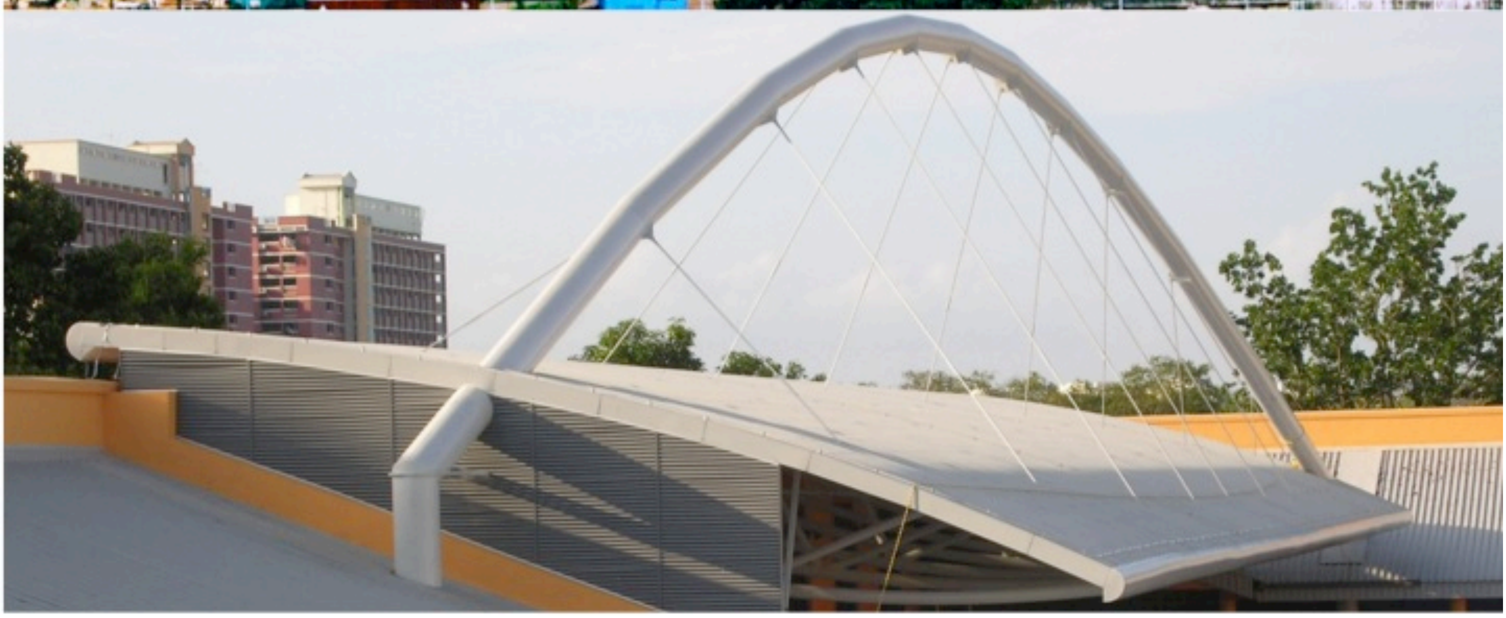
Albert Loh CONSULTANTS

USE OF STEEL TUBULARS IN THE DESIGN OF UNCONVENTIONAL ROOF STRUCTURES

UNCONVENTIONAL ROOF STRUCTURES



IES-IStructE SYMPOSIUM on
TUBULAR STEEL STRUCTURES

Use of Steel Tubulars in the Design of Unconventional Roof Structures

ABSTRACT

It is sometimes necessary to go beyond the normal textbook structures and venture into the unconventional in order to deliver the best engineering solution. Steel tubular sections are particularly well suited to this unconventional type of structure and can be effectively utilized to form efficient, yet aesthetically pleasing structures for large span roofs. This paper presents the structural concepts and some of the lessons learned on some unusual projects.

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INTRODUCTION

A beautiful roof structure can dramatically enhance the appearance, attractiveness and value of the building. 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

Steel tubular sections are particularly well suited to this unconventional type of structure and can be effectively utilized to form efficient, yet aesthetically pleasing structures for large span roofs.

This paper presents the structural concepts and some of the lessons learned on some unusual projects.

