JALAN BESAR STADIUM
MAIN GRANDSTAND ROOF

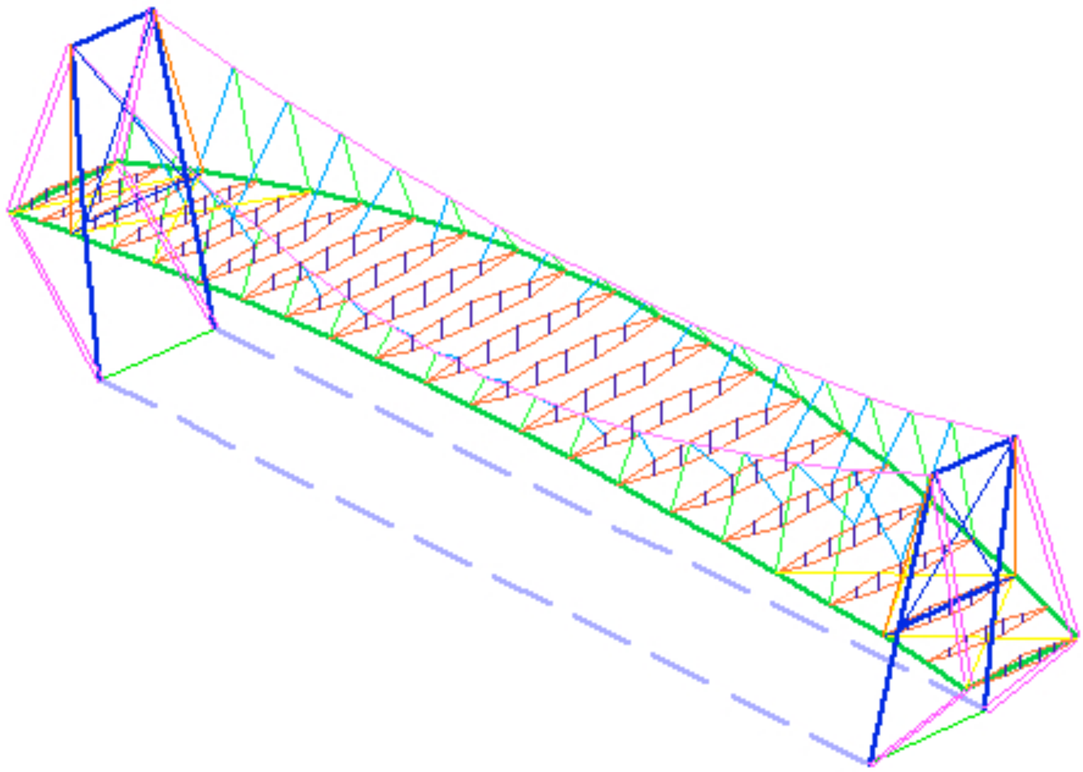
CONCEPT DEVELOPMENT

Winner of Singapore Structural Steel Society - Inaugural Structural Steel Award 2002

Judges' comment:
An extremely ingenious, novel and well executed solution to a problem driven by difficult site conditions. The engineering development is well explained in the submission. The solution is both practical and attractive. Whilst the original concept might be quite straightforward, to deliver it required proper understanding of rather complex structural behavior.

Albert Loh CONSULTANTS

CONCEPT DEVELOPMENT



The main grandstand roof of the Jalan Besar Stadium is a unique steel structure which is a revolutionary combination of cable suspension, compression arch and portal frame in a single structure. The roof is 160m long, 36m wide at the centre and is suspended from 2 inclined pylons spaced 129m apart.

A unique structural feature is the redirection of the cable tension forces at base level to contain the cable and arch forces within the structure and thus drastically reduce the loads on the foundations. Because of this, structure is column free and requires no tie-backs outside of the main pylons.

DESIGN OBJECTIVES

1. AESTHETICS
2. UNIQUENESS
3. STRUCTURAL EFFICIENCY

For a sports stadium, the shape of the roof determines the appearance and character of the entire sports complex.

The form of the roof should be not only beautiful, but strikingly different from what has already been built in other countries. It should show the flair and technical capability of our people when foreign visitors come for international events.

Therefore, the challenge for the engineer is to create a beautiful structure which is elegant, unique, yet structurally efficient. This is achieved in the Jalan Besar Stadium roof by combining the elegant curves of arches with lens trusses and dynamically inclined pylon supports augmented by a delicate cable suspension system.

