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Long Span Steel Bridges in Japan

Ponts métalliques de grande portée au Japon

Weitgespannte Stahlbrücken in Japan

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SUMMARY

The state-of-the-art in long span cable-supported steel bridges in Japan is presented, with emphasis on their design and construction features. After giving an overall review, special mention is made of two very large bridges under construction: the Akashi Straits Bridge of the suspension type, and the Tatara Bridge of the cable-stayed type, both of which will respectively have the world's longest spans when completed.

RESUME

L'état de l'art au Japon des ponts métalliques de grande portée, suspendus ou haubanés, est présenté, en insistant sur les particularités de conception et de construction. Après une présentation générale, deux ponts très importants en cours de construction sont examinés en détail: le pont suspendu du détroit d'Akashi et le pont haubané de Tatara qui, dans leur genre, seront les plus longs au monde une fois terminés.

ZUSAMMENFASSUNG

Es wird über den japanischen Stand der Technik bei abgehängten Stahlbrücken anhand von Besonderheiten in Entwurf und Ausführung berichtet. Nach einem allgemeinen Überblick werden zwei sehr lange, zur Zeit im Bau stehende Brücken, beschrieben: die Hängebrücke über die Akashi Straits und die Tatara-Schrägseilbrücke, beide einst die weitest gespannten Brücken ihrer Art in der Welt.

1. INTRODUCTION

Steel structures are extensively used in Japan as compared with other countries. This is because the structures have to withstand severe earthquakes, and the densely populated districts where many bridges have to be built are usually on soft ground. In addition steel is readily available at a reasonable price. Consumption of structural steels for bridge superstructures has reached 0.8 million tonnes per annum over the past two years.

Apart from these local situations, it goes without saying that steel structures are advantageous for long spans. Japan consists of four major islands and many other small islands. With the development of vigorous socio-economic activities, the improvement of transportation networks has been promoted. From these geographical and social circumstances, many long span bridge projects to cross straits and river mouths in urban areas, or sometimes to connect areas of reclaimed land in the coastal cities, have been undertaken. When very long span length is required, the lead has been taken by cable-supported bridges, namely suspension or cable-stayed types.

The present paper describes the state-of-the-art of these Japanese cable-supported bridges focusing on the interaction between design and construction technology in their superstructures, with particular reference to two of the most spectacular bridge projects of the respective types mentioned above. Construction of these two bridges has already started.

2. JAPANESE CABLE-SUPPORTED BRIDGES

Including medium and short spans, the construction of cable-supported bridges in Japan has been very vigorous over the past few years. The number of Japanese cable-stayed bridges amounts to approximately one third of the world total [1], while that of suspension bridges including those under construction may be more than half of the world total for the past decade. Tables 1 and 2 list major or noteworthy cable-supported steel bridges in Japan. Almost all of these bridges have been or are being built in the last quarter of this century.

2.1 Suspension bridges

Although fairly numerous, Japanese suspension bridges built before 1950's were all small, providing footway or narrow road crossings in mountainous regions, or spanning rather short distances. The start of the modern suspension bridge period was marked by the completion of the Wakato Bridge, with a center span of 367m, in 1962. The Kanmon Bridge completed in 1972 and listed at the top of Table 1 was the first really deserving to be called a long span suspension bridge. Since then, several long span suspension bridges have been built or are under construction, most of which are associated with the Honshu-Shikoku linking project.

Some features of these modern Japanese suspension bridges are as follows:
(a) More than half of these bridges are of the truss-stiffened type. Except for those built before 1985, however, this is due to unavoidable design constraints. Five suspension bridges in Table 1 are of the double-deck type and the Akashi Straits Bridge described in

more detail later has very long span length. Nowadays, suspension bridges with a box section stiffening girder are not unusual in Japan.

