Project Report

World's first PC-steel composite cable-stayed bridge using corrugated steel plate webs for PC girders

Yahagigawa Bridge on the Second Tomei Expressway

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The Toyota Junction is an interchange where the existing Tomei Expressway and the Second Tomei Expressway under construction will meet. When I approach the Tokai Ring Expressway (scheduled to open to traffic this spring) from the junction, the Yahagigawa Bridge with two main towers shaped like an inverted letter Y on the Second Tomei Expressway comes into view (Figure 1). The bridge deck is ten-odd meters high from the ground. I could not make out the scale of the bridge from such a long distance but when I view it from the bank of the Yahagi river, I am amazed by the large scale of the width of main girders, the main span of the bridge, and the height of main towers.

Figure 1　Map showing the location of the bridge

The bridge was opened to traffic at the same time as the opening of the Expo 2005 Aichi Japan. It is the largest of the bridges planned on the Second Tomei Expressway and the world's first PC-steel composite cable-stayed bridge using corrugated steel plate webs for PC girders. The span of the bridge is the longest of the PC bridges that use corrugated steel plate webs, and the bridge structure that suspends the wide girders of single-piece construction for both inbound and outbound lanes at the center of the girders is the largest in the world.

The construction conditions for the bridge situated in a built-up area under tight project schedule were very harsh. The bridge is the largest structure ever experienced by the engineers engaged in bridge construction works. With technical problems solved from various design and construction approaches, the superstructure and substructure works of the 820 m long and 43.8 m wide PC-steel composite cable-stayed bridge were completed in as few as three years and three months.

I had an opportunity to visit the bridge several times during construction to see and hear the technical features of the design and construction, and they are reported in this article.

Outline of the bridge

The Yahagi river is a limpid stream where more than one million sweetfish can be seen swimming up the river. Upstream of the point where the bridge crosses the river are the agricultural water intake of the Meiji Canal, a row of cherry blossom trees and the water leisure facilities that provide a waterside environment in the local community (Photo 1).

Photo 1 Yahagigawa Bridge under construction and a row of cherry blossom trees on the bank of the Yahagi river

In addition to these environmental conditions, the construction of the bridge was subject to various limitations on the conditions for grade separation: around the construction site are city roads and urban roads authorized in city plan; fishery rights are set up at the location of bridge piers in the river; the economies of the project as public works need to be achieved; and the bridge must be open to traffic by the opening of the Expo.

To meet these conditions, the PC-steel composite cable-stayed bridge was selected: that is, it uses corrugated steel plate web PC box girders in the cable-stayed bridge sections and steel slab box girders in the intermediate support section (Figure 2).

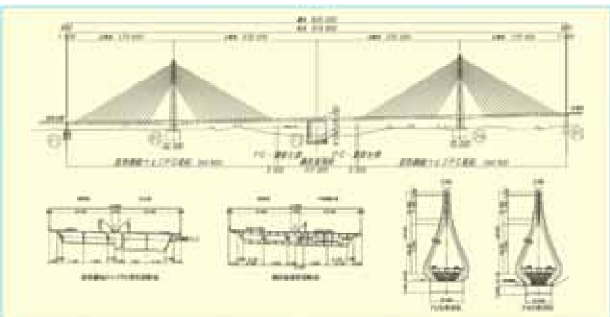

Figure 2 General drawing of the bridge

The water is a motif in the landscape design of the bridge. The surface of the main towers is curved, resembling a drop of water. They are designed speculatively to create new landscapes by harmonizing the man-made structure with nature.

Outline of the structures of main bridge components

The structural feature of the bridge is the adoption of the composite structure that takes advantages of the merits of both concrete and steel from the viewpoint of durability, cost efficiency, and constructability. The structures of main bridge components are outlined below.

Corrugated steel plate web PC box girders

The main girders of the cable-stayed bridge sections are wide box girders of 5-cell cross section, with corrugated steel plate adopted for the web. Stay cables anchored at the center of the cross section of the main girders are large-capacity shop-manufactured cables with a maximum tensile load capacity of about 25,000 kN per cable, and two stay cables each are anchored in parallel. To ensure the required capacity, durability, and constructability of the cable anchorage zone, the steel anchorage zone called the steel anchorage beam system is adopted (Figure 3).

