Creep of Concrete in Contemporary Code-Type Models

Janusz Hołowaty

Faculty of Civil Engineering and Architecture, West Pomeranian University of Technology, Szczecin PL-70-311, Poland

Abstract: The paper presents and compares the conventional models for creep in cement concrete included in the ACI (American Concrete Institute) guide, Eurocode 2 and *fib* (International Federation for Structural Concrete) Model Code 2010. For the presentation and comparison of the creep models, creep coefficients are developed. The main factors affecting the prediction of creep in concrete are outlined, comparing the influence of concrete grade, environmental conditions, member size and loading conditions. Most of the conventional models currently used for creep in cement concrete develop the code-type procedures and are calibrated for normal- and high-strength concretes. They enable a more accurate analysis and better assessment of the time-dependent deformation of concrete structures at the design stage. Their complexity is significantly reduced and a range of influencing parameters are excluded from the models for simplicity and easy adaptation. The comparison of the models shows that the *fib* Model Code 2010 model is more consistent and calibrated to avoid shortcomings in the previous models.

Key words: Creep of concrete, creep models, time dependant properties.

1. Introduction

Predicting creep in concrete structures is still highly uncertain because current models for creep in cement concrete differ a lot in their accuracy and complexity. A wide range of models for creep in cement concrete have been developed over the years [1-5]. Then as now, the most important problem concerning creep deformation has been the assessment of time-dependent losses of the prestressing forces in PC (prestressed concrete) structures, with other problems associated with deformation and displacement over time barely recognized and omitted in time-dependent structural analyses. Starting from the crude estimation of delayed deformations, formulas for creep were elaborated and calibrated in on-going research. Later, creep models were adjusted to changing concrete properties and technologies. Models for the description of long-term effects in concrete structures have changed over time and new models are still being introduced, some of which are highly sophisticated and taken into account many parameters, while some are still very simple but can be easily adapted in plain

problems. The complexity and uncertainty in predicting the effects of creep require the adoption of code-related procedures to give a general usage guidance. In this paper, these procedures are called conventional models and they cover the majority of modern standards and codes. They are not formulated to give a detailed description of creep mechanisms but to give guidance for general design purposes.

In this paper, three modern creep models, the ACI (American Concrete Institute) 209 model [1], Eurocode 2 [3] and the recently introduced *fib* MC (Model Code) 2010 (final version) [4] are discussed and compared. In some cases, in structures vulnerable to creep, simple approaches for creep estimation are too crude and more sophisticated procedures for time-dependent analysis require formulation. Conventional models assist with this, while retaining simplicity for application. These procedures allow a more precise assessment of the time-dependent deformation and forces in order to design more durable and sometimes safer structures. The progressively evolving CEB-FIB (Euro-International Concrete Committee-International Federation for Prestressing) models [2] and their implementation in EC2 (Eurocode 2) give practical and accurate methods for the

Corresponding author: Janusz Hołowaty, Dr., associate professor, research fields: testing and design of bridges. E-mail: jah@wp.pl.

prediction of creep effects. The *fib* Model Code 2010 introduced a new and improved formulation to describe creep effects as the sum of basic and drying creep deformations.

Predicted values for creep in concrete over different conventional models indicate that the results calculated for creep coefficients may differ significantly. Precise prediction of the magnitude of creep in concrete structures is still extremely difficult and sometimes requires individually-calibrated models for the accurate prediction of the time-dependent behavior of concrete structures. Conventional models currently in use may differ in the final values of the creep coefficients, but adapting the appropriate procedure of time-dependent analysis in creep-vulnerable structures under changing environmental conditions usually allows accurate rheological analysis [6, 7].