Table 1 Major suspension bridges in Japan (as of 1991)

name	max. span (m)	year	remarks
Kanmon	712	1973	truss-stiffened
In-no-shima	770	1983	truss-stiffened
Ohnaruto	876	1985	truss-stiffened, designed for highway+railway
Ohshima	560	1988	twin-trapezoidal box girder
Shimotsui	940	1988	continuous double-deck truss (highway+railway)
North Bisan	990	1988	continuous double-deck truss (highway+railway)
South Bisan	1100	1988	continuous double-deck truss (highway+railway)
Tokyo Port	570	*	double-deck truss
Hakucho	720	*	streamlined box girder, snowy district
Kurushima I	600	**	box section, three 3-span bridges linked with two shared anchorages
Kurushima II	1020	**	
Kurushima III	1030	**	
Akashi	1990	*	truss-stiffened

note: * under construction, ** started construction

(b) The three suspension bridges of the Seto Bridge project carry both highway and railway traffic. Innovative design and fabrication techniques to cope with heavy and high-speed train loading on such long span suspension bridges will be referred to in the following chapters.
(c) Except for the Shimotsui Seto Bridge in which the air spinning method was employed because of the adoption of a tunnel anchorage at the north end in order to reduce the environmental intrusion, all of the other long span suspension bridges in Table 1 are, or will be, built using prefabricated parallel wire strand cables. Although both cable erection techniques mentioned above originated in the United States of America, remarkable development of their technology has been achieved in Japan[2].

2.2 Cable-stayed bridges

Historically, Japan probably has the earliest modern cable-stayed bridges outside the sphere of German technology. The first steel and prestressed concrete bridges of this type in Japan were built in 1960 and 1963 respectively, though the latter was of only 40m span. In the light of not only the number as mentioned earlier but also the scale of steel bridges, Japan seems most active now in cable-stayed bridge construction. Five bridges under construction in Table 2 have longer span lengths than any exisiting cable-stayed bridges in the world.

Some comments on these long span cable-stayed bridges in Japan are given in the following:
(a) The types of steel girder are all based on substantially similar concepts: namely, a truss structure for double-deck bridges and a shallow box girder with orthotropic steel deck for single-deck highway bridges.
(b) Use of the multi-cable system has prevailed as with bridges of this type overseas.

(c) The Iwakuro Island Bridge and the Hitsuishi Island Bridge of the Seto Bridge Project are designed for a four-lane motorway on the upper deck and two double-track railways on the lower deck.
(d) The Katsushika Harp Bridge of the Metropolitan Express Highway is the first curved, cable-stayed bridge in the world. Because the continuous four spans are considerably unsymmetric, the two towers have quite different heights.

Table 2 Major cable-stayed steel bridges in Japan (as of 1991)

name	max. span (m)	year	remarks
Yamato River	355	1982	trapezoidal box girder, very skew
Meikoh-West	405	1985	hexagonal box with fairing
Katsushika	220	1987	spirally curved, box girder with fairing
Tokachi	250	1988	twin box, R/C tower, snowy district
Iwakuro Is.	420	1988	double deck truss (highway & railway),
Hitsuishi Is.	420	1988	standing in line
Yokohama Bay	460	1989	double-deck truss with shallow box upper chord
Tempozan	350	1990	flat hexagonal box with splitter plate
East Kobe	485	*	double deck truss
Ikuchi	490	*	twin hexagonal box, P/C girder in side spans
Tsurumi	510	*	streamlined box girder
Meikoh-Central	590	**	trapezoidal box girder
Meikoh-East	410	**	trapezoidal box girder
Tatara	890	**	streamlined box girder, P/C girder in side spans

note: * under construction, ** started construction

(e) In the cases of the Meikoh West Bridge and the Tsurumi Bridge respectively, two similar bridges will stand side by side in the future. The feasibility of constructing closely adjacent foundations, and the aerodynamic interference between two parallel bridge decks were investigated. The cables of the Tsurumi Bridge are in a single-plane for aesthetic reasons, despite the long span of 510m.
(f) The Ikuchi Bridge is the first cable-stayed bridge with a hybrid girder in Japan. Its main span of 490m is a steel girder, while the continuously extended side spans are prestressed concrete structures. The Tatara Bridge will have a similar structure.
(g) Until a few years ago, Japanese cable-stayed bridges with prestressed concrete girders had small or medium spans. Presently, however, several bridges of this type having a main span length of around 250m have been realized.

