the structure.

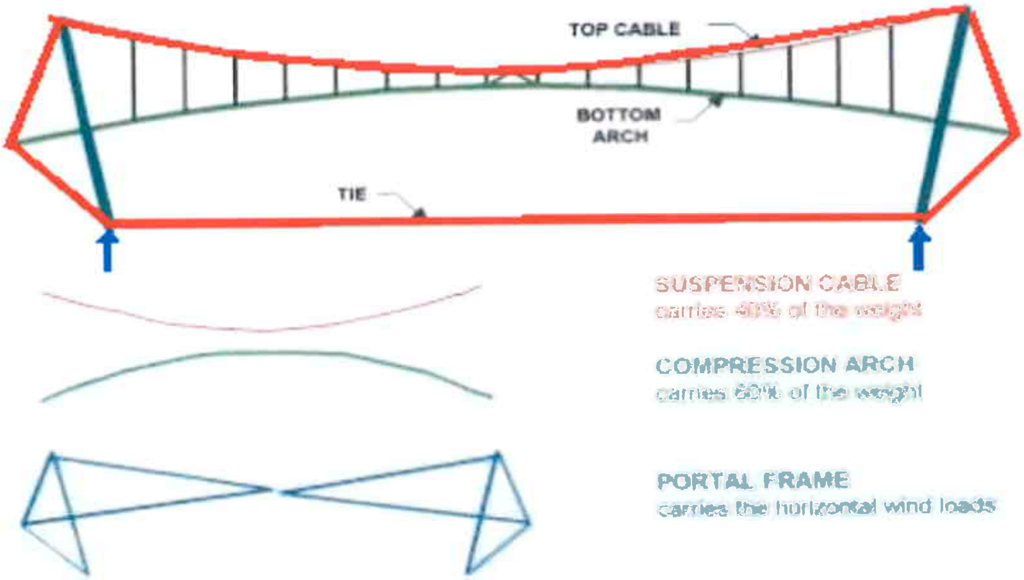


Cheaper Version

Due to budget restraints, the entire project had to be re-designed and the two staircase structures on either end of the grandstand were eliminated. They were replaced by steel columns with tie-backs to carry the tension of the roof cables.

However, the soil condition at the site is poor, with about 10 metres of marine clay and soft soil under the surface. This makes it unsuitable for the foundations to carry horizontal loads, which would have been imposed by the cable roof. The foundations for the tiebacks would have protruded outside the site boundary.

Therefore, a radical new solution had to be found. The horizontal loads due to the cable suspension of the roof had to be somehow carried within the structure instead of into the foundations. To do this, the tension forces from the main suspension cables are redirected into a tie at ground level to form a tension ring around the structure, instead of being carried by the foundations. Thus only the vertical loads are carried by the foundations, resulting in a huge savings in piling.



Radical Solution

The result is a unique new structure, which is a combination of suspension cable, compression arch and portal frame. The suspension cable carries 40% of the weight of the structure, the compression arch carries 60% of the weight and the entire structure is braced to act like a portal frame to carry horizontal loads.

Although the structure may look like a suspension bridge, it is actually completely different in its structural behaviour : -

1. For a suspension bridge, large foundations are required to resist the pull of the suspension cables, whereas in the Jalan Besar roof, all the pull of the suspension cables is balanced within the structure and only the self-weight and external forces such as live load and wind load are transmitted to the foundations. This results in a dramatic savings in foundation costs over a pure suspension structure, which relies on the foundations to carry the suspension cable tension.

