Bridge deck deflection: importance of early shrinkage

Philippe Menétrey, Claude Broquet and Francisco Pires

INGPHI Ltd, Concepteurs d'ouvrages d'art, Lausanne, Switzerland

Contact: www.ingphi.ch

Abstract

The construction of the viaduct over the A9 highway, a semi-integral prestressed concrete bridge with a total span of 351.60 m, was accompanied by uncertainties about the importance of long-term effects on the deck deformations. To clarify these, deformation measurements have been carried out using optical fibers, which turned out to be a powerful measurement tool enabling the recording of the whole construction process.

The measurements of the deck allowed identifying the various causes of deformation: an expansion period caused by the hydration heat release, a contraction due to early shrinkage; some deformations due to construction stages such as prestressing of the deck and lowering the formwork, and deformation due to creep.

Analysing the early stages of deformations allowed the development of a structural model for concrete which distinguishes the point of zero deformation and the one of zero stress. The point of zero deformation occurs after the dormant phase, some hours after concreting, when concrete is transforming from liquid to solid state. The point of zero stress occurs few days after concreting when the deformations reach a clear peak value defined as the "birth of the concrete structure". Up to this point of birth, the deformations occurring in the structure induce stress. Distinguishing these two points allows matching the experimental measurements and explaining the early cracking observed in concrete structures.

It is shown that prediction of the deformations with numerical models is possible as long as the construction stages, the long-term effects and early shrinkage are considered. However, early shrinkage occurring after the birth of the concrete structure, which reaches values around 0.3 ‰ during the first weeks, has to be added to the currently used strain values of shrinkage. Generally speaking, early shrinkage has to be considered in the design to explain and avoid early age cracking in concrete structures.

Keywords: bridge behavior, deformations measurements, early shrinkage, fibre optic sensor, creep and shrinkage, numerical simulation, construction stages, birth of concrete structure.

1 Introduction

1.1 Description of the bridge

The bridge over the A9 highway (Menétrey and al. [1]) is located near the village of Rennaz in Switzerland. This bridge has a partially curved shape and allows the new Chablais-region road to pass over the A9 highway, the RC 780 cantonal road and several farming.

The bridge has a total length of 351.60 m with 11 spans of 33 m length in average. This length is increased to 34.80 m for span T3 to pass over the highway and decreased to 26.40 m for the side spans, as shown on the longitudinal cross-section in Figure 1.

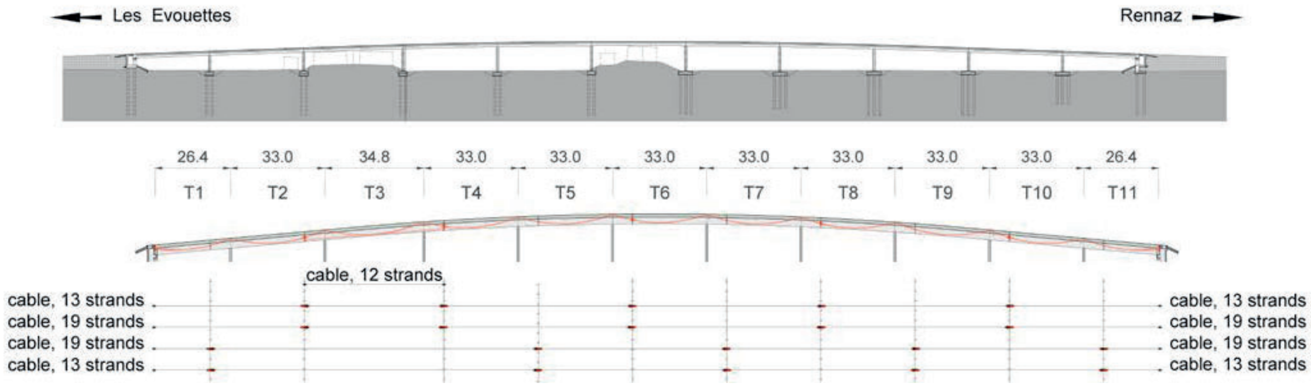

Figure 1: Longitudinal cross-section and prestressing plan

The deck is made of prestressed concrete with a constant cross-section over the whole bridge length. The deck consists of a road slab stiffened by two longitudinal ribs, each resting on the arms of V-shaped piers. These pier arms are placed on a foundation supported by piling. The transversal cross-section of the deck, piers and foundations is shown in Figure 2 while a view of the bridge in a straight section as constructed is shown in Figure 3.