Other notable features of Japanese cable-supported bridges are described in the following chapters.

3. SPECIFIC FEATURES IN DESIGN

3.1 Effects of earthquakes and wind

Earthquakes and strong winds are frequently the dominant actions in designing long span bridges in Japan. Generally speaking, earthquakes govern the proportioning of substructures and towers, while wind effects affect the design of superstructures, including the towers of cable-supported bridges. Dynamic analysis or checking is now the prevailing procedure in the design of these structures[3].

Since the girders of modern cable-stayed bridge are mostly continuous over two or more spans, selection of supporting conditions is rather adaptable owing to the existence of the stay cables and flexible towers. Recently prevailing in Japanese bridges has been elastic constraint in the longitudinal direction by connecting the girder and the tower, or the abutment, with steel bars, layered plate springs, shear-type rubber, or links, in order to control seismic forces applied to the substructures and optimize the sectional forces due to not only seismic but also temperature effects. Considerations of multiple-support excitations and long-period components of earthquake waves are made in some of the very long span bridges.

Design wind speeds for the bridges in Tables 1 and 2 are quite high (between about 50 to 75 $^{m}/s$ at deck level), and the critical wind speed for divergent response predicted from wind tunnel tests is required to be above 1.2 times these design wind speeds. Accordingly, many of the long span bridges, sometimes even steel continuous girder bridges, are provided with means for suppressing wind-induced vibrations [4]. The first choice is to select an aerodynamically stable cross section and, if necessary, fairings, flaps and other aerodynamic appendages are attached. With the growth of scale of structures these days, the use of various dampers for towers, girders and cables has also increased. In particular, towers free-standing during the construction stage often have tuned mass dampers or tuned liquid dampers installed.

3.2 Structures for rail traffic

Three suspension bridges of 1,000m span class and two cable-stayed bridges of 420m main span carry both road and rail traffic in the Seto Bridge. In order to satisfy the safety and serviceability of train operation on such flexible structures as cable-supported bridges, as well as the durability of the structure subject to repeated heavy loading, various new techniques were developed. Firstly, an innovative track structure system was placed between the tracks on the stiffening truss and those on the fixed abutment. This system aims at allowing for expansion and contraction, as well as inclination change due to live loading, which occur at the end of the stiffening truss. A set of the systems consists of four small girders having different functions. Secondly, fatigue design for high strength steels used in the stiffening truss was established on the basis of large scale fatigue tests, and careful controls on welding procedure were carried out as described in 4.1. Finally, the dynamic magnification due to high speed running of trains was taken into consideration by the appropriate impact factor specified in the design codes.

3.3 Aesthetic considerations

Although the design of Japanese infrastructure has generally been governed by safety, function and economy, visual aspects have increasingly attracted the concern of engineers over the past two decades. In cable-supported bridges, this has normally centered on the design of towers and anchorage abutments. The use of curved elements appears to be one of the developing trends, even though it is often accompanied by some increase of fabrication or construction costs. In the case of the massive concrete blocks for suspension bridge anchorages, the main surfaces have been formed from small subsurfaces with taper, which also aims at preventing radar hindrance to the navigation of ships around the structure.

3.4 Cables

Selection of cable materials, composition, formation and protection against corrosion is related to both construction techniques and maintenance. It is reported elsewhere in this symposium [5] that the newly developed high-strength cable wire could improve the design and erection process of the Akashi Straits Bridge. The erection of the main cables of other Japanese suspension bridges was already mentioned in 2.1.

As far as the stay cables of long span cable-stayed bridges are concerned, the multi-cable system using sheathed parallel wire strand has been a world-wide trend over recent years. For protection from corrosion, grouting cables within polyethylene casings has been prevailing practice, but a process for bonding the casing directly to the wire strand has also been developed quite recently. Although this polyethylene tube has been available only in black, an additional outer coating in coloured resin has now become of practical use. Another recent feature of this polyethylene tube is a notched surface adopted in the East Kobe Bridge, in order to suppress wind-induced vibrations of the stay cables.

