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Quantifying monitoring requirements for predicting creep deformations through Bayesian updating methods

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ABSTRACT

Although the majority of creep models are comprehensive and up-to-date, there is a lack of consensus in their utilisation due to substantial scatter in their predictions, even when comparisons are made under well-controlled conditions. On one hand, creep entails complex phenomena that depend on several factors and, on the other hand, these models are typically utilised on a deterministic basis without fully incorporating information related to random input variability.

In this paper, a methodology is proposed, based on Bayesian updating methods, for creep deformation prediction by combining prior model distributions obtained through Monte Carlo simulation with in-situ measurements obtained from concrete specimens. Both single point-in-time and sequential updating approaches are formulated and contrasted in the context of site data collected over a period of about six years. For the specific structure examined, the sequential updating method offers advantages in terms of the estimated variability of future predictions. The proposed methodology is suitable for quantifying the value of monitoring information, as demonstrated by considering the change in prediction variability against the length of observation period.

1. Introduction

Over the past century, European countries have developed mature and extensive transport infrastructure networks, in which bridges play a vital role. Focussing on pre-stressed concrete bridges, the most important aspect in life-cycle design is the performance-time profile of the Serviceability Limit State (SLS), usually related to cracking, excessive deflection and vibration [1], which in turn may influence other limit states. Particularly for segmental bridges, the risk of a significant increase in long-term deflections has been shown to exist [2]. For example, the collapse of the Koror-Babeldaob Bridge, Palau, was recently re-assessed and attributed to excessive long-term deflections [3]. These appeared and grew non-linearly some years after construction, as result of material interactions, i.e. creep, shrinkage (concrete) and relaxation (prestressing steel). Indeed, the time-dependent creep and shrinkage structural effects in segmental bridges are more critical than in other types of concrete bridges. Creep strains are higher when concrete is loaded at a younger age and, thus, interactions with loss of prestressing are stronger, leading to increased displacements [4]. In this context, understanding the development of creep and shrinkage deformation-time profiles is crucial.

Focussing on the creep of concrete, although most of the models are relatively recent and comprehensive, there is a lack of consensus in their utilisation due to substantial scatter in their predictions. A major obstacle to progress has been the lack of multi-decade measurements and the dependence of creep on complex interactions between material composition, element shape and size, as well as curing and environmental conditions over time. The majority of available measurement datasets do not possess a sufficient time range to provide information on the functional form of time profiles and to describe the trends associated with loading age, element thickness and environmental humidity [5]. Indeed, while lifetimes in excess of 100 years are nowadays required in designing bridges, only 5% of laboratory tests in the RILEM and NU-ITI databases have a duration over 6 years, and only 3% extend over 12 years [6]. Moreover, existing multi-decade creep tests contain only limited information regarding concrete composition and environmental effects [5], whereas the compilation of databases has revealed various shortcomings in testing, recording and reporting procedures. This has led to recommendations for more comprehensive testing protocols [5]. In this regard, substantial progress could be achieved through the generation of new multi-decade data from bridges and other structures, provided that their documentation is appropriate for

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inverse analysis [6].

The available uniaxial stress creep models have usually been developed in a deterministic framework, despite the fact that the underlying phenomena are influenced by several factors with significant randomness, even when specimens are made under relatively tight conditions. Analysis of residuals (i.e. difference between predictions and measurements) is then typically employed a posteriori to assess the accuracy of models [7,8]. Likewise, sensitivity analysis may be conducted to investigate the relative importance of the different input parameters in creep and shrinkage models [9,10]. Nonetheless, these studies are commonly underpinned by short-term measurements and do not consider uncertainty modelling in an appropriate context.

The utilisation of a Bayesian approach in creep prediction dates back over thirty years when Bažant and his associates introduced it, through a simplified (linearized) compliance model, to a number of different cases and presented in detail potential benefits and limitations arising from this approach [11,12]. Many important aspects were discussed, including the effect of correlation arising from the use of successive creep measurements and the interplay between prior models and the statistics of the likelihood function. Moreover, a Bayesian approach has been implemented at the structural level, through which improvements (i.e. reduction on the uncertainty) in estimating long-term deflections and internal forces in a segmental box girder bridge have been demonstrated [13]. However, the limited in situ data available at the time, together with computational constraints, introduced limitations to the analysis and the generated results.

