DEVELOPMENT OF MODERN PRESTRESSED CONCRETE BRIDGES IN JAPAN

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ABSTRACT

Prestressed concrete (PC) is being used all over the world in the construction of bridge structures. In Japan, the application of PC was first introduced in the 1950s, and since then, the construction of PC bridges has grown dramatically. This is largely due to several advantages such as lower initial and life-cycle cost compared to steel bridges, and superior characteristics concerning economical and aesthetical aspects compared to reinforced concrete bridges. However, many PC bridges have been deteriorating even before their designed service-life due to corrosion and other environmental effects. Therefore, the durability has become a particular concern and should be seriously considered in the design and construction of PC bridges. In Japan, a number of innovative techniques have been developed to enhance both the structural performance and the durability of PC bridges. These include the development of new materials such as pre-grouted internal tendon, high-strength concrete and structural systems such as external prestressing, highly eccentric external tendons, extradosed prestressing and corrugated steel web. This paper presents an overview of such innovated technologies of PC bridges including a brief detail of their development and background as well as their applications in the actual construction projects.

KEYWORDS: prestressed concrete, external prestressing, extradosed prestressing

1. INTRODUCTION

For more than half a century prestressed concrete (PC) is one of the most important construction materials in not only Japan but also all over the world particularly in the field of bridge construction. 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. In Japan, the first PC bridge, Tyousei Bridge, was built in 1951 and since then, the construction of PC bridges has grown dramatically (Figure 1). However, deterioration of bridges is becoming a big social issue since many bridges are getting older over 50 years.

In recent years, many PC bridges have been deteriorating even before their designed service-life due to corrosive circumstances, alkali-silica reactions, and other environmental effects. Hence, the durability has become a particular concern and should be seriously considered in the design and construction of PC bridges apart from structural safety, aesthetical appearance and economical viewpoint. In Japan, a number of innovative techniques have been developed to enhance not only the structural performance but also the durability of PC bridges. These include the development of novel structural system and the advance in new construction materials. This paper presents an overview of such innovated technologies of PC bridges including a brief detail of their development and background as well as their applications in the actual construction projects.

2. DEVELOPMENT OF INNOVATIVE MATERIALS FOR PC BRIDGES

In Japan, most of PC bridges were constructed using internally post-tensioning tendons with grouting in sheaths. Recently, however, problems regarding grouting condition have been of much concern because the insufficient grout of internal tendons was found in some existing PC bridges (Mutsuyoshi 2001). Many researches have been carried out recently for the development of new materials to enhance the performance and long-term durability of the PC bridges. In this section, application of pre-grouted internal tendons and high-strength concrete are explained with brief overview on their applications in actual PC bridge projects.

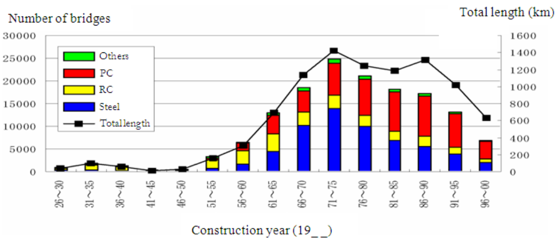

Figure 1 Trend of construction of different types of bridges in Japan

2.1 Pre-grouted prestressing tendon

Pre-grouted prestressing tendon was first developed in Japan in 1987. It is made by coating a prestressing strand with unhardened epoxy resin and a polyethylene protective tube (Figure 2) and is embedded directly into concrete with the polyethylene protective tube as a tendon for post-tensioning. Time of hardening is set for the epoxy resin filled in the polyethylene protective sheath so that post-tensioning process can be completed before hardening or the epoxy resin. The resin has viscosity like grease before hardening, and it naturally hardens with certain time after the completion of tensioning of prestressing steel and bonds with concrete to form an integrated member. As the grout is injected into the polyethylene sheath, complete grouting is ensured in this technique. Furthermore, construction work can be saved as neither in-situ insertion of prestressing tendonds nor grouting process is required. Sheath and epoxy resin also provide double layer corrosion proection to the prestressing tendons. This technique also ensures stronger bond with concrete than conventional cement grouting technique. Moreover, smaller diameter of sheath makes concrete placement relatively easier and provide higher efficiency in prestressing can be achieved as polyethylene sheath and unhardened resin reduce the friction during prestressing.

Pre-grouted prestressing tendon, primarily in the form of single strands, was generally applied to transverse prestressing of deck slabs or other work. Application to main tendons has just started in view of the above benefits (see Figure 3). When pre-grouted prestressing strands are used for main tendon, more prestressing strands are required than when conventional multiple strands are used. Numerous prestressing strands therefore should be anchored in a limited anchorage region. Hence, attention should be paid in design for the arrangement of pre-grouted prestressing tendons and details of anchorage.