4. SOME TOPICS ON FABRICATION AND ERECTION

4.1 Welding of railway truss girders

In the case of truss girders carrying combined highway and railway loads, very careful fabrication is required to ensure the fatigue strength. The fabrication specifications for the Seto Bridge project were established on the basis of fatigue test results and fracture mechanics analysis. With respect to the corner weld joints of box chord members, the permissible sizes of blowhole were specified according to the ratio of design stress range to allowable stress range. Acceptable toe profiles in particular acute angles and undercut were also determined from the fatigue requirements for each joint. An inspection system to detect small blowholes at the root of groove welding was developed. Defects in welding were recorded with regard to size and location simultaneously, and these records are used practically for maintenance inspection.

4.2 Large block erection by floating crane

One of the most outstanding features of Japanese steel bridge construction is very frequent use and development of large block erection. Generally speaking, this method can be adopted only at sites where an area of open and deep water is availabe.

The advantages of the method are shortening of construction period, reduction of labor at the site, better and easier quality control of erection, increasing safety by reducing work at high positions, and lower erection cost as a result of the first two merits. It goes without saying, however, that there are some restrictions and points of attention in adopting this method. The restrictions may be associated with compromises with navigational traffic and fisheries, and caused by rapid water flow. Careful structural analysis during erection and a prudent erection scheme are required. Cost saving is not always attained because of additional facilities and temporary or local reinforcement of the structure during erection.

Although there are several different techniques within the large block erection method, the most prevalent in Japanese steel bridges built over straits, water channels and river mouths, is the use of floating cranes. The number of large floating cranes with lifting capacities of 3000 tonf or more is now six, and the biggest has a maximum lifting capacity of 4100 tonf, a reach of 51.7m and a lifting height of 123.5m. The maximum erection weight of one structural block ever experienced is 6160 tonf, which was the complete side span of the Hitsuishi Island Bridge (Fig. 1). In this case, two floating cranes with capacities of 3500 tonf and 3000 tonf respectively, were used together. This method has been used not only for girders and trusses, but also for vertically standing blocks such as bridge piers and towers (Fig. 2).

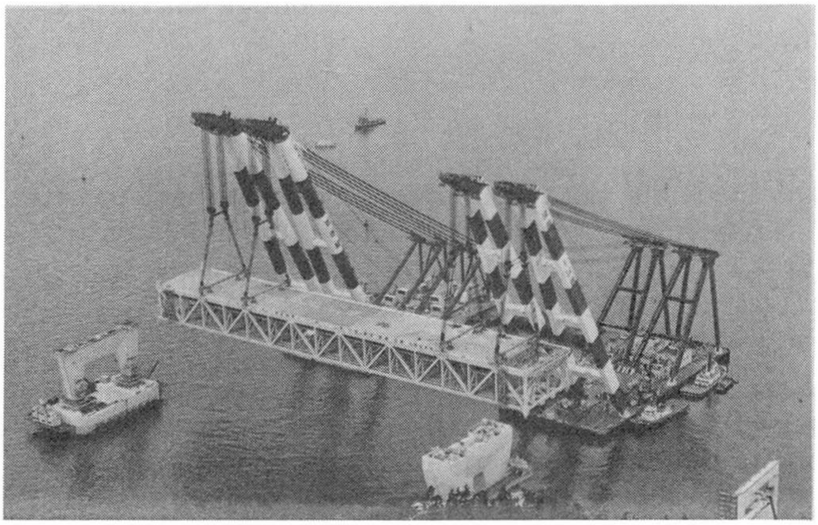

Fig. 1 Large block erection: side span of the Iwakuro Island Bridge (courtesy of the Honshu-Shikoku Bridge Authority)

