International Association
for Bridge and Structural
Engineering (IABSE)

Proceedings

IABSE Conference

Cable-Stayed Bridges
- Past, Present and Future

The Öresund Construction Site, October 1998

Malmö, Sweden 2-4 June, 1999

Jointly organized by the Danish and Swedish Groups of IABSE

Produced by Congrex Sweden AB

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Address by the President of IABSE

The Swedish and Danish Groups have taken the initiative to organise this important conference on ”Cable-Stayed Bridges - past, present and future”.
This is an excellent example of a joint arrangement in keeping with the aim of IABSE to develop and exchange know-how in order to make civil and structural engineering activities contribute to the development of society.
Several modern construction technologies for both the tunnel and bridge part have been introduced and set the trend for future major links crossing waterways.
The tunnel was specifically dealt with at the IABSE Colloquium on Tunnel Structures in Stockholm in 1998.
The 8 km bridge with a world-record combined rail and motorway cable-stayed span of 490 m will be almost completed in 1999, an excellent timing for an international conference on cable-stayed bridges to be held in Malmö in June 1999.
This event will be another high-quality event in the endeavour to assemble the structural engineering profession globally with the purpose of exchanging know-how and ideas regarding trend-setting structural engineering for the future.

Klaus H. Ostenfeld
President of IABSE

Welcome Address

The modern cable-stayed bridge has been developed during the second half of the 20th century, and is today the preferred bridge type for main spans in the range from 200 m to 500 m (and in some cases beyond).

The combined bridge and tunnel project of the Öresund link for dual mode transport of high speed railway and motorway is a vital element in the formation of a Northern European financial and commercial centre, the gateway to Scandinavia and the Scandinavian peninsula. The project is an excellent example where Scandinavian bridge and tunnel engineering with international contribution is cooperating, resulting in a high quality modern structural engineering product as a symbol of this new activity for the 21st century.

Most cable-stayed bridges are built to carry roads across rivers and straits, but in a few cases also railways are crossing over the bridges. Among the cable-stayed bridges carrying both road and railway traffic, the Öresund Bridge stands out as the biggest and most heavily loaded bridge of this type. It seems, therefore, to be a good opportunity to link the completion of this bridge to an international conference covering a wide variety of topics related to the static and dynamic behaviour of cable-stayed bridges.

For the first time in the history of IABSE two National Groups jointly arrange an international conference. As chairmen of the Danish and Swedish Groups we cordially invite all engineers interested in cable-stayed bridges to come to Malmö, Sweden in early June 1999.

Niels J. Gimsing
Chairman of the Danish
Group of IABSE
Chairman of the Scientific Committee

Hans Ingvarsson
Chairman of the Swedish
Group of IABSE
Chairman of the Organising Committee

TECHNICAL PROGRAMME

KEYNOTE LECTURES

Wednesday 2 June, 11.20-12.00

Niels J.Gimsing, Denmark, *History of Cable-Stayed Bridges*
Haifan Xiang, China, *Retrospect & Prospect of Cable-Stayed Bridges in China*

SESSION 1 - Design and Construction

Wednesday 2 June, 13.30-15.30, 16.00-18.00

1:A Chairman: Aarne Jutila, Finland *Co-chairman: Ingvar Olofsson, Sweden*
1:B Chairman: Helge Nilsson, Sweden *Co-chairman: Erik Stoltzner, Denmark*

Plenary session

Loizias M.P. *Concrete Cable-stayed Bridges in the USA*
Chandra, V. & Hsu, R. *The Innovative William Natcher Cable-Stayed Bridge*
Nagai, M., Xie. X., Yamaguchi, H. & Fujino, Y. *Identification of Minimum Width-to-span Ratio of Long-span Cable Stayed Bridges Based on Lateral Torsional Buckling and Flutter Analyses*
Pircher H., Bokan H., Bruer A. *Computer Based Optimising of the Tensioning of Cable-Stayed Bridges*
Astiz, M.A., Fernández Troyano, L., Manterola, J. *Evolution of Design Trends in Cable-Stayed Bridges*
Miyazki M. *Aerodynamic and Structural Dynamic Control System of Cable-Stayed Bridges for Wind Induced Vibration*
Hague S.T. *Seismic Design for the Cape Girardeau Cable-Stayed Bridge*
Reis A.J., Pereira A.P., Sousa D.P. & Pedr J.O. *Cable-Stayed Bridges for Urban Spaces*
Chen D. *A New Method to Assign Initial Cable Forces for Prestressed.Concrete Cable-Stayed Bridges*
T. Vejrum & Petersen, A. *Bridges with Spatial Cable Systems - Theoretical and Experimental Studies*
Christoffersen J., Hauge L., Bjerrum J., Jensen H. E. *Design and Construction of a CFRP Cable-Stayed Footbridge*
Hansvold C., Faller P., Nilsson H. & Svahn P-O *Erection of the Uddevalla Bridge*
Bræstrup M.W. *Cable Stayed GFRP Footbridge across Railway Line*
Bergman D.W. *Ting Kau Cable Stayed Bridge: Challenges in the Construction Process*

Poster Presentations

T. Sugiyama *Seismic Response of Partially Earth-anchored Cable-Stayed Bridge*
V. Chandra, Ricci A., Menn C. & McCabe R. *Charles River Crossing; A Gateway to Boston*
Firth I. *The Design and Construction of the Lockmeadow Footbridge, Maidstone*
Cruz J.S. & Almeida, J. F. *A New Model for Cable-Stayed Bridges Control and Adjustment*
Auperin M. & Dumoulin, C. *Cable Finite Element of High Accuracy*
Baumann, K. & Däniker J. *Sunniberg Bridge, Klosters, Switzerland*
Maeda K., Nakamura H., Konno M., Moroyama Y., Abe M. *Structural Countermeasures for Design of a Very Long-Span Cable-Stayed Bridge under Wind Loads*
Larsen S. V. *Aerodynamic Performance of Cable-Supported Bridges with Large Span-to-Width Ratios*
Sharpe A., Yeoward A.J., & Buckby R. J. *Cable Stayed Bridge in Bandung, Indonesia*
Fan L.C., Chen D.W., Tham L.G., Au F.T.K. & Lee P.K.K. *New Developments of Erection Control for Prestressed Concrete Cable-Stayed Bridges*
Trenkler F., Skrikerud P & Voll D.M. *The Lifting, Transport and Placing of the Öresund Pylon Caissons*
Cremer J.M. *The Val-Benoit Cable-Stayed Bridge*
Han D. & Yan Q. *Construction Control Practice for Panyu Cable-Stayed Bridge*
Wachalski K., Kaminski J. & Sudak M *Some aspects of the design of Martwa Wisla River Bridge in Gdansk*
Larose G.L. & Wagner Smitt L. *Rain/Wind Induced Vibrations of Parallel Stay Cables of the Öresund High Bridge*
Pulkkinen P. *Swietokrzyski Bridge, Warsaw*
Sham R. & Monster A. *The Design of the Zwolle Cable-Stayed Bridge - Integrating Engineering with Aesthetics*
Manabe Y., Hirahara N., Mukasa N. & Yabuno M. *Accuracy Control on the Construction of the Tatara Bridge*

KEYNOTE LECTURE

Thursday 3 June, 08.30-08.50
Michel Virlogeux, France, *Bridges with Multiple Cable-Stayed Spans*

SESSION 2 – Composite Structures

Thursday 3 June, 08.50–09.45
Chairman: William C. Brown, UK *Co-chairman: Henrik Christensen, Sweden*

Plenary Session

Svensson, H.S. *The Development of Composite Cable-Stayed Bridges*
Byers D.D., Hague S.T., McCabe S.L. & Rogowski D.M. *Comparison of Slab Participation: Assumed for Design vs. FEA*
Veje E., Møller Nielsen P., Pedersen F. & Fuglsang K. *Yamuna Cable Stayed Bridge at Allahabad/Naini, India*
de Boer A. & Waarts P.H. *Probabilistic FE analysis of a cable stayed composite bridge*

Poster Presentations
Xia G. A & Kindmann R. *A Method for the Creep Analysis of Composite Cable-Stayed Bridges*
Christensen H., Madsen K. & Petersen C.R. *Composite Structures in the Øresund Bridge*