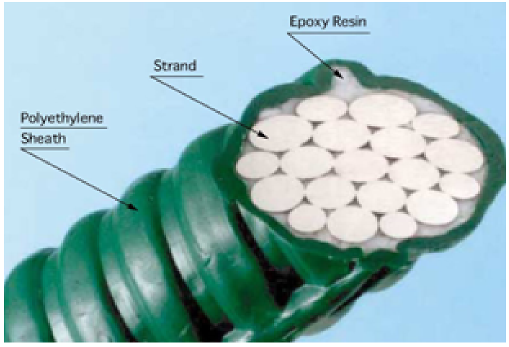

Figure 2 Pre-grouted prestressing tendon

Figure 3 Use of pre-grouted prestressing strand for main tendons

2.2 High-strength concrete

High-strength concrete (HSC) has become common in building construction in recent years as it enables the use of smaller cross-sections, longer spans, reduction in girder height and enhanced durability. In addition to this application, there are a few instances of HSC being applied to PC structures (Figure 4) (Mutsuyoshi et al. 2010). The chief advantage of using HSC is the possibility of achieving higher prestressing force compared to the normal concrete which will lead to smaller cross-section and reduction in the overall weight of the structure. Hence, the use of HSC has a good potential in the construction of large structures.

The lower water/binder ratio in HSC may, however, cause the increase in autogenous shrinkage which will lead to decrease in effective prestressing force and cracking due to restraining caused by the reinforcing steel. Conventional method of reducing autogenous-shrinkage-strain is to use expansion-producing admixture and shrinkage-reducing agents. However, these materials are expensive. This problem has been overcome by the development of new type of artificial light weight aggregate called as "J-Lite" (Figure 5). J-lite is made from environment-friendly coal ash and is twice as strong as conventional light weight aggregate. Low shrinkage ultra HSC termed as "Power Crete" with compressive strength as high as 120 MPa, has been developed with the use of J-lite together with expansion-producing admixtures and shrinkage reducing agents. As strength development in low-shrinkage HSC is independent of the curing condition, it can be used for cast-in-place applications as well.

Figure 4 AKIBA pedestrian bridge constructed with HSC (f'_c = 120 MPa) in Akihabara

Figure 5 J-lite

3. DEVELOPMENT OF MODERN 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 6). 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), has actively adopted the concept of fully external tendons for box girder bridges (Figure 6) 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 (Mutsuyoshi 2001). For the better performance of the externally prestressed concrete bridges, various new technologies have recently been developed in Japan.

3.1 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 (Virlogeux 1988). 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 7). 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 (Mutsuyoshi 2000).

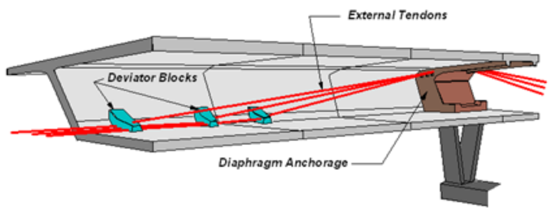

Figure 6 Typical layout of an external PC box girder bridge

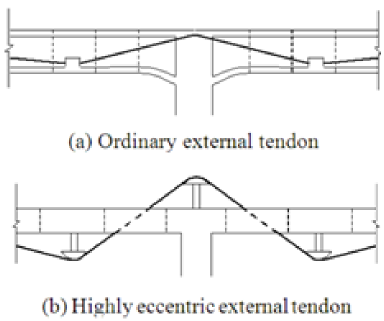

Figure 7 Ordinary vs. highly eccentric external tendon

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 (Aravinthan et al. 1999, Witchukreangkrai et al. 2000). From the test results of single-span beams, 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 8). This gives the designer to take advantage of arranging the external tendon layout freely, depending on the site conditions.

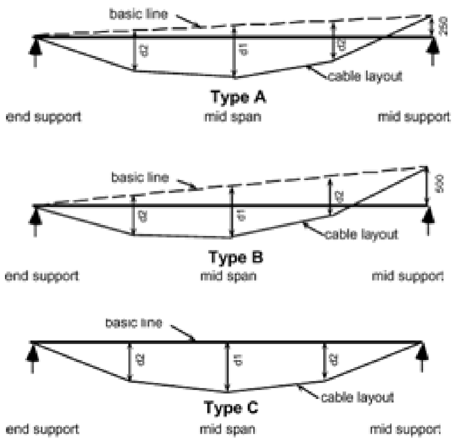

Figure 8 Linear transformation of tendon layout

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 9. 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 10.

