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Creep, Shrinkage and Durability Mechanics of Concrete and Concrete Structures

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Misprediction of long-time deflections of prestressed box girders: Causes, remedies and tendon layout effect

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ABSTRACT: The paper reviews the causes of under-estimation of the long-time future deflections of large-span prestressed concrete box girder bridges. Six causes are discussed: 1) wrong creep and shrinkage model; 2) obsolete creep analysis method; 3) ignoring randomness; 4) lack of model updating based on short-time tests; 5) wrong tendon layout; and 6) neglect of shear lag. The present paper focuses on the last two causes, while a brief review of the other causes is planned for the conference presentation. So is a discussion of why the record-span Koror-Babeldaob Bridge in Palau deflected 1.1 m more than expected in design.

1 INRODUCTION

It has frequently been experienced that the box girders of many prestressed concrete bridges deflected far more than predicted in design. The deflection evolution has often been counterintuitive, with slowly growing or negative deflections in the early years, followed later by a rapid and excessive deflection growth. Six different causes of these problems may be discerned:

1. Design based on an obsolete, oversimplified and unrealistic model for predicting creep and shrinkage properties of concrete, or of cross sections of concrete girders (Bažant 2000, Křístek et al. 2006).
2. Obsolete and unrealistic method of time-dependent analysis of structural effects of creep and shrinkage, based, for instance, on assuming the creep and shrinkage properties to be homogeneous throughout the cross section and ignoring the effects of differences of shrinkage and drying creep between the top and bottom slabs of the box girder (Křístek et al. 2006), which result from differences in drying half-times engendered by differences principally in slab thickness and secondarily in temperature history.
3. Lack of updating of the long-time creep and shrinkage predictions by means of short-time (1 month) creep and shrinkage tests and water loss tests of the particular concrete to be used (Bažant and Baweja 2000).
4. Absence of statistical deflection predictions, ignoring the large random scatter in concrete creep and shrinkage effects, and especially the fact that the total observed deflection is the difference of two large numbers—the deflection due to external loads, and the deflection due to prestress (a difference of large numbers is greatly sensitive to a small change in one of these numbers and may thus result in a significant change of the difference, i.e., in a significant change of the total deflection value).
5. Incorrect and harmful tendon layout—some tendon layouts benefiting the stress state can at the same time be harmful from the deflection viewpoint. Therefore, bridge design should be performed on two different levels: not only the common stress analysis, but also optimization of prestressing tendon layout to minimize deflections.
6. An oversimplified structural model—particularly the use of the classical mechanics of beam bending, based on the Bernoulli-Navier hypothesis of cross sections remaining plane, while the true behavior is three-dimensional, with a strong shear lag, due to large shear deformations in the webs and plates

Points 1–4 are reviewed in a plenary lecture by Bažant et al. at this conference. Let us now discuss points 5 and 6.

2 DEFLECTION INCREASE DUE TO UNDERESTIMATION OF PRESTRESS

The total calculated deflection of a prestressed box girder bridge represents a small difference between a downward deflection due to dead and live loads, and an

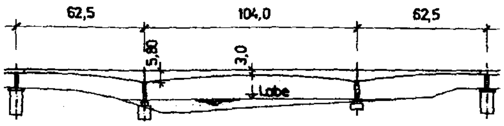


Figure 1. Bridge over river Labe (or Elbe) in Děčín, Czech Republic.

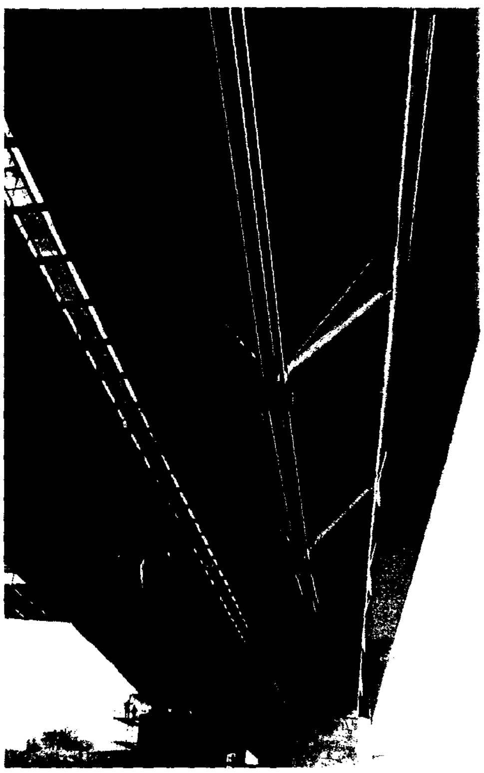
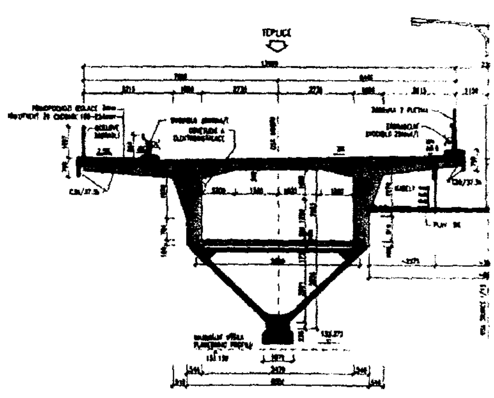