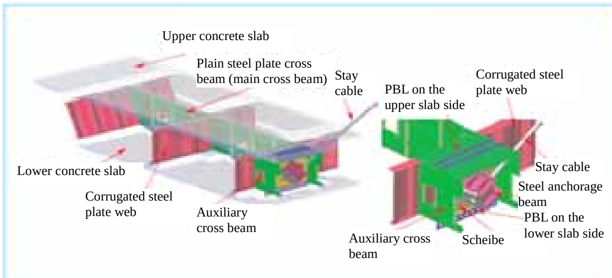

Figure 3 Structure of cable anchorage zone on the main girder side

The features of the system include (1) it ensures the required capacity and save the dead weight of the cable anchorage zone under the large tension of stay cables, (2) the use of steel for the cable anchorage zone, instead of concrete anchorage zone that generally makes the structure complex, makes it possible to manufacture unitized members at shop, and (3) because the upper concrete slab is completely separated from the lower concrete slab, the slabs can be constructed individually and work periods can be shortened.

From a structural viewpoint, it is important to transmit the tensile load of stay cables to the upper and lower concrete slabs and ensure the capacity of the concrete sections. The safety of the system was verified from various aspects: the checking of the members by the space FEM analysis; the testing to verify the load bearing capacity using a half size scale model; the fatigue testing of the steel anchorage zone under the fluctuating axial load of stay cables; and the performance testing of perforated steel dowel that is adopted as a joint system.

Structure of the lower part of main towers

The lower part of the main towers needed to be tapered due to various limitations on the conditions for grade separation. Taking advantage of this, the lower part takes a largely curved shape. To suspend the dead weight of the wide main girders with stay cables, very large sectional forces act on the lower part of the main towers. Accordingly, the steel shell structure that combines thick steel plates and is rational in terms of both structure and constructability, instead of the ordinary reinforced concrete structure that cannot ensure constructability, is adopted for the lower part of the main towers. Prestressing steel is laid out in the end girder section that supports the cantilevered main tower from the bridge pier to control cracking and ensure durability (Figure 4).

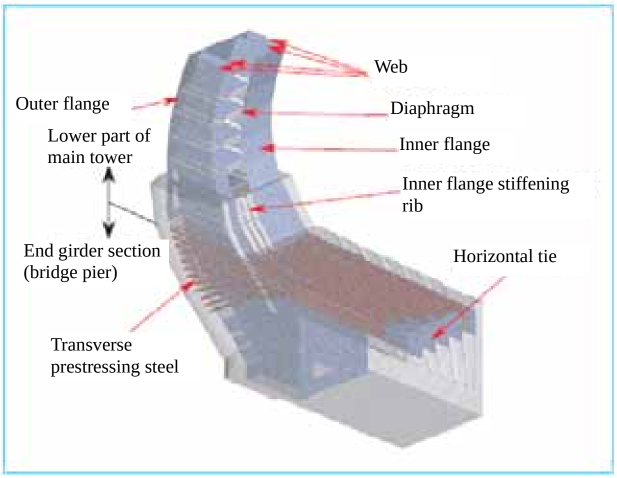

Figure 4 Structure of steel shell of the lower part of main tower

The end girder section has a shear span ratio of about 1.0 and its load bearing mechanism seemed to behave as a deep beam in an ultimate limit state. There was no track record of the structure that reinforced the end girder section using a steel shell. Considering the importance of the end girder section that plays a vital role as a pillar of the entire bridge, it was necessary to avoid a brittle failure pattern and give a predominant flexural failure pattern to the end girder section. For this reason, it became very important to evaluate the shear resistance of the end girder section. In the design phase, a method of designing the deep beam reinforced by the steel shell, including a contribution factor of the steel shell to the shear resistance, was proposed. To confirm the validity of the design, including the safety in serviceability limit and ultimate limit states, a test to confirm the load bearing capacity was conducted using a one-tenth scale model and a nonlinear FEM analysis was carried out.

This structure is a rational reinforcement structure for the members subject to large sectional forces, for which an enormous amount of reinforcements would be required and it would be difficult to ensure constructability by the conventional construction method.

Structure of the joint between corrugated steel plate web PC girder and steel girder

Basically the front and rear panel system that was used for the Kisogawa and Ibigawa Bridges was adopted for the structure of the joint between the corrugated steel plate web PC girder and steel girder. A difference in the structure from both bridges is that corrugated steel plate web is used for the PC girder. Based on the results of a 3-D FEM analysis on the characteristics of transmission of shear forces, the structure of the joint was designed to transmit the shear forces through the lining concrete without directly jointing the webs (Figure 5).

