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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*:** A simulation of the long-term deflection and internal stress-strain of a pre-stressed cantilever bridge is made. This particular bridge is selected as the deflection of the bridge after 25 years is much larger than the expected value obtained from the current design creep equation. It is expected that the underestimated deflection is attributed to the limitation of the equation to capture the real, complex behavior of the bridge. To verify this expectation, a finite element program capable of modeling multi-scale, multi-chemo physics, and nonlinear mechanics is used to analyze the long-term behavior of the bridge in details. A systematic investigation is also made to study the influences of various environmental conditions. The analysis shows 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. Based on this finding, a novel method to control the deflection of the bridge is introduced; that is, by changing the environmental states of the concrete in the bridge.

KEYWORDS: integrated computing system, creep, existing structure management

1. INTRODUCTION

A long-term field investigation of a pre-stressed bridge was carried out by the Shimizu Coorporation1). It was found that the deflection of the bridge is two to three times larger than the value obtained from the design equation based on linear-creep law and elastic response. It was also reported that the creep coefficient employing a linear-creep law should be about four to five to reproduce the measured value2). This creep coefficient is about twice the value described in JSCE3). The prediction formula specified in the code was revised in 1996. In this version, the creep coefficient was revised to consider the volume-to-surface ratio and external relative humidity4). 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. The importance of proper maintenance and management has been recognized to keep infrastructures in service for long. In case of the maintenance of pre-stressed concrete structures, the method to estimate the ultimate deformation and the time to converge is required. 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[5]. 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 (Figure-1). The thermodynamic part computes the concrete property based on the development of pore structure and the movement of water in the pores[6], 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[7]. 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. Another objective is to verify the analytical models in DuCOM-COM3. Sensitivity analysis is presented to study the relationship between macroscopic mechanical behavior and microscopic thermodynamic state in which the analysis parameter is the amount of water in fine pores.

2. Target of the analysis

2.1 The target structure

The bridge investigated in this study is the Tsukiyono Bridge located in Tsukiyono, Minakami-cho, Tone-gun, Gunnma Prefecture, Japan. The deflection of the bridge has been measured since 1982 so that it provides useful and enough data for this study[1), 2), 8)]. 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. The segment is then erected from the top of the pier. The mix proportion of concrete used is shown in Table-1.

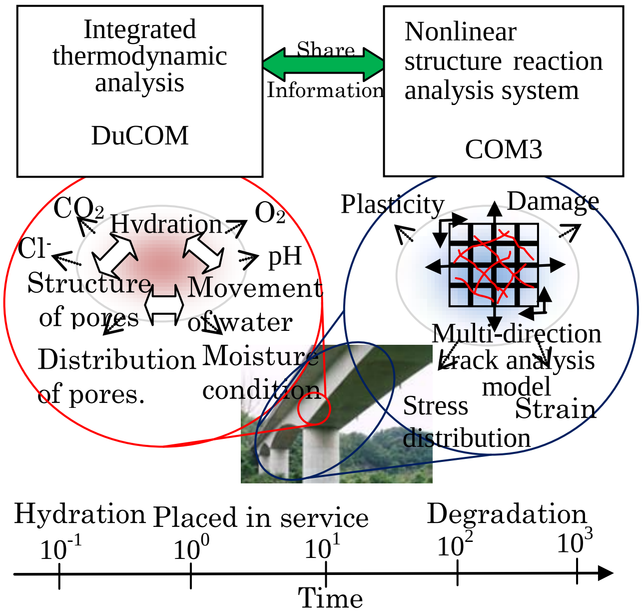

Figure-1 Abstract of multiscale integrated analysis system

Table-1 Concrete mix design

σ_{ck}	Cement	Maximum aggregate size	Air void
kgf/cm^2	Type	Mm	%
400	High-early-strength -cement	25	4

Weight (kg) (per 1m^3 concrete)					Remarks
Cement	Water	fine aggregate	Coarse aggregate	Admixture	
423	165	639	1108	1.0575	Summer
440	167	629	1099	1.1	Others

In this paper, the part between the P4 pier and the center hinge (the midspan of span P4-P5) was analyzed (Figure-2). In this part, the shrinkage data of the concrete is available, which has been obtained from several embedded strain gauges. The cross section of the bridge is a tube shape. The width of the upper flange including the railing is 10.65 m, while the width of the lower flange is 5.8 m. The thickness of the upper flange is 300 mm and constant (note that this does not include the 80 mm upper pavement layer). The thickness of the web and the bottom flanges is from 600 mm to 360 mm and 754 mm to 200 mm, respectively, gradually changes from the top of Pier P4 toward the center hinge. In Minakami, the annual average temperature is 10.2 °C. The annual average humidity is 78 %8). The humidity data was estimated from the data measured in Karuizawa, a city located near to Minakami and with a similar geometrical condition.

