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Why is the Initial Trend of Deflections of Box Girder Bridges Deceptive?

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ABSTRACT: *Large-span prestressed concrete box girders typically exhibit during the initial years deceptively small deflections, or the deflections may even go upwards. However, optimistic expectations are premature. After about three to ten years, the deflections may begin to increase rapidly, become excessive. It is shown that, in order to predict the deflections correctly, one must use a creep and shrinkage model that realistically describes the moisture diffusion process, which causes that the shrinkage and drying creep of the thick bottom slab of the box cross section are greatly delayed compared to the thin top slab. This delay cannot be predicted with the classical approach, in which either the shrinkage strain and the creep coefficient (or compliance function) are considered as uniform throughout the cross section, or the thickness effect is simply described by a multiplicative factor on shrinkage strain.*

KEY WORDS: *bridge, concrete, creep, deflection, shrinkage.*

In large-span prestressed concrete box girder bridges, the thickness of the top slab is typically uniform or nearly uniform while the thickness of the bottom plate varies greatly, increasing from the midspan to the supports. The web thickness is also variable. The thickness differences greatly affect the rate of drying and this in turns greatly affects concrete shrinkage and also influences creep. Further discrepancies in the rate of drying, and thus in shrinkage and creep, are caused by differences in the temperature and humidity conditions at the surface.

The creep and shrinkage effects on prestressed concrete box girder bridges are usually analyzed assuming the shrinkage and the creep compliance (or creep coefficient) to be uniform over the entire cross section of the box girder. The objective of this paper is to show that the result may be an incorrect prediction of long-term deflections, stress redistributions, and incorrect extrapolation of the trend of deflections observed during the initial years. The prediction is incorrect even if the slab thickness is taken into account according to some classical prediction model, such as that embodied since 1972 in ACI 209R-92 recommendation, in which the thickness effect on long-term shrinkage and creep is incorrectly described by a strain multiplier rather than scaling of time.

The traditional simplified shrinkage and creep prediction models that characterize only the overall behavior of the cross section and do not realistically capture the diffusion aspects of drying. The half-times of all diffusion processes are roughly proportional to thickness square. Increasing the thickness of a slab from d to D does not reduce the curve of shrinkage (as well as drying creep) by some thickness-dependent multiplicative factor, as in the model embodied since 1972 in the existing ACI 209R-92 recommendation, based on 1960s research. Rather, the shrinkage gets delayed as if the passage of time was slowed down by factor d^2/D^2, which is manifested by shifting the shrinkage curve in the logarithmic time scale to the right by distance $2 \log(D/d)$.

Among the available models, we adopt for the present purpose model B3 (Bazant, Baweja 1995). This model is scientifically justified by the known physical mechanisms of creep and shrinkage, fits optimally the relevant test data available in the literature, agrees with all the required simple asymptotic trends, and offers the widest choice of input parameters covering the entire practical range, and agrees with the theory of moisture diffusion including diffusion based parameters for slab thickness and environmental humidity. A recently developed Internet page www.fsv.cvut.cz/~kristek, or http://creep.fsv.cvut.cz/test/ (Kristek, Petrik, Pilhofer 2001) which makes model B3 immediately accessible to any engineer - the user can obtain the values of creep and shrinkage strain as well as the creep coefficient.

Deflection of prestressed box girder bridges represent a small difference between downward deflections due to live and dead loads, and upward deflections due to prestress. This is a difference between two large statistically variable quantities, which is always very sensitive. A small percentage change in one may cause a large percentage change in the difference. This is why realistic prediction of differential shrinkage and creep is so important.

To illustrate the phenomenon studied, Fig. 1a shows the histories of shrinkage strains for various slab thicknesses predicted by model B3, and Fig. 1b shows the differences among the individual histories, with the slab thickness of 200 mm taken as a reference. Clearly, the differences are major.

