3 SUSPENSION BRIDGES

3.1 Introduction

History

From the historical point of view, the cable theory had a firm grounding by the nineteenth century, when the *Menai Straits Bridge, Wales* was completed in 1826, which still exists, with its 177m main span.

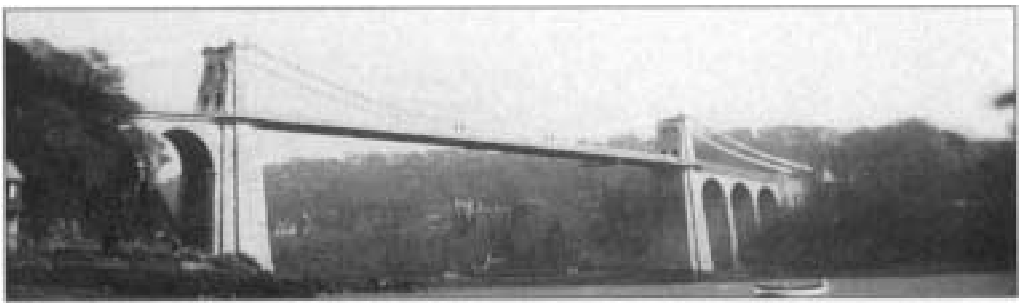


Fig. Menai Bridge

It was reported by *Needham*[1] that The predecessor in outside of Europe - China, Central and South America mastered how they build the suspension bridges. The *Fanhe Brdige* dated B.C. 206 in *Shanxhi* Province was probably made using iron chains. And also the Iron-Chain suspension bridge date from A.D. 65 was constructed in *Ynnan* Province in China; but records are not reliable as to who built these early bridges.

The native Americans did , and still do, make intricate rope pathways, and perfected these with some ingenious ways of improving the tensile properties of vine ropes.

By contrast with the earlier unknown builder of suspension bridges, the Tibetan Monk, *Thang-stong rGyal-po* may be the first renowned builder of iron chain bridges[2].

[2] H. Max. Irvine,1981. *Cable Structures,* The MIT Press, Cambridge, Massachusetts, and London, England

The famous Brooklyn Bridge is probably the most remarkable suspension bridge of the 19th century

Fig. Brooklyn Bridge

It was built during 1869-1883 in New York City across the East river between the boroughs of Manhattan and Broolkyn. The bridge has a center span of 486m and side spans of 286m, giving a total cable supported length of 1058m.

The Brooklyn Bridge –the first East River bridge- was the chief work of the bridge designer John. A, Roebling, who was born in Germany but emigrated to the United States of America at the age of 25. Before he started to design the his Booklyn Bridge construction, he had already designed the first Niagara Suspension Bridge with a main span of 250m, and the Cincinnati and Covington suspension Bridge over the Ohio River with a main span of 322m. The fatal bridge disaster of the suspension bridge across the Ohio River at Wheeling, which was destoyed by the wind in 1854, gave *Roebling* very strong impression on the Wind Effect, and he took several measures to increase the stiffness of suspension bridges beyond what is obtained by the cable itself. In his bridges, following the Wheeling disaster, he therefore introduced stiffening trusses with a considerable bending stiffness and stay-members to supplement the pure suspension system.

In the second half of the 19th century the first order theories were available to analyze the suspension bridges. In 1886, the first order or “elastic theory was further developed by *Maurice Levy*.

The trend to let the calculations influence the lay-out of the structure is clearly seen in the *Williamsburg Bridge*, the second bridge to span the East River in New York. This bridge was completed in 1903, some distance upstream form the *Blooklyn Bridge*. It has a main span of 488m. It is the first entirely made of steel. The designer’s strong desire to have a practicable mathematical model in the arrangement of the structural system led the stiffening trusses of the deck structures of *Williamsburg* bridge are exceptionally deep, and the open steel truss towers resemble high-voltage power linetowers rather than suspension bridge towers.

Fig. *Williamsburg Bridge, New York City*

In 1909, between the *Broolklyn* and *Williamsburg* bridges the Manhattan Bridge was completed. It is painted blue and has a main span of 448m. In addition to vehicular traffic, the Manhattan and Williamsburg bridges also convey metro rail traffic. This causes requirements with respect to the load carrying capacity of these bridges.

In the evaluation of cable supported bridges the *Mahattan B*ridge is notable for the fact that it was the first major suspension bridge to be

analyzed by the so-called 'deflection theory' which had been developed by *Melan in Vienna* in 1888. The deflection theory is a second order theory taking into account the displacements of the main cable under traffic load when calculating the bending moments in the stiffening girders.

Fig. Manhattan Bridge

After the opening the Manhattan Bridge little progress was made in the design of suspension bridges for a period of more than 20 years. Then in 1931 came a suspension bridge which almost doubled the free span of the previous bridges: With it's main span of 1066m, the George Wahington Bridge across the Hudson river. This was the first bridge to overcome 1000m between towers.

O.H. Ammann, the designer of George Wahington Bridge had panned from the beginning of his design to have two decks with roadway on the upper deck and subway tracks on the lower deck.

The 1930s became a decade of great achievements in the field of suspension bridges in the United States of America: the George Washington bridge was followed by such impressive structures as the San Francisco-Oakland Bay Bridge designed by *L.S.Moisseiff*, and the Golden gate Bridge designed by *J.B.Strauss*.

The West Bay Crossing consists of twin suspension bridges placed end ot end with a separating anchor pier at the center.

Fig. San Fransisco West Bay Crossing

Each of the two suspension bridges has a main span of 704m and side spans of 352m.

The majestic Golden Gate Bridge is situated at the entrance of the San Fransisco Bay. The bridge was opened to traffic in May 1937. Its 1280m main span was longest in the world until 1964 before completion of the Verrazano Bridge. This bridge was made with only two main cables each 930mm in diameter, compared to the four main cables each 910mm in diameter used in the George Washinton Bridge.

The stiffening truss of the Golden Gate Bridge represented an extreme in slenderness as the depth-to -span ratio was only 1:168. At the same time, the space truss comprised only three plane trusses, two vertical under the

cable planes and one horizontal below the bridge deck. This configuration resulted in an insignificant torsional stiffness of the truss section, but at the time when the Golden Gate Bridge was designed the importance of torsional stiffness for achieving aerodynamic stability was not fully appreciate.

A few years later the extreme slenderness of the Golden Gate Bridge was surpassed several times by the Tacoma Narrow Bridge in Washington State, USA, opened to traffic on 1st July 1940. With a main span of 853m it then ranked as the 3rd in the world. This bridge had the stiffening girder made up of plate girders with a depth-to-span ratio of only 1:350. This extreme slenderness was actually the ultimate result of the designer L.S.Moisseiff's application of the deflection theory, which gave ever decreasing bending moments with reduced bending stiffness. Despite the extreme slenderness of the stiffening girder, the bridge possessed an adequate safety against the action of the traffic load and the static wind pressure. Besides the small depth-to-span ratio, the width-to span rationof 1:72 also went beyond previous practice.

Right from its opening, the bridge had shown a tendency to oscillate in the wind, but during the first four months these oscillations were vertical, with no rotation of the cross section involved. And the oscillations were always damped down after having reached an amplitude of about 1.5m.

Then, after a few months in service, following the breaking of some stabilizing cables which prevented mutual displacements between the stiffening girder and the main cables at mid-span, the type of oscillation suddenly changed. The oscillations then took the form of torsional movements with the main span oscillating asymmetrically in two segments with a nod e at mid-span. The torsional movements became mo9re and more violent with a tilting of the roadway at the quarter points from +45 -45 . After approximately one hour of these violent self-exited oscillations, caused by negative damping of the aerodynamic forces, the hangers began to break in fatigue at the sockets and a large portion of the stiffening girder fell into the water.

During the final oscillations of the Tacoma Bridge the wind had a speed of 56-67km/h, which was well below the maximum wind speed the bridge had been designed to withstand.

After the Tacoma Bridge Disaster, aerodynamic studies became an important part of the design process for all suspension bridges to come and also suspension bridges already built were investigated to reveal if there was any danger of aerodynamic instability.

Fig. The first Tacoma Bridge

One of the bridge investigated was the Bronx-Whitestone Bridge in New York. This bridge, designed by O.H.Amman and opened to traffic in 1939, had as stiffening girder composed of two plate girders with a depth-to-span ration of 1:209.

Oscillations had been observed on the Bronx-Whitestone Bridge but they were always of the non-catastophic vertical type and with small amplitudes.

Nevertheless, in 1946 it was decided to strengthen the Bronx-Whitestone Bridge by adding a truss on top of the plate girders to double the depth of the stiffening girder, and by erecting stays from the pylon tops to the stiffening girder. And so Roebling’s vision to combine the suspension system with stays to increase the resistance against oscillations was again adopted.

