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Simulation of long-term time-dependent mechanics of an existing PC bridge by full-3D multi-scale integrated FE analysis

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Abstract

The behavior of a cantilever pre-stressed concrete bridge in Japan whose deflection has been measured for 25 years after construction. Currently, the total deflection of the bridge is much larger than the expected ones computed by the design formulae. The long-term time-dependent deflection and internal stress-strain of this bridge is simulated and compared to the site-investigation in use of the full 3D material-structural analysis code named DuCOM-COM3. This code can produce computer-based micro-scale porous media in memory cores, solve thermodynamic states of moisture, temperature and corrosion related substances, and resolve the dynamic equilibrium of macro-scale referential volumes of reinforced concrete including cracks. The analysis with considering the behavior of the water in a nano meter scale in order can capture the behavior of the actual bridge correctly. And it becomes clear that the moisture and temperature of the concrete have a major role affecting the overall deflection of the bridge, which is primarily caused by excessive creep and non-uniform shrinkage and expansion.

Keywords : integrated computing system, creep, moisture state, environmental action, existing structure

1. Introduction

A long-term field investigation of a pre-stressed bridge was carried out, and it was found that the deflection of the bridge is larger than the value obtained from the design equation based on linear-creep law and elastic response[1]. It was also reported that the creep coefficient employing a linear-creep law should be about four to five to reproduce the measured value[2]. This creep coefficient is about twice the value described in JSCE[3]. Although the formula can be used to predict the creep deformation in a small-specimen scale, further improvements are necessary for a real-scale member.

It has been known that the creep of concrete depends on the pore structure of hardened cement paste and the thermodynamic state of water in the pores. The hardened cement paste has various dimensional pores such as capillary pores, gel pores, and interlayer pores. Because the behavior of the water in the pores and the deformation of pore skeleton accompanying the water movement depend on the scale of pores, considering the characters of each fine structure is essential to build up the general model of creep deformation.

An integrated material-mechanics simulation platform namely DuCOM-COM3 has been developed recently[4]. The system is developed to reproduce the behavior of concrete from the casting to the end of service life. This integrated analytical platform consists of two main parts. The first part is a thermodynamic analytical system, which includes the hydration, pore structure development, and water movement models. This part covers the phenomenon which the scale is 10^{-3} to 10^{-10} m. The second part is a nonlinear mechanics part, which covers the phenomenon in a scale ranging from 10^{1} to 10^{-2} m (fig. 1). The thermodynamic part computes the concrete property based on the development of pore structure and the movement of water in the pores[5], while the mechanics part computes the external and the resulting reaction forces based on the updated material property from the thermodynamic part. The external forces and the internal stress-strain computed by the mechanical part are sent back to the thermo-dynamics part as a new input data[6]. This sharing process is repeated until the designated target. This analytical platform can therefore take into account a small scale phenomenon like water molecular movement as well as a large scale structural behavior.

The objective of this study is to investigate the potential causes of a long-term deformation measured from an existing bridge with an integrated analytical system.

2 Target of the analysis

2.1 The target structure

The bridge investigated in this study is a PC bridge Japan. The deflection of this bridge has been measured since 1982 so that it provides useful and enough data for this study[1], [2], [7]. The bridge consists of four spans. Each span is made of a rigid frame and was constructed by P&Z method. In P&Z method, the bridge is separated into some segments. In this paper, the part between the P4 pier and the center hinge (the midspan of span P4-P5) was analyzed (fig. 1). The environmental condition at the site[8] is estimated by the meteorological record near the site(table. 1).

