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Design and Construction of the Akashi Kaikyo Bridge's Superstructure

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Summary

This paper describes some technical features of the Akashi Kaikyo Bridge's superstructure as follows: 1) For the towers, wind resistant design was required. The towers were fabricated and erected with high vertical accuracy. 2) For the cables, erection was done by prefabricated strand (PS) method using newly developed high-tensile strength wires. The dehumidification system was newly developed to increase the life of cables. 3) For the stiffening girder, wind resistant design was done using a newly built large boundary layer wind tunnel facility. 4) Because of some displacement of foundations due to the Southern Hyogo Earthquake, design and fabrication of the stiffening girders had to be modified in order to adjust to the new configuration of the Bridge.

1. Some problems to be overcome for the superstructures

Followings were essential problems to be solved for the superstructures of the Bridge.
1) The Akashi Kaikyo Bridge is a suspension bridge spanning an international navigation channel that is more than 1.5 km wide and has a sea traffic of 1,400 ships a day. Then, the erection of superstructures had to be done not to interrupt the sea traffic.
2) Because of its long-span and high-rise structures, the bridge is very flexible and is susceptible to wind. Then, the wind induced dynamic oscillation of the tower and the stiffening girder had to be suppressed thorough the wind resistant design.
3) Some displacement of foundations occurred by the crustal movement due to the Southern Hyogo Earthquake in January 1995, when the cable erection was almost over. To the change of the Bridge's configuration, some modifications of the design and fabrication of the stiffening girders had to be done.

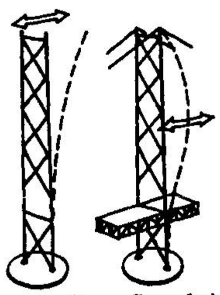
2. Technical features of tower

2.1 Wind resistant design of the tower

The tower is a steel flexible tower, with the height of 287 m. From experiences so far, the tower vibrations by the wind vortex due to the wind from the transverse direction had been a problem to be overcome, during erection. Since the primary natural frequency of the tower of the Bridge is half as low as that of other 1 km class Honshu Shikoku Bridges, it was feared that vibration would occur below the design wind velocity of 66.7 m/s, not only during erection but also even after completion of the bridge.

Table. 1 Comparison of aerodynamic properties of towers

Name of Bridge	Tower height H (m)	1st bending frequency (Hz)	Resonant wind speed (m/s)
Free standing			
Akashi Kaikyo	287.6	0.131	10.0
Kita Bisan Seto	169.5	0.256	16.5
Completion			
Akashi Kaikyo	287.6	0.465	41.8
Kita Bisan Seto	169.5	1.126	86.0



The vibration can be controlled either by aerodynamic improvement of the cross section or by installing damping devices. For aerodynamic improvement of the cross section, fabrication of corner cut-offs in the cross section was judged to be most effective to suppress vortex-induced oscillation, through several wind tunnel tests.
At the same time, damping devices had to be installed to suppress the amplitude of vortex-induced oscillation to the allowable level.
The chosen damping devices were a group of tuned mass dampers (TMD), for economical and structural reasons. TMD consists of a hanging pendulum mass, a spring and oil damper, as shown in Fig. 1. TMD-1 (84 t) is a damping device to suppress the vibration of the 1st bending mode, and TMD-2 (114 t) is for the 1st torsional mode for the completed bridge. Both devices were installed inside of the tower shafts.

