CABLE-STAYED BRIDGES OF PRESTRESSED CONCRETE

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Discusses prestressed concrete cable-stayed bridge structures. Although most cable-stayed bridges have been of steel construction, a few have been made of prestressed concrete. This type of structure is presented on a case-study basis with the intent of encouraging designers to consider the feasibility of using this type of structure which in some instances might be a more appropriate choice.

The concept of supporting a bridge deck by using one or more inclined stays was proposed in 1784 by C. J. Löscher, a German carpenter in Fribourg. It was conceived as a timber bridge consisting of timber stays attached to a timber tower.[1-4]

Unfortunately, during the birth of the cable-stayed system, the engineers of that period were unable to calculate the forces in the stays nor understand or control the equilibrium of these highly indeterminate systems. Unsuitable materials such as timber, round bars or chains were used for stays. The stays constructed in this manner were, therefore, of low strength material and could not be fully tensioned. In a slack condition they required substantial deformation of the deck before they could participate in taking the tensile load for which they were intended.

The first modern steel cable-stayed bridge, the Strömsund Bridge, was completed in Sweden in 1955 by a German contractor. Although the cable-stayed Tempul Aqueduct in Spain, designed by Torroja, was completed in 1925, the first modern prestressed concrete cable-stayed bridge structure was Morandi's Lake Maracaibo Bridge in Venezuela, completed in 1962.

Lake Maracaibo Bridge, Venezuela (The General Rafael Urdaneta Bridge)

This reinforced and prestressed concrete bridge structure ranks as one of the longest in the world. The prime contractor was Maracaibo Bridge Joint Venture comprised of Precomprimido C.A., Caracas, Venezuela and Julius Berger A.G., Wiesbaden, Germany. The designer was Prof. Riccardo Morandi of Rome. The structural analysis and detailed plans were prepared by the Maracaibo Bridge Joint Venture in conjunction with Prof. Morandi.

With the one exception, all 12 designs submitted in the competition advocated a steel superstructure. The reasons for the selection of the Maracaibo Bridge Joint Venture design by the government commission were given as follows:[5]

1. Reduction of maintenance costs as a result of the climate conditions existing at the site.
2. The aesthetics of the design.
3. The greater use of local materials and therefore less foreign exchange expended for imported materials.
4. Greater use of local engineering talent and labor.

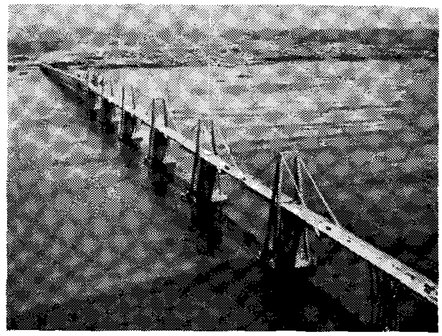

Fig. 1. Lake Maracaibo Bridge

The total length of this structure is 5.4 miles (8.7 km). The five main navigation openings consist of prestressed concrete cantilevered cable-stayed structures with suspended spans having a total 771 ft (235 m) span (see Fig. 1). Navigation requirements stipulated

