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Cable stay bridge

Puentes atirantados

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ABSTRACT

This paper presents the typological and conceptual evolution of cable stayed bridges from the Kings Meadow Bridge of 1817, to the recent Third Bosphorus Bridge 2017. The paper highlighted the breakthrough in understanding cable stay bridge structural behaviour of E. Torroja in 1926 with the Tempul Aqueduct, and the relevance of the Dischinger's publication 'Suspension for very heavy loads' published in 1949 where the design basis for stay cables were analysed for the first time.

The paper also remarks the significance of the Dusseldorf North Bridge, designed by Leonhardt where the special structural analyses issues of cable stay bridges was essentially solved. The text includes the specific aspects related to multispan cable stayed bridges as well as those particular issues Finally, some thoughts on the limits of this typology and its future development are presented, among which the use of new materials is indicated.

KEYWORDS: Cable stayed, stay, typology, conceptual design, aesthetic.

RESUMEN

En este artículo se presenta la evolución tipológica y conceptual de los puentes atirantados desde el Kings Meadow Bridge de 1817, hasta el reciente Tercer Puente del Bósforo 2017. El artículo destaca la aportación fundamental de Eduardo Torroja en 1926 en la comprensión del funcionamiento de esta tipología, con el acueducto de Tempul y el salto posterior cualitativo dado por Dischinger en 1949 con su publicación "Suspensión de cargas pesadas", en el que explicó por primera vez las pautas para el diseño de tirantes.

El artículo también destaca el Puente Norte de Dusseldorf North proyectado por Leonhardt en el que ya se resuelven los aspectos especiales del análisis estructural de esta tipología. En el texto, se incluyen además, los aspectos específicos de los puentes atirantados multivanos y aquellas cuestiones particulares correspondientes a las últimas realizaciones en las que ya se han superado ya los 1000 de luz. Por último se presentan unas reflexiones sobre los límites de esta tipología y su desarrollo futuro, entre los se indican el uso de nuevos materiales.

PALABRAS CLAVE: Puente atirantado, tirante, tipología, diseño conceptual, estética.

1.
INTRODUCTION

The concept of supporting a girder with taught cables goes back a long way, but the first proven bridge with inclined stays was Kings Meadow Bridge in England, designed by James Redpath and John Brown and constructed in 1817. However at that time the structural action was not fully understood in that the stays have to be tensioned and the forces in the stays tuned to pick up the girder load directly. Failures of these type of bridges in the early 1800's put a damper on development of stay cable cable bridges.

The break through in understanding cable stay bridge structural behaviour came in 1926 with the Tempul Aqueduct designed by Eduardo Torroja. However it was not till after the Second World War, when cable stay bridge technology flowered with Dischinger's publication 'Suspension for very heavy loads' published in 1949. In it Dischinger for the first time gives the design basis for stay cables.

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Figure 1. Stromsund Bridge, Sweden.

Figure 2. Knie Bridge, Dusseldorf, Germany.

The first modern concrete cable-stay bridge is the Donziere-Montragon Bridge in France that was completed in 1952. It was designed by Albert Caquot who stressed the high strength steel tendons to support the stiff concrete roadway and anchored the stay cables in the deck which induced compressive stresses in the deck.

The Stromsund Bridge, which represents a leap in the development of cable stay bridges, was constructed in Sweden in 1956 and is generally looked upon as the first modern cable stay steel bridge, because the concrete deck slab distributes only local wheel loads and is not composite with the steel beam, Figure 1. The concrete slab does not participate in carrying the overall main girder bending moments and normal forces and hence Stromsund Bridge is considered as a steel bridge. Dischinger advised on the design of Strosmund Bridge.

The development of lightweight steel orthotropic decks allowed cable stay bridges with slender steel decks to be constructed. The Dusseldorf bridge family of three cable stay bridges, whose planning commenced in 1952, are a significant and early application of the use of orthotropic decks. Their

Figure 3. Oberkassel Bridge, Dusseldorf, Germany.

Figure 4. St. Nazaire Bridge, France.

design, fabrication and construction initiated the development of cable stay bridges worldwide. The three bridges, Dusseldorf North Bridge, Knie Bridge, and Oberkassel Bridge were designed during 1953 and 1954 and completed in 1957, 1969 and 1976 respectively, Figures 2 & 3. The chief designer for the North Bridge and Knie Bridge was Fritz Leonhardt and for the Oberkassel Bridge the designer was Hans Grassl.

