A Realistic Method to Reduce Stresses of Pier due to Time-Dependent Effects

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Summary

The short piers of bridge which is constructed by cantilever method may not be flexible enough to accommodate longitudinal movement of box girders. The constraint effects of longitudinal movement of box girders can introduce large stresses and consequently large moments into short piers. This study is aimed at proposing a method to reduce the moment of short piers in bridge constructed by cantilever method. The proposed method has been applied to an actual bridge. Field measurements for rotation of the end of pier and for displacement of cantilever have been done. The comparison of calculated values and measured ones shows that the method is reasonable. Also, numerical result of the study represents that time-dependent behavior of piers can be controlled effectively by employing the proposed method.

Keywords: box girder, bridge, cantilever method, creep, shrinkage, time-dependent behaviour, pier, rotation, measurement.

1. Introduction

Creep and shrinkage of concrete are important factors in the design of concrete structures. Time-dependent effects of creep and shrinkage are particularly significant on long-term deformation and structural behavior in prestressed concrete bridges [1]. For example, creep and shrinkage affect the sizing and setting of expansion joints due to time-dependent axial shortening arising from creep and shrinkage effects of prestress force.

In prestressed concrete box girder bridges constructed by cantilever method, the structure with the form of continuous beam resting on bearings is not favorable in terms of seismic design, while it allows the longitudinal movement of the deck due to creep and shrinkage effects as well as thermal effects. For multispan bridges with integral linking between the decks and the piers, the constraint effects of longitudinal movement of deck due to creep and shrinkage of concrete combined with the statically indeterminate effects of longitudinal prestressing give rise to the additional bending moment in piers [2]. Bridges with short piers are less flexible enough to accommodate longitudinal movement of the girders than that with long piers. The constraint of longitudinal movement of box girder may lead to excessive moment of piers.

This study develops a realistic method for reducing the bending moment of pier, which results in the reduction of stress in pier and stress of ground under footing. The longitudinal forces to control the moment of pier are loaded at the end of cantilever of superstructure. The forces are loaded into the direction to reduce the expected moment due to time-dependent behavior by jacking rams before joining the neighbouring cantilevers at center of span. The moment due to these forces cancels out the part of moment due to creep and shrinkage effects. The proposed method has been applied to an actual prestressed concrete box girder bridge constructed by cantilever method in Korea. The results of this study represent that the method is very effective.

2. Modelling of Time-Dependent Properties of Concrete

Time-dependent behavior of concrete may be categorized into three class which is time-dependent material properties resulting in stress-strain relationships with time, and time-dependent stress originated (creep) strain, and finally time-dependent non-stress originated (shrinkage) strain. Material properties influenced by time include the strength of concrete and elasticity. The strength and elasticity increase significantly during the first moth after casting, and then they increase more slowly over the reminder of life of the structure. The compressive strength of concrete is computed using an equation of the followings

$$f_c(t) = \frac{t}{a+bt}\ f_c^{'} \qquad (1)$$

where $f_c^{'}$ is the 28 day strength, t is the time in days after casting of the concrete, and a and b are constants. The values of a and b depend on the type of cement and the curing method used for the specimen. For type I cement and moist curing, the recommended values are $a = 4.0$ and $b = 0.85$. The elastic modulus $E_c(t)$ is computed as a function of the compressive strength of concrete using the following formula ;

$$E_c(t) = 1337 w^{1.5} \sqrt{f_c(t)} \quad \text{(MPa)} \qquad (2)$$

where w is the unit weight of the concrete in ton/m^3 and $f_c(t)$ is the strength of concrete in MPa.

Several material models for shrinkage and creep of concrete have been proposed both in literature [3,4] and in international codes [5,6]. The most commonly used models are those by CEB-FIP [5], and ACI Committee 209 [6]. The amount of information on the input parameters such as environmental conditions and concrete compositions varies from model to model. Using procedure discussed in this section, creep and shrinkage predictions found by one of the codes can be automatically incorporated into a time-dependent analysis with computer program. Even though creep and shrinkage are not strictly independent, they may be treated as independent of each other and hence additive. In this study, the total strain $\varepsilon(t)$ at time is considered as a superposition of following components.