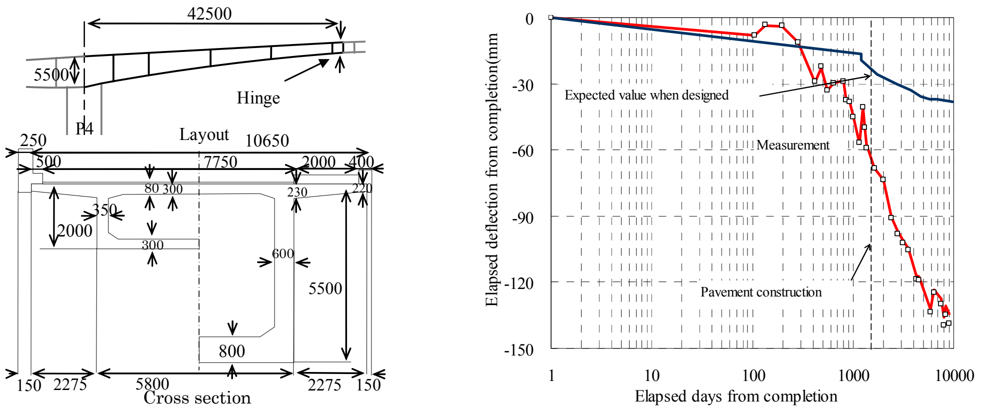

Figure 1 : Geometry of the target bridge, and the progress of its deflection

Table 1 :Estimated environmental condition at the site

Elapsed days	45	91.25	136.25	182.5	227.5	273.25	318.25	365	Ave.
Temp.(^{o}C)	-1.17	0.97	10	16.4	21.9	20	10.4	3.2	10.2
RH(%)	73	73	76	76	86.7	87.3	81	75	78

2.2 Measured creep deflection

The deflection of the center of the span has been measured by optical instrumentation since 1982 as shown in fig. 1. It is found that the measurement starts to lose touch with the expected value obtained from the equation based on linear creep law from hundreds of days after completion. The bridge was designed based on Specifications for Highway Bridges (hereinafter SHB)[9]. During the design phase, following values were used: compressive strength of concrete strength fc'=40N/mm^2, Young's modulus E =35kgf/mm^2, relative humidity 70%, volume to surface ratio V/S= 400mm, creep coefficient (SHB1978) ψ=1.58, and drying shrinkage ε =185μm[1].

3 Analysis for the long-term deflection

To simulate the long-term creep deformation of the bridge, a three-dimensional model is made in DuCOM-COM3(fig. 2). In this system, models for phenomenon in multi scale from molecular scale to structure scale are strongly integrated. When the mix proportion, construction condition, geometry, steel arrangement, and the boundary conditions of mechanics and thermodynamics are input, thermo-dynamical conditions like hydration and water content state are computed, and based on these information, response as structure is computed by the following time dependent constitutive model.

3.1 Time dependent constitutive model

In this analytical platform, the mechanical models are determined based on the information of the concrete pore structure such as the dimension of pore structure and the moisture state in each pore. The time-dependent behavior is computed by summing the contribution of small, finite elements.

The elastic response of a skeleton of cement hydrate is expressed as an elastic model (noted as (1) in fig. 3). Note (2) shown in fig. 3 is the mechanical component associated with the state of the capillary water in pore, which the size is 10^{-6}-10^{-8} m. This part is a visco-elastic part that describes a quick response and dominant at the early stage of creep. The water in gel pore, which the size is from 10^{-8} to 10^{-9} m, is modeled by two visco-plastic models (noted as (3) and (4) in fig. 3). In these models, the water is assumed to move slowly and it is non-recoverable because of the interaction between water and pore wall. These two models contribute significantly in long-term creep behavior. The interlayer pore, which the scale is 10-10 m, is closed by increasing of the surface energy, once the water comes out. This phenomenon is modeled by a plastic model (noted as (5) in fig. 3). This model is effective under the situation that water evaporates significantly such as in the case of high temperature and low humidity.

Up to now, these constitutive models and the integrated analytical platform have been verified in a small-scale specimen. The creep coefficient of the material test specimen computed by this analytical system is about 2 which depend on material age[6]. This value is much different from the value (roughly 4-5) [2] that is used to explain the long-term measurement result described at the beginning of this paper in linear creep rule.

