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Recent technology of prestressed concrete bridges in Japan

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ABSTRACT: Prestressed concrete (PC) technology is being used all over the world in the construction of a wide range of bridge structures. However, many PC bridges have been deteriorating even before the end of their design service-life due to corrosion and other environmental effects. In view of this, a number of innovative technologies have been developed in Japan to increase not only the structural performance of PC bridges, but also their long-term durability. These include the development of novel structural systems and the advancement in construction materials. This paper presents an overview of such innovative technologies on PC bridges on their development and applications in actual construction projects. Some noteworthy structures, which represent the state-of-the-art technologies in the construction of PC bridges in Japan, are also presented.

1 INTRODUCTION

Prestressed concrete (PC) technology is widely being used all over the world in construction of wide range of structures, particularly bridge structures. In Japan, the application of prestressed concrete was first introduced in the 1950s, and since then, the construction of PC bridges has grown dramatically. The increased interest in the construction of PC bridges can be attributed to the fact that the initial and life-cycle cost of PC bridges, including repair and maintenance, are much lower than those of steel bridges. Moreover, comparing to the reinforced concrete (RC) bridges, PC bridges are more economically competitive and aesthetically superior due to the employment of high-strength materials. Figure 1 shows relationship between the number of bridges (PC, RC, steel and others) in Japan, the total length of bridges and the construction year. The figure indicates that the numbers of new construction bridges increased significantly from 1950s to 1975 but they have being decreased since 1975 till now. Deterioration of bridges is becoming a big social issue since many bridges are getting older over 50 years.

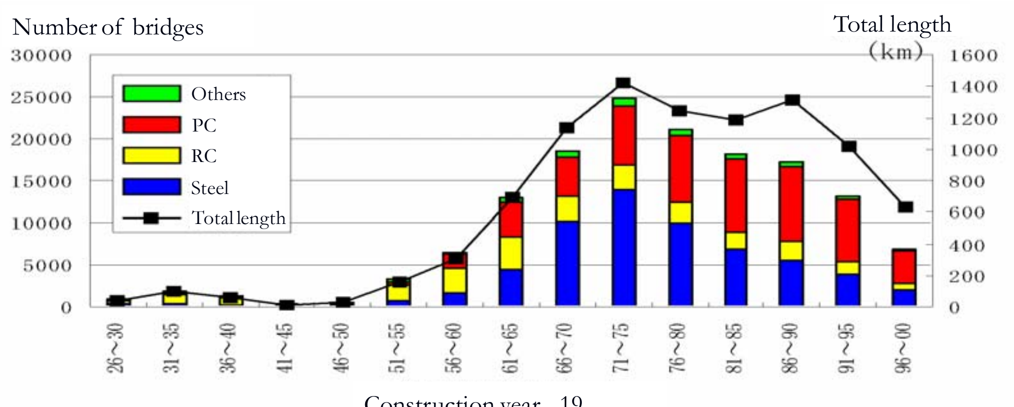


Figure 1. Number of bridges in Japan

In recent years, many PC bridges have been deteriorating even before their designed service-life due to corrosion and other environmental effects. As a consequence, the long-term durability has become a particular concern and should seriously be considered in the design and construction of PC bridges apart from the viewpoint of structural safety, aesthetics and cost. In Japan, a number of innovative technologies have been developed to increase not only the structural performance but also the long-term durability of PC bridges. These include the development of novel structural system such as external prestressing, highly eccentric external tendons and extradosed prestressing.

This paper presents an overview of such innovative technologies of PC bridges including a brief detail of their development and background as well as their applications in actual construction projects. In addition, some noteworthy structures, which represent the state-of-the-art technologies in the construction of PC bridges in Japan are also presented.

2 DEVELOPMENT OF NOVEL STRUCTURAL SYSTEMS IN PC BRIDGES

External prestressing technique is widely being used in the construction industry. Externally prestressed PC bridges are designed with prestressing tendons placed outside the concrete section, but still remaining within the bounds of the cross section of girder (Figure 2). The concept of external prestressing has become increasingly popular in the constructions of medium- and long-span bridges due to its several advantages such as reduced web thickness, possibility to control and adjust tendon forces, and ease of inspection of tendons during construction. The Japan Highway Public Corporation (abbreviated for JH; it is changed to three highway companies at present), which governed most of the highway bridges in Japan, has actively adopted the concept of fully external tendons for box girder bridges (Figure 2) since 1999 due to the improved durability performance compared to that of internally grouted tendons. It is of importance to note that, recently, a new construction of PC bridges with internally grouted tendons has been forbidden by the JH due to the bad quality of grouting of internal tendons in some existing PC bridges [1]. For the better performance of the externally prestressed concrete bridges, various new technologies have recently been developed in Japan.

