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Uncertainty based model averaging for prediction of long-time prestress losses in concrete structures

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HIGHLIGHTS

- Development of a single best model for creep and shrinkage in concrete.
- Uncertainties considered in models, in measurements, and in parameters of each model.
- Evaluation of time period for short time measurements using statistical simulations.
- The long-time predictions verified against a few experiments from NU database.
- Estimation of long-time prestress loss in post-tensioned concrete beams and slabs.

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ABSTRACT

Prestressed concrete structures are widely used in long span bridge girders and nuclear power plants. Long-time creep and shrinkage in concrete cause loss of prestress forces in the concrete structures. The creep and shrinkage models existing in the literature are empirical in nature. Each model has been developed on the basis of an arbitrary selection of data sets among all the data sets available. In this study it is claimed that each model contains some information about the creep and shrinkage patterns in the concrete structures. A single best model is developed in this study using all existing models, based on the concept of model averaging. In model averaging all the models are updated independently based on the short-time measurements. Weights are assigned to each model based on the likeliness of predictions from that model to the actual measurements. The time period for short-time measurements is evaluated using stochastic simulations. The proposed single best model for creep and shrinkage, and the time period for short-time measurements are (i) first validated against experiments reported in the Northwestern University (NU) database, and (ii) then used to predict the long-time losses of prestress forces in the concrete beams and slabs cast in the laboratory.

1. Introduction

Prestressed concrete structures are designed for the serviceability limit in the range of elastic deformations under service loads. An accurate prediction of prestress losses, due to long-time creep and shrinkage in concrete, can help in designing structures with reduced deflection and cracking. A brief description of shrinkage and creep in concrete structures is given in [1]. Various codal provisions and standard recommendations for long-time deformations in concrete structures are available in the literature such as CEB/FIP MC-1990 [2], B3 [3], GL2000 [4], AASHTO 2007 [5], ACI-209 [6], FIB MC-2010 [7] and B4 [8]. Existing models for creep and shrinkage in codal provisions and in standard recommendations do not agree in a best possible way with the available results reported from experiments [9].

Statistical variations are present in the creep and shrinkage models, in the parameters of these models, in the shrinkage and creep mechanisms, in the environmental conditions, and in the in situ measurements [10]. A statistical prediction of long-time prestress forces in prestressed concrete box girder bridges is given in [10]. A probabilistic analysis of the shrinkage and creep effects is used in [10], followed by a sensitivity analysis for obtaining the relative importance of parameters in creep and shrinkage models. In large creep sensitive structures, like long span prestressed box girders, all the available material models are not suitable for long-time predictions [11,12], and parameters of these material

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models must be updated based on short-time measurements. The variabilities in the long-time behavior of complex concrete structures are reduced in [13], by updating the parameters of the concrete deformation models, based on short-time measurements. Bayesian statistical inference is used in [14], to get a more accurate long-time prediction of prestress forces by updating parameters of deformation models. Statistical methods and large experimental database are used in [15], for selecting the most realistic model for durability and safety of concrete structures. The most realistic model is selected by comparing and ranking the existing shrinkage and creep prediction models. As reported in [15], existing prediction models give conflicting results when compared with the experimental database, as the database is dominated by short-time tests on small specimens of low strength concretes with large variation in concrete composition and low ages at loading. A modified prediction model based on existing shrinkage and creep deformation models is proposed in [16], and the parameters of the modified prediction model are adjusted using probabilistic analysis with short-time measurements. Model B4 [8] for shrinkage and creep prediction is calibrated in [17,18], by the NU database for laboratory measurements [19]. A sequential optimization algorithm is used in [20] for statistical comparison of the predictions from model B4 [8] with the prediction from existing shrinkage and creep models, where the environmental conditions are assumed to be constant or fluctuating with an almost fixed mean. In all of the above mentioned statistical methods the emphasis is upon selecting the best possible model among all existing models.

The following observations constitute the motivation for the present study.