SESSION ÖRESUND

Thursday 3 June, 10.15–12.30
Chairman: Niels J. Gimsing, Denmark *Co-chairman: Karl-Otto Sicking, Sweden*

Plenary Session
Lundhus P. *Build a Link – Goals, Principles, Strategies and Results*
Falbe-Hansen K. & Larsson Ö. *The Øresund Bridge: Project Development From Competition to Construction*
Nissen J. & Rotne G. *Getting the Balance Right. The Øresund Bridge - Design Concept*
Gimsing J. *The Øresund Bridge: The Tender Project*
Svensson E. *From Eurocodes, Special Investigations and Risk Analysis To Design Requirements for the Øresund Coast to Coast Structures*
Hauge L. & Petersen A. *Detailed Design of the Cable Stayed Bridge for the Öresund Link*
Olofsson I. *Design Coordination of a Design-build Project*
Sørensen, L.Th. & Thorsen N.E. *The Öresund Bridge, Erection of the Cable-Stayed Main Span*

KEYNOTE LECTURES
Friday 4 June, 08.30–09.15
Jörg Schlaich, Germany, *Cable-Stayed Bridges with Special Features*
Manabu Ito, Japan, *Stay Cable Technology Overview*

SESSION 3 – Cable-Stayed Bridges for Railways

Friday 4 June, 09.15–10.15
Chairman: Manabu Ito, Japan *Co-chairman: Ole Damgaard-Larsen, Denmark*

Plenary Session
Bitsch N. & Hauge L. *Design of Girder and Cables for Train Load*
Sham R. *An Innovative Technique for Fitting Trackwork Alignments Through the Railway Envelope of a Cable-Stayed Bridge*
Gimsing J. & Thomsen A. *Comfort Criteria for High Speed Trains on The Øresund Bridge*

Poster Presentations
Karoumi R. *Nonlinear Dynamic Analysis of Cable-Stayed Bridges Excited by Moving Vehicles*
Bruno D. Grimaldi A. & Leonardi A. *Deformability of Long-Span Cable-Stayed Bridges for Railways*

SESSION 4 – Stay Cable Technology

Friday 4 June, 10.45–12.15
Chairman: Manabu Ito, Japan *Co-chairman: Ole Damgaard Larsen, Denmark*

Plenary Session
Dumoulin, C. *Active Tendon Actuators for Cable-Stayed Bridge*
Marchetti M. & Lecinq B. *Stay Adjustment: From Design Perspective to On Site Practice*
Suzuki Y., Hiyama Y., Kondo T., Kawakami T, Suzuki M., Moriuchi A., *Damping Device in Stay Cables of Meiko Central Bridge*
El Kady H.M., Arockiasamy M., Samaan S., Bahie-Eldeen Y., Bakhoum M.M. & El Gammal, M.A. *Damping Characteristics of Carbon Fiber Composite Cables for Application in Cable-Stayed Bridges*
Bournand Y. *Development of New Stay Cable Dampers*
González J.L. & Sobrino J. A. *Fatigue Reliability Evaluation of Cables in Cable-Stayed Bridges. Case Study: The Sama de Langreo Bridge*
McGuire G.J. *PTI Cable Stay Recommendations*

Poster Presentations
Mizoe M., Muroi S., Horii T., Isobe T., Kiyota R. & Imada Y., *The Super High Damping Rubber Damper on the Stay-cables of Meiko East Bridge.*
Hemmert-Halswick A. & Sczyslo S. *Corrosion Protection of Locked Coil Ropes at Road Bridges*
Magonette G., Renda V., Bournand Y., Hansvold C., Jenner, A.G. & Fösterling H. *Experimental Analysis of a Large-Scale Cable-Stayed Mock-up*
Stubler J., Domage J.B. & Ladret P. *Vibration Control of Stay Cables*
Preumont A., Bossens F., Helduser S. Bonnefeld R. & Försterling H. A*ctive Tendon Control of Cable-Stayed Bridges: Control Strategy and Actuator Design*
Roos, F., Noisternig J.F. *CFRP-Tendons -Development and Testing*
Bojan J. Bevc L. & Sonda D. *Laboratory Tests of the Anchorage Plates for the Cables*
Seo-Kyung C. & Seung Wook J. *Erection of Composite Deck for Seohae Bridge*

SESSION 5 – Observation, Maintenance and Repair, followed by Closing Session

Friday 4 June, 13.45–16.30
Chairman: Jørn Lauridsen, Denmark *Co-chairman: Hans Ingvarsson, Sweden*

Plenary Session
Popa V. & Stanciu M. *Bridge Consolidation by Using Cable-Stayed Method*
Yamagiwa I, Utsuno H., Endo K. & Sugii K. *Application of the Identification of Tension and Flexural Rigidity at Once to the Bridge Cables*
Gentile C. & Martinez F. *Dynamic Characteristics of Two Newly Constructed Curved Cable-Stayed Bridges*
Suzuki Y., Mizuguchi K., Sakuma S., Maekawa T., Ueda T. & Kobayashi Y. *Field Observation on Aerodynamic Response of Meiko West Bridge*
Reinholdt P., Veje E. & Kalvslund J. *Rehabilitation of the Luangwa Bridge*
Laigaard J. & Pedersen L. *Design of Structural Monitoring Systems*
Bloomstine M.L. & Stoltzner E. *The Faroe Cable-Stayed Bridge -Maintenance Experience with Major Components*
Andersen H. & Hommel D.L. & Veje E.M. *Emergency Rehabilitation of the Zárate-Brazo Largo Bridges, Argentina*
Yamaguchi K. Manabe Y., Sasaki N. & Morishita K. *Field Observation and Vibration Test of the Tatara Bridge*

Poster Presentations
Gomez R., Muria-Vila D. Sanchez-Ramirez R. & Escobar J. A. *Second Monitoring and Surveillance of the Response of a Cable-Stayed Bridge*
Cunha Á., Caetano E., Calçada R. & Delgado R. *Dynamic Tests on Vasco da Gama Cable-Stayed Bridge*
Fuzier J.P., Stubler J. & Grattepanche D. *The Øresund Stay Cables: Design for Fatigue Resistance and Easy Maintenance*

History of cable-stayed bridges

Niels J GIMSING
Professor
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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.

Introduction

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.

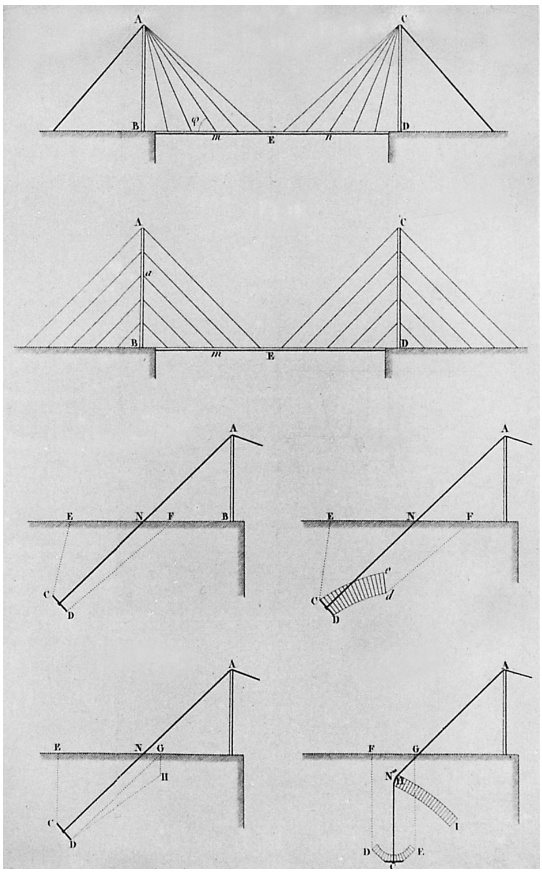

Fig.1 Bridge systems investigated by Navier in the 1820s.

In 1823 the famous French engineer and scientist *C.L. Navier* published the results of a study on bridges with the deck stiffened by wrought iron chains and with a geometry as shown on the original drawing in Fig.1.

It is interesting to note that Navier considered both a fan shaped and a harp shaped system in configurations that today would be denoted multi-cable systems. So the cable systems were actually up-to-date, but in contrast to the present practice the backstays were assumed to be earth anchored, as seen in the lower half of Fig.1.

