Structural Design of the Main Components of Large Cable Supported Bridges

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Niels J Gimsing was born in 1935, and received in 1959 his Degree in Civil Engineering from the Technical University of Denmark.
In 1976 he became full professor in Steel Structures at the same university. Along with teaching and research he has acted as specialist adviser and consultant for many bridge projects around the world.

!. Introduction

In long-span cable-stayed and suspension bridges the main components of the superstructure are the deck (stiffening girder), the pylons and the cable system.

In the design of these components many different aspects have to be considered, such as:

- Structural efficiency
- Aesthetics
- Aerodynamic behaviour
- Constructability
- Maintenance
- Durability

In the present paper the emphasis will be laid on the conceptual design of the deck/stiffening girder and the pylons.

2. Stiffening girder

In cable supported bridges with moderate spans and large width-to-span ratios the stiffening girder can be composed of elements as used in simpler bridges, i.e. concrete slabs, rectangular solid or hollow concrete girders, I-girders in steel or rectangular box girders.

With increasing spans and decreasing slenderness ratios the aerodynamic properties become more and more important and as a consequence the overall configuration must be chosen with due respect to the action of the wind.

After the problematic behaviour of large suspension bridges with stiffening girders comprising simple plate girders (First Tacoma Narrows Bridge, Bronx-Whitestone Bridge and others) the preferred configuration of the stiffening girder in large suspension bridges became the spatial truss composed of four chords interconnected by two vertical and two horizontal bracings (Figure 1). This type of stiffening girder was used in all major postwar suspension bridges in the USA, in the first major European suspension bridges (Tancarville Bridge, Emmerich Bridge, Firth of Forth Road Bridge, Tagus River Bridge, etc.) and in most of the large Japanese suspension bridges.

Fig.1 Stiffening truss (Golden Gate Bridge)

Fig.2 Cross bracings (Akashi Kaikyo Bridge)

Stiffening trusses with a depth-to-span ratio between 1/100 and 1/150 proved to give adequate aerodynamic stability and they did not present problems regarding vortex induced vibrations that could affect user comfort. On the other hand the large trusses are characterized by a considerable drag due to the many bluff members not only in the vertical trusses but also in the lower bracing and the cross bracings required to establish an efficient torsional rigidity (Figure 2).

Trusses are also characterized by large surfaces to be painted and with the many plate intersections at the nodes this lead to high maintenance costs.

Since the mid 1960.s the application of stiffening trusses has diminished in cable supported bridges with a single deck but they are still found in many double deck bridges (Figure 3).

In single deck bridges the truss was superseded by the shallow box girder in a streamlined shape first introduced at the construction of the Severn Bridge in the UK (Figure 4).

Compared to stiffening trusses the streamlined box girder is characterized by a smaller depth-to-span ratio, typically between 1/300 and 1/400. Together with the streamlined shape this results in a substantially smaller drag than on a truss.

Sufficient aerodynamic stability of suspension bridges with streamlined box girders has been achieved for spans up to 1624 m – the span found in the second longest suspension bridge in the world, the East Bridge of the Storebælt Link (Figure 5). However, the investigations carried out during the design of the East Bridge indicate that the limit for application of a single box in suspension bridges is around 2000 m, and maybe somewhat less. Thus, the critical wind speed for the East Bridge was found to be

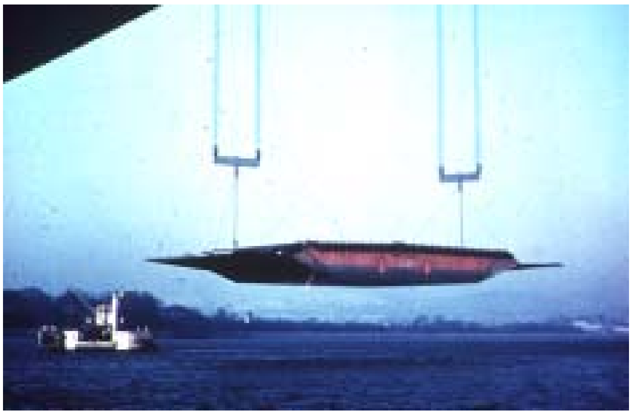

Fig.3 Double deck truss (Higashi Kobe Br.)