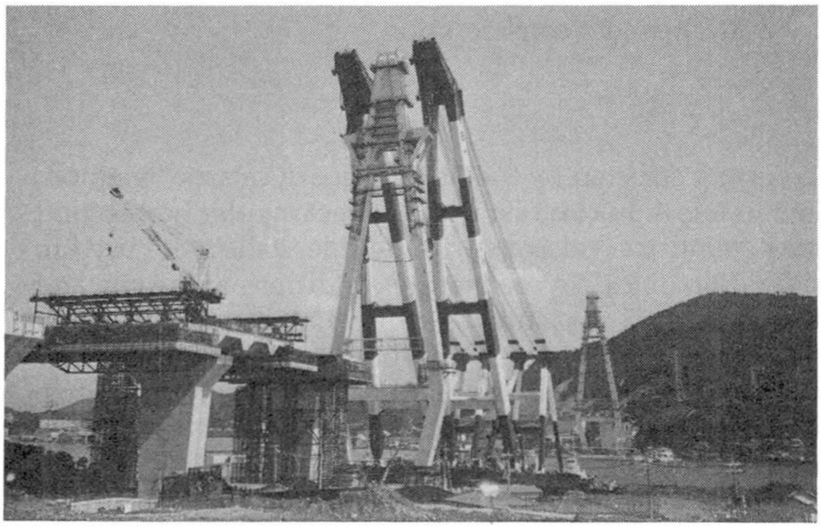

Fig. 2 Large block erection: tower of the Ikuchi Bridge (courtesy of the Honshu-Shikoku Bridge Authority)

5. THE AKASHI STRAITS BRIDGE

5.1 Outline of the project

The Akashi Straits Bridge is a three-span suspension bridge connecting the west end of Kobe city and Awaji Island. It is the bridge on one of the three routes to link Honshu (main island of Japan) and Shikoku, together with the Ohnaruto Bridge which is already open for traffic between Awaji Island and Shikoku. Construction work on the foundations of the Akashi Straits Bridge was started in 1988 by the Honshu-Shikoku Bridge Authority, and the expected period of construction is about ten years.

The work features the world's longest span bridge with a center span of 1990m and side spans of 960m each. Fig. 3 shows a general view of the bridge. Span lengths were fixed in order to minimize the total costs of superstructures and substructures, and to meet the requirements of the international navigation channel. The clear height above water of 65m is sufficient to permit passage of the world's largest vessels. The bridge will carry six lanes of heavy duty highway traffic.

5.2 Environmental conditions

The climate of this area is normally moderate, but several strong typhoons have passed near the bridge site in the past. The reference design wind speed for 10 minutes average at 10m above sea level was fixed at 46 $^{m}/_{s}$ for a return period of 150 years, on the basis of statistical analysis and wind tunnel tests with a topographic model.

Although the frequency of severe earthquakes is not large in this area as compared with other areas in Japan, an earthquake with magnitude of 8 to 8.5 may be anticipated off the Pacific coast at a distance of about 200 kilometers from the site. Considering this situation, the maximum horizontal acceleration at the bearing bed rock is specified as 180 gals in aseismic design.

The bridge site is a part of the inland sea, but tidal currents in this strait are quite rapid. A maximum current speed of 4.0 $^{m}/_{s}$ was taken into consideration.

5.3 Substructures

The main tower foundations are being constructed by the "laying-down caisson" method, the process of which is as illustrated in Fig. 4. In contrast with the rectangular box section used in the Seto Bridge project, steel cylindrical caissons with double walls were used in the Akashi Straits Bridge, in consideration of the severe marine conditions at the site and ease of caisson handling. The larger caisson measures 80m in diameter and 65m in height. The total height of this tower foundation will be 70m. Special underwater concrete will be placed inside the caisson using a concrete plant vessel. The vertical force applied at the base of tower foundations is about 0.6 million tonf each, about one fifth of which is transmitted from the tower.