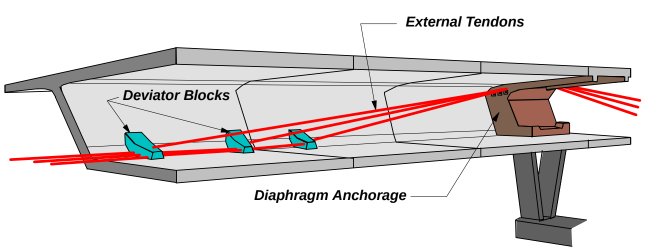
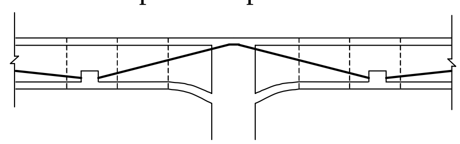
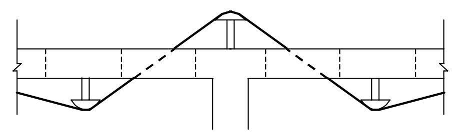


Figure 2. Typical layout of an external PC box girder



(a) Ordinary external tendon



(b) Highly eccentric external tendon

Figure 3. Ordinary vs. highly eccentric external tendon

2.1 *PC Bridges with highly eccentric external tendons*

Although externally prestressed PC bridges are well recognized to have several advantages, however, they have lower flexural strength compared to that of bridges with internally bonded tendons [2]. This is due to the smaller tendon eccentricity, which is limited by the bounds of concrete section of girder (i.e., at the bottom slab in case of box-girder bridges) as well as the reduction in tendon eccentricity at the ultimate flexural failure (so-called second-order effect). One possible method of enhancing the flexural strength of externally PC structures is to make the tendons highly eccentricity (Figure 3). This kind of construction is possible only when external prestressing is used, since this allows the tendons to be placed outside the concrete section of girder. In this concept, the compressive forces are taken by concrete and the tensile forces by external tendons, thus taking advantages of both materials effectively [3].

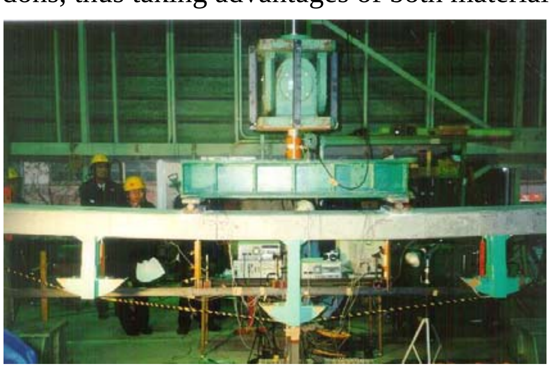


Figure 4. Loading test of single span girder with highly eccentric external tendons

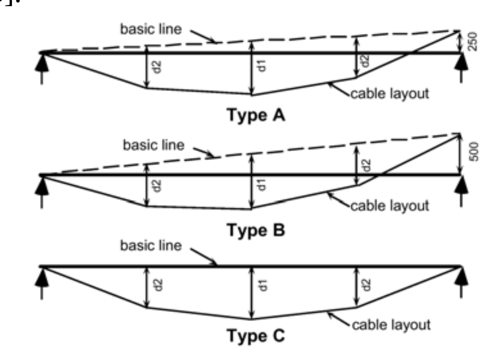


Figure 5. Linear transformation of tendon layout

There has been extensive research conducted at Saitama University both analytically and experimentally to study the fundamental behavior of girders with highly eccentric external tendons [4, 5, 6]. From the test results of single-span beams (Figure 4), it was found that by increasing tendon eccentricity, the flexural strength can be significantly improved or, conversely, the amount of prestressing reduced; the result is more economical structures. By extending the concept of highly eccentric external tendons to continuous girders, the structural performance can be further improved. In addition, the girders consisting of linearly transformed tendon profile were found to have the same overall flexural behavior (Figure 5). This gives the designer to take advantage of arranging the external tendon layout freely, depending on the site conditions.