Fig.4 Streamlined box girder (Severn Br.)

Fig.5 East Bridge (designed by CBR)

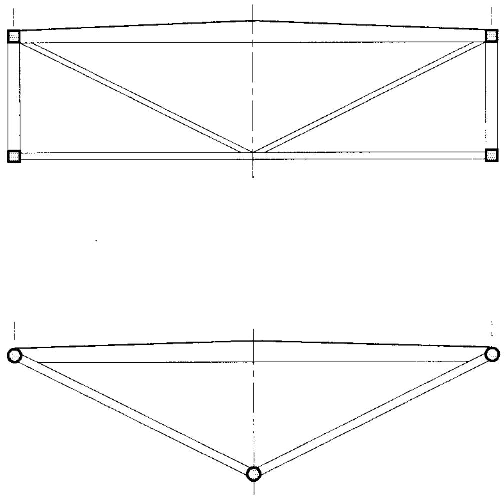

Fig.6 Conventional, rectangular truss (top), and triangular truss (bottom)

approximately 70 m/sec which was sufficient in the actual location, but in other parts of the world it would be below the specified design wind speed.

Bridges with streamlined box girders are vulnerable to vortex-induced vibrations resulting in vertical movements that are harmless for the safety of the bridge but can result in accelerations above the comfort level. This was the case for the East Bridge where vertical vibrations with an amplitude of up to 600 mm were observed after completion of the superstructure erection. A retrofit comprising addition of guide vanes at the lower soffit corners was then made prior to the opening of the bridge and this measure reduced the vertical vibrations to an insignificant magnitude.

With streamlined box girders the surfaces to be painted will be plane and also smaller than with trusses. All the complicated plate intersections will be inside the box and here painting can be avoided completely by installation of a dehumidification system.

The superior behaviour of truss girders in relation to vortex-induced vibrations could lead to considerations regarding application of trusses designed to reduce drag and simplify maintenance. A promising solution could be to apply a triangular truss composed of round (corner free) tubes (Figure 6 bottom). With such a truss the number of members will be drastically reduced as the horizontal bracing at the bottom disappears together with the cross bracings - both becoming superfluous due to the triangulation. As a result the drag on the deck might be reduced by as much as 40%.

For a stiffening girder based on the concept of the streamlined box, improved properties regarding aerodynamic actions can be obtained by applying twin boxes separated by a wide slot. This principle is for the first time being used in the cable-stayed Stonecutters Bridge in Hong Kong with a record-breaking span of 1024 m (Figure 7). This bridge will soon reach the construction stage based on a detailed design by Ove Arup & Partners as Main Consultant together with COWI as Subconsultant.

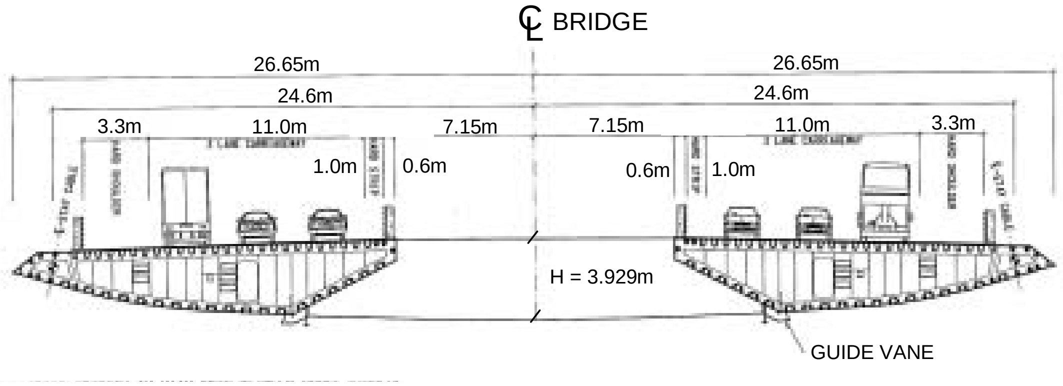

Fig.7 Cross section of the twin box forming the deck of the Stonecutters Bridge

With a twin box deck the critical wind speed for catastrophic torsional vibrations can be increased substantially, but the problems of vertical vortex-induced vibrations will still exist. For the Stonecutters Bridge it was, therefore, necessary to add guide vanes at the bottom corners of the boxes to avoid discomforting vertical accelerations of the deck.