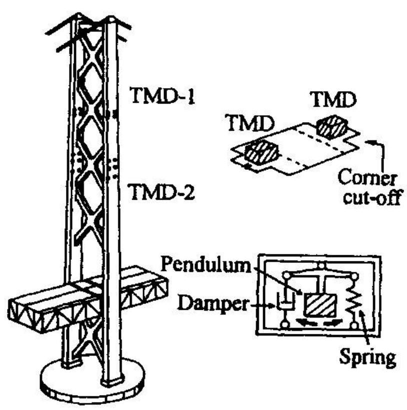


Fig. 1 Installation of Tuned Mass Damper

2. 2 Fabrication and erection

To fabricate the tower, the tower was divided into 30 blocks vertically, and each block was further divided into 3 cells, whose weight did not exceed 160 tons, the capacity of the crane. As the vertical accuracy, the tolerance at the top of the tower was specified to be less than 1/5000 × (tower height). To realize this accuracy, in the shop, each block had to be fabricated with the accuracy of less than 1/10,000. Then, in the shop, 3 cells were temporarily assembled, and the sectional planes were ground and polished to the required flatness, using a

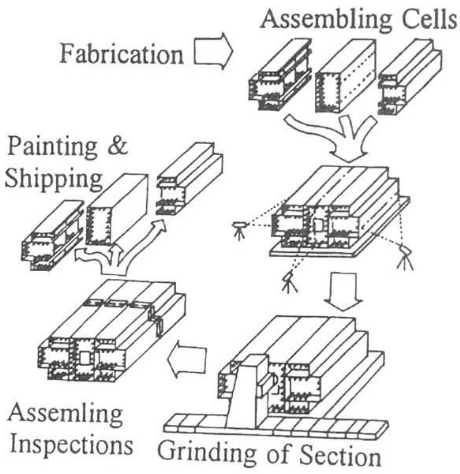


Fig. 2 Fabrication of tower shafts

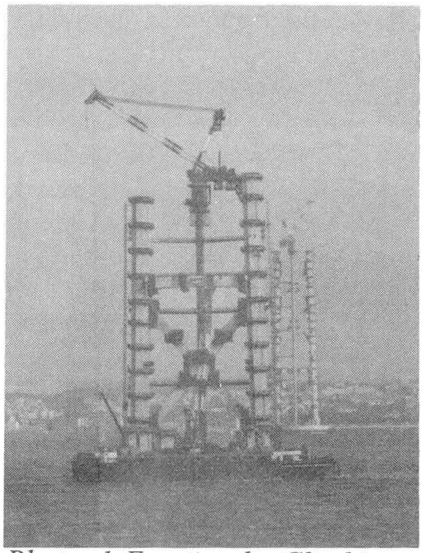


Photo. 1 Erection by Climbing Tower Crane

specially made large-size cutting & grinding machine. Afterward, the blocks were again separated into 3 cells and transported to the site. At the site, a climbing tower crane was adopted to minimize the erection period. After it had laid each block, the crane jacked itself up to the next level and hoisted up another one. The actual error at the top of towers was 39 mm at 2P and 29 mm at 3P.

3. Technical features of cable

3. 1 Development of high tensile strength wire

For more than 50 years, galvanized steel wire, with a diameter of 5 mm and with tensile strength of 155-160 kg/mm^2, had been used for the cable of suspension bridges, due to the established production technology and stable quality. The size of the cable is determined by the sag ratio and the allowable stress of wires. Using 160 kg/mm^2 class wire for the Bridge, the diameter became too large, exceeding the experience of cable erections so far. So the, double cable system (2 cable/one side) could not be avoided. But the double cable has problems, such as increased dead load, complicated structure of the girder and long erection period. To solve those problems, development of high strength galvanized steel wire was required. To increase the strength of galvanized steel wire, the following three means were considered.

1) Increasing the degree of processing during wire drawing
2) Adding small amounts of other elements
3) Controlling strength loss due to the heat reaction during galvanizing

Table. 2 Comparison of chemical ingredients of galvanized wire

	160 kg/mm^2 class	180 kg/mm^2 class
C (%)	0.75 ~ 0.80	0.80 ~ 0.85
Si (%)	0.12 ~ 0.32	0.80 ~ 1.00
Mn (%)	0.60 ~ 0.90	0.60 ~ 0.90

As a result of the investigations, low-alloy steel wire with the addition of Si proved to be the most effective way to raise the tensile strength to 180 kg/mm^2. The properties of the developed 180 kg/mm^2 class wire are shown in Table. 2. The newly developed wire showed almost the same or better quality than the conventional wires.