Fig. Bronx-Whitestone Bridge

A strong bridge in Michigan

The most remarkable of the bridges constructed in the 1950's is the one across the Mackinac Straits in Michigan, between Lake Michigan and Lake Huron. The bridge has a total length of 5,8 km. When completed in 1957, with its main span of 1158 m it ranked 2nd, directly after the Golden Gate Bridge. The two 549 m side spans are rather long compared with the main span. The steel towers are 168 m tall. *Picture 19.*

The Mackinac Bridge is claimed to be the world's strongest suspension bridge, able to withstand even winds of 632 mph or 1000 km/h. This is achieved by means of some stuctural arrangements. For instance, the two middle lanes out of four lanes in all are of open grid construction (the same arrangement is applied to the Lisbon Bridge, mentioned below). The strong steel truss deck measures 20,7 m x 11,7 m, and the navigation clearance is 45 m. On the bridge site, winter climate is severe.

19. Mackinac Straits Bridge, Michigan, claimed to withstand winds of 1000 km/h.
PHOTO MACKINAC BRIDGE AUTHORITY

Suspension bridge, again the longest-span in Europe

A notable suspension bridge was completed in 1959 across the Seine River, near Tancarville, France. After a period of nearly 70 years, with a main span of 608 m it returned the span length record from the Firth of Forth Railway Bridge (2 á 521 m) back to suspension bridges in Europe. *Picture 20.*

Instead of parallel-wire strands, the cables of the Tancarville Bridge consist of helical-wire strands. In this respect, at its completion it was the largest suspension bridge in the world. The steel truss deck measures 16,0 x 6,0 m, and the navigation clearance is 51 m.

The Tancarville Bridge towers are made of concrete, not of steel. For a long time, in this respect it was the longest-span suspension bridge. The Humber Bridge, Britain 1981, was then the longest-span suspension bridge with concrete towers. In Table I, the following bridges have concrete towers: Great Belt, Humber, Jiangyin, Tsing Ma, and Höga Kusten. The others in Table I have steel towers.

20. Tancarville Bridge, France, once the longest-span bridge in Europe.
PHOTO CHAMBRE DE COMMERCE & D'INDUSTRIE DU HAVRE

Bridges of the 1950's

In 1957, a notable bridge was opened to traffic in Wilmington, Delaware, USA. It was named Delaware Memorial Bridge, and it has a main span of 655 m. A parallel bridge was built during the following decade. The second bridge was completed in 1968, and it also has a 655 m long main span. The Delaware Memorial Twin Bridge is the longest-span twin suspension bridge in the world. *Picture 21.*

In 1957, in Philadelphia, PA, USA, a bridge called the Walt Whitman Bridge was opened to traffic. It has a main span of 2000 feet or 610 m. Its steel truss deck is 24,1 x 5,5 m in cross-section, the steel towers are 115 m in height, and the navigation clearance is 46 m.

21. Delaware Memorial Twin Bridge, USA, the world's longest-span twin bridge.

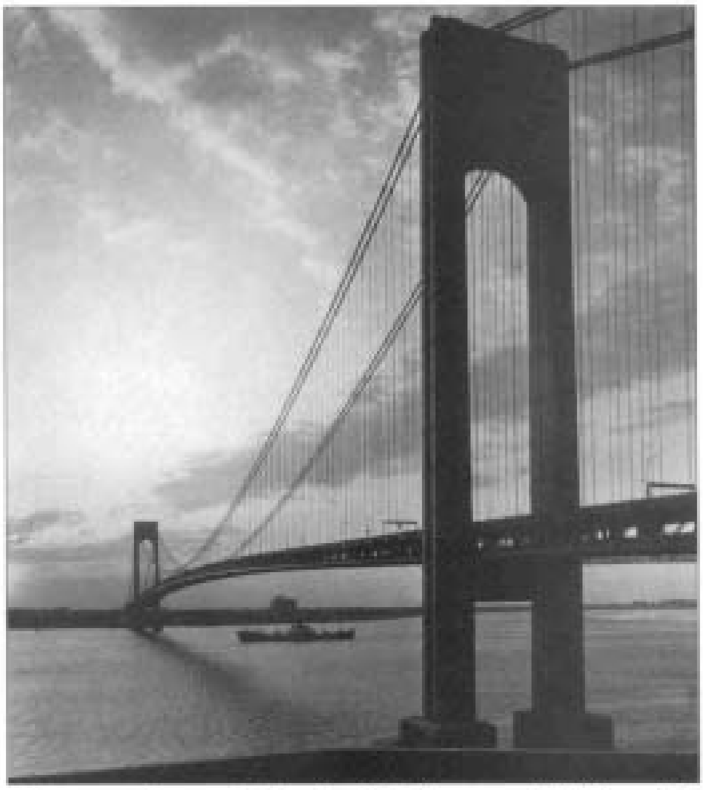
PHOTO DELAWARE RIVER PORT AUTHORITY

Bridges of the 1960's

The Verrazano-Narrows Bridge is the most remarkable bridge of the 1960's. It was completed in 1964 at the entrance of the Port of New York. With a main span of 1298 m it was the longest-span suspension bridge until the Humber Bridge was completed in 1981. The steel towers of the Verrazano bridge are 210 m tall. The bridge has four cables, each 90 cm in diameter, and two traffic levels totalling 12 lanes. The cross-section of the steel truss deck measures 31,4 x 7,3 m, and the navigation clearance is 69 m. In 1991, annual traffic volume reached 70 mill. vehicles. *Picture 22.*

Nearly one kilometre west of the famous Firth of Forth Railway Bridge off Edinburgh, Scotland, in 1964 a large suspension bridge was opened for road traffic. The main span of the Firth of Forth Road Bridge is 1100 yards or 1006 m, and this was first time in Europe when the one kilometre span was exceeded. The steel towers are 156 m high. The light steel truss deck is 23,8 m wide, totalling 36,3 m including the cantilevers for light traffic, and 8,4 m deep. The navigation clearance is 46 m. *Picture 23.*

The largest suspension bridge in South America is situated in Venezuela. It is the Angostura Bridge over the Orinoco River at Ciudad Bolivar. The bridge, main span 712 m, was completed in 1967. This American type bridge with strong stiffening trusses in the deck measures 17,8 x 7,6 m in cross-section. The steel towers are 123 m high, while the navigation clearance is 40 m. *Picture 24.*

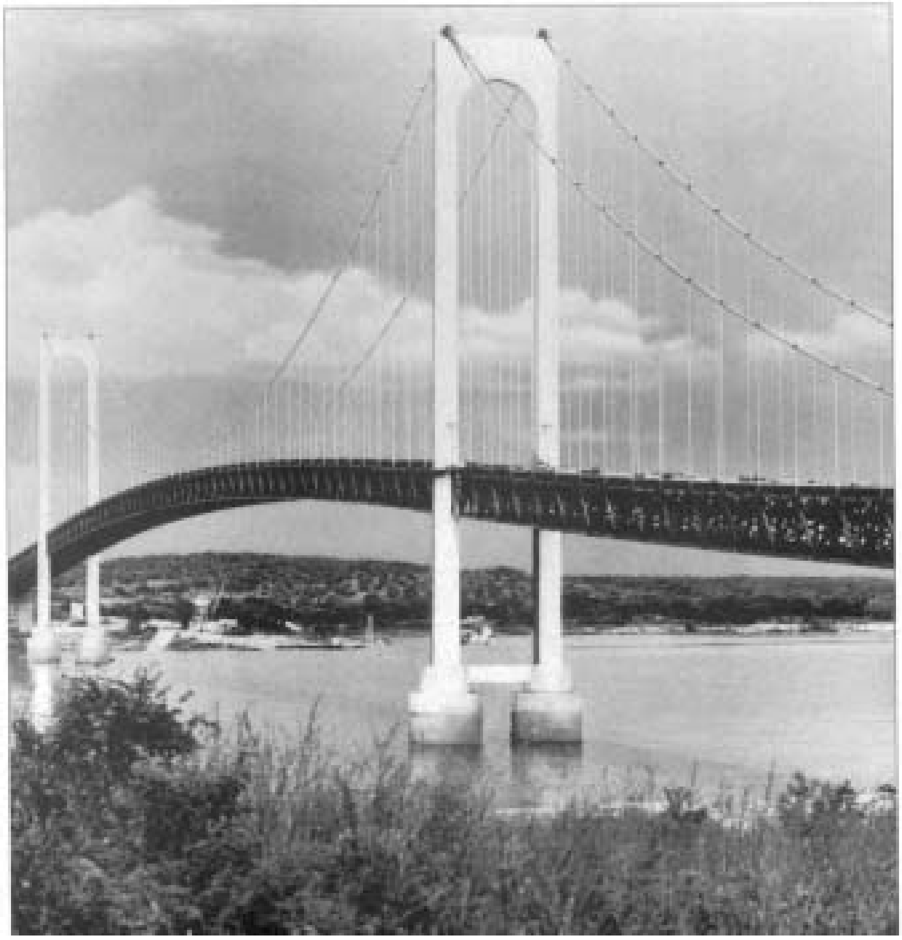


22. Verrazano-Narrows Bridge, New York City, exceeded the long-lived span length record of the Golden Gate Bridge.

PHOTO TRIBOROUGH BRIDGE AND TUNNEL AUTHORITY

23. Firth of Forth Road Bridge, Scotland, the first bridge in Europe to exceed a span length of one kilometre.
PHOTO SCOTTISH TOURIST BOARD

