From Materials to Structures: Advancement through Innovation – Samali, Attard & Song (Eds)

Feasibility study of autonomous deformation control of PC viaducts

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ABSTRACT: In view of the excessive deflections of some PC viaducts, this paper investigates a control method to minimize the time-dependent deflection of bridge viaducts and propose a cross-section consisting of two concrete mixtures having different moisture states, shrinkage, creep and stiffness. Based on this concept, field and indoor experiments were conducted to measure the creep deflection of PC mockups under varying ambient conditions, and the possibility of autonomous deformation control is discussed. Here, the applicability of the multi-scale analysis (*DuCOM-COM3*) is examined as well. The experimental results indicate that non-uniform profiles of moisture may create intrinsic curvature, which may bring about the trade-off of concrete creep, and the varying ambient states may reduce the long-term excessive deflection.

1 INTRODUCTION

1.1 *Research background*

Since the 1990s, the long-term monitoring of Tsukiyono bridge's deflection has been periodically reported by Hata *et al.* (1993) and the imperfection of design methods based upon the conventional linear creep law and shrinkage has been discussed (Watanabe *et al.* 2008). Recently, excessive deflections of cantilever PC viaducts have been reported worldwide by Bazant *et al.* (2011a, b) as well.

Maekawa *et al.* (2010) point out two main causes of excessive deflection; one is the non-uniform thermodynamic state of moisture inside micro-pores and associated creep, and the other is the delayed average shrinkage of upper and lower flanges in time. (Maekawa *et al.* 2010, Ohno *et al.* 2011).

The authors showed the simulated excessive deflection of several PC bridges by considering the non-uniform profile of thermo-dynamic states over the cross-sections and moisture dependent creep properties as shown in Figure 1. At 1250 days after the

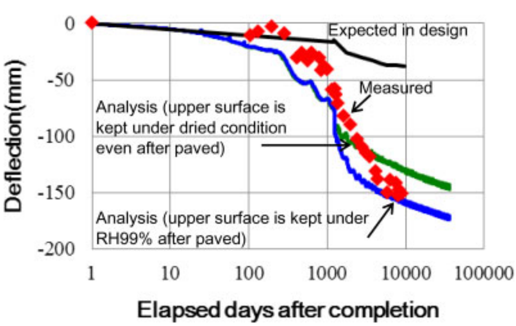

Figure 1. Analytical result of Tsukiyono bridge.

concrete construction, the bridge was paved on the upper flange. In the analysis, two extreme environmental conditions are assumed for practice. One is that the upper flange surface is exposed to the relative humidity (RH) of 99% due to the rainwater that permeates through the pavement to the concrete surface, and the other is that the upper flange surface is kept perfectly dry by the ambient air. It seems that the analytical result of the upper surface kept at RH 99% shows fair agreement with the measured deflection. As a matter of fact, the imperfect water-proof by the pavement overlay has been reported at site. However, there is no quantitative evidence for the moisture balance of bridge flanges with the long-term climate conditions. Furthermore, the multi-scale thermo-dynamic modeling of structural concrete (Maekawa *et al.* 2008), which may simulate this case, has been verified under indoor states without rain precipitation or exposure to sunlight.

1.2 *Scope*

This study aims to suggest a new method to control long-term deflections of PC viaducts without external mechanical devices for controlling deflection such as extra-prestressing, joint clamping or change of supports, which have been applied for repair and retrofitting (e.g. Burdet and Baudoux 1999). This research proposes a new design method that controls the deflection of the structural system autonomously according to the varying climate conditions at each constriction site.

The other purpose is to clarify the influence of rainfall on structural long-term deformation. The numerical simulation in past research suggests that its effect is not negligible on the overall deformation, but it has not been confirmed nor scientifically quantified.