The deck is prestressed longitudinally with 4 cables following a parabolic layout, 2 of them with 13 strands and of the other 2 with 19 strands. At each construction joint only 50% of the longitudinal cables in the same cross-section are coupled. Each of the two ribs in the T3 span above the highway is reinforced with an additional straight cable made of 12 strands and placed in the bottom part of the cross-section. The longitudinal prestressing layout is shown at the bottom of Figure 1.

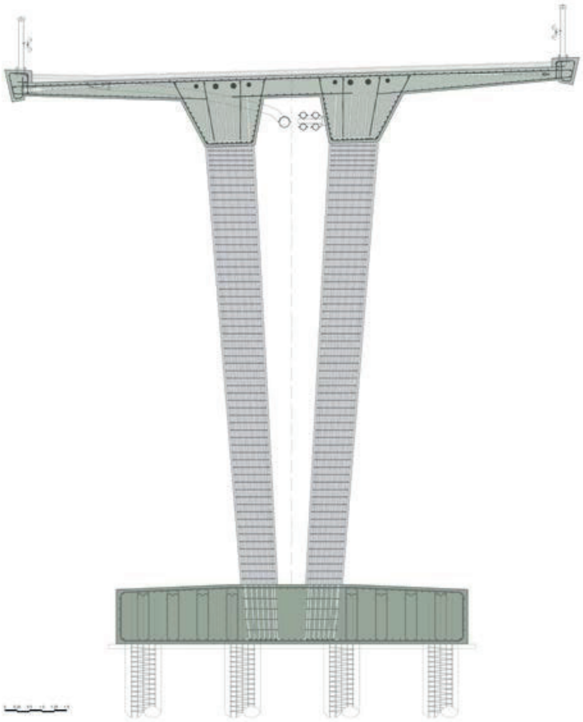

Figure 2: Transversal cross-section of the deck, the pier and the foundation

Figure 3: View of the bridge in the straight section

1.2 Construction of the bridge

The construction of the bridge started with span T3 over the highway. This has been realized with an overhead spanning gantry above the bridge deck (Menétrey and al. [2]) in order to not disturb the highway road traffic. For the other spans, the formwork was arranged span by span under the deck level and was supported only by the pile caps thus avoiding any temporary supports. The construction order of the spans followed the sequence: T3, T2, T4, T1, T5, T6 and so on.

1.3 Problems with longitudinal deformation

The viaduct is a semi-integral bridge since it is rigidly supported by all the piers except for the two end-piers on top of which a concrete hinge is created. Sliding bearings are only placed at the abutments. This static system allows limiting the maintenance by reducing the amount of mechanical bearings. However, it is necessary to control the deck deformations because shrinkage, creep and temperature variations can create bending moments in the piers.

It has been decided to measure the deck deformations and to compare it to the results obtained with numerical simulations. This article summarizes the main results of these investigations which are described in details in Menétrey et al. [3].

2 Deformation measurements

The deformation measurements of the bridge deck have been carried out on a straight section of 70 m long located in the zone which crosses the highway and including spans T2, T3 and T4.

The fiber optic sensors have been placed in 5 different locations of the deck as illustrated in Figure 4. In each location, a sensor is placed at the bottom and top fiber of each rib for a total of 20 sensors in the bridge.

These sensors record the length variation between a reference fiber and a measurement fiber as described by Glisic and al. [6] and [7]. They are placed in a 5 mm diameter nylon tube allowing recording the deck's behavior without interference.

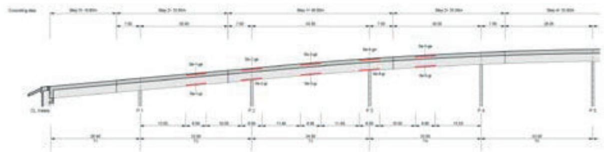

Figure 4: Location of the fiber optic sensors in the deck (deformed scale)

With these 20 sensors, measurements have been carried out during the first construction stages: after concreting, after prestressing and after lowering the formwork. For certain spans and periods, measurements have been carried out continuously.

The measured deformation is an average deformation over the 6 m sensor length.

3 Concrete deck

The concrete used for the deck has been defined per EN 206 [8] with concrete grade C 35/45, exposure classes XC3 / XD1 / XF2, content of chloride Cl 0.10, watertightness and alkali-aggregate reaction resistance.

