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DESIGN METHOD FOR RENEWAL FROM REINFORCED CONCRETE SLAB TO PRECAST PRESTRESSED CONCRETE SLAB

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ABSTRACT

In Japan, expressway bridges are aging and deteriorating because of increases in traffic volume and loading, harsh environments and other factors. Therefore, a renewal plan for bridges was drafted to address this issue in 2015. The main works include replacing reinforced concrete (RC) slabs of steel girder bridges with precast prestressed concrete (PC) slabs. In renewal plan for RC slab, if the severe deterioration occurs in the RC slab, that will be renewed to high durability precast PC slab. In the design of the new PC slab, the structure and material is determined in consideration of the degradation factors of the old RC slab. The new PC slab is necessary to have sufficient durability against the environmental action during design service life and to have sufficient safety against automobile load. In this paper, the design method and structure of the new PC slab are described.

Keywords: Reinforced concrete, precast concrete, prestressed concrete

INTRODUCTION

More than fifty years have passed since the first roadway opened for service in Japan's network of inter-city expressways managed by expressway companies, which now stretches out to more than 9,000 km. The bridges on these expressways are aging and deteriorating because of increases in traffic volume and loading, harsh environments and other factors. To address this, expressway companies in Japan drafted a new renewal plan for expressway bridges that will conduct large-scale renewal, reinforcement and repair that will enable the continuous and sustainable use of expressways into the future. In this paper, outline of this renewal plan and design method of precast PC slab for renewal are described.

DETERIORATIONS OF EXPRESSWAY BRIDGES IN JAPAN

Inspections of expressway bridges revealed that the main factors causing deterioration were fatigue, chloride attack (chloride ions penetration), alkali-silica reaction and their combined effects. From among 19,608 expressway bridges, the deterioration factors based on the judgment index shown in Table 1 applied to 8,404 bridges. This implies that fully 43% of bridges have deteriorated due to causes described in Table 1(Sakai et al. 2016).

Table 1. Deterioration Mechanism, Judgment Index

Deterioration mechanism	Estimation item	Judgment index	Number of bridges
Fatigue	Cumulative no. of 10-ton equivalent axles for large vehicle traffic*	30 million axles or more**	3,270
Chloride attack (Antifreezing agent)	Cumulative amount of antifreezing agent	1,000 t/km or more	4,862
Chloride attack (Airborne salt)	Distance from coast	Specifications for Highway Bridges Part III Class II or higher	392
Chloride attack (Salt in concrete)	Inherent salinity	Use of beach sand + Pre-chloride content limit	924
Alkali-silica reaction	Cracking condition	Appearance of cracks indicative of ASR	452
Composite deterioration	—	Multiple deterioration mechanisms present	1,496

* The max allowable axle load in Japanese expressway bridges is 10 tons.

** According to the inspection results, the deterioration for fatigue is increasing at about 30 million axles or more in Japanese expressway bridges.

OVERVIEW OF THE NEW RENEWAL PLAN

A new renewal plan was drafted based on the state of deterioration and the factors causing these deteriorations as shown in the previous section. The plan was designed to implement the measures shown in Table 2 (Sakai et al. 2016). The cost required for this plan was estimated to be 2,170 billion yen (about US$20 billion), and the schedule of works will take around 15 years to implement. In this paper, the renewal of RC floor slabs of steel girder bridges will be discussed.

Table 2. Overview of the New Renewal Plan

Measures classification	Structure	Method	Length (km)	Estimated project cost
Renewal	Floor Slab	Replacement	224	1,650 billion yen
	Girder	Replacement	13	100 billion yen
	Subtotal		237	1,750 billion yen
Reinforcement and Repair	Floor Slab	High performance waterproof, etc.	359	160 billion yen
	Girder	Reinforcement, etc.	151	260 billion yen
	Subtotal		510	420 billion yen
Total			747	2,170 billion yen

DETERIORATION OF THE RC FLOOR SLAB

Inspections of existing bridges revealed that the main factors causing deterioration of the RC slabs of steel girder bridges are fatigue from vehicle traffic through the bridge, and chloride attack due to antifreezing agents and airborne salt (Sakai et al. 2014). Degradation due to chloride attack is shown in Figures 1 and 2. Fatigue of the RC slab is accelerated by corrosion of the rebar (Maeshima et al. 2014).

