International RILEM Conference on Materials, Systems and Structures in Civil Engineering
Conference segment on Reliability
22-24 August 2016, Technical University of Denmark, Lyngby, Denmark

THE ROLE OF IN-SITU SPECIMEN MEASUREMENTS IN APPRAISING CREEP AND SHRINKAGE MODEL PREDICTIONS

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Abstract

Although the majority of shrinkage and creep models are relative recent and comprehensive, there is a lack of consensus in their utilisation due to substantial scatter in their predictions, even when comparisons are made under relatively well controlled conditions. On one hand, creep and shrinkage are complex phenomena that depend on several factors such as concrete composition and mechanical properties, shape and geometric parameters, curing and environmental conditions, etc. On the other hand, models are typically assessed on a deterministic basis without incorporating information related to input variability.

In addition, the scarcity of long-term measurements has been a major impediment in validating creep and shrinkage models over substantial periods of typical design lives, i.e. over decades rather than years. It is worth noting that although most large prestressed concrete bridges are designed for a lifetime of at least 100 years, only a small fraction of the publicly available data sets cover more than a few years. This type of information is even rarer for measurements from in-situ specimens exposed to realistic environmental conditions.

In this paper, a selection of creep and shrinkage models is assessed by considering measurements from concrete specimens located on actual bridges and, in view of the above remarks, a probabilistic approach is implemented. The suitability of the selected models in producing deformation-time profiles based on in-situ measurements and the influence of case-specific input variability is investigated via sensitivity analysis and Monte Carlo simulation. The work is supported by two well-documented testbeds offering extensive field data - the Lezíria Bridge and São João Bridge, for which a set of creep and shrinkage measurements at specimen level are available with a comprehensive characterization of the employed concrete and good understanding of the prevailing environment.

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) with dead loads. Indeed, the time-dependent creep and shrinkage 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, consequently, 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 for segmental bridge design and assessment.

Although the majority of shrinkage and creep models are relative 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. The majority of available measurements do not exhibit a sufficient time range to provide information on the functional form of time profiles and describe the trends associated with loading age, structure 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 durations 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 the 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 would suffice for inverse analysis [6].

Available creep and shrinkage models are typically developed from a deterministic viewpoint, despite the fact that the underlying phenomena depend on several factors with significant randomness even when specimens are made under relatively tight conditions, such as concrete composition and mechanical properties, environmental conditions, etc. Analysis of residuals (i.e. difference between predictions and measurements) is then typically employed *a posteriori* to assess the accuracy of models [7, 8]. In addition, 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 data dominated by short-term measurements and do not fully consider uncertainty modelling in an appropriate context.

The objective of this paper is to compare and contrast, at a specimen level, the predictions from a set of creep and shrinkage models (EC2, MC2010, GL2000 and B3) applied to multi-decade in-situ measurements with a comprehensive characterization of the employed concrete and a reasonable understanding of the prevailing environment. The most significant input parameters leading to the dispersion of predictions are identified via sensitivity analysis and the robustness of the different model predictions is discussed based on Monte Carlo simulations. Ultimately, this paper aims to contribute to a better understanding of the suitability of models to predict creep and shrinkage deformations with the aid of measurements obtained under in-situ conditions.

2. Selection of creep and shrinkage models

Several models for shrinkage and creep of concrete have been proposed in the literature and in design codes. Overall, these models are semi-empirical and are calibrated/validated using laboratory experiments. Supported by the RILEM database, recent research [7, 11] has investigated several of those models with the objective of drawing conclusions through detailed comparisons. Generally, it has been concluded that models that seem to perform better than others are the B3 and GL2000 models. In this paper, four models are selected: EC2, MC2010, GL2000 and B3, with the first two added to the "best performing" pair due to their particular interest in relation to the use of the Eurocodes. A detailed description of the four models can be found elsewhere [1, 12-14] but Table 1 summarizes the input parameters for each formulation. As a first observation, it is evident that there is no agreement in the set of input parameters. For shrinkage, the number of input parameters ranges from 5 (MC2010 and GL2000) to 9 (B3), whereas for creep it ranges from 7 (EC2 and MC2010) to 11 (B3). Moreover, in applying the models to a specific existing structure, some might be reasonably taken to be deterministic, whereas others are subjected to significant randomness, and should be treated as random variables. The identification of which input parameters are to be treated as random variables is important because it affects the dispersion of the predictions for creep and shrinkage over time. In this paper, bearing in mind the way in which these models will be compared to site specific measurements from a single structure, the following are identified 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.