To verify the application of this concept to the segmental construction method, the behavior of segmental girders with highly eccentric external tendons was also investigated and found to be nearly the same as that of monolithically cast girders. Hence, this gives considerable flexibility in selecting the method of construction when designing the bridges with highly eccentric external tendons. One of the concerns raised for this type of structure was the shear capacity as the girder height is considerably reduced. It was verified, however, from the experiment on shear characteristic of model specimens that the shear capacity of the girder with highly eccentric external tendons is much higher than that of the conventional girders due to the large increase of tensile force in external tendons.

The world's first application of the prestressing with highly eccentric external tendon to a continuous-span girder was in the construction of the Boukei Bridge in Hokkaido, Japan. Considering the site conditions, the bridge was designed with a two-span continuous and unsymmetrical girder having a total length of 57 m as shown in Figure 6. The effective width of the bridge varies from 3.0 m at the abutments to 6.0 m at the central pier. A completed view of the bridge is shown in Figure 7.

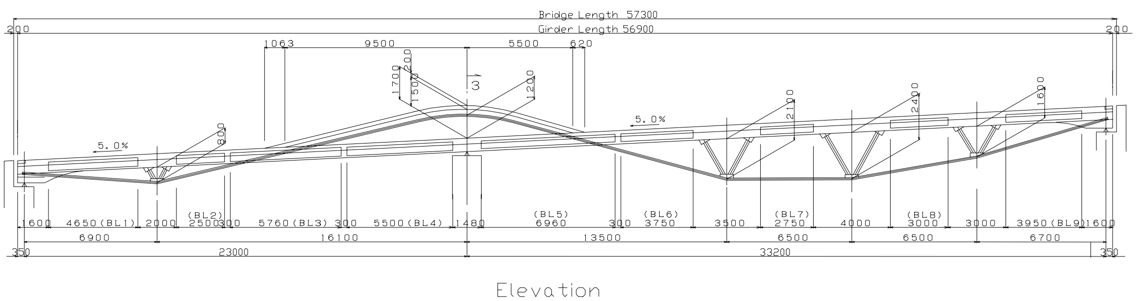


Figure 6. Layout diagram and dimension of the Boukei Bridge

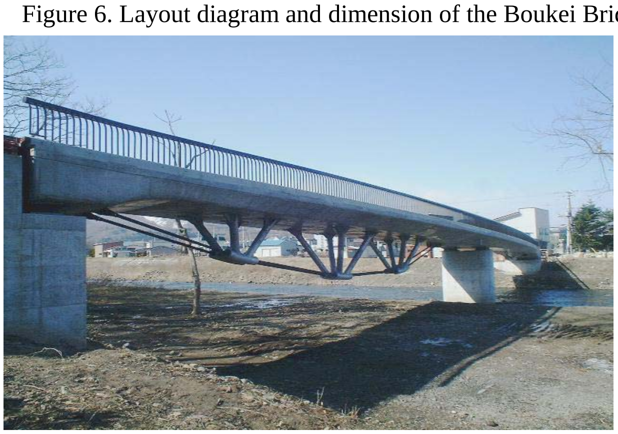


Figure 7. View of the completed Boukei Bridge

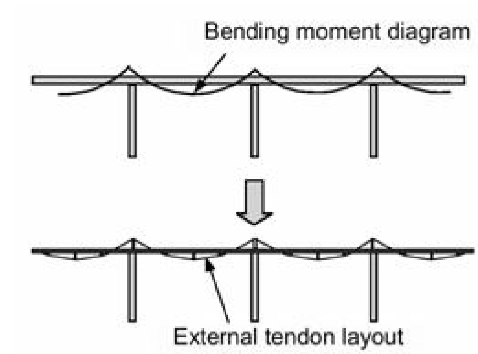


Figure 8. Schematic view of layout of external tendon

The characteristic of this innovative bridge is that the external tendon layout takes the similar shape of the bending moment diagram as shown in Figure 8. The structure was designed to form a pseudo truss, with the main girder made of concrete as compression chords, the external tendons as tension chords, and the steel deviators as diagonal members. This allowed the girder height to be reduced significantly, thus making the bridge lightweight. The external tendons are placed below the girder in the midspan region by means of steel struts, the function of which is similar to a truss. At the intermediate support region, it is placed above the bridge deck and covered with a fin-shaped concrete web member. The combination of the subtended tendons and the fin-shaped concrete web makes this bridge a unique one with aesthetically pleasing appearance.

