Research Article

Modified PCI Multipliers for Time-Dependent Deformation of PSC Bridges

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Nowadays prestressed concrete (PSC) bridges have become very common, but there are still many difficulties in predicting their long-term behavior. In order to predict the long-term behavior of PSC bridges, it is possible to use very complex formulas developed by various researchers or numerical analysis through computer, but many engineers are having difficulty in using such methods. Moreover, the accuracy of the prediction result is not satisfactory compared to the effort. On the contrary, the PCI Bridge Design Manual proposes a method that can easily predict the long-term behavior using multipliers. However, this method does not take into account various construction schedules and has some assumptions that are inadequate for the current situation in various girder sections and topping thicknesses. Therefore, in this study, new long-time factors were developed by modifying the multipliers of the PCI Bridge Design Manual by a rational manner. This allows prediction of long-term behavior of bridges taking into account various construction schedules and the characteristics of modern girder sections. The prediction results of the long-term camber and deflection of PSC bridges using the proposed multipliers were compared with those using the basic PCI Bridge Design Manual, the improved PCI Bridge Design Manual, KR C-08090 (same as ACI 318-14), and numerical analysis. As a result, the newly proposed method makes possible to predict the long-term behavior at any time after casting, and the accuracy of the prediction is also improved.

1. Introduction

Recently, the application of prestressed concrete (PSC) bridges has been increasing due to the development of high-strength concrete, the improvement of strength and quality of prestressing (PS) steel, and the development of structural analysis technology using computer program. The long-term behavior of these PSC bridges is very important because it directly affects the serviceability and safety of the bridge. In the case of high-speed railway, for example, very small deflection of the railway caused by the long-term deformation of the bridge can cause serious problems on the running ability and safety of train. Therefore, it is necessary to accurately predict the time-dependent deformation in the design and construction stages and even use stage of the bridge. However, it is very difficult to accurately calculate time-dependent deformation of PSC bridges. The calculations should take into account creep and shrinkage as well as load-induced

deformation, which can cause significant deformation over the years. Especially, unlike nonprestressed members, for prestressed members, prestress forces and prestress losses must be considered. In addition, when combined with nonprestressed members, the prediction of long-term behavior becomes more difficult.

Korea's railway design guidelines and handbooks (KR C-08090) provides a factor, λ , applied to initial deflection for estimating the additional long-term deflection of nonprestressed reinforced concrete members as shown in the following equation:

$$\lambda = \frac{\xi}{1 + 50\rho'}, \quad (1)$$

where ρ' is the ratio of compressive reinforcement and ξ is the time-dependent factor for sustained loads to be equal to 2.0 for 5 years or more, 1.4 for 12 months, 1.2 for 6 months, and 1.0 for 3 months.

TABLE 1: PCI Bridge Design Manual basic multipliers [18].

	Without composite topping	With composite topping
<i>At erection</i>		
(1) Deflection (downward) component—apply to the elastic deflection due to the member weight at transfer of prestress	1.85	1.85
(2) Camber (upward) component—apply to the elastic camber due to prestress at the time of transfer of prestress	1.80	1.80
<i>Final</i>		
(3) Deflection (downward) component—apply to the elastic deflection due to the member weight at transfer of prestress	2.70	2.40
(4) Camber (upward) component—apply to the elastic camber due to prestress at the time of transfer of prestress	2.45	2.20
(5) Deflection (downward)—apply to elastic deflection due to superimposed dead load only	3.00	3.00
(6) Deflection (downward)—apply to elastic deflection caused by the composite topping	—	2.30

It should be noted that (1) of KR C-08090 [1] actually comes from the equation presented by ACI 318-14 [2]. The ACI 318 code [2] is primarily for building applications, not for bridges. Moreover, both KR C-08090 [1] and ACI 318-14 [2] do not provide specific design guideline such as prediction equations for long-term behavior of PSC members. The ACI 318-14 [2] merely suggests an abstract guideline that additional time-dependent deflections of PSC members can be calculated by considering the stresses of concrete and steel bars under sustained load, the creep and shrinkage effects of concrete, and the relaxation of PS steels.

Alternatively, the long-term deflection of PSC bridges can be calculated by using the concrete creep coefficient and drying shrinkage formulas given in various standards [3–5]. However, such formulas are somewhat complicated to use in practice because they need to take into consideration various parameters including concrete mix proportion and surrounding environment. They also do not fully account for the effects and losses of the prestress. Moreover, even through these complex methods, there is no guarantee of highly accurate predictions.