3. Creep and shrinkage field measurements

The analysis is supported by two well-documented testbeds offering extensive field data - the Lezíria Bridge and São João Bridge, for which a set of creep and shrinkage measurements at specimen level are available with a comprehensive characterization of the employed concrete and good understanding of the prevailing environment. In both cases, SHM monitoring systems have been installed during the bridge construction [15, 16], which have allowed the collection of measurements from an early age, i.e. concrete pouring. Among the several measured parameters, special attention was given to the characterization of the employed concrete, primarily aiming at the characterization of creep and shrinkage.

As far as the Lezíria Bridge is concerned, ten concrete prisms of dimensions 15×15×55 cm with two long unsealed faces were used to measure the time-dependent deformations of concrete: six for shrinkage and the remaining four for creep. Similar curing conditions

were assured for the prisms to obtain representative measurements of the concrete poured on the bridge. The concrete prisms were positioned inside and outside of the box girder, to take into account the effect of the different surrounding environments in the time-dependent deformations of the box-girder concrete. For the purpose of this work, only the concrete specimens positioned outside the box girder are considered i.e. two concrete prisms for shrinkage and two concrete prisms for creep. Taking into account the small differences between these measurements, an average value is considered (i.e. average value from the two concrete prisms for creep and shrinkage respectively).
Regarding the São João Bridge, fifteen specimen were cast with two long unsealed faces and different sections: (i) six specimens with dimensions 30×30×60 cm, (ii) six with dimensions 30×35×60 cm and (iii) the remaining three with dimensions 30×50×60 cm. An equal number of specimen with the same dimensions were used for the characterisation of creep. All these samples were kept in an experimental stave, placed next to the bridge, on the south bank river. For this work, only the concrete specimens with a notional size of 300 mm are considered.

Table 1: List of input parameters for creep and shrinkage models.

Input parameter		**Creep**				**Shrinkage**			
		EC2	MC2010	GL2000	B3	EC2	MC2010	GL2000	B3
Mean compressive strength, 28d	$f_{cm,28d}$	✓	✓	✓	✓	✓	✓	✓	✓
Characteristic comp. strength	f_{ck}					✓			
Young's modulus, 28d	$E_{cm,28}$	✓	✓	✓	✓				✓
Young's modulus at loading	$E_c(t_0)$	✓	✓	✓					
Strength development	s	✓	✓	✓					
Curing conditions	-								✓
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				✓				

4. Uncertainty modelling

The use of current formulations for creep and shrinkage results in considerable prediction scatter stemming from several sources of uncertainty (e.g. random variability, statistical uncertainty, model uncertainty). In order to assess the influence of input variability on the dispersion of model predictions, and the robustness of these models to predict measured creep and shrinkage deformations in specimens located in-situ conditions (i.e. on/near the bridges), site-specific uncertainty modelling is undertaken. Table 2 presents probabilistic models for the set of input parameters (from Table 1) considered as random variables.

The presented values are based on in-situ information (i.e. utilising data available from the two specific bridges) related to the employed concrete and surrounding environmental conditions [16-18]. In the particular case of the concrete composition parameters, i.e. *C*, *W/C* and *A/C*, and in the absence of more precise information, the CoV was set based on information available in the literature [19, 20]. In addition, the statistical dependence between random variables needs to be taken into account. Hence, according to information available in the literature [5, 10], the correlation matrix presented in Table 3 is adopted.

Regarding the remaining variables, the following points are relevant: (i) the characteristic compressive strength, f_{ck}, is derived from the mean compressive strength at 28d, $f_{cm,28d}$ by considering the relation $f_{cm} = f_{ck} + 8$, i.e. assuming a standard deviation for standard grade concrete of 8 MPa [1] (ii) the strength development parameter, *s*, is set equal to 0.21 and 0.24 for the Lezíria Bridge and São João Bridge [17], (iii) the curing conditions is considered moist, (iv) the concrete is exposed to drying at $t_s = 1$ day and (v) loaded at $t_0 = 3$ days for the case of Lezíria Bridge and $t_0 = 7$ days for the case of São João Bridge, (vi) the Volume-Surface ratio, *V/S*, is 75 mm for the case of Lezíria Bridge and 150 mm for the case of São João Bridge, (vii) the notional size, h_0, is 150 mm for the case of Lezíria Bridge and 300 mm for the case of São João Bridge, (viii) the shape of the cross section is assumed to be an infinite square prism and (ix) the type of cement is IV 32.5 for the case of Lezíria Bridge and CEM I 42.5 R for the case of São João Bridge.