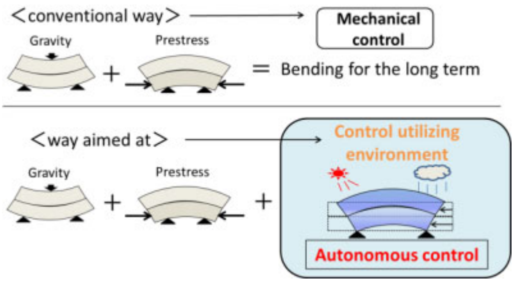

Figure 2. The concept of autonomous control of deflections.

For rationalization of the structural design based upon environmental factors, a way of specifying the boundary conditions is necessary for the surfaces which are exposed to the natural environment.

2 METHODOLOGY

In the present design codes across the world, the only counteractions to bending moments caused by gravity action are prestressing forces. But, the past large deflections observed in practice indicate that the prestressing forces may not sufficiently control serviceability. The authors propose a new deflection control concept referred to as *autonomous* which utilizes annually varying environmental actions represented by relative humidity (*RH*), rainfall and the solar intensity as counteractions to gravity forces (Figure 2). One of the causes of excessive deflection is the difference in averaged shrinkages between upper and lower flanges.

In the *autonomous* control, the responses to the environmental action of upper and lower flanges are varied intentionally. The method allows the designers to specify time-dependent deflection properties against gravity forces. For this purpose, some practical methods are thought to exist, for example, differentiating thicknesses of flanges, water to cement ratio (W/C), or quantities of steel and/or reinforcing bars inside flanges. The possibility of this control concept is discussed in the following sections.

For evaluating the impact of rainfall on structural deformation, the proof-of-concept specimens for *autonomous* control are specifically designed. The specimen is designed to deflect depending strongly on the surrounding environmental conditions. Both specimens are placed on a field; one with a roof, and one without. As this is the only difference between the two specimens, the difference in their deflections must reflect the influence of the rain water.

3 SIMULATION AND PRE-ANALYSIS

3.1 *Outline of multi-scale integrated model*

In the analytical simulation of this study, the *DuCOM-COM3* (Maekawa *et al.* 2008) system is used. This

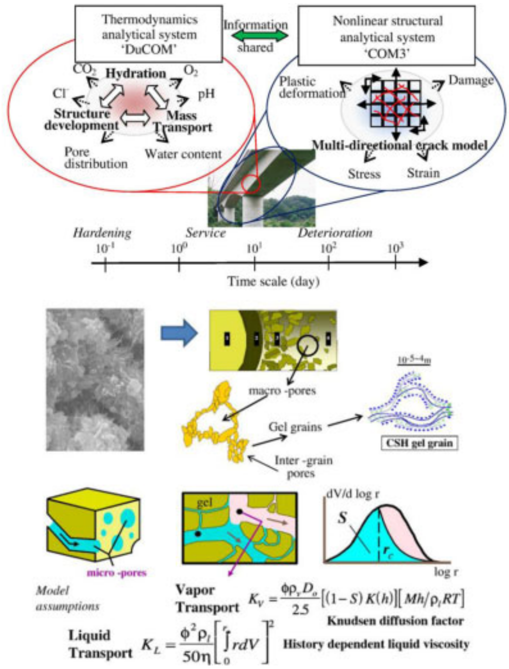

Figure 3. Outline of the multi-scale integrated analytical system, *DuCOM-COM3*.

is a multi-scale analysis code that links the thermo-chemo-physics platforms *DuCOM* (Maekawa *et al.* 1999, 2008) and *COM3* (Maekawa *et al.* 2003) as shown in Figure 2. *DuCOM* is an integrated thermo-hygro analysis code that includes cement hydration in concrete mixture, micro-pore structure formation and mass transport models for concrete ranging from 10^{-3} to 10^{-9} meter scales of micro-voids, while *COM3* is a 3D finite-element analysis platform for structural concrete with and without cracks. As a result, *DuCOM-COM3* is capable of predicting the change in concrete material properties from casting to dismantling of entire structures and taking this material development into account for predicting the response of structural concrete.

