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Scientific paper

An Investigation into the Long-Term Excessive Deflection of PC Viaducts by Using 3D Multi-scale Integrated Analysis

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Abstract

This paper investigates the causes of excessive long-term deflection of PC bridge viaducts by using 3D integrated material-structural analyses to take into account the coupled chemo-physics at various scales from the molecular size of water to the structural members. The excessive deflection observed at site is found to be rooted in the deformation of cement paste stemming from both externally applied loads and internal stresses driven by capillary surface tension and disjoining pressures in micro-pores. Not only the former but also the later effect is focused in the serviceability control of PC viaducts. It is found that the nonlinear, long-term deflection of the bridge viaduct can be approximately separated into the components of deflections provoked by external mechanistic and internal thermodynamic actions, even though each component is nonlinearly associated with the thermodynamic states of moisture in micro-pores of cement hydrates.

1. Introduction

A number of prestressed concrete (PC) bridges worldwide have been recently found to exhibit vertical deflection far exceeding the predicted value (Hata *et al* 1993, Bazant *et al* 2010, Burdet 2010, and Burdet and Baudoux 1999). Tsukiyono Bridge in Gunma prefecture, Japan, for instance, experiences creep deflection more than what was expected in design based on the Japan Road Association code (JRA, 1978) after only a few years of service (Watanabe *et al* 2008). **Figure 1** illustrates the discrepancy between the measured and predicted mid-span deflections of the bridge viaduct plotted against time after construction in a semi logarithmic scale. After 25 years of service, the measured deflection was approximately three times higher than the predicted value by the design formulae and has a tendency to keep growing over the next decades. This evidence brings a great concern on the current prediction procedure of long-term deflection, which typically had been derived from small-scale laboratory creep tests, that may be insufficient when applied to PC bridge viaducts of large size. It is, therefore, crucial to evaluate the reliability of current design procedures in predicting the ultimate long-term deflection and to develop a more accurate method for predicting the complete history up to the serviceability limit state.

In Japan, PC bridge viaducts that currently exhibit excessive deflections were constructed before 1990s (Watanabe *et al* 2008). The long-term deflections of these bridge viaducts were generally calculated based on domestic and international code specifications in practice (JSCE 1974, CEB, ACI). As a matter of fact, worldwide concrete standards generally have described the procedure to predict creep strain based upon the so called linear creep law. While this procedure is practically simple, it has the following two major drawbacks:

1) Creep coefficient derives from the data of small-scale laboratory test specimens conducted mostly within a few years. Here, the creep coefficient is typically assumed to be constant or a value obtained from empirical equations derived from small-scale test specimens cured mostly within a few years. Its applicability for both longer period of time and much larger member sizes, which may exhibit quite different profiles of moisture in space and time, has not yet been well verified nor validated.
2) Assumption of uniform concrete drying shrinkage is applied throughout member depth for simplicity of structural analyses. In reality, the intrinsic shrinkage between the surface and the core of a RC member is much different. As parts of the member may vary in thickness and contain different reinforcement ratios, this differential shrinkage often causes internal stresses to develop. Different creep deformations can also be expected and contribute to the overall member deflection. Since concrete creep and shrinkage are greatly influenced by the micro-pore structures of the hardened cement paste and the moisture state in the pores, it is essential to consider these detailed phenomena in order to realistically model the long-term behaviors of structural concrete.

Recently, the authors have developed a 3D multi-scale analysis for concrete structures, namely *DuCOM-COM3* (Maekawa *et al* 2008). The multi-scale analysis provides an integration of the thermo-hygro chemo-physics models of cementitious composites (Maekawa

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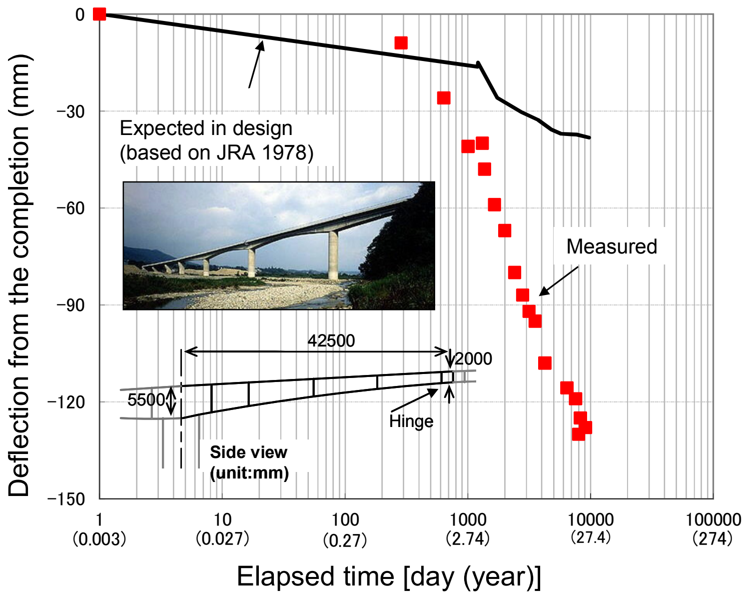


Fig. 1 Observed and predicted displacement of Tsukiyono Bridge.

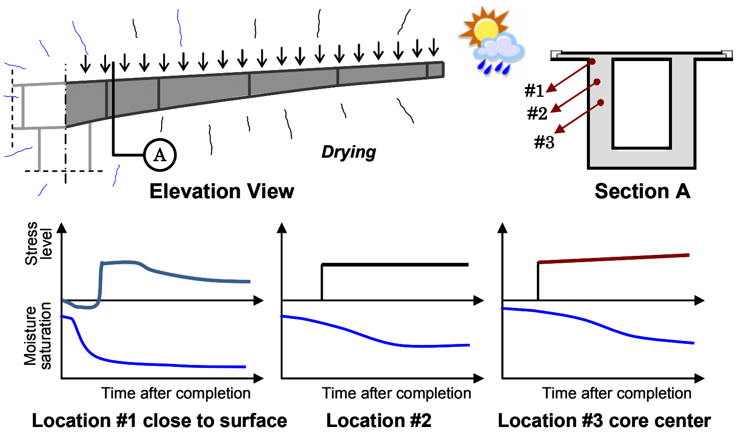


Fig. 2 Problem of interest.

et al 1999) and the mechanical models of reinforced concrete (Maekawa *et al.* 2003). The thermo-hygro models are responsible for computing cement hydration reactions in the composite mixture and the pore structure formation as well as moisture migration in a coupled manner from nm to μm scales, while the mechanical models are responsible for predicting the material-structure response from mm to meter scale based on the space-averaged constitutive laws of cracked concrete. Thus, it is considered that this analysis system is particularly suitable for studying the long-term structural responses of large concrete structures kept under ambient states.