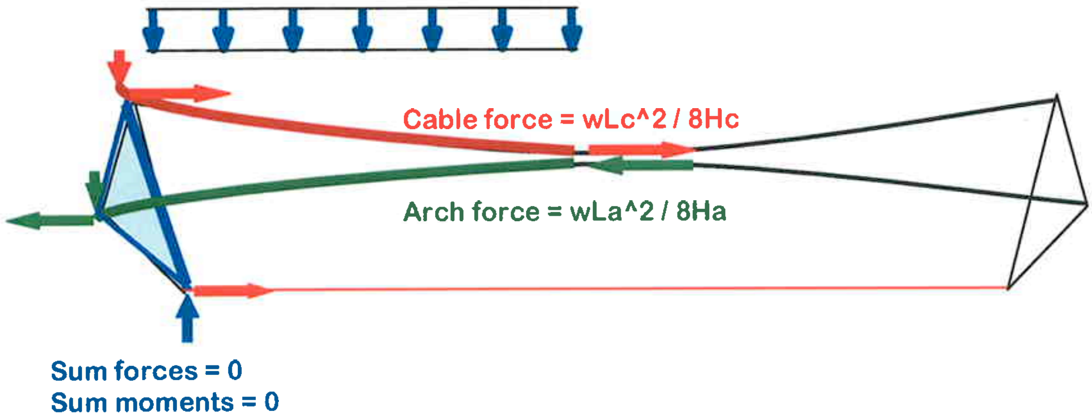
2. For a suspension bridge, only the cables carry the vertical load of the structure, whereas in the Jalan Besar roof structure, the arch and suspension cables share the vertical load, and therefore, the suspension cable and arch both have very shallow (flat) profiles. This contributes greatly to the graceful appearance of the structure.

3. Another major difference is that a suspension bridge behaves as a flexible structure which deforms under uneven loads, whereas the Jalan Besar roof structure behaves as a rigid unit with much less deflection under different loading conditions

ENGINEERING THE STRUCTURE

As the structure is entirely unique, no textbook solutions were available, and analysis of the structure had to start from first principles.

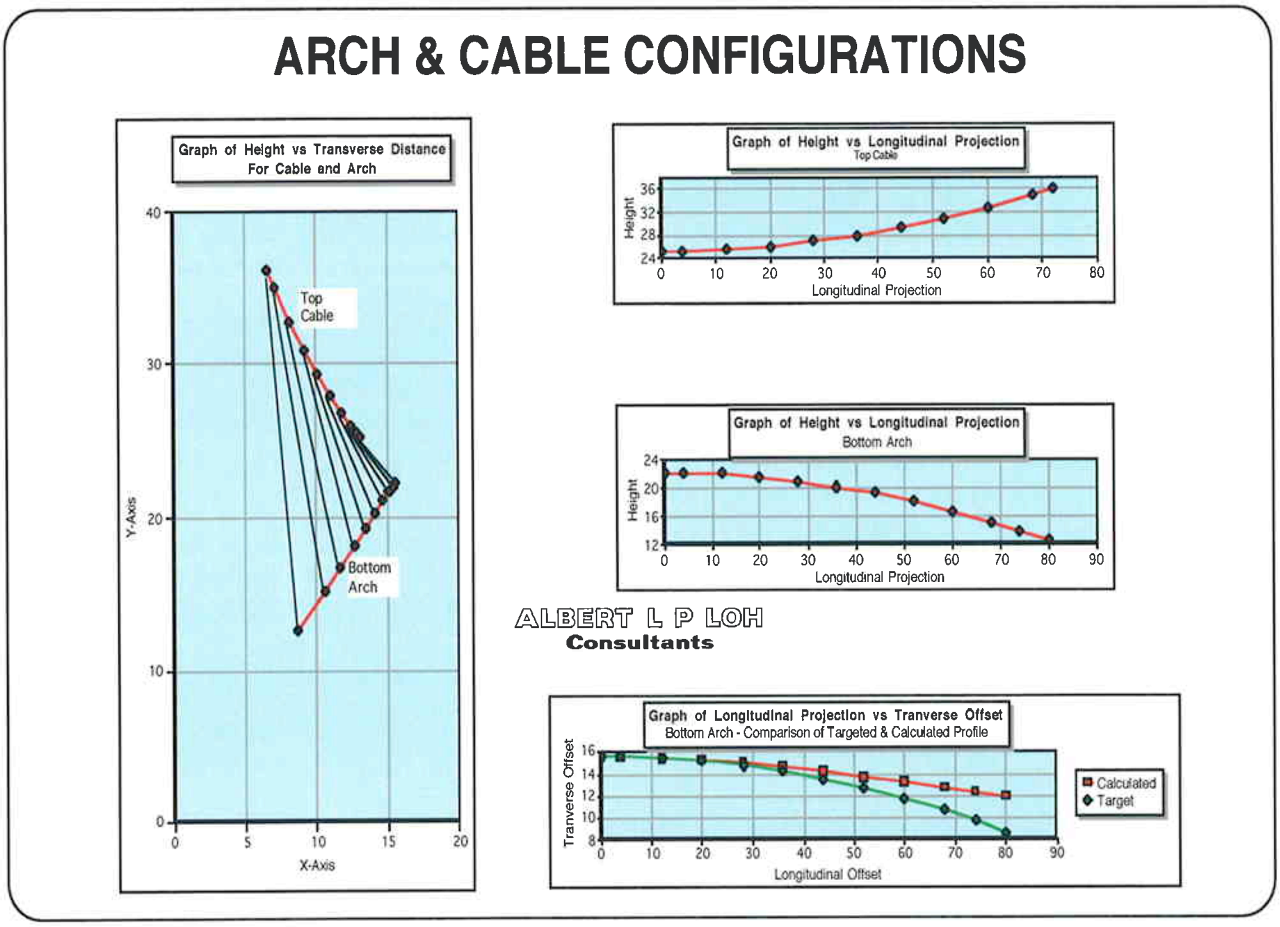
The modeling began with a physical scale model to be able to touch and feel the behaviour of this unique structure. Very thin piano wire was used for the first model, so that any buckling effects would be exaggerated. The physical model also helped to show any possible instability in all 6 degrees of freedom, and was of great help in shaping the structure and locating the secondary bracing members.



