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History of Cable-Stayed Bridges

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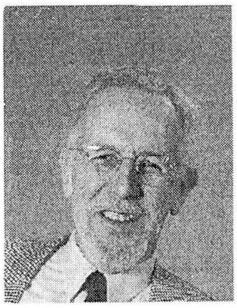

Niels J Gimsing, born 1935, is professor at the Technical University of Denmark since 1976. He has at several occasions acted as specialist consultant during the design of major bridges.

Abstract

The principle of supporting a bridge deck by inclined tension members leading to towers on either side of the span has been known for centuries but it did not become an interesting option until the beginning of the 19th century when wrought iron bars, and later steel wires, with a reliable tensile strength were developed. A limited number of bridges based on the stayed girder system were built – and more proposed – but the system was never generally accepted at that time.

In the second half of the 19th century a considerable number of bridges were built with a cable system comprising a suspension system with parabolic main cables and vertical hangers as well as stay cables radiating from the pylon tops. As an example, Fig.1 shows the Albert Bridge across the Thames in London. In this bridge from 1873 both the parabolic top 'cable' and the stays were made of eye bar chains.

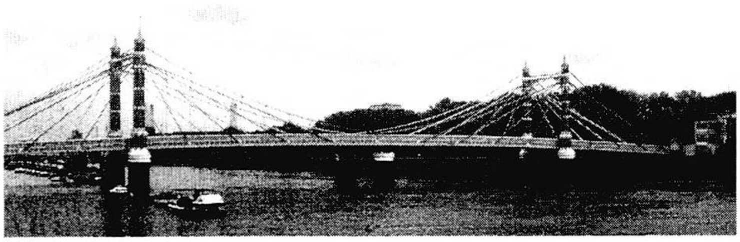

Fig.1 The Albert Bridge across the Thames in London.

The combination of the suspension and the stayed system was also applied in a number of bridges built in France in the 1880s, but the most notable bridges of this type were designed by *John A. Roebling* and built in the United States – among these the longest cable supported bridge of the 19th century: the Brooklyn Bridge.

Cable-stayed bridges as we know them today, i.e. self anchored systems with compression in the deck, were built in France already in the beginning of the 20th century but the Strömsund Bridge in Sweden is generally regarded as the first modern cable-stayed bridge where the efficiency of all cables in the final structure as well as a favorable distribution of dead load moments in the deck is achieved by carefully analysing the erection process.

After the Strömsund Bridge the next true cable-stayed bridge to be erected was the Theodor Heuss Bridge across the Rhine at Düsseldorf. During the 1960s this bridge was followed by many others in Germany where all the major developments took place for over a decade. Among these developments, the introduction of the multi-cable system was of special significance as it simplified the erection procedure and made it easier to design the bridge for stay cable replacements.
These advantages should subsequently result in a general acceptance of the multi-cable system in almost all cable-stayed bridges. However, in that process it should later be realized that the multi-

cable system also presented some disadvantages such as a higher vulnerability to excitations and increased total wind load on the cable system.

Another important development during the 'German Era' was the first application of parallel-wire monocable strands (in the Mannheim-Ludwigshafen Bridge from 1972).

The German cable-stayed bridges were dominated by steel as structural material not only in the cables and the girders but also in the deck plate (orthotropic deck) and the pylons.

Cable-stayed concrete bridges were few during the first decades of the cable-stayed bridge development. However, as a remarkable exception a cable-stayed bridge of unusual proportions had been completed already in 1962: The Maracaibo Bridge in Venezuela. Here both the pylons and the deck girder were made of concrete..

During the 1970s the concrete cable-stayed bridges were further developed and often they proved to be competitive to steel bridges. The first multi-cable concrete bridge was the Brotonne Bridge across the Seine but it was soon followed by many others.

In 1984 the completion of the Barrios de Luna Bridge in Spain gave a further indication of the competitiveness of concrete as structural. With a main span of 440 m the Barrios de Luna Bridge became for a couple of years the record-holder amongst cable-stayed bridges.

During the 1980s the development also included composite girders and for a period of five years the Alex Fraser Bridge with its main span of 465 m became the record-holder.