24. Angostura Bridge, Venezuela, the longest-span bridge in South America.
PHOTO UNITED STATES STEEL INTERNATIONAL



A beautiful red suspension bridge at Lisbon

Lisbon's first bridge across the Tagus River was completed in 1966. It was named Ponte Salazar. During the April 1974 revolution, the bridge was renamed Ponte 25 de Abril. The main span of the bridge, 1013 m, was the longest in Europe until 1970, when the Bosporus Bridge was completed. The steel towers are 190 m tall, tallest in Europe until completion of the Great Belt Bridge in 1997. The foundation depth of the south tower of the Lisbon Bridge is 80 m below water level, and the navigation clearance of the deck is 70 m. At completion, these two figures were records for long-span suspension bridges. The steel truss deck measures 21,0 x 10,7 m, and there is a plan to add a railway onto the lower level of deck. The April 25th Bridge is painted in a beautiful red colour and sometimes it is referred to as *Lisbon's Golden Gate Bridge. Picture 25.*

25. Ponte 25 de Abril, because of its beautiful red colour sometimes named Lisbon's Golden Gate Bridge.
PHOTO MINISTÉRIO DAS OBRAS PÚBLICAS

A novel streamlined suspension bridge off Bristol

In 1966, a novel suspension bridge was opened to traffic over the Severn River near Bristol, Britain. Its main span is 988 m long. It is the first long-span suspension bridge to have both a streamlined steel box girder deck and inclined hangers. The deck is 3,0 m deep, 22,9 m wide, and totals a width of 31,9 m with the cantilevers for light traffic. The steel towers are 136 m high, while the navigation clearance is 37 m.

The Severn Bridge exposes an exceptional feature. Instead of conventional vertical hangers, its hangers are inclined. They form a zigzag figure in the longitudinal profile of bridge. The inclined hangers are a means to achieve better damping against vibrations, caused by wind and traffic loads. In Table I, only the following three bridges have inclined hangers: Humber, Bosporus, and Severn, while the others have vertical hangers. Because of increasing traffic loads, the Severn Bridge was refurbished in the 1980's. The hangers were replaced (they are still inclined) and the deck and towers were strengthened. *Picture 26.*

26. Severn Bridge, Britain, the first major suspension bridge to have both a streamlined steel box girder deck and inclined hangers.
PHOTO BRITISH ROPES LTD

In Table I, the following 10 bridges have steel box girder decks: Great Belt, Humber, Jiangyin, Tsing Ma, Höga Kusten, Fatih Sultan Mehmet, Bosporus, Kurushima-3, Kurushima-2, and Severn, while the 10 others have steel truss decks.

Some suspension bridges with extraordinary hangers

In Mozambique, earlier Portuguese East Africa, there are two rare suspension bridges with inclined hangers /4/. They both have a prestressed concrete girder deck and five successive suspension spans. The hangers form a zigzag figure in the longitudinal profile of bridge. The Save River Bridge at Vila Franca do Save, opened to traffic in 1971, is the longer one of these two. Its spans are 100 + 3 x 210 + 100 m; *Picture 27.* The Zambezi River Bridge at Tete, dated 1972, is the smaller one, with spans 90 + 3 x 180 + 90 m.

In El Salvador, Central America, there is even a more extraordinary multi-span suspension bridge. It is the San Marcos Bridge across the Lempa River, dated 1952. The bridge has five successive suspension spans of 76 + 159 + 204 + 159 + 76 m. Its hangers are at a rare criss-cross position in the longitudinal profile of bridge. *Picture 28.*

27. Save Bridge, Mozambique, five successive suspension spans, concrete deck structure, and inclined hangers.
PHOTO JUNTA AUTÓNOMA DE ESTRADAS DE MOÇAMBIQUE

28. San Marcos Bridge, El Salvador, a rare feature of criss-cross hangers.
PHOTO MINISTÉRIO DE OBRAS PUBLICAS

Bridges of the 1970's

In Europe, in the 1970's two notable suspension bridges were opened to traffic. The Bosporus Bridge in Istanbul, completed in 1973, is the larger of these. With a 1074 m main span it was Europe's longest-span suspension bridge until completion of the Humber Bridge in 1981. Like the Severn Bridge, the Bosporus bridge also has inclined hangers and a streamlined steel box girder deck. The deck is 3,0 m deep, 28,0 m wide, while the total width is 33,0 m including the cantilevers for light traffic. The steel towers are 165 m tall. Only the main span is suspended, the side spans are unsuspended. *Picture 29.*

At completion in 1970, the Little Belt Bridge, Denmark, with a main span of 600 m was the largest suspension bridge in Scandinavia. Like the Tancarville Bridge, the Little Belt Bridge has cables consisting of helical-wire strands instead of parallel-wire strands. Its 120 m high towers are also made of concrete. The streamlined steel box girder deck measures 33,3 x 3,0 m, while the navigation clearance is 42 m. *Picture 30.*

29. Bosporus Bridge, Istanbul, a three millenniums dream of a bridge between Europe and Asia.
PHOTO KARAYOLLARI GENEL MUDURLUGU

The largest suspension bridge of the Far East was completed in 1973 across the Kanmon Straits, between Kyushu and Honshu Islands in Japan. The Kanmon Bridge has a main span of 712 m. This conventional American type suspension bridge has a heavy steel truss deck, measuring 29,0 x 9,0 m in cross-section. The steel towers are 143 m high, and the navigation clearance is 61 m.

30. Little Belt Bridge, Denmark, once the largest suspension bridge in Scandinavia.
PHOTO OSTENFELD & JØNSON

Bridges of the 1980's

The bridge across the Humber Estuary at Kingston-upon-Hull, Britain, is the most remarkable suspension bridge of the 1980's. It was opened to traffic in 1981. The 1410 m main span of the Humber Bridge returned the record from America to Europe, first time since 1890. It will be the world's longest-span suspension bridge until completion of the Great Belt Bridge in 1997. The deck of the Humber Bridge is 4,5 m deep (50 % deeper than in the Severn and Bosporus bridges), 22,0 m wide, and 28,5 m wide in all including the cantilevers for light traffic.

The Humber Bridge is a unique long-span suspension bridge. It exposes the following three technical features: concrete towers (163 m tall), inclined hangers, and a streamlined steel box girder deck. The Humber Bridge is the last major suspension bridge constructed with inclined hangers. In bridges built later, vertical hangers are used again. The unequal length of the both side spans, 280 m and 530 m, is also a feature of the Humber Bridge. *Picture 31.*

In 1988, the second suspension bridge was completed across the Bosporus in Istanbul. It is located some kilometres upstream from the first bridge. The second crossing is called the Fatih Sultan Mehmet Bridge. It has a main span of 1090 m, a few metres longer than that of the first bridge. Similarly to the first bridge, the second bridge also has a streamlined steel box girder deck, but contrary to the first bridge the second bridge has vertical hangers. The second bridge has 4 + 4 traffic lanes, while the first bridge has 3 + 3 lanes. Its deck is 3,0 m deep, 33,8 m wide, and 39,4 m wide including the cantilevers for light traffic. At completion, it was the widest long-span suspension bridge in the world. The two Bosporus bridges are equipped with pedestrian/bicycle paths on both sides, though not in use (nominally for safety reasons). Both bridges have a navigation clearance of 64 m. The second bridge is situated between steep river banks. It has no side spans at all, thus it is a single-span suspension bridge. The towers are 100 m high above the piers, and 165 m above the water level. *Picture 32.*

In the same year, 1988, a long succession of bridges was completed between Honshu and Shikoku Islands, along the Kojima-Sakaide Route in Japan. This bridge succession includes some remarkable cable-stayed and suspension bridges, and it is called the Seto-Ohashi Bridge. Its total length, 12,3 km, makes it the world's longest highway/railway bridge.