CONSTRAINTS

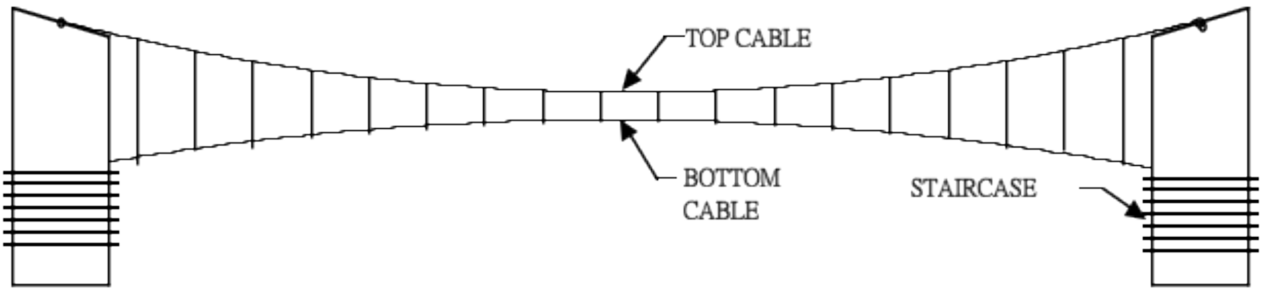
1. NARROW SITE
2. CLEAR LINE OF VISION

The site for the stadium is extremely restricted, and there is very little room to locate columns or tie-backs for the roof.

To achieve a clear line of vision , the enclosed area had to be column free.

Given the site constraints, the architect envisaged a long-span steel truss over the length of the grandstand between two staircase blocks on either end of the structure.

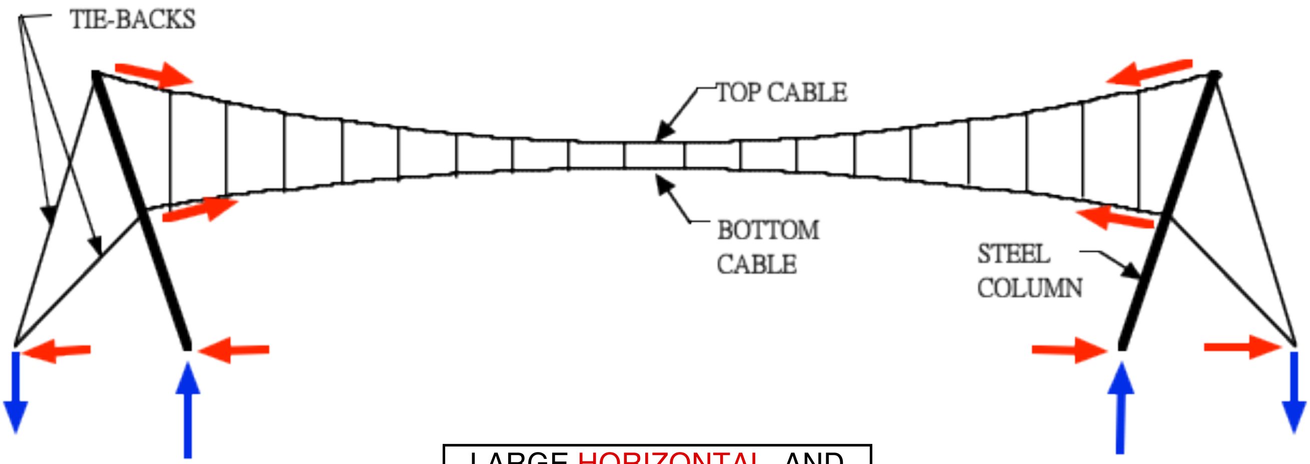
ENGINEER’S SOLUTION



In order to reduce the weight of the structure, the 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.