The special structural analyses issues of cable stay bridges was essentially solved with the design of the Dusseldorf North Bridge: such as the development of their influence lines including stress influence lines; non-linear effects from compression with bending in the deck; the free selection of the run of moments under permanent loads; and the structural analyses of the free-cantilevering construction. The structural issues of the buckling of the free-standing towers, loaded and elastically supported by the stay cables were resolved.

The span range of Dusseldorf bridge family was modest in the range of 260-319 m, and the number of stays used were also modest, a maximum of four primarily because of the limitations of doing analyses by hand. The advent of computers has had a significant effect on computation powers, which meant that cable stay bridges with a large number of stays could be analysed.

The first bridge to break the 400 m span barrier is the two tower St. Nazaire Bridge across the River Loire in France with a span of 404 m, which was completed in 1975. The steel box girder deck is continuous over the three stayed spans and has an aerodynamically shaped cross-section, Figure 4.

Cable stay bridges with concrete decks were also being developed and with the construction of the 235 m main span Maracaibo Bridge in 1962, Figure 5, designed by Riccardo Morandi, they tend to now form the preferred economical system

Figure 5. Maracaibo Bridge, Venezuela.

Figure 6. Brotonne Bridge, France.

Figure 7. Barrios de Luna Bridge, Spain

Figure 8. Alex Fraser Bridge, Vancouver, Canada.

for spans in the range of 200-300 m, especially in developing countries where concrete construction is more economic than steel construction.

Brotonne Bridge in Normandy France, Figure 6, designed by Jean Muller and completed in 1977, has a unique main span single cell box girder with inclined webs. The box was constructed using precast webs and in situ concrete for the rest. All elements of the box girder are post-tensioned, the webs, top slab, bottom slab and the inclined ties.

In the 1980's concrete deck spans in excess of 400 m were realised. Spanish designers and constructors have usually been in the fore-front in the use of concrete. Javier Manterola and Carlos Fernando Casados designed the concrete box girder deck Barrios de Luna Bridge in Spain with a record span of 440 m which was completed in 1983, Figure 7, and was the longest span for any type of cable stay bridge at that time. With back spans of 99 m, the span ratio of backspan to main span is only 0.23 compared to the usual ratio of 0.4. This required unique heavy 35 m long concrete abutments on both sides as counterweights. The decks are monolithic with the abutments and there is a longitudinal movement joint at midspan to cater for temperature variations and shrinkage and creep.

Steel concrete - composite bridges also began to be used increasingly due to their economy and constructability. Compared to steel bridges, savings are achieved because concrete can carry compression forces more economically than steel, and a concrete deck slab is more economic than an orthotropic deck. Also compared to concrete bridges less cable steel and smaller foundations are required. A typical composite deck consists of longitudinal steel I-section or boxes along the edges and transverse I-section girders with a composite insitu or precast concrete deck slab. The deck can be constructed in small units with steel main and cross girders and precast road slabs erected with light lifting equipment.

The next increase in span length of whatever deck type came in 1986, with the construction of the composite ladder deck Alex Fraser Bridge in Vancouver with an H-tower and span of 465m, Figure 8. The designers were Peter Buckland and Peter Taylor who used steel I-section girders along the edges with transverse I-section girders and composite deck slab, which are typical for composite decks.

The 500 m span barrier was broken in 1991 with the construction of the 530 m main span Skarsundet Bridge at Trondheim in Norway. This is still the longest concrete cable stayed span in the world. The concrete towers have a box girder cross-section, and the main girder has an aerodynamically advantageous triangular box cross-section which is solid in the relatively short backspans to provide counterweight, Figure 9.

The 600 m span barrier was broken in 1993 with the construction of the 602 m span Yang Pu Bridge in Shanghai, China, Figure 10. The main span comprises of two edge steel box girders connected with steel transverse girders and a concrete deck slab. The bridge was designed by the Shanghai Municipal Design Institute (SMEDI) under the direction of Lin Yuan Pei.

The major significant jump in span length came in 1995 with the completion of the Normandy Bridge in France, the lead engineer for which was Michel Virlegeoux. The bridge has a span of 856m and concrete A-frame towers, Figure 11. The main span comprises of a central 624 m orthotropic box

Figure 9. Skarsundet Bridge, Trondheim, Norway.