According to Table I, there are three large suspension bridges on this route: Minami-Bisan seto (main span 1100 m), Kita-Bisan seto (990 m), and Shimotsui-seto (940 m). The Minami and Kita bridges have three normal suspension spans. In the Shimotsui Bridge only the main span is suspended and the side spans are unsuspended. All three bridges have steel towers and 2-level steel truss decks.

Until the 1997 completion of the Tsing Ma Bridge, the 1100 m main span of the Minami Bridge for the time being makes it the world's longest-span highway/railway bridge. The steel towers of the Minami Bridge are of different height, 194 m and 186 m. The steel truss deck measures 30,0 x 13,0 m, and the navigation clearance is 65 m. The bridge has two cables 1070 mm in diameter, and this is the first suspension bridge ever to have cables larger than one metre. Picture 33.

In 1985, on the Kobe-Naruto Route between Honshu and Hokkaido Islands, Japan, the Ohnaruto Bridge was completed. It is situated south of the gigantic Akashi-Kaikyo Bridge on the same route. The 876 m main span places the Ohnaruto Bridge after the bridges listed in Table I. It has a steel truss deck, 34,0 x 12,5 m, and the steel towers are 145 m high.

31. Humber Bridge, Britain, returned the span length record from America back to Europe.
PHOTO HUMBER BRIDGE BOARD

32. Fatih Sultan Mehmet Bridge, Istanbul, the widest long-span suspension bridge at completion.
PHOTO KARAYOLLARI GENEL MÜDÜRLÜGÜ

33. Seto-Ohashi succession of bridges, Japan, currently the world's longest higway/railway bridge.
PHOTO HONSHU-SHIKOKU BRIDGE AUTHORITY

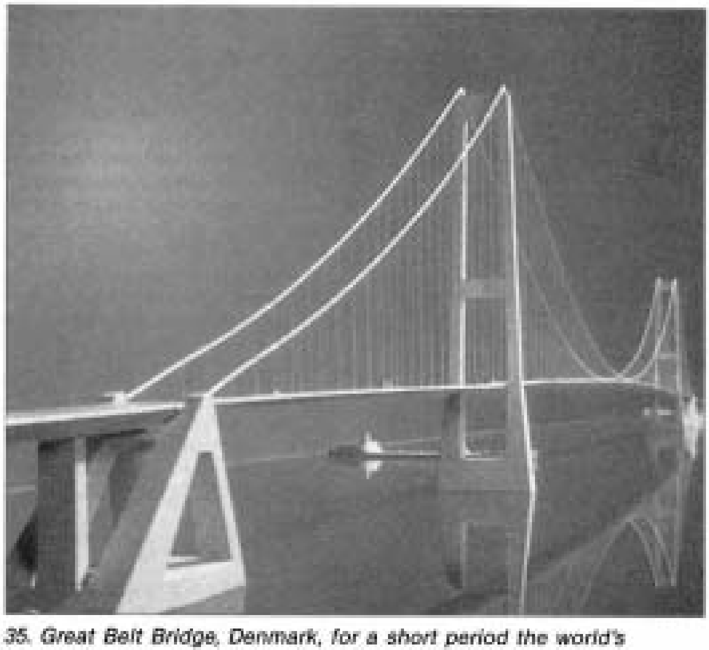
Bridges of the 1990's

The last decade of the ending millennium, the 1990's, can with reason be referred to as *The Decade of Great Bridges*. During this period, for instance, two of the largest ever built suspension bridges and many other notable bridges, particularly cable-stayed bridges, as well as some large concrete bridges (see Table III) will be completed.

During 1993-1997, a large suspension bridge across the Ångerman River in Sweden, is under construction. It will be located a few kilometres downstream from the Sandöbron, a graceful concrete arch bridge (main span 264 m; 1943). The new suspension bridge is called the Höga Kusten Bridge, and its main span of 1210 m will rank 8th in the world, directly after the Golden Gate Bridge. The Höga Kusten Bridge has concrete towers, 180 m in height, a streamlined steel box girder deck, 22,0 x 4,0 m in cross-section, and a navigation clearance of 40 m. For a start the deck will have two traffic lanes, in the future probably four lanes. The side spans will also be suspended, for aesthetic reasons. *Picture 34.*

34. Höga Kusten Bridge, Sweden, 8th with respect to span length at the change of the millennium.
PHOTO VÄGVERKET REGION MITT

For some time, the Great Belt East Bridge, under construction in Denmark during 1991-1997, will be the world's longest-span suspension bridge (until completion of the Akashi Bridge). Its 1624 m main span is the first one to exceed one mile (1609 m). It will also have the world's tallest concrete towers, 254 m. The streamlined steel box girder deck, 31,0 x 4,0 m, is continuous beyond the towers at a length of 2700 m, from anchorage to anchorage. This is likely the longest continuous steel girder bridge deck in the world. There was a dispute between Finland and Denmark concerning the navigation clearance of 65 m, which is not high enough for some vessels. In Autumn 1992, however, an agreement was reached. *Picture 35.*



35. Great Belt Bridge, Denmark, for a short period the world's longest-span suspension bridge.
PHOTO STOREBAELTSFORBINDELSEN

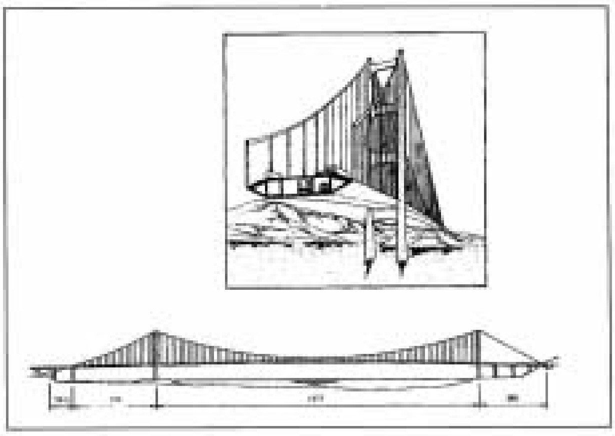
During 1992—1997 in Hong Kong, which will be returned to China in 1997, a large suspension bridge is under construction. The structure is called the Tsing Ma Bridge, and it leads to the new Chek Lap Kok Airport. The 1377 m main span will make the 2-level Tsing Ma Bridge the world's longest-span highway/railway bridge. The longer side span, 359 m, is suspended, while the shorter side span, 300 m, is unsuspended. The bridge has two cables 1100 mm in diameter. The deck, 41,0 x 7,3 m, is a combination of a steel truss and a box construction. At completion, it will be the widest long-span suspension bridge in the world. The upper level accommodates 6 lanes for highway traffic. The railway traffic runs along the lower level inside the box, where there are also two emergency lanes for road traffic, to be used in case of violent typhoons. The navigation clearance will be 79 m, highest in the world among large suspension bridges. *Picture 36.*

In Jingsu Province in China, the large Jiangyin Bridge over River Yangtze is under construction. The bridge is expected to be completed by the change of the millennium. Its 1385 m main span will rank 4th in the world. Only the main span is suspended, the two side spans are not. Thus it will be the longest-span partial suspension bridge. The bridge will have concrete towers, 196 m in height, and a streamlined steel box girder deck, measuring 36,0 x 3,5 m in cross-section. *Picture 37.*

By 1998, the Tiger Gate Bridge will be completed across the Pearl River at Humen, China. Its 888 m main span places it just after the bridges listed in Table I. The bridge will have concrete towers and a streamlined steel box girder deck. The cables are constructed of prefabricated parallel-wire strands.

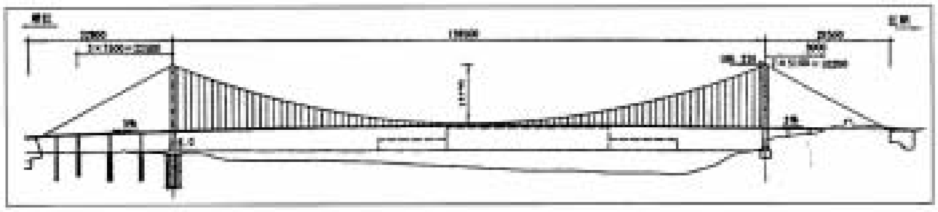
Between Honshu and Hokkaido Islands, on the Onomichi-Imabari Route in Japan, there are Kurushima bridges currently under construction.