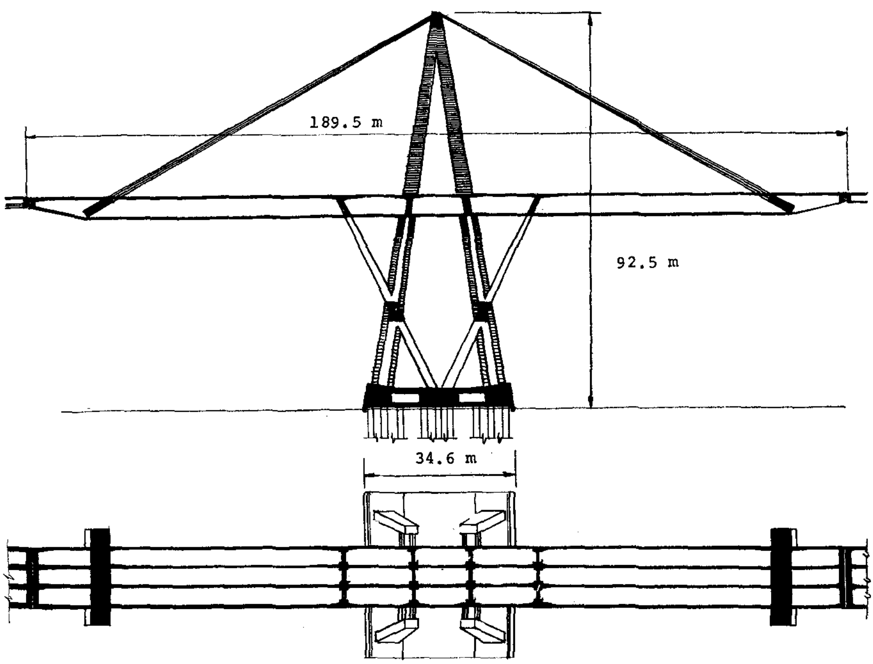

Fig. 2. Main span tower and X frames

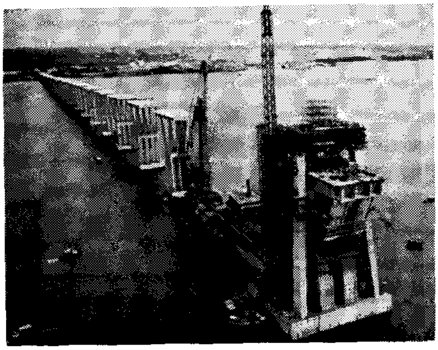

Fig. 3. Pier caps with X frames

a horizontal clearance of 656.2 ft (200 m) and a vertical clearance of 147.6 ft (45 m). To preclude any possible damage as a result of unequal foundation settlement or earthquake forces, the central spans had to be statically determinate. Thus, a main span is divided into cantilever sections with a simply supported suspended center portion.

The pier foundation width of 113.5 ft (34.6 m), Fig. 2, was determined from transferring longitudinal bending moments, resulting from the placing of the suspended span and from unsymmetrical traffic loads. With a 656.2 ft (200 m) clear span requirement and a 150.9 ft (46 m) suspended span, the

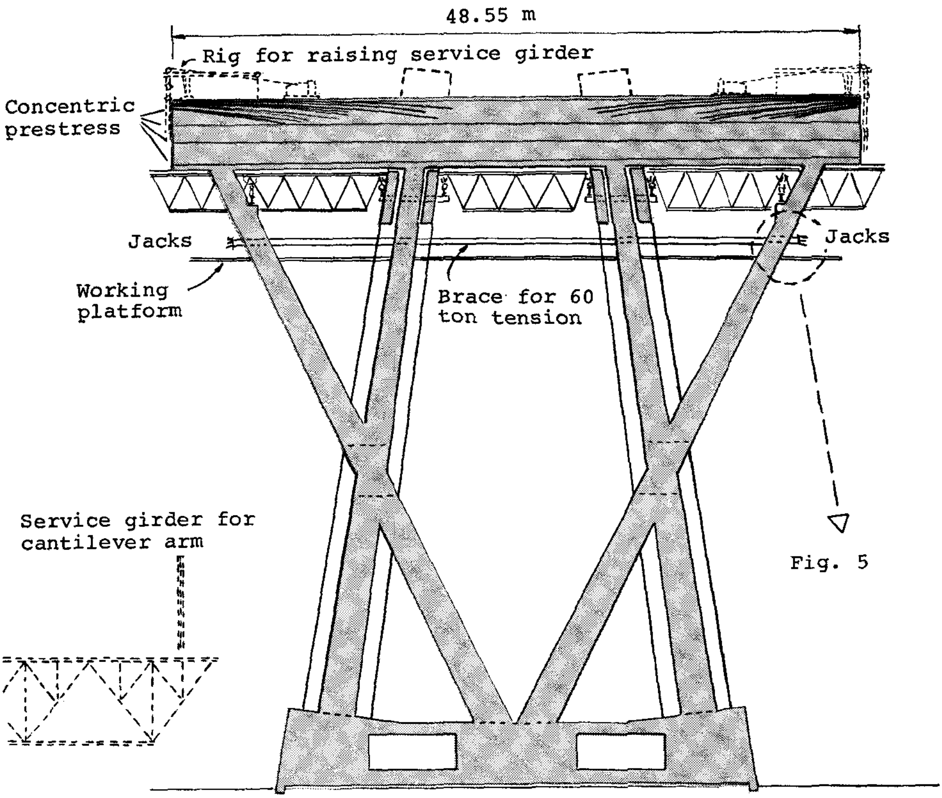

Fig. 4. Pier cap of a main span and service girder

cantilever arm extends 252.6 ft (77 m) beyond the pier foundation. To avoid the large depth associated with a cantilever of this dimension, cable stays were used as a supporting system from the 303.5 ft (92.5 m) high towers. Any other system of support would have required deeper girders and thus would have changed the roadway elevation or infringed on the required navigational clearance.