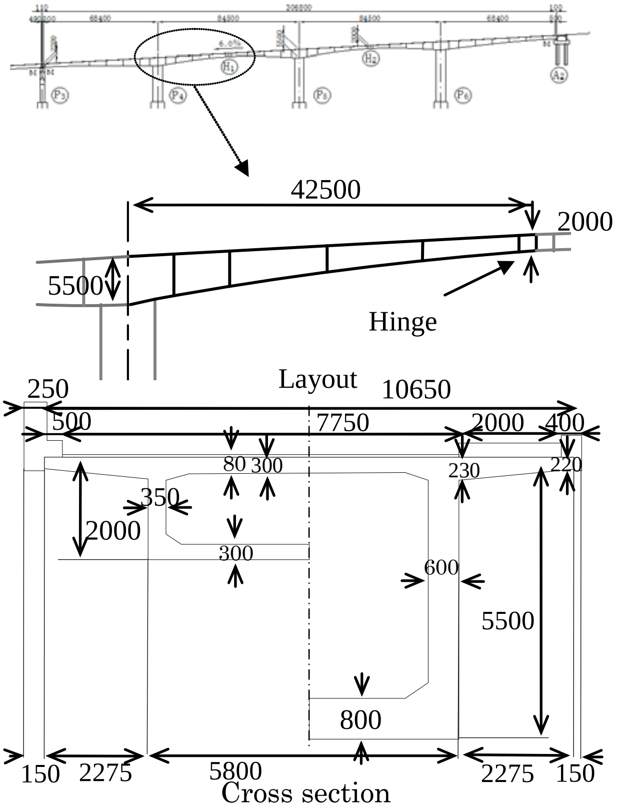

Figure-2 Tsukiyono Bridge the object part

2.2 Measured creep deflection

The deflection of the center of the span has been measured by optical instrumentation since 1982 as shown in Figure 3. 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. Tsukiyono Bridge was designed based on Specifications for Highway Bridges (hereinafter SHB). During the design phase, following values were used: compressive strength of concrete strength $f_c'=40\text{N/mm}^2$, Young's modulus $E_c=35\text{kgf/mm}^2$, relative humidity 70%, volume to surface ratio V/S= 400mm, creep coefficient (SHB1978) $\phi=1.58$, and drying shrinkage $\varepsilon_{sh}=185\mu\text{m}$1).

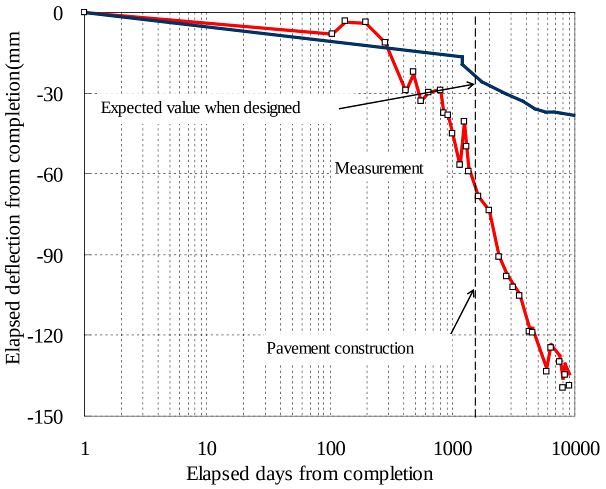

Figure-3 Difference of between the measurement and expectation when designed

3. Factors Influences on the Creep Deflection of the Bridge

To understand the mechanisms of creep deformation of the Tsukiyono Bridge, a three-dimensional model is made in DuCOM-COM3. In this system, models for phenomenon in multi scale from molecular scale to structure scale are strongly integrated. When the mix proportion, construction condition, structural properties (size, volume to surface ration, and 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 Figure 4].

Note (2) shown in Figure 4 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 Figure 4]. 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 Figure 4]. 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 specimen7) . This platform can be used to predict autogeneous and drying shrinkage, basic and drying creep for small-scale test specimen. It is of interest here to evaluate the applicability of the platform in predicting the behavior of a real scale member.