Until recently, many researchers have proposed various methods to predict the long-term behavior of PSC bridges [6–11]. However, the reliability of such predictions has not been sufficiently verified, and these methods are difficult and complicated for designers to understand and use. In addition, due to recent advances in computer technology, many researchers are trying to predict and evaluate the long-term behavior of PSC bridges by numerical analysis using the finite difference method or finite element method [12–17], but for designers, a simple and clear prediction method is more preferable.

On the contrary, the PCI Bridge Design Manual [18] presents multipliers that can be easily used to predict long-term deformation of PSC bridges. However, in the PCI Bridge Design Manual [18], the multipliers can be applied only to two points of time, erection and final. In practice, the timing of the girder construction of PSC bridges can vary greatly depending on the site conditions, and the long-term

deflection should be checked out at any important time in addition to the time of erection and final depending on various construction plans and processes. Furthermore, since the PCI Bridge Design Manual [18] multipliers are based on the 1977 Martin's study [19], it is difficult to say that they properly reflect the characteristics of various cross sections of modern PSC bridges.

Therefore, in this study, modified PCI multipliers for long-term deflection of PSC bridges considering various construction schedules and cross sections of modern PSC bridges were proposed so that the time-dependent deformation of PSC bridges can be more easily and accurately predicted.

2. PCI Bridge Design Manual Basic Multipliers

Table 1 shows the basic multipliers presented in the PCI Bridge Design Manual [18] for predicting long-term cambers and deflections of PSC members. Derivation of these multipliers is in [19].

In (1), for the nonprestressed concrete, the base factor for additional long-term deflection, μ_b , is 2.0 in the absence of compressive reinforcement. For PSC members, however, since the elastic deflection due to member weight at the release of the prestress, not at the standard age of 28 days, is multiplied by the long-time factor, the factor should be calculated considering the elastic modulus E_{ci} at the time of release, not the elastic modulus E_c at 28 days, as follows:

$$\mu_{df} = \frac{E_{ci}}{E_c} \mu_b. \quad (2)$$

Since E_{ci} is about 85% of E_c and μ_b is 2.0, (2) would then become $\mu_{df} = 1.7$. As shown in Table 1, therefore, the multiplier for deflection at final is $1 + \mu_{df} = 2.7$.

In the PCI Bridge Design Manual [18], it is assumed that the period from casting to erection is about 30–60 days, and in this period, creep and drying shrinkage, which are the main factors of the long-term behavior, will have reached about 40 to 60% of the ultimate value. Using the average

TABLE 2: PCI Bridge Design Manual improved multipliers [20].

Load condition	Erection time		Final time	
	Formula	Average	Formula	Average
Initial prestress	$1 + C_a$	1.96	$1 + C_u$	2.88
Prestress loss	$\alpha_a (1 + \chi C_a)$	1.00	$(1 + \chi C_u)$	2.32
Self-weight	$1 + C_a$	1.96	$1 + C_u$	2.88
Dead load on plain beam	1.00	1.00	$1 + C_u'$	2.50
Dead load on composite beam	1.00	1.00	$1 + C_u'$	2.50

C_u = ultimate creep coefficient for loads applied immediately after transfer, and the average value is 1.88. C_u' = ultimate creep coefficient for loads applied at time of erection, and the average value is 1.50. C_a = creep coefficient for loading applied immediately after transfer and strains measured at time of erection, and the average value is 0.96. α_a = time-dependent prestress loss at erection divided by total time-dependent prestress loss, and the average value is 0.60. χ = Bazant's aging coefficient, and the average value is 0.70.

value of 50%, therefore, the long-term deflection coefficient at erection is presented as the following equation:

$$1 + \mu_{de} = 1 + 0.5\mu_{df}. \quad (3)$$

The multiplier for deflection at erection would then be $1 + 0.5(1.7) = 1.85$.

In deriving the multiplier for the camber in the PCI Bridge Design Manual [18], the prestress loss is taken into account. That is, the method of obtaining the long-term camber by multiplying the long-time factor by the elastic camber at the release of the prestress is the same as (2), but considering the prestress loss, which is a phenomenon in which the prestress as a sustained load decreases over time. The long-term prestress loss is assumed to be 15% of the initial force. Therefore, using μ_{df} in (2), factor for final long-time camber can be expressed as follows:

$$\mu_{pf} = \mu_{df} \frac{P}{P_0}. \quad (4)$$

Therefore, the multiplier used to determine the camber due to prestress is $1 + \mu_{pf} = 1 + 1.7(0.85) = 2.45$.