The cantilever span is supported on X frames while the cable stays are supported on two A frames with a portal member at the top. There is no connection anywhere between the X and A frames (see Fig. 2). The continuous cantilever girder is a three-cell box-girder 16.4 ft (5 m) deep by 46.7 ft (14.22 m) wide. An axial prestress force is induced into the girder as a result of the horizontal component of cable force. Thus, for the most part, only conventional reinforcement is required. Additional prestressing tendons were required for negative moment above the X frame support and the transverse cable-stay anchorage beams.[5]

The pier cap consists of the three cell box girder with the X frames continued up into the girder to act as transverse diaphragms (see Figs. 3 and 4). After completion of the pier, service girders are raised into position to be used in the construction of the cantilever arm. Due to the additional moment, produced during this construction stage by the service girder and weight of the cantilever arm, additional concentric prestressing was required in the pier cap (see Fig. 4). To avoid overstressing of the X frames during this operation, temporary horizontal ties were installed and tensioned by hydraulic jacks (see Figs. 4 and 5).

In the construction of the cantilever arms, special steel trusses (service girders) were used for formwork. They were supported at one end by the completed pier cap and at the other end by auxiliary piers and foundations as shown in Fig. 6.

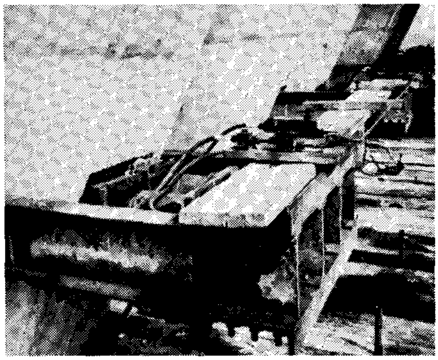

Fig. 5. Brace members bear against X frames after being tensioned by hydraulic jacks

The anchorages for the cable stays are located in a 73.8 ft (22.5 m) long prestressed inclined transverse girder. The reinforcing cages for these members were fabricated on shore in a position corresponding to the inclination of the cables. They weighed 60 tons and contained 70 prestressing tendons (see Fig. 7). The cable stays are housed in thick walled steel pipes (see Fig. 8),

