Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte
Band: 52 (1986)

Artikel: The Honshu-Shikoku bridge project
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DOI: https://doi.org/10.5169/seals-40339

The Honshu-Shikoku Bridge Project

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1. PREFACE

The Honshu-Shikoku Bridge Project is to link Honshu and Shikoku which are separated by the Seto-Inland Sea through three routes of highway and railroad as part of the country-wide trunk traffic network.
It is expected that when this Project is completed not only will the flow of traffic between Honshu and Shikoku be drastically improved, but it will also greatly contribute to the balanced development of the nation and the improvement of the economy and standards of living of the regions affected.
The concept of linking Honshu and Shikoku with bridges goes back as far as a century ago, and the feasibility study for it was started from the latter half of the 1950's both by the Ministry of Construction and the Japanese National Railways. Investigations and studies conducted for about 10 years verified that the Honshu-Shikoku Bridge Project would be feasible both technically and economically.
Subsequenty, in 1970, the Honshu-Shikoku Bridge Authority was established by law to be the public corporation which would be responsible for executing comprehensively and efficiently the construction and management of highways (toll roads) and railroads relating to the Honshu-Shikoku Bridge Project.
Following a postponement of the Project due to the oil crisis in 1973, work was started again in 1975 from Ohnaruto Bridge of the Kobe-Naruto route, Ohmishima Bridge, Innoshima Bridge, Hakata-Ohshima Bridge of the Onomichi-Imabari route, and Kojima-Sakaide route which are combined highway-railroad routes first connecting Honshu and Shikoku. These are collectively called the "1 route and 4 bridges". At present Ohnaruto Bridge, Ohmishima Bridge, and Innoshima Bridge have already been put into service and the Kojima-Sakaide route will be completed toward the end of the fiscal year 1987 and Hakata-Ohshima Bridge toward the end of 1987. For this fiscal year, more private capital was going to be introduced into the Project and the construction of Akashi Kaikyo Bridge of Kobe-Naruto route (3-span highway suspension bridge with center span of 1,990 m) and Ikuchi Bridge of Onomichi-Imabari route (highway cable stayed bridge with center span of 490 m) were newly approved as the government's policy to expand domestic demand.

2. ENGINEERING AND SOCIAL PROBLEMS PECULIAR TO THIS PROJECT AND SYSTEMS IMPLEMENTED TO SOLVE THEM

The Honshu-Shikoku connecting roads and railroad constitute an important section of the country-wide trunk traffic network. Each route makes its own peculiar demands on traffic and therefore no alternative path can be taken as would be possible on a land route. The Project includes the construction of many long span bridges on an international scale under severe natural conditions and in a peculiar social environment. The following are major engineering and social problems of distinctive features [7]:

(1) Prominently susceptible to earthquakes and typhoons

In a long-span suspension bridge, in particular, its stability against wind and its earthquake resistance would greatly affect the safety of the completed structure.

(2) Combined highway-railroad bridges on which high-speed trains are running

The effects on a suspension bridge caused by the passing of trains and the effect on the safety of train operation due to the behavior of suspension bridges are to be evaluated and adequate measures must be taken. Also, prudent measures must be taken against fatigue in the welded joints, because thick quenched high tensile strength steel plates are used in quantity.

(3) Safe and reliable construction methods of foundation

Construction methods of foundation should conform to the site condition in a strait of great depth and strong tidal currents. In the case of Akashi Kaikyo Bridge, even though the center span was extended to 1,990 m, it was necessary to construct foundations reaching as deep as 70 m below sea level under the severe natural conditions of a sea depth of 40 m and a maximum tidal current speed of 4.5 m/sec.

(4) Method of erecting the superstructure in severe meteorological and marine conditions

The method of reducing the volume of work at site, shortening the construction period and selecting safe and secure methods of construction, greatly affect the safety and quality of the completed structures.