The multiplier for the camber due to prestress at the time of erection is derived in the same way as (3) is derived. The long-term loss of prestress is governed by long-term behavior factors such as creep and shrinkage of concrete. So, if these long-term behavior factors occur 50% of ultimate at erection, prestress loss will also result in one-half of the long-time total loss 15%. Applying this to (4), the multiplier for the camber caused by the prestress at the time of erection can be calculated as follows:

$$1 + \mu_{pe} = 1 + \mu_{de} (1 - 0.15 \times 0.50). \quad (5)$$

Therefore, the multiplier applied to the initial upward camber caused by prestressing force is equal to be $1 + \mu_{pe} = 1 + 0.85(0.925) \approx 1.80$.

Since the long-term deflection due to the superimposed sustained dead load depends on the creep, the multiplier is expressed by the following equation using the basic factor $\mu_b = 2.0$:

$$1 + \mu_{sdf} = 1 + 2.0 = 3.0. \quad (6)$$

In addition, the PCI Bridge Design Manual [18] provides multipliers for composite members by taking into account the effect of increased moment of inertia due to topping. As shown in the following equations, the effect of topping on

the deflection and camber is taken into account by multiplying the difference between long-time factors at erection and final by the ratio of noncomposite to composite moments of inertia, I_o/I_c :

$$\mu_{dfc} = \mu_{de} + (\mu_{df} - \mu_{de}) \left(\frac{I_o}{I_c} \right), \quad (7)$$

$$\mu_{pfc} = \mu_{pe} + (\mu_{pf} - \mu_{pe}) \left(\frac{I_o}{I_c} \right). \quad (8)$$

Here the PCI Bridge Design Manual [18] assumes that the section becomes composite at about the time of erection. The thickness of the topping is assumed to be 2 inches, and the value of I_o/I_c is assumed to be 0.65 for commonly used members. Therefore, if these values are substituted in (7 and 8), the multiplier for deflection and camber of the composite member with topping is 2.40 and 2.20, respectively, as shown in Table 1.

3. PCI Bridge Design Manual Improved Multipliers

As shown in Table 2, the PCI Bridge Design Manual, 2nd Edition [20], suggested an improved multiplier method proposed by Tadros et al. [21]. This method is very similar to the basic multiplier method described in the preceding section. According to the manual, however, this method provides two improvements. First, it provides more accurate coefficients for cases where the reliable creep coefficient is known or high-performance concrete with a very low creep coefficient is used. Second, the prediction of the deflection caused by the prestress loss can be calculated by considering the amount of prestress loss actually occurred. However, it is not easy to know the correct creep coefficient and the actual prestress loss at the design stage. Moreover, there are many variables that must be calculated separately to derive the multiplier, which is somewhat inconvenient for designers to use. However, since the average value is presented, it can be used effectively. It is noted that the improved multiplier method has been deleted in the current PCI Bridge Design Manual, 3rd Edition [18].

4. Development of Proposed Multipliers

4.1. Modification of PCI Multipliers for Prediction at Any Time. As mentioned earlier, the PCI Bridge Design Manual [18] provides multipliers only for at the time of erection and final.

FIGURE 1: Rate of creep and drying shrinkage over time.

Moreover, it is assumed that the erection time is about 30–60 days after casting. In practice, however, the time of erection is very flexible depending on the site conditions. Therefore, in this study, the multipliers applicable at any time including the various time of erection were suggested by considering the rate of creep and drying shrinkage. It can be useful for field construction management and maintenance of structures, if the camber or deflection can be predicted at any time after casting.

Equations (3) and (5) were modified using r_t , the rate of creep, and drying shrinkage over time:

$$1 + \mu_{dt} = 1 + r_t \times \mu_{df}, \quad (9)$$

$$1 + \mu_{pt} = 1 + \mu_{dt} (1 - 0.15 \times r_t), \quad (10)$$

where t is the time after casting and μ_{dt} and μ_{pt} are the factors for time-dependent deflection and camber at the time of t applied to initial deformation caused by member weight and prestressing force, respectively. μ_{df} is 1.7 as in the PCI Bridge Design Manual [18]. If the time of the erection is $t(e)$, the multiplier for the deflection and camber at erection can be expressed by substituting $t(e)$ in (9) and (10) as follows:

$$\begin{aligned} 1 + \mu_{dt(e)} &= 1 + r_{t(e)} \times \mu_{df}, \\ 1 + \mu_{pt(e)} &= 1 + \mu_{dt(e)} (1 - 0.15 \times r_{t(e)}). \end{aligned} \quad (11)$$