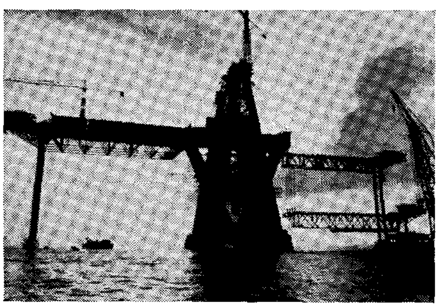

Fig. 6. Placing service girders for forming cantilever girders

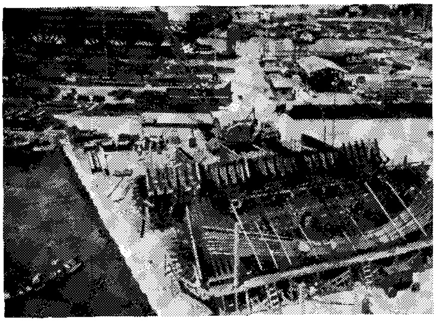

Fig. 7. Fabrication of anchorage beam

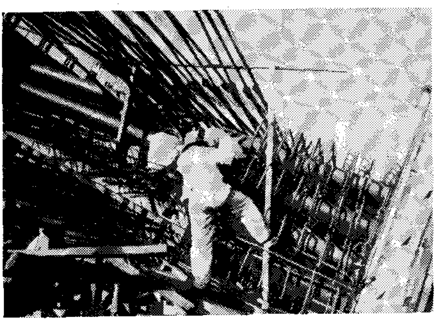

Fig. 8. Housing for cable stays

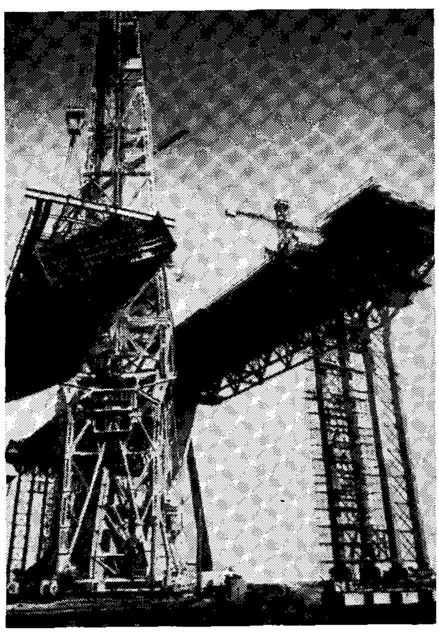

Fig. 9. Erection of reinforcing cage for prestressed transverse anchoring girder

which were welded to steel plates at their extremity. A special steel spreader beam was used to erect the fabricated cage in its proper orientation as shown in Fig. 9.

The suspended spans were composed of four prestressed T sections (see Fig. 10).

Polcevera Viaduct, Genoa, Italy

This structure was also designed by Morandi and is similar in design and appearance to the Maracaibo Bridge (see Fig. 11). It is a high level viaduct 3600 ft (1100 m) long with the roadway at an elevation of 181 ft (55 m) above the terrain. The three main cable-stayed spans have lengths of 664, 689, and 460 ft (200, 210, and 140 m).[6] The bridge carries the Genoa-Savona motorway over an area composed of railway yards, roads, industrial plants, and the "Polcevera" creek. The top of the cable-stayed supporting A frame is 139.5 ft (42.5 m) above the roadway elevation. As in the Maracaibo structure the A frame has a longitudinal girder at the roadway level and a transverse girder at the top. The deck girder in this structure is a five-cell box girder. Center suspended girders are 118 ft (36 m) long. The transverse cable-stay anchorage girders in this structure are box girders requiring that the cable stays divide above the roadway and anchor through the webs of the anchorage girder. The cable stays are composed of pretensioned high-tensile steel strands encased in a protective concrete shell.[6]

Wadi Kuf Bridge, Libya

The Wadi Kuf Bridge (see Fig. 12) is another Morandi design with three spans. The structure has a 925 ft (280 m) center span, and 320 ft (98 m) end spans with a total length of 1565 ft

(475 m). The familiar A frame towers are 459 and 400 ft (140 and 122 m) high with the deck clearing the valley at its lowest point by 597 ft (182 m). The superstructure is a single-cell box girder of variable depth with cantilever flanges forming a 42.7-ft (13 m) deck.[7]

Because of the height and difficult terrain the contractor used traveling forms to construct the box girder and deck in a balanced cantilever construction. Temporary cable stays were used to support the cantilever arms during construction as they progressed in both directions from the tower until the permanent stays were installed.

The simply supported "drop-in" center portion of the span consisted of three 180 ft (55 m) long double-T beams weighing approximately 220 tons each.[6]