This paper demonstrates the superiority of the 3D multi-scale integrated analysis (Maekawa *et al* 2008) over the conventional methods not only in predicting, but also in explaining the mechanisms of excessive long-term deflections of large PC viaducts in service. As will be demonstrated later, the conventional method is ineffective for two reasons. First, as the thermodynamics states and loading histories in a large structure vary from one location to another as illustrated in **Fig. 2**, a very large number of laboratory tests would be required to predict accurately the long-term behavior of concrete segments under variable environmental conditions. Second, these one-to-one comparisons between laboratory data and parts of structural members would not also be truly valid since there are over a hundred of interaction effects among them (Maekawa *et al* 2008).

On the other hand, the multi-scale integrated analysis allows for the possibility of capturing automatically the different thermodynamics states in structural concrete, including hydration progress, pore-structure formation, and moisture migration, in a coupled manner, while maintaining equilibrium of forces and compatibility of deformations. This study particularly demonstrates the role of two primary factors influencing the excessive deflection, namely: the mechanically and the thermodynamically induced deformational components in time (see **Fig. 3**), and demonstrates that these two compo-

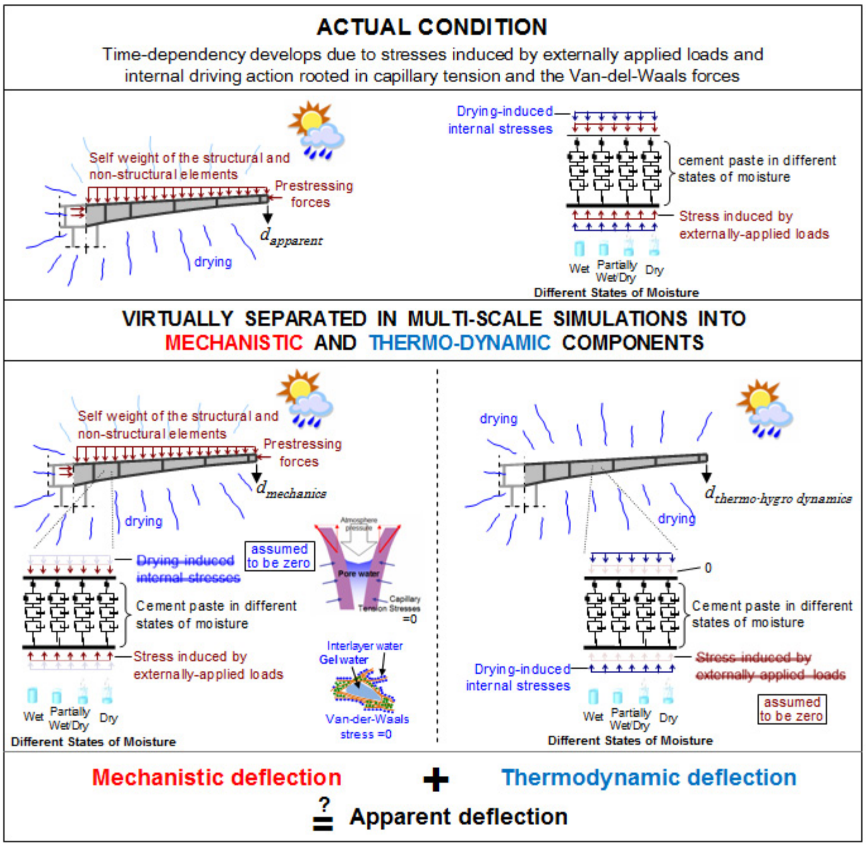


Fig. 3 Target of this study.

nents can be approximately summed up to obtain the apparent deflection. This simple summation of both nonlinear events with regard to deformation was experimentally examined in deep thoughts based upon laboratory-scale specimens by Nagataki and Yonekura (1984) of which offered one of explanation of so called *Pickett effect* of drying creep (Pickett 1942, Bazant 2001). This paper is to take over this discussion on the real-scale structures by means of the multi-scale and multi-chemo physics approach.

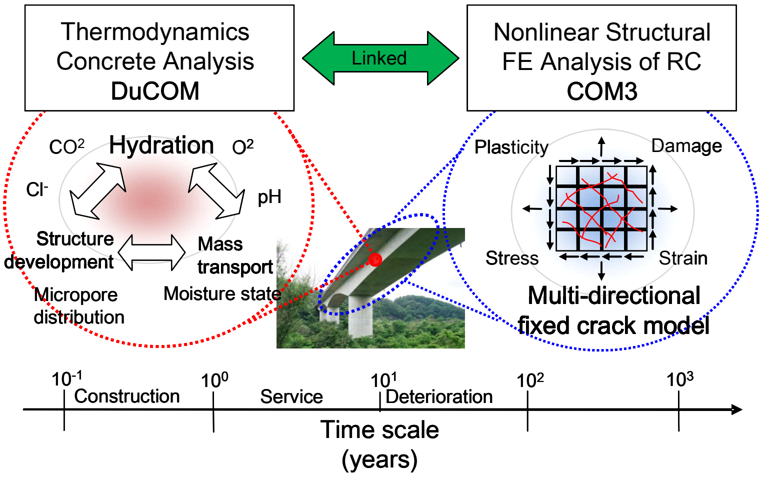
2. Three-dimensional multi-scale coupled thermodynamic and mechanical modeling