A DIFFERENT KIND OF ENGINEERING

Most structures are designed to fit into an architect's outline. This usually leads to a compromised structural form and ugly inefficient structures which have to be hidden from sight by ceiling/cladding.

A different approach is for the engineer to propose a correct structural form from the start and develop the concept with an emphasis on a pleasing aesthetic form as well as structural efficiency.

Using this approach for steel roof structures results in elegant and efficient structures as illustrated by the following projects.

Natural Forms

Conventional steel beams and trusses are designed to carry loads in the transverse direction. This makes them usually inefficient and aesthetically unpleasant.

Natural forms such as arches and catenaries direct the loads axially in a more efficient manner along the axis of the member and results in elegant curvilinear shapes. Arches and cables transmit large horizontal loads onto their supports, which can be eliminated by using a tied arch, lens truss or other combination to arrive at more economical support/foundations for the structure.

Correct Shape

Calculating the correct shape geometry is an essential part of designing natural forms. The correct shape is one in which there are no bending moments in the main members. We use the following iterative procedure for calculating the correct shape:

Starting from one end of the cable/arch, with a given angle and assumed axial force,

1. The force equilibrium is computed at each node.
2. The force equilibrium changes the angle of the cable/arch.
3. The next point of the arch is then projected from the new angle.
4. The entire process is repeated for the next node until the other end of the cable/arch.
5. Finally, the initial angle and assumed axial force are iteratively adjusted until the final coordinates in step 4 match the target coordinates.

Scale Model

Nowadays, it is customary for an engineer to feed numbers into a computer and expect it to design the structure. This is not sufficient for dealing with unconventional structures. Construction of a scale model allows everyone including the owner and the architect to actually see what is being designed, and for the engineer, there is nothing better than to actually touch and feel the model to get a better understanding of how the structure behaves.

The scale model should mimic the structural behaviour as closely as possible and will also yield valuable insights and help to verify:

- Appearance
- Geometry
- Stability
- Behaviour under load
- Construction sequence

Construction Sequence

Consideration of the construction sequence is even more crucial for unconventional structures. We generally incorporate this into the Tender stage to let every party be aware of the problems likely to be encountered

ADVANTAGES OF TUBULAR SECTIONS

Steel tubulars have several distinct advantages compared to normal rolled sections. They are strong in compression, which makes them particularly suitable for arch and truss members carrying direct compression forces. They are strong in torsion, which helps make more robust structures, and makes calculation a lot easier, as the engineer does not have to worry about lateral and torsional instability.

A good structure should look good from the inside as well as the outside. For structures which are exposed to view, tubulars have a much neater and tidier appearance. The clean surfaces and minimum surface area of tubulars also makes it easier and cheaper to paint and maintain the structure.

CONCLUSION

"Any time you depart from established practice, make ten times the effort, ten times the investigations" - William LeMessurier

Unconventional structures require unconventional engineering. Special effort must be paid to ensure that their shape is correct, their behaviour is understood and they can be safely constructed.

The projects shown here illustrate the extra care that must be taken to ensure that unexpected structural behaviour is understood and controlled. Conventional textbook methods of analysis may not be sufficient. Even computer finite element programs may give misleading results. It is recommended that at least one, preferably more scale structural models be built to better understand unusual modes of structural behaviour.

With slimmer and more graceful structures, it is important to consider non-linear second-order structural behaviour as well.

Designing unconventional structures is an exciting and satisfying experience. With every new structure, we find that there is more scope for creating more exciting new structures which perform their function better than the conventional.

Much greater effort is required to take the step into the unknown. The difficulty for the structural engineer is not only to tackle the technical issues but also to solve the commercial aspect of keeping his design costs within check.

BISHAN STADIUM

A sports stadium is a public gathering place. The appearance of the stadium must be something the community can be proud of. Therefore the solution provided by the architect and engineer must be better than just basic shelter for spectators. The design must stand out as unique, innovative and elegant.

The Bishan Sports Complex consists of a Sports hall 110m x 60m with a capacity of 4600 spectators and an Outdoor Stadium 104m x 25m with a seating capacity of 3200.

The roof structures are radically different, with particular attention being paid by the structural engineer to aesthetics and uniqueness in the design concept.