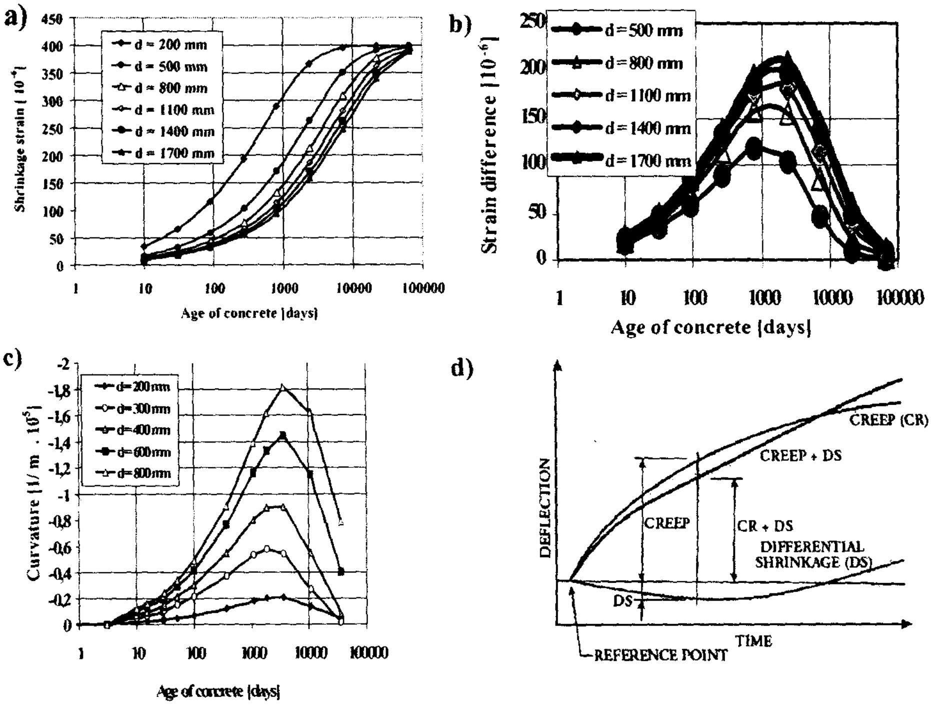

Figure 1. *a) histories of shrinkage strains, b) differences among the strain histories, c) histories of the girder curvature, d) delay of deflections*

Creep also may be important because even a small difference in creep strain histories among the individual parts of the cross section causes a coupling between the effects of bending moments and axial forces. An axial force applied at the centroid of the box cross section will produce not only axial displacements of the cross section but also rotations increasing with time. Vice versa, an applied bending moment will produce rotations and also increasing axial displacements. Such moment-force coupling will change the lever arm of the forces in the tendons.

Differential effects will modify the evolution of curvature of the girder. The magnitude of these effects depends upon the structural system and geometry (mainly differences in thickness), and also, of course, upon the shrinkage and creep characteristics. Fig. 1c shows the histories of curvature for various thicknesses of the bottom slab of a typical segment.

The performed computational results of parametric studies illuminated the box girder behaviour. If the bottom slab is thicker, its shrinkage lags compared to the top flange (because of a difference in the volume-surface ratio, a minor lag appears even if both the top and bottom slabs have the same thickness but different width). Consequently, a positive curvature must develop initially and cause upward deflections at the end of the cantilever. If the bottom slab is much thicker, the upward deflection can be large and continue for many years (the longer, the thicker the slab). A maximum eventually occurs when the shrinkage of the thin top plate nears completion and the rate shrinkage of the thick bottom plate picks up. After that, differential shrinkage cause negative curvature and downward deflections. If the bottom plate is very thick, the result is a delay of many years in the onset of significant downward deflections of box girder (see curve CREEP+DS in Fig. 1d). They get shifted to a much later period than what would be expected according to the common level of understanding. This can create serious problems for serviceability, durability and long-time reliability of such bridges.

This delay of deflection development has often deceived the engineers monitoring deflections. Measuring only the first few years of lection history, one is tempted to extrapolate and optimistically expect the deflections to remain small, only to be unpleasantly surprised when, after several years, the deflections suddenly accelerate. Without realistic calculations, one may even misinterpret the reason for such a sudden acceleration of deflection and undertake some inappropriate corrective actions, which may induce enormous bending moments overstressing the bridge and possibly be a cause of serious damages.

Box girder in the final structural system: The deflections of the cantilevers due to the differential shrinkage evolve freely only until their free ends are joined to create the final structural system of the bridge. Two type of joining are used in the practice:

1. Hinge. In this case, there is no restraint against continuing rotations in the hinge and the vertical force that develops in the hinge is normally of marginal importance (unless the age difference between the two cantilevers is great). Therefore, the bridge deflections due to differential shrinkage may continue to evolve almost freely, like in the original cantilevers, and no significant secondary internal forces are induced in the structure after the cantilevers are joined.

2. Moment-Resisting Joint. Because, in this case, further relative rotations between the joined ends are prevented after the girder is made continuous, a bending moment gradually develops in the joint. Long-span box girders erected by the cantilever construction method are typically tapered, having a variable cross section with different concrete ages in individual segments. It has been proven that also for these complex situations, differential shrinkage causes only small and short-lived deflection variations in the final structural system with a moment-resisting joint. Generally, continuous box girders suffer much smaller deflections in the internal spans than girders with midspan hinges.

Significant additional redundant bending moments may nevertheless develop due to the differential shrinkage after installing a moment-resisting joint. Their evolution can be quite complex, possibly changing from negative to positive values. The magnitude of these moments is roughly proportional to the girder stiffness. Thus stiff cross sections near the support may engender bending moments that are quite high for the light cross sections near the midspan, resulting in significant additional stresses in the midspan region.