It comprises three successive suspension bridges, with two shared cable anchorages. The Kurushima bridges, to be completed in 1999, have streamlined steel box girder decks. The Kurushima-1 Bridge is the smallest one. It has a main span of 600 m and all three spans are suspended. The Kurushima-2 Bridge is in the middle. It has a main span of 1020 m. The main span and one of the side spans are suspended. The Kurushima-3 Bridge is the largest one of these three suspension bridges. Its main main span is 1030 m long, and only that is suspended. The alignment of outermost side span of the Kurushima-3 Bridge is curved and the cables descend beyond the side span down to the end anchorage, as illustrated by the accompanying picture. The steel box girder deck of the Kurushima-3 Bridge measures 32,0 x 4,3 m, and the navigation clearance is 65 m. *Picture 38.*



36. Tsing Ma Bridge, Hong Kong, the world's longest-span highway/railway bridge. PICTURE CONSTRUCTION TODAY

38. Kurushima Bridges, Japan, a rare construction of three successive suspension bridges with two shared cable anchorages. PHOTO HONSHU-SHIKOKU BRIDGE AUTHORITY



37. Jiangyin Bridge, China, the longest-span suspension bridge with unsuspended side spans. PICTURE TONGJI UNIVERSITY SHANGHAI

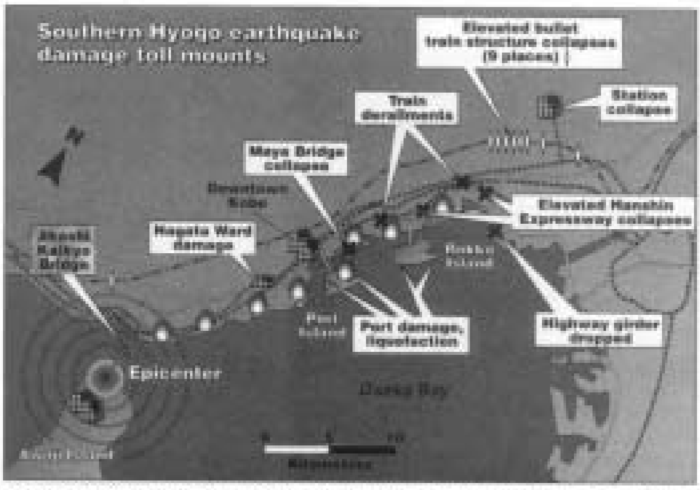
A gigantic bridge in a strong earthquake

During 1988-1998, north of the above mentioned Ohnaruto Bridge, a gigantic suspension bridge is under construction across the Akashi Straits. The bridge is situated on the Kobe-Naruto Route, between Honshu and Shikoku Islands, Japan, south-west of Kobe City. The 1991 m main span of the Akashi-Kaikyo Bridge is the first one to exceed a nautical mile (1852 m). The two 960 m side spans are also enormously long. The steel towers are 297 m high, tallest bridge towers in the world. The steel truss deck accommodates 6 lanes for highway traffic, and the navigation clearance is 65 m. The deck measures 35,5 x 14,0 m in cross-section, and the deck is deeper than in any other long-span suspension bridge.

Originally there was a plan to accommodate a railway onto the lower level of the deck, but this plan was abandoned. The railway load would have required four cables, while two cables are sufficient for the road traffic. The two cables are 1122 mm in diameter, which is a record. The steel wires of the cables have an ultimate tensile strength of 1800 MPa, which also is a record. The cables were constructed of prefabricated parallel-wire strands. Consequently, this technique is suitable even for suspension bridges of this magnitude. The pilot wire was carried across the straits by a helicopter, a technique applied for the first time ever. *Picture 39.*

39. Akashi-Kaikyo Bridge, Japan, record bridge in many respects, among them the longest main span of any bridges.
PHOTO HONSHU-SHIKOKU BRIDGE AUTHORITY

In January 1995, an earthquake of 7,2 on the Richter scale occurred in Kobe area, and more than 5000 people were killed. According to *Picture 40*, the epicentre of the earthquke was located at the south end of the Akashi Bridge, several kilometres away from Kobe City itself. The bridge experienced a severe earthquake resistance test. When the earthquake occurred, the towers of the bridge and its cables were newly completed, and the construction of the deck was to be commenced. According to *Picture 40*, buildings and bridges collapsed even at a distance of 50 km from the Akashi Bridge.



40. The epicentre of the Kobe earthquake occurred at the site of the Akashi Bridge, several kilometres away from Kobe City itself.
PICTURE HANSHIN EXPRESSWAY PUBLIC CORPORATION

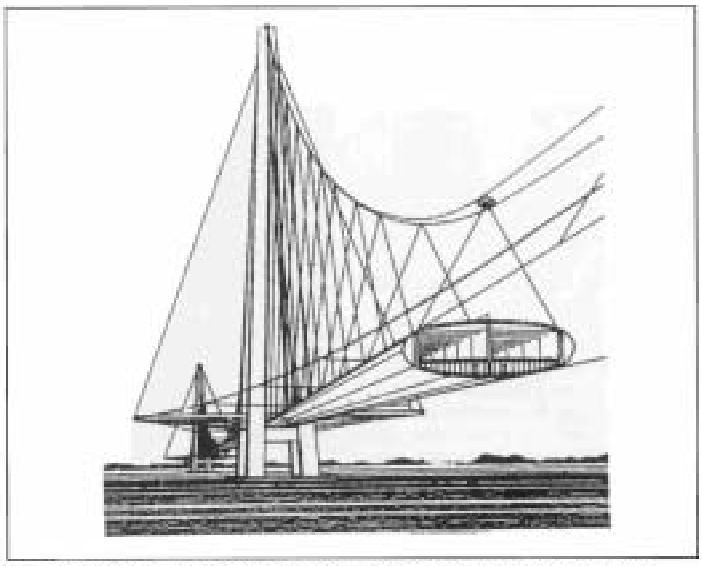
According to a preliminary research /10/, the Akashi Bridge, having a design load of 8,5 on the Richter scale earthquakes, survived with minor damages. Because of the movement of the earth, the distance between the foundations of the towers increased 80 cm and the tops of the towers inclined 10 cm. The main span increased 80 cm and became nearly 1991 m, and as a result the sag of the cables decreased by 130 cm. It is estimated that the damages would not have been this slight had the cables not been already installed. Despite the earthquake, the Akashi Bridge is expected to be completed according to the original schedule, in May 1998.

Long-span bridges of the future

In Japan, there is a proposal to build a gigantic bridge across the Tsugaru Straits between Honshu and Hokkaido Islands. The bridge would include five successive main spans of 2000 m each, and the greatest foundation depth would be about 230 m. An estimated commencement of the project would be around the year 2010. Since 1988 there already is a tunnel, called the Seikan Tunnel, for railway traffic under the Tsugaru Straits. It is 53,8 km long, currently the world's longest railway tunnel, a few kilometres longer than the Eurotunnel under the English Channel.

During the past few decades, various proposals have been made to build a bridge/tunnel across the Messina Straits between Sicily and Italy. One of the schemes presents a suspension bridge with a main span of 3500 m. The towers would be 600 m high.

Similarly, between Spain and Marocco across the Gibraltar Strait, various bridge/tunnel alternatives have been proposed /5/. One recent plan suggests an enormous suspension bridge with two successive main spans 5000 m each and two 2000 m long side spans. The foundation depth would be 300 m. *Picture 41.*



41. A proposal for a huge suspension bridge across the Gibraltar Strait, two successive 5000 m long spans and two side spans both 2000 m long.
PICTURE K. OSTENFELD

I. THE 20 LONGEST-SPAN SUSPENSION BRIDGES WORLDWIDE

(completed or under construction 1995)

No.	Bridge	Span	Location	Year
1	Akashi-Kaikyo	1991 m	Kobe-Naruto, Japan	1998
2	Great Belt East	1624 m	Halsskov-Sprogø, Denmark	1997
3	Humber	1410 m	Hull, Britain	1981
4	Jiangyin	1385 m	Jiangsu Prov., China	1999
5	Tsing Ma**	1377 m	Tsing Yi, Hong Kong	1997
6	Verrazano-Narrows	1298 m	New York, NY, USA	1964
7	Golden Gate	1280 m	San Francisco, CA, USA	1937
8	Höga Kusten	1210 m	Veda, Sweden	1997
9	Mackinac	1158 m	Mackinaw City, MI, USA	1957
10	Minami Bisan-seto**	1100 m	Kojima-Sakaide, Japan	1988
11	Fatih Sultan Mehmet	1090 m	Istanbul, Turkey	1988
12	Bosporus	1074 m	Istanbul, Turkey	1973
13	George Washington	1067 m	New York, NY, USA	1931
14	Kurushima-3	1030 m	Onomichi-Imabari, Japan	1999
15	Kurushima-2	1020 m	Onomichi-Imabari, Japan	1999
16	Ponte 25 de Abril	1013 m	Lisbon, Portugal	1966
17	Forth Road	1006 m	Edinburgh, Britain	1964
18	Kita Bisan-seto**	990 m	Kojima-Sakaide, Japan	1988
19	Severn	988 m	Bristol, Britain	1966
20	Shimotsui-seto**	940 m	Kojima-Sakaide, Japan	1988