Innovative Structural Concepts

The design of the roof structures is innovative and unorthodox. The structural system was chosen to present the best view of the structures as seen from the entrance driveway into the complex. This resulted in a longitudinal external arch to show off the structure for the sports hall and a lens truss to show off its profile in the outdoor stadium.

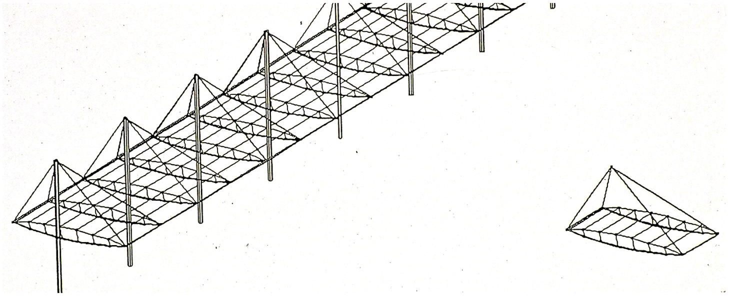
The final product is meant to be a showcase of the engineering and construction capability available for steelwork in Singapore.

Outdoor Stadium

The outdoor stadium is based on the form of an aeroplane wing. The cross section is defined by the shape of a lens truss which is both elegant and efficient.

The structural concept is a modular arrangement of twin lens trusses suspended from vertical steel columns. Lens shaped trusses were selected both for their unique form as well as for their structural efficiency. The appearance of the individual trusses was further improved by not having any diagonal members within the truss, thus giving a clean and uncluttered feeling to the roof.

The modular system allows for more prefabrication on the ground before erection. Pin-jointed connections allow rapid erection of the structure.



Uplift

The challenging part of the design was in handling the uplift as well as the lateral wind loads. Because of its light weight, uplift was a bigger problem for the structure than the normal loading. For uplift, since the nett upward forces are much smaller, the structure is designed to act in a totally different manner than for normal loads. In order to retain the elegant slim proportions of the main hanger rods, the structure is designed to act as a cantilever when resisting uplift. The diagonal ties which carry the uplift forces are purposely designed to work in tension only and thus can be very slender to maintain a sleek and uncluttered appearance.

The back tie-downs have to be increased in diameter to take compression, but this actually improves the appearance of the structure.

Lateral Loading

Hanging structures from the top of the columns means that the lateral loads are transmitted to the top of the columns. This will overstress the columns and there was no room to install diagonal tie-downs to cater for the lateral loads. The answer Is that the issue was solved using an ingenious combination of lateral bracing and lateral thinking.

First, the grandstand itself was considered to act as a diagonal strut. This reduced the lever arm of the lateral forces by more than half. To make the structure simpler and more efficient, the columns were mounted on top of the grandstand.

Than, to reduce the moment on the columns even further, small braces were added from the lens to the column, thus eliminating the need for diagonal tie-downs.

In unconventional structures, often it is small members put in strategic locations that make a huge difference to the strength and stability of the structure. Therefore, a good understanding of where to place vital bracing members is crucial to good structural design. The key to understanding an unconventional structure is in the construction of a scale model complemented by accurate computer modeling.

Sports Hall

The sports hall roof structure consists of twin inclined tied-arches spanning longitudinally and joined in a basket handle configuration. The twin arch configuration was chosen for its beauty as well as for strength and stability to lateral loading. The arch structure was purposely exposed externally and the arches were oriented longitudinally to present the maximum visual impact when viewed from the entrance of the stadium.

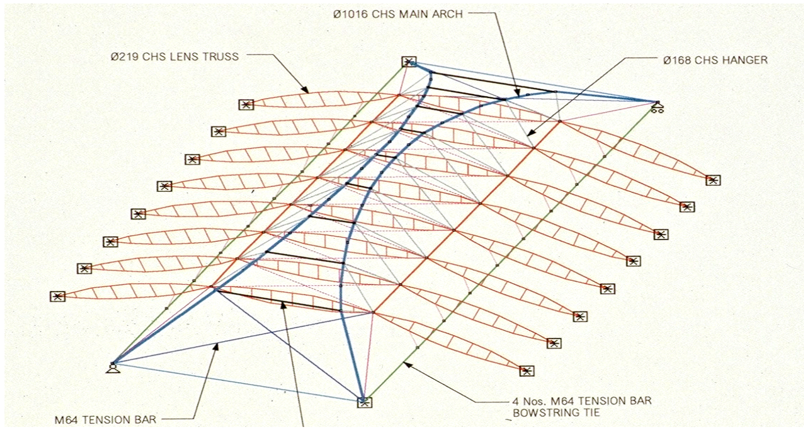
The original concept was for a space frame roof suspended from twin arches floating over the sports hall. However, space frames are expensive and complicated, and a more radical structural system of consisting of a series of 3 lens trusses to match the outdoor stadium was developed as a simpler, more elegant solution than the space frame.