3. 2 Erection of the cable

To minimize the erection period, the prefabricated parallel wire method (PS method) was adopted. The composition of the cable was shown in Fig. 3.

The cable erection was started by carrying a pilot rope from shore to shore. The conventional way to carry a pilot rope is to pull a rope with floats by a tug-boat or to pull a rope by a tall crane ship. But these methods required sea traffic to be halted, so it was decided to pull the rope by the helicopter, so as not to interrupt the sea traffic on the international navigation channel. For the helicopter, the pilot rope had to be light, strong and easy to handle. So, a poliaramid fiber rope, with a diameter of 10 mm, weight of 0.0917 kg/m and tensile strength of 4700 kg, was used.

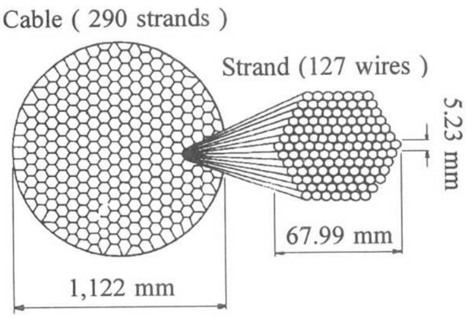


Fig. 3 Cross section of cable

The pilot ropes were connected with steel ropes, and were pulled for the replacement to the stronger ropes. These works were repeated, and the system to haul cable strands were completed. Using this system, catwalk ropes were erected with floors on them. Cable strands were erected as follows: 1) strand reels were transported to the yard of 1A, 2) each strand was pulled by a strand carrier on a hauling system along the catwalk. Cable sag was measured and adjusted during the night when the temperature is stable.

Photo.2 Carrying a pilot rope by helicopter

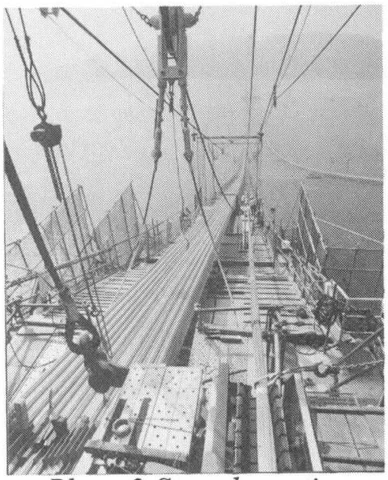


Photo.3 Strand erection by hauling system

To minimize the erection period two hauling systems were used for one cable.