** highway/railway bridge

THE LONGEST-SPAN SUSPENSION BRIDGE IN FINLAND

1	Kirjalansalmi	220 m	Parainen

3.2 Cable

3.2.1 Materials

3.2.11 Change in tension strength of bridge wire

- Brooklyn Bridge (1882)
  $\sigma_u = 1100 \ {}^{N}\!/_{mm^2}$ for $\phi = 4.2 \ mm$ diameter
  Galvanized wire

- Manhattan Bridge (1909)
  $\sigma_u = 1470 \ {}^{N}\!/_{mm^2}$ Upgraded

- George Washington Bridge (1932)
  $\sigma_u = 1520 \ {}^{N}\!/_{mm^2}$

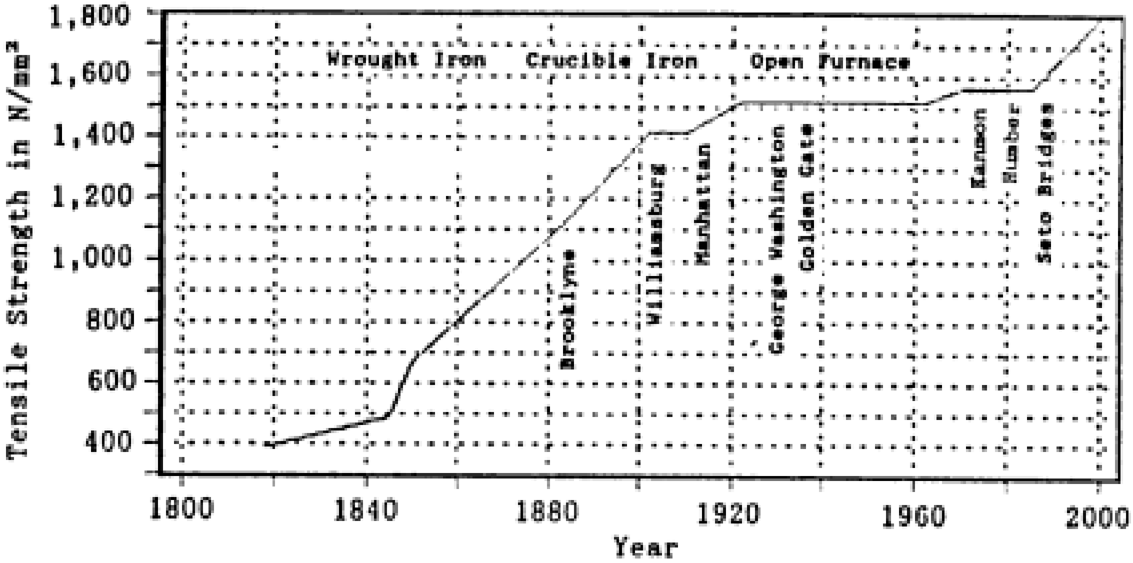


Fig. Historical Change in Tensile Strength of Bridge Wire
(by M. Ohashi)

3.2.12 Wire for wire ropes

- Spiral Rope

  Made of round galvanized wires having a diameter of approximately $\phi = 5\ mm$ (4 to 6 mm)

  $\sigma_u = 1500 \text{ to } 1600\ {}^{N}\!/_{mm^2}$

- Locked Coil Ropes

  Are composed of round wires
  T-shaped (Semi-locked trapezoidal) and
  Z-shaped (fully locked) wires

3.2.13 Galvanized Wire for “PWS” and Ultra Long Lay Cable

- “PWS”

  Stay cables were also fabricated
  from parallel wire strands of 5 *mm* diameter
  galvanized wire in Japan

- “PWC”

  Parallel wire cable made of prestressing wire

- Ultra Long Lay Cables

  Are fabricated using 7 *mm* diameter
  galvanized wire

3.2.14 Prestressing Steels

Post-tensioning tendons made of wire
7-wire strand or bar

3.2.15 Future of Cable Materials

$\sigma_u = 1100 \ {}^{N}\!/\!_{mm^2}$ to $1600 \ {}^{N}\!/\!_{mm^2}$ more than 50 years

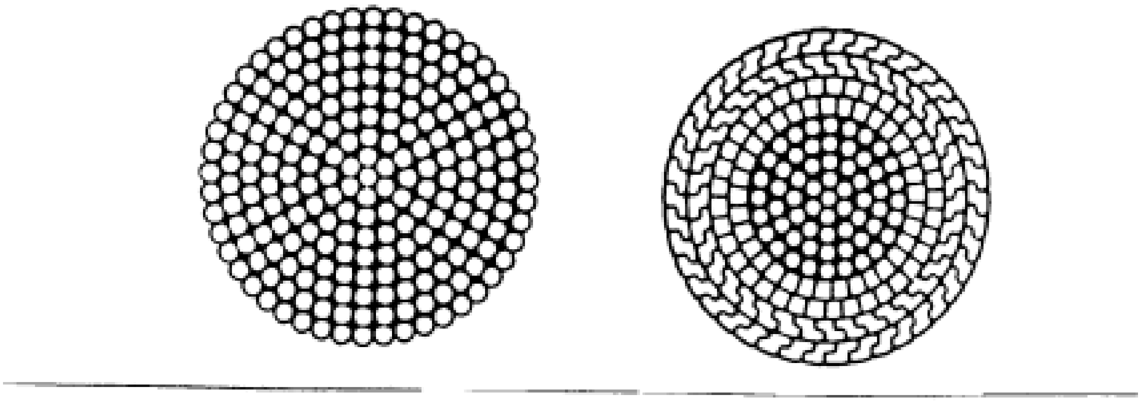
$\sigma_u = 1800 \ {}^{N}\!/\!_{mm^2}$ for main cable of the Akashi Strait Bridge $\phi = 7 \ mm$

3.2.2 Types of Stay Cables

The requirements for the structural cables are :

1. High load bearing capacity
2. High and stable Young's modulus
3. Compact cross section
4. High fatigue resistance
5. Ease in corrosion protection
6. Ease in handling and installation, and
7. Low cost

3 2 21 Wire Ropes



(a) Spiral Rope (b) Locked Coil Rope

Fig. Wire Ropes

3.2.22 Parallel Wire Strand

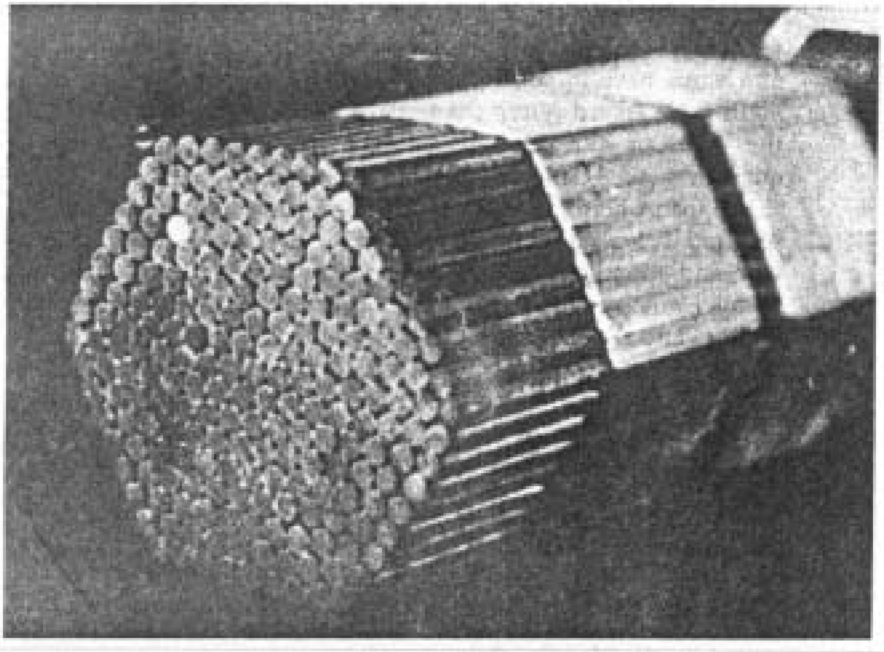
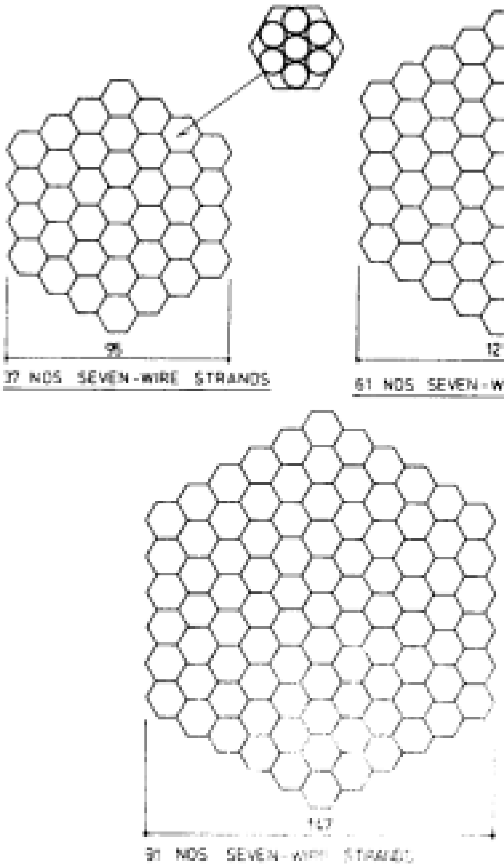