2.1 Multi-chemo-physics Integrated analysis

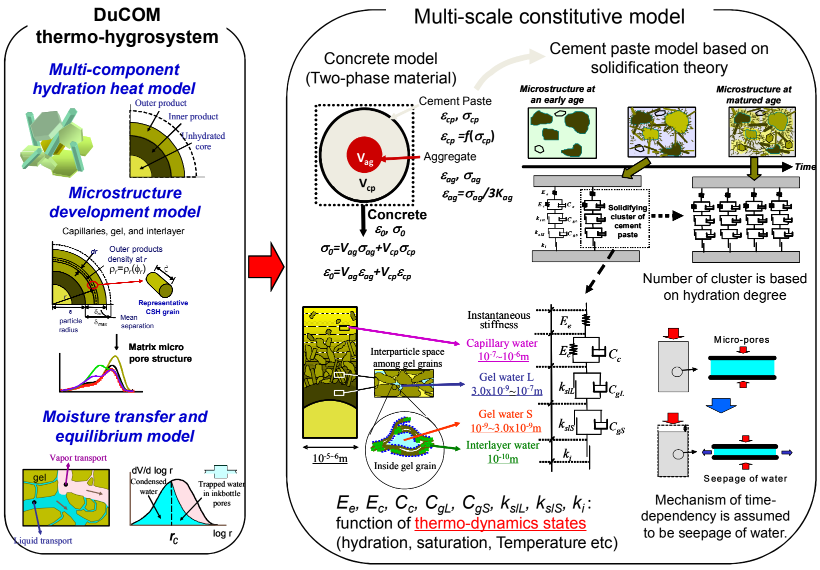
DuCOM-COM3 (Maekawa *et al* 2008) is a multi-scale analysis code that links chemo-physics platforms *DuCOM* (Maekawa *et al* 1999) and *COM3* (Maekawa *et al* 2003) as shown in **Fig. 4a**. *DuCOM* is an integrated thermo-hygro analysis platform that includes hydration, micro-pore structure and mass transport models for concrete ranging from 10^{-3} to 10^{-9} meter scale, 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, long-term structural response under actual ambient conditions can be predicted in a realistic manner. **Figure 4b** illustrates the *DuCOM-COM3* linkage for computing the nonlinear, time-dependent responses of reinforced concrete. The two analysis platforms are linked with time-dependent constitutive models (Asamoto *et al* 2006) and will be discussed in the following subsection.

2.2 Time-dependent constitutive model

A schematic representation of the time-dependent constitutive models for concrete is shown in **Fig. 5** (Maekawa *et al* 2009, Mabrouk *et al* 2004, and Asamoto *et al* 2006). Numbers 1 to 5 in the figure illustrate five components assigned to account for different phenomena in concrete composite in accordance with the dimensions of micro-pore structures and the state of moisture in the pores. Component 1 is an elastic model to account for the instantaneous elastic strain caused by the deformation of the hardened cement hydrates. Component 2 is a visco-elastic model to represent the response associated with the state of the capillary water in large pores of the scale 10^{-6} to 10^{-8} m. This component contributes significantly to the progress of creep at the initial stage of loading. Components 3 and 4 are visco-plastic models for representing the non-recovery deformations due to the migration of water in gel pores of the scale 10^{-8} to 10^{-9} m. These two parts play a dominant role over a long-term loading history. Component 5 is a plastic model for representing the phenomena in inter-



(a) General overview of DuCOM-COM3 linkage



(b) Scheme of time-dependent modeling associated with thermo-hydro states (Maekawa *et al* 2008)

Fig. 4 Outline of the multi-scale integrated analysis system.

layer pores of the scale of 10^{-10} m associated with extremely severe ambient conditions such as under high temperature or low humidity, when the evaporation of water is of great significance.

Note that as the state of moisture in concrete at a point of interest varies with time depending on the boundary conditions involved (for example, the distance to the concrete surface, environmental conditions), the values of the parameters assigned in Components 2 to 5 obviously varies with time, depending on the thermodynamics moisture state. The values of the parameters assigned for different states of moisture at different scales are given in Asamoto *et al* (2006). The proposed time-dependent models have been validated by using laboratory-scale concrete specimens for predicting behaviors of autogenous and drying shrinkage as well as basic and drying creep under various ambient conditions with high accuracy (Maekawa *et al* 2008 and Asamoto *et al* 2006).

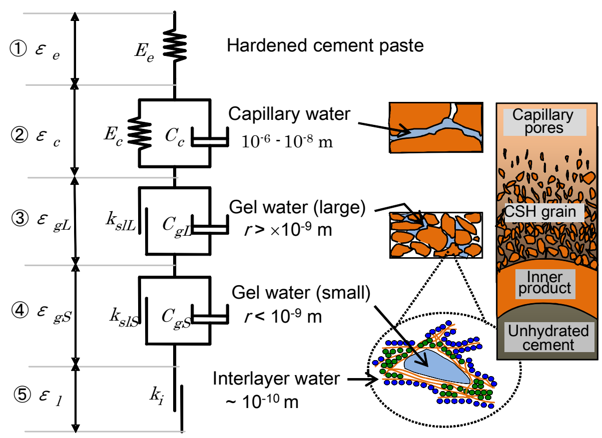


Fig. 5 Schematic views of time-dependent constitutive models in DuCOM-COM3.

3. Application to long-term deflection analysis of PC bridge viaducts

3.1 Details of four PC bridges Viaducts in Japan

Four PC bridges in Japan are modeled and analyzed, namely Tsukiyono, Konaru, Fukarani, and Urado Bridges. These bridges were completed in 1982, 1987, 1987 and 1972, respectively. After its completion, Urado Bridge held the world record on the span length for a segmentally-erected PC viaducts. The design drawings, constructions procedure and field-measurement data of these bridges have been preserved in detail and can be partly found in Nakamura *et al* (1982), Watanabe *et al* (2008) and Bazant *et al* (2010).