Also, the multiplier for the long-term deflection due to the superimposed dead load at any time can be expressed by the following equation:

$$1 + \mu_{sdt} = 1 + r_{[t-t(s)]} \times \mu_{sdf}, \quad (12)$$

where μ_{sdt} is the factor for additional long-time deflection at time, t , applied to initial deflection caused by superimposed dead load and $t(s)$ is the time at which the superimposed

dead load is applied. μ_{sdf} is 2.0 as in the PCI Bridge Design Manual [18].

The creep and drying shrinkage predictions presented in ACI 209R-92 [3] were used to calculate the rate of creep and shrinkage over time, r_t . For creep and shrinkage under standard condition, the relationship between at any time and at final is given by (13) and (14), respectively.

$$v_t = \frac{t^{0.6}}{10 + t^{0.6}} v_u, \quad (13)$$

$$(\epsilon_{sh})_t = \frac{t}{35 + t} (\epsilon_{sh})_u, \quad (14)$$

where t = time in days, v_t = creep coefficient at any time, v_u = ultimate creep coefficient, $(\epsilon_{sh})_t$ = shrinkage strain at any time, and $(\epsilon_{sh})_u$ = ultimate shrinkage strain.

Long-term behavior is both affected by creep and drying shrinkage at the same time. Therefore, r_t , the rate of creep and drying shrinkage over time, were derived from the average of (13) and (14) as shown in (15). Figure 1 shows the graphs of creep and drying shrinkage rates over time.

$$r_t = \frac{1}{2} \left(\frac{t^{0.6}}{10 + t^{0.6}} + \frac{t}{35 + t} \right). \quad (15)$$

4.2. Modification of Multipliers for Composite Member. As mentioned earlier, in the PCI Bridge Design Manual [18], for the composite member, the thickness of the topping is assumed to be 2 inches, and the ratio of noncomposite to composite moments of inertia, I_o/I_c , is 0.65 for all cases regardless of the shape of cross section. However, given the variety of girder geometry and the recent bridge slab deck

FIGURE 2: Typical cross sections of PSC bridges. (a) I girder; (b) box girder; (c) WPC girder.

TABLE 3: Cross section dimension of I, box, and WPC girders by span (mm).

Type	I girder			Box girder			WPC girder		
Span	25 m	30 m	35 m	30 m	35 m	40 m	30 m	35 m	40 m
a	1000	1000	1000	1200	1200	1200	3580	3580	2650
b	400	400	400	220	220	220	150	150	150
c	200	200	200	50	50	50	100	100	100
d	80	150	150	660	660	660	982	1135	1514
e	90	120	120	2000	2400	2600	116	115	86
f	1520	1550	1950	1900	2300	2500	350	500	450
g	240	180	180	30	30	30	98	113	151
h	320	200	200	70	70	70	1181	1150	865
i	2350	2200	2600	400	350	350	730	730	370
j	240	350	350	50	50	50	110	110	110
k	200	200	200	1080	1530	1730	145	175	205
l	680	900	900	220	220	220	1610	1550	1280
m	—	—	—	250	250	250	1700	2000	2300
n	—	—	—	30	30	30	1450	1750	2050
o	—	—	—	220	220	220	135	135	135
p	—	—	—	760	760	760	115	115	115
q	—	—	—	1260	1260	1260	480	480	120
r	—	—	—	—	—	—	250	250	250

thickness, the assumptions for composite members in the PCI Bridge Design Manual [18] are not likely to reflect modern bridge characteristics. Therefore, in this study, the multipliers for the long-term behavior of composite member were proposed by analyzing the representative cross sections of the recent bridges.

Currently, girder sections commonly used in single-span railway bridges in Korea are I girder, box girder, and WPC (wide flange prestressed concrete). In general, a thickness of slab placed on the girder is 280 mm. Figure 2 and Table 3 show the details of the cross sections of I girder, box girder, and WPC, which are the representative girder sections actually used in practice. Table 4 shows I_o/I_c for all cross

sections of Figure 2 and Table 3. As shown in Table 4, the value of I_o/I_c is different from 0.65 of the PCI Bridge Design Manual [18]. I_o/I_c was in the range of 0.51 to 0.56, and box girder bridges and long span bridges tend to have relatively large I_o/I_c . For the convenience of design, this study proposed to use the total average value of 0.53 for I_o/I_c .

