NIPPON STEEL TECHNICAL REPORT No. 73 APRIL 1997

UDC624.5.071.23

Cable Erection Technology for World's Longest Suspension Bridge - Akashi Kaikyo Bridge

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Abstract:

The Akashi Kaikyo Bridge now under construction will become the world's longest suspension bridge with a total length of 3,910 m when completed. Each main cable measures about 1.1 m in diameter, totaling about 50,500 tons in weight, and represents an unprecedented large-scale project. Long engaged in the development of cable design and fabrication methods, Nippon Steel has realized the PPWS (prefabricated parallel wire strand) method and bridge cable wires with a high strength of 180 kgf/mm^2. The company also has tackled the development of various methods for bridge cable erection. An overview is given here of the cable erection work of the Akashi Kaikyo Bridge.

1. Introduction

The Akashi Kaikyo Bridge is a three-span, two-hinged, stiffening-truss suspension bridge with a total length of 3,910 m and center span of 1,990 m over the Akashi Straight between the Tarumi Ward of Kobe and the Awaji Island, Hyogo Prefecture, as part of the Kobe-Naruto route of the Honshu-Shikoku bridge construction projects[1)]. When completed, it will become the world's longest suspension bridge. As listed in **Table 1**, several long suspension bridges are under construction, mainly in Asia and Europe. The Akashi Kaikyo Bridge towers above its competitors.

With its site construction work started in May 1987, the Akashi Kaikyo Bridge is now in the final phase of the project toward its opening in the spring of 1998. A joint venture composed of Nippon Steel Corporation and Kobe Steel, Ltd., was awarded a contract for the cable erection work of the Akashi Kaikyo Bridge by the Honshu-Shikoku Bridge Authority in July 1991. The joint venture completed the first phase of the work by December 1995 and is now carrying out the second phase a contract for which was newly awarded.

The side view of the Akashi Kaikyo Bridge is shown in **Fig. 1**. The main cables to support about 87,000 tons of stiffening girders are unprecedentedly large with a diameter of about 1.1 m each and total weight of about 50,500 tons. This huge scale made it a necessity to introduce new technology in the planning and design stages of the entire cable system. Coupled with the design rationalization of the huge cable system, the development and application of galvanized steel wires with a tensile strength of 180 kgf/mm^2 are making great contributions to reductions in the construction cost and time.

The prefabricated parallel wire strand (PPWS) method, long pushed by Nippon Steel, was adopted in the construction of the Akashi Kaikyo Bridge. The bridge embodies all of the bridge

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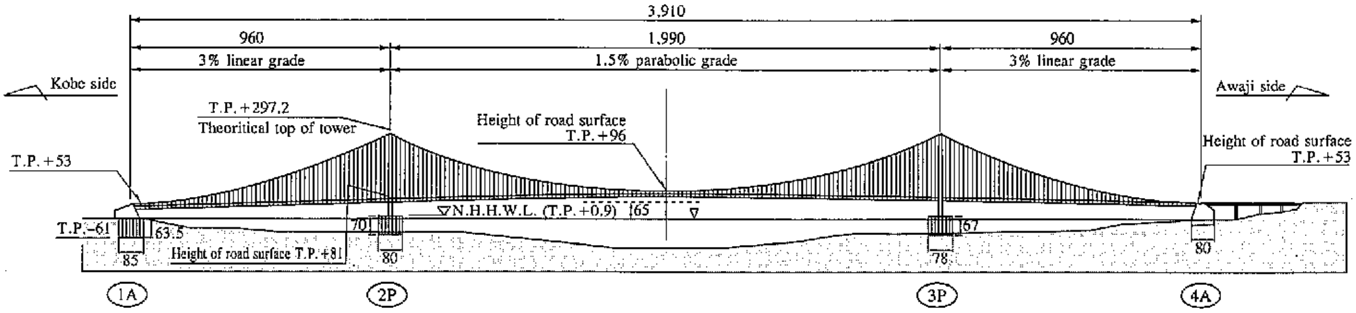
Table 1 Long-span suspension bridges in world

Rank	Bridge	Center span length (m)	Approximate cable weight (t)	Year of completion	Country
1	Akashi Kaikyo	1,990	50,500	Under construction	Japan
2	Great Belt East Road	1,624	19,000	Under construction	Denmark
3	Humber	1,410	11,000	1981	UK
4	Jiangyin Yangtze River	1,385	16,800	Under construction	China
5	Tsing Ma	1,377	28,000	Under construction	Hong Kong
6	Verrazano-Narrows	1,298	34,700	1964	USA
7	Golden Gate	1,280	19,500	1937	USA
8	High Coast	1,210	8,000	Under construction	Sweden
9	Mackinac	1,158	10,100	1957	USA
10	Minami Bisan Seto	1,100	20,000	1988	Japan



T.P. : Mean sea level of Tokyo Bay   N.H.H.W.L. : Nearly highest high water level

Fig. 1 Side view of Akashi Kaikyo Bridge

technologies Nippon Steel has developed to date. Some characteristics of the cable erection work of the Akashi Kaikyo Bridge are here reported.

2. Outline of Akashi Kaikyo Bridge Cable Erection Work

The cable erection work and schedule of the Akashi Kaikyo Bridge are summarized in **Table 2** and **Fig. 2**, respectively. The cable data are given in **Table 3**.

Table 2 Description of work

Item	Quantity	Approximate weight (t)
Fabrication and erection of tower top saddles	4 units	620
Fabrication and erection of spray saddles	4 units	1,390
Fabrication and erection of cable strands	580 strands	50,460
Cable squeeze	1 set	
Fabrication and erection of cable bands	550 bands	2,300
Fabrication and erection of hanger ropes	1,068 ropes	2,050

3. Crossing of Pilot Rope by Helicopter[2)]

3.1 Outline

The cable erection work of a bridge is started when the main towers and the cable anchorages are completed. The first phase of the work starts with the installation of a pilot rope as foothold over the entire span connecting the main towers and anchorages. The pilot rope is then used to install a rope drive system (rope hauling system), erect catwalks, and erect cables.

Traditionally, pilot ropes were drawn and erected by tugboats or large floating cranes on the sea. The Akashi Straight has a heavy traffic of over 1,400 ships per day, is wide, and the tidal current is rapid. Given these severe natural conditions, the pilot rope of the Akashi Kaikyo Bridge was aerially erected by a large helicopter without using the sea surface.

This work was conducted on November 10, 1993. As shown in **Fig. 3**, a large helicopter hung an extending machine carrying a reel of pilot rope and strung the pilot rope from one anchorage to the first main tower, then to the second main tower, and finally to the other anchorage while paying out the pilot rope from the reel. The general performance data of the helicopter are shown in **Fig. 4**. The pilot rope used was a 10-mm diameter polyaramid fiber rope. Its specifications are given in **Fig. 5**. This feat was made possible by the availability of a large commercial helicopter and the development of a new rope constructed of superlight and high-strength material.

3.2 Technical problems and their solutions

Helicopters have successfully worked in stringing aerial electric power lines in the past. In the Akashi Strait environment where the helicopter pulling of the pilot rope could have a serious impact on people working there, it was considered dangerous to depend solely on the maneuvering skills of the helicopter pilot and extending machine operator. The use of a helicopter in the project was considered to be too risky. Safe execution of this task called for an accumulation of quantitative skills. Possible problems were quantitatively grasped one by one by various experiments.