SIMPLIFIED PARAMETRIC MODEL

After this, a simplified mathematical model was created to investigate the main structural parameters and determine the effects of different arch and cable curvatures. The final configuration chosen has extremely shallow curves for both main suspension cable and arch girder, with 60% of the vertical load carried by the arch and 40% on the cable.

Different angles of tilt for the main pylons was investigated, and the final tilt of the pylons was set at 11 degrees. This angle is perpendicular to the ends of the main arches, and in addition to being structurally correct it also gives a dynamic appearance to the entire roof structure.

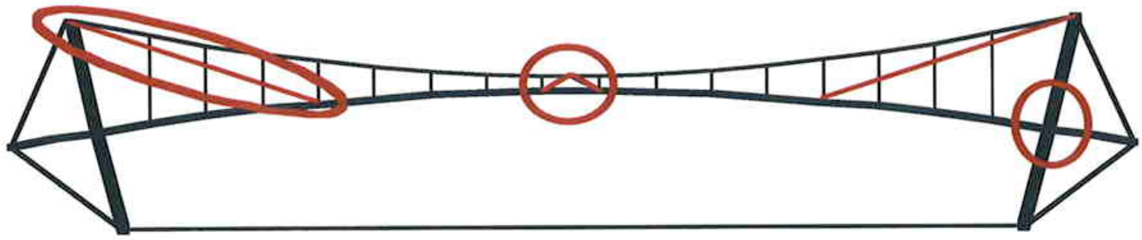


When the physical scale model of the structure was first built, it was immediately apparent that the cable and arch configuration was very different from a simple catenary or parabolic arch. A mathematical model of the cable and arch shape had to be developed in order to be able to define the coordinates of the structure.

This proved to be quite a challenging exercise, as the cable and arch are both curved in 3 dimensions and connected together by cable hangers. Therefore, the cable shape is also affected by the arch shape in addition to its natural catenary.

Development of the cable arch configuration model allowed correct outlines to be defined for both the cable and arch for minimum distortion of the structure.

OVERCOMING SPECIAL PROBLEMS



1) Special care had to be taken in developing the unusual structure to ensure its strength and stability. In particular, the members were located so that all cables remain in tension and no large scale buckling or lateral instability can occur.