An analysis was performed for the *La Lutrive* bridge, built in 1973 in Switzerland, with hinges at midspans (Fig. 2a,b). The midspan deflections gradually increased, as depicted in Fig.2c, and in 15 years they exceeded 150 mm.

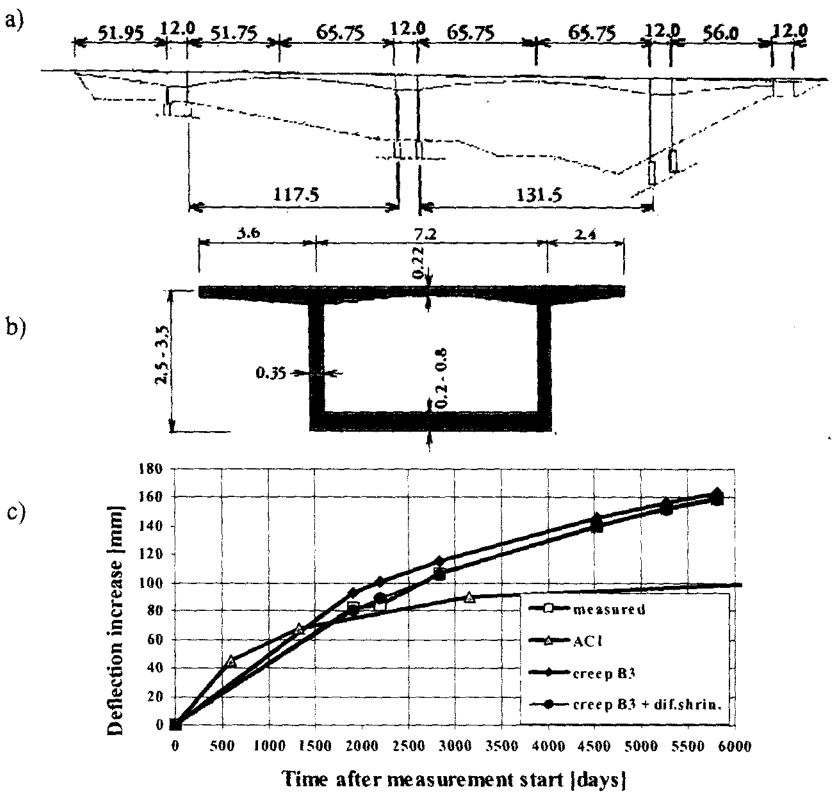

Figure 2. *La Lutrive bridge: results of analysis and comparisons with observation*

The total maximum upward deflection due to differential shrinkage is about 22 mm and is reached at the age of concrete of 1300 days. This is used as a component of the corresponding curve in Fig. 2c. The bridge deflections are plotted in Fig. 2c for three types of analysis: (1) ignoring differential shrinkage and creep and using model B3 for the mean cross section characteristics, (2) same, but taking differential shrinkage and creep into account, and (3) using the oversimplified ACI 209R-92 model. It should be emphasized that all these curves represent only the deflection increase after the start of the monitoring of the bridge.

The comparison of the calculated and measured deflections as shown in Fig. 2c confirms that (1) the measured deflections agree well with the calculations taking into account differential shrinkage according to model B3 (see the best-fit curve in Fig. 2c); (2) the time lag is captured (in contrast to the calculations based on mean cross section behavior); and (3) the curve corresponding to the simplistic ACI 209R-92 model exhibits excessively steep initial deflection curve and grossly underestimates long-term deflections.

Conclusions

1. The prestressed box girder bridges typically exhibit only a portion of deflections during the first years and then continue to deflect. The cause is primarily a difference in shrinkage between the top and bottom slabs of the box cross section and, to a lesser degree, a difference in the drying creep part of creep coefficient.
2. This difference is explained by a large difference between the thicknesses of the top and bottom slabs.
3. To predict the long-term deflections correctly, the diffusion nature of drying must be realistically reflected in the creep and shrinkage prediction model. This means that an increase of slab thickness causes its shrinkage and drying creep to be delayed but not reduced by a multiplicative factor, and that the delay should be proportional to the square of the thickness ratio (Bazant, Baweja 1995). Also, the shape of the shrinkage and drying creep curves in the shrinkage and creep prediction model must not contradict diffusion theory, which means the initial shrinkage should evolve as a square root of drying time and the final value should be approached exponentially (Bazant, Baweja 1995). A creep and shrinkage prediction model with the correct features is model B3 (Bazant, Baweja 1995). The model from the current ACI 209R-92 recommendation does not have the correct features.
4. Excessive deflections can usually be significantly reduced by installing a moment-resisting joint at midspan and by precasting the segments.
5. Extensive monitoring on many bridges confirms these observations.
6. Because of excessive deflections, many bridges must be either closed or repaired well before the end of their initially projected lifespan. The cost to the owners and users is tremendous. In fact, it greatly exceeds, in strictly economic terms, the cost of catastrophic failure due to mispredicted safety margin.

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