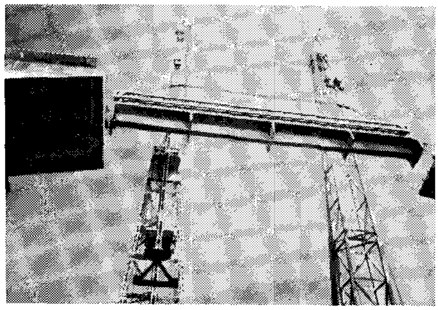

Fig. 10. Erection of suspended girder

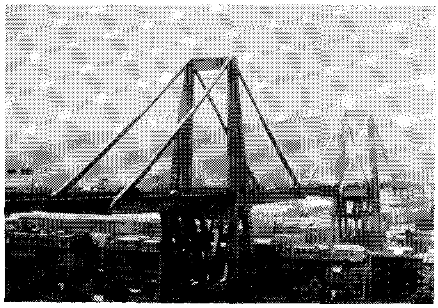

***Fig. 11.** Polcevera Creek Bridge*

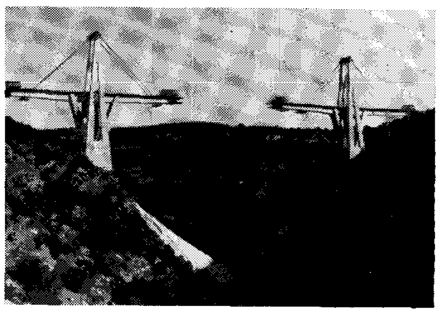

***Fig. 12.** Wadi Kuff Bridge*

Magliana Viaduct

This is still another example of Morandi's structures. This particular bridge carries the roadway of the Rome-Fiumicino Airport over a swamp area formed by a bend of the Tiber river. The site was unavoidable because of the proximity of the Rome to Pisa railway line. This structure, as shown in Fig. 13, has a single portal type tower and a total length of 652 ft (198.6 m) with 476 and 176 ft (145 and 53.6 m) spans. The 476-ft (145 m) span is composed of a 206 ft (63 m) suspended span and a 269 ft (82 m) cantilever span which is supported by a forestay at 226 ft (69 m) from the tower. The structure is further complicated in that the roadway at the site of the structure has a horizontal curve of 1558 ft (475 m) radius. The seven-cell box girder cantilever deck is 70.5 ft (21.5 m) wide plus the variable overhang on each side to make up a 79 ft (24.2 m) roadway width. The suspended span is composed of eight prestressed T-beams.[8]

In this structure Morandi abandoned the fixity achieved by the X shaped piers and A frame towers which was his trademark in his previous structures and resorted to a fully-articulated structure. The tower is hinged at its base. Also, the cantilever span contains hinges at the tower and the anchor

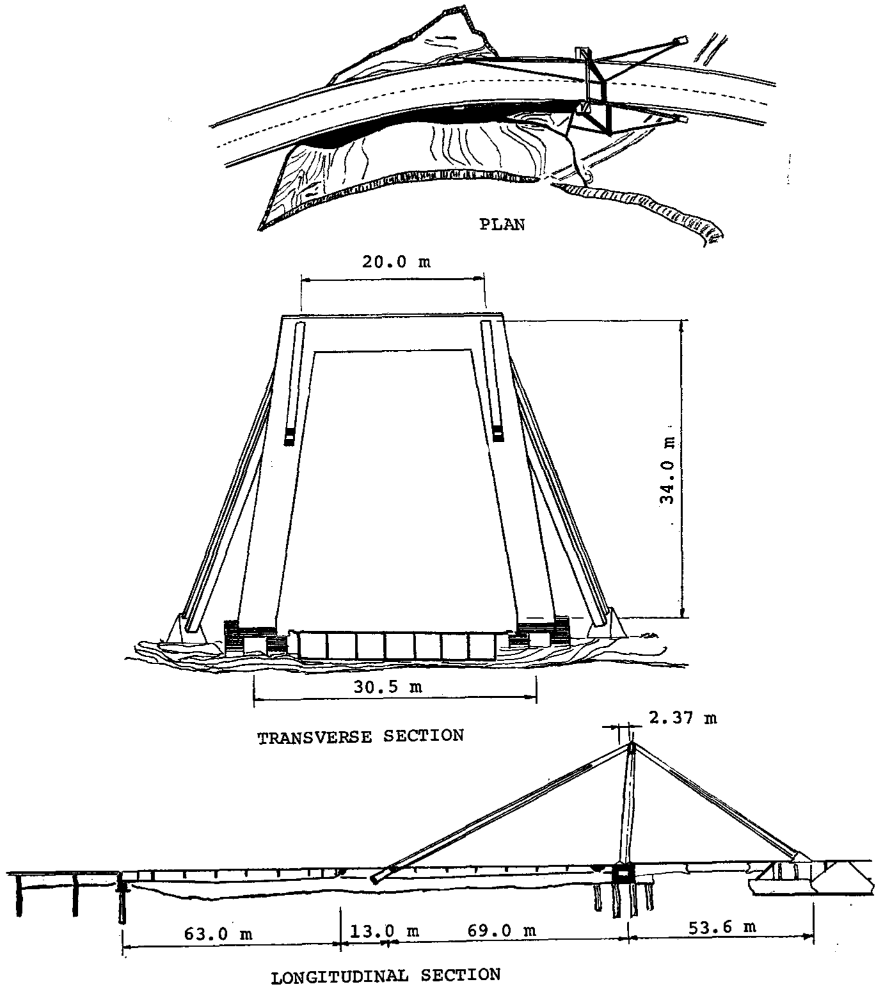

Fig. 13. Magliana Viaduct

span. The hinges are large radius steel lined concrete surfaces that extend the full width of the deck (see Fig. 14).[8]

The transverse stay anchorage beam is a box section that is 26 ft (8 m) deep and 8.8 ft (2.7 m) wide and similar to the Polcevera viaduct. The fore stay is divided to accommodate the anchorage into each web (see Fig. 15). Prestressing for the anchorage beam consists of 76 cables of sixteen 0.2 in. (5 mm) diameter wires (see Fig. 16).