Tsukiyono Bridge is a 4-span segmentally-erected PC hinged bridge constructed with the P&Z method in which two bridge segments extending from a new pier were cast onsite and then prestressed after complete construction of a half span from the previous pier (Nakamura *et al* 1982). Only half span between Piers P4 and P5 is subjected to the analysis (see **Fig. 6**). The bridge girder cross-section has a hollow shape, with a depth which varies between 5.5 and 2.0 m from the location above the pier to the center span hinge. The top flange thickness is constant at 0.30 m, while the bottom flange thickness varies between 0.3 and 0.8 m, and the web thickness varies from 0.35 to 0.6 m, varying continuously from the location above the bridge pier to the hinge at the span center. The width of the bridge cross-section including guide-railing is 10.65 m, with the upper flange sticking out from the web by 2.4 m. The reinforcement ratios in the upper flange of the girders is of approximately 0.86%, while the reinforcement ratios in the side and bottom flanges vary between 0.16 and 0.27%, and 0.14 to 0.57%, from the location above the pier to the mid-span, respectively.

The dimensions of Konaru, Fukutani, and Urado Bridges are also shown in **Fig. 6**. Similar to Tsukiyono Bridge, they are all PC viaducts, having a hinge at their each center span and hollow-shape girders. The dimension of each bridge cross section is given in details in **Fig. 6**. Without repeating the details again here, one

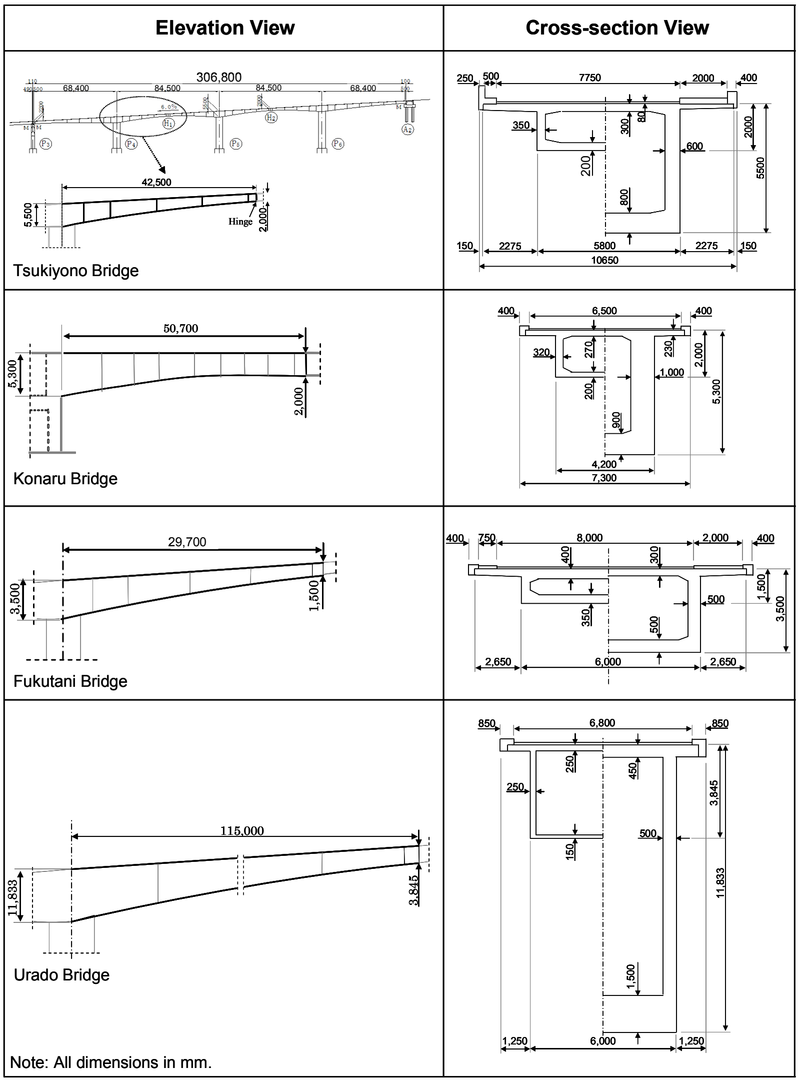


Fig. 6 Details of the four bridges.

should refer the dimensions directly to the figure. The reinforcement ratios in the flanges of the bridge girders are comparable to those of the Tsukiyono Bridge.

Each bridge is modeled as a statically determinate cantilever, representing the half selected span from the girder above the support to the hinge at the center span, with no exception to Fukatani Bridge, whose center hinge was firmly connected after ten years due to the excessive deflection. In the analysis, this retrofit is not taken into account for investigating the limit state on the long-term deflection.

3.2 Finite-element discretization

Figure 7 shows finite element discretization used for all bridges. The element size near the structural surface was set in the order of mm scale because of the occurrence of high local moisture and pore water pressure gradients as a result of continuous exposure to the ambient conditions, particularly immediately after removal of formworks. The fine mesh size is needed to achieve a numerically stable convergence of moisture profiles (Bathe and Cimento 1980). The element size along the longitudinal direction of the viaduct is set at a range of 0.5 to 1.5 m. This discretization has been determined after a careful check on the potential ill-condition due to shear lock in the mechanistic term. For the flexure-dominant mode of this particular problem, the selected dimensions were confirmed to be efficient after checking the convergence with regard to the slenderness ratio of elements with the double-precision direct matrix solver. The high element slenderness ratio near the surface has been confirmed not to affect the accuracy of moisture profiles as well. If we have more increased slenderness of elements, the shear locking definitely takes place.

Furthermore, a time step of 0.01 day is set forth just after framework stripping to maintain the convergence stability. After a couple of months, a time step of 0.1 year is considered as local moisture gradients have become smaller. To complete one simulation of a bridge, a computation time of approximately one day is required on a desktop computer with an 8-core 3.0 GHz processor and 48 GB of RAM. The memory usage for the computation was about 2 to 3 GB.

3.3 Analysis conditions

For all analyses, the self-weight of the viaduct, pavement and parapets are applied to the structure as external loads. The prestressing force is simulated by applying a pre-strain to the high-strength tendons, which are computationally anchored to the main body of the viaduct two weeks after concrete casting at once. For these long-span bridges, the traffic load is ignored in the analysis as its impact to the long-term deformation is considered to be minor, as compared to that of the self-weight. The deflection at the time of loading is defined as the initial one, and the computed incremental deflection is compared with the site measurement. As the real construction process for one span took about six months and the origin of the measurement was at completion of construction, it should be kept in mind that the analysis result in the period of first several months must overestimate the measured deflection.