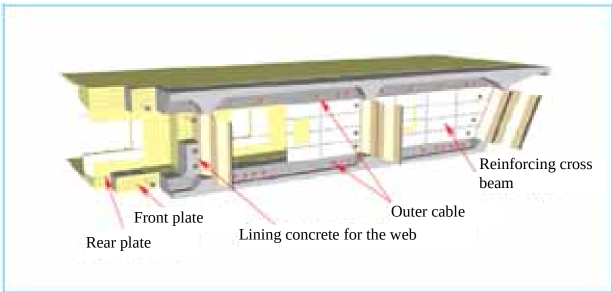

Figure 5 Structure of the joint between PC and steel girders

The adoption of this structure allows the closure of the joint between PC and steel girders by the placing of concrete that makes it easier to absorb errors during erection than the connection of steel main girders. To prevent harmful cracks from being produced in the concrete 43.8 m wide by 1.95 m long in the direction of bridge axis, measurements were made at the site, a thermal stress analysis was carried out, and studies were conducted on separators, the selection of cement and the procedures for placing concrete in steel girder cells.

Outline of the erection

Erection of main girders

For the erection of PC girders, after the supports for the piers were constructed, cable anchorage blocks were erected using a supersized form traveler (capable of 8 m long blocks) by the cantilever method (Photo 2). For the PC girders between P3 and P5 to be erected by the cantilever method that were started late, steel members of main girders (corrugated steel plate web, plain steel plate cross beam and cable anchorage zone), steel reinforcement and upper slab forms were prefabricated to shorten work periods.

Photo 2 PC girders being erected by the cantilever erection method using a supersized form traveller

For the prefabrication of the main girders, the cross section of the main girder was divided into two outer-cell units and three center-cell units having the cable anchorage zone, and a yard for prefabricating a total of six units for both P3 and P5 sides were secured under the bridge girders. The prefabricated units were pulled onto bogies on the rails at the center of the yard, transported to the front of the P4 main tower, and lifted up to the bridge deck using the lifter installed on the girder on the bridge deck (Photo 3). The adoption of this construction method allowed the process of erecting one block of main girder, including the erection of stay cables, in a cycle of 11 days.

Photo 3 Prefabricated unit of main girder being lifted

For the erection of the steel slab box girders (133.4 m in total length and 4,250 tons in total weight) just above the Yahagi river, a falsework bent was installed on the P3 bridge pier to erect them by the balanced cantilever method (Photo 4). Construction periods were limited in the low-water season and the erection of the girders was completed in three months in real terms.

Photo 4 Steel girders being erected by the balanced cantilever method

Structure of main towers

The main towers are 109.6 m high from the bride seat and the highest of the concrete main towers in Japan. The sections from the bridge pier to the bifurcation of the inverted letter Y (two leaning columns) and to the first cable anchorage zone after closed were the critical path of the construction work, and the shortening of work periods and the assurance of constructability at high elevations were required of the sections.

The climbing scaffolding as shown in Photo 5 was used for the construction of the main towers at the bifurcation. The scaffolding was jacked up in increments of 4.5 m per lift as the construction work proceeded. The climbing scaffolding allowed construction equipment to be concentrated in a single place, which assured safety and saved labor. In addition to the climbing scaffolding, the prefabrication of steel reinforcement and the use of large paneled forms made it possible to construct the three-dimensionally curbed bifurcation at high speeds.

Photo 5 Climbing scaffolding at the bifurcation of the main tower

Photo 6 Completed Yahagigawa Bridge (aerial photo)

To use high-strength concrete having a specified design strength of 60 N/mm^2, a thermal stress analysis was carried out and a test to confirm constructability was conducted. Construction work was carried out with the greatest care, including the selection of materials according to the location of use.

In addition, to meet the need for removing forms as early as possible aiming at speeding up the process, the durability of the concrete was ensured by managing the concrete strength by the temperature tracking type curing method and the application of a silane/siloxane-based anti-permeable water absorption agent to the concrete.

The construction of the P2 superstructure was commenced in September 2002, the main towers and main girders were erected at the same time, and the connection of the main girders of the superstructure was completed in October 2004.

The bridge of the world's first structural type was built by using various design and construction approaches in addition to those introduced in this article. The scope of application of corrugated steel plate webs is extended to the range largely surpassing the range of extra-dozed bridges. This bridge gives some indication of the possibilities of long PC bridges.

Lastly, I would like to express my appreciation to those who dedicated their efforts day and night toward the construction work and thank the Chubu Regional Bureau of Japan Highway Public Corporation and the JV of Yahagigawa Bridge East and West Superstructure Works for their cooperation in collecting information for this article.