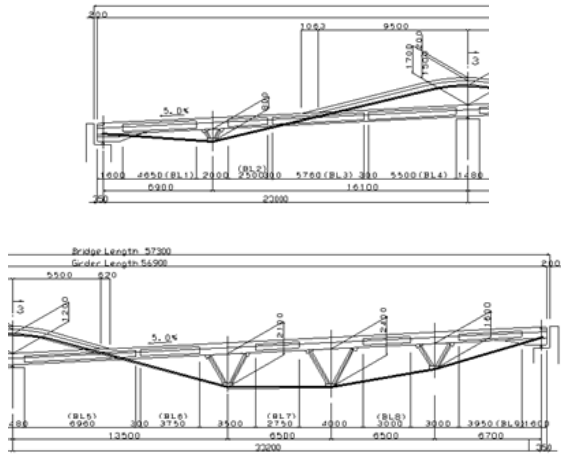

Figure 9 Layout diagram and dimension of the Boukei Bridge

Figure 10 Completed view of the Boukei Bridge

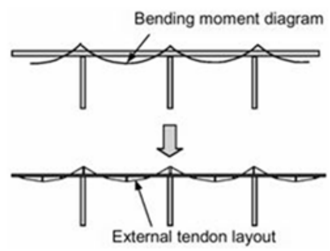

Figure 11 Schematic view of layout of external tendon

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 11. 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.

3.2 Extradosed PC bridges

An extradosed prestressing concept, which was first proposed by Mathivat in France (Mathivat 1988), 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 12, 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 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) (Japan Road Association 2002).

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.

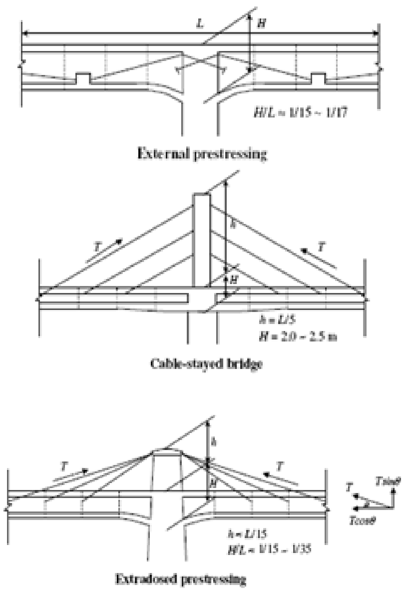

Figure 12 Comparison among externally box-girder, extradosed and cable-stayed PC bridges

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.

In case of extradosed bridges it is neccessary to provide an 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 13 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.

3.3 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" (Japan Prestressed Concrete Engineering Association 2009). 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 14 shows the relationship between the allowable tensile stress (*fa*) 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 13. 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).

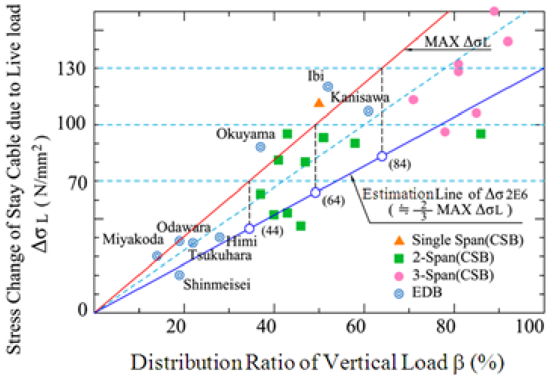

Figure 13 Distribution ratio of vertical load and stress change of stay cable

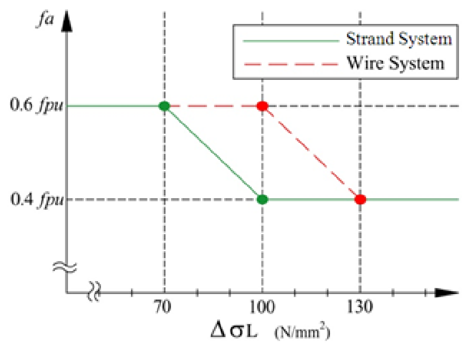

Figure 14 Allowable tensile stress and stress change of stay cable

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.

Figure 15 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 16 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 15 Odawara Blue Way bridge

Figure 16 Shin Meisei bridge (prospective view)

3.4 Corrugated steel web 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 17). 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 18). 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.

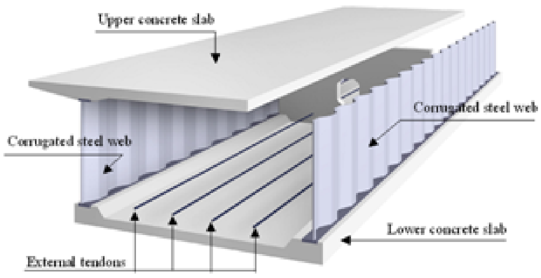

Figure 17 Typical section of PC bridge with corrugated steel web

Figure 18 Ginzanmiyuki bridge with corrugated steel web

Rittoh Bridge located in the southern edge of Lake Biwa, 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. The bridge consists of four-span and five-span continuous rigid-frame structure with total span length of 495m and 555m, respectively (Figure 19).

Figure 19 Rittoh Bridge (Extradosed PC bridge with corrugated steel web)

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.

Considering the development of new construction materials, the application of pre-grouted internal tendons and use of low-shrinkage HSC were discussed. 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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