The concrete mix proportions used in the bridges are listed in **Table 1**. The mix proportion for Konaru Bridge is assumed to be the same to that used in Tsukiyono Bridge. This assumption is made since the two bridges were designed based on the same design code and were constructed at the same decade. Furthermore, the specified concrete grade used in various bridge projects in Japan at that period of time was quite similar in terms of the compressive strength and slump so as those used in the two bridges. Based on the mix proportions listed, the property of the concrete used in the bridge are computed at each time step.

The environmental conditions used in the analysis are shown in **Fig. 8** and **Table 2**, obtained from the meteorological data near the site. The monthly average temperature and humidity were considered to take the seasonal fluctuation into account. These environmental

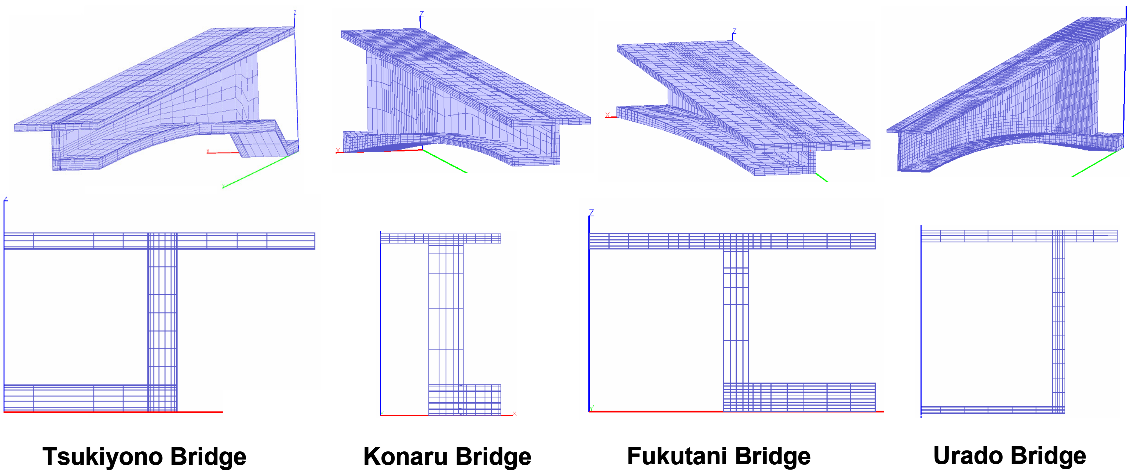


Fig. 7 Finite element meshes of the bridges targeted in this study.

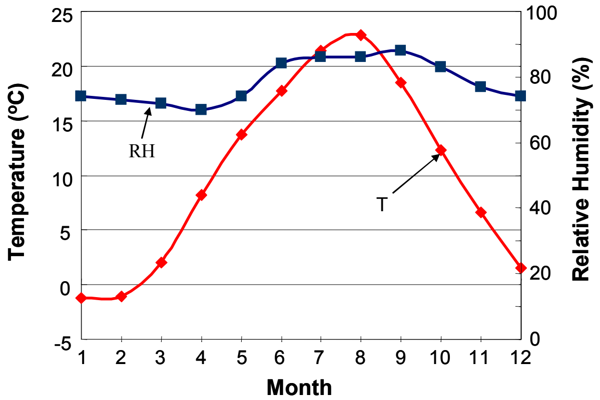


Fig. 8 Monthly temperature and relative humidity variations at a site near Tsukiyono Bridge.

conditions are applied to inside and outside the bridge girders, except for the top flange surfaces below the pavement, which are considered to be sealed in terms of moisture migration.

3.4 Verification of coupled analysis modeling

Figure 9 shows the comparisons of the vertical deflections of the four bridges based on the field measurement, design prediction, and analysis results. In general, the 3D coupled analysis is capable of reproducing the excessive deflections of the four bridges, while the design code predictions always underestimate the measured ones except for Urado Bridge, in which the creep coefficient in design was set approximately 60% higher. The fluctuations seen in the analysis-predicted deflections are caused by temperature and humidity seasonal variations. The importance of considering this seasonal fluctuation is discussed in details by Maekawa *et al* (2011). It is interesting to note that the rate of the time-dependent deflections starts to evolve after approximately 100 days, attributed primarily to the migration of water in concrete gel pores. The difference between measurement and analysis in the early period is thought to attribute to the simplified construction process in the analysis as stated previously. This simplification was confirmed to result in a marginal difference in the calculated displacement of the Tsukiyono Bridge after several years of construction over the the calculated displacement considering detailed construction processes (construction sequence, prestressing, and curing) (Maekawa *et al* 2011).

Table 2 Annual temperature and relative humidity ranges in monthly average values.

Bridge	T (°C)	RH (%)
Tsukiyono	-1 - 23	70 - 88
Konaru	5.2 - 27	62.5 -72.3
Fukutani	3.3 - 26.5	66 -79
Urado	6.1 - 27.2	59 -79

For the Konaru Bridge (see **Fig. 9b**), the analysis predicted deflections reflect the measured values as well. The progress of the bridge deflection can be more clearly seen from the analysis results than from the very limited measurement data. It appears that the bridge deflection will converge to a value of approximately 230 mm.

Figure 9c compares the measured and predicted mid-span deflection of Fukatani Bridge. Two sets of field-measurement and design-prediction data are available. The measurement data were obtained from two different locations, while the two design-predicted deflections were the results of considering both sides of cantilever from the main span. Apparent differences between measurement and analysis can also be seen during the first 100 days, with the analysis predicted deflections always overestimate the measured values. In addition to the simplified construction procedure, this overestimation is attributed to higher W/C concrete than those used in the other three bridges, leading to slower development of concrete mechanical properties.

The comparison of the deflection history of Urado Bridge based on field-measurement, design prediction, and analysis is shown in **Fig. 9d**. Once again, the analysis based prediction provides a better estimation of the long-term displacement than the design-based one. Not only the final long-term creep deflections, but the displacement progress can also be well simulated. In contrast to the results reported by Bazant *et al* (2010), the

Table 1 Composition and mix proportion of concrete.