Although having several advantages, PC bridges with highly eccentric external tendons should be carefully designed and constructed concerning the following important points. Since the main girder, struts and highly eccentric external tendons form a truss in this type of structure, construction precision of individual members has a significant influence on the structure. For this, it is necessary to give special consideration to the techniques and procedures for constructing the falsework, formwork and external tendons. Moreover, the vibration characteristics under service load may be of concern due to the smaller stiffness of the main girder caused by the reduction in girder height. Nevertheless, the authors believe that this new concept of prestressing would pave way to a wider use of external prestressing technology in the construction industry, leading to improved structural performance as well as cost effective PC bridges. The research is in progress regarding the possibility of applying these kind of structures to highway bridges using precast segmental construction.

2.2 *Extradosed PC Bridges*

An extradosed prestressing concept, which was first proposed by Mathivat in France [7], is a new type of structural system in which the tendons are installed outside and above the main girder and deviated by short towers located at supports. Considering its definition, this type of bridge is placed between cable-stayed bridges and ordinary girder bridges with internal or external tendons.

Extradosed PC bridges have several positive characteristics. The girder height may be lower than that of ordinary girder bridges, thus reducing self-weight of structures. As shown in Figure 9, the ratio of the girder height to the span length (H/L) in extradosed bridges ranges between 1/15 and 1/35, while it is approximately 1/15~1/17 for box-girder bridges. Comparing to cable-stayed bridges, the height of the main tower in extradosed bridges is lower; hence, a reduction in labor costs of construction can be achieved.

Because of a lower main tower in extradosed bridges, vertical loads are partly resisted by main girders and stress variations in stay cables produced by live loads are smaller than those in cable-stayed bridges. This is quite similar to the behavior of box-girder bridges, where the main girder itself has a decisive influence on the structure rigidity and live loads produce only limited stress variations in tendons. Based on these facts, the Japan Road Association [8] has recommended that the safety factor for the stayed cables in extradosed bridges under design loads shall be taken as 1.67 (0.6 fpu; fpu = tensile strength of tendons), which is same as that for tendons in ordinary girder bridges. For cable-stayed bridges, this value is specified to be 2.5 (0.4 fpu).

The major difference among box-girder, extradosed and cable-stayed bridges can be further revealed by comparing the relationship between materials used with span lengths. In box-girder bridges, the average concrete thickness increases with the span length, since the girder height is a function of the span length. On the other hand, in cable-stayed bridges, there is almost no increase in the average depth of concrete because the girder height is generally designed to be 2.0~2.5 m, regardless of the span length. It is interesting to note that extradosed bridges are placed between these two types, and the rate of increase is also thought to be midway between the rates of the other two types of bridges.

Similarly, with increasing span length, the quantity of prestressing tendons in box-girder bridges shows a more increase than that in cable-stayed bridges, whereas extradosed bridges yield the intermediate value between the other two types.

From the above discussion, it can be concluded that an extradosed bridge is similar in construction and appearance to a cable-stayed bridge. In the light of structural properties, however, an extradosed bridge is closed to ordinary PC girder bridges, and the design specifications may be considered to be the same for both types of bridges.