1. Losses occur in prestressed concrete structures, due to creep and shrinkage in concrete. The existing models for creep and shrinkage are empirical in nature, and the statistical variations present in these models need to be considered.
2. In the existing statistical methods, the emphasis is upon selecting the best possible model among all existing models. The parameters of the creep and shrinkage models are updated based on short-time measurements, and the best model is selected based on the likeliness of the predictions from each model to the measured data.
3. In the existing statistical methods for estimating long-time creep and shrinkage in concrete, most of the authors have been inclined to select a single model, rather than taking all the possibilities into consideration. However, a model selection is based on the hardly realistic assumption that we can select a correct one from the available set of models. A single best model among all existing models needs to be developed, when uncertainties are present in the models, in the measurements, and in the parameters of each model.
4. The error in measurement can be expressed through various forms of uncertainty like (i) Gaussian noise with probabilistic analysis, (ii) plus minus ranges with interval analysis, and (iii) hybrid representation using imprecise probability analysis, where the measurement error is expressed as Gaussian noise with specified ranges for mean and standard deviation. The model builder decides the type of uncertainty model to choose from [21]. The single best model must consider various forms of uncertainty, that may come across in the prediction of long-time creep and shrinkage in concrete structures.
5. The common practice has been to carry out shrinkage and creep test for 6–12 months [22], and based on the data for this time period extrapolate the creep and shrinkage for 40–50 years. However there is no concrete guidelines available in the literature, for the time period up to which measurements are required to be taken, so that the models updated using measurements up to this short-time period can predict the long-time creep and shrinkage more accurately.

As an application vide project [23], prestress losses are predicted for nuclear reactors in India, at 50 years of service life. Post-tensioned beams and slabs are cast in the laboratory, and are placed inside humidity chambers with different controlled relative humidity and temperature. Based on the short-time measurements on post-tensioned beams and slabs, the long-time losses of prestress forces in the beams and slabs are estimated. Though the application considered in this study is towards estimating long-time prestress losses in nuclear reactors, the present study can directly be applied to other prestressed concrete structures with different concrete properties, and environmental conditions. The manuscript is organized based on the steps involved in estimating the long-time prestress losses in beams and slabs, and are briefly described below.

1. Since the models of creep and shrinkage are updated based on short-time measurements, it is necessary to find out the time period for short-time measurements. In Section 2, the time period for short-time measurements is evaluated using statistical simulations for all models.
2. After obtaining short-time measurements, the next task is to develop a single best model among all the available models, to estimate the long-time creep and shrinkage in concrete. In Section 3, a single best model is developed base on uncertainty based model averaging, when uncertainties are present in the models, in the measurements, and in the parameters of each models. Uncertainty bounds on the long-time prediction are evaluated using three types of uncertainty models, probabilistic uncertainty, interval uncertainty, and imprecise probability.
3. In Section 4, the long-time creep and shrinkage in concrete, predicted from the single best model using measurements up to the short-time period, are verified against a few experiments from NU database.
4. The proposed single best model for creep and shrinkage in concrete, and the time period for short-time measurements, after being verified using experiments from the NU database, are then used in Section 5 to predict the long-time prestress losses in post-tensioned beams and slabs.

2. Time period for short-time measurements

Time period for short-time measurements is the minimum time in days, up to which measurements are needed to be taken to update the creep and shrinkage models, so as to be able to predict the long-time creep and shrinkage accurately. The major parameters in the creep and shrinkage models are compressive strength (f_c), elastic modulus (E_c), relative humidity (RH), volume to surface ratio (VS), age at loading (t_0), age at start of drying (t_c), cement content (c), water cement ratio (w/c), and aggregate cement ratio (a/c). The time period for short-time measurement is chosen in such a way that it is applicable to all combinations of values of each parameter. That is, the longest time among all the time periods for every combination of parameter is selected. To evaluate this a large number of statistically simulated responses are generated for each sample of the joint distribution, where all the parameters are taken as random variables with marginal distributions given in Table 1 and correlation matrix given in Table 2. The distributions of the random variables and their correlation matrix are taken from the literature given in [19]. Then for each simulated response the time period for short-time measurements is evaluated as follows.