Composition of concrete					
Bridge	f_c' kg/cm^2	Cement Type	Maximum Aggregate Size, mm	Air Content %	Slump cm
Tsukiyono	400	High early strength	25	4	-
Fukutani				3-5	8.5-13.5
Urado				2-4	3-8

Mix proportion of concrete						
Bridge	Weight (kg/m^3)					Remarks
	Cement	Water	Fine Aggregate	Coarse Aggregate	Admixture	
Tsukiyono	423	165	639	1108	1.0575	Summer
	440	167	629	1099	1.1000	Other seasons
Fukutani	416	177	684	1036	1.0400	-
Urado	400	152	645	1217	1.0000	-

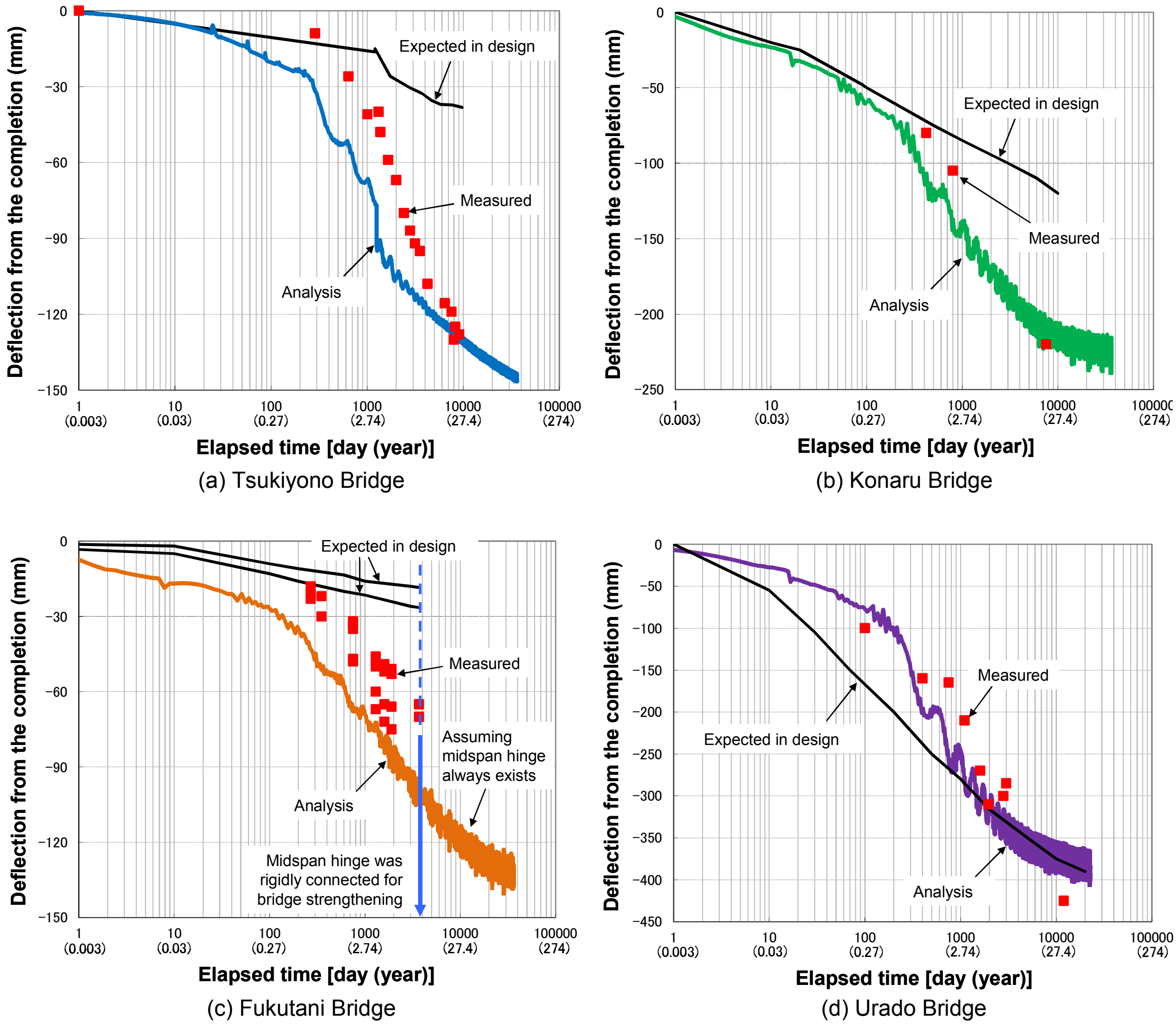


Fig. 9 Comparisons of the mid-span deflections of the analyzed bridge viaducts based on field measurement, design expectation, and the full coupling analysis results.

rate of the bridge deflection after 30 years is predicted to be milder and has a tendency to soon converge.

The successful reproduction of the long-term creep deflections of the four bridges having different structural geometries, material properties, and ambient conditions validates the applicability of the integrated analysis system. Since the deflections of the bridges are predicted to still progress and converge in the next half century, continuous monitoring of the bridge deflections is essential for further computational validation in the future.

4. Mechanistic and thermo-hygral induced deformations - delayed shrinkage -

Two time-dependent mechanisms as illustrated in **Fig. 3** are thought to be responsible for the excessive deflections observed; mechanistic-induced creep and thermo-hygral-induced creep or delayed shrinkage in appearance. The mechanistic creep is thought to arise from the self-weight and the externally applied loads, while the thermo-hygral creep is from the internal capillary tensile and Van-der-Waals stresses in the concrete gel pores, namely hereafter the *internal driving force*. It is expected that the magnitude of this force greatly varies across the bridge depth due to differences in moisture content. As the upper flanges typically contain more numbers of PC strands, their shrinkage rooted in the internal driving forces is comparatively restrained more than the lower flange. As a result, additional curvature further develops and causes the bridge girder to deflect.