3.2 Analytical condition

Although the bridge was constructed segmentally, it is assumed in the analysis that the bridge is constructed at once. The pre-stress is also introduced only at once. The gravity load is considered as a volumetric load, while the weight of the pavement and bridge railing are considered as a distributed load on the top surface of the bridge deck. In all the figures, origin of time and deflection of the analytical result are reset at the value after all the pre-stress and external force are loaded.

Some environmental conditions are assumed. (a) is that the temperature and humidity is constant at annual average, (b) is that temperature is constant at highest value in the year though humidity is constant at annual average, (c) is that temperature changes according to the meteorological record though humidity is constant at annual average, (d) is that temperature constant at annual average and humidity is constant at 60%RH, and (e) is that the temperature is constant at annual average though humidity is changed according to the meteorological record. Environmental conditions for the inside and outside of the box girder are assumed same. Heat and moisture transfer is neglected at the top flange of the bridge girder because it is fully covered with a pavement.

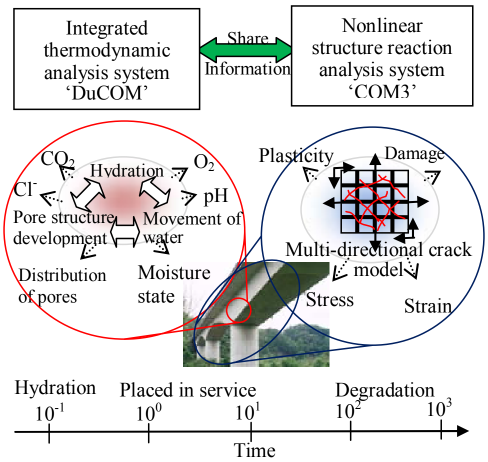

Figure 2 : Image of DuCOM-COM3 system

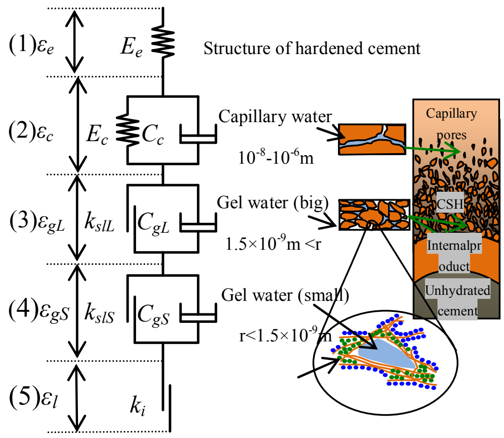

Figure 3 : Multi-scale time dependent constitutive model

3.3 Analytical result of long-term creep

The analytical result is shown in fig.4. The Difference between (a) and (b) means the ultimate displacement becomes larger according to the external temperature. As observed, the movement of the pore water and the shrinkage under high temperature is accelerated. Consequently, the creep deformation is also accelerated. And the result (c) means the deflection rate in the case that the temperature is allowed to vary according to the environment is lower than that when the temperature is kept constant. However, the ultimate deflection values of the two predictions are comparable. The creep deformation progresses significantly during the hot season, and it is not recoverable. The deflection is thus accumulated every hot season, and finally it reaches the value when the deflection is computed based on the highest temperature in a year.

Difference between (a) and (d) is caused because the shrinkage between upper flange and bottom flange is different. Drying speed of the concrete depends on the absolute distance to the unsealed surface and RH of environment. In case of this bridge, the upper surface of the bridge can be assumed as sealed, so the shrinkage of the upper flange becomes smaller than bottom flange. And this difference of the shrinkage becomes large when the drying speed is fast, in other words, the RH of environment is low. There are not so significant difference between (a) and (e). This is because the moisture state at the in internal concrete is hard to change in short term.

Among these analytical conditions, (c) is the case that is the closest to the reality as the input condition. The analytical result also shows that it is the most comparable to the measured value. It is observed that the rate of the creep becomes large after 1,000 days as same as measured one. The difference between analysis and measurement until about 100 days tends to be caused by construction procedure; the actual bridge was constructed segmentally and hence the age of the each segment is different. In contrast, the analysis assumes that the bridge is constructed at the same time.