2. Influencing Factors and Creep

A great number of both variable and uncertain factors influence the time-dependent deformation of concrete. The magnitude and development of creep strains depend on a wide range of factors including the stress range, the dimensions of the element, the degree of hydration, the concrete mix properties, the coarse gravel content, the cement content, the type of cement, the water/cement ratio, the amount and distribution of reinforcement, the ambient humidity, the temperature, the age of concrete at loading, the type and duration of curing and maturity, etc. As considerable progress in concrete technology and types of concrete has been made over the last few decades, more factors influencing concrete creep should be taken into account when calibrating the creep formulas.

Including most of these in creep, effect calculations are tedious and sometimes practically impossible. As a result of many of the parameters being unknown to a concrete structure designer during the design stage, more comprehensive code-related models for creep in concrete were created. These conventional models try to limit the number of influencing factors for simplicity

of use. Therefore, to avoid using concrete composition parameters, which are usually unknown at the design stages, compressive strength of concrete is developed. The modern code-type models limit the number of influencing parameters to usually known at the design stage. In these models for describing the creep deformation of concrete, the compressive strength of concrete, the class of cement, the mean *RH* (relative humidity) and the age of concrete at loading t_0 are used.

Physically, several components and types of creep strain can be distinguished. These are extensively used in the literature to describe the creep phenomenon. Methods for time-dependent analysis given in the literature and codes are sometimes too simplified, leading to misunderstandings in the real-time behavior of concrete structures [6-9]. Many variable parameters induce significant differences in the long-term deformation estimation and lead to serviceability problems in creep sensitive structures if they are treated too crudely.

3. Creep Coefficient

In code-related concrete models, creep is usually described by the so-called creep coefficient φ , which represents the ratio of delayed deformation—creep strain $\varepsilon_{cc}(t, t_0)$ to initial elastic strain ε_{ci} in concrete at the age of 28 days under the same stress $\sigma_c(t_0)$ applied at the age of concrete t_0 . The creep coefficient $\varphi(t, t_0)$ can be expressed as:

$$\varphi(t, t_0) = \frac{\varepsilon_{cc}(t, t_0)}{\varepsilon_{ci}} = \frac{\varepsilon_{cc}(t, t_0)}{\sigma_c(t_0)} E_{ci} \quad (1)$$

where, t is the age of the concrete, t_0 is the age of the concrete at loading in days and E_{ci} is the tangent modulus of elasticity of the concrete at 28 days. For simple time-dependent analysis, the majority of codes introduced values of final creep coefficient $\varphi(\infty, t_0) = \varphi(t, t_0)$, taking into account time $t = 50$ years or 70 years. The values are tabulated or given in graphs for practical usage. Such an approach is sufficient for typical concrete structures where the creep effects are not

significant. For larger concrete structures or for structures with staged construction, delayed deformation may be more relevant and the development of creep over time is calculated using numerical formulas. Creep models usually use a product time function expressing a notional creep coefficient and a function describing creep development with time after loading. The creep coefficient is calculated from the formula:

$$\varphi(t, t_0) = \varphi_0 \beta(t, t_0) \quad (2)$$

where, φ_0 is the notional creep coefficient and $\beta(t, t_0)$ is a coefficient to describe the development of creep over time after loading. Many factors are used in calculating these coefficients depending on the creep model. For *fib* Model Code 1990 [2] and Eurocode 2, the concrete mix parameters are replaced by concrete strength. This is not the case with ACI 209 R-92:2008, which still takes into account some concrete mix parameters as well as the curing effect. In the recently established *fib* Model Code 2010, a new formulation was introduced by representing the total creep deformation by the sum of two deformation components: basic and drying creep. The product type approach is followed for each component. The creep coefficient is calculated from the formula:

$$\varphi(t, t_0) = \varphi_{0,b} \beta_{bc}(t, t_0) + \varphi_{0,d} \beta_{dc}(t, t_0) \quad (3)$$

where, $\varphi_{0,b}$ and $\varphi_{0,d}$ are the notional basic and drying creep coefficients, respectively. Functions $\beta_{bc}(t, t_0)$ and $\beta_{dc}(t, t_0)$ are coefficients to describe development of basic and drying creep with time after loading. Basic creep is defined as the creep that occurs when concrete is sealed (no moisture movement) and drying creep is the additional creep that occurs when concrete dries while under load. The creep formulation in MC 2010 is similar to shrinkage modeling and is necessary to accurately describe delayed deformations in high strength concrete. Separation of creep into basic creep and drying creep was introduced earlier in some models for creep recovery. Basic creep is well established and occurs when loaded concrete is prevented from drying.