3. 3 Corrosion protection method of cable

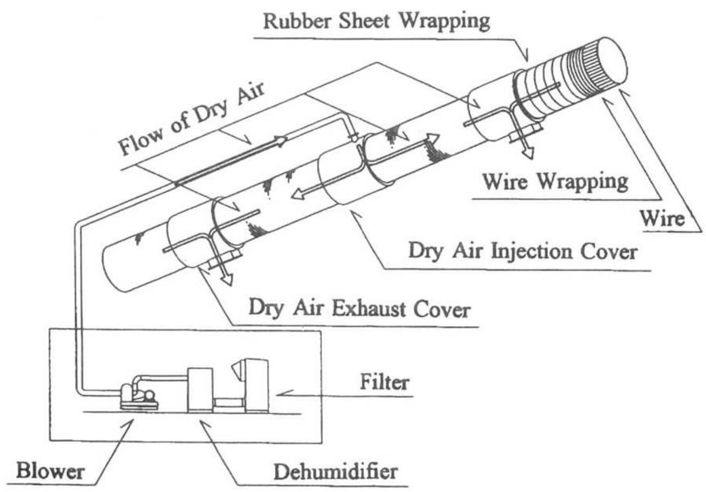


Fig. 4 Dehumidification system of cable

The conventional corrosion protection system for cables consists of a surface paste on the wire, wrapping wire and top coating. But the waterproofing provided by this system is not always satisfactory due to surface paste aging and thermal cracks developing in the top coating. Through several studies, it was found that the atmosphere environment inside of the cable can be improved by injecting dried air into the cable. In this system, a cable surface is completely wrapped by both wires and rubber sheets. Dry air is injected from a cable cover and is exhausted from another cable-cover about 140 meters apart from the injection cover. The pressure within the cable bundle is planned to keep within 0.03 atmospheric pressure so that the rupture of the seals and sheathing materials does not occur.

4. Technical features of stiffening girder

4.1 Wind resistant design of the stiffening girder

Due to its flexible structure, vibration, especially flutter due to wind, was the most important problem at the design stage of the stiffening girder. In the design code, it is specified that flutter must not occur under the wind speed of 78 m/s in the wind tunnel test within the attack angle from -3 deg. to +3 deg..

To determine the type of the stiffening girder, several types of girders as shown in Fig. 5 were investigated. Fig. 5 also shows the relationships between the onset wind speed of flutter and deck weight for the investigated girders. From these results, the truss girder and compounds stiffness box girder were selected as prospective types. The compound stiffness box girder is a bridge system that arranges high-tortionally-stiffened girders around the tower and aerodynamically-well flat girders at the central portion of the bridge. From the comparison of these two types of girders, truss was finally selected due to its ease of its erection on the international navigation channel, because the erection of the truss can be done by not using the navigation channel.

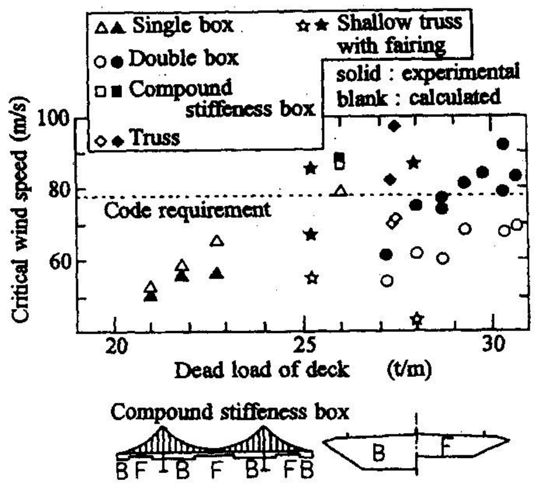


Fig. 5 Girder types and their flutter speed

The dynamic behavior of suspension bridges due to the wind has been investigated mainly by wind tunnel tests using sectional models so far. For the Akashi Kaikyo Bridge, however, a full model test in a large wind tunnel facility was required for the following reasons. 1) The deflection of the bridge due to wind is large. 2) Along the bridge axis with the length of 4 km, there is a large variation of wind properties. 3) The effect of the main cables cannot be neglected. 4) The effect of the turbulent flow cannot be neglected. Therefore, we built a large boundary layer wind tunnel facility with width of 41 m, height of 4 m, and length of 30 m. As a result of the experiment of a scale of 1/100, it was confirmed that the required wind resistancy could be obtained by installing some gratings on the road deck and a vertical stabilizing device along the truss girder as shown in Fig. 6.

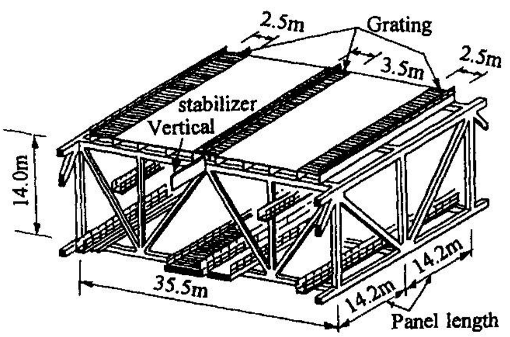


Fig. 6 Stiffening girder of the bridge

4.2 Erection of stiffening girder

Girder erection was started by lifting large-block truss girders using a 3,500 - 4,100 ton floating crane at six places, front sides of anchorages and sides of the two towers. As, these areas are located outside of the navigation channel, those methods could be applied. At those six places, pre-assembled plane truss members with a length of 28 meters were lifted up on