(5) Navigational safety

As the strait over which the Honshu-Shikoku Bridges are constructed constitutes a main navigational route, including international vessels, it is congested with shipping, in addition to fishing boats operating in the peripheral sea region. Therefore, prudent safety measures for navigation must be taken during construction and even after its completion.

(6) Maintenance

The structures are extremely large scale and unique in nature, thus making it difficult to rebuild or replace their members. Consequently, an important factor is the maintenance of the bridges to secure their safety and quality over a long period of time.

(7) Environmental consideration

Since the routes are running in the beautiful and charming Seto-Inland Sea National Park, the harmonization of the structures with landscape and the preservation of natural and living environment are extremely important.

The engineering problems mentioned above cover some fields where technological experience is lacking and which basically affect the safety and quality of structures and their safety during construction. The basic concept to meet this challenge to solve those problems are as follows:

(1) Integrated consideration should be taken in all phases at planning, design, construction and maintenance, which are closely interrelated.
(2) Standards and specifications should be established for design, construction and maintenance, incorporating wide and interdisciplinary knowledge.
(3) As the construction must be performed in the strait and under severe natural and social conditions, the methods of construction should preferably be designed so that they are simplified, labour saving, large scale and quantitative.

To meet these requirements, investigations, research and technical development have been in progress for many years and in this Project the following approaches have been adopted for execution to ensure safety and quality [7]:

(1) With regard to comprehensive and fundamental technical matters and individual problems or subjects, the Technical Advisory Board and the Special Technical Committees, respectively have been organized. This Board and Committees are to point out ways of solving problems, investigations, tests, technical development, etc., and to evaluate and suggest on the results of investigations or examinations performed and proposals made by Honshu-Shikoku Bridge Authority. The Authority, based on these results, prepares 51 types of Standards and Specifications, some of which examples are as follows:
   (a) Standards for Structural Design of Superstructures,
   (b) Standards for Structural Design of Substructures,
   (c) Standards for Wind Proof Design
   (d) Standards for Aseismic Design,
   (e) Standards for Fabrication of Steel Bridges,
   (f) Standards for Fabrication of Cast and Tempered Steel Products,
   (g) Standards for Coating of Steel Bridges,
   (h) Standards for Pavement on Steel Plate Floor,
   (i) Standards for Construction of Mass Concrete Structures,
   (j) Honshu-Shikoku Bridge Standards of Material for Steel Plates, Cable, High-strength Bolt, Paints, etc.
   (k) Specifications for Buffer Structures
   (l) Specifications for Tower Design
   (m) Specifications for Transition Girders

(2) With regard to newly developed method of construction, experimental constructions, and testings are to be performed to verify their workability, safety, quality achieved, accuracy, etc., and their adoption is determined depending on the results.

(3) The design for the structures is let out to the Consultants. In this case, the design methods are specified and they are bound to conform to the above Standards and the results are examined by the Authority. In concluding the Contract for Construction, the methods of construction are specified as required, and in addition, the Particular Specifications are provided supplementing the above standards to make certain that the safety and quality are ensured.

(4) Prior to the commencement of construction, the Contractors are asked to submit the construction plan, which will be thoroughly examined and they are bound thereby. The Contractors are held responsible for quality assurance of the construction. In turn, the authority will confirm the safety and quality through the supervision and inspection of the construction [8].

3. SOME CONSIDERATION ON ENGINEERING ACHIEVEMENTS FROM THE VIEWPOINTS OF SAFETY AND QUALITY ASSURANCE

In this Project many structures are to be constructed concurrently, safely, surely and in a short period and put into service meeting strict internal requirements and satisfying various external conditions. In view of this situation, prudent investigations and research on safety and reliability of construction through experimental work, simplification of on-site works incorporating shop fabrication by a large margin, development of construction techniques aiming at labour saving, introduction of a diagnosis system of soundness of structures both on the spot and over the long term, etc., were performed. In this section, specific examples of the above are introduced and their effects are examined.