The use of parallel prestressing wire in the stays was a new innovation on this project. Fig. 17 shows a closeup of the cable-stay tendons at the juncture with the prestressing tendons in the anchorage girder.[8]

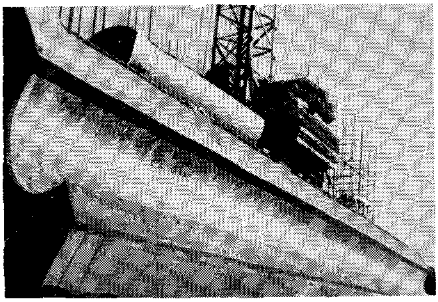

Fig. 14. Steel lined hinge

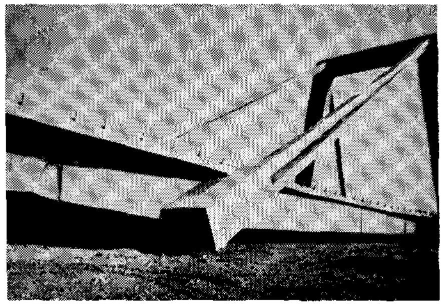

Fig. 15. Fore stay

Danish Great Belt Bridge Competition

A third prize winner in this competition was the Morandi style design proposed by the English consulting firm of White, Young, and Partners (see Fig. 18). Design requirements were for three lanes of road traffic in each direction and a single rail traffic in each direction. Rail traffic was based on speeds of up to 100 mph. Navigation requirements stipulated a bridge deck height of 220 ft (67 m) above water level and a clear width of 1130 ft (345 m).[9]

The deck is envisioned as two parallel single-cell box girders (see Fig. 19), where the rail traffic would be carried inside the box on the bottom flange and the road traffic would be carried on the surface of the top flange. The box girder will probably have a 23.5 ft (7.2 m) depth and a 27.75 ft (8.45 m) width with the top flange cantilevered out 12 ft (3.675 m) on each side.[10]

The piers are planned to be cast-in-place and capable of carrying the deck units. The deck units will be precast at various locations on shore and floated into position for erection. The maximum weight of a box unit is estimated to be 2200 tons. The bridge is designed using only reinforced and prestressed concrete.

This structure is notable in that the

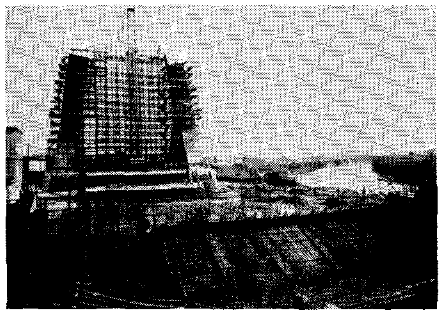

Fig. 16. Prestress tendons in anchorage beam

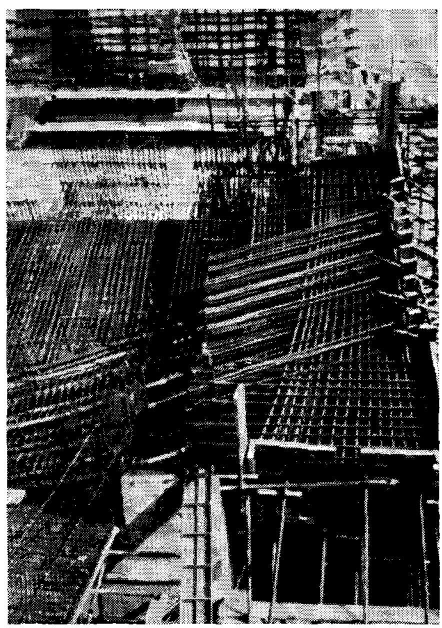

Fig. 17. Juncture of stay with anchorage beam

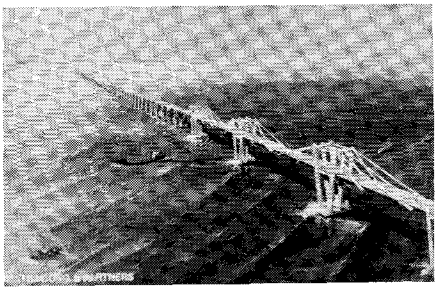

Fig. 18. Danish Great Belt Bridge

cable-stay configuration in a transverse direction consists of three vertical planes as shown in Fig. 18.