Figure 1. Corrosion of Rebar and Spalling of Concrete on the Upper Surface of Slab

Figure 2. Corrosion of Rebar and Spalling of Concrete on the Lower Surface of Slab

RENEWAL PLAN FOR RC FLOOR SLAB OF STEEL GIRDER BRIDGES

The renewal plan for RC floor slab of steel girder bridges is a program to replace current RC floor slabs, depicted in Figure 3, with new ones when abnormalities in the floor slab due to fatigue, chloride attack and other factors have advanced to a stage where its structural performance falls below the required performance for expressway bridge slabs.

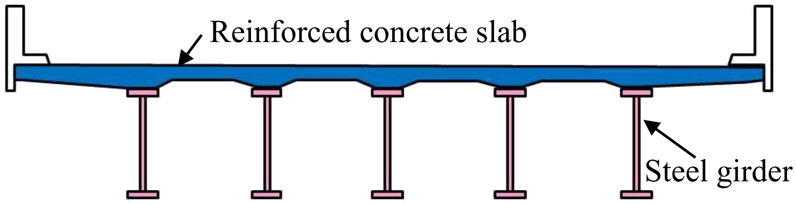


Figure 3. Cross Section of Steel Girder Bridge with RC Floor Slab

DESIGN METHOD FOR RENEWAL SLAB

Design Policy.
The slab for use in the renewal will be designed based on the policy stated below. The renewal slab will use precast PC slab since, according to previous research, it is safer against fatigue and has higher durability against chloride attack and carbonation compared to present RC slabs and can be constructed easily. When designing the renewal slab, the causes and state of degradation in the target structure will be investigated and the performance requirements will be set based on the investigation. The renewal slab materials and structure will be set such that its performance during its design service life does not fall below the performance requirements because of degradation. The objective of design service life of the renewal slab is set to 100 years, because design service life of the new expressway bridges is set to 100 years in Japan. When selecting materials and structures for the renewal slab, new technology and construction methods will be actively adopted and efforts will be made to reduce costs and shorten the construction period. The design procedure for renewal PC slab is shown in Figure 2.
The main factors causing deterioration of the RC deck slabs are fatigue and chloride attack. As for fatigue, it is confirmed by the moving load fatigue test that fatigue failure will not occur during the design service life, if it has a deck slab thickness of a certain value (20cm) or more.

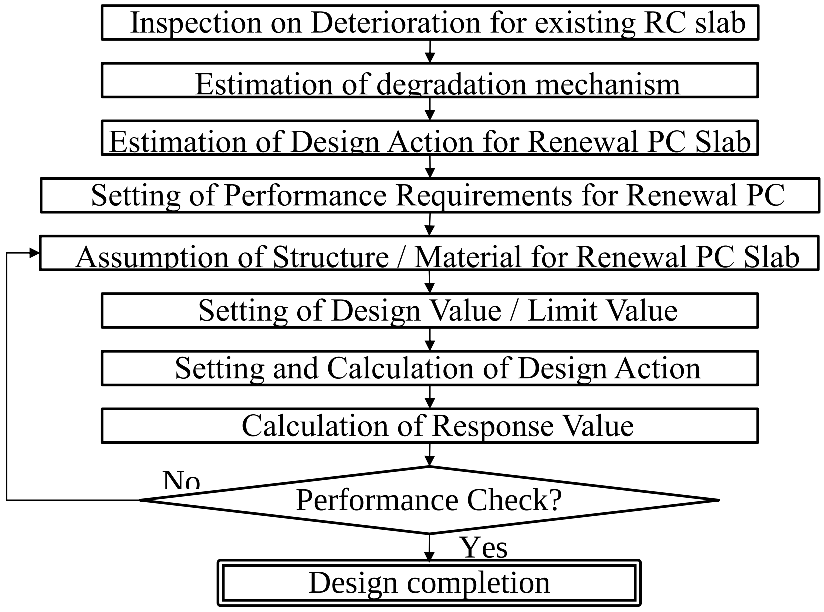
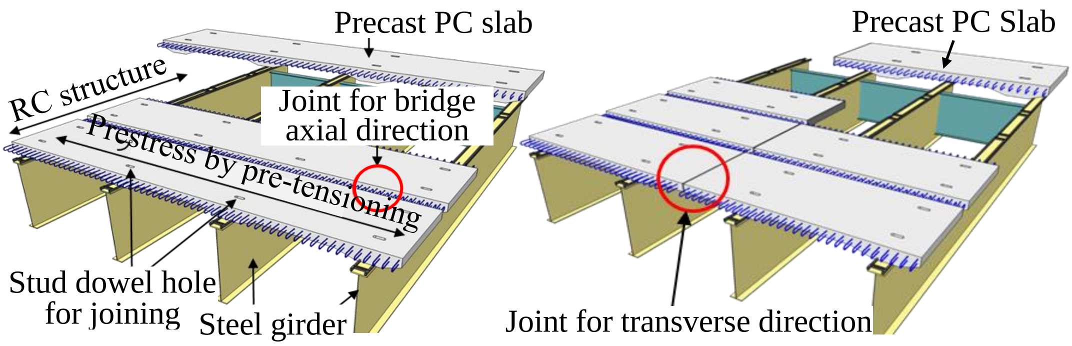