Navier's final conclusion was that the suspension system should be used instead of the stayed system [1]. This conclusion was to a large extent based on observations of stayed bridges that had failed.

In the early stayed bridges it proved very difficult to arrive at an even distribution of the load between all stays. Thus imperfections during fabrication and erection could easily lead to a structure where some stays were slack and others overstressed. The stays were generally attached to the girder and pylon by pinned connections that did not allow a controlled tensioning.

The problems encountered and the recommendation by Navier resulted in a very limited number of stayed girder bridges being built up to the 1950s, whereas systems where the suspension system was combined with the stayed system was used in many major bridges built in the second half of the 19th century.

As an example, Fig.2 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. The Albert Bridge still exists so the system has certainly proved its durability.

Fig.2 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 [2].

Introduction of the self anchored cable-stayed bridge system

Around the turn of the century the French engineer *A.V. Gisclard* developed an earth anchored, stayed system in which not only the inclined stays but also the tension members at the deck level were made of cables. In the 1920s the system by Gisclard was developed further by substituting the horizontal cables by the deck girders and changing the earth anchored system to a self anchored system with compression rather than tension along the deck – for example used in the Lezardrieux Bridge from 1925. So in reality the system of the modern, self anchored cable-stayed bridges was developed at that time.

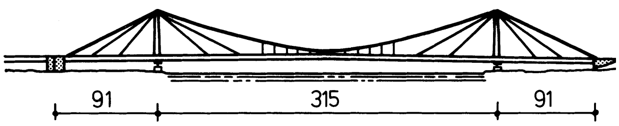

Fig.3 Dischinger's proposal for a bridge between Köln and Mühlheim.

The combined suspension and stayed system used extensively at the end of the 19th century was abandoned from the beginning of the 20th century and substituted by pure suspension systems. However, in 1938 *Dischinger* proposed a system in which the central part of the span was carried by a suspension system whereas the outer parts were carried by stays radiating from the pylon top. This system was proposed for a cable supported bridge with a 750 m main span to be built across the Elbe River in Hamburg.

In connection with the reconstruction of German bridges after the war, the Dischinger system was proposed at several occasions (Fig.3) but it was never used for actual construction. One of the reasons is undoubtedly the pronounced discontinuity of the system both with respect to the structural behavior and to the appearance. The discontinuity reflects Dischinger's discontent at the original Roebling system with its much more continuous configuration achieved by overlapping the multi-cable stayed system and the suspension system. In the publication of his own system, Dischinger categorically stated that the stays of Roebling's bridges had proved to be completely inefficient!

Although never adopted for actual construction, the proposals by Dischinger undoubtedly had a considerable influence on the subsequent introduction of the pure cable-stayed bridge. Thus, the Strömsund Bridge, which is generally regarded as the first modern cable-stayed bridge was designed by Dischinger. The bridge was of the three-span type, a system commonly used for suspension bridges, and it had a main span of 182.6 m flanked by two side spans of 74.7 m (Fig.4). The stays were arranged according to the pure fan system with two pairs of stays radiating from each pylon top. The steel pylons were of the portal type supporting the two vertical cable systems arranged on either side of the bridge deck. The deck girder contained two plate girders positioned outside the cable planes to allow an "invisible" anchoring of the stays inside the plate girders.

Fig.4 The Strömsund Bridge.

The start of a new era for cable-stayed bridges was to a large extent due to the improved technique of structural analysis allowing calculation of cable forces throughout the erection period and thereby assuring the efficiency of all cables in the final structure as well as a favorable distribution of dead load moments in the deck. Probably, such calculations were for the first time made for the erection of the Strömsund Bridge.

Regarded as a plane system, the Strömsund Bridge is statically indeterminate to the eighth degree, but by dividing the load into a symmetrical and an antisymmetrical part, the number of redundants could be reduced to four. This was well within acceptable limits for the numerical work that could be performed with the slide rule and the mechanical calculators available at the beginning of the 1950s.

The German era

After the Strömsund Bridge the next true cable-stayed bridge to be erected was the Theodor Heuss Bridge across the Rhine at Düsseldorf - opened to traffic in 1957 (Fig. 5). With a main span of 260 m and side spans of 108 m it was considerably larger than the Strömsund Bridge. Also, the Theodor Heuss Bridge was more innovative by introducing the harp shaped cable system with parallel stays and a pylon composed of two free-standing posts fixed to the bridge deck structure. The harp configuration was chosen primarily for aesthetic reasons giving a more pleasant appearance of the two cable systems when viewed from a skew angle.

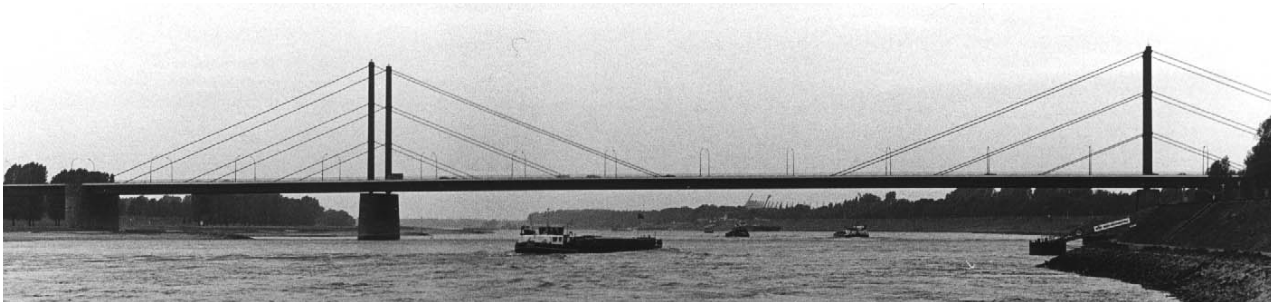

Fig.5 The Theodor Heuss Bridge.

The Theodor Heuss Bridge gave a very clear indication of the cable-stayed bridges' potentials initiating an impressive development of cable-stayed bridges first in Germany and later throughout the world in the decades to follow.

The second cable-stayed bridge to be erected in Germany was the Severins Bridge in Köln (Fig.6). This bridge featured the first application of an A-shaped pylon combined with transversally inclined cable planes, and it was the first to be constructed as an asymmetrical two span bridge with a single pylon positioned at only one of the river banks. The cable system of the Severins Bridge was of the efficient fan shaped type, which is in good harmony with the A-shaped pylon. The cross section of the deck girder was essentially the same as used in the Theodor Heuss Bridge with two box girders connected by the orthotropic steel deck. Because of the substantial compression in the girder due to the one-sided arrangement of the pylon, the application of a steel deck was particularly advantageous in the Severins Bridge, as axial compression could be distributed over a large cross-sectional area. At both ends of the cable-stayed portion, the deck girder was made continuous into the adjacent box girder spans.

Fig.6 The Severins Bridge in Köln.

Although one of the very first cable-stayed bridges, the Severins Bridge still stands as a most successful bridge. The design of the pylon with its pronounced dimensions and the way the deck girder "floats" through the pylon constitute fine solutions to the design problems faced.
The third German cable-stayed bridge, the Norderelbe Bridge at Hamburg, introduced the central cable plane with pylons and stay cables positioned in the central reserve of the motorway - a system that in the following years became the preferred system for the majority of cable-stayed bridges to be constructed in Germany - as well as in several other countries.

Fig.7 The original Norderelbe Bridge.

In some of its other design features the Norderelbe Bridge was more unusual, e.g. with pylons twice as high as required for structural reasons and with a cable system looking as if the main task was to support the pylon and not the deck girder (Fig.7).

In the mid 1980s the Norderelbe Bridge had to go through a major rehabilitation program and as part of this the cable system was modified to a more sensible configuration. So today the Norderelbe Bridge is less peculiar in its appearance.

After the Norderelbe Bridge came the Leverkusen Bridge (opened in 1964) across the Rhine. This bridge had the same centrally arranged cable plane, but here the cable system was of the harp configuration with two sets of stays connected to each pylon. Each stay comprised two individual cables composed of seven locked-coil strands.

The multi-cable system

In the early cable-stayed bridges built at the end of the 1950s and the beginning of the 1960s each stay cables was generally composed of several prefabricated strands to achieve the large cross sections required in these bridges with their limited number of cables. However, the multi-strand arrangement of the individual stay gave a number of drawbacks such as complicated anchorage details in the girder and difficulties in replacement of strands. These drawbacks could be eliminated if the number of stays was increased so that each stay cable could be made of a single strand and this led to the introduction of the multi-cable system.