Each of the anchorages must resist a pull from the cables of about 120 thousand tonf. Since the bearing layer of the north anchorage is about 60m deep from the ground surface, the underground continuous wall method was adopted for this foundation, the

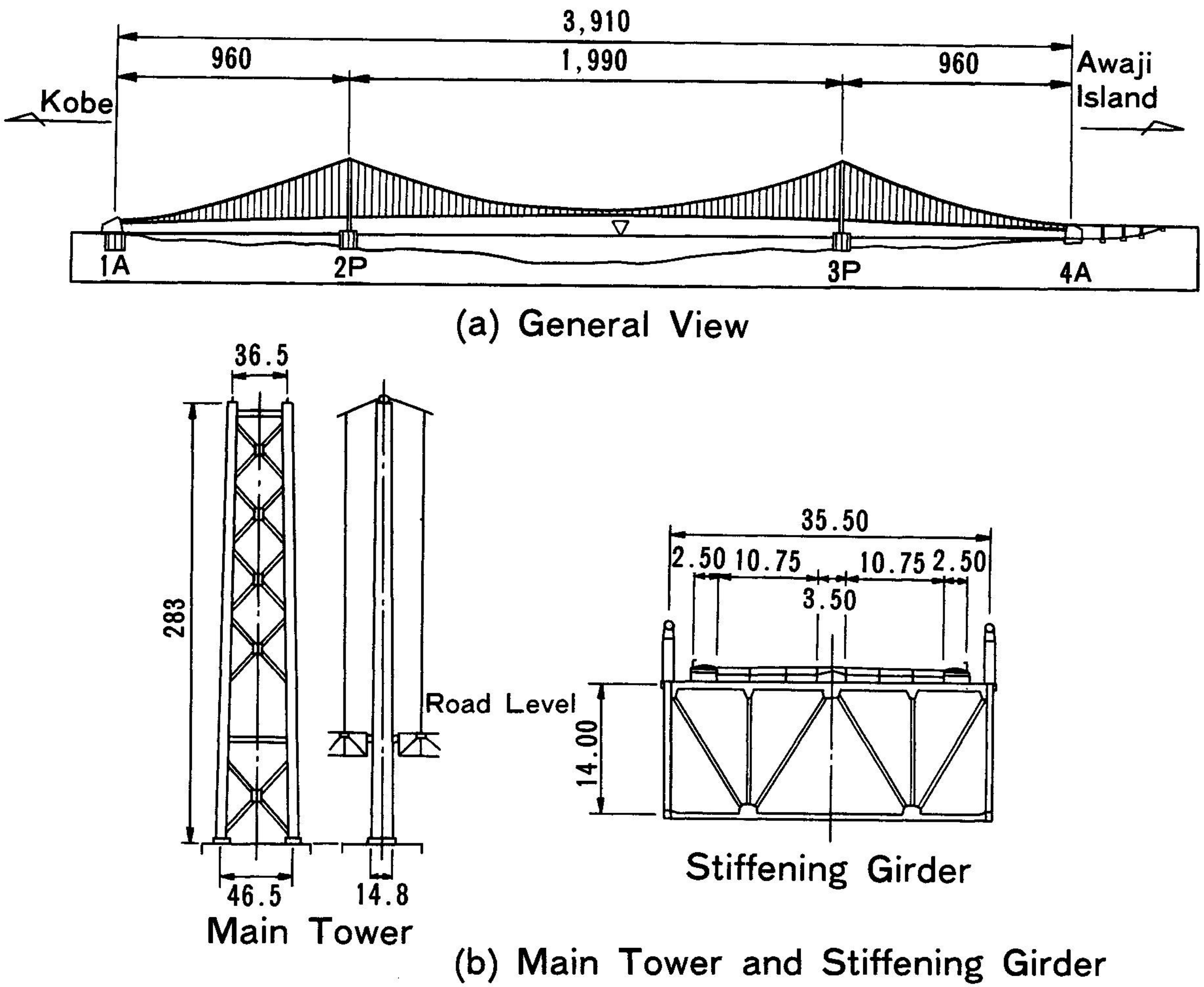

Fig. 3 The Akashi Straits Bridge

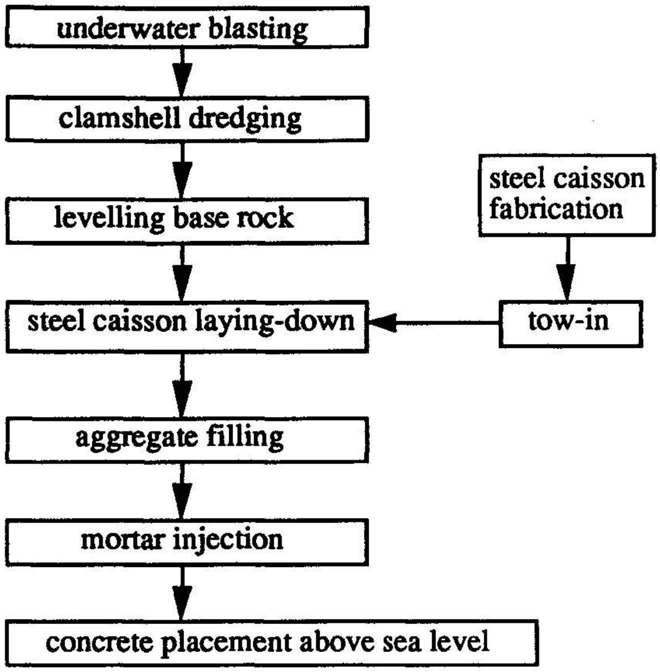

Fig.4 Process of the "laying-down" caisson method

size of which is 85m in diameter and 75.5m in height. Concrete will be placed inside the wall. On the other hand, the south anchorage is built on a sloping but shallow granite layer. In this case, the open excavation method using retaining walls is to be adopted.

5.4 Superstructure

The material and design for the main cables will be discussed in a partner paper in this symposium [5]. The main towers supporting these cables have heights of 297.2m above mean water level. The cellular steel tower shafts standing vertically have a constant width of 6.6m in the tower plane and a varying width of 14.8m to 10.0m in the direction of the bridge axis. The erection of tower blocks will be executed using a climbing crane. The largest block fabricated at the shop will weigh 460 tonf. In constructing such a tall structure, very careful accuracy control is required as shown in Table 3. In order to plane the large components of tower blocks, the fabricators have equipped with a large facing machine using numerical control.

Table 3 Permissible accuracy in tower construction

verticality	1/10,000
degree of metal touch : main plate (rib)	above 50 (25)% within 0.04mm
maximum opening	0.20mm