With this integration, the long-term structural response under actual ambient conditions can be predicted in a realistic manner. Figure 3 illustrates the code linkage for computing the nonlinear, time-dependent responses of reinforced concrete.

3.2 *Pre-analyses before field experiments*

In order to verify the concept of *autonomous* deflection control, the behavioral simulation of the box-sectional PC beams having upper and lower flanges composed of different W/C ratio-concretes is conducted. The dimension of the target specimens is described in Figure 4. In the pre-analysis, three combinations of upper and lower flanges W/C ratios are assumed. One is the monolithic case (W/C is 62%), the second uses different W/C ratios in the two flanges (upper: W/C

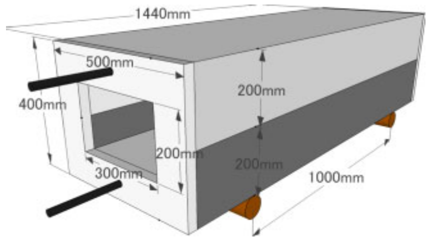

Figure 4. Shape and dimensions of the specimen.

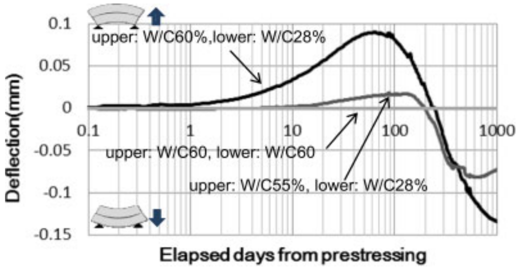

Figure 5. Simulated deflection of the specimen whose upper flange and bottom flange are composed of different water to cement ratios.

55%, lower: 39%), the third uses further variation between W/C ratios with high strength concrete which tends towards self-desiccation (upper W/C 60%, bottom 28%). The assumed environmental conditions are kept at a constant temperature of 20° C, and a constant RH of 60%. Specimens are exposed to the air after 14 days sealed curing, and a 250 kN prestressing force is applied to the upper and lower flanges individually.

When the upper and lower flanges of the beam are composed of the same concrete, the specimen does not deflect upwards or downwards owing to the symmetry of responses under the negligible gravity effects. The PC beam with flanges of different composition cambers until 100 days and then begins to deflect downwards. It is thought that the PC beam with extremely different compositions begins to deflect downwards sharply. If this analysis would assume a cantilever beam instead of a simply-supported beam, the tendency of upwards and downward deflection would be reversed.

By considering this definition, Figure 5 indicates that PC beams whose flanges have different compositions possess a characteristic of counteracting long-term deflections from a long-range standpoint. The deflections are generated based on the difference in volumetric change between upper and lowers flanges caused mainly by drying inside micro-pores and secondarily by creep under sustained stresses.

Figure 6 shows the computed volumetric change of concrete using different W/C ratios, which causes free-stress straining according to the moisture loss from micro-pores of concrete. The PC beams which are composed of different W/C ratios undergo different time-dependent deflections. If these features are

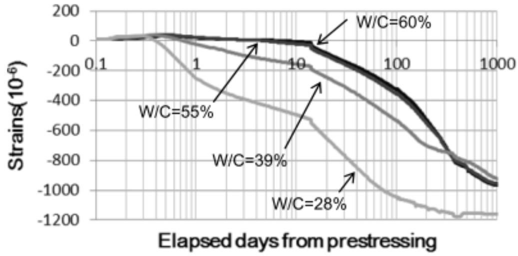

Figure 6. Simulated total strains of the each flange.

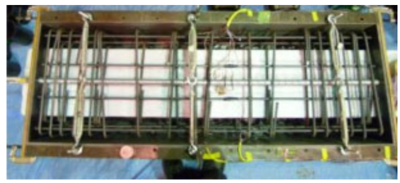

Figure 7. Arrangement of reinforcement: *The diameter of deformed bars is 10 mm. 17 shear reinforcement bars and 14 axial reinforcement bars are arranged.*

Figure 8. Experimental setup: *The machine (left side of the specimen) is to control the temperature and humidity inside the hollow core.*

utilized to counteract the long-term deflections under gravity, it may be possible to compensate deformations autonomously.