Table 2: Description of random variables.

Variable	**Lezíria Bridge**		**São João**		**Distribution**	**Units**
	Mean	CoV	Mean	CoV		
$f_{cm,28d}$	55.5	0.05	51.1	0.07	Log-normal	MPa
$E_{cm,28d}$	38.4	0.12	34.7	0.07	Log-normal	GPa
RH	64.0	0.05	70.0	0.05	Extreme Value	%
C	440	0.10	474	0.10	Log-normal	Kg/m^3
W/C	0.39	0.10	0.39	0.10	Log-normal	-
A/C	3.96	0.10	3.60	0.10	Log-normal	-

Table 3: Correlation matrix.

	$f_{cm,28d}$	$E_{c,28d}$	*RH*	*C*	*W/C*	*A/C*
$f_{cm,28d}$	1.0	0.6	0.0	0.5	-0.6	-0.4
$E_{c,28d}$		1.0	0.0	0.3	-0.3	-0.1
RH			1.0	0.0	0.0	0.0
C				1.0	-0.8	-0.9
W/C					1.0	0.8
A/C						1.0

4.1 Sensitivity analysis

A simple sensitivity analysis is conducted first in order to better understand the influence of each input parameter in model predictions. This allows the identification of variables that have a predominant effect in the dispersion of model predictions with time. In this analysis, the criterion used to rank variables is the CoV of model predictions at selected points-in-time compared to the CoV of the input variable. More specifically, the CoVs of the model predictions for two different time instances are calculated: (i) t = 10^2 days, in order to assess the variability at an early stage and (ii) t = 10^5 days in order to assess the long-term variability.

Figure 1 and Figure 2 summarizes the results obtained for the case of the Lezíria Bridge and the São João Bridge. The graphs present the ratio between the CoV of the model prediction and the CoV of the input random variable. It should be mentioned that the statistical dependence between random variables is disregarded in this analysis. Its purpose is to obtain a first impression on which variables are most important, and also to demonstrate the different way in which input variables can affect the response over time. A comprehensive sensitivity analysis, accounting for statistical dependence, may be found in [10].

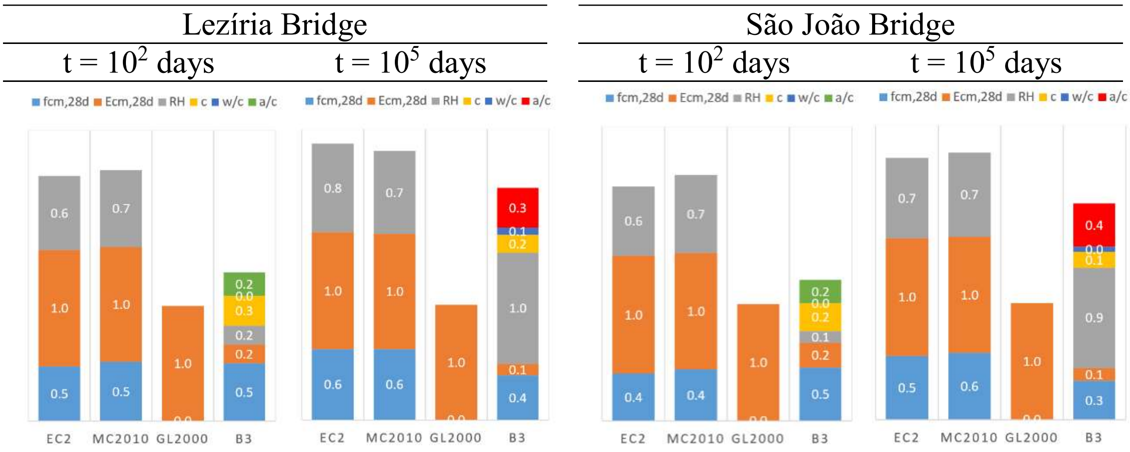

Figure 1: CoV from the sensitivity analysis on creep models.