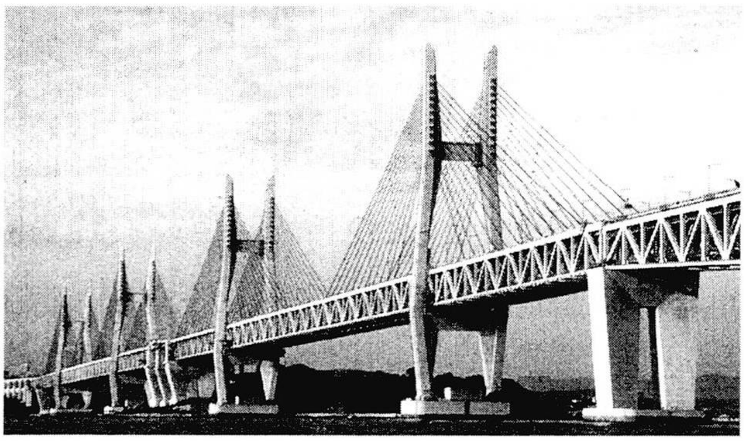

Fig.2 The Hitsuishijima and Iwagurojima Bridges

In Japan the development of cable-stayed bridges comprised the Rokko Bridge, the first double deck cable-stayed bridge, and later in a much larger scale, the double deck concept was used for the twin cable-stayed bridges, the Hitsuishijima and the Iwagurojima Bridges (Fig.2) forming a part of the Seto Ohashi between Honshu and Shikoku. These bridges carry a four-lane expressway on the upper deck and a double track railway - with provisions for a later addition of two more tracks on the lower deck.

In Tokyo a tricky design problem was overcome in the late 1980s by constructing the world's first S-curved cable-stayed bridge (the Katsuhika Harp Bridge).

During the 1990s the development of the cable-stayed bridges have continued and a substantial increase of the span range has occurred. Also, during this decade the geographical point of gravity has switched. Thus, in 2000 seven of the ten longest cable-stayed bridges will be found in the Far East (China and Japan).

Retrospect & Prospect of Cable-Stayed Bridges in China

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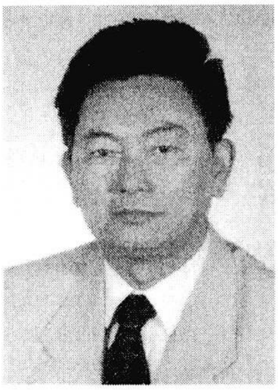

Haifan Xiang, born 1935, finished his postgraduate study in civil engineering at Tongji University in 1958

Abstract

The construction of modern cable-stayed bridges in China initiated in 1972, relatively later compared with other developed countries, but in last two decades of this century, a number of cable-stayed bridges have been built, the span length from 54m of the first bridge has been increased beyond 600m, about 9 cable-stayed bridges with spans over 400m have been opened to traffic, and 3 with spans over 600 m are now under construction. Table 1 shows the main cable-stayed bridges in China with spans over 400m.

	Bridge Name	Location	Main Span	Year of Completion	Deck Type
1	Nanpu Bridge	Shanghai	423 m	1991	composite
2	Yangpu Bridge	Shanghai	602 m	1994	composite
3	Yunxian Bridge / Han River	Hubei	414 m	1994	P.C.
4	2nd Wuhan Bridge / Yangtse River	Hubei	400 m	1995	P.C.
5	Tongling Bridge / Yangtse River	Anhui	436 m	1995	P.C.
6	2nd Chongqing Bridge / Yangtse R.	Chongqing	444 m	1995	P.C.
7	Xupu Bridge	Shanghai	590 m	1996	composite
8	Kap Shui Mun Bridge	Hong Kong	430 m	1997	steel
9	Ting Kau Bridge	Hong Kong	475 m	1998	composite
10	2nd Santou Bay Bridge	Guangdong	518 m	u.c. (1999)	mixed
11	2nd Nanjing Bridge / Yangtse River	Jiangsu Prov.	628 m	u.c. (2001)	steel
12	3rd Wuhan Bridge / Yangtse River	Hubei Prov.	618 m	u.c.(2002)	mixed
13	Jingsha Bridge / Yangtse River	Hubei Prov.	500 m	u.c. (2002)	P.C.
14	Qingzhoulu Bridge	Fujian Prov.	605 m	u.c.	composite
15	Zhanjiang Bay Bridge	Guangdong	480 m	u.c.	P. C.
16	Lingdingyang West Channel	Guangdong	950 m	u.p.	steel
17	Chongming Bridge	Shanghai	1200 m	u.p.	steel
18	Zhenyang Bridge	Jiangsu	625 m	u.p.	steel