Figure 10. Yang Pu Bridge, Shanghai, China.

girder, with the outer 116m on each side being an extension of the concrete box girder backspans. An innovation in this bridge is the deck which is embedded with the towers and with a pronounced curved vertical profile. The effects of the temperature variation are catered for by the vertical deflection of the curved deck.

Normandy Bridge was followed soon after by the 890 m span Tatara bridge in Japan with a diamond shaped tower and a steel orthotropic box girder deck, which was completed in 1999, Figure 12. The bridge was designed by the consultant Chodai. Steel towers have been used to minimise load on the foundations and hence reduce their size.

The bridges mentioned above were single deck road bridges. It was realised that cable stay bridges with a deep deck could provide the necessary stiffness for railway bridges and that cable stay bridges could be designed and constucted to carry both rail and road. The Kap Shui Mun Bridge in Hong Kong, completed in 1997 with a span of 430 m has a compos-

Figure 11. Normandy Bridge, France.

Figure 12. Tatara Bridge, Japan.

Figure 13. Kap Shui Mun Bridge, Hong Kong.

Figure 14. Oresund Crossing, Denmark & Sweden.

Figure 15. Sutong Bridge, China.

ite box girder deck and H-shaped towers carries six lanes road traffic at the top level and two lanes of road and two mass transit rail tracks at the lower level, Figure 13.

A contemporary to Kap Shui Mun Bridge is the Oresund Crossing between Denmark and Sweden which was completed in 2000 and has a composite truss deck that carries four lanes plus two hardshoulders road traffic at the top level and two heavy rail tracks at the lower level, Figure 14. Oresund Crossing with a span of 490m has free standing towers similar in principle to the Dusseldorf Bridge Family of the 1950's and is a departure from the heavier looking A, H and Diamond shaped towers that were becoming the norm for cable stay bridges. It held the world record for the longest span cable stayed rail bridge span at its opening. The competition winning concept design was led by Jorgen Nissen of Arup.

Since the 1990's by far the major development in cable stay bridges has taken place in the Far East particularly in China with its necessary push on economic development, that has required the crossing of very wide rivers and estuaries with road and rail bridges to reduce journey times and enable efficient transportation of goods and people. Major fundamental research in all aspects of bridge design and construction has and is being carried out in Chinese universities.

At the the turn of the 20th century two major cable stay bridges with spans in excess of 1000 m were constructed in China. Sutong Bridge in mainland China with a span of 1088 m was completed in 2008, Figure 15, followed a year later in 2009 by the 1018 m span Stonecutters Bridge in Hong Kong China, Figure 16.

Sutong Bridge which carries six lanes of traffic crosses the Yangtze river near Shanghai and has a single orthotropic steel box girder, A-shaped towers and two outer cable stay planes giving a high torsional resistance and good aerodynamic stability. The 300 m high concrete box shaped towers have the simple shape of a straight A, which in the Chinese culture reflects the harmony between heaven and earth. The bridge was designed by China Highway Planning and Design Institute (HPDI).

Figure 16. Stonecutters Bridge, Hong Kong.

Figure 17. Russki Bridge, Vladivostok, Russia.

Figure 18. Tiangxingzhou Bridge, Wuhan, China.

Stonecutters Bridge by contrast is particularly unique. It is situated in Hong Kong Harbour which is encompassed with tall buildings in a hilly terrain. At 300 m it has the highest hollow circular monopole bridge towers in the world, which visually blend with the tall buildings and do not compete with them. There is a world first stainless steel-concrete composite section in the upper part of the tower, and the deck which carries six lanes of traffic comprises two separated streamlined steel orthotropic box girders, which is ideally suited to cope with turbulent and high speed typhoon winds, Figure 16. The concept design of the bridge was done by Ian Firth, with the detail design being done under the leadership of Naeem Hussain of Arup.

The trend in longer spans has continued with the completion in 2012 of the Russki bridge in Vladivostok in Far East Russia with a span of 1104 m, which is currently the longest cable stayed span in the world. It has an orthotropic deck and kinked A-shaped towers. Figure 17.