2) To maintain structural efficiency, the structural members should carry pure tension or compression and secondary bending moments should be eliminated. Initially, huge secondary bending moments were found at the junction between the main column and compression arch. To eliminate these bending moments, special hinged members were designed at the junction between pylon and main arch. Location of cross ties had to be optimised with many computer runs of different configurations.

3) To carry lateral loads in the longitudinal direction, A-braces were added at mid span between the main cable and arch. These made a tremendous contribution to structural stability.

4) Arches and suspension structures function best under uniform loading. When subjected to uneven loads, they are less efficient. Thus, diagonal ties were added from the pylon top to the main arch to take care of uneven loads. The entire structure is braced together as a rigid unit.

5) Lateral sway stability has caused particular problems in other structures. To solve this, the cables and arches were intentionally curved in the horizontal plane. Diagonal and cross ties were added to control horizontal sway.

6) Of particular interest is lateral control of the suspension cables. It became apparent from our physical model that the inclined main cables tended to move sideways under loading. Therefore, special braces were added to control lateral movement of the main cables.

7) At all times, the aesthetics of the structure remained a prime concern, and the location of the additional members was carefully selected so as not to adversely affect the purity of the structural lines.

SUMMARY

The Main Grandstand Roof of the Jalan Besar Stadium is a new type of structure which combines the properties of a suspension, arch and portal frame.

Combining an arch with a suspension structure allows the structural forces to be internally balanced, and both the arch and suspension cables to have very shallow profiles. Steel material is utilized effectively resulting in a light and efficient structure.

The shallow curve of the main arch gives a graceful, light form to the roof and stands out as the main architectural feature of the stadium complex.

This type of structure can be used in general for large spans of more than 100m and requires the minimum foundations as all the suspension and arch reactions are carried within the structure, rather than being transmitted into the foundations

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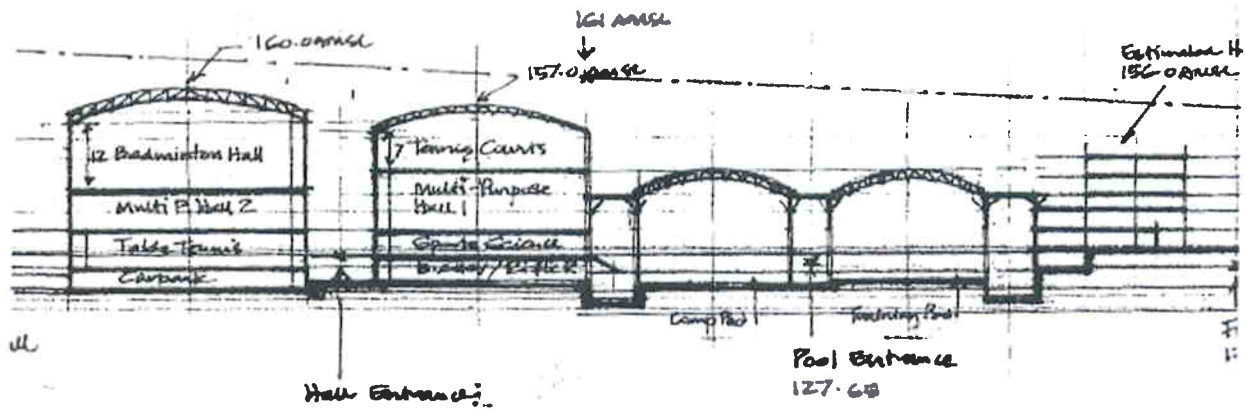
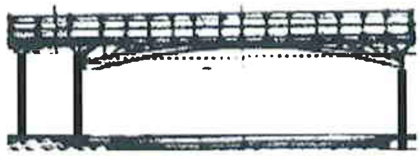
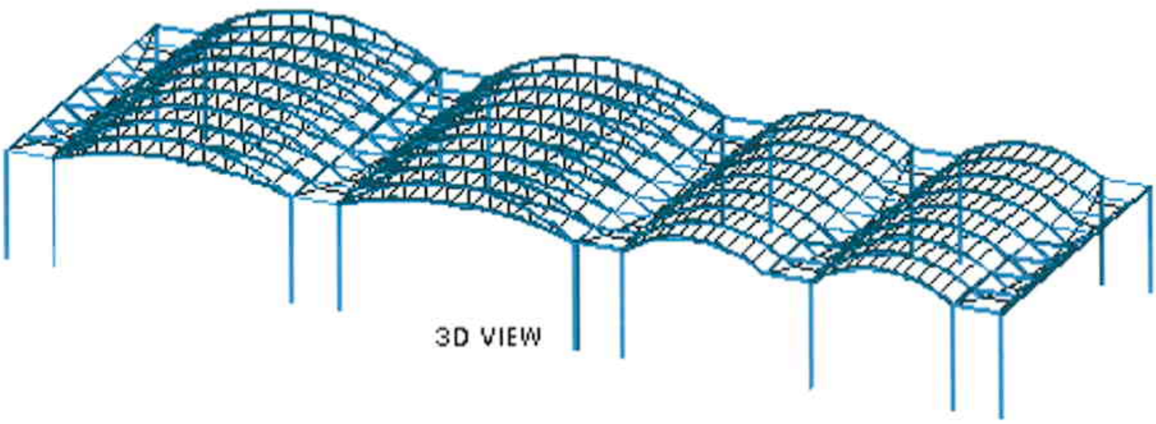
SINGAPORE SPORTS SCHOOL