Fig.8 The Rees Bridge.

The first two multi-cable bridges to be built were the Friedrich Ebert

Bridge and the Rees Bridge both designed by *H. Homberg* and built across the Rhine. The Friedrich Ebert Bridge contains a central cable plane with two pylons, each supporting 2×20 stays with diameters ranging from 91 to 123 mm, depending on the position of the actual stay. In the Rees Bridge two cable planes each containing a harp-shaped multi-cable system with 2×10 stays were used (Fig.8).

Multi-cable systems lead to a more continuous support of the deck girder, and at the same time the cable forces to be transmitted at each anchor point are reduced, so that a local strengthening of the girder at the anchorages can be avoided. During erection advantages are to be found due to the much shorter deck cantilevers required to reach from one anchor point to the next, and in the final structure the smaller stay units will ease a replacement. These advantages would 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.

Fig.9 The Knie Bridge in Düsseldorf.

In 1969 a notable cable-stayed bridge, the Knie Bridge, was opened to traffic in Düsseldorf (Fig.9). In this bridge the cable system was of the harp configuration with relatively few parallel stays, but in contrast to earlier bridges with the harp system, intermediate supports were added under every cable anchor point in the side span. This increased the efficiency of the harp system to such an extent that it was possible to use a very slender deck girder with an open cross section, i.e. with insignificant torsional stiffness.

In the Knie Bridge an asymmetrical layout similar to that of the Severins Bridge was used with the pylon placed on one of the river banks only. Despite the considerable height of the pylon (114 m) it was possible to compose it of two free-standing posts without any struts or bracing to stabilize laterally.

First parallel-wire strands

In 1972 the completion of the Mannheim-Ludwigshafen Bridge across the Rhine marked the first application of a parallel-wire strand in a major cable-stayed bridge. Each strand (with 295 ungalvanized wires of 7 mm diameter) was anchored by a new type of socket called a HiAm socket with increased fatigue resistance due to the application of a cold filling material containing epoxy compound. Furthermore, the Mannheim-Ludwigshafen Bridge introduced an interesting combination of materials, with the deck girder made entirely of steel in the main span and entirely of concrete in the side span (Fig.10). This combination was very well justified, as the side span (through the application of an intermediate pier) had a maximum free span of 65 m, whereas the main span had a free length of 287 m. Actually, the higher dead load of the side span proved directly advantageous as it reduced the requirement for a vertical anchoring of the girder.

Fig.10 The Mannheim-Ludwigshafen Bridge under construction.

The combination of concrete girders with intermediate supports in the side span and steel girders in the main span was subsequently used in several notable cable-stayed bridges constructed in the 1980s and 1990s.

The cable-stayed Köhlbrand Bridge in the port of Hamburg exhibits the first application of the multi-cable system in a bridge with double cable planes supported by A-shaped pylons (Fig.11). The modified fan system was one of high efficiency which gave advantages not only in the design of the final structures but also during erection as no temporary supports or temporary stays were required.

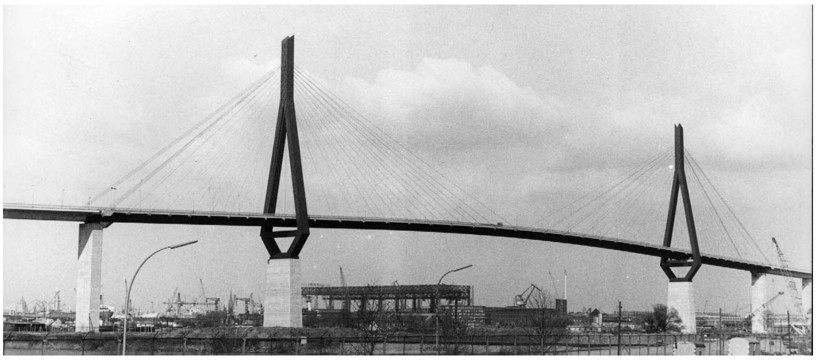

Fig.11 The Köhlbrand Bridge.

From the same period is another remarkable German cable-stayed bridge: the Düsseldorf-Flehe Bridge across the Rhine. Despite a main span length of 367 m it was chosen to build a two-span cable-stayed structure with only one pylon on one of the river banks. This necessitated a pylon with a height of 150 m above ground. In contrast to the general German practice the pylon was made of concrete, and its lambda (λ) configuration was chosen to give support to the central cable plane with a harp shaped cable system in the side span and a modified harp in the main span. In appearance the pylon of the Flehe Bridge is not very harmonic, especially when compared to other, more recent λ-shaped pylons.

For a period of almost twenty years the evolution of cable-stayed bridges was to a very large extent taking place in Germany but in the following years the activities shifted to other locations on the globe.

The evolution outside Germany

During the late 1950s and the 1960s a relatively modest number of cable-stayed bridges were built outside Germany and most of these bridges were based entirely on the German design philosophy.

In the UK the Wye Bridge on the Welsh approach to the Severn Suspension Bridge had been completed in 1965 and this bridge was quite unique by having only one set of stays leading from the pylons to the deck. Based on a similar design concept the Erskine Bridge in Scotland (Fig.12) followed in 1971. Despite its main span of considerable length it also had only one stay leading from each of the two pylons to the deck girder in the 305 m long main span so the girder had to span more than 100 m without support from the cable system. Despite this fact, the deck girder was designed with a depth of only 3.05 m, which is of the same magnitude as found in cable-stayed bridges with several stays supporting the girder at much smaller intervals. As the stay had to be made with a very large cross-sectional area it was composed of 24 helical strands each 76 mm in diameter.

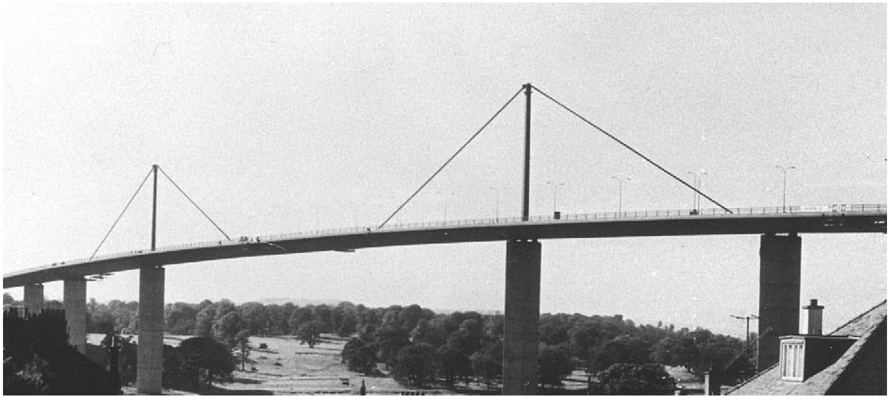

Fig.12 The Erskine Bridge.

During erection of the system with only one permanent stay from each pylon it was necessary to use two temporary stays to reduce the moment in the deck girder when cantilevering from the pylon to the adjacent cable anchor point in the main span.

In France the completion in 1975 of the Saint Nazaire Bridge across the Loire River marked a step further for the cable-stayed bridges as it was the first bridge of this type to span more than 400 m. The pylons consist of an upper A-shaped part of steel and a lower pier shaft of concrete. The cable system is of the multi-cable fan type with each stay made of a single locked-coil strand.