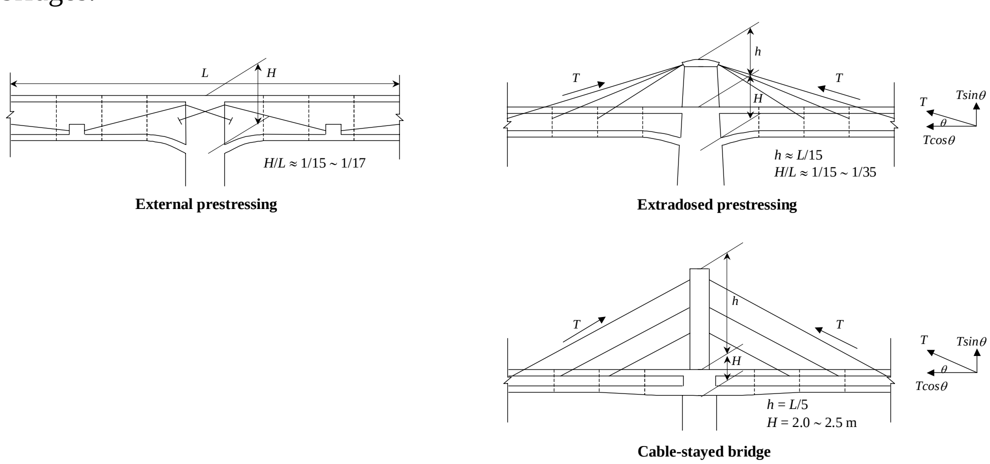


Figure 9. Comparison among externally box-girder, extradosed and cable-stayed PC bridges

2.3 *Difference between cable-stayed bridges and extradosed bridges*

The differences between cable-stayed bridges and extradosed bridges have being debated by numerous researchers. Both types of these bridges have structures that use stay cables as reinforcements. However, in case of extradosed bridges it is neccessary to provide a structural rationale rather than simply assuming an allowable stress of 0.6fpu in design of the bridges. In this point, attention focuses on the distribution ratio of vertical load carried by the girders and the stay cables. Figure 10 shows the relationship between the distribution ratio of vertical load (β) and maximum stress change of stay cable due to design live load ($\Delta\sigma_L$) of various cable-stayed bridges and extradosed bridges constructed in Japan. As shown in the figure, it is difficult to clearly distinguish between extradosed bridges and cable-stayed bridges in terms of structural mechanics since many of the cable-stayed bridges are very similar to extradosed bridges. In designing stay cables, stress change due to design live loads provides an effective index that can be easily determined through the design process.