3. Pylons

When looking at the cable supported bridges built in the past it is obvious that they are recognizable largely by the shape of their pylons. The deck will in any case appear as a slender element of constant depth and width - and finer differences in the exterior configuration cannot be detected when looking at the entire structure from a distance. Such considerations have clearly been in the minds of many designers and as a result, the pylon designs show a larger variation than any of the other elements in cable supported bridges.

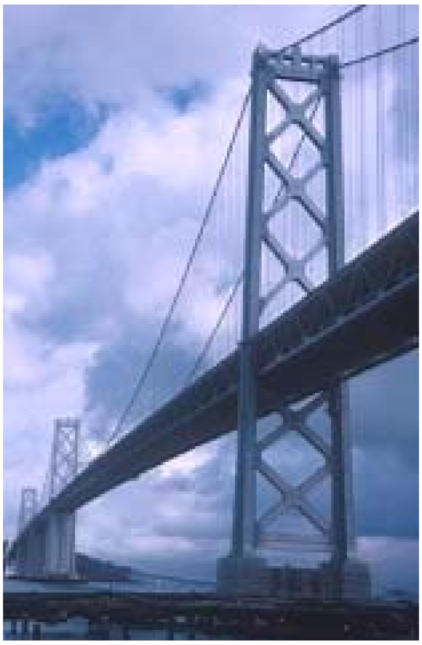

Fig.8 Pylons with diagonal bracings (Bay Bridge)

The primary function of pylons in cable supported bridges is to transfer the vertical resultant of the cable forces to the ground. The most direct way to perform this task is by vertical columns.

After introduction of steel as structural material for pylons in the beginning of the 20th century it became common to build the pylons as two vertical or quasi-vertical columns interconnected by diagonal bracings or cross beams (Figure 8).

In the 1950s concrete was introduced as structural material for pylons – a natural choice considering that the pylons primarily had to transfer a vertical force inducing pure compression in the pylon legs.

In their main configuration the concrete pylons were designed in a similar way as steel pylons, i.e. as two vertical or quasi-vertical columns interconnected by cross beams or shear walls (Figure 9).

Fig.9 Pylon of the Tancarville Bridge

Fig.10 Pylon of the Strömsund Bridge

The modern cable-stayed bridge was introduced in the mid 1950.s at the construction of the Strömsund Bridge in Sweden (Figure 10). In this bridge the pylon was made of steel and in the form of a portal basically as seen in suspension bridges.

Already in the second cable-stayed bridge, the Theodor Heuss Bridge across the Rhine, the pylon design deviated from the contemporary suspension bridge tradition as the pylons comprised vertical columns without any interconnecting members above the bridge deck (Figure 11).

Fig.11 Pylon of the Theodor Heuss Bridge

Fig.12 Pylon of the Severins Bridge

Fig.13 Pylons of the East Bridge

Fig.14 Pylons of the Øresund Bridge

In the third of the modern cable-stayed bridges, the Severins Bridge in Cologne, yet another new configuration of the pylon was seen as the pylon had the shape of an A with two inclined legs joined at the top (Figure 12).

In the following years a large variation of pylon forms were seen within cable-stayed bridges whereas suspension bridge pylons of both steel and concrete remained in the traditional portal configuration. However, a trend towards a cleaner and more clarified form was seen at the end of the 20th century (Figure 13).

Within cable-stayed bridges the portal shape almost vanished at the end of the 20th century as it was substituted by pylons in shapes denoted as A-, λ-, I-, H- and diamond-shape. The most prominent example on the H-shape is seen in the Øresund Bridge with its 203 m high pylons without any cross beams above the bridge deck (Figure 14), and the supreme example on the I-shape will soon be seen in the Stonecutters Bridge with pylons reaching a height of 300 m (Figure 15).

In bridges with free-standing columns of concrete it is essential that the pylon legs are subjected to pure compression from their dead load and from the vertical load acting on the bridge deck. Therefore, the cable planes must be vertical and be positioned so that the vertical centroid of the pylon will be in that plane. In the Øresund Bridge this condition was achieved by adding triangular brackets or outriggers extending from the vertical main trusses to the cable anchor points, Figure 16.