The first major cable-stayed bridge with an earth anchored cable system, the Indiano Bridge across the Arno near Firenze (Fig.13), had a 206 m long main span supported by two fans radiating from the tops of 45 m high pylons leaning slightly backwards. From the pylons, earth anchored back stays

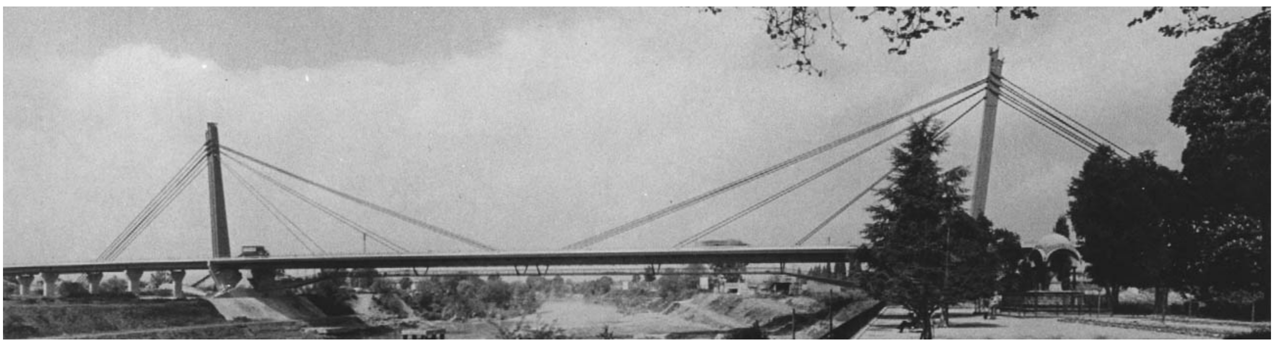

Fig.13 The Indiano Bridge across the Arno at Firenze.

continue to anchor blocks transmitting both the vertical and the horizontal component of the cable force to the soil.

The special problems related to the construction of cable-stayed bridges with earth anchored cable systems were overcome in the Arno Bridge by erecting the deck girder on temporary piers before adding the pylons and the cable system.

Cable-stayed concrete bridges

In the first two decades after the completion of the Strömsund Bridge the evolution of cable-stayed bridges was to a very large extent dominated by steel bridges with orthotropic decks together with plate or box girders and cellular pylons.

However, as a remarkable exception from this a cable-stayed bridge of unusual proportions (and based on a very different design philosophy) had been completed already in 1962: The Maracaibo Bridge in Venezuela, designed by *Riccardo Morandi* (Fig.14). Here both the pylons and the deck girder were made of concrete, thereby introducing a structural material that had not earlier been used in the main elements of cable supported bridge superstructures. Furthermore, it was the first multi-span cable-stayed bridge.

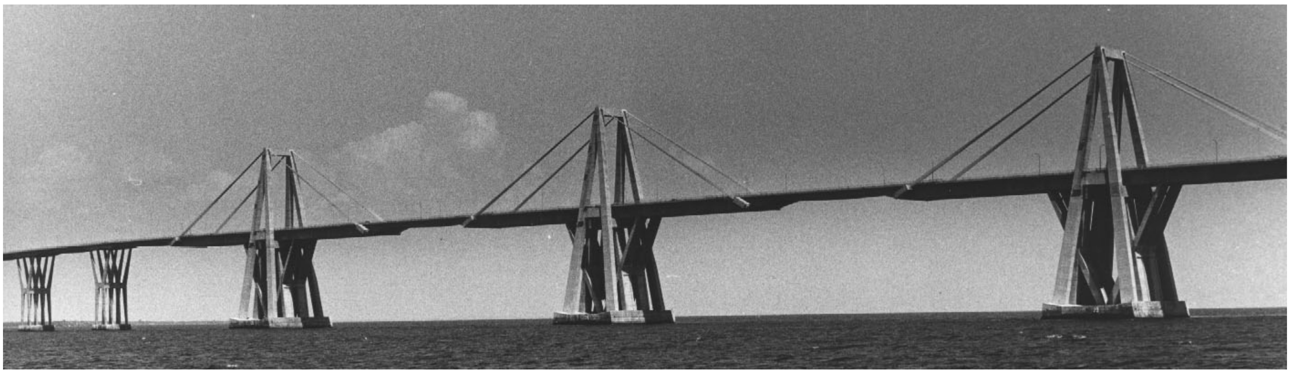

Fig.14 The Maracaibo Bridge.

To allow one-way traffic of ships in and out of Lake Maracaibo, it was chosen to build a bridge with five 235 m long main spans. Each of these spans comprises a double cantilever supported by only one pair of stays radiating from a triangular pylon structure designed to stabilize the system for asymmetrical loads. Between the ends of the cantilevers small suspended spans are arranged, so that the system regarded as a plane system is externally determinate. The application of only one set of stays necessitated a heavy box girder to span from the pylon to the cable supported point, and during construction a large truss was required to support the formwork.

The Maracaibo Bridge was later followed by two other major cable-stayed bridges designed by Morandi, the Polcevara Viaduct in Genova and the Wadi Kuf Bridge in Libya.

However, all of the designs of Morandi were of such a personal style that they did not to any large extent serve as models for the cable-stayed bridges of concrete to come.

A pioneer among the type of concrete cable-stayed bridge to become more fashionable was the Donaukanal Bridge in Vienna (Fig.15) with a main span of 119 m. The deck contains a concrete box girder and the stays are composed of parallel mono strands. The Donaukanal Bridge has a very pleasing appearance and harmonic proportions, and the construction procedure was quite unique as the bridge was cast in two halves on either side of the canal and subsequently turned into position after installation and tensioning of the stay cables.

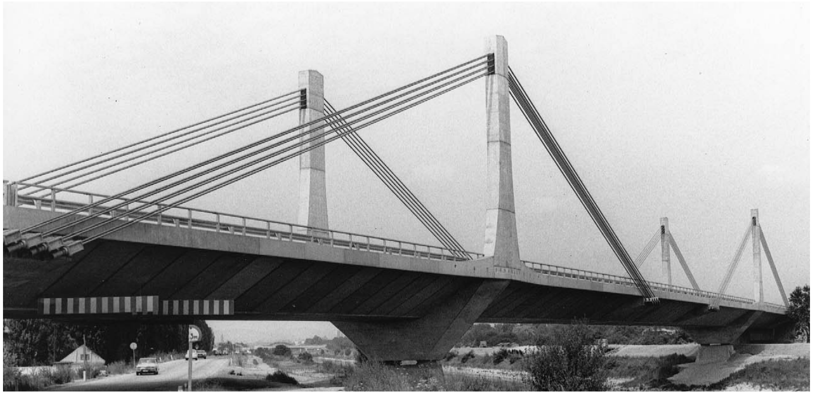

Fig.15 The Donaukanal Bridge in Vienna.

The application of a multi-cable system in a cable-stayed concrete bridge was first seen in the Brotonne Bridge across the Seine. Here a central cable plane was combined with a box-shaped deck girder, made partially of prefabricated elements. The stays were made of parallel seven-wire strands of a type used for tendons in post-tensioned concrete. Corrosion protection was achieved by inserting the parallel strands in stainless steel tubes, subsequently filled with cement grout. The anchoring of the seven-wire strands was initially made by ordinary wedge anchors, but to increase the fatigue strength, especially for pulsating loads, a supplementary anchoring was established by adding epoxy mortar inside a steel tube extending from the wedge anchorages.

Fig.16 The Pasco-Kennewick Bridge.

Another example on the use of the multi-cable system in a cable-stayed concrete bridge can be found in the Pasco-Kennewick (Fig.16). Here, the double cable systems in the fan configuration assure an efficient support of the deck both vertically and torsionally. The stays, each made of a single parallel-wire strand, are inside a grouted polyethylene tube and with HiAm anchors. The deck girder was erected by the segmental method using heavy prefabricated elements having the full width of the roadway.

The twin bridges across the Parana River in Argentina (Fig.17) from1978, were in many ways based on the same design philosophy as used for the Pasco-Kennewick design. However, the deck girders of the Parana Bridges were made of steel. They were the first cable-stayed bridges to transfer heavy railway loading. This gave special design problems which to a certain extent were accentuated by a one-sided position of the single track subjecting the two vertical cable systems to traffic loads of different intensity. For this reason it was necessary to use different dimensions for the stays in the two sides, the heavier cables being required for the railway side.

After less than 20 years of service one of the stay cables in the Parana Bridges broke without warning and as a result a major repair work had to be initiated at the end of the 1990s.

Fig.17 The Parana Bridge.

Fig.18 The Tjörn Bridge.

The superiority of cable supported bridges in crossing navigable waters was clearly demonstrated in the early 1980s when a new cable-stayed Tjörn Bridge was built to replace the original arch bridge after it had been hit by a misnavigated ship. The new bridge was built with a span of 366 m, 86 m more than the span of the arch bridge, and this allowed both pylons to be located on land 25 m from the coastline.