River Foyle Bridge

This proposed structure will cross the River Foyle at Madam's Bank near Londonderry, Northern Ireland. It will consist of dual three-lane roadways with a centrally located walkway. From the west abutment the approach spans are one at 164 ft (50 m) and two at 229.7 ft (70 m) to the pylon, a center span starting at the pylon of 689 ft (210 m) and east approach spans of six at 229.7 ft (70 m) and one at 164 ft (50 m) to the west abutment (see Fig. 20). The main span will have a navigational clearance of 105 ft (32 m).

The superstructure is planned to be a single trapezoidal prestressed box girder with side cantilevers of constant depth and continuous over the total length of structure. Although alternate methods are being considered, the current thought is to have the superstructure made up of precast units with an epoxy resin at the joints.

The center span will be supported at 229.7-ft (70 m) intervals by cable stays from an inverted Y-pylon. The pylon is to be cast in place up to deck level and the approach spans constructed by balanced cantilever 115 ft (35 m) into the main span at each end. The A-frame portion of the pylon will be cast next allowing the lower back stay to be an-

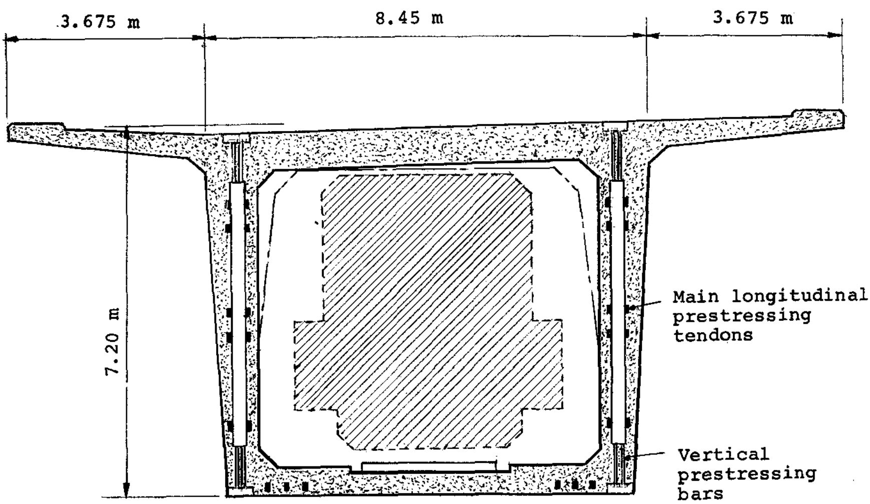

Fig. 19. Danish Great Belt Bridge (Section through deck beam at expansion and contraction joints)

chored to an approach pier and a temporary stay to be positioned 115 ft (35 m) from the pylon into the main span. This procedure will enable the deck to be cantilevered out another 115 ft (35 m). Initially, the mast part of the tower will be constructed and then the first permanent fore stay will be positioned 229.7 ft (70 m) from the pylon allowing the deck to be cantilevered another 115 ft (35 m). The cantilever type construction method will then be repeated until the center span is cantilevered out 574 ft (175 m) from the tower and all permanent stays are positioned. The box girder will be erected by this cantilever method with the transverse ribs and deck slabs added later.