The PCI Bridge Design Manual [18] assumed that the section becomes composite at about the time of erection, but it is not always. Rather, there are many cases where topping is not applied when the girder is erected because of field condition and construction schedules. Therefore, multipliers have been proposed to enable the prediction of deflection and camber of the composite member at any time t by considering the time, $t(c)$, at which the section becomes composite. This can be expressed as follows using (7)–(10):

$$1 + \mu_{dtc} = 1 + \mu_{dt(c)} + (\mu_{dt} - \mu_{dt(c)}) \left(\frac{I_o}{I_c} \right), \quad (16)$$

$$1 + \mu_{ptc} = 1 + \mu_{pt(c)} + (\mu_{pt} - \mu_{pt(c)}) \left(\frac{I_o}{I_c} \right),$$

where I_o/I_c is 0.53.

The factor for long-term deflection by a composite topping should be also modified by the ratio of I_o/I_c because the elastic deflection caused by the placement of the topping, to which the factor is applied, is calculated using the non-composite section as follows

$$1 + \mu_{tt} = 1 + \mu_{sd} \left(\frac{I_o}{I_c} \right), \quad (17)$$

where μ_{tt} is the factor for additional long-term deflection caused by topping at any time, t .

As a result, the multipliers of the PCI Bridge Design Manual [18] in Table 1 were revised as shown in Table 5.

TABLE 4: Ratio of noncomposite to composite moments of inertia by girder type and span.

Span	PCI Bridge Design Manual	I girder	Box girder	WPC girder	Average
25 m		0.51	—	—	0.51
30 m		0.49	0.54	0.53	0.52
35 m	0.65	0.52	0.56	0.50	0.53
40 m		—	0.57	0.54	0.56
Average	0.65	0.51	0.56	0.52	0.53

TABLE 5: Proposed multipliers.

	Without topping	With topping
<i>At erection</i>		
(1) Deflection (downward) component—apply to the elastic deflection due to the member weight at transfer of prestress	$1 + 1.7r_{t(e)}$	$1 + 1.7r_{t(e)}$
(2) Camber (upward) component—apply to the elastic camber due to prestress at the time of transfer of prestress	$1 + 1.7r_{t(e)}(1 - 0.15r_{t(e)})$	$1 + 1.7r_{t(e)}(1 - 0.15r_{t(e)})$
<i>At certain time</i>		
(3) Deflection (downward) component—apply to the elastic deflection due to the member weight at transfer of prestress	$1 + 1.7r_t$	$1 + 0.8r_{t(c)} + 0.9r_t$
(4) Camber (upward) component—apply to the elastic camber due to prestress at the time of transfer of prestress	$1 + 1.7r_t(1 - 0.15r_t)$	$1 + 0.8r_{t(c)}(1 - 0.15r_{t(c)}) + 0.9r_t(1 - 0.15 \times r_t)$
(5) Deflection (downward)—apply to elastic deflection due to superimposed dead load only	$1 + 2.0r_{[t-t(s)]}$	$1 + 2.0r_{[t-t(s)]}$
(6) Deflection (downward)—apply to elastic deflection caused by the composite topping	—	$1 + 1.06r_{[t-t(c)]}$
<i>Final</i>		
(7) Deflection (downward) component—apply to the elastic deflection due to the member weight at transfer of prestress	2.70	$1.9 + 0.8r_{t(c)}$
(8) Camber (upward) component—apply to the elastic camber due to prestress at the time of transfer of prestress	2.45	$1.765 + 0.8r_{t(c)}(1 - 0.15r_{t(c)})$
(9) Deflection (downward)—apply to elastic deflection due to superimposed dead load only	3.00	3.00
(10) Deflection (downward)—apply to elastic deflection caused by the composite topping	—	2.06

5. Verification of Proposed Multipliers

In order to verify the proposed multipliers, for actually constructed PSC bridges, the predictions of long-term camber and deflection by the proposed multipliers were compared with those by the basic PCI multipliers [18], the improved PCI multipliers [20], and KR C-08090 [1] (same as ACI 318-14 [2]). In addition, numerical analysis was performed, and the results were compared with the results from other prediction methods.