The Singapore Sports School has a series of curved roofs covering the two 50m swimming pools and the badminton hall. These roofs have an unusual structure that is integrated into the curved shape of the roof and utilizes the curves of the roof to transfer the structural loads.



The original architect's scheme for the swimming pool roof called for curved rafter beams spanning 36m supported by a large steel truss spanning 54m between the columns



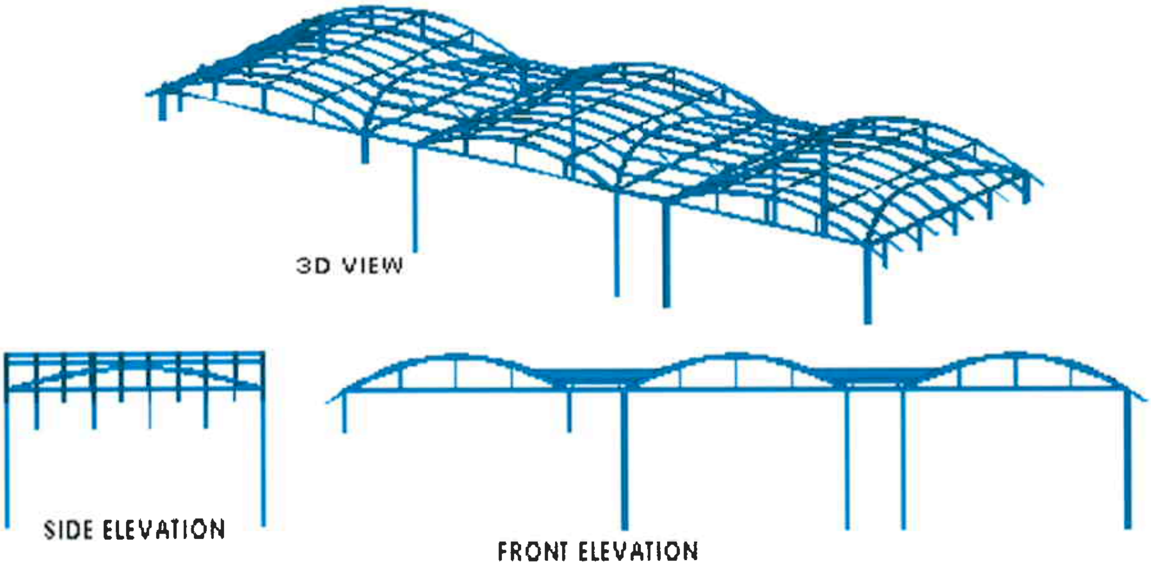


FRONT ELEVATION

SIDE ELEVATION

After further development, the engineer's solution called for tubular rafters supported on a light truss consisting of mainly tension members

Due to budget constraints, the roof was redesigned to eliminate the main trusses spanning the columns. This resulted in a unique structure that spans a grid of 36m x 40.5m without the need for any structural members outside of the curve of the roof itself.