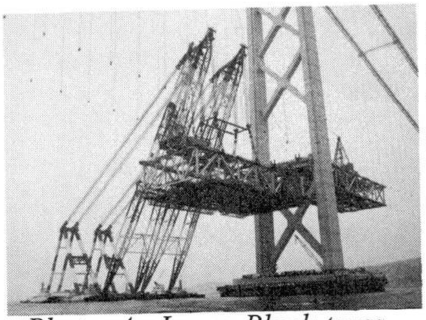


Photo. 4 *Large-Block truss girder erection*

the deck, carried to the front of the erected girders, and connected to them. By adopting this erection procedure, it was possible not to interrupt the sea traffic. The direction of girder's cantilever-out was as follows: 1) Center span: from two towers to the center of the straits. 2) Side spans: from each anchorage to the tower. This erection procedure was selected so that the inclination of the erected girder did not exceed 6 %, within which stability of several machines on the girder could be secured. It took 13 months from the start to the closure of the stiffening girder.

4.3 Effect of the Southern Hyogo Earthquake

On January 17, 1995, just after the cables had been erected, the Magnitude 7.2 Southern Hyogo Earthquake occurred. Its epicenter was only 3.5 km east from the center of the Bridge. After the earthquake, displacement of foundations by crustal movements was found. As a result, the basic configuration of the Bridge changed like Fig. 7. Then modified design of stiffening girder was absolutely required soon after the earthquake. There was almost no damage on the completed structures. At that stage, fabrication of some girders had just started, but fabrication of suspenders had almost finished. As for the configuration of the Bridge, the horizontal change of angle along the bridge axis was found to be small, less than 0.04 degrees at a tower. Those angles were judged to be absorbed by the expansion joints.

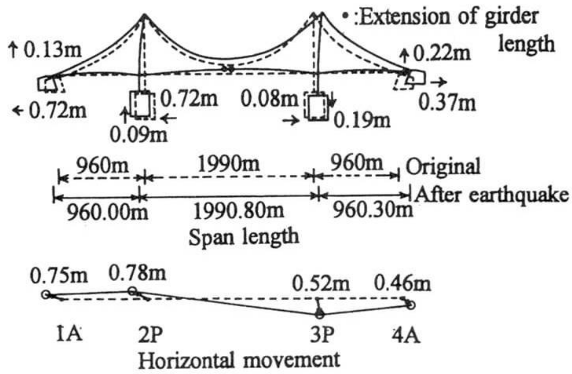


Fig. 7 *Displacement of the Bridge after the earthquake*

The elongation of spans were 0.8 m at the center span and 0.3 m at the Awaji side outer span, and cable sags became shallow. Changes of span length were not negligible, so the length of girders had to be changed at unfabricated girders. Then, we decided to increase the length of the last two girder sections of the center span by 80 cm, and also the length of the last girder section of the Awaji side span by 34 cm respectively. The location of cable bands and suspenders were also changed. The additional stress of the structure due to the change of the bridge configuration was calculated through three-dimensional structural analysis, and was found to be small.

5. Concluding Remark

For the design and construction of the Akashi Kaikyo Bridge's superstructure, various investigations were carried out. Because of its long-span and high-rise structures, and its site location over the busy sea traffic, a lot of studies had to be done to select the adequate construction methods, and to improve the structural design methods. Through these studies, we could develop new technologies like high-tensile strength wires, wind resistant design method, new corrosion protection system for cables, and reasonable construction methods. At the same time, we could overcome the problem of the change of bridge's configuration after the earthquake. We hope that our experiences of the Bridge will be utilized for longer span bridges in the future.