5.1. PSC Bridges for Verification. PSC bridges A and B, which were recently constructed on a new line from Wonju to Gangneung in Korea's high-speed railway, were selected to verify the prediction methods. Bridge A is a WPC type with a span of 38.8 m, and bridge B is constructed with an I-girder type with a span of 34 m. The cross-sectional details of the bridges at midspan are shown in Figure 3. Tables 6 and 7

show the construction history of the bridges and the elastic deformation due to the applied load, respectively.

5.2. Numerical Analysis for Long-Term Behavior of PSC Bridges. Long-term behavior of the bridges A and B was predicted using MIDAS Civil, a general-purpose finite element analysis program. The validity of the MIDAS Civil has already been confirmed through previous researches [22–24]. In general, the prediction of long-term behavior using a finite element analysis is known to have a higher accuracy than that of the methods using a multiplier such as the PCI Bridge Design Manual [18, 20], although the design convenience is poor [25–28]. Therefore, the numerical analysis results were used to verify the newly proposed multipliers.

The material model was selected from the database of the MIDAS Civil program. C40 and C27 were selected for the girder and deck concrete, respectively, and the strand of SWPC7B Ø15.2 mm was selected for PS steel. These

FIGURE 3: Cross-sectional details of bridges (a) A and (b) B.

materials are the same as concrete and PS steel actually used for bridges A and B. The structural members of the bridges were modeled based on structural calculations and design drawings of bridges A and B. According to the design drawing, the strands were arranged by setting the actual coordinates of the strand on the girder nodes using the 3-D input type from tendon profile option of MIDAS Civil. The CEB-FIP MC90 model [5] was used to calculate creep and drying shrinkage of concrete. For the relaxation of the tendon, the Magura 45 model was used to consider the time-dependent loss of the prestress. Based on the construction history of the bridges A and B in Table 6, construction sequence analysis was carried out. After the cast of deck, composite behavior of the girder and the deck was simulated through the node connection using the rigid type of elastic link. In the same way, common duct which is the additional superimposed dead load was also simulated for composite behavior after its installation. At the final stage, the deformation patterns of bridges A and B are shown in Figure 4. As a result, the bridges A and B in the midspan showed 32.4 mm and 39.3 mm of camber at girder erection and 29.7 mm and 19.2 mm of camber at final, respectively.

5.3. Comparison of Predictions of Long-Term Deformation.

Tables 8 and 9 and Figure 5 show the predictions of the long-term deformation of bridges A and B by using the proposed multipliers, the basic PCI multipliers [18], the improved PCI multipliers [20], KR C-08090 [1], and numerical analysis. For the improved PCI multipliers [20], the average values in Table 2 were used because the actual creep coefficient and the amount of the prestress loss can hardly be known.

Although the values of predictions by the proposed multipliers and KR C-08090 [1] were somewhat different

TABLE 6: Construction history of bridges A and B.

Event	Time from casting (days)	
	Bridge A	Bridge B
(1) Release	1	1
(2) Erection ($t(e)$)	30	150
(3) Topping ($t(c)$)	240	157
(4) 1st random time (t_1)	270	180
(5) Superimposed dead load ($t(s)$)	390	360
(6) 2nd random time (t_2)	700	1000
(7) Final	5 years or more	5 years or more

TABLE 7: Elastic camber and deflection of bridges A and B.

Load	Camber (+) or deflection (-)	
	Bridge A	Bridge B
Self-weight	-22.3	-16.5
Prestressing force	+46.1	+35.3
Topping	-8.0	-7.5
Superimposed dead load	-2.5	-2.65

from the prediction by numerical analysis, their prediction trends of the camber over time were generally similar because they provided available multipliers at any time. In the case of the basic PCI multipliers [18], however, the long-term behavior after the erection was quite different from other prediction methods because there are no applicable long-term factors for the period between the erection and the final.

The girder of bridge A was erected on the 30th day after casting, while the girder of bridge B was erected on the 150th day, relatively long time after casting. The basic PCI

FIGURE 4: Analysis result of final deformation of bridges (a) A and (b) B.

multiplier method [18] calculated the long-term camber using the same multiplier for both bridges regardless of the different erection time, while the new proposed method used different long-term multipliers for the bridges A and B in order to consider different creep and shrinkage rates. As a result, the predictions at erection by the proposed method were smaller for bridge A and larger for bridge B than those by the basic PCI multiplier method [18], as shown in Figure 5.