$$\varepsilon(t) = \varepsilon_{el}(t) + \varepsilon_{cr}(t) + \varepsilon_{sh}(t) + \varepsilon_{th}(t) \qquad (3)$$

where $\varepsilon_{el}(t)$ =elastic strain; $\varepsilon_{cr}(t)$ =creep strain; $\varepsilon_{sh}(t)$ =shrinkage strain; $\varepsilon_{th}(t)$ =thermal strain. Shrinkage strain $\varepsilon_{sh}(t)$ at time t is calculated from following equation.

$$\varepsilon_{sh}(t) = \varepsilon_{s0}\ f(t, t_s) \qquad (4)$$

where ε_{s0} is the ultimate shrinkage, $f(t,t_s)$ is the function to describe the development of shrinkage with time, and t_s is the age of concrete at the beginning of shrinkage.

Creep strain of concrete is calculated by the integral formulation. Creep strain ε_{cr} may be expressed in terms of the following integral.

$$\varepsilon_{cr}(t) = \int_0^t J(t,\tau) \frac{d\sigma(\tau)}{d\tau} d\tau \qquad (5)$$

where $J(t,\tau)$ is the specific creep compliance function for observation time t under initial loading at time τ. In the form of this creep strain relation, its direct evaluation is impractical because it requires integration over the entire history of stresses in an element. This can require a tremendous numerical effort and data storage capacity for the solution of realistic problem. The need for storing and using the complete history of stresses can be eliminated by approximations of the creep compliance function $J(t,\tau)$, also known as kernel, with a so-called degenerate kernel. This basic approach has been developed by several researchers [7,8]. The most general degenerate kernel takes the form of a Dirichlet series which can be written as

$$J(t,\tau) = \sum_{i=1}^{m} a_i(\tau) \left[1 - e^{(y_i(\tau) - y_i(t))}\right] \qquad (6)$$

where $a_i(\tau)$ are the creep compliance coefficient. In this study $y_i(t) = t/\Gamma_i$ is used, the instantaneous elastic strain is not included in the kernel, and the degenerate kernel takes the form as following,

$$J(t,\tau) = \sum_{i=1}^{m} a_i(\tau) \left[1 - e^{-(t-\tau)/\Gamma_i}\right] \qquad (7)$$

The recursive relationships for computing the creep strain may be derived by substituting the degenerate kernel of Eq. (6) into the convolution integral of Eq. (5). The resulting expression for $\varepsilon_{cr}(t)$ may be written as

$$\varepsilon_{cr}(t) = \int_0^t \sum_{i=1}^{m} a_i(\tau) \left[1 - e^{(y_i(\tau) - y_i(t))}\right] \frac{d\sigma(\tau)}{dy_i(\tau)} \frac{dy_i(\tau)}{d\tau} d\tau \qquad (8)$$

3. Control Method

The major characteristic of the proposed method is to introduce the moment into the lower end of pier by jacking force at cantilever state during construction of box girder bridge. The introduced moment by jacking force cancel out the moment due to creep and shrinkage effects as well as longitudinal prestressing effects. The method involves the following steps.

Step 1 : Erect box girders successively with prestressing cantilever tendons

Step 2 : Install jacking brackets, struts and rams at both top and bottom slabs of box girders. And then, using appropriate jacking equipment such as ram, push the ends of joined box girders outward to introduce moment into the lower section of pier of determinate structural state.

Step 3 : Place and cure concrete at closure segments of center of span. The jacking equipments maintain during this stage.

Step 4: Release jacking forces when concrete of closure segment has reached satisfactory strength. And then, remove all jacking equipments such as rams.