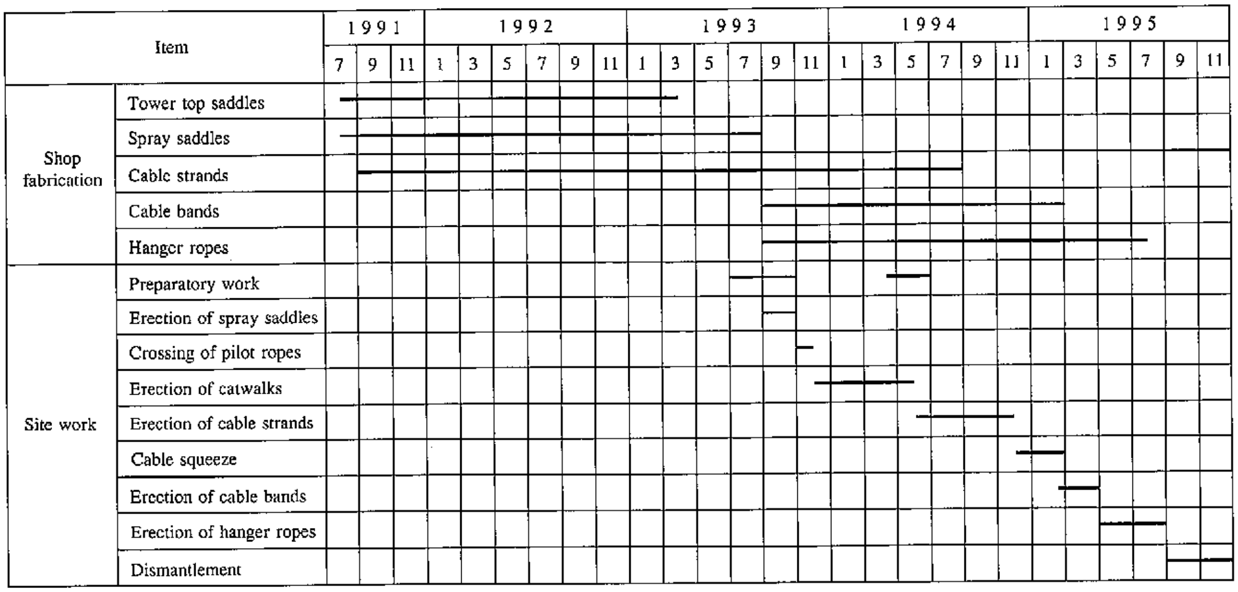
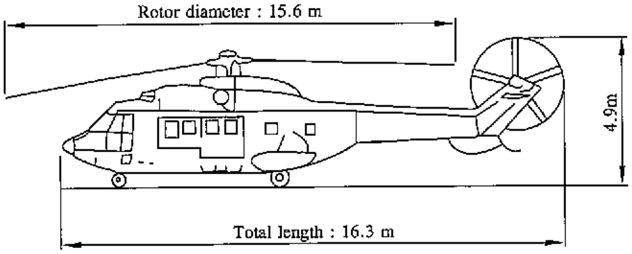


Fig. 2 Work schedule

Table 3 Cable data

Galvanized steel wire	Tensile strength	180-200kgf/mm²
	Wire diameter	5.23mm
Strand	Number of wires	127 wires/strand
	Unit weight	21.36kg/m
Cable	Number of strands	290 strands
	Diameter	1,122mm



Helicopter data

Engine : 1,500 PS×2
Effective loading capacity : 4,180 kg
Number of passenger seats : Maximum of 20
Maximum spring-suspended capacity : 4,500 kg

Fig. 4 Large helicopter used for crossing of pilot rope

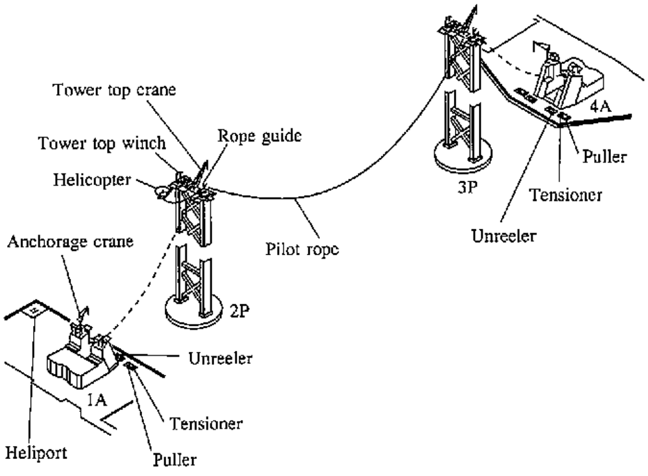
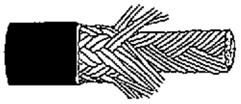
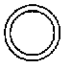


Fig. 3 Procedure for crossing of pilot rope



Type	Construction	Material	Characteristic
008B-BC		Inner layer: Aramid fiber Middle layer: Polyester fiber Outer layer: Urethane resin (#129)	Rotation-resistant, waterproof construction

Diameter (standard) (mm)	Inner-layer aramid fiber diameter (braid) (mm)	Outer layer thickness (urethane + fiber) (mm)	Aramid fiber cross-sectional area (mm²)	Weight (g/m)	Tensile strength (kN[tf])
10	8.0	1.0	25.9	91.7	46.1 [4.70]

Fig. 5 Specifications of pilot rope

3.2.1 Extending machine system

The extending machine for the aerial stringing of the pilot rope is shown in **Fig. 6**. A disk brake was hydraulically controlled to adjust the tension of the pilot rope being paid out from the reel. The mechanism was made extremely simple for lower weight. The extending machine was experimentally studied for the abilities to unreel the pilot rope at high speed and control the tension of the pilot rope with high reliability. The payoff stability of the pilot rope was considered as a function of the winding tension and unreeling speed of the pilot rope. As a result it was decided to use the extending machine with a winding tension of 200 kgf and unreeling speed of 150 to 200 m/min. When the relationship between the tension and hydraulic pressure was measured, it was confirmed that the extending machine could be satisfactorily operated under hydraulic pressure control.

3.2.2 Pulling force of helicopter

The large helicopter used in the project has design requirements to be met, including the maximum weight with respect to the vertical load. It has not been fully studied for its horizontal pulling force as required for extending the pilot rope, however. A pulling force experiment was conducted as shown in **Fig. 7**, and the relationship between the rope tension and critical pulling angle was obtained as shown in **Fig. 8**. The calculated values in **Fig. 8** were obtained from the simple equilibrium of forces and correlate well with the results of the experiment in which the helicopter hovered. Based on these data, the pilot rope extending tension and other details were planned.