Figure 2. View of external tendons (Děčín).



3. Cross section (Děčín).

upward deflection due to prestress. This small difference between two large and variable quantities is very sensitive to small errors in these deflections. A small change in one may cause a large percentage change in the total deflection.

An example is the excessive deflection that required reconstruction of the box girder bridge over river Labe (or Elbe) in Děčín in North Bohemia (Fig. 1). The structural system of this bridge is a three-span continuous box girder (with spans 62.5 + 104.0 + 62.5 m; Fig. 1). It is tapered shape and was erected using the cantilever technology.

The bridge was monitored since its erection in 1993. The midspan deflection increased annually by about 8 mm. The total difference between the theoretical and measured road levels reached about 140 mm just before start of reconstruction. There are several probable reasons for the excessive deflection:

- A lower value of modulus of elasticity of concrete; neglect of the shear effect on deflection in the design;
- Incorrect compliance function for the evolution of creep in time; and
- A higher influence of relaxation of prestressing steel.

In the reconstruction, the stiffness of the structure was increased by adding external prestressing tendons, as shown in Fig. 2, 3.

3 EFFECT OF TENDON LAYOUT ON LONG-TERM DFLECTIONS

Slender prestressed bridges are extremely sensitive to deflections in general. The total deflection results from two opposite actions: 1) the vertical dead and live loads, and 2) the effect of prestress. Both actions, when acting separately, would produce individually significant deflections of opposite directions. The resulting deformation due to simultaneous action of both is a difference of two large numbers, and a small change in one may cause a large relative change of their difference, as exemplified by the bridge in Děčín.

In reality, all the parameters are of course random. The dead and live loads are usually known rather reliably. On the other hand, the prestress can deviate greatly from the value assumed in design. So the randomness of prestressing plays a significant role in predicting deflections.

The choice of prestress tendon layout, i.e. the location and profile, is often governed by construction stages, as well as the cross-section geometry. But it is important to optimize the layout of tendons so as to minimize deflections.

Low deflections during the cantilever construction stages do not ensure acceptable deflections during the service life. The tendons installed during cantilever erection stages are usually very efficient during construction. However, after changes of the structural system (e.g., closing of the midspan joints) to make the structure continuous, the cantilever tendons might not significantly inhibit the long-term deflection growth because creep produces additional forces due to the redundancy of the new structural system.

This can easily be demonstrated by an elementary example: Two opposite cantilevers are prestressed by tendons anchored at their end cross-sections, as shown by arrows in Fig. 4. This arrangement of prestressing layout is very efficient in reducing the deflections during the cantilever stage, but is very inefficient in reducing *deflection increments* after the cantilevers are made continuous to form the final structural system. Such a final system is equivalent to a single clamped (fixed-end) beam, which deflects vertically as if no prestress existed (because the prestress induces statically indeterminate increments of end moments which offset the bending moments due to prestress).

To understand the sensitivity to tendon location, an example of a bridge whose final structural system is a three-span continuous beam is instructive. Consider the influence line $y(x)$ of the vertical concentrated load F on the midspan deflection v (Fig. 5). Instead of prestress, a uniform bending moment $M = Fdx$ in the segment (x_1, x_2) may be imposed by two opposite couples of vertical forces $F = M/dx$, each with the arm dx, at locations x_1 and x_2. They produce the

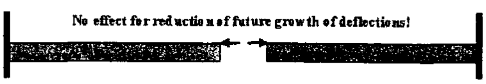


Figure 4. Prestressing in the cantilever stage.