To provide the first indication of the two creep mechanisms, a parametric analysis on a cylinder specimen of diameter 100 mm and height 200 mm subjected to compression is made. Computationally the cylinder specimen is first submerged in 20°C water for 28 days,

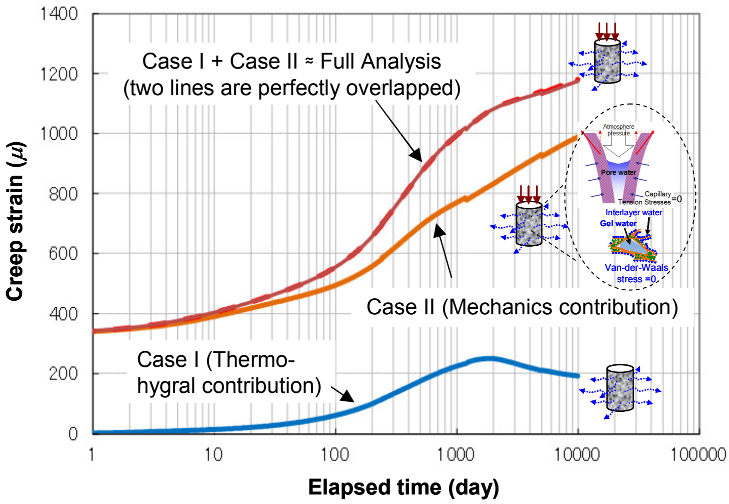


Fig. 10 Contribution of thermo-hygral and mechanical creep deformations in a cylinder specimen subjected to compression.

and then loaded in a sealed condition. Two analysis cases are discussed for contrast; Case I, which aims to study the sole effect of thermo-hygral creep, considers no self-weight and external loads, and Case II, which aims to study the sole effect of mechanistic creep, assumes no internal driving force occurring in the concrete (no capillary and Van der Waals stresses in concrete gel pores; for definition refer to Asamoto *et al* (2006)). Note that although the internal driving force in Case II is neglected, the transport and the consumption of moisture for concrete hydration are still considered. This means that the moisture-dependent creep rate associated with the mechanistic actions is still taken into account. The result of the analysis is shown in **Fig. 10**. It can be seen that the time-dependent deformations of the cylinder in consideration of simultaneous drying and loading is the same as the total deformation obtained from drying and mechanical loading alone.

To further develop a better understanding of the external and internal mechanisms in real-scale structures, parametric analyses are made to the four bridges of interest. These bridges are analyzed for the same analysis cases as aforementioned used for the cylinder specimen. That is, Case I considers no loads acting on the bridge, while Case II considers all the self-weight and external loads and assumes no internal driving force in the concrete. The service load in Case II is neglected as its magnitude is comparatively small, as compared to that of the self-weight, and as it does not trigger cracking. The 3D multi-scale analysis for structural concrete makes it possible to perform these two virtual analysis cases for better understanding of the underlying mechanisms. The temperature and relative humidity in the analysis are maintained constant at 15.8°C and 67%, respectively. **Figure 11** shows the contribution of the thermo-hygral and mechanical deflection of each bridge in time. As can be seen, the contribution of the thermo-hygral internal force-induced deflection (Case I) is notably significant of approximately 25% to 45% of the total deflection. As can also be seen, it is interesting to consistently observe that the long-term displacement of the four bridges considering drying and loading at the same time (Full Analysis) is approximately similar to the one obtained from adding the displacement caused by internal thermodynamics actions (Case I) to the displacement due to the external loads (Case II), although the two analysis responses are highly nonlinear in nature with respect to thermodynamic states of moisture.

This summation is possible since the applied stress level is relatively low and within the serviceability limit state. Moreover, it can also be seen from both analysis cases (Cases I and II) that the rate of the deflection is accelerated after about 100 days. This acceleration is thought to be caused by the transport of moisture in concrete gel pores as well as additional creep caused by the *internal driving force* provoked by drying. Thus, it is obvious that full consideration of moisture transport in the concrete pores is of heightened importance to predict accurately the long-term deflections of large PC viaducts. Failure to do so, e.g. simply using the linear creep law, will result in significant underestimation of the long-term deflection of cantilever hollow type PC viaducts, as currently observed in several long-span bridges (Watanabe *et al* 2008). In other words, the conventional approach may hardly treat the apparent delayed shrinkage of large scale members owing to the delayed moisture loss rather than the smaller test specimens on which the empirical formula of shrinkage derived.

The computed deflections of the four bridges as shown in **Fig. 11** also indicate that they settle down at approximately 30 years after construction. This phenomenon computationally occurs by two reasons. First, the reduced rate in the computed deflection after long time exposure is attributed to the gradual release of trapped water in small pores due to so-called inkbottle mechanism (Ishida *et al* 1998). The consideration of this mechanism would be important for the prediction over a