3.2.3 Setup of entire system

The final experiment to confirm the entire system on the basis of the above-mentioned characteristic data was carried out by using two floating cranes (FCs) as shown in **Fig. 9**. The main purpose of the experiment was to determine the degree to which the sag of the pilot rope could be controlled, depending on the pilot rope extending method employed. The sag control greatly depended on the extending machine operating pattern. The helicopter can fly over a short pilot rope stringing span while maintaining the maximum tension of the pilot rope throughout the

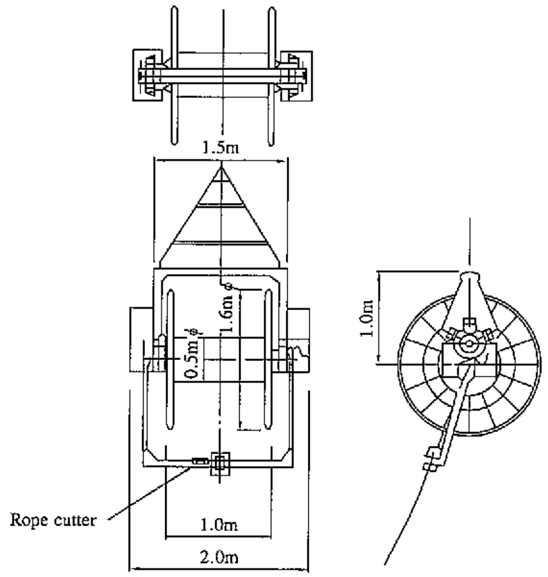


Fig. 6 Extending machine for crossing of pilot rope

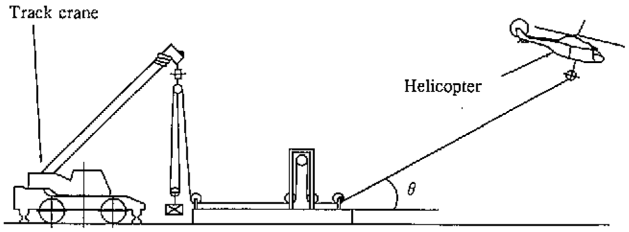


Fig. 7 Helicopter pulling force experiment

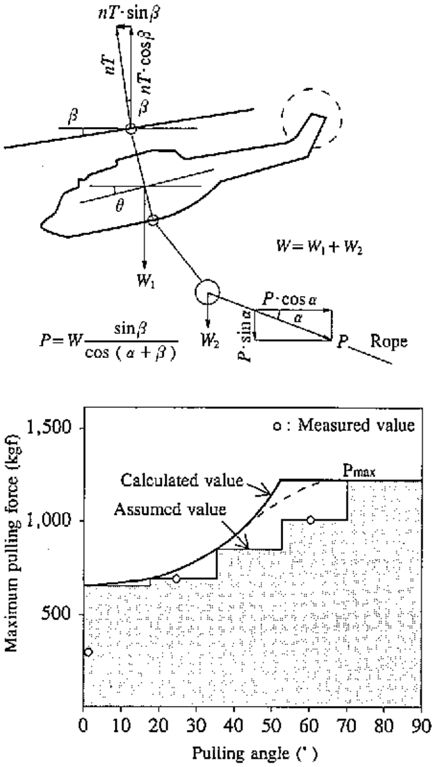


Fig. 8 Relationship between helicopter pulling force and angle

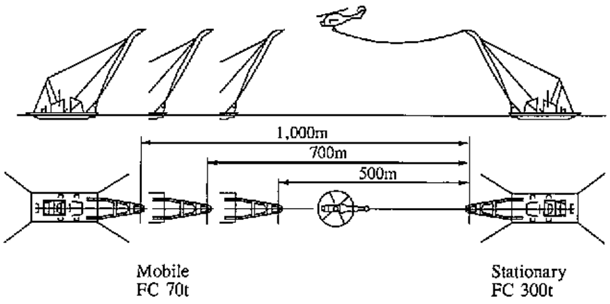


Fig. 9 Experiment to confirm entire system

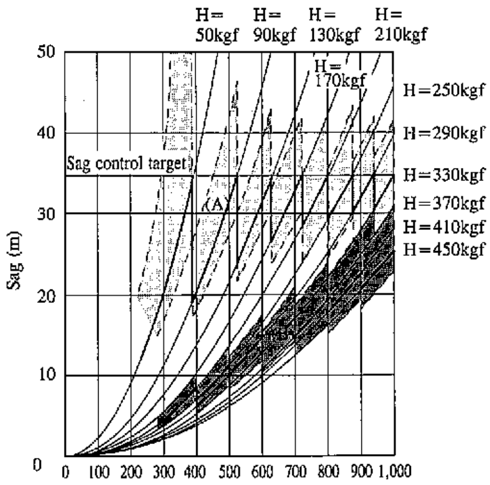


Fig. 10 Setup of rope tension

flight. This is difficult to perform in view of helicopter maneuvering over such a long span as in the present project, and the tension of the pilot rope must be changed several times throughout the flight.

When the tension of the pilot rope is changed, such a situation is expected to occur that the helicopter may fly beyond its navigation limits due to an accumulation of timing delays and tension control errors. **Fig. 10** shows the relationship between the flight distance and the preset tension. Under pattern A in **Fig. 10**, the above-mentioned errors are likely to cause the sag of the pilot rope to greatly exceed the control limit. When the helicopter was experimentally operated according to this pattern, the rope sometimes touched the sea surface. When the tension of the rope was changed as early as shown under pattern B, the sag of the rope was confirmed to be stably controllable. This advanced the pilot rope sea crossing plan by a large extent.

When making the plan for the sea crossing of the pilot rope according to the results of the quantitatively confirmatory experiments noted above, the pilot rope was marked to indicate the position of each tension change. Various other measures were implemented to ensure the certainty of the work. After an overall rehearsal at the site, the pilot rope was successfully pulled across the three spans in a short time of about 3 hours.

4. Erection of Catwalks

4.1 Experiment for development of catwalk structure without storm ropes

The catwalks of the Akashi Kaikyo Bridge were expected to become huge as compared with those of conventional 1,000-m span suspension bridges when designed in the same way as their conventional counterparts. The method of doing away with the storm system was proposed as the most drastic plan to save both construction time and cost. The storm system has the principal function of improving stability against wind. Prestressing provides the storm system with the following functions as well. After thorough dynamic and static investigations to assure safety, it was finally decided to eliminate the storm system. The main items studied are:

(1) Increase stability against wind during work.
(2) Increase vertical stiffness during work.
(3) Set back the main tower in the side span.
(4) Adjust the floor system to the profile of the cable erection line.

4.1.1 Check of static deformation state

The storm system is strung in a reverse shape of the floor system to fix the floor system through hangers and restrain the deformation of the floor system against the wind load and floor system dead load. The effect of the deformation capacity drop that may result from the elimination of the storm system was quantitatively evaluated.

(1) Storm displacement : With attention focused on the torsion and lateral displacement of the floor system when exposed to the wind load, its loading experiment and analysis were performed. The relationship shown in **Fig. 11** was obtained. The angle of inclination of the floor system would increase by about 25% when the storm system is eliminated, resulting in an increased drag force. The angle of inclination can be reduced by reducing the distance between the cross bridges. The torsion of the floor system was thus found to be properly taken care of in terms of design. There were obtained such results that the lateral displacement of the floor system would be a maximum of 66.2 m at the center of the center span when the storm system was installed and would markedly increase to 107.3 m when the storm system was eliminated. It was judged that the two floor systems would laterally slide but would not fall into such a divergent condition that the entire system would turn over.

(2) Vertical displacement : It was made clear that when a strand was pulled onto the floor system to the middle of the span, the floor system would badly lose its shape under the dead load and interfere with the existing cable. The floor system was thus confirmed to lack vertical stiffness. This problem could be countered by connecting the floor system and the existing cable by wire so that they would both change in shape in the same way.