Since the turn of the century long and very long span cable stay bridges for combined road and rail have been developed and constructed in China. The Tiangxingzhou double deck cable stay bridge with a main span of 504 m for high speed rail across the Yangtze River in Wuhan has been completed in 2009, Figure 18. It carries 6 lanes of road traffic at the top and 4 railway tracks at lower level. The bridge was designed under the leadership of Gao Zhongyu of China Railway Major Bridge Reconnaissance Design Institute Co., Ltd (BRDI)

The Pingtan Strait Sea Crossing in Fujian Province, has three navigation channel bridges, all cable stayed composite double deck for road and railway with main spans of 532 m, 364 m and 336 m. The bridges are currently under construction and will be completed in 2019, Figure 19. It carries 6 lanes of road traffic at the top and 2 railway tracks at lower level.The bridges were designed under the leadership of Fan Lilong of China Railway Construction Bridge Engineering Group.

The longest span combined road railway cable stayed bridge will be the 1092 m mainspan Hutong Bridge near Shanghai, which is scheduled for completion in September 2019, Figure 20. It carries 6 lanes of road traffic at the top and

Figure 19. Pintan Strait Crossing, Fujian, China.

Figure 20. Hutong Bridge, Shanghai, China.

4 railway tracks at lower level. The bridge was designed under the leadership of Gao Zhongyu of China Railway Major Bridge Reconnaissance Design Institute Co., Ltd (BRDI).

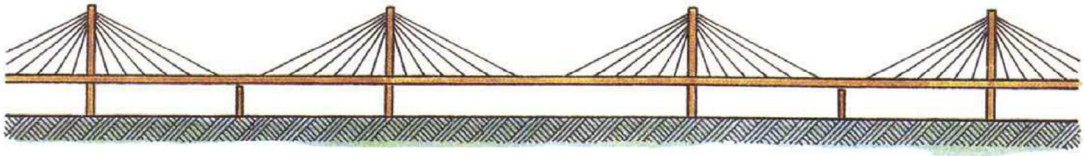
The project linking Hainan Island to the mainland in Southern China is the Qiongzhou Strait Sea Crossing currently under planning for which bridge and tunnel options are being considered. Prof. XIANG Haifan of Tongji University has suggested a 3-tower cable stayed bridge with either 2x1300 m or 2x800 m main spans.

For longer crossings or locations with unique site conditions, multiple span cable stay bridges have been used. As is well known the load transfer of a three span cable stayed bridge from the main spans to the anchor pier or abutment runs from the forestay cables via the tower head into the backstay cables which are anchored to holding down piers and anchor piers. For multiple span cable stay bridges, the backstays, which restrain the horizontal deflection of the tower head, are missing. The issue then is how to restrain the excessive horizontal deflection of the tower head due to live loads which also results in large vertical deflection of the deck. A number of solutions, also well known, are possible to restrain the excesive deflections as shown in Figure 21.

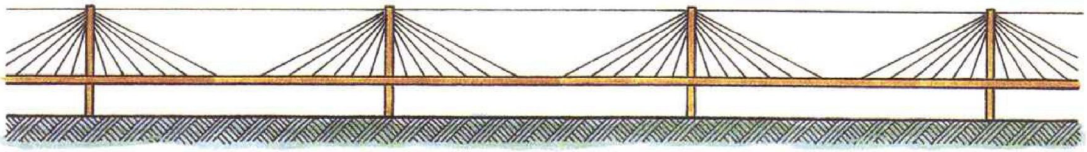
The first solution is to have anchor piers in every second span of multiple span cable stay bridges. Another possibility for restraining the tower head is by means of various cable arrangement. The first one is to connect the top of the towers with horizontal cables which itself is anchored at the outer tie-down piers. A second solution is to tie the tower head by cables anchored to the junction of the side towers and main girder at deck level. A third solution is to overlap the stay cables in the adjacent spans, in which live loads in one of the main spans produces compression (unloading) in the stays of the adjacent spans.

The Second Orinico Bridge has a central anchor pier that is an A-frame in the longitudinal direction which not only restrains the tower head but also caters for the longitudinal rail braking loads, Figure 22.