In this context, this paper re-visits the Bayesian approach applied to the problem of creep deformation prediction by combining prior model distributions obtained through Monte Carlo simulation with in-situ measurements obtained from concrete creep specimens placed in a field environment over a period of several years. In particular, it focuses on aspects of the Bayesian methodology that need to be tailored to the problem in hand, depending on availability and robustness characteristics of in-situ data. Both single point-in-time and sequential updating approaches are developed and demonstrated through a case study that utilises such data from a pre-stressed concrete bridge collected over a period of more than six years. The objective is to understand the limitations of having to rely on small samples and incomplete information on actual conditions, leading to a range of predictive distributions for creep compliance. The question of how long the in-situ measurements should be extended in time is addressed, in the light of monitoring considerations, e.g. feasibility/robustness of data acquisition and costs, within a value of information context represented by the reduction in prediction variability vis-à-vis the length of the observation period.

2. Creep deformations

2.1. Analytical models

Codified models for concrete creep are semi-empirical and are calibrated/validated using laboratory experiments. Supported by the RILEM database, researchers [7,14] have investigated several of those models with the objective of drawing conclusions through detailed comparisons. Generally, it has been concluded that the B3 and GL2000 models exhibit a better performance overall. Recently, in response to advances in concrete technology, the B4 model has been adopted by RILEM [15], which represents an improvement over B3, though its general mathematical form has remained the same, except for the part dealing with autogenous shrinkage. Considering the age and construction characteristics of the bridge analysed as a case study in this work, the B3 model is selected for further use, alongside the GL2000 model and the current Eurocode (EC2) model, the latter being of particular interest to practitioners in Europe. A detailed description of the selected models can be found elsewhere [1,16,17] with Table 1 summarizing their input parameters. The number of input parameters ranges from 7 (EC2) to 11 (B3) with evident differences. In applying the models to an existing structure, some of the input parameters might be reasonably taken to be deterministic, whereas others should be treated as random variables. The identification of the latter is important since it affects considerably the dispersion of the predictions for creep over time. In this paper, bearing in mind the way in which these models will be utilised as prior predictions to be combined with site specific measurements from a single structure, the following are singled out as random variables: (i) mean compressive strength of concrete at 28 days ($f_{cm,28d}$), (ii) Young's modulus of concrete at 28 days ($E_{cm,28d}$) (iii) relative humidity (RH), (iv) cement content (C), (v) water-cement ratio (W/C) and (vi) aggregate-cement ratio (A/C). As can be seen, these are related to mix composition, mechanical properties and prevailing environmental conditions. In contrast, it is assumed that, for a specific structure, the type of cement used, key points in time related to curing and loading and certain geometric parameters can be taken as deterministic.

Table 1
List of input parameters for creep models.

Input parameter		B3	EC2	GL2000
Mean compressive strength, 28 d	$f_{cm,28d}$	✓	✓	✓
Young's modulus, 28 d	$E_{cm,28d}$	✓	✓	✓
Young's modulus at loading	$E_c(t_0)$		✓	✓
Strength development	s		✓	✓
Relative Humidity	RH	✓	✓	
Beginning of drying	t_c	✓		✓
Age of concrete at loading	t_0	✓	✓	✓
Volume-Surface ratio	V/S	✓		✓
Notional size	h_0		✓	
Shape of cross-section	–	✓		
Type of cement	–			✓
Cement content	C	✓		
Water content	W	✓		
Water-Cement ratio	W/C	✓		
Aggregate-Cement ratio	A/C	✓		

2.2. Field measurements

The analysis presented herein is supported by a well-documented testbed offering extensive field data – the São João Bridge, for which a set of creep measurements at specimen level are available with a comprehensive characterization of the employed concrete and good understanding of the prevailing environment. A monitoring system was installed during the bridge construction [18], which has allowed the collection of measurements from an early age, i.e. concrete pouring. Among several monitored parameters, special attention was given to the characterization of the employed concrete and, in turn, of creep and shrinkage. Specifically, fifteen specimens were cast with two long unsealed faces and different sections: (i) six with dimensions 30 × 30 × 60 cm, (ii) six with dimensions 30 × 35 × 60 cm and (iii) three with dimensions 30 × 50 × 60 cm. An equal number of specimens with the same dimensions were used for the characterization of creep. All these samples were kept in an experimental stave, placed next to the bridge, on the south riverbank. More specifically, a vibrating wire strain gauge was placed inside each prism to measure the concrete strain. Whereas the shrinkage specimens were not loaded and subjected only to the environmental conditions, the creep specimens, of interest herein, were subjected to a constant uniaxial load imposed by a hydraulic-based jack system that maintains a constant pressure, which in this case was set to 5 MPa [19]. This value is representative of the magnitude of the operational (serviceability) stress level in the concrete of the bridge [18], which is also well within the limit of $0.45f_{ck}$ suggested in EC2 [1] to ensure that the material behaviour lies within the linear creep domain.