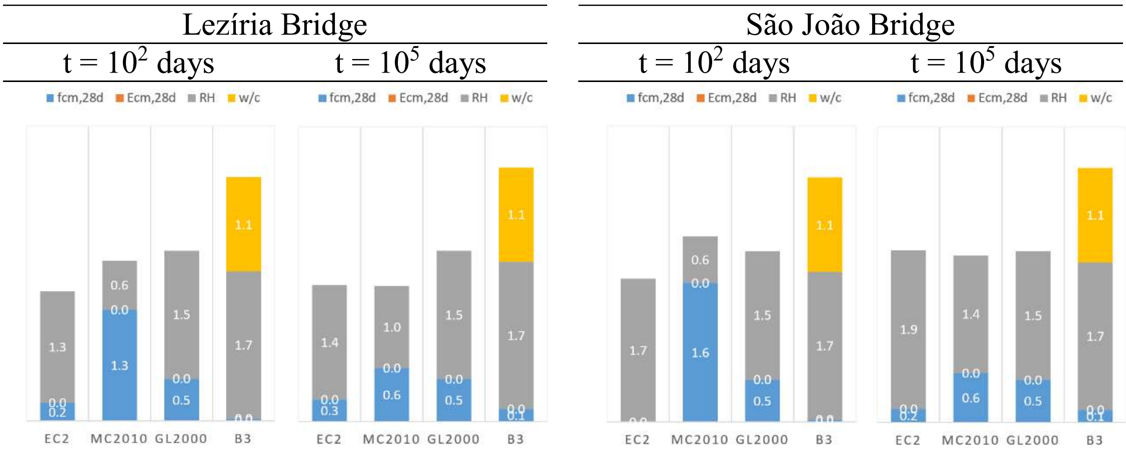

Figure 2: CoV from the sensitivity analysis on shrinkage models.

With regard to creep, it is found that the random variables with highest influence in the long-term, are the mechanical properties (i.e. Young's modulus of elasticity at 28 days, $E_{cm,28d}$, and mean compressive strength at 28 days, f_{cm28d}) and RH, except for the GL2000 model where only the Young's modulus at 28 days, $E_{cm,28d}$, has an important contribution. The remaining input parameters have only a minor effect in the creep predictions. It is also worth noting that, of the four models, only B3 displays noticeable differences in the variable ranking between the two selected points-in-time, with relative humidity assuming greater importance at longer time periods.

As far as shrinkage is concerned, it is found that the random variables with highest influence are the RH, mean compressive strength at 28 days, f_{cm28d}, (as observed for creep) and water content, *W* (via water-cement ratio variable, *W/C*). Time differences are generally small, with the possible exception of the importance of RH in MC2100.

4.2 Monte Carlo simulation

The robustness of the different creep and shrinkage models is examined by undertaking Monte Carlo simulation. The aim is to explore the role of in-situ measurements collected from the Lezíria Bridge and São João Bridge to appraise creep and shrinkage model predictions over time. In order to limit sampling errors associated with the Monte-Carlo method, sample sizes with up to 5,000 realisations were considered and the final sample size was fixed at 2,500.

Figure 3 and Figure 4 show the results obtained for creep and shrinkage, respectively. The measurements from the Lezíria Bridge and the São João Bridge are also included in these figures in order to get an impression of how they relate to the spread that is generated by the site-specific *a priori* uncertainty modelling.