Because of the limited space on the ground, the arch was truncated, arch ties were added, and entire roof was designed to sit on top of concrete columns.

The base of the arches are tied in both directions to take care of horizontal thrust loads from the arches and only vertical loads are transmitted to the support columns.

The hanger rods are set in the same plane as the arches so that no bending or torsional moments are imposed on the arches. The rods are installed in a V-configuration to take care of uneven loads on the arch.

A strange behavior we discovered from the physical scale model was that the entire structure would move sideways under uneven vertical loading due to the effect of the inclined hangers. This required additional diagonal bracing to control the movement.



Construction

Proposed construction sequence issued at the tender stage resulted in close cooperation between steel erector and main contractor.

The building had to be partially built before steel fabrication could start. Fabrication of the roof arches took place on the completed first floor of the sports hall

Then the partially completed roof structure was jacked up to its final level. Here it was left for 3 months as the building and the columns supporting the roof were constructed under the steelwork.

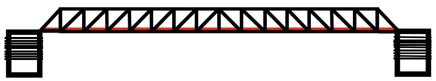
The Bishan sports hall is good example of how consideration of the erection sequence at the design stage can result in close cooperation between steel erector and main contractor.

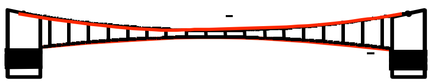
JALAN BESAR STADIUM

For a sports stadium, the primary design objective is to achieve an aesthetically pleasing roof form; therefore, the challenge for the structural engineer is to achieve a beautiful shape which is unique, elegant yet structurally efficient.

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 so as to eliminate 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.



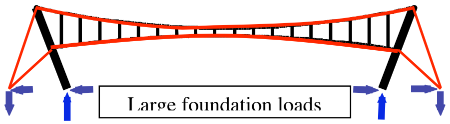


Site Constraints

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.

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.

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.



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.

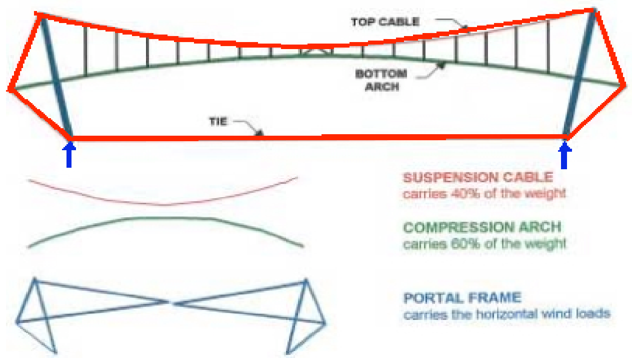
However, the soil condition at the site is poor, with about 10 meters of marine clay and soft soil under the surface. This makes it unsuitable for the foundations to carry horizontal loads, which would have been imposed by the cable roof. The foundations for the tiebacks would have protruded outside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

A Radical Solution

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 lower cable was made into an arch to carry compression instead of tension. A tie was added connecting the base of the columns at ground level.

The tension forces from the main suspension cables are redirected into the tie at ground level to form a tension ring around the structure, instead of being carried by the foundations. 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.

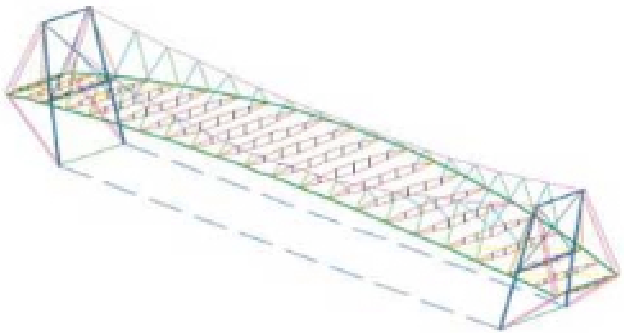


Although the structure may look like a suspension bridge, it is actually completely different in its structural behaviour: -

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



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.