Table 1. Major Cable-stayed Bridges in China ($L > 400$ m)

During the progress of building these large cable-stayed bridges, the Chinese bridge engineers and researchers obtained experiences in the design and construction techniques and furthermore gathered more scientific results related to the topics of structural details, earthquake-resistant and wind-resistant design as well as construction control. In this paper, the state of art including some innovative points, for example, general structural systems, stay cable technology and the construction control technique considering creep effects for P. C. cable-stayed bridges will be introduced.

Most of large cable-stayed bridges have been or will be built along the pacific coast of China, the most economic developed region in China. As the coastal line is often hit by typhoons, the wind-induced problems play an important role in designing these large bridges. The State Key Laboratory for Disaster Reduction in Civil Engineering(SKLDCE) at Tongji University has been charged with their wind-resistant studies, where there are three boundary wind tunnels, in which the largest one has a testing dimension of 15m wide, 2 m high and 14 m long. In this paper some of the activities of the group of bridge aerodynamics especially related to cable-stayed bridges will also be introduced.

As the requirement of several strait crossings in China, the span length of cable-stayed bridges will increase to a new record. A traditional cable-stayed bridge with a span length of 950 m has been proposed by the Bridge Design Institute of Tongji University, which has been selected in the design competition for further optimization. In this paper some of the main conceptual considerations for this bridge will be presented for discussion.

In the first two decades of next century, China will be one of the world's hot places in building cable-stayed bridges. Although Chinese bridge engineers have now confidence to build cable-stayed bridges with longer spans, international colleagues are welcome for co-operation.

Bridges with Multiple Cable-Stayed Spans

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Michel Virlogeux, born 1946, worked as civil servant in Tunisia (1970-1974) and then in France at the SETRA. Head of the large bridge division (1980-1994), he designed many bridges among which the Normandie Bridge and the Ré Island Bridge. Now Consulting engineer, he worked as consultant for the Portuguese Administration for the Vasco de Gama bridge.

Abstract

This paper is devoted to a very important development of cable-stayed bridges, bridges with multiple cable-stayed spans. Beginning with historical reference to pioneer bridges by Ricardo Morandi, it evokes the very few bridges built with several cable-stayed spans. It ends with the presentation of recent and important projects which evidence the possibilities of this new concept.

1. Historical background. The specific problem of multiple cable-stayed spans.

The first bridge with multiple cable-stayed spans is the Maracaibo Bridge, designed by Ricardo Morandi and completed in 1962, with six pylons and five main cable-stayed spans 235 metres long ; the pylons are extremely rigid, with an inverted V shape longitudinally and with an additional V to support the deck ; they are rigidly connected to a deck section cantilevering on both sides ; the bridge is completed with simply supported spans to close the bays between the different cantilevers tied to their pylons.

This concept is perfectly adapted to the specific problems of bridges with multiple cable-stayed spans : the pylons are extremely rigid and can directly balance the effects of live loads on either sides ; and with the drop-in spans between the cantilevers supported by the pylons, length variations produced by temperature variations and by concrete creep and shrinkage can freely develop. The single drawback of this solution is its high cost and weight.