Fig. Model of the Parallel Wire Strand used the Rokko Bridge in Kobe, Japan (217 nos 5mm wires) $E \quad 196 \, {}^{N}\!/_{mm}$



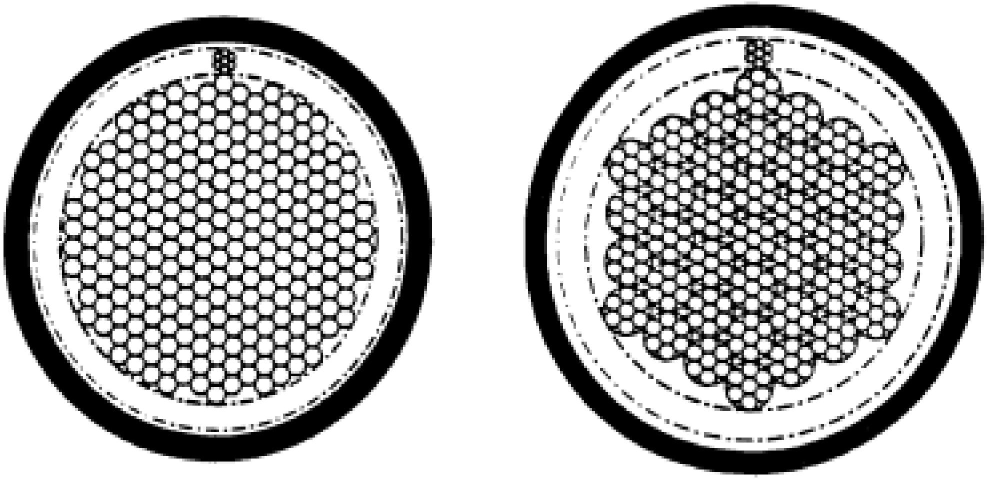
37 NOS SEVEN-WIRE STRANDS

61 NOS SEVEN-WIRE STRANDS

91 NOS SEVEN-WIRE STRANDS

Fig. Parallel Strand Cables made of Seven Wire Strands

3.2.23 Parallel Wire Cables and Parallel Strand Cables



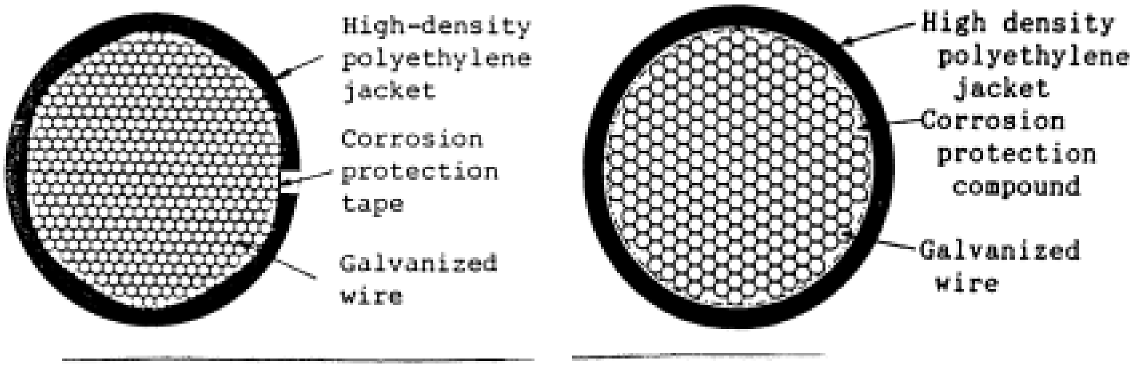
(a) A Parallel Wire Cable (b) A Parallel Strand Cable

"PWC"
A parallel wire bundle of prestressing wire is incorporated as a tension member in a polyethylene pipe filled with cement grout as corrosion protection.

"PSC"
The parallel strand cables are either shop-fabricated or site-fabricated.
A cost saving is claimed by the site-fabrication of stay cables with individual strands pushed through a pre-installed polyethylene pipe, steel pipe or FRP pipe.

3.2.24 Ultra Long Lay Cables

Developing strand in the early 1980's

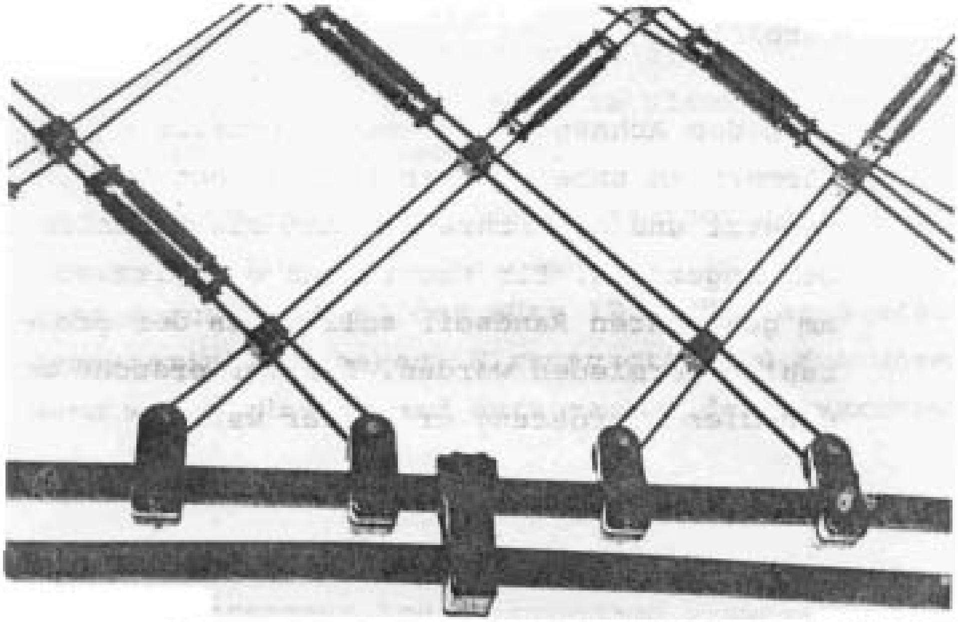


(a) New PWS

(b) SPWC

Fig. Ultra Long Lay Cable

3.2.3 Cable Anchorage and Connection



Cable Connection at Edge Cable

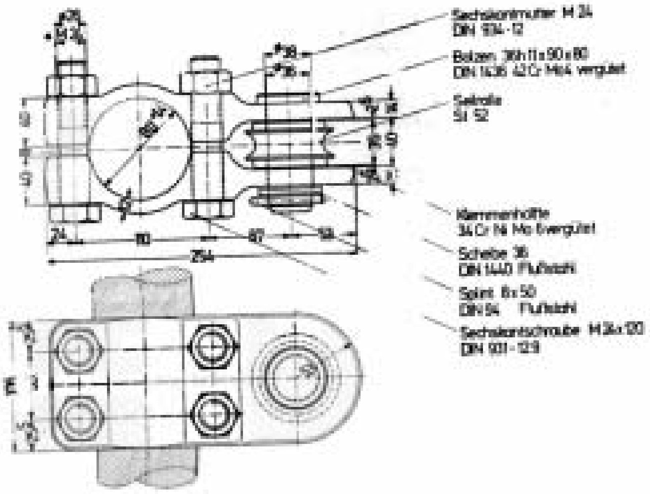


Bild 29: 4-Schraubenklemme

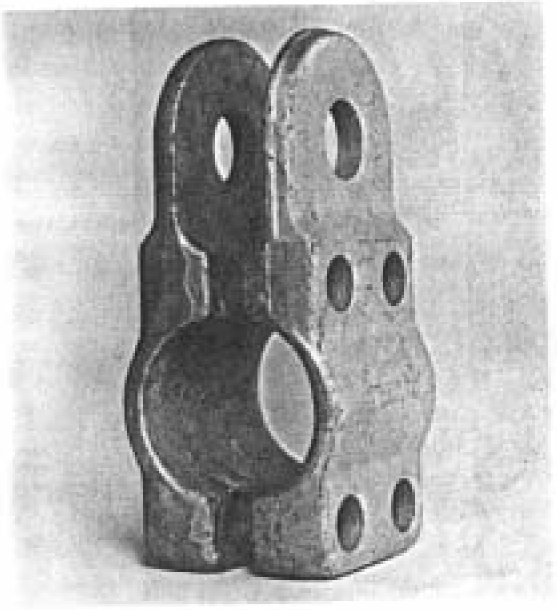


Bild 3o: 4-Schraubenklemme

3.2.31 Anchoring of the Single Strand

The anchoring of the single strands is influenced by the following features :