In terms of the long-term behavior after erection, the camber predicted by KR C-08090 [1] was generally the largest among all prediction methods. KR C-08090 [1] does not take into account prestress loss, so it overestimates the camber by prestress force. The predictions by the proposed method were larger than the predictions by numerical analysis until about 200 days after superimposed dead load was applied, and thereafter, they were smaller than the predictions by numerical analysis.

When comparing the camber at final, the predictions were large in the order of KR C-08090 [1], numerical analysis, proposed method, improved PCI multipliers [20], and basic PCI multipliers [18] for both bridges A and B. Numerical analysis seems to estimate the effect of creep and

shrinkage on long-term deformation weaker than other methods. In comparison with numerical analysis for deformation at the final, difference rates of the proposed method, basic PCI multipliers [18], improved PCI multipliers [20], and KR C-08090 [1] were 10.1%, 25.9%, 11.6%, and 34.3% for bridge A, respectively, and 14.6%, 33.1%, 14.3%, and 35.0% for bridge B, respectively. It is interesting to note that the proposed formula and the improved PCI multiplier method [20] show very similar prediction results of ultimate deformation at final.

Figure 6 shows the long-term behavior predicted by the proposed multipliers for each load type. In early ages, a relatively large amount of camber was observed due to the prestress, but as time went by, the rate of increase of camber by prestress decreased sharply because the amount of creep and drying shrinkage converged and the PS steel relaxation increased. The amount of deflection due to self-weight was smaller than the camber due to the prestress, but the tendency of deflection over time was very similar to that of camber. On the contrary, after the girder erection, a considerable amount of immediate deflection and long-term deflection due to dead loads such as topping and common duct partially offset the camber.

TABLE 8: Predictions by various methods for bridge A (unit: mm).

Method	Load	(1) Release	(2) Erection $t(e)$	(3) Topping $t(c)$	(4) 1st random time $(t1)$	Multiplier	(5) Superimposed dead load $(t(s))$	(6) 2nd random time $(t2)$	Multiplier	(7) Final
Proposed multipliers	Self-weight	-22.30	1.76	2.36	-52.65	2.37	-53.64	-54.53	2.45	-56.65
	Prestress	46.10	1.71	2.20	101.30	2.21	102.84	104.20	2.33	107.34
	Topping				-8.00	1.48	-14.27	-15.33	2.06	-16.48
	Superimposed dead load						-2.50	-6.64	3.00	-7.50
	Total	23.80	39.57	40.66	37.00		32.43	27.71		26.71
PCI Bridge Design Manual (BDM)	Self-weight	-22.30	1.85	-41.26	-41.26		-41.26		2.40	-53.52
	Prestress	46.10	1.80	82.98	82.98		82.98		2.20	101.42
	Topping			-8.00	-8.00		-8.00		2.30	-18.40
	Superimposed dead load						-2.50		3.00	-7.50
	Total	23.80	41.73	33.73			31.23			22.00
Improved PCI BDM	Self-weight	-22.30	1.96	-43.71	-43.71		-43.71		2.88	-64.22
	Prestress	46.10	1.96	90.36	90.36		90.36		2.88	132.77
	Prestress loss	-6.92	1.00	-6.92	-6.92		-6.92		2.32	-16.04
	Topping			-8.00	-8.00		-8.00		2.50	-20.00
	Superimposed dead load						-2.50		2.50	-6.25
	Total	23.80	39.73	31.73			29.23			26.25
KR C-08090	Self-weight	-22.30	1.50	2.27	-50.62	2.30	-54.64	-59.10	3.00	-66.90
	Prestress	46.10	1.50	2.27	104.65	2.30	112.95	122.17	3.00	138.30
	Topping			-8.00	-8.00	1.50	-17.20	-20.00	3.00	-24.00
	Superimposed dead load						-2.50	-5.88	3.00	-7.50
	Total	23.80	35.70	46.03	42.74		38.61	37.20		39.90
Numerical analysis	Total	23.48	32.37	34.46	32.40		29.88	28.94		29.70

TABLE 9: Predictions by various methods for bridge B (unit: mm).