The concrete is made with 375 kg/m^3 of type Bisolvo cement, which is a Portland cement that consists of CEM II / B-M (V-LL) 32, 5R. The hydration heat release tests show a heat release of 73'900 kJ/m^3 after 48 hours and 91'100 kJ/m^3 after 120 hours. The average compressive resistance on a cube after 28 days varies between 51.6 MPa and 62.5 MPa. The concrete of span T2 has a lower average resistance of 42.0 MPa, probably since it has been mixed with antifreeze due to cold temperatures.

Deformation on the cylinder due to shrinkage is ε_{cs} (28 days) = 0.311 ‰, ε_{cs} (365 days) = 0.527 ‰

and the creep coefficient under a stress of 14 MPa is ϕ (365 days) = 1.75.

4 Measured deck deformation

4.1 Presentation of the results

The deformation measurements of the deck allow the identification of the various causes of deformation. First, just after concreting, some random deformations are reported. Afterwards, there is a period with no deformation, the dormant period, followed by an expansion period in two stages caused by the hydration heat release. Then, the deformation reaches a maximum value followed by a contraction phenomenon due to early shrinkage. Next, the deformation in the bridge deck is caused by prestressing of the deck and lowering the formwork. The effects of these operations on side spans are significant. Finally, creep effects are identified.

4.2 Birth of concrete structure

The deformation measurements of the deck at early age allow observing that there is always a short period with no deformation after concreting (at time t_0), followed by an expansion of the concrete until a very clear maximum value is reached, succeeded by a shortening as visible in Figure 5.

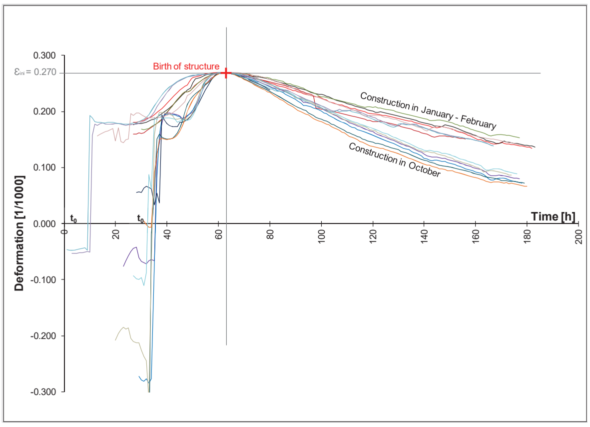

Figure 5: Deformations measured in the sensors

After concreting, as reported by Glisic [6] and [7], the dormant phase is characterized with a horizontal plateau in the deformation-time curve, lasting from 4 to 10 hours, at the end of which the cement paste transforms from liquid to solid.

Thereafter, there is an expansion stage caused by the heating resulting from the concrete constituent hydration, an exothermic reaction, as mentioned by Neville [9].

The expansion stage can be decomposed in a first quick and important expansion, then a plateau and finally a second expansion phase. The first quick expansion (vertical response) is the sign that the cement paste has been transformed from liquid phase to solid one as the thermal effect induces deformations of the sensors. After the expansion phase, the deformation reaches a maximum value meaning that the chemical exothermic reactions are reducing.

With all these measurements, one problem was encountered: what is the point of zero deformation? This question is due to the large discrepancy observed during the first hours of the measurements. For similar concrete and bridge deck, the measured deformation varies from 0.10 ‰ to 0.50 ‰ before reaching the maximum deformation point. This problem was solved by choosing the maximum deformation point as a common reference for all the measurements. Following that choice, the responses of all the sensors are superimposed as presented in Figure 5.

The point of maximum deformation occurs around 25 to 60 hours after concreting. This instant of maximum deformation is defined as the **birth of the concrete structure**. It is ideal to consider this point as the birth of the concrete structure as the measured deformations in fresh concrete are not reliable and the point corresponding to the maximum deformation is as well defined as the start of any well-known event can be. Physically, when reaching the maximum deformation point, the concrete is hardening and has some stiffness.

It has to be mentioned that the birth of the concrete structure cannot be the origin of deformation as clearly showed by the measurement of deformations. To best fit the measurements of deformation and the analysis described in the next section, the zero deformation was shifted to $\varepsilon_{ini} = 0.27$ ‰, before the birth of the concrete structure as shown in Figure 5.

4.3 Structural model for concrete at early age

By analyzing the measured responses, a structural model for describing concrete behavior at early age is developed and illustrated in Figure 6. The purpose of the model is to be useful at the structural level and it is therefore a simplification of what is happening at the material level during hydration.