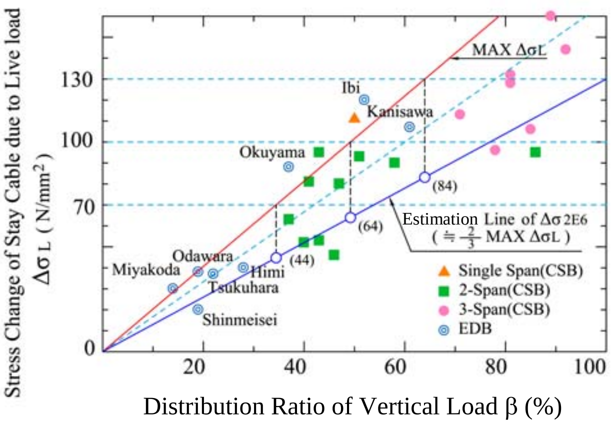


Figure 10. Distribution ratio of vertical load and stress change of stay cable

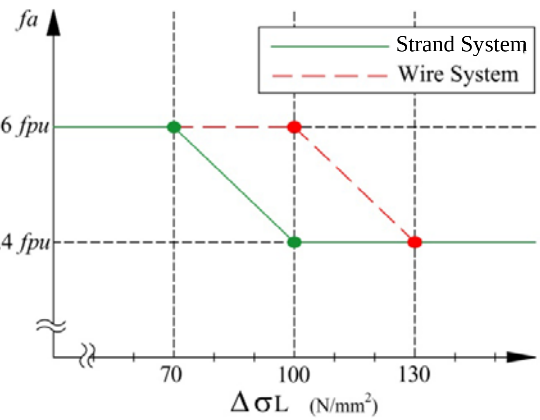


Figure 11. Allowable tensile stress and stress change of stay cable

2.4 *Approximated design method for stay cables*

The fatigue limit state is usually critical in the design of stay cables. When bridge structures reinforced by stay cables, the design of stay cables would be structural rationale by focusing on the stress change in the stay cables rather than defining whether bridges are cable-stayed or extradosed by assuming allowable stress for the stay cables. This would make it possible to design each stay cable separately and enable the allowable stress to be set individually for each stay cable. Unlike suspension bridges, the stress change in a cable-stayed bridge will differ depending on the stay cables and it is not rational to define the allowable stress using a single value of 0.4*fpu*. This is reflected in the "Specifications for Design and Construction of Cable-Stayed PC Bridges and Extradosed Bridges" [9]. The specification allows two kinds of design method. Method A is normal fatigue design using fatigue load and design lifetime of a bridge. However, it is usually difficult to estimate the amount of future traffic and heavy trucks, especially in local roads. In that case, method B using stress change in stay cables due to design vehicular live loads is introduced. Figure 11 shows the relationship between the allowable tensile stress of stay cable for highway bridges and the stress change due to live load $\Delta\sigma_L$ regulated in the specifications. The difference in fatigue strength between prefabricated wire type and strand type is considered. By using prior experience in Japan with cable-stayed, extradosed and similar bridges having spans of up to about 250 m, method B is defined so as to ensure adequate safety in comparison with bridges designed using method A.

Fatigue design was performed for the estimation line of stress range for two million cycles ($\Delta\sigma_{2E6}$) including secondary flexural bending due to girder deflection (determined according to design conditions on a design service life of 50 years and average daily traffic of 70,000 mixing 50% trucks) by using the structural models of the Odawara Blueway bridge, the Tsukuhara bridge, and the Ibi River bridge as shown in Figure 10. Based on the calculations the stress change due to fatigue load is about 1/3 of that due to design live loads and the stress level due to secondary flexural bending is the same as that due to axial forces of stay cables. It is noted that the estimation line of $\Delta\sigma_{2E6}$ is assumed to be 2(1/3)(Max$\Delta\sigma_L$). The safety margin of method B can be confirmed by comparing $\Delta\sigma_{2E6}$ with fatigue strength (f_{scrd}) divided by a safety factor (γ_b).

In the stay cables designed by method B, $\Delta\sigma_L$ is determined to require a safety factor of about 2.0 for $\Delta\sigma_{2E6}$ with respect to f_{scrd}/γ_b, in order to take into consideration the fact that the method includes more uncertainties than method A, and in order that the safety of stay cables does not vary greatly from that of cable-stayed and extradosed bridges constructed to date. In the most of extradosed bridges and some cable-stayed bridges, the tensile stress of 0.6*fpu* can be used because stress changes are low (20 to 50N/mm^2). Moreover the most rational point of this specification is that we can choose the tensile stress in each stay cable from 0.4*fpu* to 0.6*fpu* continuously. This is based on the concept that one value of tensile stress in one bridge is not structurally rational.

2.5 *Application of extradosed prestressing*

Nowadays, a great number of PC bridges using extradosed prestressing are being constructed in Japan. Attempts are also being made to apply this structural concept to other innovated technologies, such as corrugated steel web, precast segmental construction, and combined structures with steel girders.

Figure 12 shows the Odawara Blue-Way Bridge, which is the first extradosed PC box girder bridge in the world and was completed in 1994. This bridge was designed with a three-span continuous box-girder with extradosed prestressing, having a middle span length of 122 m, a tower height (h) of 10.5 m, and a girder height at supports (H) of 3.5 m. The ratios of h/L and H/L are approximately 1/12 and 1/35, respectively.

Figure 13 shows the prospective view of the Shin-Meisei bridge on Nagoya Expressway No. 3 crossing the class-1 Shonai River in western Nagoya. From both aesthetic and economic viewpoints, the bridge was designed with a three-span continuous rigid-frame structure with extradosed prestressing, which is to become a landmark of Nagoya's western threshold. The length of the middle span (L) is 122 m, a tower height (h) of 16.5 m, and a girder height at supports (H) of 3.5 m, giving the ratios of h/L and H/L of 1/7.4 and 1/35, respectively

Figure 12. Odawara Blue Way Bridge
(3-span continuous extradosed PC bridge)

Figure 13. Shin Meisei Bridge (prospective view)
(3-span continuous extradosed PC bridge)

2.6 *Corrugated steel web and its application to bridges*

In PC bridges with corrugated steel webs, light-weight corrugated steel plates are used instead of concrete webs. The corrugated steel plate webs are capable of withstanding shear forces without absorbing unwanted axial stresses due to prestressing, thus enabling efficient prestressing of top and bottom concrete deck slabs, thus resulting in an "accordion effect" (Figure 14). Moreover, the corrugated webs also provide high shear buckling resistance. Use of light-weight corrugated steel plates for webs causes a reduction of self weight of about 25% of main girders. Therefore, this enables the use of longer spans and reduction of construction cost. The weight of a segment to be cantilevered during erection can also be reduced, thus longer erection segments can be adopted and construction period can be shortened. This also eliminates assembly of reinforcement, cable arrangement and concrete placement for concrete webs. Thus, saving of construction manpower, quality enhancement and improvement of durability are expected. In addition, replacing the damaged deck slabs is easier than that in ordinary PC bridges.