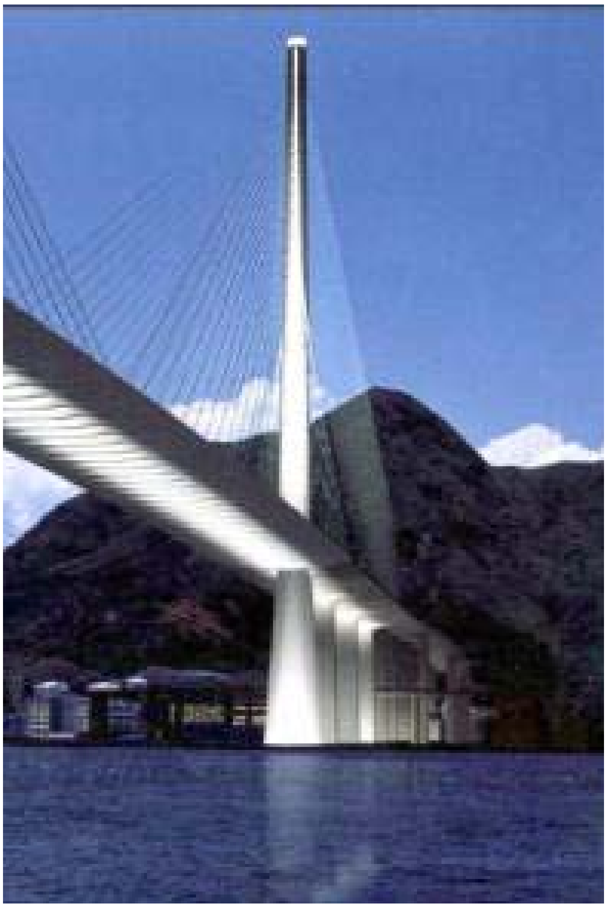

Fig.15 Pylon of the Stonecutters Bridge

Fig.16 Outriggers of the Øresund Bridge

The effect of adding a cross beam at the top (and the associated frame action) on the maximum bending moments in the pylon legs is illustrated in Figure 17 showing the moment diagrams for pylons subjected to lateral wind load on the pylons themselves. It is seen that for this loading the moment at the lower cross beam is only increased by 50% when omitting the cross beam at the top.

For a lateral force acting at the pylon top (e.g. from wind load on the cable system) the increase of the bending moment will be 100% when changing from the portal configuration to the H-figuration. It should, however, be emphasised that the mentioned increase of the bending moment is based on the assumption that the pylon legs have a constant cross section and that the cross beam at the top has an infinite flexural stiffness. If the pylon legs are tapered (which is often the case) and the cross beam has a certain flexural flexibility then the moment in the pylon legs of the portal will be larger at the deck level.

In the construction phase a tower with vertical legs and no upper cross beams will be simple to construct by applying either slipforms or jump forms. As new segments are cast their weight will induce pure compression in the cross sections below. This will result in a favourable prestressing that will improve the pylon’s ability to transfer the moments due to lateral load.

Within suspension bridges, pylons composed of free-standing columns have not been seen in major bridges constructed in recent times.

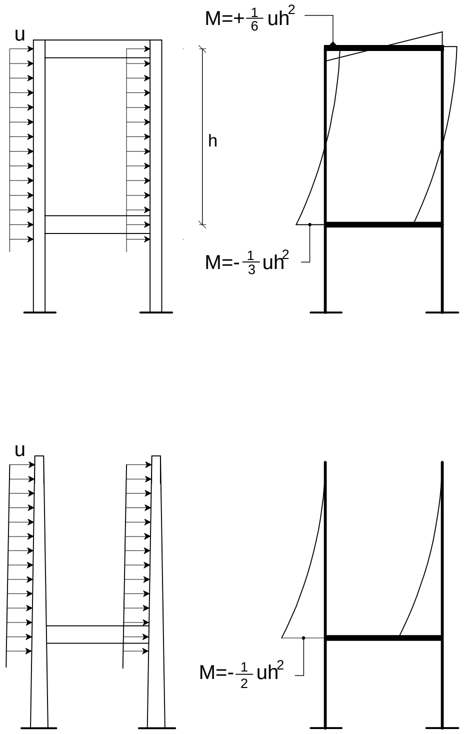

Fig.17 Moment diagrams for portal and H-pylon subjected to wind load

Fig.18 The Tsing Lung Bridge project

During detailed design of the Tsing Lung Bridge in Hong Kong a thorough investigation on the pylon configurations was carried out, and as a result it was concluded that the detailed design should be based on the principle of free-standing pylon legs, Figure 18.

