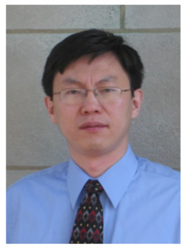
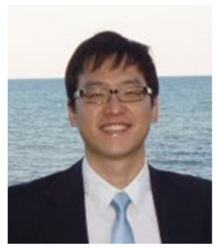
EXCESSIVE MULTI-DECADE DEFLECTIONS OF PRESTRESSED CONCRETE BRIDGES: HOW TO AVOID THEM AND HOW TO EXPLOIT THEIR MONITORING TO IMPROVE CREEP PREDICTION MODEL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Abstract

Stimulated by the excessive deflections and collapse of the KB Bridge of world-rercord span, the deflection histories of 56 similar bridges, most of them excessive, have been collected by RILEM TC-MDC. They amount to a wake-up call: The standard creep recommendations of engineering societies have been misleading, and thus their revision is imperative. They also confirm a simple feature: The multi-decade trend of bridge deflection, and by implication also the concrete creep law, is a logarithmic curve in time, which has no final bound, in contrast to the existing standard recommendations. Despite the lack of success in obtaining full information on the highly deflected bridges, it is possible to benefit by statistical analysis from the bridge deflection data for improvements of the concrete creep model. The proceedings paper briefly outlines how to do that, and the full paper presents some more detail and the figures.

Keywords: Concrete creep, Bridge deflections, Prestressed box girders, Standard recommendations for creep, Statistical analysis, Sustainable design.

1 Paradigm of excessive deflections of KB Bridge in Palau and several Japanese segmental bridges

A recent article (Bazant, Yu et al. 2010) reported a detailed analysis of the data on the collapse of the Koror-Babeldaob (KB) Bridge in Palau, released in 2008. Built in 1977, this prestressed segmentally erected box girder had the world-record span of 241 m. It deflected within 18 years by 1.61 m, compared to the design camber, and its tendons (bonded bars) suffered the average prestress loss of 49 %, as revealed by measurements (see Fig. 1). Remedial prestressing undertaken in 1996 caused, with a 3-month delay, a sudden collapse (triggered by delamination creep buckling).

In 2008, the data from the investigation and litigation of this collapse were released to Northwestern University. This made possible a three-dimensional finite-element step-by-step creep analysis of the KB Bridge, taking into account the effects of cracking, concrete aging, shear lags in slabs and walls, non-uniform shrinkage, non-uniform drying creep properties, temperature and gradual steel relaxation in prestressing tendons at variable strain of steel.

The resulting deflection and prestress loss curves will be shown at the conference and in Fig. 1, where the data points represent the measurements. The curves Set 1 and Set 2 are the predictions of model B3, which is a RILEM Recommendation (Bazant and Baweja 1995, 2000). The curves Set 1 are strict design predictions, obtained for creep parameters predicted from the strength and composition of concrete, the latter being partly known and partly estimated. The curves Set 2 are optimum fits of the measurements with model B3. The fact that the creep parameter values required to match the data are reasonable, and in fact agree with the 30-year laboratory creep test data of Brooks (2005) in Leeds, proves that the huge deflections can be logically explained (rather than attributed to `poor construction') and can be predicted if Brooks' data are reused.

The responses obtained according to the models of various engineering societies, particularly CEB-*fib*, ACI, GL (Canada) and JSCE (Japan) are also shown, for comparison. It must be noted that these curves differ from those published in Bažant and Yu (2010), but only slightly. The engineer who supervised in the mid-1970s the segmental construction (Raymond Zelinski, now retired) read this previous publication and then offered to provide some previously missing data.

As shown in Bažant and Yu (2010), similar calculations were made for three (among many) excessively deflecting Japanese segmental bridges (thanks to detailed data graciously provided by Y. Watanabe, chief engineer of Shimizu). The results were similar.

The following lessons have been learned: 1) None of the existing creep and shrinkage prediction models is satisfactory as a purely predictive tool, although model B3 gives a significantly better predictions than the others and, after adjustment based on Brooks' laboratory data, fits the measurements perfectly. 2) Consequently, revisions of material creep model in the recommendations of *fib*, ACI and other engineering societies are requisite. 3) The main and major source of error is poor prediction of creep model parameters from concrete strength and composition. 4) Second in terms of the error magnitude is oversimplification of creep structural analysis as currently used (3D, rather than 1D beam-type, analysis in time steps is required). 5) The effects of the differences in slab thicknesses within the cross sections on the shrinkage and drying creep rates must be considered. So must temperature differences, tensile cracking, and moisture diffusivity of concrete. 6) The classical estimates of prestress loss are for large-span box girders inadequate. The prestress loss must be computed as part the overall three-dimensional time-step creep analysis. 7) The Latin hypercube sampling method should be used to provide the coefficients of variation and 95 % confidence limits for deflections and prestress loss, and 8) proper short-time tests of creep, shrinkage and water loss should be conducted during design to allow recalibration of model B3.