For the comparison of creep deformation in different creep models, the creep coefficient is used as a simple and practical parameter. The creep coefficient is usually determined in the codes as the function of several parameters, such as ambient humidity, composition of the concrete mix, age at loading and member dimensions. When a structure requires more detailed time-dependent analyses, the total stress-produced strain is calculated using creep function $J(t, t_0)$.

4. Code-Type Creep Models

For the comparison of creep, three conventional models are selected which represent a simplified approach for design purposes. The ACI 209 model, the Eurocode 2 model and *fib* Model Code 2010 are compared using the same parameters as the initial data. The models are a compromise between accuracy and simplicity. Two of the models consider that basic creep and drying creep may be calculated as independent, in Eurocode 2 partially for high strength concretes. In the ACI 209 model and the general section of Eurocode 2, creep is dependent and calculated using a product type formula. In the models, an effort was made to represent varying characteristics of high strength concretes. The creep models are presented and compared in terms of better calibration. They are physically consistent at the time when they were elaborated and they try to avoid some shortcomings in the former models by taking into consideration concrete technology development, but they can still be used for conventional concrete with some exceptions. For consistency, the results are presented for selected parameters which are the same for the concretes used for comparison. Creep coefficients are presented for concrete loaded at $t_0 = 3, 5, 7, 14, 28, 60, 90, 180, 360, 700$ and 1,400 days after casting for C20 and C80 concrete grades, at relative humidity of 50% and 80%, and for notional member size $h_0 = 100$ mm.

Two different concrete mixes are used in estimations of creep in normal and high strength concretes, C20

and C80, respectively. Stress range is assumed to be lower than $0.4f_{cm}$ (f_{cm} is a mean value of concrete cylinder compressive strength) and the ambient temperature within normal range with seasonal variations used in the models. The models are also valid for variations in relative humidity around the values given in the models.

The oldest model is the ACI 209 model which was devised in 1971, modified in 1982, developed by ACI in 1992 and reapproved in 2008 (without any corrections). Its main advantage is simplicity and a

long time of use with minimal background knowledge. For creep-sensitive structures, more advanced models and methods of structural time-dependent analysis are suggested in the ACI guide [8]. The time development of creep predicted by the ACI 209 model for two concrete grades and the initial data are presented in Fig. 1. For normal strength concrete, the final creep coefficient values are established at age $t = 70$ years as for Eurocode 2 and $t = 10^5$ days for high strength concretes.

Eurocode 2 model is based on improved series of

Fig. 1 Creep coefficient $\phi(t, t_0)$ in ACI 209 model for concretes: (a) C20/25, $RH = 50\%$; (b) C80/95, $RH = 50\%$; (c) C20/25, $RH = 80\%$; (d) C80/95, $RH = 80\%$.

CEB-FIB models, i.e., MC 90 and MC 90-99. The strength grades are covered up to C90. In general part, for practical purposes, EC2 gives a graphical method for establishing the final value of creep coefficients which may be used for creep non-sensitive structures. When knowledge of creep development over time is necessary, EC2 gives formulas for numerical calculation of creep coefficients. EC2 is the first code which developed concrete compressive strength to represent many parameters of concrete mixtures. This attitude is followed in *fib* MC 2010.