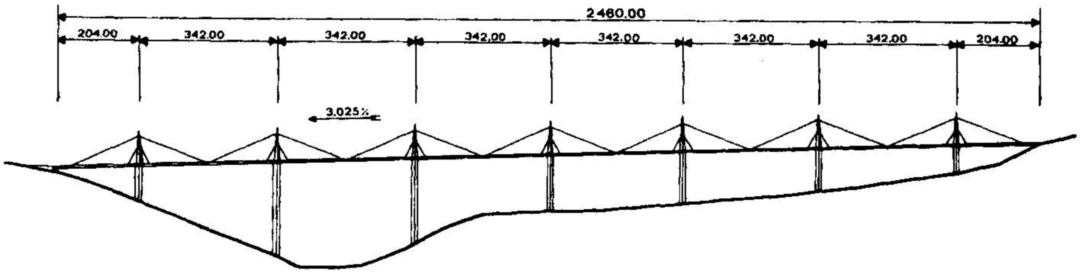
Several solutions others than Morandi's design could be developed, such as the use of head cables or of special cable-stays designed to fix (or tending to fix) the pylons. But, the best solution is the research of an adapted distribution of rigidities between deck , piers and pylons to resist bending forces and limit deflections. Length variations can develop freely if sliding bearings are installed on most of supports ; one line of bearings is enough if the deck is very rigid, but two lines are needed to take advantage of the rigidity of piers. In both cases, the excentricity of the reactions on the piers produced by the deck movements must be considered in the analyses. Another solution consists in designing piers made of two parallel flexible shafts which provide the desired bending rigidity, but which do not strongly oppose to longitudinal movements. A last solution consists in introducing an expansion joint in some spans, with a continuity beam to transfer bending forces through the joint.

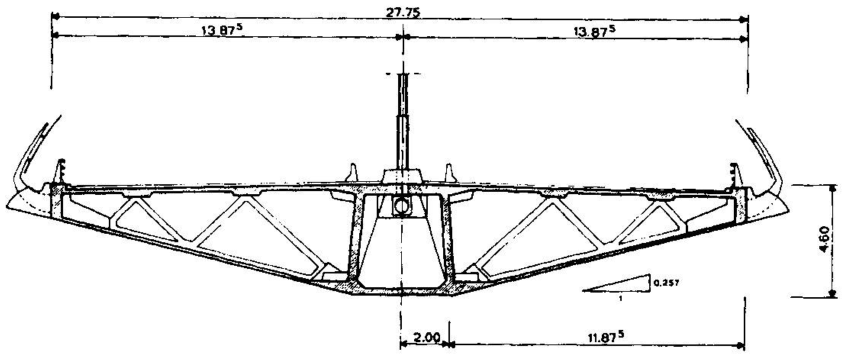
Though some bridges have been built with more than one central cable-stayed span - such as the Kwang-Fu Bridge in Taiwan, the Colindres Bridge and the Arena Viaduct in Spain and the Mezcala Bridge in Mexico - none really used these concepts, because most of them were limited to two central cable-stayed spans, with only one pylon without backstays.

2. New projects

The Pont de la Rade in Geneva, designed by Jean François Klein and Pierre Moia in 1993 - 1994, has four pylons and three central spans 350 metres long. It has a slightly curved alignment for the bridge elegance. The deck is extremely wide, 33.46 metres. Its design is specially elegant, balancing rigidity between a relatively slender deck (an elegant streamlined box-girder, 3.50 metres deep), and rather rigid piers and pylons. Length variations are permitted by the relatively limited distance between the central point and the extreme pylons, but also by soil conditions. Unfortunately the Geneva population voted against the project for financial reasons.

The Millau viaduct is even more ambitious ; almost 2.5 kilometres long, it comprises seven pylons and six central spans 342 metres long with two piers about 240 metres tall. The development of the project has been extremely complex, with an initial design by the SETRA between 1990 and 1993 and with two design competitions. The cable-stayed solution with multiple spans, developed from our conceptual design by SOGELERG - Europe Etudes Gecti - SERF and the British architect Sir Norman Foster, was selected in July, 1996, and the project has been completed in September, 1998.Two alternatives are proposed, the deck being either in prestressed concrete or in steel, with almost the same design adapted to the specific conditions