4.1.2 Check of stability against wind

To confirm the stability against wind of the floor system when the storm system was eliminated, a 1/10-scale partial model of the floor system was built and tested for free vibration and aerodynamic force. Since the angle of inclination was assumed to increase for the catwalk floor system without the storm system, the free vibration test was conducted by assuming the angle of

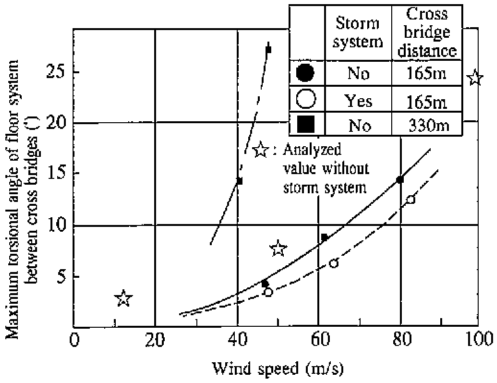


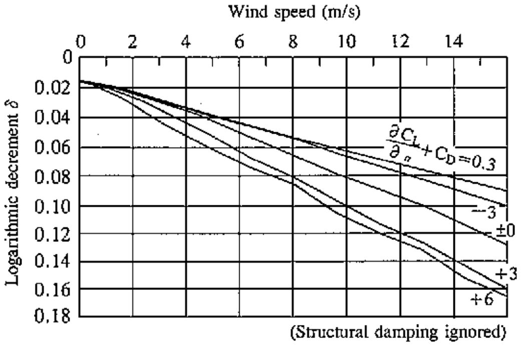
Fig. 11 Maximum torsional angle of floor system between cross bridges

attack that was greater than in the past. The results of the spring support test are shown in **Fig. 12**. The test results agreed well with the results calculated by quasi-steady theory using aerodynamic test results at all possible wind speeds. This verified again that the catwalks were fully stable structural sections aerodynamically.

4.1.3 Check of dynamic stability

The catwalk model was tested for vibration, in order to determine the effect of the storm system on the vibration characteristics of the catwalk. The catwalk model was coupled to a vibrating machine at one point and was tested for resonance or free vibration at the resonance frequency. The local catwalk floor system sandwiched between the cross bridges was also forcibly torsioned and tested for free vibration.

Fig. 13 shows resonance modes and frequencies with and without storm ropes. The storm system is effective in improving the frequency by 5 to 20% and reducing the response amplitude. The logarithmic decrement measurement differs little with whether or not the storm system is installed. This confirmed that the dynamic stability of the entire system can be statically evaluated and does not hamper the elimination of the storm system.



(Structural damping ignored)

C_L : Coefficient of lift C_D : Coefficient of drag

Fig. 12 Results of spring support test

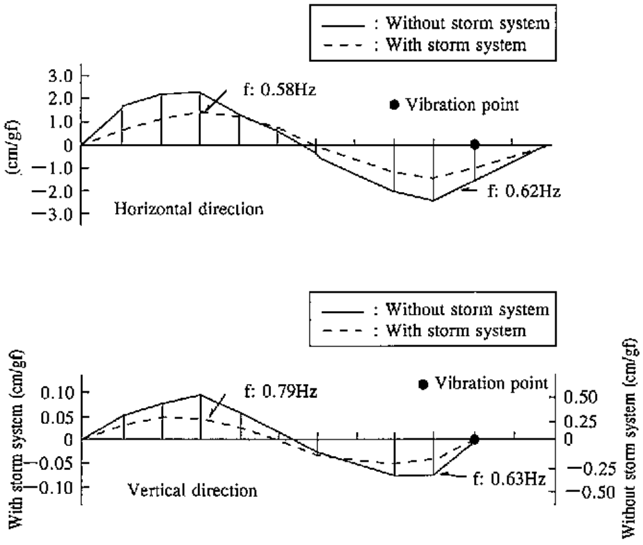


Fig. 13 Examples of resonance mode and resonance frequency

In the test in which the floor system was locally subjected to free vibration, the floor system with the storm system exhibited clearly larger damping as evident from **Fig. 14**. This is probably because the local vibration of the floor system is transmitted to the entire system through the hangers and storm ropes, resulting in apparently large damping. Some measures were thus considered necessary against the local vibration of the floor system.

4.2 Outline of design of catwalk without storm ropes

4.2.1 Adoption of high-strength spiral ropes

The Akashi Kaikyo Bridge is so huge in scale that ropes of large diameter were still required as center-span catwalk ropes (CWRs) when the storm system was eliminated as already described. Nippon Steel tackled the increase in the strength of CWR wire and developed a wire of 200 kgf/mm^2 strength jointly with a rope manufacturer. As the rope is wound on the reel in an increasing number of layers, it is more likely to drop from one layer into the next lower layer under high tension, resulting in the deterioration of unreelability and safety. For fear of this problem, the rope construction was changed from conventional strand rope Independent Wire Rope Core (6×37) to spiral rope (1×127) with an increased cross-sectional filling ratio.

4.2.2 Design of entire system

(1) Setback of main towers

The general view of the catwalks is shown in **Fig. 15**, and the compositions of the catwalk ropes in the center and side spans are listed in **Table 4**. The most complex problem with the design of the catwalk without the storm system was the setback of the main towers that was conventionally adjusted by regulating the tension introduced into the storm ropes in the side spans. For the Akashi Kaikyo Bridge, the problem was solved by ensuring a proper catwalk weight balance between the center and side spans.

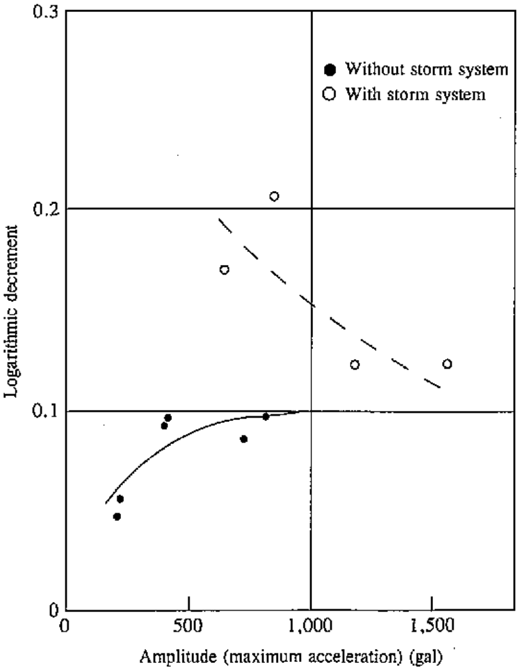


Fig. 14 Logarithmic decrement of torsional vibration

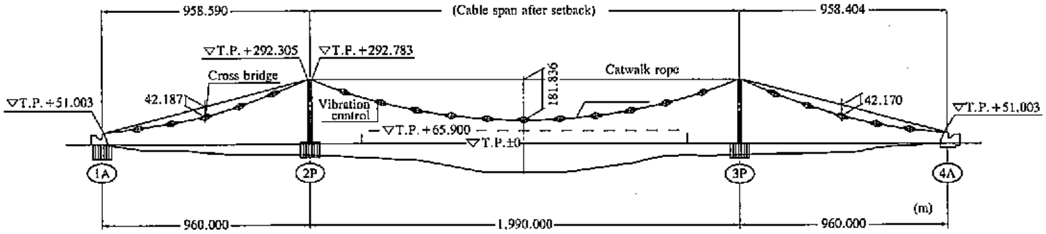


Fig. 15 General view of catwalk system

Table 4 Catwalk rope data

Type	Span	Rope composition	Rope specification	Guaranteed breaking force	Unit weight
Catwalk rope	Center	52 mm×12 ropes	1×127 super high-strength wire	290 t ×12=3,480 t	13.6 kg/m/rope
	Side	64 mm×12 ropes	1×169 class A, type 2	371 t×12=4,452 t	20.5 kg/m/rope