The design of the stiffening girder was dominated by wind effects because a critical wind speed of 78m/s or more is required for divergent oscillations. Although a variety of box girder alternatives had been proposed [6], a conventional stiffening truss, to which a vertical stabilizer may be attached, was finally adopted in the light of aerodynamic stability, economy and erection problems. Considerable quantities of high strength steels (up to 80 kgf/mm^2 class) will be used for the stiffening truss. The height and width of the cross section of truss girder are 14m and 35.3m respectively. As far as the aerodynamic stability is concerned, very tall towers are also susceptible to wind excitation. Various aerodynamic measures have been tested in wind tunnels, but the installation of some mechanical dampers is anticipated.

6. THE TATARA BRIDGE

6.1 Outline of the project

The Tatara Bridge is also one of the Honshu-Shikoku linking bridges to connect Ikuchi-jima and Ohmishima on the most western route. The main span of 890m will be the world's longest in a cable-stayed bridge when completed. Construction was started in 1990 and a construction period of about seven years is expected. The bridge carries four lanes of highway traffic.

The original scheme was naturally a suspension bridge for such long span. However, the execution of a massive anchorage on the Ikuchi-jima side would have forced serious change to the ground configuration, resulting in damage to the landscape, and the road alignment on the same side has a sharp curve near the end of the bridge. As a result, the alternative cable-stayed bridge design was conceived. Comparative studies have shown the preferability of a stayed bridge over a suspension bridge in the light of both cost and construction period, leaving only the problem of lack of experience with such a long span.