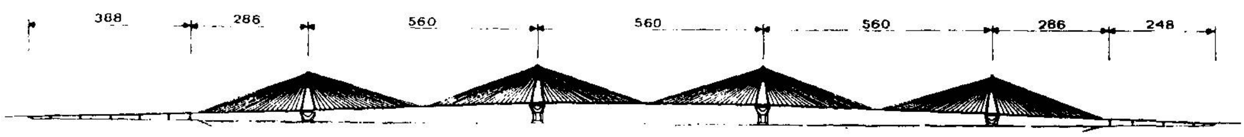




of multiple cable-stayed spans and to the extreme wind forces due to the high position of the bridge in the valley. The rigidity is distributed between the deck, piers and pylons. The deck is a trapezoidal box-girder, with a rather narrow bottom flange. The pylons, 90 metres tall, have the shape of inverted V for a very high rigidity. The design of piers is more complex, since the taller ones have to resist important forces due wind and second-order effects ; and the extreme ones - about 90 metres high - must adapt to very important length variations due to the bridge size ; this led to the final design of solid piers which divide into twin flexible shafts in the upper part, 90 metres high.

A last idea must be evoked to complete this overview : the total suspension concept. It adapts very well to multiple cable-stayed spans since it allows for free length variations without any interference with the rigidity of piers and pylons.

The conceptual design of the Rion-Antirion Bridge was developed by the Grands Travaux de Marseille following the Morandi's concept with drop-in spans between cantilevers. We suggested to have a continuous deck, totally suspended from the four pylons. The concept has been immedialely adopted with many advantages as compared to the initial design : continuity, a regular distribution of cable-stays in the spans to perfectly balance loads... Rigidity this time comes from the pylons, made of four legs with an inverted V-shape in both directions. The final project, now being detailed by GTM and Ingerop, has a continuous deck with five spans, 286 - 3 x 560 and 286 metres long ; and pylons are rigidly connected to the piers, a much more comfortable situation than installing a cantilever on sliding bearings and dampers to reduce seismic forces.



Cable-Stayed Bridges with Special Features

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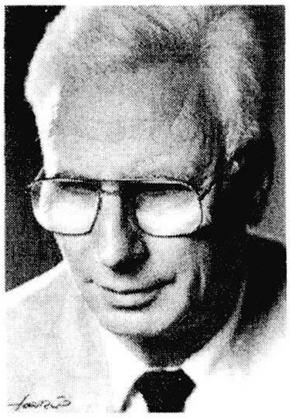

Jörg Schlaich, born 1934 received his civil engineering degree from the Univ. of Berlin and his Dr.-Ing. from the Univ. of Stuttgart, Germany. Since 1974 he is professor and director of the Institute for Structural Design, Univ. of Stuttgart and since 1980 partner of Schlaich Bergermann und Partner, Consulting Engineers, Stuttgart, Germany.

Abstract

Usually if we speak of cable-stayed bridge design parameters, we have their cable-arrangement, pylon-geometry, the cross-sections and the materials of their deck etc. in mind. But the overall layout is considered to be more or less invariable: a three-span arrangement with two pylons, a main-span and two holding down side-spans, and occasionally half of that with one pylon.

However, the cable-stayed bridge concept offers more and can adapt to very special boundary conditions, from local availability of only certain materials or wires to unusual topographical conditions.

The outcome may be e.g. one out of a large number of feasible multi-span arrangements, or a combination of cable-stayed and cable-supported. Other situations may call for cable- stayed bridges, where the deck is not straight in plan but curved, resulting in a horizontal arching action or even for convertible or folding decks.

The author has collected some experience with such special features and will exemplify them by several projected or really built large and small cable-stayed bridges such as the Hooghly Bridge in Calcutta (the first composite-deck cable-stayed bridge with a rivetted steel deck), the Evripos Bridge in Greece (with a solid concrete slab deck), the Argen Bridge in Germany (combining cable-stayed with cable-supported), the Ting Kau Bridge in Hong Kong (with 3 masts and 4 spans), the Fjörde Bridge in Kiel, Germany (a cable-stayed folding bridge) etc..