1. The force in the strand is concentrated on a small cross-sectional area due to the high stress.
2. Welding, bolting or riveting used to connect other parts of steel structures can not be used to connect steel wires to other structural parts.

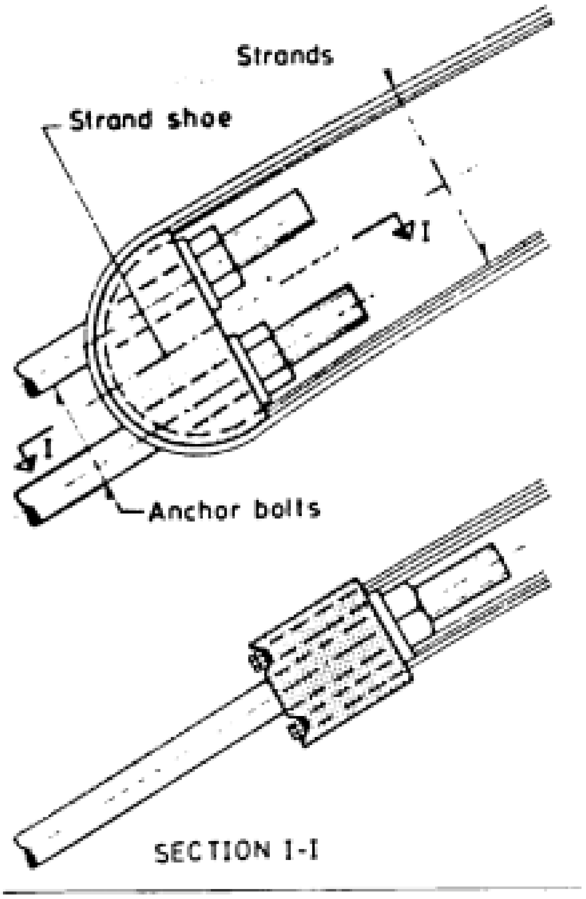


Fig. Strand Shoe for Anchoring Strands Erected by the Air Spinning Method

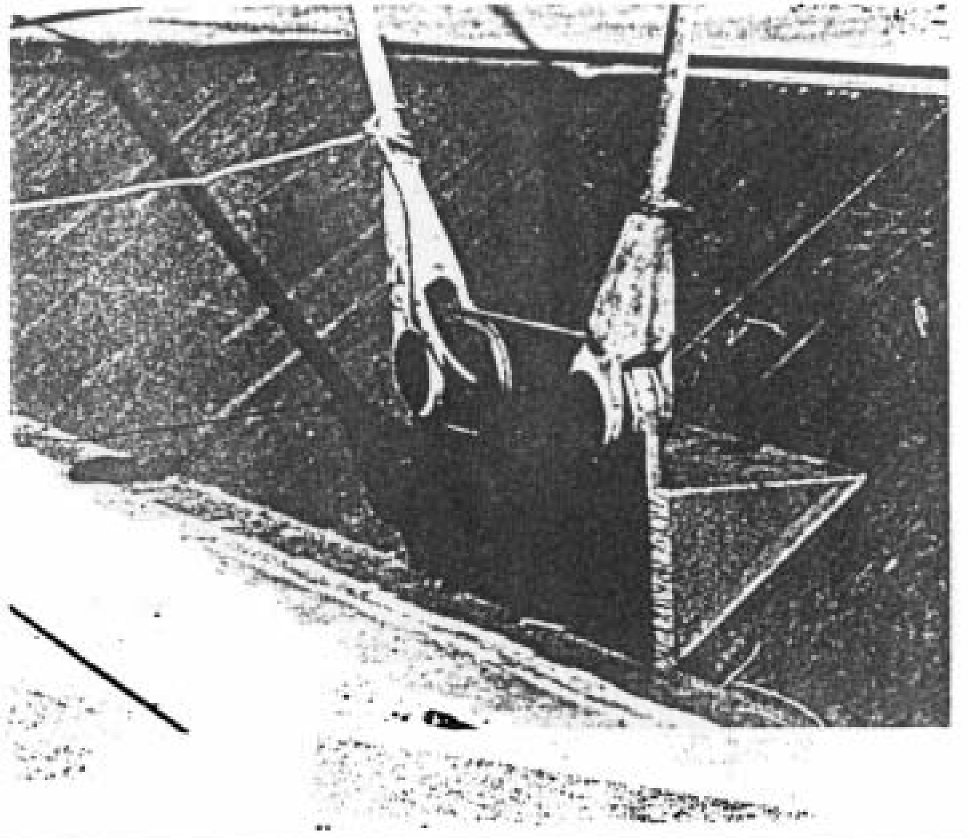


Fig. Open Sockets used on the Inclined Hangers of the Severn Bridge

3.2.32 End Fittings of Cables

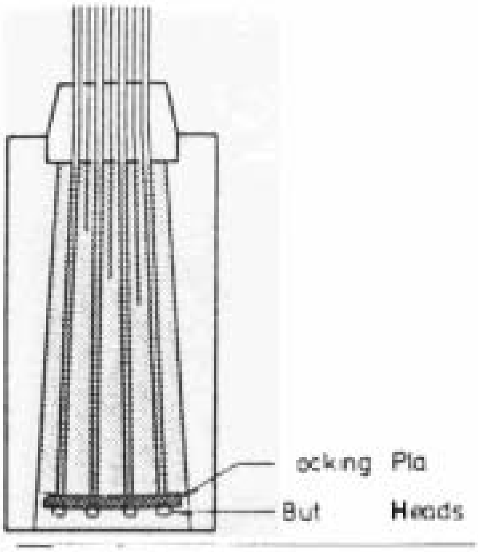


Fig Socket for Parallel Wire

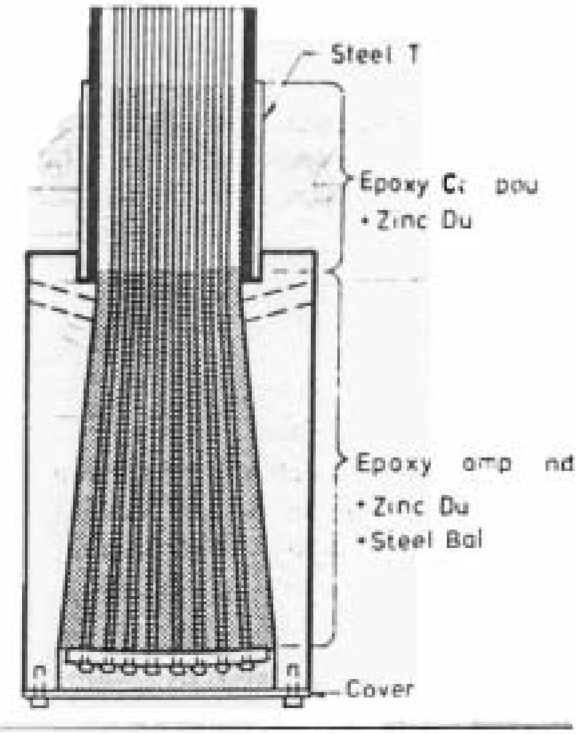


Fig. HiAm Socket

3.3 Analysis Methods of Cables

3.3.1 Analytic Method

- **Catenary Cable**
  - **Static Analysis**
  - **Dynamic analysis**
- **Parabolic Cable**
  - **Static Analysis**
  - **Dynamic analysis**
- **Elastic Catenary Method**

3.3.2 Finite Element Method

4 Analysis Method of Suspension Bridges

4.1 Analytic Method

4.2 Finite Element Method