Recently, the use of corrugated steel web has been applied to a variety of new constructions of PC bridges in Japan (Figure 15). In addition to the rigid or box girder bridges, the concept of corrugated steel web was also successfully adopted in the constructions of extradosed and cable-stayed PC bridges.

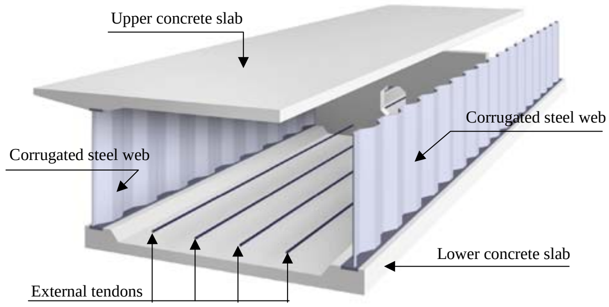


Figure 14. Typical section of PC bridge with corrugated web

Figure 15. Ginzanmiyuki Bridge with corrugated web using atmospheric corrosion resisting steel

3 APPLICATION OF INNOVATIVE TECHNOLOGIES IN PC BRIDGES

The state of art technologies described in this paper with regards to the structural system and construction materials have already been implemented in PC bridges in Japan. Some of the noteworthy structures, which represent the state-of-the-art technologies in the construction of PC bridges in Japan are presented here.

3.1 *Kiso and Ibi River Bridges*

The Kiso River and the Ibi River Bridges were constructed as a part of the New Meishin Expressway that will connect Nagoya and Kobe. The 1,145m long Kiso River Bridge (Figure 16) and the 1,379m long Ibi River Bridge (Figure 17) are located approximately 1,300m apart, crossing the two major rivers. The total width of both bridges is 33m, accommodating 6 traffic lanes. The center and the side spans are over 270 m and 150 m, respectively.

The extradosed PC bridge type and steel composite girders were selected to cope with such long spans, taking economy, construction time and workability into consideration. This is the most unique feature of these bridges, making them the world's first extradosed bridges with a composite structure. Steel girders were used in the central sections of approximately 100 m to reduce the weight of superstructure, while high-strength concrete girders were used for the remaining sections. Further reduction of the dead load is achieved by placing some of the tendons externally inside the box girder section, which makes thin webs possible.

The precast segment method is employed for the concrete sections of the girders. Each segment with weight of 300 to 400 ton is precast using high strength concrete of 60N/mm^2 by the short line match casting method in the fabrication yard located about 10 to 15 km away from the project sites. The segments for the main girders are transported to the sites by ship and placed into position by large temporary facilities, such as erection noses and erection trusses except the pier head tables, each of which was divided into three and installed by a 600 ton floating crane. The steel girder sections, which weigh about 2000 ton each, are fabricated in a factory and transported to the sites and then erected at one time by reaction girders attached to both ends of the concrete girders after completion of the concrete segments installation.

The construction of the Kiso and Ibi River Bridges has demonstrated that the concept of extradosed prestressing could be successfully applied to long-span bridges having composite structures. Based on the creation of standards and experience up to now, the extradosed PC bridges, streamlined in terms of both structural properties and economic considerations, will undoubtedly continue to develop in the future.