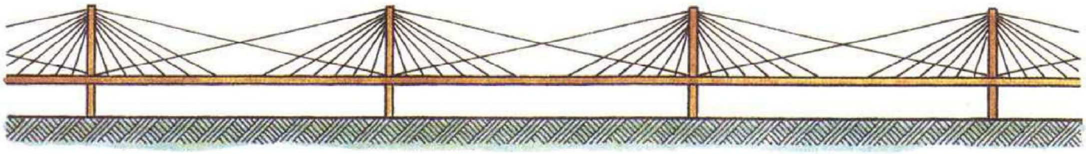
Ting Kau Bridge Bridge in Hong Kong, with six lanes of traffic and two hard shoulders was designed by Jorg Schlaich. It has three slim monopole towers with composite ladder deck



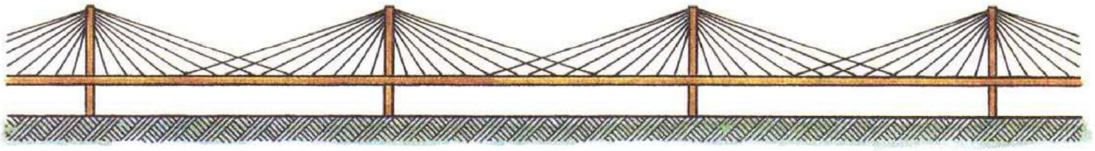
a） 每两跨加中间支柱



b） 塔顶水平拉索



c） 从塔顶到旁边塔的桥面之间增加一条长拉索



d） 由两边塔的部分斜拉索交叉承受每一跨中部的荷载

Figure 21. Restraining of tower head of multi-span cable stayed bridges.

Figure 22. Orinico Bridge, Venezuela.

Figure 23. Ting Kau Bridge, Hong Kong.

Figure 24. Queensferry Crossing, Scotland.

and spans of 448 m and 475 m. The restraining of the central tower is ensured by providing stabilising cables between the top of the tower and the junction of the side towers and deck, Figure 23.

Queensferry Crossing in Scotland, with four lanes of traffic and two hard shoulders has three slim monopole towers with composite box girder deck and spans of 650 m. The restraining of the central tower is ensured by crossing the stay cables at midspan of the adjacent spans, Figure 24. The concept design was done by Naeem Hussain and the bridge was completed in 2017.

Another way of overcoming the problem of restraining the deflection of the intermediate towers is to stiffen the towers themselves. This can be done by using A-towers in the longitudinal direction or using pyramid shaped towers.

The stunning Millau Viaduct in France with spans of 342 m and an orthotropic deck has multiple towers. The restraining of the towers in the longitudinal direction is ensured by use of A- towers above deck level in the longitudinal direction that provide the necessary stiffness, Figure 25. The bridge was designed by Michel Virlegeoux.

Figure 25. Millau Viaduct, France.

Figure 26. Rion Anterion Bridge, Greece.

Figure 27. Yavuz Sultan Bridge, Istanbul, Turkey.

Rion Anterion Bridge in Greece with four towers and composite ladder deck with spans of 560 m is located in a high seismic zone. The restraining of the towers in the longitudinal direction is achieved with use of pyramid towers above deck level that provide the necessary stiffness. The towers are founded on caissons in deep water which rest on a gravel mat on top of the sea bed, reinforced with pile inclusions. In the case of a major seismic event the stone mats act as seismic fuses in that the towers can move on the mats and dissipate energy, Figure 26.

What is the future of cable-stayed bridges? In 1986 there were about 150 major cable-stayed bridges in the world and their number has increased to more than 1000. For many locations it is likely to be the preferred bridge type in the range of 200 – 1200 m with decks being in concrete, composite and steel depending upon the span length. Theoretical studies have shown that cable-stayed bidges could be economic up to spans of 1500 m, but the main constraint on larger spans is likely to be the stay cables as their stiffness will be lower with longer lengths and they will be susceptible to oscillations. Special dampers will be required both at the top and bottom of the stay cables combined with use of tuned mass dampers for the girders to limit parametric stay cable oscillations. Carbon fibre stay cables may be used.

Another major development is the use of hybrid cable-stayed plus suspension bridges. The Third Bosporus Bridge (Yavuz Selim Bridge) for road and rail with a span of 1450 m and completed in 2017 is a major breakthrough in use of hybrid solutions for very long span combined road and rail bridges, Figure 27.

The future development of cable-stayed bridges will continue to take place with possible use of composite materials and construction ingenuity being deployed on a world wide basis.

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