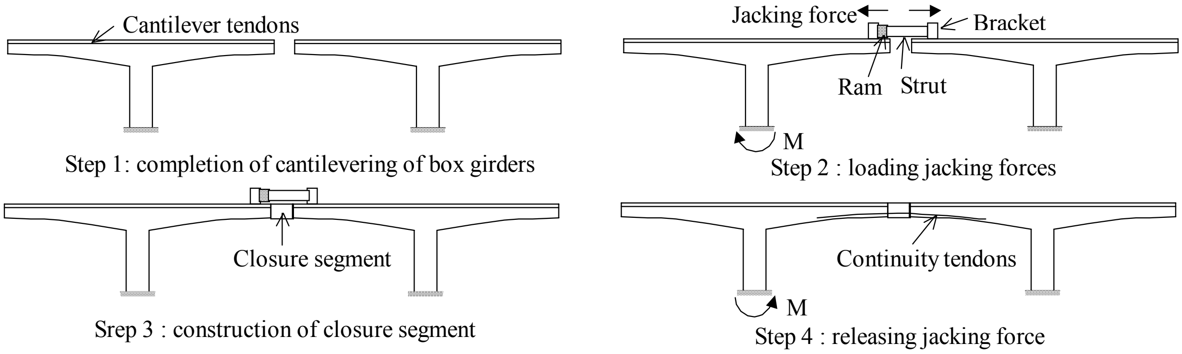

Fig. 1 Steps of control method

In step 2, transferring jacking force introduces outward longitudinal displacement of girders and moments into the lower end of piers. On the other hand, in step 4, prestressing the continuity tendons shorten the box girders axially, and introduce moment into the lower end of piers in opposite direction to moment introduced in step 2. Moment introduced in step 2 and that in step 4 cancel out each other. Consequently, such moment introduction at construction stage reduces the effects of creep and shrinkage during service life of bridges.

4. Application to an Actual Bridge

4.1 Description of Structure

Fig.2 Kangdong Bridge over the Han River

The proposed method was applied to the construction of Kangdong Bridge over the Han River in Seoul of Korea. The Kangdong Bridge consists of two bridges which carry northbound and southbound traffic respectively. The southbound bridge is considered in this study. The bridge is composed of two 82.5m exterior spans and five 125m interior spans. The total length of bridge is 790m. The bridge was constructed by cantilever method with in-situ concreting of segments. The elevation of bridge is shown in Fig. 3.

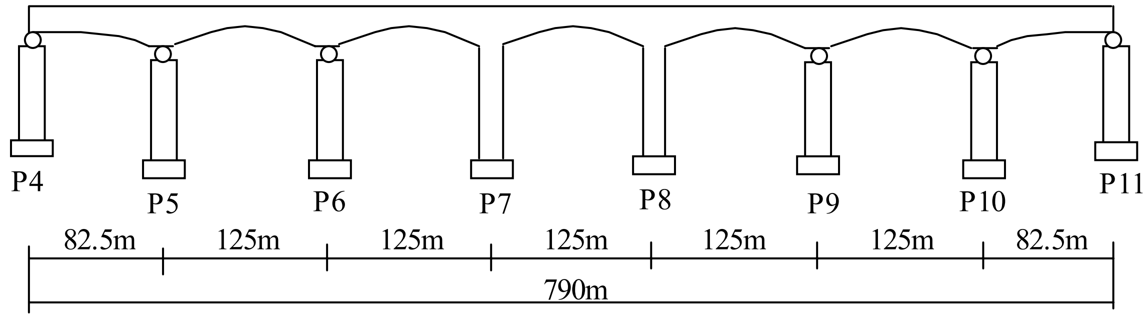

Fig. 3 Elevation of bridge

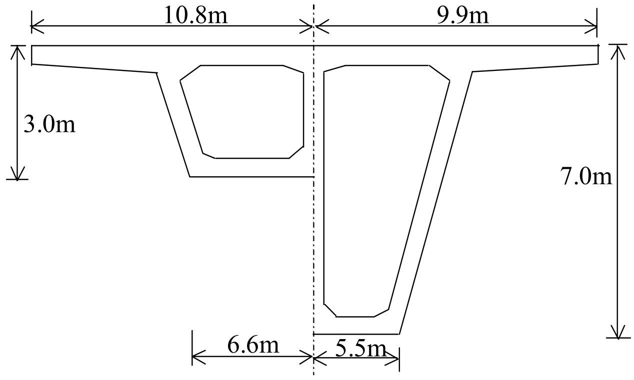

Fig. 4. Cross section

Fig. 5. Equipment of struts and jacking rams

The bridge has eight piers. The height of typical pier is 25.8m. Bearings are located between superstructure and pier 4 through pier 6, and pier 9 through pier 11. Pier 7 and Pier 8 are connected to superstructure rigidly. However, longitudinal movement due to creep, shrinkage and temperature change are restrained by statically redundant connections in pier 7 and pier 8, which give rise to redundant section force in these piers. The girders are cantilevered from the piers using cast in place segments, and is later made continuous with a cast in place girder near pier 4 and pier 11, and with the adjoining cantilevered girder at midspan. The geometry characteristics of interior spans are similar to each other. The interior span of the box girder has fourteen segments per cantilever (i.e., per half-span). The segments are placed symmetrically on both sides of the span. The cantilevers are joined at midspan. The cantilever tendons located in top slab were stressed at the time of construction of the segment, whereas the continuity tendons located in bottom slab were stressed after midspan joining.