Figure 16. Kiso River Bridge

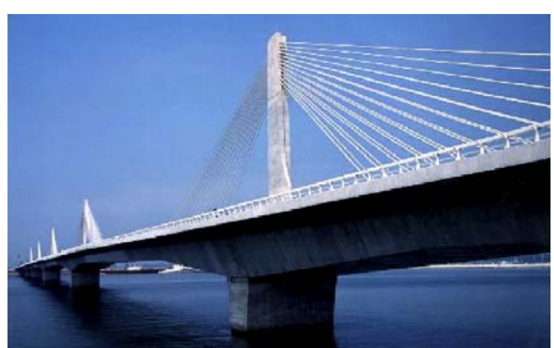


Figure 17. Ibi River Bridge

3.2 *Shibakawa Viaduct*

The Shibakawa Viaduct was constructed under the New Tomei Expressway project about 160 km west of Tokyo (Figure 18). The structure was designed as two separate bridges consisting of the inbound and outbound lines using continuous PC box-girder bridges with struts constructed by the cantilever method (Figure 19).
The main characteristic of the Shibakawa Viaduct is the use of inclined struts with box-girder bridges (Figure 19). In the Shibakawa Viaduct, which has high piers of over 80 m, the construction costs of piers and foundations are relatively large compared to the total construction costs. By adopting the inclined struts to support the cantilever slabs, the dead load of the superstructure was reduced to approximately 80% and the volume of concrete that was used for the bridge piers and foundations was reduced to approximately 50%, thus leading to a significant reduction in the total construction costs.

Figure 18. Shibakawa Viaduct
(Continuous PC box girder with inclined struts)

Figure 19. PC box girder with inclined struts

3.3 *Shiosai Bridge*

The Shiosai Bridge in Shizuoka, Japan, is a prestressed concrete four-span stress-ribbon bridge with roadway slab decks, which forms a so-called inverted suspension bridge as shown in Figure 20 [10]. The bridge, for cyclists and pedestrians, was completed in 1995. The superstructure consists of roadway slab decks, columns which support the slab decks, and stress ribbons forming the lower cord. The bridge length is 232 m, the clear width is 3.0 m, and the span lengths are 55, 61, 61 and 55 m.

In this structure, loads are transferred via the slab decks into the columns, which are supported by the stress ribbons that in turn are supported by the piers and abutments. Overall stiffness was increased using elastic connections with horizontal neoprene bearings, which were installed between the ends of the roadway slabs and the abutments. Most of the superstructures were precast using lightweight concrete, in order to minimize the horizontal forces acting on the abutments, thus making the structure more economical. To ensure corrosion protection, epoxy-coated prestressing strands were used for bearing cables and prestressing cables for the stress ribbon.

Figure 20. Shiosai Bridge (4-span continuous stress-ribbon PC bridge)

3.4 *Rittoh Bridge*

Rittoh Bridge located in the southern edge of Lake Biwa, about midway between Otsu Junction and Shigarai

Interchange on the New Meishin Expressway was constructed utilizing several innovative construction technologies. It is the first extradosed PC bridge with corrugated steel web whose main girder has a three-celled cross section, making it suitable for a bilaterally suspended structure with a wide roadway.

Figure. 21 Rittoh Bridge (Extradosed PC bridge with corrugated steel web)

The bridge consists of four-span and five-span continuous rigid-frame structure with total span length of 495m and 555m, respectively (Figure 21). Due to construction restrictions, the erection of supports at the side span portions was impossible. Hence, an innovative technology was used for the construction of side span closures by first installing a corrugated steel web as integrated steel girders, and then applying the load of the main deck concrete to the corrugated steel web girder. This construction method made it possible to construct side spans without the need for large-scale erection equipment, resulting in significant cost savings.

The most significant aspect of this bridge is the use of a composite structure for the cable anchorage. In this bridge steel diaphragm structure is used for the extradosed cable anchorage at the main girder instead of the conventional concrete diaphragm which significantly reduced the dead weight. The extradosed cables are directly attached to the steel diaphragm. The horizontal component of force from the extradosed cables is transmitted to the concrete behind the steel diaphragm, while the vertical component of force is transmitted directly to the steel diaphragm.

4 CONCLUSIONS

Recent techniques in design and construction of PC bridges in Japan were presented in this paper, with emphasis on their background and development as well as their applications in actual structures. Not only to improve the structural properties in terms of safety, aesthetic and economical aspects, such innovated technologies were developed to enhance the long-term durability, which is becoming one of the serious problems in concrete structures nowadays.

In light of new structural systems, external prestressing with highly eccentric tendons and extradosed prestressing are excellent examples of a wider use of external prestressing technology to achieve a PC bridge with improved structural performance as well as cost-effective outlook. The corrugated steel webs, which take advantages of steel and concrete, have proved to be one of promising solutions that can reduce the self-weight of main girders, thereby enabling the use of longer spans and reduction of construction cost.

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