As described before, to explain the hardening process, two points have to be distinguished: the point of zero deformation $P\varepsilon_0$ and the one of zero stresses $P\sigma_0$ defined as the "birth of the concrete structure". The point of zero deformation occurs after the dormant phase, 3 to 10 hours after concreting when the concrete is transforming from liquid to solid state. Once the concrete is starts solidifying, the hydration heat induces deformation on the sensors, which are observed with the sudden elongation (vertical response). The point of zero stress, or "birth of the concrete structure", occurs around 25 to 60 hours after concreting when the deformations reach a well-defined peak value. Up to this point of birth, the deformation occurring in the structure induces stresses.

The schematic representation of cement particles, as presented by Soroka [10], is correlated in Figure 6 to the deformations observed at the structural level.

Distinguishing these two points allows matching the experimental measurements. It also allows explaining the early age cracking in concrete structures as the contraction, occurring after the birth of the concrete structure due to early shrinkage easily reaches 0.30 ‰. This deformation induces stresses which can easily exceed the tensile strength of concrete and therefore induces concrete cracking.

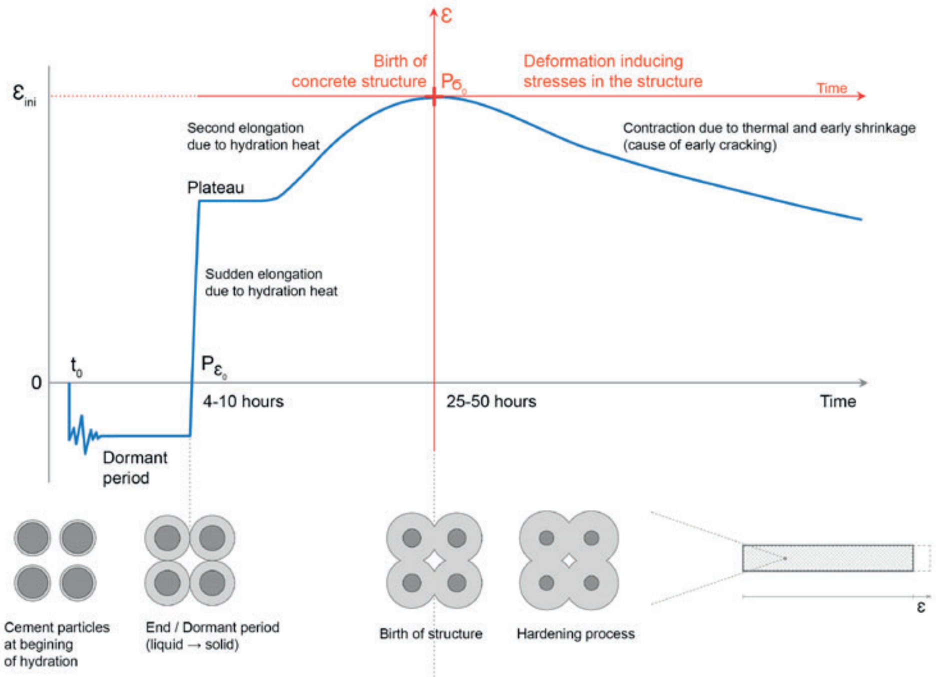

Figure 6: simplified model of hardening concrete at the structural level

5 Analysis of the deformation with numerical simulations

5.1 Numerical models

The construction of the deck has been simulated numerically to decompose and analyze the deformation happening in the bridge deck. The complete bridge has been modeled with the RM Bridge program [11]. The deck and the piers have been modeled in 3D with finite beam elements. The prestressed cables are modeled in an independent way as a cable element considering the prestressed losses according to the Eurocode 2 [4]. The considered loads are the self-weight loads. The formwork is also considered in the model with a vertical rigid connection to the bridge. For all the carried-out simulations, the behavior of the material is assumed to be linear elastic, which is justified by the fact that the deck is prestressed.

For all these simulations, the early shrinkage of 0.3 ‰ is considered by shifting the measured values of deformation by 0.3 ‰.

In the following figures, the measurements in span T3 are compared to the results obtained by different numerical simulations, separating the sensors situated in the bottom and the top part of the section.

5.2 Instant building simulation

The **instant building simulation** consists of a model without consideration of construction stages.

The resulting forces at the middle of span T3 are a normal force N = -27'000 kN and a bending moment M = -2'000 kNm which lead to the elastic deformations of respectively -0.1 ‰ and -0.2 ‰.