For structures sensitive to creep deformations, in EC2 Part 2 (for concrete bridges), there are presented structural method for time dependent analysis. Additionally, a creep model for high strength concretes is included in Part 2 as the model in the general part of the code may not give adequate results for such concretes. This model should be used for strength greater than C50 with or without silica fume, made with high strength cements (Class R). Concrete creep according to Eurocode 2 for the same initial parameter is presented in Fig. 2. The narrow ranges of final creep

Fig. 2 Creep coefficient $\phi(t, t_0)$ in Eurocode 2 for concretes: (a) C20/25, $RH = 50\%$; (b) C80/95, $RH = 50\%$; (c) C20/25, $RH = 80\%$; (d) C80/95, $RH = 80\%$.

Fig. 3 Creep coefficient $\phi(t, t_0)$ in *fib* Model Code 2010 for concretes: (a) C20/25, $RH = 50\%$; (b) C80/95, $RH = 50\%$; (c) C20/25, $RH = 50\%$; (d) C80/95, $RH = 80\%$.

coefficients for high-strength concrete are pronounced.

The new *fib* Model Code 2010 (MC 2010) has recently been approved and introduces new formulas for creep description returning to the well-established basic creep concept [4, 10]. The range of applicability is enlarged up to concrete strength grade C120. The creep formulas for ordinary normal weight concrete are applicable to both NSC (normal strength concrete) and HSC (high strength concrete). MC 2010 has new and improved formulas for describing the time-dependent behavior of structural concrete to better represent the

real performance of concrete. The time development of grades and the established initial data are shown in Fig. 3. For high strength concrete, the results are presented for time $t = 10^5$ days, as some scientists expect that the durability of such concretes may reach a few hundred years. However, the increase in the magnitude of concrete creep over a longer period of time is not significant. In MC 2010, basic creep is modeled using a logarithm function which is infinitely ongoing deformation, while drying creep approaches a finite value (hyperbolic function).

5. Comparison for Creep

The comparison investigates the differences between the creep results for different but improved models. For consistency, the results are presented for selected parameters which are the same for the concretes used for comparison. Creep coefficients are presented for concrete loaded at $t_0 = 7$ days and 28 days after casting, at relative humidity of 50% and 80%, and for notional member size $h_0 = 100$ mm. For concrete grades higher than C16, rapid hardening high-strength cement is used. In all models, the creep in high strength concrete is significantly lower. The ACI 209 model is very sensitive to concrete mix composition, and for different mixes and the same concrete grade, different values of creep coefficient are obtained. Models in the Eurocode 2 and MC 2010 are independent of concrete mixes but dependent on the type of cement. A comparison of the final values of creep coefficient $\varphi(70\text{yr}, t_0)$ after 70 years of loading versus concrete strength is shown in Fig. 4. The 70-year period is chosen as the validity given in EC2. The MC 2010 model was calibrated on laboratory test for the time development of creep up to 30 years and it is estimated that the model gives correct values of creep coefficient up to 50 years (service life for buildings). However,

recent observations show higher creep deformations after 30~50 years in service than predicted by the model. It is not clearly understood at the moment.

There is some discontinuity in the EC2 models for normal strength- and high-strength concrete (Fig. 4). The graph clearly shows that the amount of creep is dependent on the concrete grade. Higher grade concretes may be used not only to increase durability but also to control creep. Creep coefficients for normal- and high-strength concrete have got decreasing values with increasing strength class of concrete.

A comparison of the creep development in time $\varphi(t, t_0)$, which is described by three models: ACI, EC2 and MC 2010, is presented in Fig. 5. Creep coefficients are presented for concrete loaded at $t_0 = 7$ days and 28 days after casting for C20 and C80 concrete grades, at relative humidity of 50% and 80%, and for notional member size $h_0 = 100$ mm. Higher values of creep coefficients which are predicted by MC 2010 than Eurocode 2 are clearly visible.

6. Conclusions

The paper outlines concrete creep models for conventional concrete, the majority of which are in use

Fig. 4 Comparison of final creep coefficient $\varphi(70, t_0)$ for 70 years of loading versus concrete grades in Eurocode 2 and MC 2010, for concrete loaded at $t_0 = 7$ days and 28 days for: (a) $RH = 50\%$; (b) $RH = 80\%$.