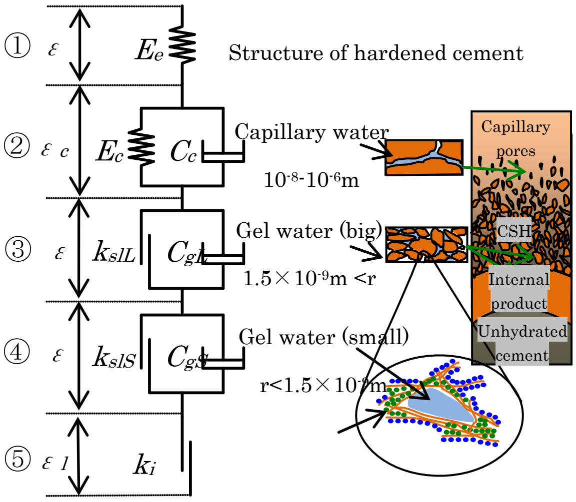

Figure-4 Nonlinear creep model

As mentioned previously, the main objective of this paper is to verify that this analytical platform in predicting the behavior of a real-scale bridge. The creep coefficient of the material test specimen computed by this analytical system is about 2 which depend on material age7). 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 Mesh model for the analysis

The potential gradient of the thermal energy (temperature) and pore pressure (moisture status) grows among air and internal concrete structure. For the convergence of the solution, the element size in this zone is 1-3 mm. Since the temperature and humidity variations of the concrete inside a structural member are not significant, the sizes of the elements in the cross-section of the bridge were varied from 4 to 20 cm. The element size along the longitudinal bridge direction is about 3 to 5 m.

3.3 Analytical condition

Although the bridge was constructed segmentally within approximately 6 months, 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. Environmental conditions for the inside and outside of the box girder are same. It is assumed that no moisture and heat movement occurs at the top flange of the bridge girder because it is fully covered with a pavement.

Table-2 Pattern of temperature seasonal change

Elapsed days	45	91.25	136.25	182.5
External Temperature(℃)	-1.17	0.97	10	16.4
Elapsed days (rest)	227.5	273.25	318.25	365
External Temperature(℃)	21.9	20	10.4	3.2

3.4 Analytical result of long-term creep

A simplification was made to the real environmental condition of the bridge (Table 2). The fluctuation of the temperature is assumed to be in a few variations, while the relative humidity is assumed to be a constant value 78%, which was the average value as reported.

Figure 5 shows that the deflection in analysis is comparable to the measured value. It is observed that the rate of the creep becomes large after 1,000 days. The analytical result captures a similar tendency after 100 days only. The difference 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.

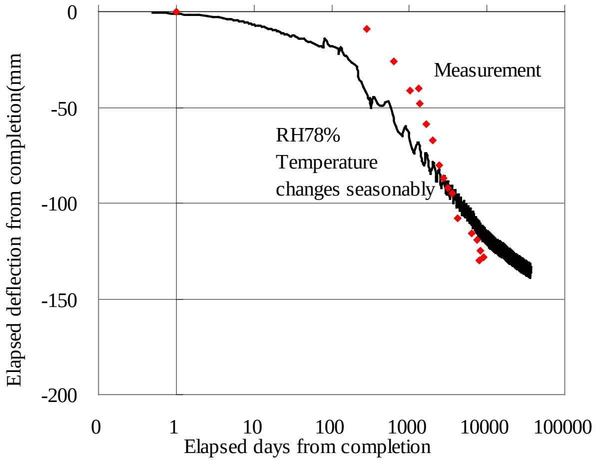

Figure-5 Result of reproduce of Tsukiyono Bridge creep displacement

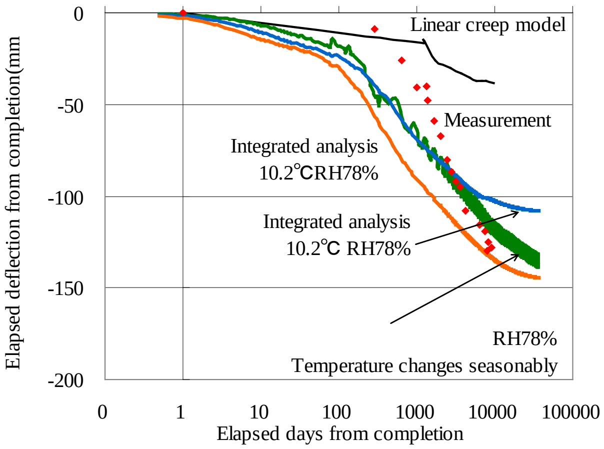

Figure-6 Difference of displacement process under various constant temperatures

4. Influence of each factor on the creep deflection of the actual bridge

In the previous section, it has been confirmed that the analysis system can reproduce the creep of the bridge. Here, the influences of temperature, relative humidity volume-to-surface ratio, steel ratio, and countermeasure against creep deflection are focused.