Typical cross sections of box girders are shown in Fig. 4. The cross section consists of two cell box with wide cantilevered slabs. Transverse slab tendons are designed in the top slab, but are not included in this numerical analysis. The girder depth varies from a maximum of 7m at the piers to a minimum of 3m at midspan. Also, due to the sloping webs and haunched girder, the bottom slab width varies from a maximum of 6.6m at midspan to a minimum of 5.5m at the piers.

4.2 Measurement

Before girders cantilevered from the piers were made continuous, horizontal control force of 5880kN was applied with jacking rams. The jacking brackets, struts, and rams are shown in Fig. 5. After bridge was made continuous, jacking forces were released, and then jacking equipments were removed. Instrumentation and measurement for rotation of the end of pier during loading control force have been done. The surface of bottom slab of box girder just above pier 7 and pier 8 was equipped with tiltmeter as shown in Fig. 6. While control force was loaded before closure of the center span joint, the rotation of the end of pier with regard to foundation was measured by tiltmeter. Also, while control force was loaded, horizontal displacement of the end of box girders was measured by four dial gauges (LVDT) as shown in Fig. 7. Two dial gauges were located at top slab of the end of box girders. Measured values through these two dial gauges were averaged to be compared with calculated ones. Other two dial gauges were located at bottom slab of the end of box girders. Also, theses measured values were averaged.

Fig. 6 Instrumentation of tiltmeter

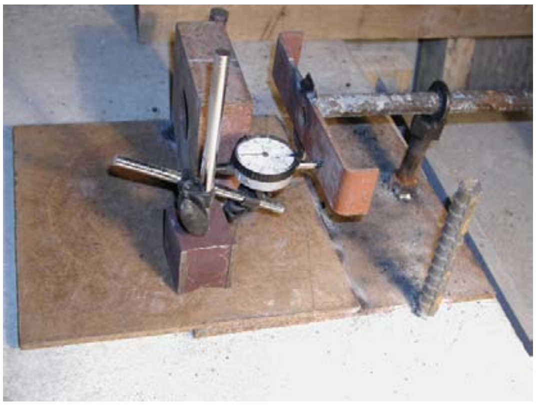

Fig. 7 Instrumentation of LVDT

4.3 Numerical Analysis and Results

Finite element analysis was carried out with a symmetrical half of the structure. Center of span between pier 7 and pier 8 is restrained against displacement in the global x-direction (longitudinal) and rotation about the global z-axis. The bridge is analyzed for the actual construction sequence, in which each segment is cast and post tensioned and the continuity tendons and superimposed dead load are applied after closure, and then for a 10000 days service period afterward.

The following steps in the analysis take place.
(1) Building of cantilever structure of box girder starting from pier 5
(2) Building of box girder near pier 4 with full staging method.
(3) Closure of center of span between pier 4 and pier 5
(4) Building of cantilever structure of box girder starting from pier 6
(5) Closure of center of span between pier 5 and pier 6
(6) Building of cantilever structure of box girder starting from pier 7
(7) Loading horizontal control force of 5880kN at the end of box girder
(8) Closure of center of span between pier 7 and pier 8
(9) Closure of center of span between pier 6 and pier 7