The obtained internal forces at the pier are a normal force N = -27'000 kN and a bending moment M = -2'050 kNm. The elastic deformations are -0.11 ‰ at the top fiber and -0.16 ‰ at the bottom fiber.

The deformations obtained with the instant building simulation allows only approaching the measured deformations at the end of the construction process as shown in the following Figures.

5.3 Construction stages simulation

The **construction stages have** been taken into account in the simulation by considering concreting, prestressing and lowering of the formwork in each span. No time effects whatsoever were included.

By modeling the construction stages, the computed deformations get closer to the one obtained from the measurements. However, the shifting due to time effects (creep and shrinkage) is clearly missing.

Finally, for **the construction stages simulation with creep and shrinkage**, the influence of time effects (creep and shrinkage) is considered as a function of time according to the Eurocode 2 [4].

It can be observed that the computed deformations are even closer to the measured ones, especially for the mid span. Over the pier there is a difference between the measured and the computed deformations, probably since the stresses over the pier are inclined in the pier direction and not parallel to the neutral axis.

It can be observed that at the top of the mid-span section where compressive stress is high, the creep effect is more significant than in other sections.

Creep and shrinkage design values given by Eurocode 2 [4], coupled with the construction simulations, are leading to nice predictions of the deformation in the bridge deck during construction. However, early shrinkage occurring after the birth of the concrete structure is not included in the shrinkage values given by the Eurocode 2 [4]. The shifting of the measured deformation of 0.3 ‰ shows the importance of the phenomenon as it allows matching experimental and numerical deformation. This early shrinkage has to be considered in the design so that early cracking observed in concrete structures can be explained and avoided.

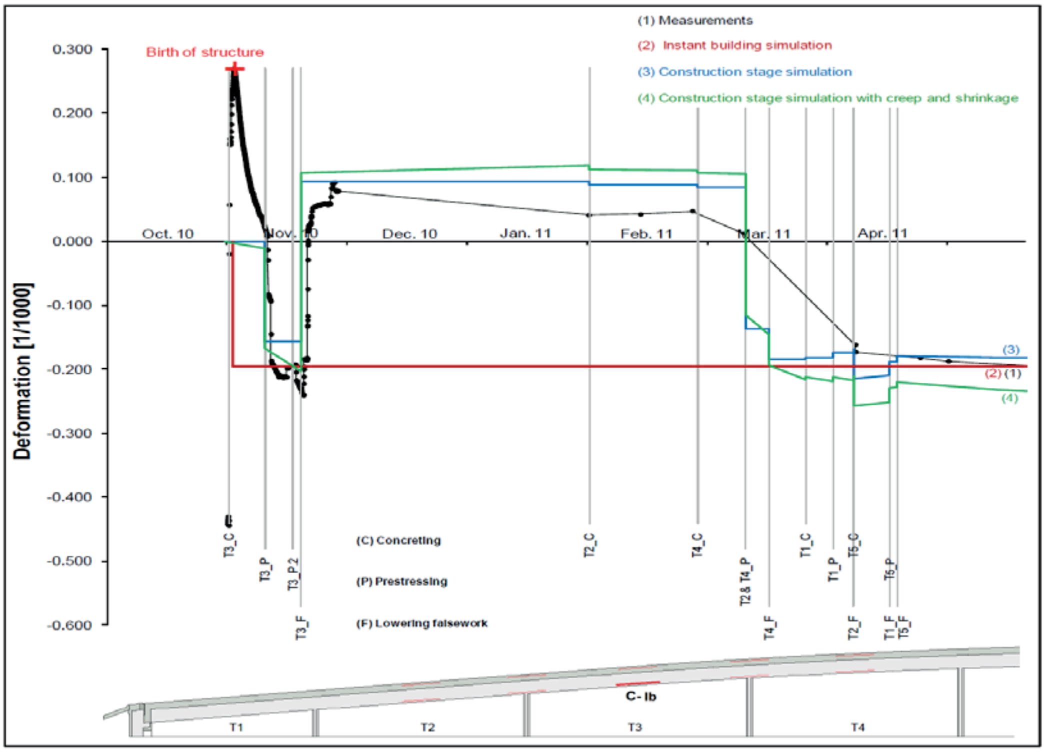

Figure 7: Measured and simulated deformations in the middle span (bottom sensor)