Method	Load	(1) Release	(2) Erection $t(e)$	(3) Topping $t(c)$	Multiplier	(4) 1st random time (t_1)	Multiplier	(5) Superimposed dead load ($t(s)$)	Multiplier	(6) 2nd random time (t_2)	Multiplier	(7) Final
Proposed multipliers	Self-weight	-16.50	2.26	2.27	-37.44	2.29	-37.71	2.36	2.42	-39.94	2.50	-41.20
	Prestress	35.30	2.12	2.13	75.08	2.14	75.53	2.19	2.24	79.09	2.30	81.02
	Topping			-7.50	-7.50	1.42	-10.65	1.83	1.96	-14.70	2.06	-15.45
	Superimposed dead load							-2.65	2.78	-7.36	3.00	-7.95
	Total	18.80	37.52	30.14		27.17		22.18		17.10		16.42
PCI Bridge Design Manual (BDM)	Self-weight	-16.50	1.85	-30.53	-30.53			-30.53			2.40	-39.60
	Prestress	35.30	1.80	63.54	63.54			63.54			2.20	77.66
	Topping			-7.50	-7.50			-7.50			2.30	-17.25
	Superimposed dead load							-2.65			3.00	-7.95
	Total	18.80	33.02	25.52				22.87				12.86
Improved PCI BDM	Self-weight	-16.50	1.96	-32.34	-32.34			-32.34			2.88	-47.52
	Prestress	35.30	1.96	69.19	69.19			69.19			2.88	101.66
	Prestress loss	-5.30	1.00	-5.30	-5.30			-5.30			2.32	-12.28
	Topping			-7.50	-7.50			-7.50			2.50	-18.75
	Superimposed dead load							-2.65			2.50	-6.63
	Total	18.80	31.55	24.05				21.40				16.48
KR C-08090	Self-weight	-16.50	2.10	2.11	-34.82	2.20	-36.30	2.40	2.80	-46.20	3.00	-49.50
	Prestress	35.30	2.10	2.11	74.48	2.20	77.66	2.40	2.80	98.84	3.00	105.90
	Topping			-7.50	-7.50	1.50	-11.25	2.20	2.75	-20.63	3.00	-22.50
	Superimposed dead load							-2.65	2.65	-7.02	3.00	-7.95
	Total	18.80	39.48	32.17		30.11		25.97		24.99		25.95
Numerical analysis	Total	17.92	39.26	28.66		25.36		21.38		19.54		19.23

FIGURE 5: Comparison of various predictions for bridges (a) A and (b) B.

FIGURE 6: Predictions by the proposed multipliers for each load type. (a) Bridge A. (b) Bridge B.

Consequently, the proposed multipliers method provided not only the closest prediction values but also the most similar long-term behavior trend to the numerical analysis.

6. Conclusions

Since the current PCI Bridge Design Manual [18] provides the long-term deformation multipliers only at erection and final, it cannot consider various construction processes. Furthermore, the multipliers for the composite cross section are also required to be modified to reflect the characteristics of the cross section used in modern PSC bridges. Therefore, in this study, new modified PCI multipliers were proposed to overcome these problems. The conclusions drawn from this study are as follows:

- (1) The new modified PCI multipliers were proposed by using the rate of creep and shrinkage over time. Unlike the existing PCI Bridge Design Manual [18] method, it is possible to reflect the actual girder erection time and predict the long-term deformation for any construction schedule. Moreover, through the new method, camber and deflection of PSC bridges can be predicted at any time including design stage, construction stage, and use stage.
- (2) The ratio of noncomposite to composite moments of inertia, I_o/I_c , was 0.51–0.56 as a result of analyzing representative cross sections used in practice by span, while the PCI Bridge Design Manual [18] suggests 0.65 of I_o/I_c . Therefore, it is suggested to use the average value of 0.53 for I_o/I_c in order to predict the long-term behavior of composite members.

- (3) In order to verify the proposed multipliers, for actually constructed PSC bridges, the predictions of long-term camber and deflection by the proposed multipliers were compared with those by the basic PCI multipliers [18], improved PCI multipliers [20], KR C-08090 [1], and numerical analysis. As a result, KR C-08090 [1] predictions were significantly higher than the other predictions, and the basic PCI multipliers [18] did not show a reasonable tendency in the long-term behavior between the erection time and the final. Among all methods except the proposed method, the improved PCI multipliers [20] showed the most similar predictions to the numerical analysis. However, this improved PCI multiplier method also has limitations in finding the long-term deflection or camber of the bridge at any time, and there are several variables such as the creep coefficient that must be known precisely, in order to use the multipliers, which is inconvenient for designers to use. However, the predictions through the newly proposed multipliers showed a reasonable long-term behavior trend, and the amount of the final camber was also the most similar to the numerical analysis result. Above all, the proposed method can make it possible for the designer to predict the long-term behavior of the bridge very easily according to any construction schedule.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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