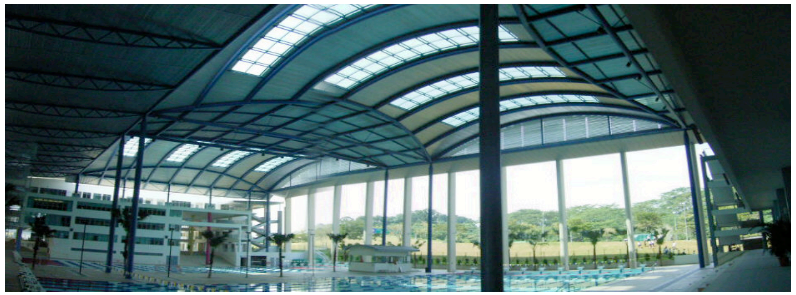
Combining an arch with a suspension structure allows the structural forces to be internally balanced, and both the arch and suspension cables to have very shallow profiles. Steel material is utilized effectively resulting in a light and efficient structure.

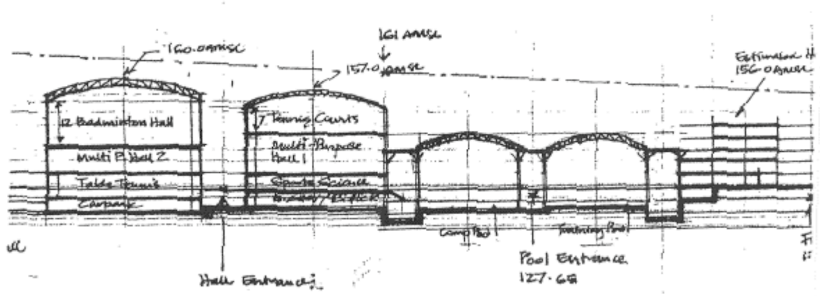
The shallow curve of the main arch gives a graceful, light form to the roof and stands out as the main architectural feature of the stadium complex.

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.

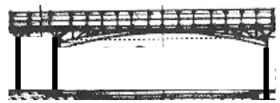
SINGAPORE SPORTS SCHOOL

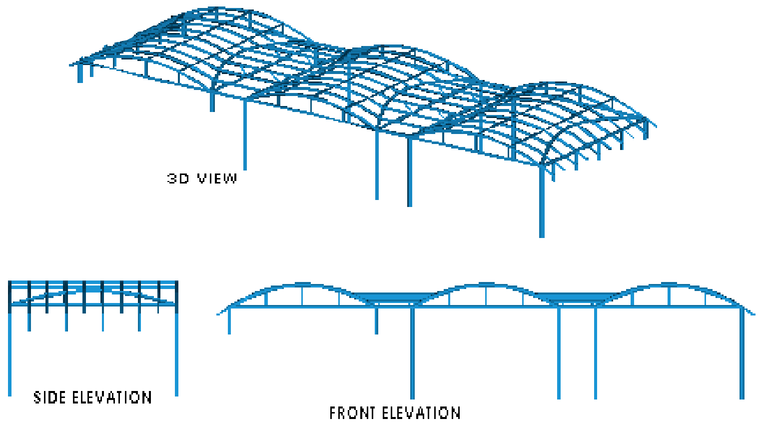
The Singapore Sports School has a series of curved roofs covering the auditorium, the 2 swimming pools and the badminton hall. These roofs have an unusual structure that is integrated into the curved shape of the roof and utilizes the curves of the roof to transfer the structural loads.





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





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. 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.