4 Influence of each microscopic event on the macroscopic behavior as structure

In the analytical system used in this research, the interaction between the phenomenon in multi scale as nano to macro scale is considered. In this section, sensitivity analysis is conducted by changing some part of the time dependent constitutive model in order to understand the phenomenon of creep in a real-scale structure in more details.

4.1 Analytical condition

The analysis conditions in sensitivity analysis are as follow: (A) original models as they are as a reference, (B) capillary tension, which affects shrinkage, is assumed to be zero, (C) saturation of gel void is kept 100% that means the viscous property of the water in gel water is constant. The temperature and relative humidity are set at 10.2°C and 78%.

4.2 Analytical result

The results are shown in fig. 5. From the comparison between (A) and (B), the deflection in (B) starts to increase around tens of days earlier than (A). This means that capillary tension influences the behavior of the whole structure at the earlier stage of the creep. The deflection of (C) is smaller than (A) after 1,000 days. This means that the increase of deflection rate after 1,000 days is due to the movement of gel water. These results clearly show that it is still necessary to consider the behavior of the water in a nano meter scale in order to capture the behavior of the actual bridge correctly.

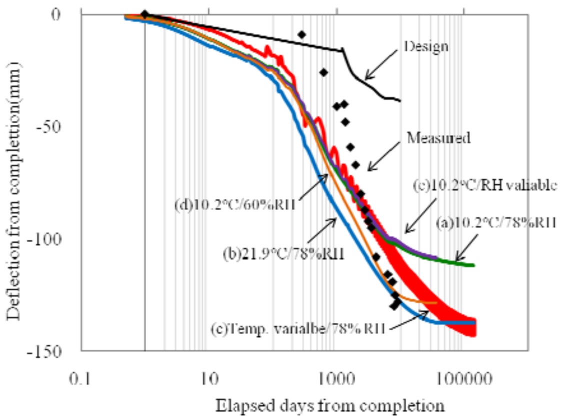

Figure 4 : Analytical result of the deflection of the bridge

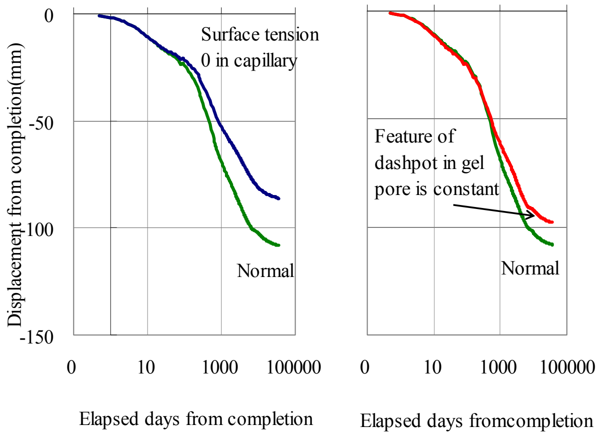

Figure 5 :Influence of each microscopic behavior

5 Conclusion

The findings from this research are listed as follows:

1) The history of deflection in a real bridge can be reproduced by using a multi-scale integrated analytical platform that considers the phenomena occurring from microscopic to macroscopic scales.

2) The higher external temperature is the more creep deformation progresses. The deflection caused by creep is sensitive to the external temperature. When the external temperature changes, the ultimate deflection of the structure is the same as the value obtained with the highest temperature in a year.

3) The deflection caused by creep is influenced by the distribution of relative humidity in a cross section. The change of relative humidity for a few months does not significantly influence the deflection.

4) From the sensitivity analysis, the capillary tension in the pore influences the creep deformation in a short period. In contrast, gel water starts to move after a period of time and it increases the rate of creep. It is still necessary to consider the phenomenon in micro pores to accurately predict the behavior of a real-scale structure.

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