3.1 Aseismic design and wind-proof design standards

In the design of substructure, it is necessary to determine static behavior of the substructure at the time of an earthquake and conditions for stability must be met. For this purpose, earthquakes to be subjected for investigation were selected from the earthquake activities records in the Seto-Inland Sea region as those occurred at slightly longer range and with higher effects (epicenters located between 100 and 150 km from the site), assuming a recurrence interval of 100 years and a magnitude of about 8 in Richter scale. In the design, a whole system model of the superstructure and substructure was used to perform spector analysis and the reaction obtained was substituted onto the substructures model as the external force for stability calculations.
Meanwhile, the wind-proof design was the design consisting of the static design placing emphasis on the section design of structural members and the dynamic design performed using a wind-tunnel test to avoid self-excited oscillation which is catastrophic in case of storm and to control vortex-induced oscillation when the bridge is put into service. The basic wind velocity used that becomes the basis of these designs was the mean wind velocity for 10 minutes at 10 m above seal level assuming the recurrence interval to be 150 years, which is 43 m/sec in the Akashi Strait. The design wind is calculated by the structure incorporating its elevation, response characteristics, space characteristics of wind, etc., into the basic wind velocity. The sections of members determined for static loading conditions under normal conditions and abnormal conditions, such as typhoon, earthquake, etc., were improved in the section configuration, etc., using the wind tunnel testing by reference within the range of 1.2 times the design wind speed, as well as verifying the coefficient of aerodynamic force assumed in the static design. The validity of the Wind Tunnel Testing Standards has been confirmed by large scale model experiments in the natural environment (scale 1/10). In addition, the confirmation of vibration characteristics by the compulsory vibration tests after the completion and the behavior observation have also been performed to verify the modes, frequencies and damping ratio so that a consistent safety of structure can be pursued.

3.2 Some features on combined highway-railroad bridges

The problems associated with combined highway-railroad bridges of large scale are safety of train traffic and fatigue design.

(1) Assurance of train traffic safety

Large scale suspension bridges have structures that are subject to deflection and, in particular, at the ends of girders large expansion/contraction and angular bend tend to occur. To permit trains to travel safely on structures such as these, the continuous girder was adopted as the stiffening girder structure to reduce the locations where expansion/contraction and angular bend would occur and by shortening the side span length their values were minimized as much as possible. And as a system to absorb expansion/contraction and angular bend, a buffer girder was developed and its contribution to safety was confirmed by experiments using actual traveling trains, thereby making it possible to allow the expansion /contraction and angular bend caused on the anchorage to ±75 cm maximum and 10 ‰. Also, in the design the deformation that is caused by running trains and its dynamic effects were analyzed and it was discovered that the coefficient of impact of approximately 0.2 would be suitably used. For the Bannosu Elevated Bridge on the shore, as the bearing stratum was deep sandy ground and the pile foundation had to be penetrated deep into the ground (max. 74m), and also the bridge pier was high (max. 72 m) the possibility of train derailment was avoided by staggering the vibration cycle of the structures and that of the trains in case of an earthquake.

(2) Use of high-tensile strength steel and some considerations on fatigue of welded joints [4],[5]

As the bridges had to be combined highway-railway bridges, the structures inevitably became larger in scale and the use of quenched high-tensile strength steel plates of large thickness was necessary for the major structural members, i.e. maximum tensile strength of 80 kgf/mm^2 class on thickness of 160 mm class.
Because of the sensitivity and brittleness of the material, quenched high-tensile strength steel plates, consideration on the fatigue of welded joints due to the repeated travel load of trains had to be made in the design and fabrication.