The entire structure would be anchored into the two staircase blocks at either end of the grandstand

CHEAPER VERSION



LARGE HORIZONTAL AND VERTICAL REACTIONS ON FOUNDATION

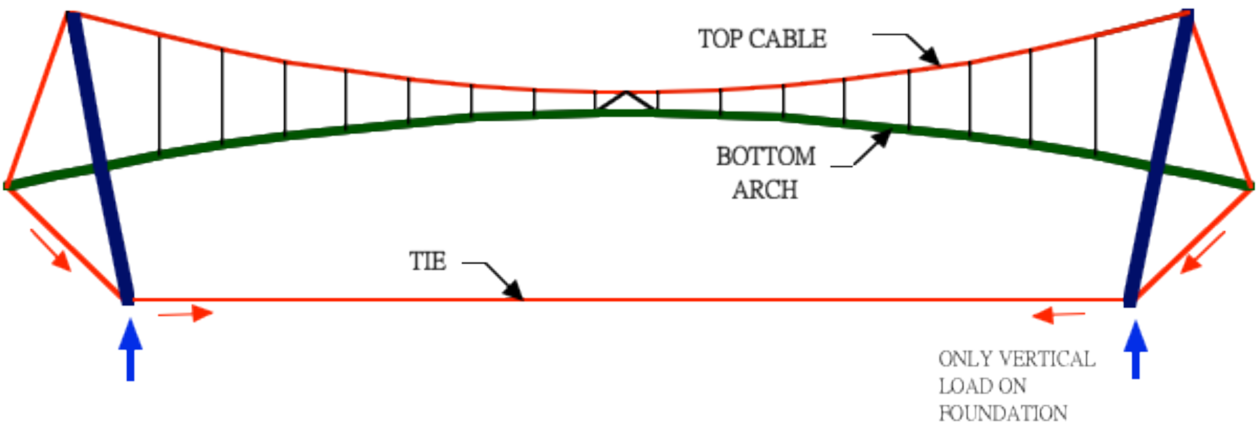
Due to budget restraints, the entire project had to be re-designed and the two staircase structures on either end of the grandstand were eliminated. They were replaced by steel columns with tie-backs to carry the tension of the roof cables.

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 tie-backs would have protruded outside the site boundary.

Therefore, a radical new solution had to be found.

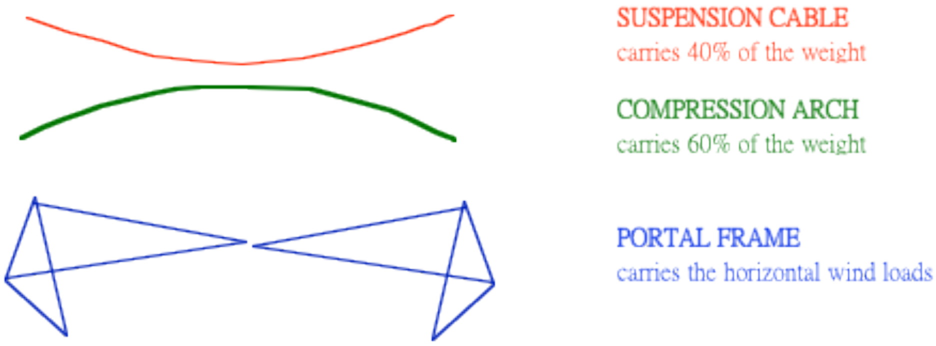
BREAKTHROUGH !