The Tsing Lung Bridge was characterised by an unusually small sag ratio (1/15) of the main cables due to the location close to the new airport. At the same time the bridge deck with its twin box configuration was very wide so the two cable planes were far apart. Both the relatively modest height of the pylons and the wide spacing of the cable planes (as well as the relatively short length of the backstays) favoured the application of free-standing pylons in this particular bridge.

Among the many variations seen in the shape of pylons for cable-stayed bridges it is quite common to see pylons with legs having a pronounced inclination, e.g. in A-shaped, diamond-shaped or V-shaped pylons. If concrete is to be used in such pylons it must be considered that stresses induced during construction will be larger and more unevenly distributed than in vertical pylons. This is illustrated in Figure 19 showing the stresses induced from dead load in a vertical and a moderately inclined pylon leg cast by jump forms in segments with the same height as the width. It is seen that already with two segments cast, the axial stress will be zero at one side of the inclined pylon. With three segments cast tension will be induced at the upper face and this might result in cracks developing at an early age.

In the final condition the tensions developing during construction will often disappear as they will be exceeded by the compression induced by the cable system. Therefore, additional reinforcement needed during construction to limit crack widths might be superfluous in the final stage.

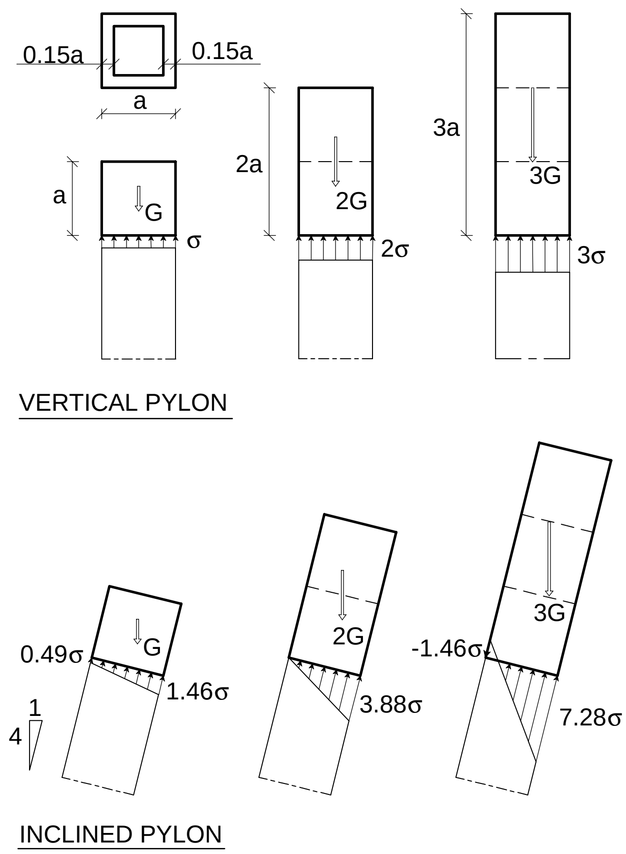

Fig.19 Axial stresses from dead load of pylon segments in vertical and inclined pylon leg

Fig.20 Pylon of the Farø Bridge under construction

To counteract the uneven stress distribution in the pylon legs during construction it is often necessary to arrange temporary lateral support to inclined legs. In case the pylon is symmetrical with two legs leaning in opposite directions the supplementary lateral support can consist of temporary struts between the two legs, as it was seen during construction of the pylons for the Farø Bridge, Figure 20. Here the two upper struts were temporary whereas the lower strut (tie) between the kinks of the pylon legs was permanent.

In case a pylon leg is inclined individually (without an oppositely inclined leg) then the temporary lateral support needed during construction might be quite complicated and expensive.

4. No pylons

In rare cases earth anchored suspension bridges can be built without pylons – if the topography at the site allows the anchor blocks to be positioned above the bridge deck.