Therefore, in the standardization of the design, provisions were made for confirming the fatigue strength of welded joints through the testing of each joint using a fatigue testing facility with dynamic loading amplitude of 400 tonf and an allowable value of initial defects of welded joints incorporating the safe-life concept in the fracture mechanics and testing methods. As the fabrication of stiffening girders for the three suspension bridges of the Kojima-Sakaide route, about 110,000 tons in quantity, had to be divided among the fabrication shops of 24 companies and performed almost concurrently and required uniform in quality, a full-sized member was fabricated experimentally at each fabrication shop prior to the actual manufacturing and a welding method to meet the required quality was established. Automatic supersonic inspection was performed on the welded joints at frequencies corresponding to the fatigue classification and it was confirmed that the required quality had been obtained. The data for this inspection will be reflected in the follow-up investigation of defects in the maintenance of structures, contributing to assuring of safety against destruction by fatigue.

(3) Method of main cable installation [2]

Demands for large scale suspension bridges and combined highway-railway bridges have made the main cables larger both in length and diameter. Consequently, labour saving in the site construction and shortening of construction period became necessary resulting in the development of construction techniques of the Prefabricated Parallel Wire Strand method, Aerial Spinning method.
The PS method is the method in which a shop fabricated strand that is made up of 127 plies of wire socketed at both ends delivered to the site and stayed. This method is resistant against a variety of weather conditions, such as wind, etc., and effective in reducing volume of the site work and shortening of construction period, enabling us to install the high quality parallel cables of diameter reaching as large as 1 meter with low percentage of voids.
Also in the AS method, non-adjustment of sag of wires during composing a strand and simultaneous drawing of four wires, etc., were performed, achieving reduction of the site work and shortening of construction period compared with the conventional AS method. Cables of quality as good as those obtained by the PS method, were obtained.

3.3 Selection of construction methods making use of the characterisitics of marine works

Marine works are characterized by disadvantages such as transportation of equipment and materials, raw materials, and labours had to be dependent upon meteorological and marine conditions, but on the other hand, by making positive use of the sea enviroment, the construction of large scale structures was made possible. As a result, prefabrication of members in the shops was accelerated and a new method of civil engineering construction was created. In this Section, some of the features and examples of technology development achieved which were derived therefrom are introduced.

(1) Laying-down caisson method [1],[3]

In the Kojima-Sakaide route 11 undersea foundations, for suspension bridges and cable stayed bridges, were constructed. As one of the methods of construction common to these the laying-down caisson method was developed in which a steel caisson fabricated in the dock was installed on the sea bed which had been blasted, excavated and finshed in advance. Then coarse aggregate was thrown in the caisson followed by mortar injection to complete the foundation. This method made marine works at deep sea level possible to be constructed, safely, reliably and in a short period. Problems in this method are the undersea blasting and the prepacked concrete method. The latter is technology related to safety and quality assurance. Therefore, since the time of the feasibility study, large scale experimental works had been performed to confirm that high quality construction was possible. A mortar plant barge was developed by the Authority and was lent to the contractors to provide stable supply of mortar. (Capacity: 240 m^3/hr). For placement of concrete volume of maximum 230,000 m^3 per foundation (mortar injection of 12,000 m^3) and 85 hours of continuous injection operation was performed.

(2) Prefabricated large block erection

An example of labour saving and simplification of the site work and shortening of construction period was the erection of prefabricated large blocks using a large floating crane (hereinafter referred to as F.C.), which was adopted for construction of many superstructures and substructures of the Honshu-Shikoku Bridges. The most typical examples were erection of cable anchor frames, towers and girders, the largest of which was 6,100 ton (185 m long) which was erected using two FC's. Also, the aerial jointing of girder blocks using F.C. was performed with a careful construction plan and an advanced barge maneuvering techniques, which has now become one of the most representative construction techniques used in the construction of bridges in the strait. Use of the prefabricated large block erection resulted in the improvement of quality and accuracy in construction, saving in cost due to reduction of weight by reducing splices and reduction of the numbers of construction equipment and materials. Also the prefabicated large blocks are, in principle, shop painted, resulting in improved durability of the coating film.