As already described, high-strength catwalk ropes were adopted in the center span to minimize the catwalk weight, while catwalk ropes of conventional strength (160 kgf/mm^2) but larger diameter were used in the side spans. Any remaining unbalance force was removed by adjusting the auxiliary equipment weight on the floor system. The actual catwalk shape adjustment called for a considerable amount of labor in finely adjusting the catwalk weight with thin ropes. Careful weight adjustment from the planning stage allowed the weight adjustment to be completed with high accuracy.

(2) Arrangement of cross bridges

The arrangement of cross bridges had a great impact on the torsional stability of the catwalks as noted above, coupled with work coordination with the east and west cables. It was decided to install cross bridges more closely than in the past. That is, 11 cross bridges were arranged in the center span at intervals of about 165 m, and 5 cross bridges were arranged in each side span at intervals of about 155 m.

(3) Adoption of vibration control measures

As already described, the elimination of the storm system was found to make the catwalk more likely to sway under external forces as work developed on the catwalk. Lest the resultant vibration should cause turning aside a hauling rope and interfere with the erection of cables, vibration control measures were implemented to improve the local stiffness of the catwalks. The vibration control measures comprised the vibration control stay method and the rotary damper method as shown in **Fig. 16**. The vibration control stay method involved installing frames above and below the cross bridge at each end and stringing stay ropes aslant from the frames to the floor system. The rotary damper method involved installing rotary viscous dampers at each end of the cross bridge and connecting the dampers to the floor system by wire.

The stay ropes were installed to add out-of-plane stiffness to the floor system against torsional vibration and arranged on all cross bridges. The rotary dampers were installed to alleviate the horizontal vibration of the floor system. These were arranged near the center of the center span where horizontal vibration was observed during cable erection on other suspension bridges. The wire fixing positions were determined by considering the modes of vibration to be controlled. Before these vibration control measures were reflected in the design of the catwalks, their benefits were verified by experimentation with a 1/3-scale model.

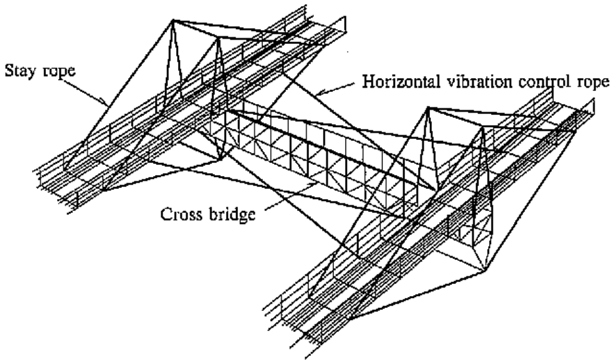


Fig. 16 Schematic of vibration control devices

4.3 Erection of catwalk floor system in divided sections[3]

The floor system was traditionally installed on the catwalk ropes by dividing the floor system into short panels, carrying them on erection cars and installing them in place, or by connecting coils of wire mesh at the tower top and continuously running them down the catwalk. Since the catwalk erection distance was long for the Akashi Kaikyo Bridge, the former method involved large loss in car travel time, while the latter involved large frictional forces between the floor and rope. This made it difficult to pull the entire length of the floor. It was thus decided to adopt the method whereby the floor system was divided into suitable units and sliding them into place from the tower top (see **Photo 1**).

The problems with this floor system erection method were determining an appropriate division length by considering the frictional force between the floor system and the catwalk ropes and ensuring the stable operation of small cars to carry workers for the installation of the floor system. The frictional force between the floor system and the catwalk ropes was estimated from the results of floor system installations in the past. The division length of the floor system was set at the cross bridge interval of about 160 m. The worker transport cars were mainly operated by

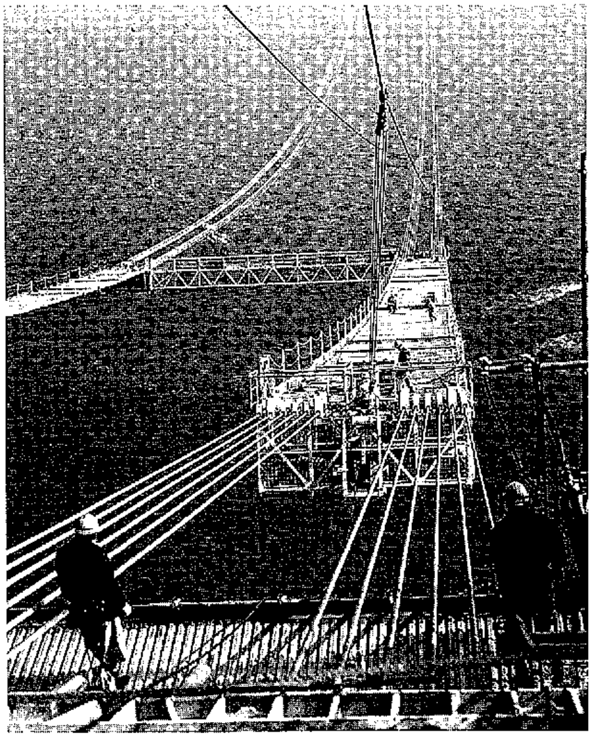


Photo 1 Continuous floor system divided section method

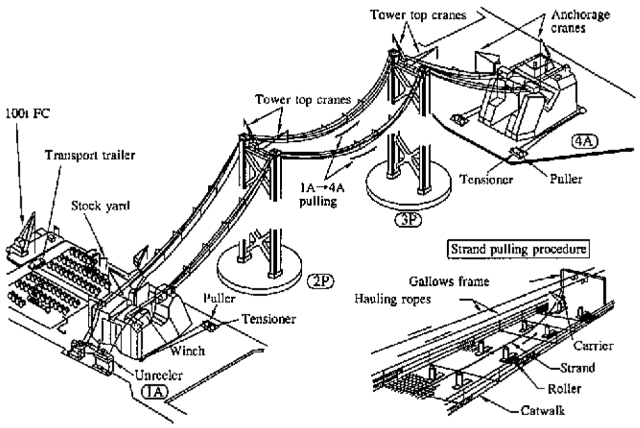


Fig. 17 Procedure for erecting strands

Table 5 Puller winch capacity

	CWR erection		PWS erection		PWS erection (carrier back)	
	Winding	Braking	Winding	Braking	Winding	Braking
Rope tension	max 55t	max 3.5t	max 25t	max 15t	max 15t	max 15t
Rope speed	0-30m/min		0-60m/min		0-90m/min	

Table 6 Tensioner winch capacity

	CWR erection		PWS erection		PWS erection (carrier back)	
	Winding	Braking	Winding	Braking	Winding	Braking
Rope tension	max 35t	max 35t	max 25t	max 15t	max 15t	max 15t
Rope speed	0-30m/min		0-60m/min		0-90m/min	

the hauling system that could finely adjust their travel speed and were counteracted by winch ropes from the tower top as safety measure. The actual frictional force was somewhat greater than expected and sometimes reached the winch capacity limit, but the erection of the floor system was carried out smoothly at a rate comparable to that of floor systems for past suspension bridges.