85% REDUCTION IN FOUNDATION PILING



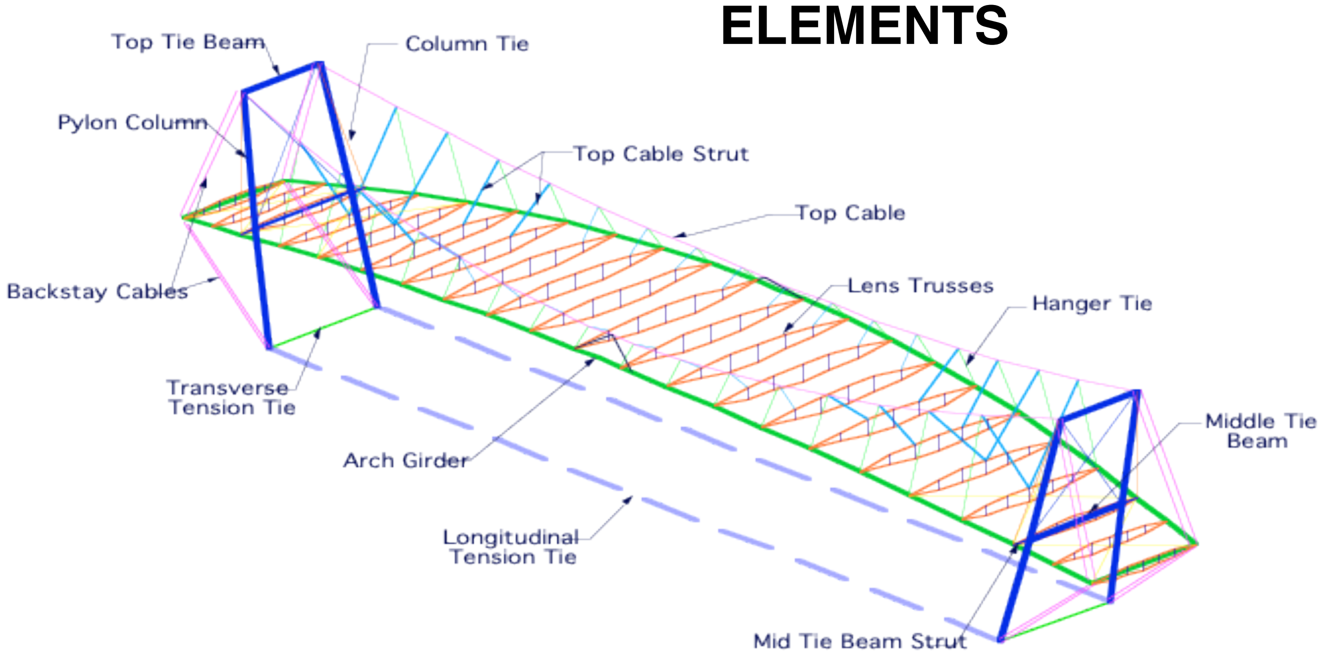
The horizontal loads due to the cable suspension of the roof had to be somehow carried within the structure instead of into the foundations. To do this, the roof itself became a compression arch to resist the tension of the cables. The tension force of the suspension cable was redirected back into the base of the pylons and a tie was added at ground level,

Thus, all the internal forces in the structure are self contained, and only the vertical weight of the structure is carried into the foundations. This allowed a savings of 85% in the foundation piling required.



This created a unique new structural system which is a combination of suspension, arch and portal frame.

MAIN STRUCTURAL ELEMENTS



The roof structure consists of the following main structural elements:-

* **Inclined pylons** of Ø 1219 x 25mm API 5Lx52 steel pipe at each end supporting the entire structure. The columns of the pylons are inclined at 11 degrees so that they are perpendicular to the ends of the arch. This gives the structure a dynamic appearance and also serves to balance the tension on the backstay cables.

* **Suspension cables** 115mm in diameter hanging between the tops of the pylons. These cables carry about 40% of the roof weight.

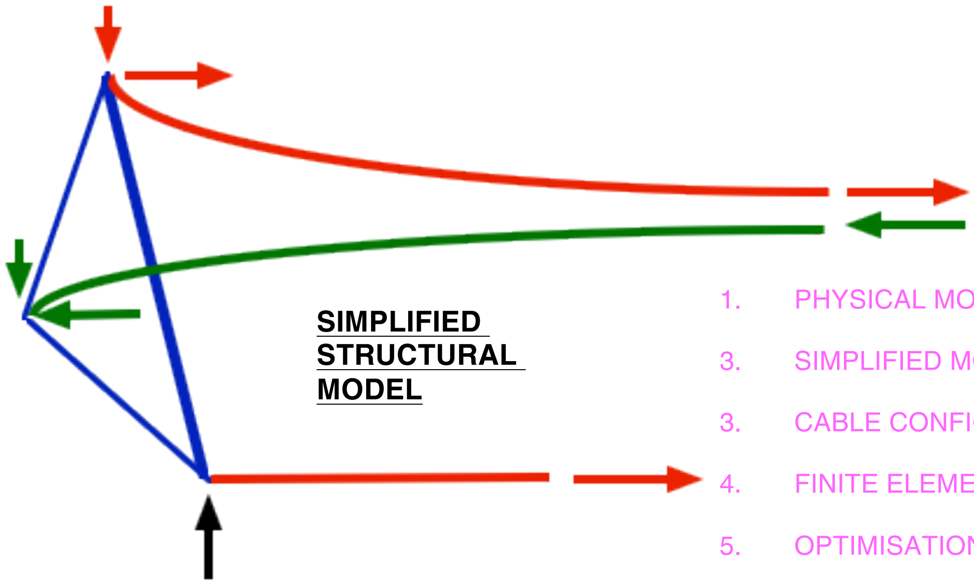
* **Arch girders** of Ø 914 x 25mm API 5Lx52 steel pipe carrying about 60% of the roof weight. The arch girders are curved in both vertically and horizontally.