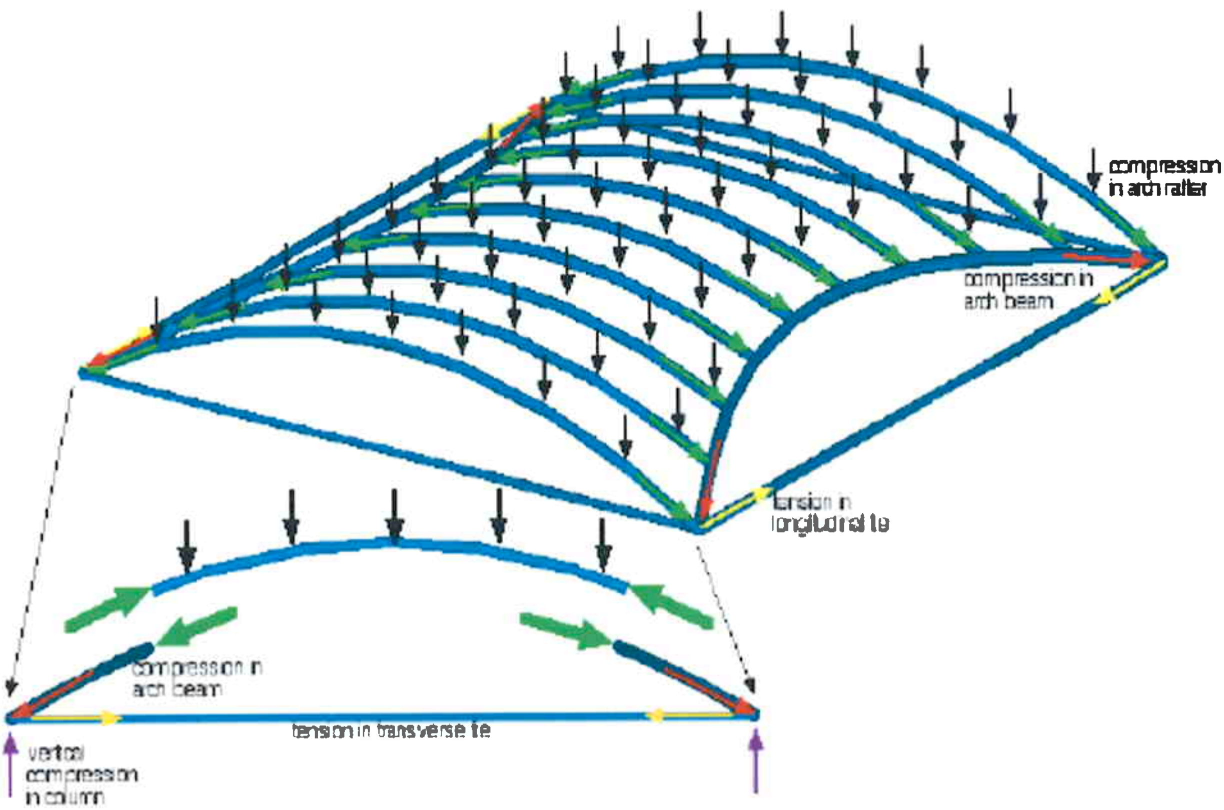
DESIGN CONCEPT

The structural system of the roof is unique and yet simple. The system comprises arches hidden within the curve of the roof.

Tubular arch rafters at 9.0m centers span 36 m across the width of the roof. A longitudinal arch "beam" spanning 40.5 m between columns supports these arch rafters. The arch beam is inclined and integrated within the plane of the roof slope in order to both hide the structure within the roof space as well as to support the arch rafters in the plane of the arch rafters. This enables the loads from the arch rafters to be transferred directly into the arch beam without any eccentricities.