5. Erection of Cable Strands

5.1 Method for simultaneously pulling two lines

5.1.1 Hauling system

Fig. 17 illustrates the overall procedure for erecting cable strands. Each strand was drawn from the unreeler installed behind the Maiko-side anchorage 1A over the catwalk to the opposite anchorage 4A. This strand drawing equipment is a hauling system. Hauling systems come in the loop type and single-line type. A single-line hauling system capable of accommodating the high tension developed was adopted during the erection of catwalk ropes.

The single-line hauling system has already worked successfully on the Seto Ohashi Bridges and other suspension bridges. It calls for utmost care to be exercised because the pulling speed governs the erection process. Puller and tensioner capacity data are given in **Tables 5** and **6**, respectively. The pullers and tensioners were provided with capacities several times greater than those of conventional models, so that they could develop speeds up to 90 m/min.

Before the decision was made as to the overall system, several methods were studied, including one with unreelers installed at both sides and the double-loop method whereby each strand would be returned back from the center of the center span. Given a further reduction in the construction period and other governing conditions, the system adopted involved the arrangement of the aforementioned single-line hauling rope in two lines per side and the pulling of strands in one direction.

DC motors were selected as drives for the winches of the hauling system after checking that they would be capable of meeting the high tension and speed requirements established. In the design of the hauling system, safety assessment was conducted according to the " Safety Guidelines for Mechanical Equipment for Erection of Superstructure of Akashi Kaikyo Bridge". Remedial measures against failures and malfunctions were thus developed and reflected in the design of the hauling system. The puller and tensioner safety devices developed are listed in **Fig. 18**.

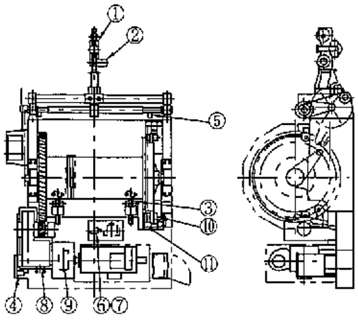
5.1.2 Erection process

Four strands per cable could be erected at a time after the middle of the erection process, and over 50,000 tons of strands were completely erected in a short period of about 4.5 months. Particularly, pulling became a critical path after the middle of the erection process, and equipment troubles directly led to delays in the erection process. It should be especially noted that hauling ropes never came off the guide rollers. This is probably due to the aforementioned local vibration control measures for the catwalks and due to the fact that conventional guide rollers were replaced by those having bottom support rollers provided with reaction force and the fact that the weight of end carriers was reduced. (See **Photo 2**.)

5.2 Development of pulling system

Pulling devices are installed on the anchorages and tower top bents and used to pull and anchor catwalk ropes and strands. A hydraulic system that expands and contracts by hydraulic cylinders over a pulling stroke of 10 m or less and a winch system that has pulleys, sheaves and other devices installed at the side of the bent and pulls ropes and strands with a winch were traditionally adopted as pulling units. The pulling force of 70 tons and a stroke of about 20 m required for the Akashi Kaikyo Bridge were difficult for the conventional systems to meet and led to the adoption of a direct-pulling electric winch system for the first time.

The direct-pulling electric winch system is simple in construction with a motor, speed reducer, drum, and control panel as shown in **Fig. 19**. Since the number of rollers and similar parts is small, a winch rope of small diameter suffices, and a long pulling stroke can be employed. In the development and fabrication of the system, particular care was exercised with respect to safety devices. A feature rarely observed in conventional winches is that an electromagnetic brake and a disk brake were installed together to ensure safety when the catwalk ropes and strands hang free. The pulling system was operated from a remote control



List of safety devices

No.	Name	Type	Purpose and operation
①	Rope tension sensor	Load cell	Tension is indicated on control panel, and abnormal tension is detected. When tension greater or smaller than preset value is detected, high or low tension alarm is issued by lamp and buzzer, and brake is simultaneously applied for automatic stop.
②	Rope length and speed sensor	Pulse generator	Speed is indicated on control panel, and abnormal speed is detected. Rope length is indicated on control panel, and wind and unwind limits are detected. When overspeed is detected with respect to speed preset in low, medium, and high speed operating modes, abnormal speed alarm is issued by lamp and buzzer, and brake is simultaneously applied for automatic stop.
③	Over-wind and over-unwind preventive device	Touch roller-type limit switch	Rope wind diameter is detected. When preset value is reached, over-wind or over-unwind alarm is issued by lamp and buzzer, and brake is simultaneously applied for automatic stop.
④	Overspeed sensor	Centrifugal speed switch	Backup for abnormal speed sensor circuit for above two items. When speed reducer input shaft speed reaches maximum speed, abnormal speed alarm is issued by lamp and buzzer, and brake is simultaneously applied for automatic stop.
⑤	Rope shifter overshoot preventive device	Roller lever-type limit switch	When rope shifter overshoot is detected, shifter overshoot alarm is issued by lamp and buzzer, and screw is immediately reversed.
⑥	Disk brake release hydraulic unit pressure sensor	Pressure switch	When hydraulic pressure is lower than preset, low hydraulic pressure alarm is issued by lamp and buzzer, and brake is simultaneously applied for automatic stop.
⑦	Disk brake release hydraulic unit temperature sensor	Temperature switch	When hydraulic oil temperature is higher than preset, high oil temperature alarm is issued by lamp and buzzer.
⑧	Speed change position check device	Roller lever-type limit switch	Speed reducer speed change position is checked and indicated on control panel.
⑨	Electromagnetic brake	Electromagnetic type	Braking force 150%
⑩	Disk brake	Disk type	Braking force 125%
⑪	Parking brake	Ratchet type	Holding of load at stop