4 EXPERIMENT OF A PC BEAM UNDER ROOM CONDITION AND ANALYSIS

The analytical result in Section 3 suggests the possibility of non-mechanical *autonomous* control by using concrete with different compositions in upper and lower flanges. The purpose of this section is to verify the analytical results and confirm the concept analytically, as well as to verify the applicability of the coupled multi-scale modeling *DuCOM-COM3* under variable environmental conditions. The detailed dimensioning of the target PC beam is shown Figure 7 and Figure 8. The compositions of upper and lower flanges are $W/C = 61.5\%$ and 28%. The deflection and axial strains of upper and lower flanges are measured. The deflection in this study is defined at the mid-span of the specimen and proportional to the curvature since the gravity effect is negligibly small. The

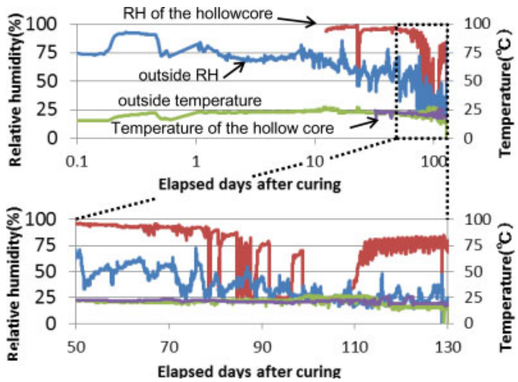

Figure 9. Temperature and relative humidity histograms, outside an inside of the hollow core.

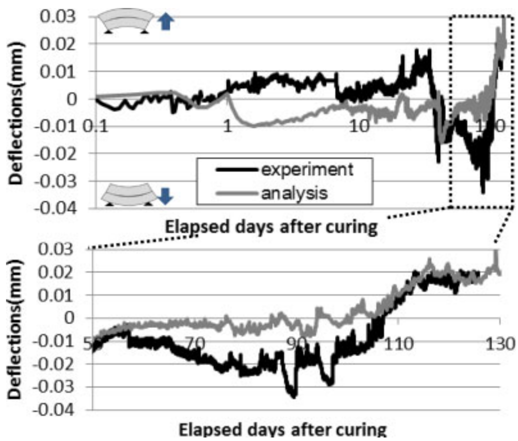

Figure 10. The computed and measured deflection.

specimen was cured for 24 days under sealed conditions, and then exposed to the air in the laboratory. The prestressing force was applied 56 days after casting. The temperature and the relative humidity of the hollow core were controlled from 34 days after casting. The deformational behaviors of the specimens are also computed by *DuCOM-COM3* in accordance with environmental conditions on site.

Figure 10 shows the time-dependent beam deflection after exposure to the air in the laboratory. It can be seen that the different W/C ratios of the upper and lower flanges may lead to the beam cambering as discussed in section 3.

The deflection is rooted in different axial mean strains of upper and lower flanges where the rate of moisture loss and associated shrinkage are not the same. Before operating the environment control inside the hollow core, the specimen tended to warp. This is because the autogenous shrinkage of the lower flange ($W/C = 28\%$) is greater than the upper one ($W/C = 61.5\%$) during early ages. If the period of curing were shorter than the case of this experiment, the effect of autogenous shrinkage would become greater, and the deflection of the specimen would camber more than the observed. Hence, the period of curing should be of great importance in practice.

Figure 9 and Figure 10 show that the relative humidity inside the hollow core has a strong influence on the beam deflection. When the RH is restricted to low levels using environmental conditioning, the PC beam tends to bend downwards because the low RH accelerates the drying and the associated shrinkage of the upper flange ($W/C = 61.5\%$).