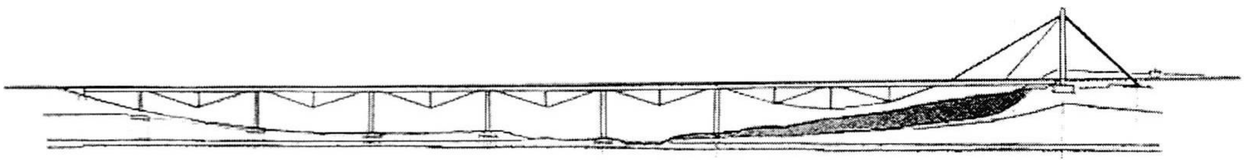

Fig. 1: "Obere Argen Bridge": Proposal

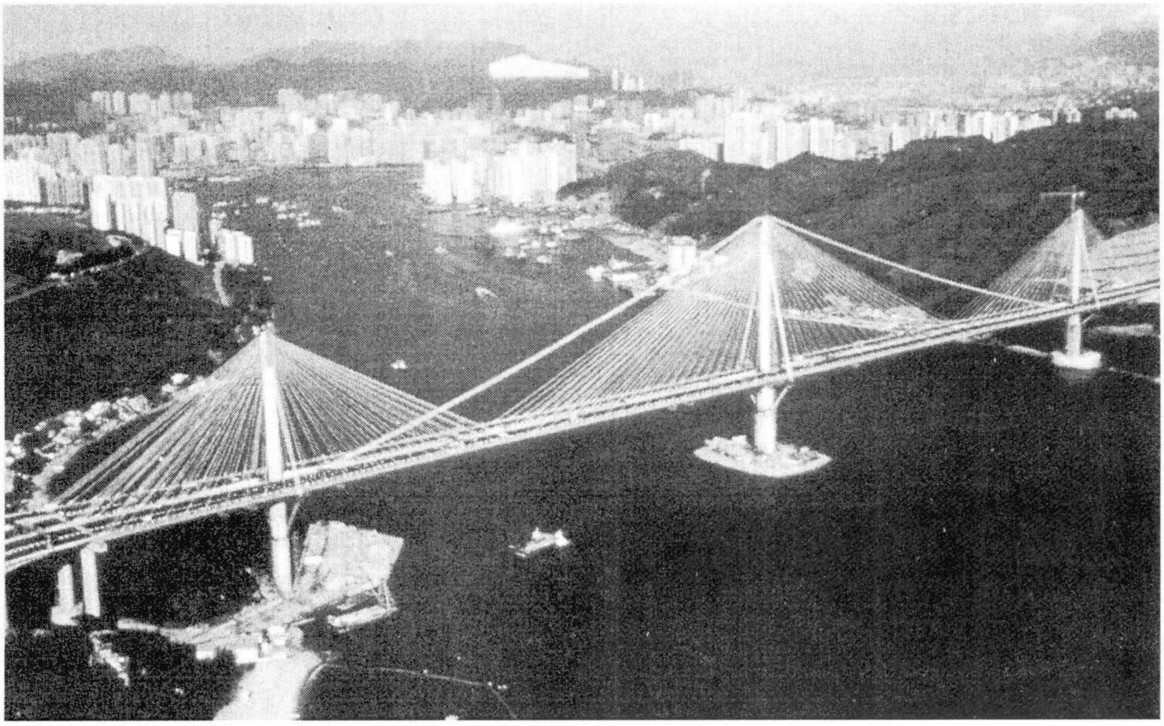

Fig. 2: Ting Kau Bridge, Hong Kong, completed 1998

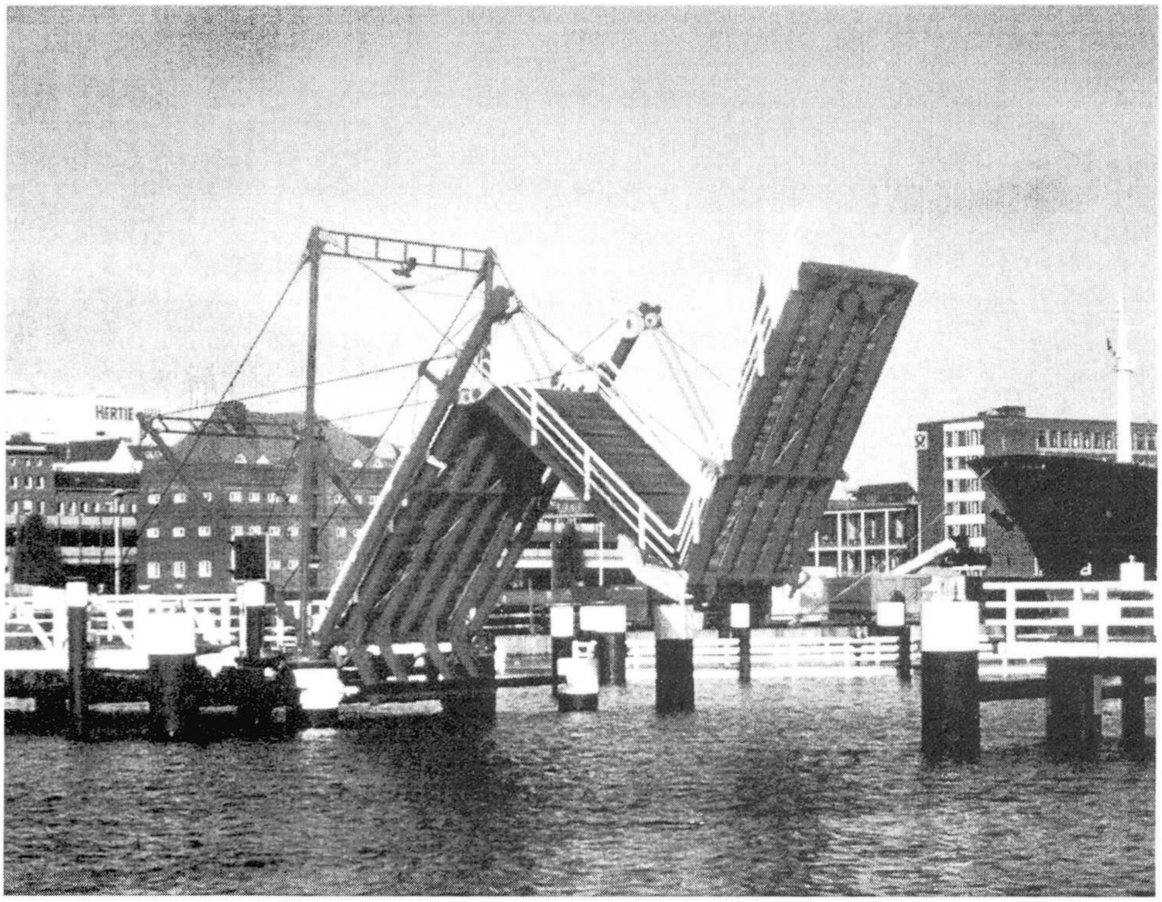

Fig. 3: Folding Bridge, Kiel, completed 1998

Stay Cable Technology: Overview

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Manabu Ito, graduated in 1953 and given Dr. Eng. degree in 1959 from the University of Tokyo, had engaged in teaching and research of bridge engineering at his alma mater. After the retirement in 1991,he moved to Saitama and Takushoku universities. He has been involved in many large bridge projects in Japan, while he is a former vice-president of IABSE.

Abstract

1. Introduction

The stay cables are required to have superb mechanical properties (such as high tensile strength, high elastic modulus and satisfactory fatigue resistance), sectional compactness and excellent corrosion resistance, as well as easiness of handling and installation, and naturally not to be costly.

2. Types of Stay Cable

Helical wire ropes including locked coil ropes were widely used in the earlier steel cable-stayed bridges and have been long adopted on many European bridges. On the other hand, parallel wire or parallel strand cables have better mechanical properties than helical wire ropes, although inferior in easiness of handling. Among them, the parallel strand ropes consisting of the seven-wire strands have been prevalent in prestressed concrete (PC) cable-stayed bridges, and recently further in steel and steel/concrete hybrid bridges. The parallel wire cables covered by a high density polyethylene (HDPE) tube and provided with HiAm anchor sockets have been also popular in both PC and steel cable-stayed bridges. In Japan the shop-fabricated parallel wire strands (PPWS) extensively used on suspension bridges had been preferred for steel cable-stayed bridges until being taken the place by "New PWS".