* **Backstay cables** 115mm in diameter which transmit the tension in the suspension cable and longitudinal tension ties to compress the arch girder. The cables are the same size as the main suspension cables, but arranged in pairs.

* **Longitudinal tension** ties at ground level to balance the suspension cable tension force. These ties are normal prestressing tendons embedded within concrete ground beams integrated into the main grandstand structure, which serve both as corrosion protection as well as to considerably increase the stiffness of the ties.

The structure contains 200 tons of steel in the pylons and 300 tons in the arches and lens trusses. The entire roof cost S$4.3 million, including all roof sheeting, gutters as well as architectural cladding for the pylon.

ROOF MODELLING & ANALYSIS



1. PHYSICAL MODEL
3. SIMPLIFIED MODEL
3. CABLE CONFIGURATIONS
4. FINITE ELEMENT MODEL
5. OPTIMISATION

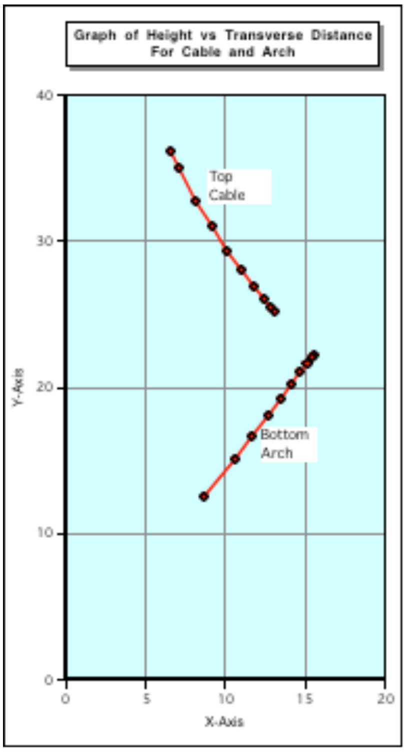
As the structure is entirely unique, no textbook solutions were available, and analysis of the structure had to start from first principles.

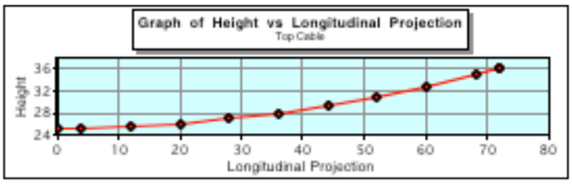
The modelling began with a physical scale model to be able to touch and feel the behaviour of this unique structure. Very thin piano wire was used for the first model, so that any buckling effects would be exaggerated. The physical model also helped to show any possible instability in all 6 degrees of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

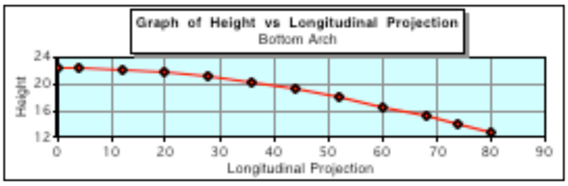
After this, a simplified mathematical model was created to investigate the main structural parameters and determine the effects of different arch and cable curvatures. The final configuration chosen has extremely shallow curves for both main suspension cable and arch girder, with 60% of the vertical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

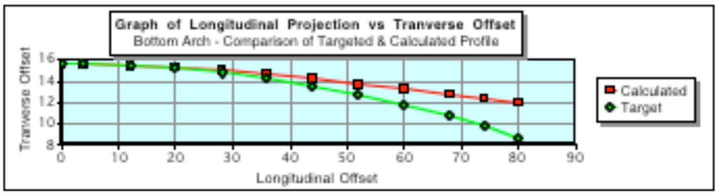
Different angles of tilt for the main pylons was investigated, and the final tilt of the pylons was set at 11 degrees. This angle is perpendicular to the ends of the main arches, and in addition to being structurally correct it also gives a dynamic appearance to the entire roof structure.