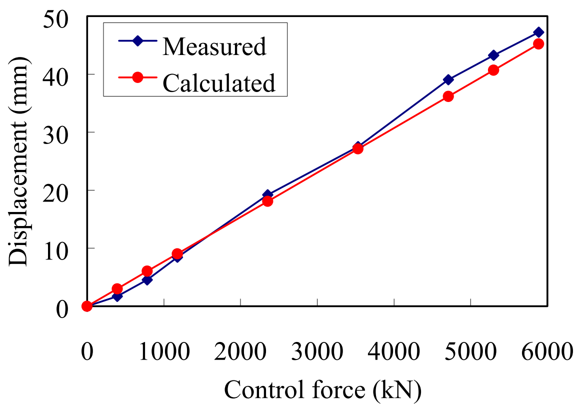

Fig. 8 Comparison of the calculated and measured horizontal displacement

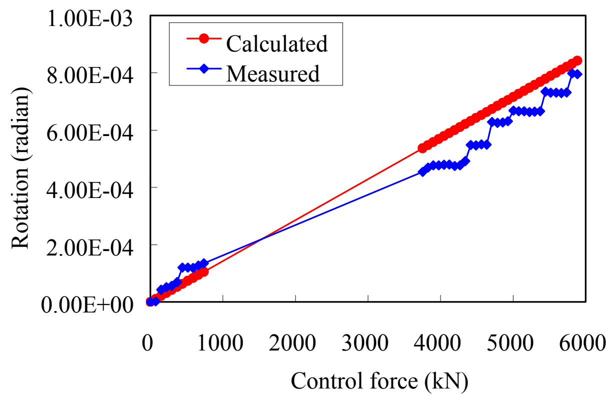

Fig. 9 Comparison of the calculated and measured rotation of the end of pier

Material properties assumed for the time dependent analysis are as follows. The concrete which are modeled using the ACI committee 209 recommendations [6] has compressive strength of 28 days = 40MPa, ultimate creep factor = 2.35, and ultimate shrinkage strain=0.0008. Time dependent development of creep and shrinkage use the standard ACI parameters derived for these properties recommended by ACI.

The comparison of the calculated and measured horizontal displacement of the end of box girders during loading of control force before joining at center of span is shown in Fig. 8. The calculated displacement is almost same as measured one. Also, the comparison of the calculated and measured rotation of the upper end of pier 7 during loading of control force is shown in Fig. 9.

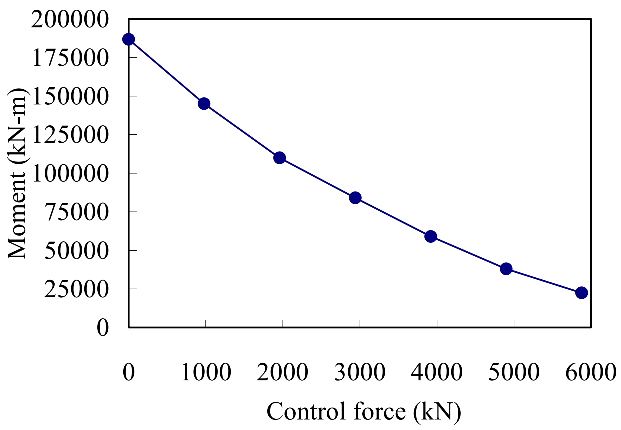

Fig. 10 Prediction of moment after 10000 day service period

Although the calculated rotation is a little greater than the measured one, the difference is not significant. From Fig. 8 and Fig. 9, it can be inferred that intended control force is loaded and that the moment is introduced into the lower section of pier.

Time dependent analysis result of moment in pier at 10000 days after bridge completion is shown in Fig. 10. Moment variation according to control force of 0 though 5880kN are shown in the figure. Moment is not linearly proportional to control force. This results from nonlinear characteristics of creep and shrinkage of concrete, and also nonlinear redistribution of stresses.

The moment resisted by stresses in cross section of pier do redistribute. This redistribution is due to the effects of creep and shrinkage and prestressing losses in tendons of superstructure. Also, numerical result represents that time-dependent structural behavior of piers can be controlled effectively by loading control force at construction stage.

5. Conclusions

For bridges constructed by cantilever method with short piers, short piers may not be flexible enough to accommodate longitudinal movement of superstructure, and hence experience the large moments. In such a case, the method to reduce, or control rationally the moment of piers was proposed. The control force is loaded before joining the cantilevers at center of span, and the force introduce moment into the pier. The proposed method was applied to an actual prestressed concrete box girder bridges. The comparison of calculated values through finite element analysis and measured ones shows that the moment can be introduced into the piers on purpose. Also, numerical analysis result through finite element represents that time-dependent moment of piers can be effectively reduced, or controlled by introduced moments in advance at construction stage. The adoption of such an approach as developed in this study would improve the long-term structural behavior of non-flexible short piers.

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