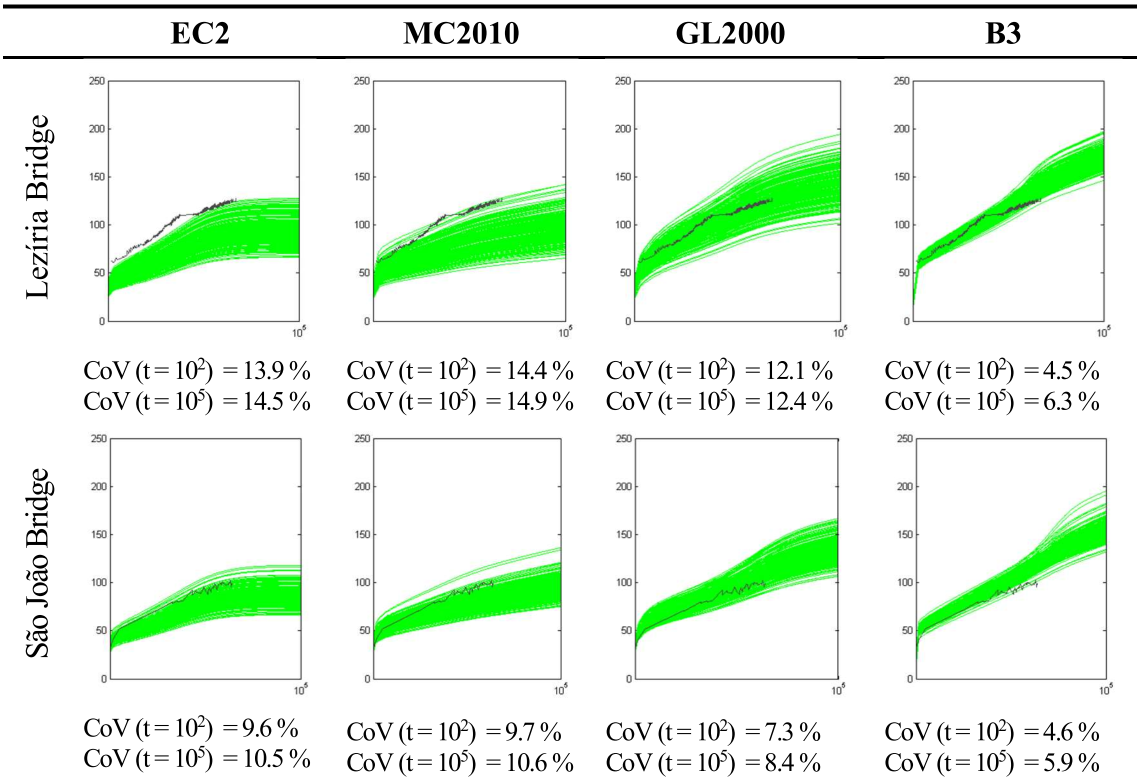

Figure 3: Creep – measurements vs. model predictions.

Starting with creep, Figure 3 shows the compliance function for the four models (i.e. EC2, MC2010, GL2000 and B3). In the long-term, i.e. t = 10^5 days, the predicted compliance ranges from approximately 60 $\mu\varepsilon$/MPa (for the EC2 and MC2010 models) to almost 200 $\mu\varepsilon$/MPa (for the GL200 and B3 models), which underlines the spread associated with the level of uncertainty that is present even on a site-specific basis. It is worthy to note that the EC2 model (the one with the lowest final compliance envelope) is the only one that reveals an asymptotic value by t=10^5 days. Regarding model dispersion, three models display similar CoVs (for each bridge), the clear exception being the B3 model which shows a much lower dispersion. Overall, the model that seems to align better with the measurements so far is the GL2000 model. For both EC2 and MC2010 the in-situ measurements correspond to very high fractiles, though the trends are still statistically feasible.