The New PWS is an ultra-long lay cable strand being composed by 7mm wires. Twisting up to 4^{o} enables the wire bundle to ease reeling and make the strand self-compacting under axial tension without spoiling the mechanical properties. The similar idea was applied to HiAm-SPWC in Europe. The New PWS is also featured by extruding HDPE cover directly onto the wire bundle so that no void will exist between the wires and the surrounding cover. Bar stay cables covered by a steel pipe and filled with cement grout are scarcely used on stay cables, in particular for large cable-stayed bridges.

3. Corrosion Protection

Today the multiple-barrier corrosion system is routine for the stay cables. They consist of at least two barriers: the internal barrier immediately adjacent to the main tension element and the exterior barrier or covering. The wires are mostly zinc-galvanized or coated by epoxy, but non-galvanized wires are used when hydrogen brittlement caused by reaction with grouted cement mortar is feared. The wires of helical wire ropes are galvanized. In addition, voids of spiral ropes are filled with a sealing compound such as metalcoat. On the other hand, recent practice for a locked coil rope stay is to fill the inner voids with polyurethane with zinc dust or linseed oil with red lead, and to coat the outer surface of the rope by polyurethane.

Covering the strand or cable as the exterior barrier is now common to other types of stay cables than helical wire strands. The covering by a metal tube made of steel, stainless steel or aluminum alloy has been prevalent in PC cable-stayed bridges. In case of the steel pipe, coating is required. Anyhow, the installation of metal pipes is to be done at the erection site, and their stiffness may cause some difficulty in handling when a cable is long.

Use of a fiber reinforced plastic or HDPE tube are more popular. The latter is either shop-fabricated or site-fabricated. In case of New PWS and seven-wire strands, the covering is completely shop fabricated by a directly extruded HDPE sheath after executing the internal barrier. Although the original color of the PE covering is black, cable coloring techniques are now available. Supplementary wrapping with colored Tedler tapes is an alternative.

The typical blocking compound filled between the main tension member and the outer sheathing is cement mortar. But the chemical reaction with zinc and the occurrence of cracks are feared. Use of polymer cement or cement grout plasticized with polyurethane may improve the situation. Synthetic resin material based on polybutadiene was once used on Japanese bridges. These alternatives are, however, more costly. Grease and wax are also the blocking compound for PWS and prestrssing strands in combining use with other measures.

4. Preventive Measures against Wind-Induced Vibrations

The stay cables has become vulnerable to wind-induced vibrations since the introduction of multi-stay system with thin cables covered by polyethylene sheath having smooth surface. Particular care should be taken for vortex excitation, wake galloping and rain-wind-induced vibration. Preventive measures can be classified into mechanical and aerodynamic means. It must be borne in mind that the exciting mechanisms of different phenomena differ.

Occurrence of wake galloping depends on the spacing of neighboring cables. Small spacing not larger than two times or quite wide spacing more than six times the cable diameter can remarkably moderate the response. Otherwise the cable vibration can be suppressed by connecting the both cables by a few spacers or small mechanical dampers.

One of the common mechanical means being used for all the vibration types are the secondary thin cables connecting the stay cables and often terminating at the deck. But care must be taken on the rupture of the secondary cables and the fatigue failure of the connection fittings due to repeated loading. On the other hand, seemingly the most effective and prevalent measure is to install viscous dampers between the cable and the bridge deck. First recommendation is to place such damping materials as neoprene ring or high-damping rubber between cable and steel exit pipe at pylon and deck anchorage. Further additional damping can be provided by the hydraulic dampers or shear-viscous dampers near the anchorage at the deck. Aesthetic consideration is desirable at this time. However, it is not easy to make compromise between the requirement to lower the dampers and the efficacy of the damper. The classical Stockbridge type tuned-mass damper that once used on a few European bridges may spoil the appearance of the structure.

The aerodynamic means for the round cables are to modify the cable surface. Helical fins are used to suppress vortex excitation if the appearance is not spoiled. The measures developed for preventing rain-wind-induced vibration are the axial protuberances in the form of longitudinal ribs or grooves and pattern-indented surface with roughness applied disorderly in a convex or a concave pattern. Attention should be paid on the increase of drag coefficient in these cases.