

Uncertainty and sensitivity analysis of time-dependent effects in concrete structures

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Abstract

The purpose of this paper is to propose the method of uncertainty and sensitivity analysis of time-dependent effects due to creep and shrinkage of concrete in concrete structures. The uncertainty and sensitivity analyses are performed using the Latin Hypercube sampling method. For each sample, a time-dependent structural analysis is performed to produce response data, which are then analyzed statistically. Two measures are examined to quantify the sensitivity of the outputs to each of the input variables. These are partial rank correlation coefficient (PRCC) and standardized rank regression coefficient (SRRC) computed from the ranks of the observations. Three possible sources of the uncertainties of the structural response have been taken into account — creep and shrinkage model uncertainty, variation of material properties and environmental conditions. The proposed theory is applied to the uncertainty and sensitivity of time-dependent axial shortening and time-dependent prestress forces in an actual concrete girder bridge. The numerical results indicate that the creep model uncertainty factor and relative humidity appear to be the most dominant factors with regard to the model output uncertainty. The method provides a realistic method of determining the uncertainty analysis of concrete structures and identifies the most important factors in the long-term prediction of time-dependent effects in those structures. © 2006 Elsevier Ltd. All rights reserved.

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1. Introduction

Time-dependent effects of concrete structures result from creep and shrinkage of concrete. Creep and shrinkage are important factors in the design of concrete structures. For example, they affect the setting of bearings of concrete bridges including the size of sliding plates or laminated bearing pads. They also affect the sizing and setting of expansion joints due to time-dependent axial shortening arising from creep and shrinkage effects of prestress force and thereby also affect the secondary moments in prestressed concrete bridges. The creep and shrinkage models which are capable of predicting long-term structural response are specified in design codes such as ACI 209-92 [1], CEB-FIP Model Code 90 [2], etc. However, the application of current code formulations may result in considerable prediction errors stemming from several sources of uncertainty. They predict only mean values and cannot predict the statistical variation. Therefore, a method to

deal with the uncertainty involved in the prediction of creep and shrinkage effects of concrete is necessary.

Creep and shrinkage in concrete structures are very complex phenomena in which various uncertainties exist with regard to inherent material variations as well as modelling uncertainties. The study on the uncertainties in creep and shrinkage effects has been continuously an area of significant efforts. Particular attention has given to the problem of creep and shrinkage with uncertainty modelling [3–7] and with the variability in external loads [8,9]. The variation of creep and shrinkage properties is caused by various factors commonly classified as internal and external factors [10]. The change of environmental conditions, such as humidity, may be considered as an external factor. The internal factors include the variation of the quality and the mix composition of the materials used in concrete and the variation due to internal mechanism of creep and shrinkage.

In the prediction formulas of creep and shrinkage of concrete, various kinds of parameters are involved to express the characteristics of concrete under consideration, i.e. the mix proportion of concrete, the shape of the structure, relative humidity, etc. Since it is not possible to remove the statistical

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variation involved in the parameters, it may be necessary to estimate how much the variation of each parameter influences the predicted values. Several different approaches of sensitivity analysis have been developed as numerical tools for reliability assessment of structures [11–15]. Also, a review of different methods for this sensitivity analysis has been provided by Novák et al. [16]. Another example for sensitivity analysis is shown by Tsubaki [17].

The aim of the present study is to propose an analytical approach for the uncertainty and sensitivity analyses of creep and shrinkage effects in concrete structures utilizing the models in the design codes. The present study deals with the uncertainties in the long-term prediction of creep and shrinkage effects, taking into account the statistical variation of both internal and external factors as well as the uncertainty of the model itself. The sensitivity analysis is performed to show the relative importance of individual random variables employed in the creep and shrinkage models. The time-dependent axial shortening of a prestressed concrete girder bridge is analyzed to show the application of proposed method.

2. Uncertainty modelling of creep and shrinkage of concrete

Several material models for shrinkage and creep of concrete have been proposed both in the literature and in the design codes. The most commonly used models in the codes are those suggested by ACI Committee 209 [1] and CEB-FIP MC 90 [2].