(3) Successive full-splice jointing method in stiffening girder erection

As construction sites of the Honshu-Shikoku Bridges are located in a region susceptible to typhoons, it is necessary that their wind-proof safety must be assured at the time of erection of stiffening girders for suspension bridges. Therefore, the successive full-splice jointing method in which the blocks to be erected are rigidly jointed one after another, was adopted. In this method, however, as excessive stress is caused with diagonal members and hanger at the tip of erection and the stiffening truss, erection hinges were provided to reduce the stress.

In the construction of Ohnaruto Bridge, as the fequency of strong wind is high, if not of typhoons, further wind-proof consideration during the erection was required, it was decided not to use the erection hinges, becuase they could be a weakness in case of strong wind. Instead, the tip of the block being installed was drawn simultaneously using two or three hangers, the adoption of which resulted in the shortening of erection period.

3.4 Various coordinations of structure with navigation

The Seto-Inland Sea where the Honshu-Shikoku Bridges are to be constructed has a complicated waterway topography, and severe meteorological and marine conditions from the viewpoint of navigational safety. In addition, as the Sea forms an important route for marine traffic it is necessary that safety of ship navigation be secured both during the construction and after the completion of bridges. In this connection, establishment of the construction zones, posting of alert boats, provision of information to construction boats (barges) from the information control center, etc., have been made during the construction and the following measures will be taken after the completion.

(1) Measures against radar interference

A forecast was made on the occurrence of false image due to the mirror reflection phenomenon caused by a bridge constructed at sea or the false image of multiple reflection caused by repeated reflection of radar waves among the bridge members, and measures for their abatement such as pasting wave absorber materials on parts of the main tower and the stiffening girders or providing multi-stage slopes on wall faces of the anchorage, etc., are being taken.

(2) Buffer structure [6]

To minimize damage to the hull and the bridge pier should a ship collide with the undersea foundation, buffers will be provided around the foundation.

(3) Navigational aid system

To help make navigation safe in foggy weather, a navigational aid system, such as visibility automatic response system, automatic detecting and indicating system for ship's movement, etc., will be provided.

3.5 Maintenance system

The bridge portion of the Honshu-Shikoku Bridges are taken up a large percentage of about 40% and the long-span bridges are concentrated on the strait. As there is no alternative to this route, the traffic control and the maintenance of the road to keep the bridges in good operating condition becomes a matter of extreme importance.
For this reason, consideration is given for it to be centrally monitored and controlled by providing a traffic monitoring system and weather observation system in addition to accelerometers, seismometers, displacement gages, etc., as its movement observation systems. In particular, the movement observation system follows the secular change of the bridges and judges their soundness, and in addition, detects damage and its location shortly after the occurrence of abnormal conditions (e.g. earthquake, typhoon, etc.) making it possible to resume the service of the bridges as soon as possible.
To make inspection, maintenance and repair operations of the bridges which are composed of multi-functions and multi-members easier, many passages for inspection and inspection vehicles with high accessibility to various locations are provided.

4. CONCLUSION

The Honshu-Shikoku Bridges Project have constructed and are presently constructing combined highway-railroad bridges of large scale and is managing them under the severe natural conditions and environment of typhoons, earthquakes, large water depth and strong tidal currents, etc., and the social conditions of navigation, among others.
The Honshu-Shikoku Bridge Authority, through the execution of the entire undertakings of design, construction and management of the bridges, has been performing comprehensive and efficient operations, securing safety and quality at each stage. The technological development achieved and established in the design and construction of these bridges are as follows:

(1) Establishment of aseismic and wind-proof designs based on the assumption of 100 year durability.
(2) Standardizing safety against travelling of trains and fatigue destruction of the combined highway-railway bridges.
(3) Selection of the laying-down caisson method and the prefabricated large block erection method making use of the marine works and aiming at improving safety and quality and shortening of construction period, and the PS method in the installation of the main cables, the full-splice jointing method in the erection of stiffening girders.
(4) Various coordinations of structures with navigation of ships from the viewpoint of safety both during construction and after its completion.
(5) Development of a maintenance system to secure constant soundness of the bridges.

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