4.1 Analysis on temperature

Unlike that adopted in the previous chapter, in which the temperature was varied according to the real environment, this section attempts to use only the high and average temperature of the data and set the two patterns of each temperature.

The analytical result shown in Figure 6 shows that 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. 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.

4.2 Analysis on relative humidity

To know the influences of relative humidity, two patterns of environmental conditions are assumed. The first one is a constant relative humidity, and the other one is the actual relative humidity as shown in Table-3.

Table-3 Pattern of RH seasonal change

Elapsed days	45	91.25	136.25	182.5
External RH (%)	73	73	76	76
Elapsed days (rest)	227.5	273.25	318.25	365
External RH (%)	86.7	87.3	81	75

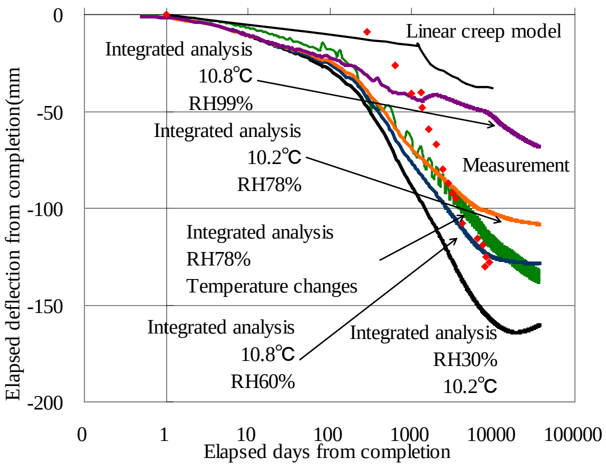

Figure-7 Difference of displacement process under various constant relative humidities.

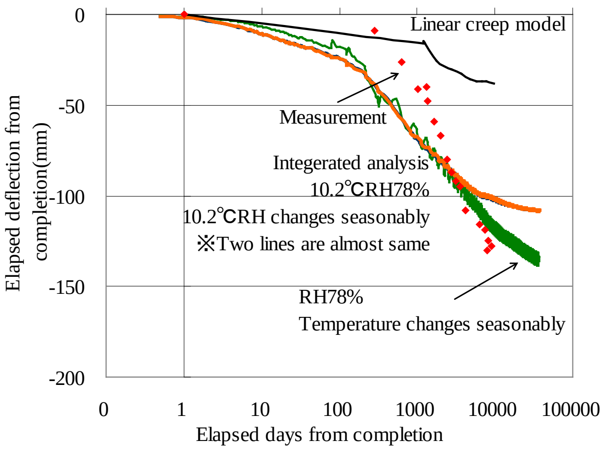

Figure-8 Difference of displacement process under relative humidity changing seasonally

In the first case, the analysis is conducted under a constant relative humidity 99%, 78%, 60%, and 30% in which the results are shown in Figure 7. The lower the relative humidity is, the larger the deflection is. The relative humidity between the upper and the lower flanges is different when the bridge deflects. This occurs because the evaporation from the top surface of the bridge is not permitted (representing the coverage provided by the pavement in the real situation). When the concrete dries, it shrinks and the creep progresses more rapidly. When the lower flange is dryer than the upper one, a significant shrinkage difference occurs in the axial direction of the bridge. As a result, the bridge bends down. Under more severe drying condition, the difference of the relative humidity between the top and bottom flanges becomes larger and therefore leads to a larger deflection.

In the second case, there are no notable differences of the displacement compared to the previous case with a constant humidity value. It is because the relative humidity inside concrete is not sensitive to the short term change in relative humidity outside concrete.

4.3 Analysis on volume to surface ratio

To highlight the influence of volume-to-surface ratio on creep deflection, a geometrically similar scaled-down analytical model is prepared. Although the body forces and the applied load can also be scaled down, it is difficult to scale down the concrete strength. When the stress distribution is different, the creep deflection also progresses differently. To make distribution of stress level constant, the gravitational acceleration is scaled down.