2.1. ACI committee 209 recommendations

ACI committee 209 suggests the use of the following equation for prediction of shrinkage strain.

$$\varepsilon_{sh}(t, t_0) = \Psi_1 \frac{(t - t_0)}{f + (t - t_0)} \varepsilon_{sh}^u \quad (1)$$

where, $\varepsilon_{sh}(t, t_0)$ = shrinkage strain at any time t ; ε_{sh}^u = ultimate shrinkage strain determined by experiments; f = factor dependent on curing condition (35 for moist cured concrete, 55 for steam cured concrete); t_0 = the age of concrete starting drying (days); t = observation (current) time (days); Ψ_1 = model uncertainty factor for shrinkage model. Creep coefficient is expressed by the following equation:

$$C(t, \tau) = \Psi_2 \frac{(t - \tau)^{0.6}}{10 + (t - \tau)^{0.6}} C_u \quad (2)$$

where, $C(t, \tau)$ = creep coefficient at any time t ; C_u = ultimate creep coefficient determined by experiments; τ = the age of concrete at first loading (days); t = observation time (days); Ψ_2 = model uncertainty factor for creep model. In the absence of specific creep and shrinkage data for local aggregates and material conditions, the average values suggested for C_u and ε_{sh}^u are, respectively:

$$C_u = 2.35\gamma_c \quad \text{and} \quad \varepsilon_{sh}^u = 780 \times 10^{-6} \gamma_{sh} \quad (3)$$

where, γ_c and γ_{sh} represent some correction coefficients.

The coefficients Ψ_1 and Ψ_2 are model uncertainty factors. Information on model uncertainty can be obtained from the work of Bažant and Baweja [6]. The mean value and coefficients of variation of a time-averaged value of Ψ 's are estimated. From their study it is found that the coefficients of variation of the creep and shrinkage properties were 55.3% for shrinkage and 52.8% for creep, respectively. The mean values and coefficient of variation of the Ψ factors reported are:

$$E[\Psi_1^*] = 1; V_{\Psi_1^*} = 0.553 \quad (4a)$$

$$E[\Psi_2^*] = 1; V_{\Psi_2^*} = 0.528. \quad (4b)$$

The coefficients Ψ_1^* and Ψ_2^* are prediction error terms that account for the uncertainty inherent in the theoretical model and the uncertainty of the micro-mechanism of creep and shrinkage that has been neglected. The values in Eq. (4) include several sources of uncertainties and may be written as follows:

$$\Psi_i^* = \Psi_i \Psi_\alpha \Psi_\beta \quad (i = 1, 2) \quad (5)$$

where, Ψ_i = factor due to inadequacy of the prediction formula; Ψ_α = factor due to internal uncertainty; Ψ_β = factor due to measurement errors and uncertainty in the laboratory (or site) environment.

The factors to be used in Eqs. (1) and (2) are prediction model uncertainty Ψ_i , and the coefficient of variations in Eq. (4) must therefore be corrected to include only model uncertainty. The factors in Eq. (5) are assumed independent, and the relation between the coefficients of variation [18] is:

$$(1 + V_{\Psi_i^*}^2) = (1 + V_{\Psi_i}^2)(1 + V_{\Psi_\alpha}^2)(1 + V_{\Psi_\beta}^2) \quad (i = 1, 2). \quad (6)$$

Few data are available for the estimation of V_{Ψ_α} , but the results by Reinhardt et al. [19] indicate that a value between 0.06 and 0.10 is reasonable for test specimens. The coefficient of variation V_{Ψ_β} was estimated as 0.05 by Madsen [4]. In this study, the following corrected values for model uncertainties Ψ_i are obtained from Eqs. (4) and (6):

$$\text{Shrinkage } E[\Psi_1] = 1; V_{\Psi_1} = 0.542 \quad (7a)$$

$$\text{Creep } E[\Psi_2] = 1; V_{\Psi_2} = 0.517. \quad (7b)$$

2.2. CEB-FIP model code 90

The total shrinkage $\varepsilon_{cs}(t, t_s)$ is calculated from:

$$\varepsilon_{cs}(t, t_s) = \Psi_1 \varepsilon_{cs0} \beta_s(t - t_s) \quad (8)$$

where ε_{cs0} = the notional shrinkage coefficient; β_s = the coefficient to describe the development of shrinkage with time; t = the age of concrete (days) and t_s = the age of concrete (days) at the beginning of shrinkage.

For a constant stress applied at time t_0 , the creep strain $\varepsilon_{cc}(t, \tau)$ at any time t is calculated as following equation:

$$\varepsilon_{cc}(t, \tau) = \frac{\sigma_c(\tau)}{E_{ci}} \phi(t, \tau) \quad (9)$$

where, $\phi(t, \tau)$ = creep coefficient; E_{ci} = modulus of elasticity; $\sigma_c(\tau)$ = sustained stress.

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