Figure 2. Examination Procedure for Renewal PC Slab

Structure of Precast PC Slab

The precast PC slab for use in the renewal will be fabricated at the shop or onsite yard with prestressing forces introduced through a pre-tensioning system and will be transported to the bridge site by trailer trucks or similar means for erection. The slab will normally be segmented into a width (of about 2 to 2.5 m in general) in the longitudinal direction of the bridge that is transportable by trailer trucks or similar means. Further segmentation in the bridge transverse direction may also be done when the bridge roadway is wide or when road traffic control during construction calls for it. In general, joints between slabs will be built in-situ as RC structures using loop rebar joint. A standard structure of the precast PC slab and joints between slabs using loop rebar joint is shown in Figures 3 to 5.



(a) Full Width Replacement of Slab (b) Half Width Replacement of Slab

Figure 3. Standard Structure of Precast PC Slab

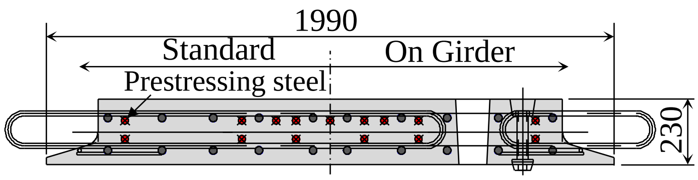


Figure 4. Cross Section of Precast PC Slab

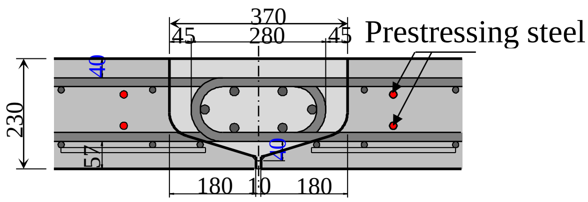


Figure 5. Cross Section of Joints

The joining of the steel girder and the deck slab is done by welding the stud dowel to the steel girder, afterwards in order of shrinkage-compensating mortar, shrinkage-compensating concrete, and polymer-cement mortar as shown Figure 6.

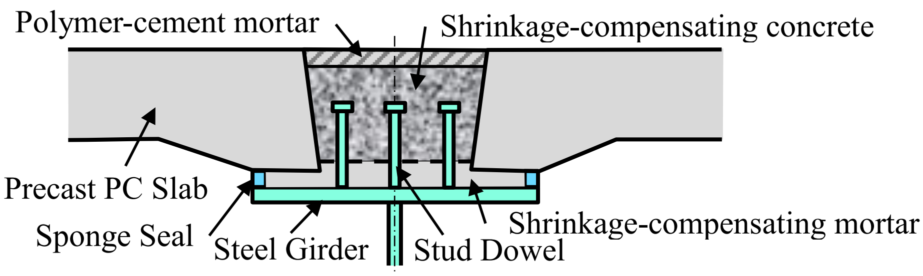


Figure 6. Joining of the Steel Girder and the Deck Slab

Allowable Stresses in Serviceability Limit State

In order to prevent corrosion of steel due to the occurrence of cracks, the stresses of concrete at the bridge transverse direction in the serviceability limit state is set to not less than the design bending tensile stress. Regarding slabs of the longitudinal direction of the bridge in the serviceability limit state, cracks are occurred because the RC structure is the standard. Therefore, it is necessary to set the chloride ion concentration at location of steel to the steel material corrosion occurrence limit concentration or less. As other methods, corrosion protection of steel materials, or PC structure must be adopted.

Design Method for Chloride Attack

Among the main factors of deterioration of the slab, chloride attack is the most significant factor. In order to prevent corrosion of reinforcing bars and prestressing steel due to chloride attack during design service life, chloride ion concentration at the location of steel needs to be kept below a certain value. The chloride ion concentration at the location of steel is calculated by the solution to a diffusion equation of chloride ion in the concrete based on the Fick's second law. This equation is shown in Equation 1 (JSCE 2017).

$$C_d = \gamma_{cl} \cdot C_0 \left\{ 1 - erf\left(\frac{0.1 \cdot c_d}{2\sqrt{D_d \cdot t}} \right) \right\} + C_i \quad (1)$$

where C_d = design value of chloride ion concentration at location of steel (kg/m^3); γ_{cl} = factor of safety that takes variability of C_d into consideration; C_0 = chloride ion concentration at concrete surface (kg/m^3); c_d = expected value of concrete cover (mm); D_d = design diffusion coefficient of chloride ion (cm^3/year); t = service life against intrusion of chloride ions (year); C_i = Initial chloride ion concentration (kg/m^3).