The loads from the rafters impose compressive stresses into the arch beam that in turn results in tension forces at the supports. As the arch beam is inclined, there are also tension forces acting in the direction of inclination of the arch beam. These tension forces at the supports are resolved by placing ties at the support locations hence canceling each other out.

The result of this structural concept is a roof that does not require any trusses even though the columns are set at 36m x 40.5m apart. The structure is entirely contained within the curved surface of the roof.



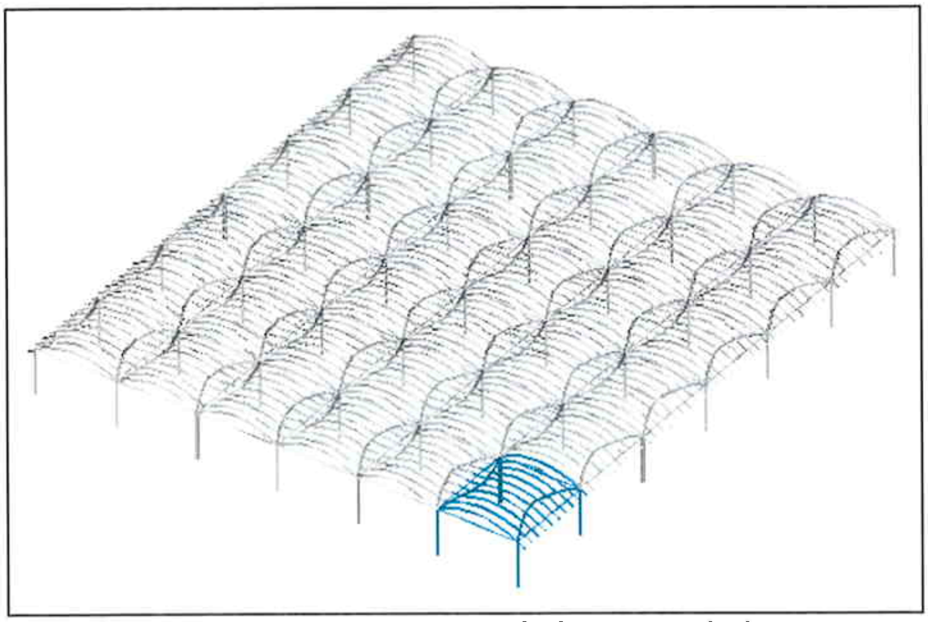
ADVANTAGES

The structural concept of the roof does not require any trusses even though the columns are set at 36m x 40.5m apart. The structure is entirely contained within the curved surface of the roof.

Keeping all the structural members within the plane of the curved roof results in a clean and elegant appearance and maximum headroom in the enclosed space, ideal for sporting activities.

INTERIOR OF SPORTS HALL

ROOF OVER SWIMMING POOL



This structural system can easily be expanded to cover mega spaces with column grids of 40-60 m.

SUMMARY

The Singapore Sports School Swimming Pool and Sports Hall Roof is a unique new development of the classical arch to span over a large space.

By imbedding a second series of arches within the curved surface of the roof, it effectively redirects the distributed roof loads into a few widely spaced columns.

The curved intermediate roof formed by connecting the second series of arches strengthens the structure, drains rain run-off water in the longitudinal direction and also gives the roof an exciting form (see picture below).

By minimizing the bending moments using the arch effect, the steel material is utilized effectively resulting in a light and efficient structure.

The structural system does not require any trusses even though the columns are set at 36m x 40.5m apart. The structure is entirely contained within the curved surface of the roof.

This structural system can be expanded to cover mega spaces with column grids of 40-60 m.

CONCLUSION

JALAN BESAR STADIUM MAIN GRANDSTAND ROOF

SINGAPORE SPORTS SCHOOL SWIMMING POOL ROOF

The above structures show how steel can be effectively utilized to form efficient, yet aesthetically pleasing structures for large span roofs.

Designing unconventional structures is an exciting and satisfying experience. However, much greater effort is required to take the step into the unknown.

The difficulty for the structural engineer in Singapore is not only to tackle the technical issues but also to solve the commercial aspect of keeping his design costs within check.