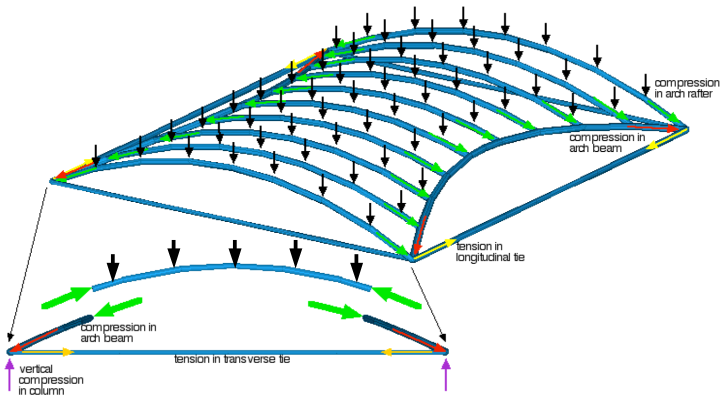
Design concept

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 spanning 40.5 m between columns supports these arch rafters. This longitudinal arch is inclined and integrated within the plane of the roof slope in order to keep all the structure within the roof surface. This enables the loads from the arch rafters to be transferred directly into the longitudinal arch without any eccentricities, and presents the minimum structure to view.

The loads from the rafters impose compressive forces into the longitudinal arch which are balanced by horizontal ties around the perimeter of the structural module. Thus only vertical forces are passed onto the support columns.

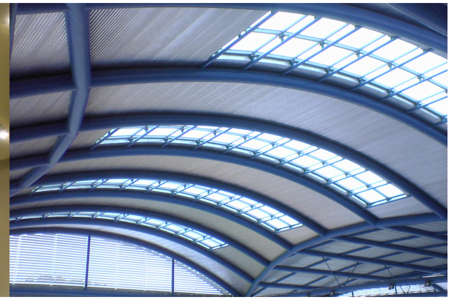
The result of this structural concept is a roof that does not require any trusses even though the columns are set at 36m x 40.5m apart. The structure is entirely contained within the curved surface of the roof.



This illustration shows how the structure works :-

1) The vertical loads on the roof are transmitted through the roof rafters which act like an arch in compression.
2) At the ends of the rafters, the arch thrust is re-directed to the corners of the structure by longitudinal arches which lie in plane of the roof.
3) Horizontal tension members tie the four corners of the structure thereby restraining the compression forces.

INTERIOR OF SPORTS HALL



ROOF OVER SWIMMING POOL

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

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.

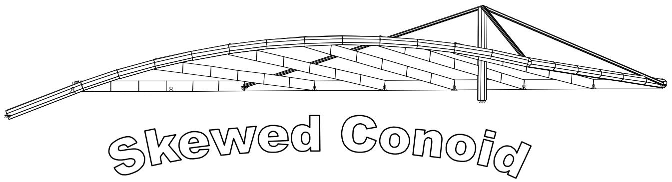
The structural system does not require any trusses even though the columns are set at 36m x 40.5m apart. The structure is entirely contained within the curved surface of the roof. This system of directing the forces along arch members is much simpler than the more commonly seen diagrid system.

This structural system can be expanded to cover mega spaces with column grids of 40-60 m. This is comparable in size to the grid used in some major airport terminal buildings.

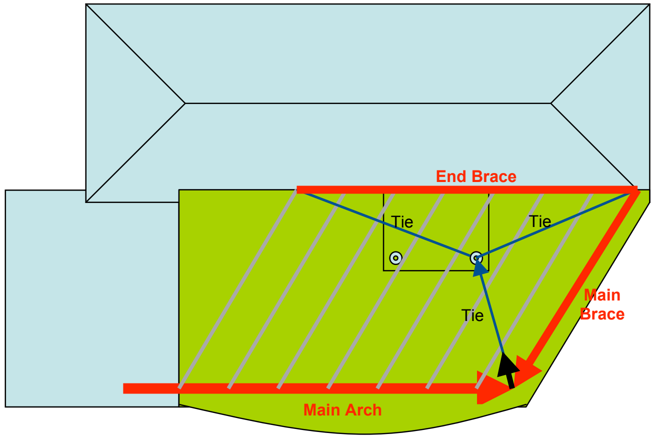
CONOID CAR PORCH ROOF

This particular car porch roof is the most unusual of the structures we have designed. It covers a trapezoidal shaped area and uniquely piggy-backs an existing porch column in order to give a column free covered space. The car porch faces a hill slope, which would have caused a claustrophobic feeling under a normal flat roof.

The roof is in the shape of a conoid, which is a curved arch transitioning into a straight edge to fit perfectly under the eave of the existing house roof. In addition, the conoid is skewed to cover the trapezoidal area. The shape and thinness of the roof gives an light airy form which ideally suits the site constraints and provides a basis for a innovative and efficient structure.