On the basis of C_d calculated by Eq. 1, corrosion of steel caused by chloride ions intrusion is checked by Equation 2 (JSCE 2017).

$$\gamma_i \frac{C_d}{C_{lim}} \leq 1.0 \quad (2)$$

where C_{lim} = limit value of concentration of steel material corrosion occurrence; γ_i = factor of safety that takes importance of structures, and social impact into consideration.

In general, γ_{cl} is adopted 1.3, and γ_i is adopted 1.0. Since the design standard strength of renewal PC slab concrete is 50 MPa in general, C_{lim} is adopted 1.8 to 2.3 kg/m^3. C_0 is determined by investigating the chloride ion concentration acting on the existing RC slab. For past investigation cases in Japan, chloride ion concentration exceeding 10 kg/m^3 are measured in areas where antifreezing agent (NaCl) are to be used in winter as shown in the Table 3 (Sakai et al. 2017). D_d needs to set the value of concrete for renewal PC slab from test and past test cases.

Table 3. Example of Chloride Ion Concentration at RC Floor Slab Surface

Item		Investigation section*			
		Section A	Section B	Section C	Section D
One year's antifreezing agent spraying amount**(t/km)		23.1	11.6	17.8	15.8
C_0 *** (kg/m^3)	Mean value	0.86	0.89	0.78	1.85
	Standard deviation	0.67	0.7	0.82	2.03
	Maximum value	5.25	6.87	7.20	16.36

* The investigation sections are RC floor slabs of the area to be sprayed with

antifreezing agent in winter, with a service period of about 40 years.
**Spraying amount per 1 km of road length.
*** Chloride ion concentration at concrete surface. About 200 bridges data on expressway 4 routes.

Materials of Precast PC Slab

The RC slabs targeted for renewal are members which require replacement because of degradation from fatigue, chloride attack, alkali-silica reaction and other factors. Thus, the precast PC slabs for use in replacing them will have to be designed so that degradation similar to those found in the existing slabs will not occur. In particular, when designing renewal precast PC slabs subject to the environment and which may degrade from chloride attack, suitable materials should be used to ensure their durability. Material selection is to be conducted using the policy stated below. The examination procedure for chloride attack is shown in Figure 7.