6.2 Preliminary design

Two types of cable-stayed bridge design were compared: one was the self-anchored type with intermediate piers in the side spans, while in the other type, several outer stay cables in the side spans were anchored to the ground. Although the latter was found advantageous for vertical loadings and on stress variation in stay cables, the former design was adopted because a reasonable distribution of sectional forces is attained in all parts of the structure if the girder is allowed to move at all supports and the appropriate elastic-constraint springs are installed between tower and girder at their connection. Because the side spans are relatively short (as shown in Fig. 5), the continuous girder consists of a steel box portion in the center span and prestressed concrete portions in the side spans. The steel box girder with an orthotropic steel deck and fairings is 25.3m in width and 2.5m in depth. The height of the tower is about 216m.

The dimensions and rigidities of the structure are determined by parametric analysis. Safety against earthquakes and winds seems to be satisfied, though further investigation is on going. The chief concern at the moment is the overall elastic stability of the structural system during and after erection. A large scale model test for this problem is under consideration, together with a finite displacement analysis.

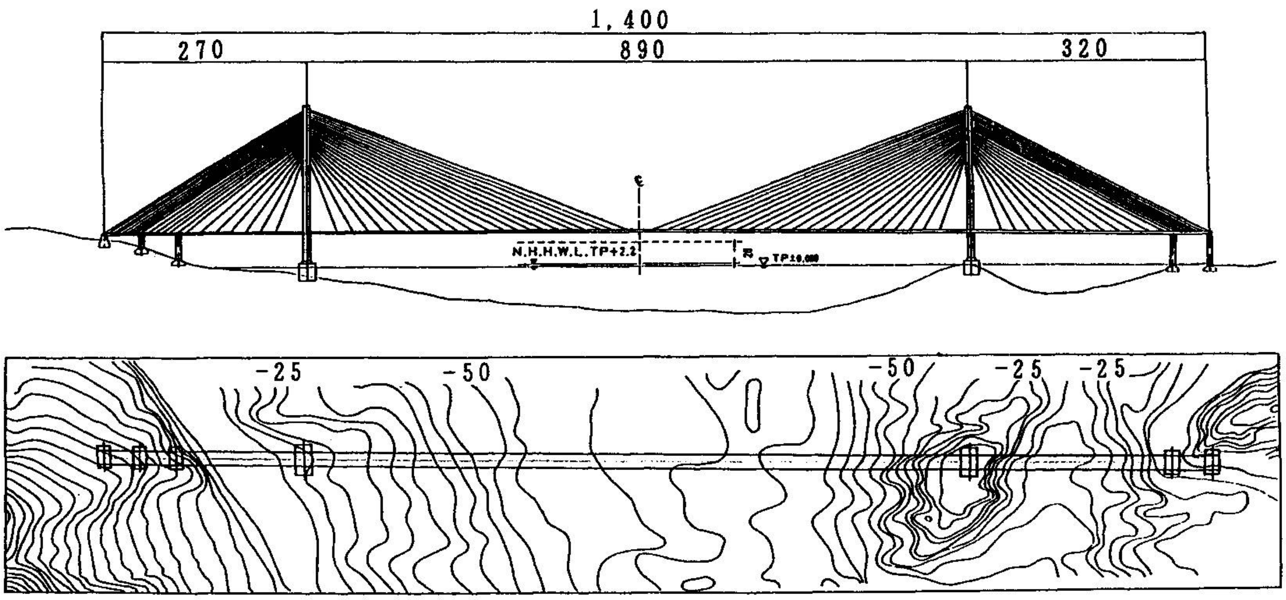

Fig. 5 The Tatara Bridge

7. ADDITIONAL REMARKS

Generally speaking, it is expected that these long span bridges will achieve longer lifetimes in view of the large investments made. Additionally it is noted that better quality and higher accuracy are required in the building of these larger structures. To satisfy these requirements, a cooperative system throughout design, fabrication and erection should be established, in particular for large scale steel structures.

As reported in this paper, Japanese bridge-building technology seems now to be leading the world. Nevertheless, there are problems, such as a decrease in the number of young and skilled manual workers in the industry, and a solution to this problem is now being sought through labour-saving, automation, as well as simplification and standardization of the fabrication and erection of works.

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