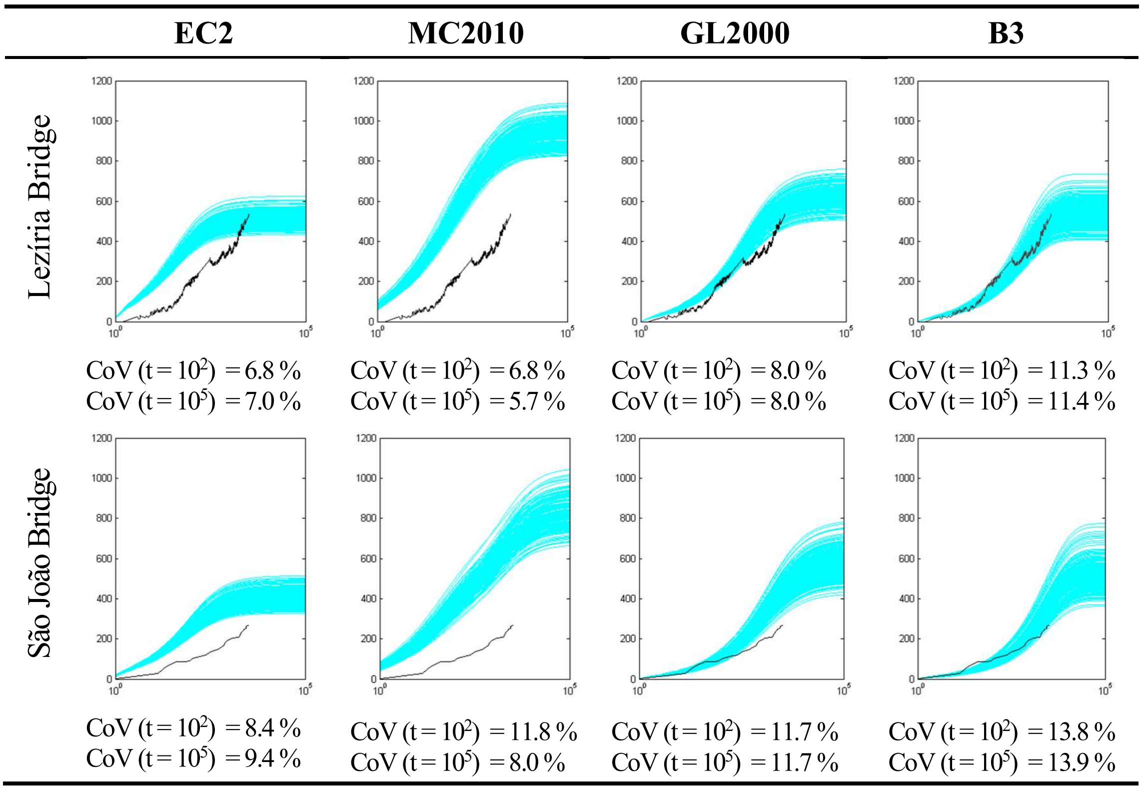

Figure 4: Shrinkage – measurements vs. model predictions.

As far as shrinkage is concerned, Figure 4 shows the corresponding predictions. In the long-term, i.e. $t = 10^5$ days, the predicted shrinkage deformations range from 400 $\mu\varepsilon$ (for the EC2 and B3 models) to approximately 1100 $\mu\varepsilon$ (for the MC2010 model). In contrast to the observation made above, the B3 model exhibits the highest CoV compared to the other three models whose CoVs are once again comparable. In this case, however, the in-situ measurements lie outside the predicted spreads for both EC2 and MC2010, with both over-estimating the actual deformations. The measurements are better estimated by the other two models, more so by the B3 model, with the measurements falling largely within the prediction envelope.

5. Conclusions

The objective of this paper was to analyse, at the specimen level, a set of creep and shrinkage models (EC2, MC2010, GL2000 and B3) applied to in-situ measurements with a comprehensive characterization of the employed concrete and a good understanding of the prevailing environment. The most significant input parameters leading to the dispersion of predictions were identified via sensitivity analysis. In general, it was found that the Young's modulus of elasticity at 28 days, $E_{cm,28d}$, mean compressive strength at 28 days, f_{cm28d}, and RH are the most important random variables for creep predictions, whereas for shrinkage predictions the RH, mean compressive strength at 28 days, f_{cm28d}, and water content, W (via water-cement ratio variable, W/C) are the most important random variables.

The robustness of the different models was examined via Monte Carlo simulation. In-situ measurements, collected from two modern pre-stressed bridges, were used to appraise model predictions over time. It is evident that, even under relatively tightly controlled site-specific uncertainty modelling (as opposed to the wider uncertainty in considering a population of pre-stressed bridges), the prediction envelopes for creep and shrinkage deformations are quite wide. The potential benefit of introducing Bayesian updating, for cases where in-situ measurements are available over substantial time periods, becomes evident when the results shown in Figures 3 and 4 are appraised. This will be considered in the next phase of this work.

Acknowledgments

The first author acknowledges the support from the European Commission through the Marie Curie grant Fellowship grant 660275 - LostPreCon under the program H2020-MSCA-IF-2014. The COST Action TU1402 on Quantifying the Value of Structural Health Monitoring has provided networking support. Finally, support from the infrastructure owner, BRISA, is also gratefully acknowledged.

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