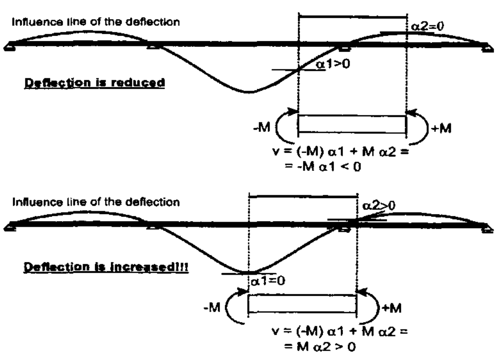


Figure 5. Different layouts of a prestressing tendon resulting in opposite midspan deflections: a) midspan deflection is reduced; b) midspan deflection is increased.

midspan deflection

$$v = [F(y + dy) - F(y)]_{x_2} - [F(y + dy) - F(y)]_{x_1}$$
$$= [Fdy]_{x_2} - [Fdy]_{x_1} = M\alpha_2 - M\alpha_1 \quad (1)$$

where $\alpha = dy/dx$ = slope of the influence line (Fig. 5).

More generally, for variable prestress moment $M(x)$, one may use the general expression

$$v = \int_{x_1}^{x_2} p(x)y(x)dx \quad (2)$$

where $p(x) = d^2M/dx^2$. Integration by parts yields

$$v = [y(dM/dx)]_{x_1}^{x_2} - \int_{x_1}^{x_2} (dy/dx)dM(x) \quad (3)$$

Considering the integral as a Stieltjes integral from x_1^- to x_2^+ (with jumps at ends), the first term vanishes and the integral gives, for the special case of a uniform $M(x)$, the same expression as before.

The effects of two locations of the prestressing tendon on the midspan deflection may now be compared. From Fig. 5 it is immediately clear that, upon a relatively small shift of the tendon location shown in the figure, the tendons shown have opposite effects on the midspan deflection (Fig. 5).

Let us now present an example from practice, elucidating the significance of tendon layout and the efficiency of various layouts in reducing the deflections. The example is the bridge over the river Labe (Elbe) in Mělník: A three-span tapered continuous box girder (with spans 72.05 + 146.2 + 72.05 m; Fig. 6), built in 1992 in Central Bohemia and erected using the cantilever technology. We are interested to identify a possible unsuitable tendon layout that would be harmful, causing a long-time increase (rather than a decrease) of the midspan deflection.

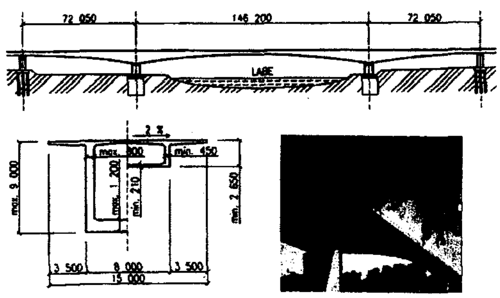


Figure 6. Bridge over the River Labe (Elbe) in Mělník.

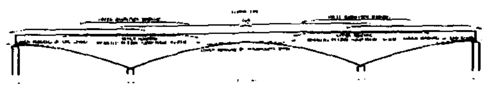


Figure 7. Schematic layout of prestressing tendons.

Tendons of several categories were installed during the individual stages of the construction process (Fig. 7):

1. Tendons located at the top surface, installed during cantilever erection stage;
2. Tendons located at the bottom surface of the middle (main) span;
3. Tendons located at the bottom surface of the first and third spans; and
4. Tendons located at the top surface over the interior supports, installed at the time when the box girder cantilevers are joined continuously at their ends to form the final structural system.

The effects of individual tendons were evaluated by applying computer program OPTI 1.1 developed in Prague for this purpose. The results, indicating how individual tendons affect the midspan deflection, are summarized in Table 1.

As seen, 22% of the all prestressing tendons affect this bridge unfavorably, i.e., contribute to an increase of deflection. The tendons of category C, located at the bottom surface of the first and third spans (see Fig. 7), prove to be extremely harmful, since all of them enhance the deflections in the central region of the main span.

Among the tendons located at the top surface, installed during cantilever erection, the straight ones, which are passively anchored in the vicinity of internal supports and follow the top surface, are harmful. In this particular bridge, the unfavorable tendons in the first, as well as the third, span are anchored typically at distance of approximately 15 m from the ends of the bridge, and the unfavorable tendons in the main span are anchored typically at distances of approximately 30 m from the midspan (see Fig. 7).