ARCH & CABLE CONFIGURATIONS







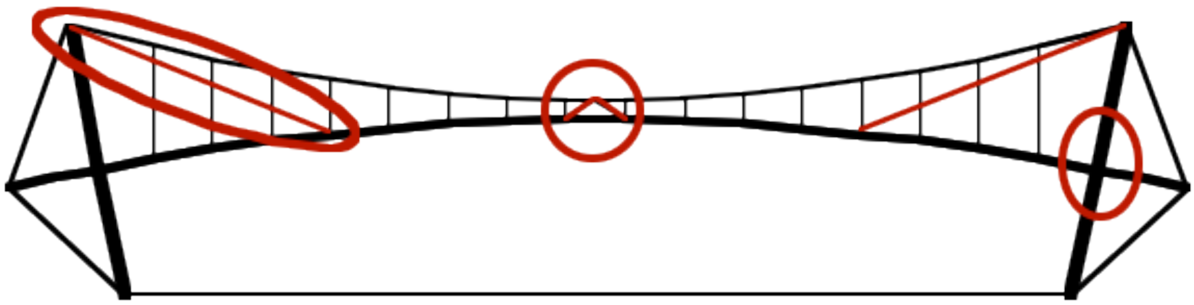


When the physical scale model of the structure was first built, it was immediately apparent that the cable and arch configuration was very different from a simple catenary or parabolic arch. A mathematical model of the cable and arch shape had to be developed in order to be able to define the coordinates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

SPECIAL CONSIDERATIONS



In developing any radical new structural configuration, special care had to be taken to ensure its strength and stability. In particular, the members had to be located so that all cables remain in tension and no large scale buckling or lateral instability can occur. No guidelines were available and the design team relied on testing with the physical scale model, confirming and optimising with the computer FEM model.

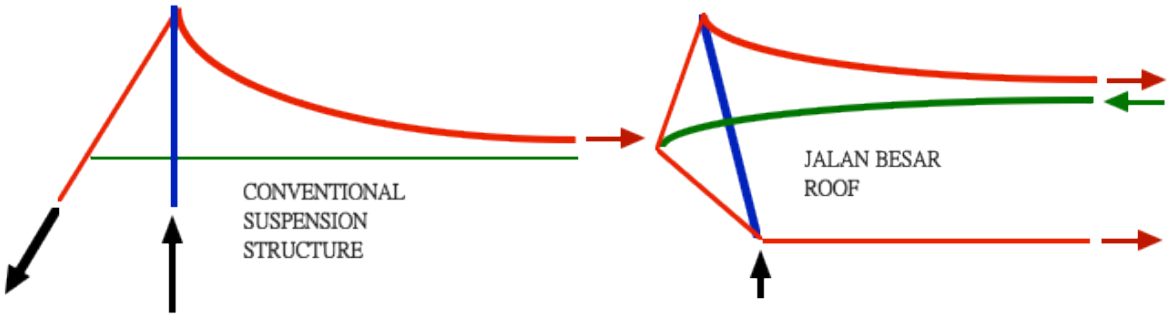
To maintain structural efficiency, the main structural members should carry pure tension or compression, Secondary bending moments should be eliminated as far as possible. This required special hinged members to be designed at the junction between pylon and main arch. Location of cross ties had to be optimised with many computer runs of different configurations. Eliminating secondary moments enabled the main pylon columns to be reduced in size from 2000 mm to 1200 mm diameter.

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.

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. A-braces were added at mid span between the main cable and arch. These made a tremendous contribution to structural stability in the horizontal axis. The entire structure is braced together as a rigid unit.

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.

At all times, the aesthetics of the structure remained a prime concern, and the location of the additional members had to be done so as not to adversely affect the purity of the structural form.



ADVANTAGES

1. SAVINGS IN FOUNDATIONS
2. SMALL FOOTPRINT
3. SHALLOW ARCH AND CABLE

The Jalan Besar Stadium main grandstand roof structure is an innovative combination of suspension cable, steel arch and portal frame into a single structure.. It uses both suspension cable and arch forces to carry vertical loads and acts like a 3-hinged portal frame in resisting horizontal loads. Although the structure may look like a suspension structure, the actual behaviour is completely different and gives several distinct advantages:-

1. By redirecting the tension force of the cables underground, all the tension of the suspension cables is balanced by the thrust of the arches and only the self weight, 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. The footprint of the structure is also much smaller. The entire structure is rests on only 4 points. No external ties are required, making it ideal for the small Jalan Besar site.

3. The arch and suspension cables share the vertical load, and act in a composite manner. Therefore, the suspension cable and arch both have very shallow (flat) profiles. This contributes greatly to the graceful appearance of the structure.

4. By adding braces in strategic locations, the entire roof structure behaves as a rigid unit when subjected to horizontal loads or uneven loading conditions. Therefore, there is no buckling or large scale deformations associated with conventional suspension structures.

The result is a revolutionary new application of engineering principles in creating an aesthetically pleasing yet strong and lightweight steel structure..