After 90 days, the beam began to rapidly camber once more. This is because the increasing humidity caused the upper flange to expand and this compensates for the drying shrinkage. This fact means that adjusting environmental conditions of the hollow core such as temperature and the relative humidity is also an effective way to control deflections.

Figure 10 also shows that *DuCOM-COM3* reproduces the tendency of the deflection of the beam even under varying environmental conditions inside the hollow core.

5 PC BEAMS UNDER AMBIENT CONDITIONS

5.1 *Purpose of the outdoor experiment*

From the experiment under the indoor conditions, the possibility of controlling deflection autonomously is verified. However, there might be potential environmental factors which may have strong influence on the deformational behaviors under ambient outdoor conditions, such as rainfall, snow, wind and solar radiation. The first purpose of this experiment is to grasp the influence of meteorological effects of outside conditions on the *autonomous* control of deflections.

The second purpose is verifying the assumption made in the simulation for Tsukiyono bridge. The influence of the rainfall on the relative humidity of the upper flange is the core of this discussion.

5.2 *Experimental result*

Two specimens with the same properties as that used in the indoor experiment are prepared. One of them was set in the field with a roof and the other was set in the field without a roof (see Figure 11). A PC beam with a roof is not influenced by rainfall and sunlight, whereas a PC beam without a roof is. The difference in their response reflects the influence of the rainfall and sunlight. Two PC beams were exposed to the air after two weeks sealed curing, and a 250 kN prestressing force is applied to both upper and lower flanges 3 days after curing. The information of the daily rainfall has been acquired from the meteorological bureau.

To measure the relative humidity and temperature inside the concrete specimens, small pipes were set before casting and recorders were put in the pipes after demolding (see Figure 12). Figure 13 shows that deflections of the two PC beams drew apart as the time passed and the PC beam without a roof does not deflect even though the PC beam with a roof deflects. The main cause of this difference is the rainfall and

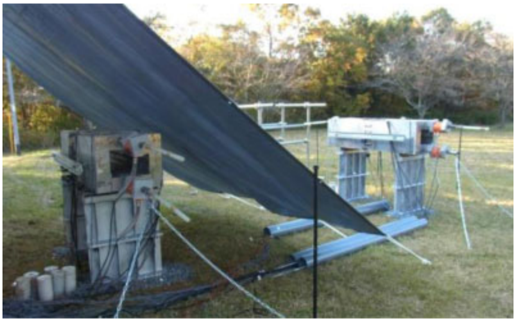

Figure 11. Experimental conditions. *The left side is the PC beam with a roof and the right side is the PC beam without a roof and receives the influence of rainfall, solar-radiation.*

Figure 12. Left: small recorder of temperature and RH Right: the way to measure the internal RH and temperature of both flanges.

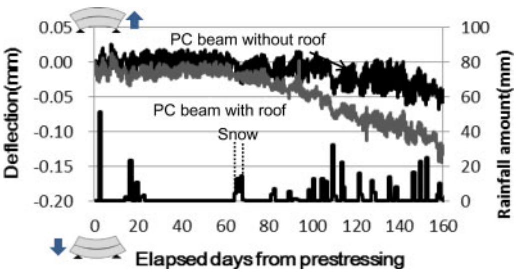

Figure 13. Comparison of deflections with rainfall amounts.

snow in 2012. Rain caused a noticeable increase in the difference in deflection, and snow caused an even more substantial increase. This fact means that the rainfall provided water to the upper surface of the structural concrete, and prevented the upper flange from shrinking. In the case of snow, it covered the surface and supplied water for a longer period than rainfall. This is why the difference in deflections became larger when the snow was observed. Based on these results, the rainfall and the snow have a influence on *autonomous* responses of the member. It implies that rainfall and snow are useful for autonomous control if designing PC bridges which can utilize this impact appropriately.