The Tjörn Bridge belongs to the group of cable-stayed bridges with different structural materials in the side spans and the main span (Fig.18). The side spans are designed as continuous concrete girders with intermediate column supports at each cable anchor point whereas the main span is made as a steel box with orthotropic steel deck overhangs.

During the 1980s the activity within the field of cable-stayed bridges was considerably reduced in Europe compared to the previous decades, and most of the bridges built did not deviate much in size or design features from those already constructed. There were, however, a few exceptions from this rule.

In 1984 the completion of the Barrios de Luna Bridge in Spain gave a further indication of the competitiveness of concrete as structural material not only for the pylons but also in the girder of cable-stayed bridges (Fig.19). With a main span of 440 m the Barrios de Luna Bridge surpassed the span of the Saint Nazaire Bridge by a margin of almost 10% and became for a couple of years the record-holder amongst cable-stayed bridges.

The Farø Bridge in Denmark was opened in 1985 and it comprised a 290 m long main span supported by a central cable plane. The girder had originally been designed by the owner as a concrete box but an alternative bid based on a steel box proved to be competitive and was chosen for construction. The concrete pylons form a further development of the diamond-shaped pylons originally introduced in the Köhlbrand Bridge. Thus, in the Farø Bridge the lower triangle is extended all the way down to the water surface (Fig.20) rather than being supported on high pier shafts. Furthermore, the Farø Bridge showed the first application of corrosion protection of the box girder interior by dehumidification of the air.

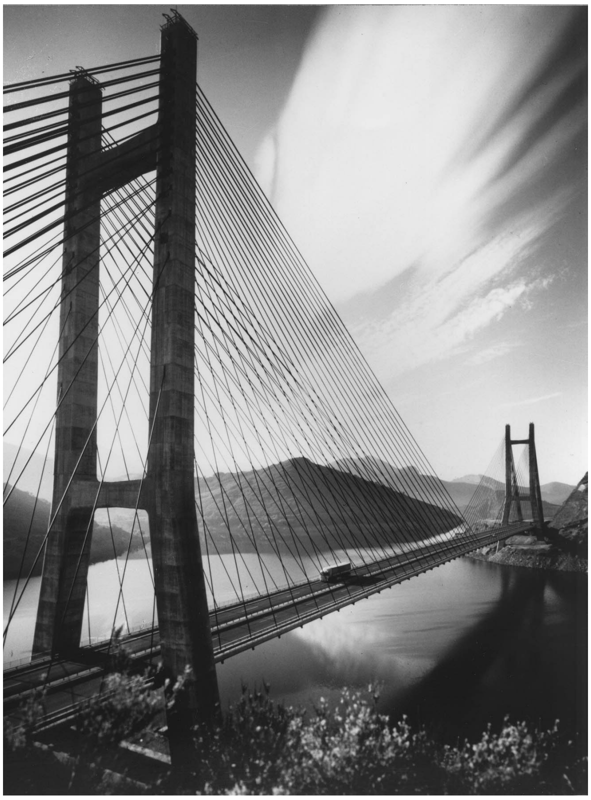

Fig.19 The Barrios de Luna Bridge.

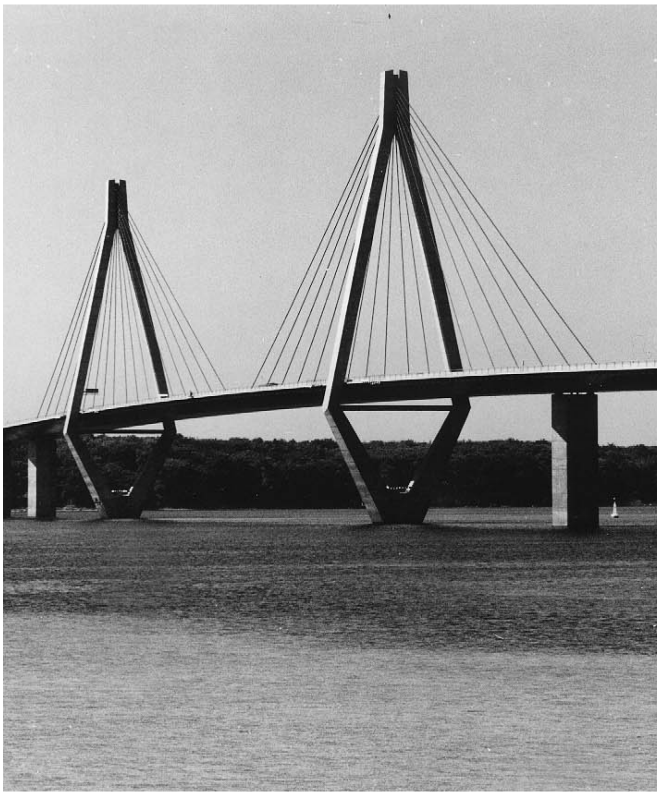

Fig.20 The Farø Bridge.

Within cable-stayed bridges both the type with a central cable plane above the median reserve and the type with two cable planes outside the roadway area had been extensively applied in the first three decades of the modern evolution. To some extent the choice between the two options seemed to depend on the designer's preference rather than on a rational, unbiased comparison between advantages and drawbacks.

H. Homberg had clearly preferred the central cable plane concept wherever it was applicable, i.e. where the road to be carried had a median reserve. It is therefore not surprising that Homberg's largest cable-stayed bridge, the Rama IX Bridge in Bangkok was designed with a central cable plane, despite the span of 450 m. The cable system is of the multi-cable, modified fan configuration and all stays are made of single locked-coil strands, among these the largest diameter locked-coil strand fabricated so far with a diameter of 174 mm. The deck girder in the main span is a quasi trapezoidal, five cell box with the full width of the bridge deck (32.5 m) and with a depth of only 4 m.

The American experience

A pioneer among cable-stayed bridges in North America was completed in Montreal already in 1969: the Papineau Bridge (Fig.21) with a main span of 241 m. In several of its design features this bridge could resemble the Leverkusen Bridge and other German bridges with a central cable plane and a deep, but relatively narrow, box girder under the wide orthotropic bridge deck. The cable system was of the fan type with only two sets of stays radiating from each pylon top. Each stay cable was composed of several helical bridge strands of galvanized wires, and as a novelty each strand was covered by a hot extruded polyethylene coating with a minimum cover of 5 mm - a protective system that should later be used extensively.

Fig.21 The Papineau Bridge in Montreal.

Apart from the Papineau Bridge and a limited number of other bridges the activity within construction of cable-stayed bridges had been very low in North America during the 1960s and the early 1970s, but from then on the situation changed dramatically.

In Florida a ship collision accident had given a clear indication of the inadequacy of the navigation opening in the 250 m long main span of the Sunshine Skyway. It was, therefore, decided to replace the existing two parallel bridges by a single bridge having a 360 m long cable-stayed main span. Two designs were prepared for the bridge, one based on a composite deck and two cable planes along the edges of the bridge deck, and the other as a pure concrete box and a single central cable plane. Both designs were put out for tender and the result showed a very close race between the two options.

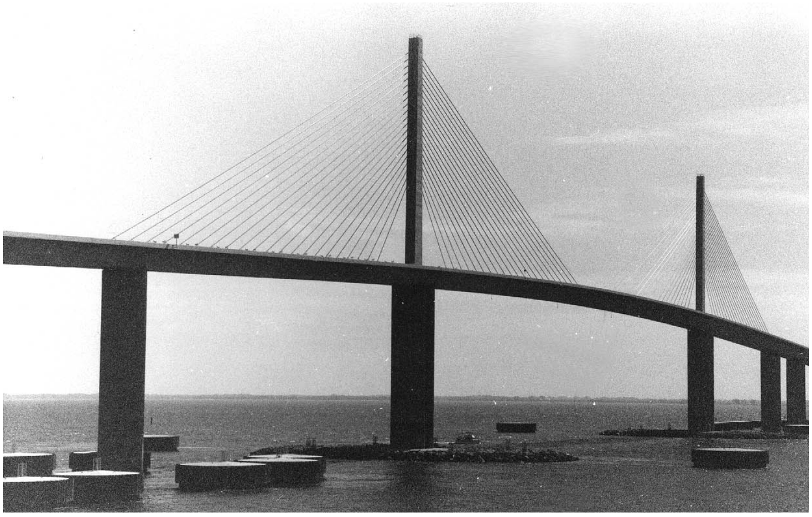

Fig.22 The Sunshine Skyway Bridge.