Fig. 18 Puller and tensioner safety devices

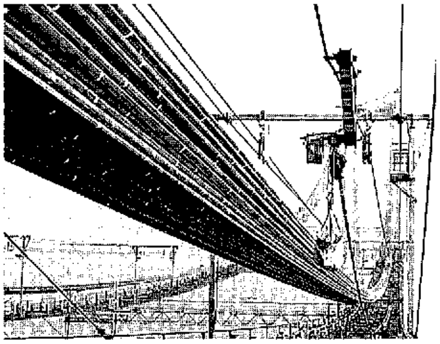


Photo 2 Strands being pulled

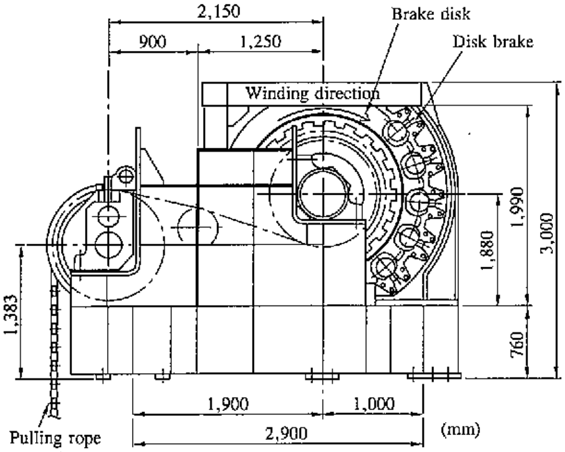


Fig. 19 Pulling unit

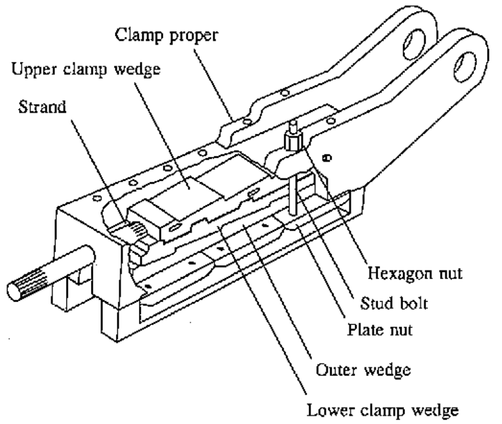


Fig. 20 Construction of pulling clamp

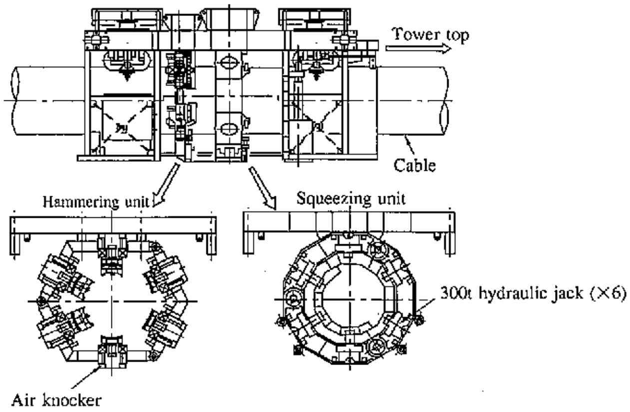


Fig. 21 Squeezing machine

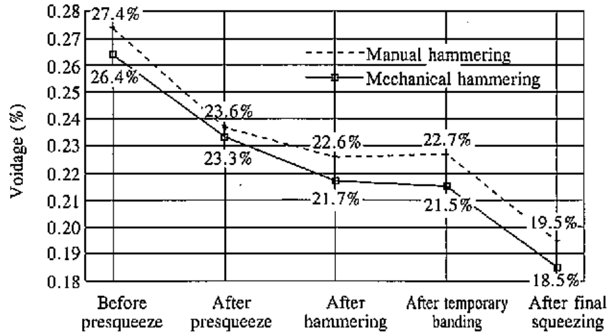


Fig. 22 Effect of hammering unit

panel installed near the work site. The pulling tension and speed were indicated on the remote control panel, and the drum winding condition was monitored using a television camera. Every possible safety measure was instituted in this way.

5.3 Size reduction of pulling clamps

Strand pulling clamps were traditionally made of U-bolts and single-plane wedges. Since the pulling tension was more than doubled, close to 70 tons in the Akashi Kaikyo Bridge, double-plane wedges and high-strength bolts were used in combination as shown in **Fig. 20**. To prevent the clamping force of strands from dropping due to wire rearrangement and tension variation under impact, wedge surfaces were coated with hard chromium to ensure a positive wedge effect. These pulling clamps provided enough clamping force with their small size so that the strands were pulled with higher efficiency and speed.

6. Development of Squeezing Machine

Each group of erected strands constitutes a hexagonal cross section with a maximum diameter of about 1,400 mm. This hexagonal cross section is tightened by a squeezing machine into a circular section of about 1,100 mm diameter.

The squeezing machine used for the Akashi Kaikyo Bridge consisted of six hydraulic jacks, each with a maximum thrust of 300 tons (**Fig. 21**). One to six jacks were made to meet specific needs. The hydraulic pump unit was built to automatically change from high to low pressure and vice versa and was operated at high speed until the shoes contacted the cable, shortening the working time. The variations in cable damage with the shape, material, and contact pressure were checked by simulative squeeze experiments. According to the experimental results, the detailed shoe structure was determined.

Traditionally, when the cable was squeezed, its surface was struck with a wooden hammer to reduce the frictional resistance between the wires and to enhance the squeezing effect. A mechanical hammering unit with air knockers was developed for this purpose. The effectiveness of the mechanical hammering unit was experimentally verified as being the same as that of manual hammering as shown in **Fig. 22**.

The strength of wires used for the bridge was 180 kgf/mm^2 as compared with 160 kgf/mm^2 for conventional bridge wires. The increased strength is presumed to have reduced the deformation and intersection of the erected strands and improved their parallelism. The surface damage, deformation, and intersection of the strands erected for the Akashi Kaikyo Bridge are less than those of strands squeezed on other bridges. These data verify the satisfactory performance of the squeezing machine newly developed for the strands of the Akashi Kaikyo Bridge.

7. Erection of Cable Bands and Hanger Ropes[4]

7.1 Development of new band and hanger system

Conventional hangers were wire ropes (structural CFRC (Center fit rope core) ropes) that consisted of galvanized wires and were painted. They were anchored by saddling to cable bands. In reality, however, it is impossible to cover an irregular rope surface with a waterproof paint layer, and internal water collection is unavoidable. For this reason it is difficult to perform thorough inspection and maintenance on CFRC ropes. The wind-induced horizontal displacement perpendicular to the longitudinal bridge axis is so large that high fatigue strength against bending is required of the end of each anchor socket.

For hanger ropes to solve these two problems, it was decided to adopt the Nippon Steel-developed new polyethylene-coated cable NEW-PWS that calls for no painting, excels in corrosion protection and maintenance, and possesses high bending fatigue strength. Since the polyethylene-coated cable cannot be bent to a small diameter equivalent to its diameter, a cable band of the pin anchor type was devised that allows the pin anchoring of hanger ropes without saddling as shown in **Fig. 23**. Structurally, the cable hangers are pin anchored at both ends, and the cable band is composed of two pin plates of the same width as the top chord. Short hangers have a universal joint at each pin end to follow the horizontal displacement perpendicular to the longitudinal bridge axis.

7.2 Erection of cable bands with erection cars

Normally, each cable band is loaded on a car at the tower top, carried over the main cable to an erection point, and erected there. The Akashi Kaikyo Bridge has as many as 540 cable bands, which must be transported to a maximum distance of 1,000 m (more than twice longer than required for conventional suspension bridges). If they were erected by the conventional method, their erection efficiency would badly suffer. For this reason, the cable bands were carried and erected by using separate cars as shown in **Fig. 24**.

Since the cable bands had pin plates at their bottom, the center of gravity of their transport car had to be raised to provide a sufficient clearance from the catwalk floor surface. For this purpose, the transport car was fitted with a greater number of travel rollers into a bogie type. The installation of spring-loaded outriggers and the adoption of plastic rollers allowed high-speed running stability and size and weight reductions. Since the transport and erection of cable bands, which were critical in the construction schedule, were accommodated by separate cars in this way, all cable bands were erected in a short period of 3 weeks.

7.3 Axial force control with ultrasonic bolt axial force meter

The cable bands have an important role in transferring the load of the stiffening girder to the main cable. The cable band bolts must be strictly controlled as to their axial force, so that the specified sliding safety factor can be met. If the cable band bolts are found to have declined in their axial force after the erection of the cable bands, they must be retightened. The axial force control of the cable band bolts thus continues to be performed after the erection of the cable bands.