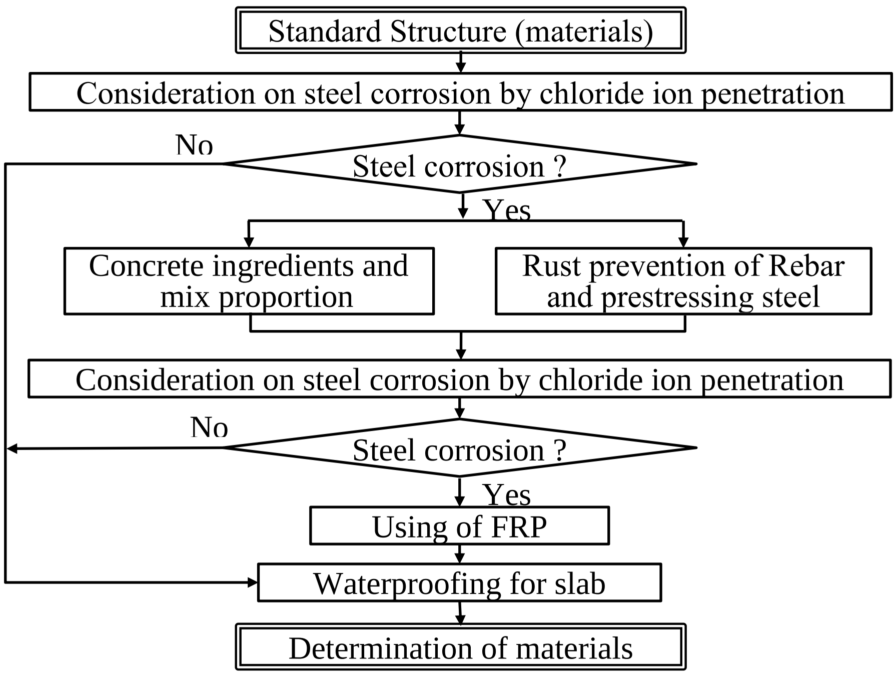


Figure 7. Examination Procedure for Chloride Attack

When selecting concrete ingredients and mix proportion, measures will be taken to reduce chloride ion diffusion coefficient in the concrete. Examples of such measures include lowering the water-cement ratio or using admixture that can reduce the diffusion coefficient. Possible admixtures include ground granulated blast-furnace slag (Sakai et al. 2002) and fly ash (Nakamura et al. 2014). In the past cases, 50% of the amount of high-early-strength portland cement was replaced with ground granulated blast-furnace slag (Sakai et al. 2017), and 15% was replaced with fly ash.
In the past study, the specimen using admixture was immersed in an aqueous solution with a sodium chloride concentration of 10% for 20 months. The tests were carried out

on specimens using high-early-strength portland cement at 40% water-binder ratio, specimens with 50% of cement replaced with ground granulated blast-furnace slag, and specimens with 20% of cement replaced with fly ash. Figure 8 shows the values of diffusion coefficient of chloride ion calculated using Equation 3 based on the chloride ion concentration obtained from the test results (PWRI 2016). As shown in Figure 8, when the ground granulated blast-furnace slag or the fly ash is used as the admixture, the chloride ion concentration at location of steel can be greatly reduced.

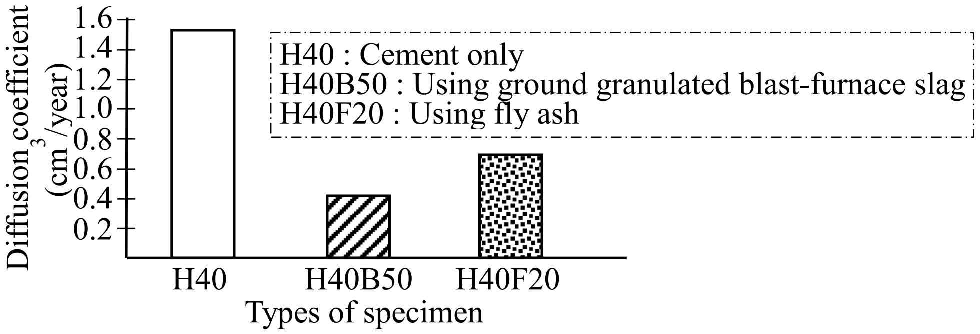


Figure 8. Diffusion Coefficient of Chloride Ion by Tests

$$C(x,t) = C_0\left\{1 - erf\left(\frac{0.1 \cdot x}{2\sqrt{D_{ap} \cdot t}}\right)\right\} + C_i \quad (3)$$

where x = distance from the surface of specimen (mm); t = test period (year); $C(x,t)$ = chloride ion concentration at distance x, test period t (kg/m^3); C_0 = chloride ion concentration at concrete surface (kg/m^3); C_i = Initial chloride ion concentration (kg/m^3); D_{ap} = apparent diffusion coefficient of chloride ion (cm^3/year).

When steel contained in the concrete (rebars and prestressing tendons) can potentially corrode even after implementing the measures given in the previous paragraph, the use of epoxy-coated (Tanaka et al. 2006) or stainless steel rebars (Shinoda et al. 2007) and FRP (Fiber Reinforced Polymer) reinforcements will be considered. Similarly, the use of epoxy-coated or stainless steel tendons and FRP tendons will be considered. As the FRP, CFRP (Carbon Fiber Reinforced Polymers) and AFRP (Aramid Fiber Reinforced Polymers) are contemplated. For the design and construction of precast PC slabs using FRP, reference should be made to the existing criteria (JSCE 1996).

CONCLUSIONS

In this study, the design method of replacing the RC deck slab of the steel girder bridge with the precast PC deck slab was described. This renewal plan is a program to implement measures that extend the design service life of target bridges to roughly 100 years. Therefore, when implementing these measures, identifying the causes of abnormalities in the target bridges and performing their design and construction such that the same abnormalities do not develop afterward is utmost importance.

The main factors causing deterioration of the RC deck slabs are fatigue and chloride attack. As for fatigue, it is confirmed by the moving load fatigue test that fatigue failure will not occur during the design service life, if it has a deck slab thickness of a certain value or more. For chloride attack, rational examination becomes possible by using the design method shown in this study. Therefore, in environmental action where high chloride ion is supplied, it is necessary to take measures such as the use of admixture capable of lowering the diffusion coefficient of chloride ion and adoption of FRP.

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