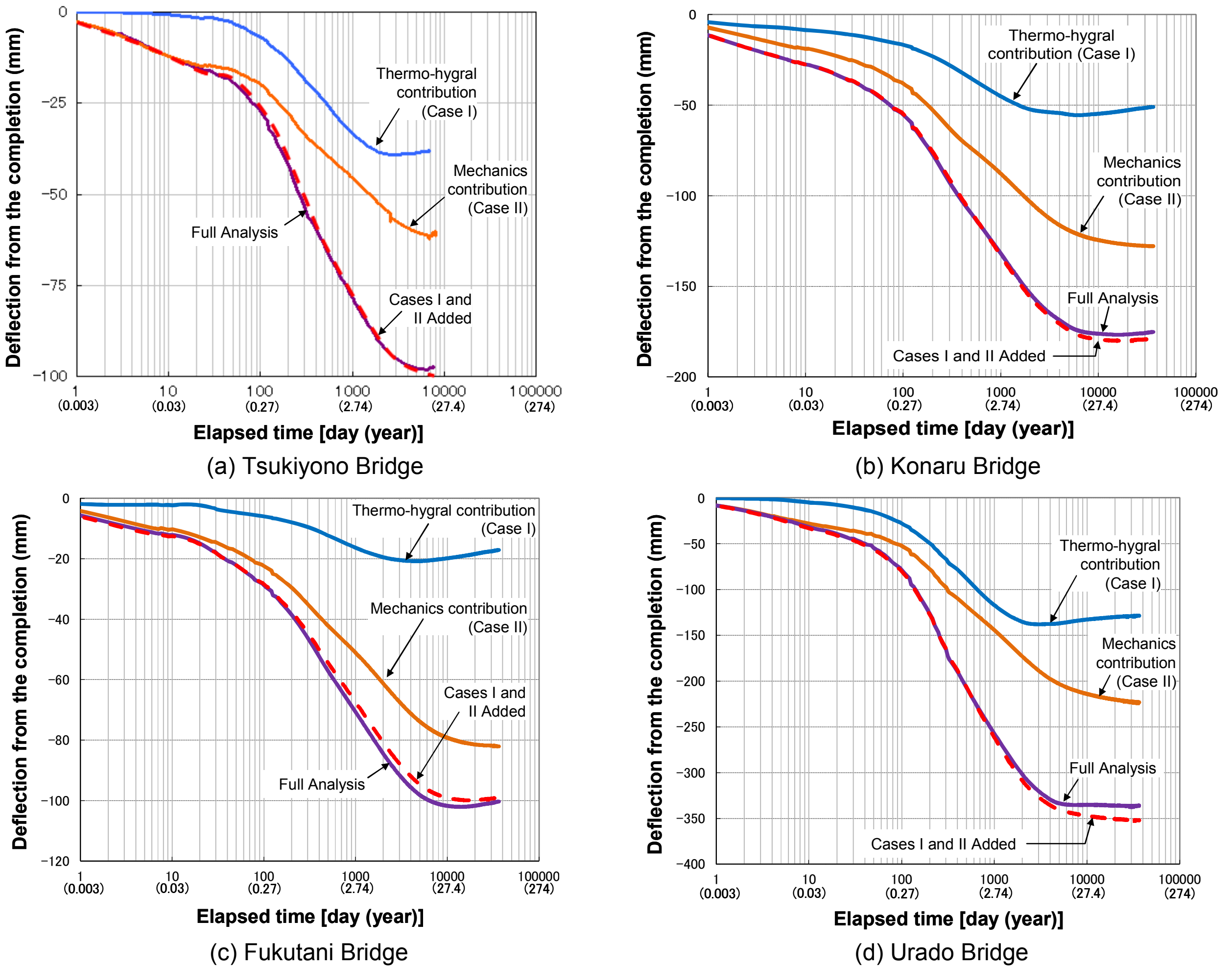


Fig. 11 Long-term internal driving force-induced deflections attributed to concrete drying and the effect of externally-applied loads.

century, and is open for discussion due to limited experimental drying creep data available for such a long term exposure to date. Second, the parametric analysis shown simplifies the problem by assuming a constant average humidity and temperature. The assumption in constant temperature was found to decrease the apparent deflection rate at long time exposure (Maekawa *et al* 2011), thus leading to an apparently earlier time of terminated deflection.

Finally, an attempt is made to explicitly evaluate the thermo-hygral deflection observed by relating the bridge cross-sectional curvature to the overall mid-span deflection of the viaducts. The following equation is considered to be approximate based on the beam-fiber hypothesis, i.e., in-plane theory as,

$$\omega = -\frac{\varphi}{2}L^2 = -K\frac{\Delta\varepsilon}{2h}L^2 \qquad (1)$$

where ω is the bridge deflection at the tip of the cantilever-span, φ is the bridge cross-sectional curvature, L is the span length from the face of the pier, $\Delta\varepsilon$ is the strain difference between the upper and the lower flanges, h is the average depth of the box girder, and K is a shape factor to account for the depth change of the bridge segments from pier to mid-span. It is expected that the value of K should be in the range of 0.8 to 1.0, with a value of 1.0 representing a uniform depth. In this paper, a value of 0.9 is assumed. **Table 3** compares the results

Table 3 Comparison of mid-span deflection based on full 3D analysis and simplified equation.

Bridge	L mm	h mm	$\Delta\varepsilon$ μ	d (Analysis Case 1) mm	d (Eq. 1) mm
Tsukiyono	39,450	3,136	182	40.2	40.7
Konaru	50,700	3,168	152	55.6	55.5
Fukutani	27,950	2,232	130	20.8	20.5
Urado	111,250	6,830	170	138	138.6

of full coupled FE analysis and Equation 1 for the four bridges. As can be seen, the comparison is within a practically reasonable range, provided that the $\Delta\varepsilon$ values are the values obtained from the coupled analysis. Given the $\Delta\varepsilon$ values of the four bridges are within a small range (130-182 μ), it is encouraging to obtain a general estimation of the $\Delta\varepsilon$ values over a wide range of conditions. It should be noted that these strain values are highly moisture-dependent, and hence might be hardly estimated by some empirical formulae for drying creep even though the Pickett effect (1942) has been taken into account at the size of concrete specimen. By contrast, the multi-scale approach brings about a rational basis regardless of size and time scales as demonstrated in the previous chapter and in Maekawa *et al* (2011). Some practical way of expressing these values, without high performance computation, remains undeveloped. This is a challenge of future study especially for revising design code specifications.

6. Conclusions

Conclusions achieved in this study are shown below.

1. The integration of thermodynamics and mechanistic models enables the prediction of long-term deflection of PC bridges well, provided that the analysis is capable of relating the development of concrete properties and the states of moisture in the concrete at different locations to the overall structural response.
2. The analysis demonstrates that excessive creep deflection is due to both externally-applied forces and thermodynamic states of moisture in the concrete micro-pores. The design-predicted deflection grossly underestimates the actual deflection as it does not consider the coupling between the mechanical creep and the thermo-hygral creep on the deflection computation.
3. The long-term time-dependent deflection caused by delayed drying shrinkage of the concrete contributes of approximately 25% to 45% of the total deflection of four real bridges observed and hence must not be practically neglected in design.
4. The nonlinear long-term deflection of PC bridge viaducts can be approximated by adding the mechanical and thermo–hygral components of transient deformation over the years, provided that the stresses in the concrete are within the serviceability limit state.

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