Fig. 5 Comparison of creep coefficient $\phi(t, t_0)$ in ACI 209, Eurocode 2, MC 2010 for concretes: (a) C20/25, $RH = 50\%$; (b) C80/95, $RH = 50\%$; (c) C20/25, $RH = 80\%$; (d) C80/95, $RH = 80\%$.

for typical concrete structures. Conventional concretes are now ordinary-normal-weight concretes with NSC and HSC. Predicting creep deformations in concrete structures are still highly uncertain, with current models for creep in cement concrete differing in their accuracy and complexity. The paper presents and shortly compares the models for creep in cement concrete included in the ACI guide, Eurocode 2 and *fib* Model Code 2010. For the presentation and comparison of the creep models, creep coefficients are used as the simplest approach. The development and magnitude of creep deformations are presented for

NSC and HSC. ACI 209 model is the oldest one but was positively verified for HSC. In EC2 and MC 2010 models, the code-type modeling for concrete behavior is applied. EC2 presents different creep models for NSC and HSC. MC 2010 model for creep introduces new and improved formulas and some inconsistencies existing in older models had been removed. MC 2010 model is introducing the old well-known subdivision of creep into basic and drying components. This attitude is used for HSC as well as for NSC. Lower creep values for higher concrete grades or larger humidity are characteristic for all the models. It indicates that higher

concrete grades may be used not only to increase durability but also to control creep.

Conventional models for cement concrete creep are based on many years' theoretical and experimental research. They enable a more accurate analysis and better assessment of the time-dependent deformation of concrete structures at the design stage. Their complexity is significantly reduced using code-type formulas. The range of influencing parameters is limited in the models for simplicity and easy adaptation at the design stage. The models give the general guidance on the creep behavior of ordinary concrete under normal environmental conditions with protection against excessive loss of moisture. For structures which are more prone to creep deformations, it is necessary to identify the creep parameters included in the models by experimental identification procedures.

References

- [1] ACI Committee 209. 2009. *Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures*. Report of ACI Committee 209.
- [2] CEB-FIB (Euro-International Concrete Committee-International Federation for Prestressing). 1993. *CEB-FIB Model Code 1990. Design Code*. London: Thomas Telford.
- [3] CEN (European Committee for Standardization). 2004. *EN 1992-1-1. Eurocode 2: Design of concrete structures. Part 1-1: General Rules for Buildings*. CEN.
- [4] International Federation for Structural Concrete. 2013. *fib Model Code for Concrete Structures 2010*. Berlin: Ernest & Sohn.
- [5] Bažant, Z. P., Li, G. H., and Yu, Q. 2009. "Prediction of Creep and Shrinkage and Their Effects in Concrete Structures: Critical Appraisal." In *Proceedings of the 8th International Conference on Creep, Shrinkage and Durability Mechanics of Concrete and Concrete Structures*, 1275-89.
- [6] Ghali, R. F., and Elbadry, M. 2012. *Concrete Structures: Stresses and Deformations: Analysis and Design for Serviceability*. New York: Spon Press.
- [7] Gilbert, R. I., and Ranzi, G. 2011. *Time-Dependent Behaviour of Concrete Structures*. New York: Spon Press.
- [8] ACI Committee 209. *Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete*. Report of ACI Committee 209.
- [9] Hołowaty, J. 2013. "Comparison of Eurocode 2 and Polish Bridge Standards for Creep and Shrinkage of Concrete—Necessity for Implementation." In *Proceedings of the 9th Central European Congress on Concrete Engineering*, 76-9.
- [10] Müller, H. S., Anders, I., Breiner, R., and Vogel, M. 2013. "Concrete: Treatment of Types and Properties in *fib Model Code 2010*." *Journal of the fib—Structural Concrete* 14 (4): 320-34.