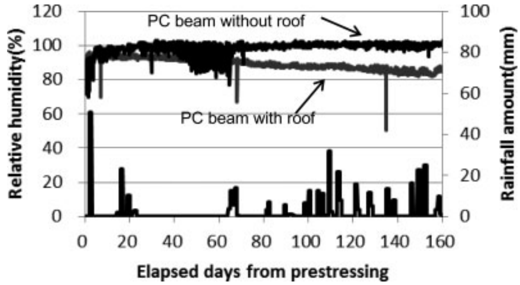

Figure 14. Internal RH of both upper flanges (the PC beam with a roof and the PC beam without a roof) and rainfall amount.

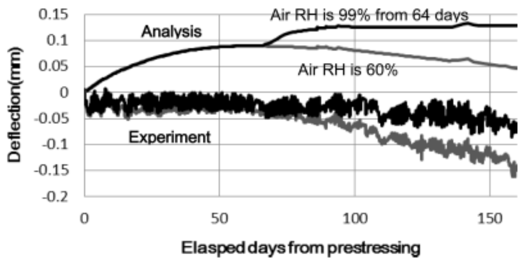

Figure 15. Analysis about deflections of a PC beam in rainy condition and a PC beam which don't take the rainy influence.

Figure 14 shows the change of RH in the upper flanges. In case of the beam with a roof, the RH decreases gradually. On the other hand, the RH of the upper flange without a roof is kept at almost 100%, because occasional rainfall provides the upper flange with water. The impact of one incidence of rainfall lasts for several days.

5.3 *Analytical result of PC beams under rainfall*

In order to understand kinematics of the two PC beams deeply, the simulation is conducted. In reproducing the behavior of the beam with roof, constant environmental conditions (temperature: 20 degree of Celsius, RH: 60%) are assumed. In the analysis to reproduce the beam without roof, the environmental condition from exposure until the 64th day is as same as the beam with roof. After the 64th day, which corresponds to the first day of frequent rainfall, the upper surface is kept under a temperature of 20°C, and a RH of 99%. A 250 kN prestress force is applied to the upper and lower flange of the beams at 14 days from casting.

The analytical result shows initially larger deflections than the experiment because the analysis overestimates autogenous shrinkages of lower flange composed of low W/C ratio-concretes in the early age. The analytical model, especially for early age, is under improvement based on the behavior of micro pore waters. Even in the current model, deflections after 64days can be accurately estimated because the prediction accuracy about strains of low W/C ratio-concretes becomes higher as the hydration proceeds.

The deflection of the beam without a roof does not change much even after raining. The analytical result shows the same tendency. Even though it rains intermittently, the effect on the concrete last for several days after the rain, and its effect can be approximated as RH 99%. In the analysis of the PC beam with roof also reproduces the deflection change observed in the experiment. The main driving force of the deflection is the shrinkage of the upper flange.

In the analyses of Tsukiyono bridge viaduct (Nakamura *et al.* 1982, Maekawa *et al.* 2011), the analytical result assuming the upper flange surface under pavement is kept at RH 99% gives good agreement with the measured deflection. The agreement between experimental and analytical results in this section supports this analytical assumption. The rainwater may penetrate the pavement through fine paths, and it keeps the upper surface of the upper flange wet. This remark shall be verified by some destructive testing in future.

6 CONCLUSIONS

This paper presents research into the autonomous control of PC bridges deflections based on the concept of using different W/C ratio-concretes in one PC bridge member.

1. PC bridge members whose upper and lower flanges consist of different water-cement ratio concretes have the possibility to control deflections autonomously according to the climate variations.
2. Environmental control inside the hollow core of PC viaducts is a possible way to control deflections.
3. The environmental effects of rain and snowfall may contribute favorably to the autonomous deflections against the gravity action by different W/C ratios in upper and lower flanges.
4. Rainfall provides the upper flanges of bridges with water, and by considering this effect, *DuCOM-COM3* can be used for estimating long-term deflections of structures more precisely.

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