The result of the analysis is shown in Figure 9. In the figure, the vertical axis is the ratio of displacement to span. In case of the reference, the rate of the creep deflection increases at about 1,000 days after the construction. When the bridge is scaled down, the rate of the creep deflection increase becomes earlier. The result clearly shows that when volume-to-surface ratio is small, the concrete inside the structure dries faster and the creep deflection accelerates earlier. It is because the drying rate depends on the absolute distance of the concrete from the outer surface of the member.

4.4 Influence of steel ratio on creep deflection

To understand the influences of reinforcement ratio between the upper flange and bottom flange to creep deflection, the reinforcement ratio in the upper flange is changed. The assumptions of the reinforcement ratio in the upper flange are the same ratio, half ratio, twice ratio, and ten times ratio as Tsukiyono Bridge. The reinforcement ratio in the lower flange is constant.

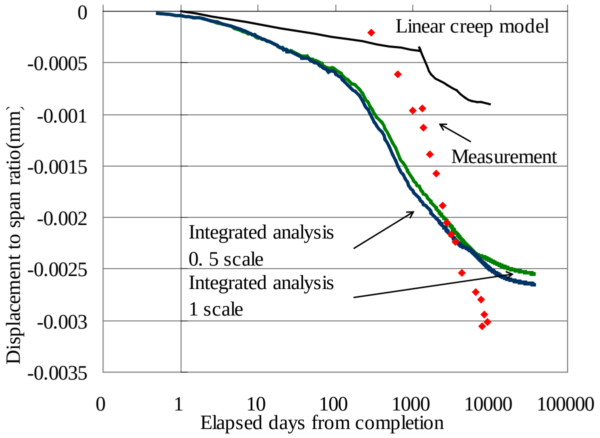

Figure-9 Difference of displacement process under virtual dimensional change

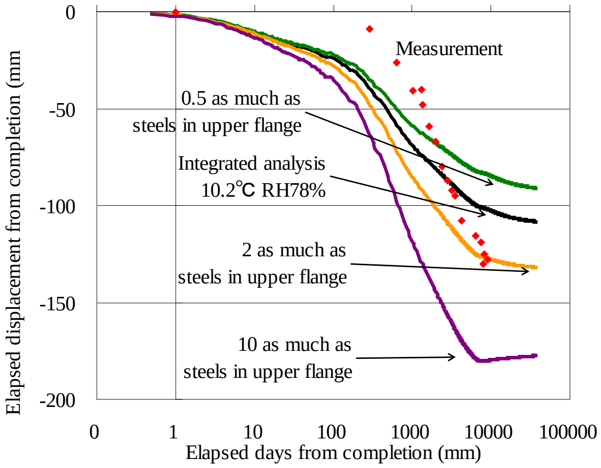

Figure-10 Difference of displacement process under changing steel amounts of upper flange

The results are shown in Figure-11. It is found that the displacement varies according to the reinforcement amounts of the upper flange. The shrinkage of the concrete along the longitudinal bridge direction is confined more strongly if the amount of the steel is larger. If the amount of the steel in upper flange is larger than that in the lower flange, the concrete in the lower flange shrinks more than that in the upper flange. As a result, bending moment occurs, and the displacement of the center of span increases.

4.5. Control displacement by changing moisture condition

In this section, a method to control the displacement of the bridge is discussed. Through the discussion above, it is clear that the distribution of relative humidity and temperature in the bridge cross section and steel ratio influence the ultimate deflection significantly. This result indicates a possibility to control the bridge deflection by changing the moisture state or heat distribution in the bridge cross section. In addition, it is easier to control relative humidity than to control temperature and steel ratio after completion. When water is given to the bottom flange of the bridge girder, the bottom flange can expand toward the axial direction of the bridge. Accordingly, a negative moment can develop. This possibility is then applied in the analysis, and the applicability is verified. In the analysis, two cases are assumed to be the time of starting to give water. The first case is during the construction phase, and the second case is after 30 years.

The analytical result is shown in Figure 11. It is found that the excessive deflection can be recovered. The effects of wetting the bottom flange can be obtained also in the case that wetting done after 30 years after construction. This result indicates that the excess deflection can be controlled not only by a physical operation with huge energy consumption but also with a thermo dynamical operation. It is hope of the authors that this method can be used to the real bridge.