The structure makes use of the curved front edge of the conoid to act as an arch to carry the roof rafters. The way the arch thrust is resisted us entirely unique. An extension of an existing column within the covered area is used to carry a tension tie that suspends the corner of the roof as well as resisting the arch force, This tension tie is complemented by another 2 tension ties which anchor the forces into the side of the existing building. Thus, only vertical loads are imposed on the column. The structure uses only 60% of the steel in a more conventional alternative structure designed for the same site.



PLAN VIEW

The plan view of the structure shows how the arch thrust is balanced by the thrust from the main brace and the tension tie. The tension tie not only serves to balance the arch thrust but also to carry the cantilevered overhanging corner of the roof.

The structure was load tested after construction, and performs well under loads. No movement can be observed even in fairly strong winds.

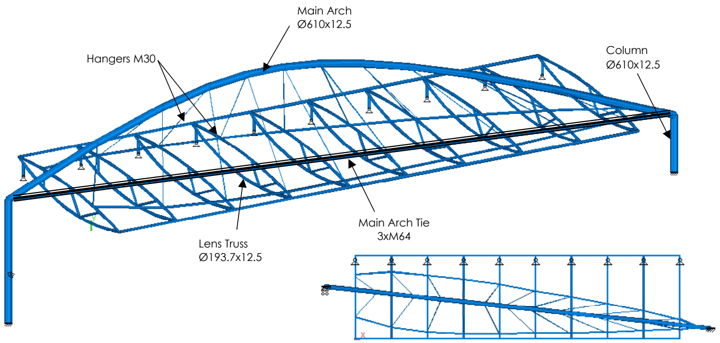
The conoid car porch roof shows the benefits of using an unconventional shape to suit the site. The aesthetic shape is used at the same time as a unique structural form. It blends well with the existing structure, and yet provides a startling and attractive contrasting form which sets the property apart from its neighbours.

TAMPINES SWIMMING COMPLEX

The Tampines Swimming Complex gallery roof was rebuilt and extended on top of an existing facility. Therefore, the existing seats and concrete structure had to be maintained and the construction of new foundations and tie-backs had to be minimized.

The design concept was chosen for its aesthetic appearance, as the client wanted a special structure which would enhance the complex.

A longitudinal arch structure was used to minimize the foundation requirement and still provide a column free view of the competition pool. The existing columns at the back of the seats were re-used, and the arch carried the weight of the front of the roof.

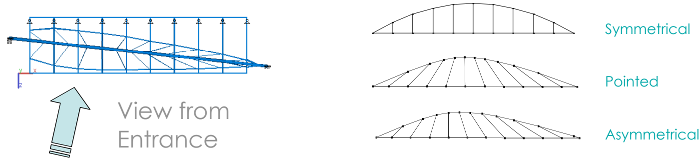


StructuralConcept

Force-Balanced Skewed Arch Structure with Radial Hangers

By skewing the arch diagonally across the roof, the following were achieved:-

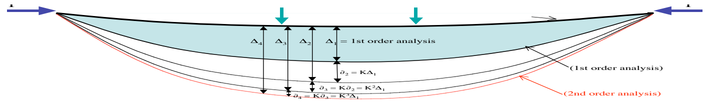
1) The arch supports would be located in a less obtrusive area to suit the existing facility.
2) The arch would be orientated to face the main entrance of the complex.
3) The natural shape of the arch would be more exciting, dynamic and asymmetrical by tilting the hanger rods towards the centre of the arch.



Skewing the arch gave significant benefits aesthetically and functionally, but the engineering was extremely difficult and demanding due unbalanced forces on the structure caused by the asymmetric arch. The problem of unbalanced forces was finally solved by making the hanger rods symmetrical about the arch longitudinal axis, and by adding additional members to tie together the base of the hangers.

Second Order Analysis

In order to account for the lateral buckling of the arch, a second order analysis was done using a special new technique with a linear structural program. This technique basically consists of repeatedly running the analysis using the deflected shape of the structure until the deflections converge.



The second order analysis revealed a special buckling mode in which the corner of the arch at its intersection with the supporting column could become unstable.

The Tampines Sports Complex roof is an example of how complex behaviour can manifest when an unconventional solution is chosen.