2 Multi-decade creep effects in other bridges and studies in newly formed RILEM Committee TC-MDC

Are the dismal predictions based on the standard recommendations of engineering societies merely a chancy bad experience? Or are they endemic to the segmental box girders, of which probably over a thousand have been built around the world? Will similar creep and shrinkage problems affect the recently built super-tall buildings? And what is the experience with cable-stayed bridges, in which the concrete beams and supporting towers are also sensitive to creep?

To study these questions is one objective of the newly founded RILEM Committee TC-MDC (Multi-Decade Creep). A search of various journals and society reports has led to a list of 56 large-span prestressed box girders (except for one arch), most of which deflect excessively or are bound to so before their planned lifetime. Probably over a hundred more exist around the world, although the information is very hard to get. So, the experience in Palau is not unique but typical. One more feature is striking: The long-time deflection curves show no sign of approaching an asymptotic bound and are very simple—a logarithmic curve. The results are presented in Fig. 2.

The simple and systematic form of the multi-decade deflection curve suggests that it must be possible to predict its slope analytically by simple considerations of viscoelasticity. Indeed, a simple formula for the asymptotic slope appears to be possible and is planned to be presented at the conference. Conversely, the use of this formula makes it possible to infer the multi-decade characteristics of the creep law of the material.

However, not all the large-span prestressed segmental box girders have deflected excessively even if a realistic creep model was unavailable in design. One example is the 140 m span Pine Valley Creek Bridge in California, built in 1975. This must have been caused by a deliberate or intuitive adoption of various deflection reducing measures listed at the end of Bazant and Yu's (2010) paper. Most of these measures, of course, do not come for free. They may increase the cost and restrict the maximum feasible span substantially.

3 Exploiting multi-decade bridge deflection data to improve material model for concrete creep

In the largest existing worldwide database of the laboratory creep tests of concrete, only about 5% of the data correpsond to creep durations >6 years, and less than 1% to creep durations >12 years. The idea in RILEM TC-MDC is to enhance this database by inverse analysis of long-term bridge deflections. This is a rather challenging goal, which is pursued in collaboration between the Infrastructure Technology Institute of Northwestern University and the Civil Engineering Faculty of CTU in Prague.

The details of approach and progress will be presented at the Conference, but a few comments can me made now: 1) For the 56 bridges in Fig. 2 and others behaving similarly, it seems next to impossible to obtain sufficient data on concrete composition, geometry, erection and prestressing to idnetifiy the material model by inverse statistical three-dimensional finite element creep analysis. 2) A simplified statistical evaluation of the terminal deflection slopes is nevertheless possible, exploiting the fact that, after a few years, the complex effects of segmental erection, prestressing sequence, age differences of concrete and drying rate differences between the top and bottom slabs must die out. 3) The statistics of terminal slopes in 21 must be combined with the laboratory database assembled at Northwestern University which contains 680 test curves and 12000 data points, in which the only Brooks‘ data, the only modern multi-decade test data, which are assigned very large weight since they represent only 4% of all data. 4) The statistical optimization of material model employs sensitivity analysis of composition parameters of concrete and a genetic algorithm of material identification, while the combination of database with bridge slopes is approached either as a Bayesian problem, the bridge data being the prior, or simply by weighted least-square fitting. 5) A preliminary analysis of this kind, conducted at Northwestern, indicated that the parameters q_3 and q_4 of model B3 should be multiplied by the factor of about 1.6.

4 Closing comment on engineering ethics

In many cases, the technical data on structural failures and severe damages have been sealed by courts as a result of legal litigation. A resolution proposed by Bažant and adopted by the last

Structural Engineers' World Congress labelled such an outcome as a violation of engineering ethics. It is suggested to engineering societies, including *fib* and ACI, to incorporate the same into their ethics codes.

Thanks are due to the US Department of Transportation for funding through the Infrastructure Technology Institute of Northwestern University under Grant 23120, and to the Grant Agency of the Czech Republic for Grant P104/11/1301 and Grant GAP105/10/2400 to CTU Prague.

References

[1] Bažant, Z.P., Yu, Q., Li, G.-H., Klein, G.J., and Křístek, V. (2010), "Excessive deflections of record-span prestressed box girder: Lessons learned from the collapse of the Koror-Babeldaob Bridge in Palau." *ACI Concrete International* 32 (6), June, 44-52.

[2] Bažant, Z.P. and Baweja, S. (1995). "Creep and shrinkage prediction model for analysis and design of concrete structures: Model B3" (RILEM Recommendation) *Materials and Structures* 28, pp. 357--367 (Errata, Vol. 29, p. 126).

[3] Bažant, Z.P. and Baweja, S. (2000). "Creep and shrinkage prediction model for analysis and design of concrete structures: Model B3." *Adam Neville Symposium: Creep and Shrinkage---Structural Design Effects*, ACI SP--194, A. Al-Manaseer, ed., pp. 1--83 (update of 1995 RILEM Recommendation).

[4] Brooks, J.J., (2005) "30-year creep and shrinkage of concrete," Magazine of concrete research 57, pg. 545-556.

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