A very innovative design for a suspension bridge without pylons was prepared by Ove Arup & Partners for the Metsovitikos Bridge in Greece. This bridge shiuyld be built to connect two tunnel portals positioned halfway down to the bottom of a valley. Therefore, it was possible to position the anchor blocks further up the valley slopes and connect them by two 800 m long suspension bridge main cables. These cables then supported a 500 m long twin box girder carrying the motorway across from one tunnel portal to the other, Figure 21.

Fig. 21 The Metsovitikos Bridge Project in Greece

A special feature of the Metsovitikos Bridge was the application of transversally inclined cable planes – a feature that would result in a very exciting experience when exiting the tunnel and move across the valley, Figure 22.

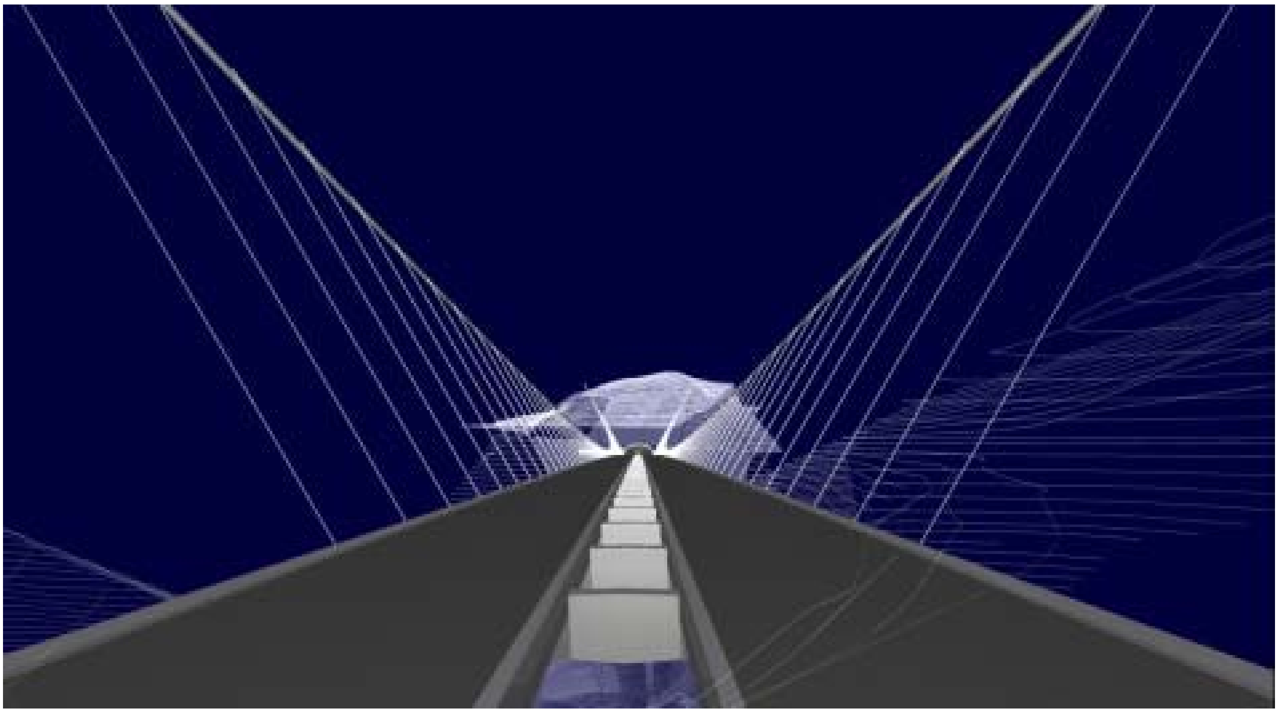

Fig.22 The Metsovitikos Bridge as it would be viewed along the deck

Conclusion

After the introduction of the streamlined box girder for the deck of suspension bridges the stiffening truss has to a large degree been reserved for double deck bridges. It seems, however, that there would be scope for a further development of the stiffening truss, e.g. in the form of a triangular truss composed of tubular members.

Within cable-stayed bridges a large variation of pylon shapes have been seen in the last decades, whereas the shape of suspension bridge pylons is limited to minor modifications of the conventional portal configuration.