The permanent stays will be parallel wire cables using conventional prestressing anchorages, with dead end anchorages at the deck and jacking end anchorages at the pylon. The two permanent back stays will be anchored to the piers, thus, increasing the rigidity of the structure.[11]

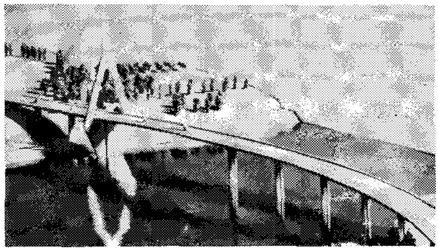

Fig. 20. River Foyle Bridge

Inter-Continental Peace Bridge

The proposed structure across the Bearing Strait would link Alaska and Siberia and provide a transportation link connecting five continents. Geographically, the Bearing Strait is roughly equidistant from Honolulu, San Francisco, Tokyo, Moscow, New York, London, Paris, and Berlin.[12]

In concept this structure is a combined railway and highway bridge 50 miles (80.5 km) long requiring approximately 260 spans at 1000 ft (304.8 m) each. This would be a record breaking length. It would not necessarily, however, be an unrealistic goal. The Diomede Islands roughly divide this length in two and the feasibility of using 25 mile (40.25 km) long bridges can be attested to by the Lake Pontchartrain, Louisiana structures. As demonstrated by spanning the Wadi Kuf and the Danish Great Belt, a bridge across this 1000-ft (304.8 m) span is possible with today's technology.

The maximum water depth across the Bearing Straits is 180 ft (55 m) with an average of 150 ft (45.7 m). These depths are manageable today. For example, the Naragansett Bay Bridge at Newport, Rhode Island, has piers in 160 ft (48.8 m) of water and offshore oil drilling rigs have been built in 340 ft (103.6 m) depths of water with some designs being planned up to 1000-ft (304.8 m) depths.[12]

The present concept envisions the piers to be prefabricated as one piece at some shore location, floated into position and sunk. Since there is only a 20-ft (6.1 m) sediment cover over bedrock the piers will have to be anchored by prestressing cables to the bedrock. Because the ice pressure might develop in any direction, the pier concept is circular with curving slopes at the water line to help break ice floes in bending as they push forward and upward along the curve.

Likewise, the superstructure is envisioned to be prefabricated and transported in two span lengths for a total 2000 ft (610 m). It will then be supported on barges at the quarter points. Each assembly will weigh approximately, 30,000 tons (27,215 metric tons).[13]

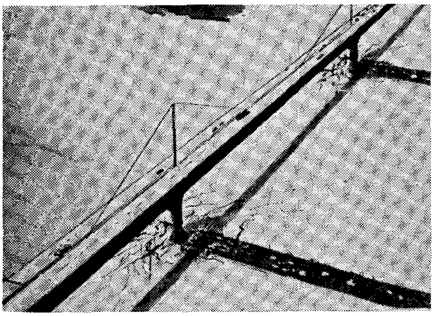

Fig. 21. Inter-Continental Peace Bridge

An artist's rendering of one such concept, a cable-stayed structure, is illustrated in Fig. 21.

Other structures

The Soviet Union's largest cable-stayed bridge is presently under construction over the Dnieper River at Kiev (see Fig. 22). The bridge has a 984-ft (300 m) span and reportedly will be of concrete construction. It is scheduled for completion in 1974.[14,15]

Amman and Whitney is constructing a bridge at Corrientes, Argentina, over the River Parana. This bridge, which has a 837-ft (255 m) span, was scheduled for completion in late 1972.

Morandi designed the twin Zarate-Brazo Largo rail-highway bridge over the River Parana in Mesopotamia, Argentina. This bridge has a 1116-ft (340 m) span and was scheduled for completion in 1972. It has a steel truss deck and the superstructure is supported on prestressed concrete pylons.

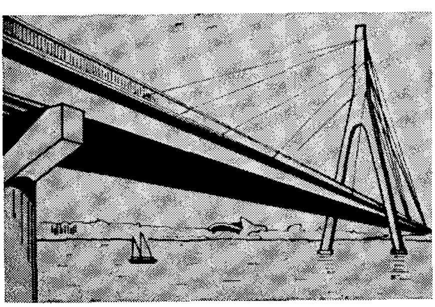

Fig. 22. Dnieper River Bridge at Kiev

Conclusion

With today's advanced techniques of prefabrication, post-tensioning, segmental cantilever construction, and cable-stayed design and construction, prestressed concrete bridges spanning more than 1000 ft (304.8 m) are possible. We have the technology; what is now needed is greater implementation.

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White, Young, and Partners, London (Danish Great Belt Bridge).

Civil Engineering and Public Works Review, London (River Foyle Bridge).

Prof. T. Y. Lin (Inter-Continental Peace Bridge)

Juhani Virola, Finland (Dnieper River Bridge).

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