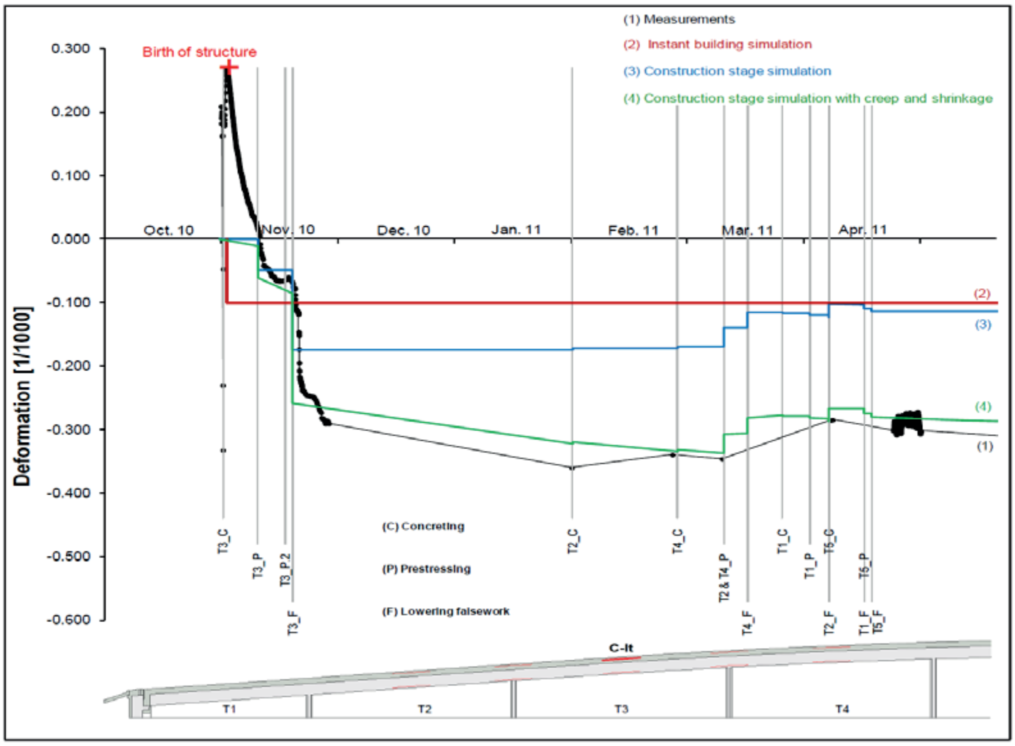

Figure 8: measured and simulated deformations in the middle span (top sensor)

6 Conclusion

The construction of the viaduct over the A9, a semi-integral prestressed concrete bridge with a total length of 351.60 m was accompanied by uncertainties about the importance of long-term effects on the deck deformations. To clarify these, deformation measurements have been carried out using optical fibers. These fiber optic sensors turned out to be powerful measurement tools enabling the recording of the whole construction process.

The deformation measurements of the deck allowed identifying the various causes of deformation. First, just after concreting, some random deformations are reported. Afterwards, there is a period with no deformation, the dormant period, followed by an expansion period in two stages caused by the hydration heat release. Then, the deformations reach a maximum value followed by a contraction phenomenon due to early shrinkage. Next, the deformation in the bridge deck is caused by prestressing of the deck and lowering the formwork. The effects of these operations on side spans are significant. Finally, the creep effects are identified.

By analyzing the early stages of deformation, a structural model for concrete at early age was developed which distinguishes the point of zero deformation and the one of zero stresses. The point of zero deformation occurs after the dormant phase, some 3 to 10 hours after concreting, when the concrete is transforming from liquid to solid state. The point of zero stress occurs around 25 to 60 hours after concreting when the deformation reaches a clear peak value defined as the "birth of the concrete structure". Up to this point of birth, the deformations occurring in the structure induce stresses. Distinguishing these two points allows matching the experimental measurements and explaining early age cracking in concrete structure.

To decompose and analyze the deformation behavior of the bridge deck, the measurements were compared to the results obtained with different numerical models. This revealed that to match the deformation measurements, construction stages, time effects and early shrinkage have to be considered in the simulations.

It is shown that the design value of creep and shrinkage allowed a nice prediction of the deformation in the bridge deck during construction. However, the early shrinkage occurring after the birth of the concrete structure, which reaches values around 0.3 ‰ during the first weeks, has to be added in the design value of shrinkage.

Generally speaking, this early shrinkage must be considered in the design so that early age cracking in concrete structures can be explained and avoided.

7 References

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