In this way, the consequences of the tendon layout fro deflections have been elucidated and a method to assess them quantitatively has been developed. The advantage of this method is its ease of application, which allows the optimal tendon layout to be readily determined. The method has been programmed and is freely available on a web site and is proposed as a simple design aid avoiding expensive solutions. The practicing engineers can benefit in the design of sensitive bridges from the computer program OPTI 1.1, which has been developed at the Czech Technical University in Prague to make the assessment of the tendon layout immediately accessible to any engineer. This program is free to download from the internet address:

Table 1. Effect of tendon layout on deflection.

Tendon category	Total number of tendons	Tendons increasing midspan deflection: Number	[%]
A	80	14	18
B	12	1	8
C	8	8	100
D	4	0	0
Total	104	23	22

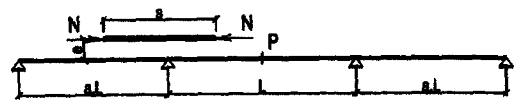


Figure 8. Location of the tendon.

http://concrete.fsv.cvut.cz/veda/science_en.php. It suffices to fill out the boxes for the data on the bridge and its tendon layouts, and the output is the deflection contributions of the individual tendons.

The location of a tendon that is most efficient for reducing deflections can be determined by a simple graphical method. The objective is to determine the location of a tendon of length s with eccentricity e to produce maximum upward deflection of a bridge at cross-section P (see Fig. 8). Provided that concrete creep represents the dominant effect, the time increment of deflections of a bridge of a common arrangement in the final structural system caused by creep may be approximated as

$$\Delta y(t) = [\varphi(t, t_0) - \varphi(t_r, t_0)]y_e \qquad (4)$$

in which φ = creep coefficient, t_0 = age of concrete at loading, t_r = age of concrete at the instant of change of structural system, t = current age of concrete, and y_e = instantaneous deflection in the final structural system caused by the applied loads.

The procedure consists of the following steps:

1. Construct the diagram of the derivative of the influence line of bridge deflection at cross section P (the full line in Fig. 9).
2. Move this diagram towards the left along the bridge axis by a distance equal to the tendon length s (the dashed line in Fig. 9).
3. The cross sections with extreme differences between the two lines indicate the most efficient cross section A (Fig. 9) or the most harmful cross section Z (Fig. 9) for the location of the left anchor of the tendon.

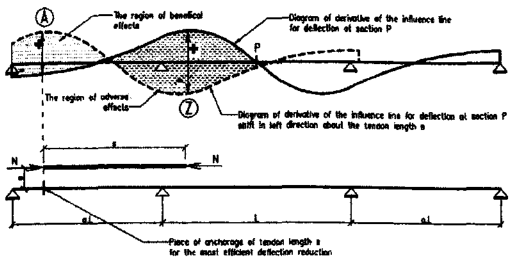


Figure 9. Simple graphical tool to determine the most efficient location of a tendon for deflection reduction.

4. The intersections of both lines indicate the anchorage locations that have no effect on the deflection at cross-section *P*.
5. The intersections of both lines also delimit the regions of beneficial effects (the dotted area in Fig. 9) and of adverse effects (the dashed area in Fig. 9)

This procedure allows eliminating the 'tricky' tendons (i.e., those that are beneficial for eliminating tensile stresses but have a layout that significantly contributes to long-time deflections).

The lesson to be learned from the deflections of the existing bridges is that the bridge design should be performed in two different and equally important phases—not only the usual stress analysis, but also the optimization of prestressing tendon layout. The latter is a necessity for ensuring acceptable longterm deflections.

4 CLOSING COMMENTS: DEFLECTIONS OF KOROR-BABELDAOB BRIDGE IN PALAU

A prestressed box girder of record span 241 m was build in 1977 in Palau (Yee 1979). In design, the midspan deflection was expected to reach about 0.3 m but in 19 years it reached 1.4 m. The subsequent remedial measures in 1997 lead to collapse, with loss of life. Several investigators discussed the causes of collapse (Parker 1996, Pilz 1997, McDonald et al 2003, Burgoyne & Scantlebury 2006), but definite analysis has been impossible because the technical data have been unavailable. Thanks to a resolution of the 3rd Structural Engineers World Congress in Bangalore in November 2007, calling for a release of the technical data, there is progress on the data release, and the analysis of causes has begun at Northwestern University. Unfortunately, the analysis has not progressed enough to be presented in this pre-conference article, but its presentation is planned for the conference.

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