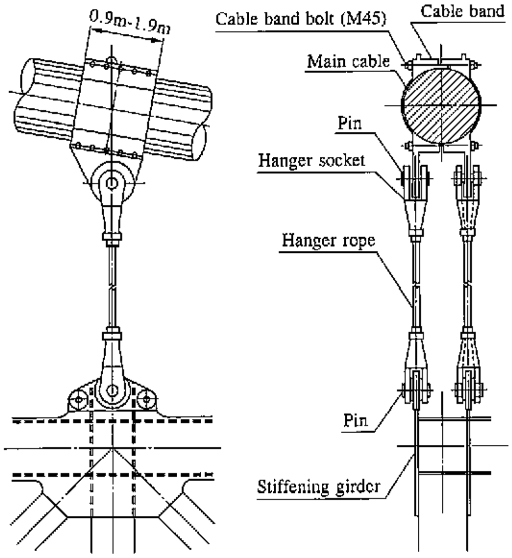


Fig. 23 Cable band and hanger structure

A conventional axial force measuring method consisted of measuring the elongation of cable band bolts with a micrometer and calculating their axial force from their elongation-axial force relationship.

Since the Akashi Kaikyo Bridge has cable hangers pin anchored to cable bands as described previously, it is difficult to install instruments for measuring the axial force of cable band bolts. For more efficient axial force control of as many as 7,000 cable band bolts, the method of ultrasonically measuring the axial force of cable band bolts was studied. The system illustrated in **Fig. 25** was developed for stably measuring the axial force of even slightly bent bolts. An ultrasonic wave is transmitted at one end of a bolt and received at the other end. The time taken by the ultrasonic wave to propagate through the bolt is measured with and without application of the axial force. The measured time is converted to length to calculate the axial force of the bolt.

This system allowed the measurement of axial force and the processing of measured results to be performed only with a small axial force meter. The 7,000 cable band bolts were retightened

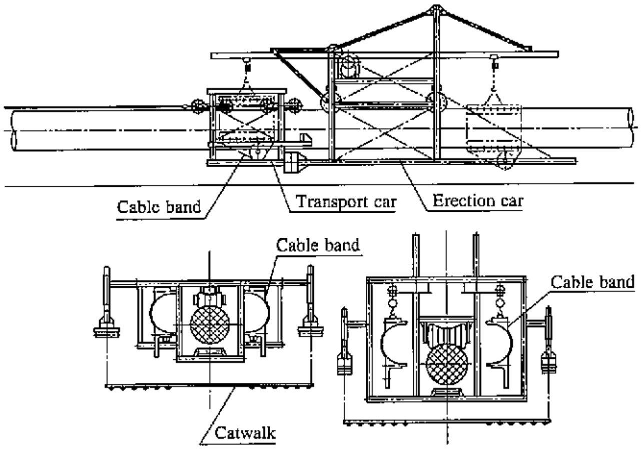


Fig. 24 Cable band cars

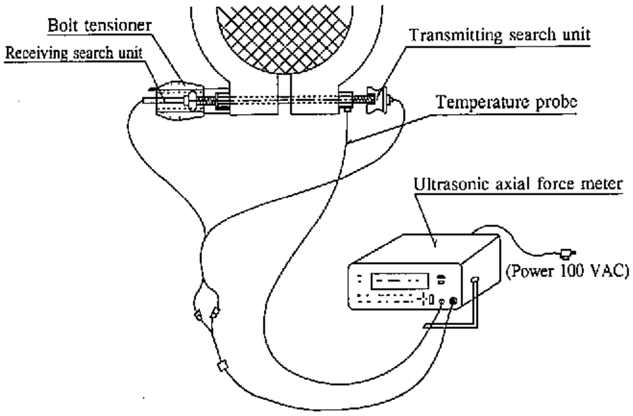


Fig. 25 Ultrasonic bolt axial force measuring system

four times before the start of service. The ability of the meter to measure the axial force of each bolt simply by applying search units to its ends simplified the axial force measuring task and substantially shortened the construction period.

7.4 Erection of polyethylene-coated parallel wire strand (PWS) hangers

Conventional CFRC ropes were stranded so that they were flexible and easy to handle. After erection at the site, they were painted so that they had little visual damage when erected. The polyethylene-coated PWS hangers adopted on the Akashi Kaikyo Bridge were larger in unit weight and smaller in flexibility, so that they were more difficult to handle during erection. Since they were also erected in the completed product condition, their contamination and damage protection and repair methods had to be fully studied.

The polyethylene-coated PWS hangers were 200 m long at most and numbered more than 1,000. Their size and quantity presented an erection challenge. The hangers were transported, erected, and anchored according to their length as described below.

7.4.1 Method for suspending and carrying hangers

The hangers near each tower are particularly long and difficult to erect from above the catwalk floor system. For this reason, an unreeler was installed below the tower, and each hanger was rolled out from the unreeler by a tower top crane and carried as vertically suspended through a gondola to its erection position (see **Photo 3**). This method has the advantages of minimum coating damage and smooth transport. The hangers can be anchored to the cable bands directly below the cable bands by using chain blocks and can be thus erected without undue force and damage.

7.4.2 Method for pulling hanger ropes from above catwalk floor system

The above-mentioned method made it difficult to transport hanger ropes across the cross bridges. Rollers were installed on the catwalk floor system and used to transport hanger ropes other than those near the towers. With this method it is essential to prevent the set of hanger ropes wound on reels and protect them at the pulling rollers. Hanger ropes were tested for unreeling at the shop, the pulling tension and the roller interval were studied, and the formation of waves in hanger ropes was prevented.

Since hanger rope sockets were pinned below cable bands, a balance was installed on the cable band and used to securely anchor the hanger ropes. Any necessary fine adjustment was made with socket erection jigs. This method allowed the positioning of hanger ropes as suspended through floor openings and the insertion of pins into sockets to be safety performed from the catwalk floor.

Short hanger ropes must be transported over a long distance, so that they are critical as far as the construction schedule is concerned. For this reason, 100 m or shorter hangers were wound two per node on a reel and carried and anchored together.

8. Conclusions

The Akashi Kaikyo Bridge was a dream project for the Japanese bridge industry. Nippon Steel has spent more than 30 years in the development and study of new products and methods for the bridge.

Long participation in the projects to build long suspension bridges like the Seto Ohashi Bridges and huge accumulation of technologies through these projects have been a driving force for the realization of the world's longest suspension bridge.

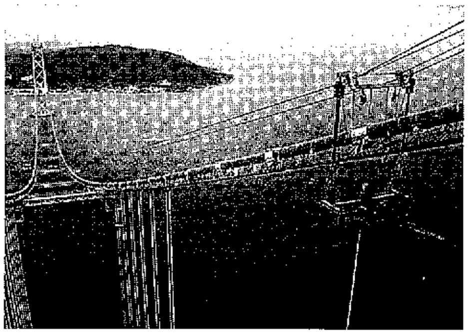


Photo 3 Hanger being erected

The authors would like to sincerely thank the personnel of the Honshu-Shikoku Bridge Authority for their guidance over many years and those people who have cooperated in the fabrication and erection of suspension bridge cables.

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