The final choice was to construct the concrete bridge according to a design based on the principles initially introduced during design and construction of the Brotonne Bridge in France. With its main span of 366 m the Sunshine Skyway was at its completion in 1986 the longest cable-stayed bridge in the USA (Fig 22).

The composite girder alternative for the Sunshine Skyway was based on a system with two longitudinal plate girders directly under the cable planes and a large number of transverse girders to give support to the deck slab of reinforced concrete. In its main features this concept was subsequently applied in another North American bridge, the Alex Fraser Bridge (Annacis Island Bridge) at Vancouver in Canada. With its main span of 465 m the Alex Fraser Bridge (Fig.23) became the record-holder among cable-stayed bridges for a period of five years.

The potentials of the composite girder concept was clearly demonstrated during the construction of the Alex Fraser Bridge. Thus, the cantilevering from one cable anchor point to the next was easily accomplished by the relatively light steel girders, allowing the stay cables to be added before the heavy concrete deck was erected using precast slabs. At the same time the concrete slab could be efficiently utilized to transfer the axial compression induced into the girder by the horizontal components of the stay cable forces.

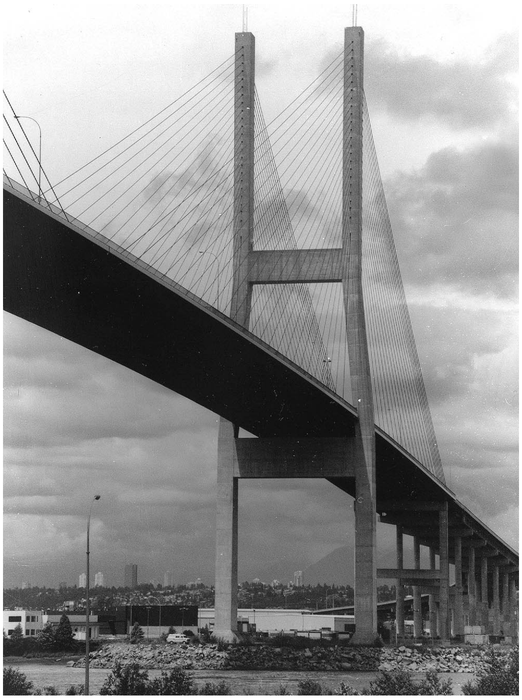
Fig.23 The Alex Fraser Bridge.

The advantages of applying composite girders in cable-stayed bridges should in the years to follow the construction of the Alex Fraser Bridge lead to a situation where this system was gradually being preferred for the majority of cable-stayed bridges in North America.

In the USA the general trend throughout the 1980s was to simplify the design of especially the girders in cable-stayed bridges. Within concrete bridges a good example on this trend is the Dames Point Bridge at Jacksonville in Florida. With a main span of 396 m the bridge surpassed the Sunshine Skyway as the longest concrete cable-stayed bridge in North America.

The cable system of the Dames Point bridge is a multi-cable harp system supported by concrete pylons with a considerable flexural stiffness in the longitudinal direction. This gave the cable system very good deformational characteristics so that the girder could be made with a depth of only 1.5 m corresponding to 1/260 of the main span length.

In principle the structural system of the girder in the Dames Point Bridge corresponds to that of the Alex Fraser Bridge, i.e. with two longitudinal girders beneath the cable planes and numerous transverse girders. However, in the Dames Point Bridge the longitudinal girders are made as solid concrete ribs with a depth of 1.5 m and a width of 2.5 m allowing a most efficient anchoring of the stay cables.

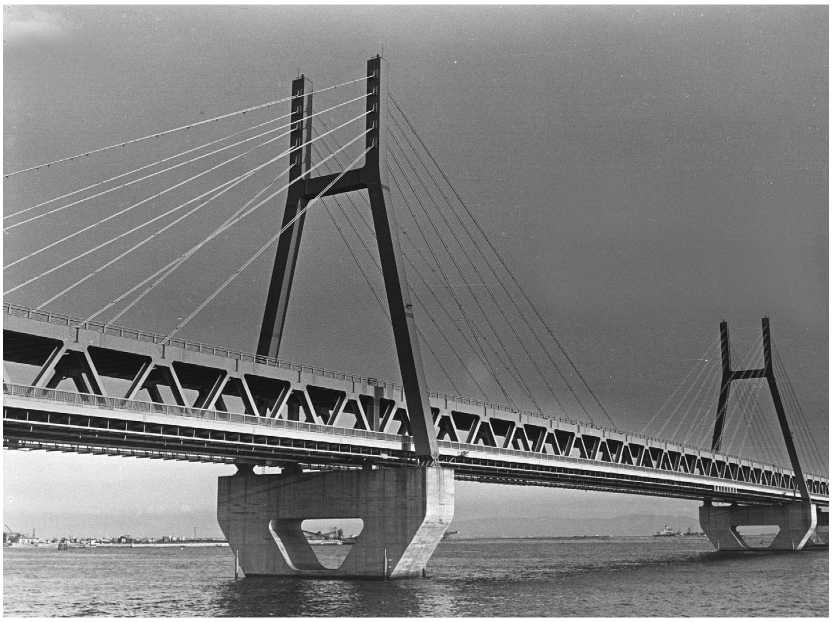
Fig.24 The Rokko Bridge in Kobe.

Seen in comparison with the Pasco-Kennewick Bridge - the first major concrete cable-stayed bridge in North America - the Dames Point Bridge clearly shows the simplifications in girder design.

The Japanese development

In Japan the cable-stayed bridges were introduced already in the late 1950s but the first bridges of this type were not characterized by special design features so they had little influence on the further developments. However, in 1977 the Rokko Bridge, the very first double deck cable-stayed bridge, was completed in Japan (Fig.24). The deck is made as a truss with a depth of approx.8 m to give ample headroom, daylight, and fresh air on the lower deck. The cable system is of the multi-cable type with each stay composed of two parallel-wire, mono-strand cables.

In a much larger scale the double deck concept was later used for the twin cable-stayed bridges, the Hitsuishijima and the Iwagurojima Bridges (Fig.25), that form a part of the Seto Ohashi between Honshu and Shikoku. Each of the two neighbor bridges has spans of 185 m - 420 m - 185 m. The traffic is running on a two level truss with a four-lane expressway on the upper deck and a double

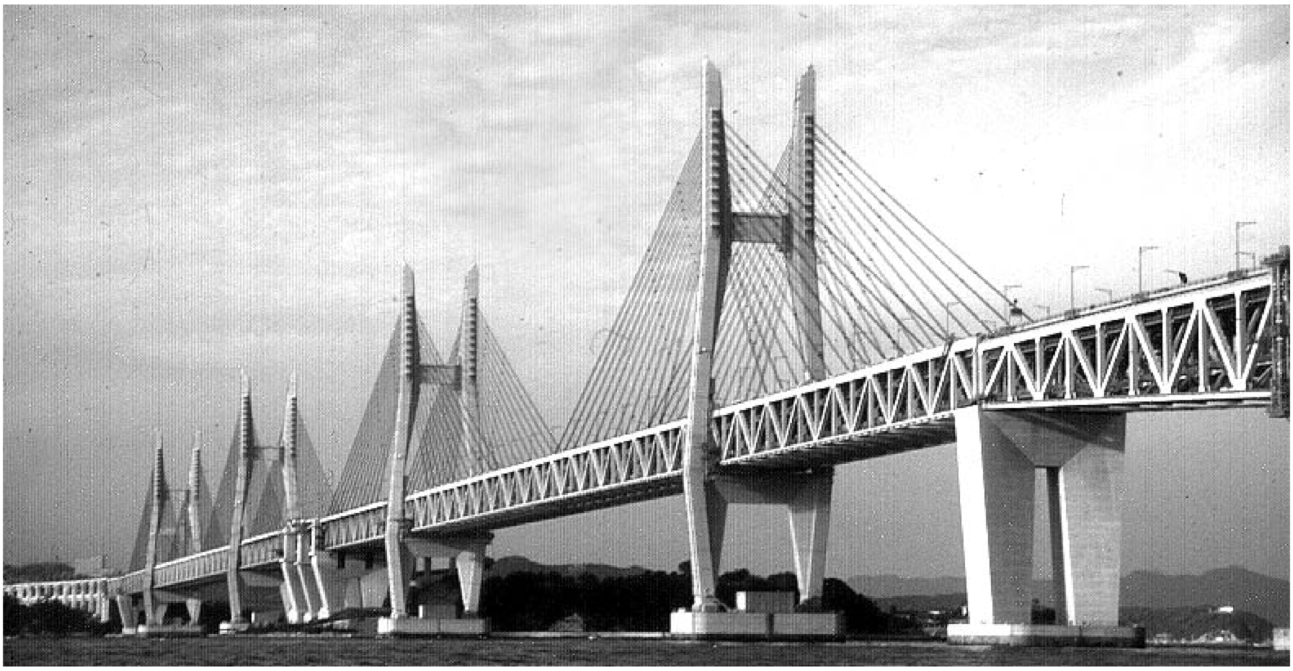

Fig.25 The Hitsuishijima and Iwagurojima Bridges of the Seto Ohashi.

track railway (with provisions for a later addition of two more tracks) on the lower deck. The cable systems are of the modified fan configuration with two vertical cable planes positioned directly above the deck trusses. Thus, a high efficiency of the cable supporting for both vertical and torsional loading is achieved.