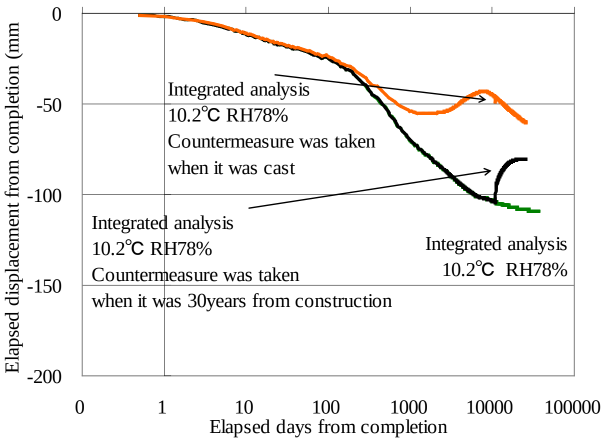

Figure-11 Different of displacement process under watering the bottom of the tube of the bridge beam

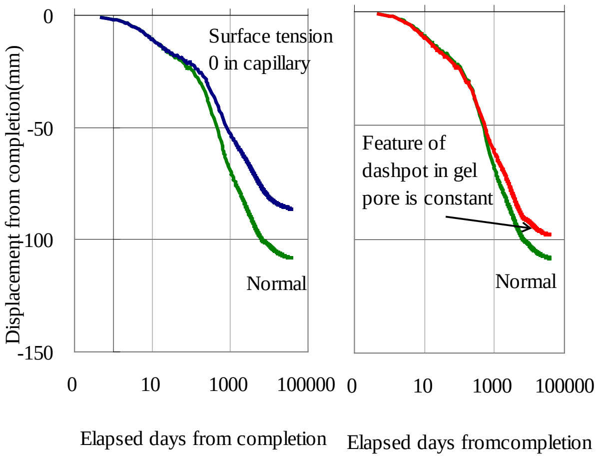

Figure-12 Influence of each microscopic event on reaction of existing structures scale

5. 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.

5.1 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^{o}C and 78%.

5.2 Results

The results are shown in Figure 12. From the comparison between Case A and B, the deflection in Case B starts to increase around tens of days earlier than Case A. This means that capillary tension influences the behavior of the whole structure at the earlier stage of the creep.

The deflection of Case C is smaller than Case 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.

6. Future prediction of the creep deformation of Tsukiyono Bridge

Based on the discussion in Section 4, the creep deformation of Tsukiyono Bridge is predicted by the integrated of material-mechanics analytical platform. Here, three environmental conditions are assumed. The first one is that external temperature is kept constant at the highest value of the year. In this case, the deflection may progress at a fast rate. The second one is that the actual temperature data. It is expected that the result of the prediction must close to the real situation. The third one is to consider the countermeasure discussed in section 4.5 after 30years.

The result of the prediction is shown in Figure 13. The deflection of Tsukiyono Bridge converges to about 140 mm after 170 years. If the lower flange is subjected to water at present, the deflection of the bridge can be reduced to 80 mm.

7. Conclusion

The findings from this research are listed as follows:

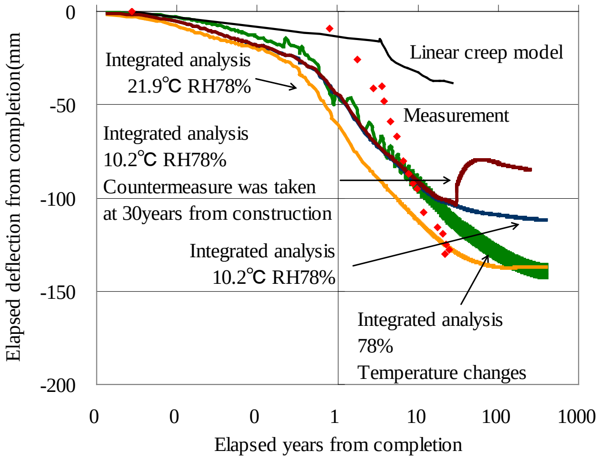

Figure-13 Prediction of future displacement process with the system

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. Even if the geometric shape of the bridge is same, the progress of creep deflection is not same. This is due to the drying rate of the concrete that is governed by the absolute distance from the surface.
5. The multi-scale integrated analytical system predicts the deflection of Tsukiyono Bridge will converge at 140 mm 170 years after its construction.

6. 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.
7. It is expected that controlling the moisture state of the concrete can be used as a simple but effective way to recover the excess deflection of the Tsukiyono Bridge.

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