Fig.26 The Meiko Nishi Bridge in Nagoya.

An elegant cable-stayed bridge was completed in Japan in 1985 across the port of Nagoya, the Meiko Nishi Bridge (fig.26). Here the roadway is carried by a semi-streamlined box girder supported by two inclined cable planes radiating from the top of A-shaped pylons. With the chosen pylon shape and the fan shaped cable systems, the Meiko Nishi Bridge constitutes a fine example of a highly efficient cable-stayed bridge.

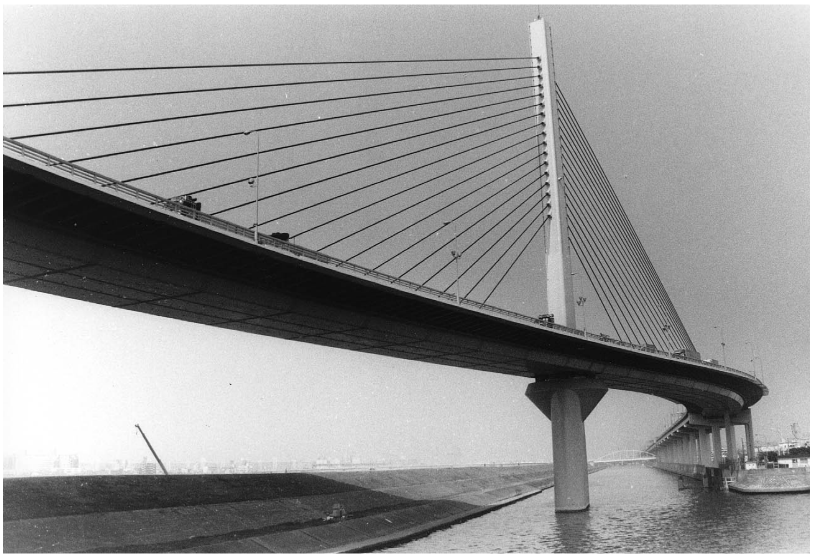

Fig.27 The S-shaped Katsuhika Harp Bridge in Tokyo.

In Tokyo a tricky design problem was overcome in the late 1980.s by constructing the world's first S-curved cable-stayed bridge (the Katsuhika Harp Bridge) comprising a central 'twisted' cable plane and two pylons of different height (Fig.27).

The double deck configuration was again applied in the Yokohama Bay Bridge opened to traffic in 1989. With its main span of 460 m the bridge was only 5 m shorter than the Alex Fraser Bridge in Canada - at that time the record-holder amongst cable-stayed bridges. The truss of the Yokohama Bay Bridge has its top chord made as a 39 m wide and 3 m deep, streamlined box girder, whereas the bottom chord and the diagonals are of more conventional bluff box sections. The total depth of the truss is 12 m corresponding to 1/38 of the main span length.

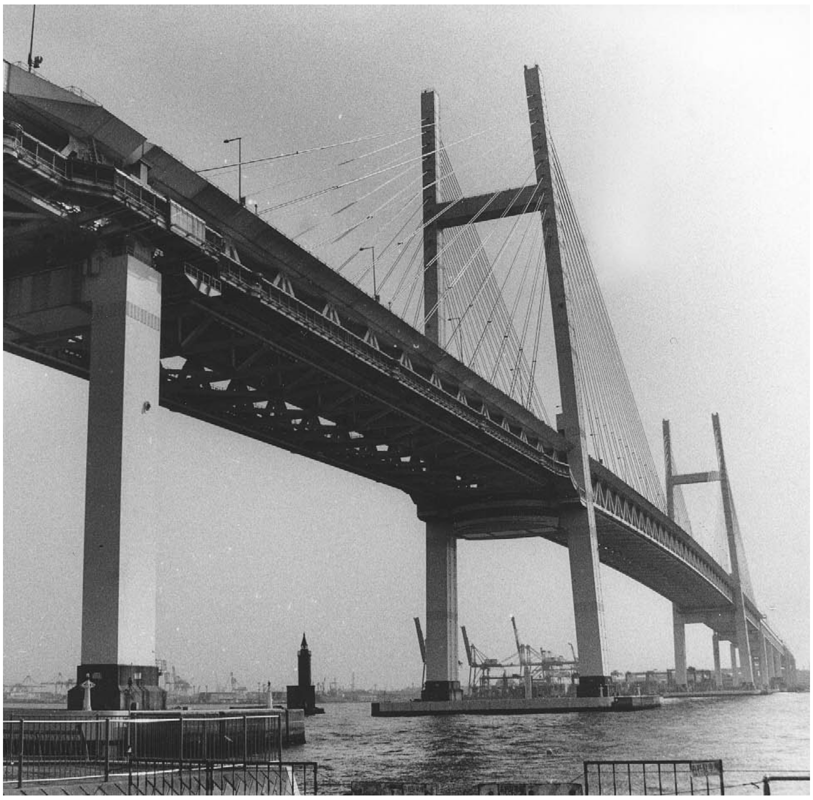

Fig.28 The Yokohama Bay Bridge

From the point of view of appearance the Yokohama Bay Bridge is quite successful as the truss is well-proportioned and the pylons have a clear and simple geometry (Fig.28). Eventually, the bridge will carry 12 lanes of vehicular traffic on two decks but initially only the upper deck has been opened to traffic.

In Japan the parallel-wire strands have been used extensively and new types have been developed to improve the corrosion protection.

Conclusion

With the description of some cable-stayed bridges completed at the end of the 1980s the historical review shall be concluded, but to show that the evolution of cable-stayed bridges has continued into the 1990s Table 1 shows the ten longest cable-stayed spans to be found at the turn of the millenium. It is seen that all of these bridges have been completed during the 1990s.

Longest cable-stayed bridges in the year 2000

No.	*Name*	*Span*	*Traffic*	*Country*	*Year*
1	Tatara Bridge	890 m	Road	Japan	1999
2	Normandie Bridge	856 m	Road	France	1995
3	Qingzhou Minjiang Br.	605 m	Road	China	1998
4	Yangpu Bridge	602 m	Road	China	1993
5	Meiko Chuo Bridge	590 m	Road	Japan	1997
6	Xupu Bridge	590 m	Road	China	1996
7	Skarnsund Bridge	530 m	Road	Norway	1991
8	Tsurumi Fairway Bridge	510 m	Road	Japan	1994
9	Øresund Bridge	490 m	**Road+rail**	Denmark/Sweden	2000
10	Iguchi Bridge	490 m	Road	Japan	1991

Table 1. The ten longest cable-stayed bridges at the turn of the millennium

It is interesting to note that seven of the ten longest cable-stayed bridges are located in the Far East (China and Japan), and that the remaining three bridges on the list are from Europe.

In the four and a half decade passed since the Strömsund Bridge was opened the cable-stayed bridges have developed to become dominating in the span range from 200 m to 500 m. Under specific conditions the cable-stayed bridges might even be competitive against suspension bridges up to spans of more than 1000 m. However, it remains to be seen if in the near future the cable-stayed bridges will actually pass the present maximum span length of 890 m in the Tatara Bridge.

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