SP 76-1

Dealing with the Effects of Concrete Volume Changes on Concrete Structures — A Designer's View

By Max Zar

Synopsis: Creep, shrinkage, and temperature effects on concrete structures are discussed from a design perspective. Research into these problems and various solutions to these problems are looked at. Also emphasized is the importance of complex, sophisticated techniques of analysis for special structures, such as nuclear reactor containments.

Keywords: concretes; creep properties; failure; fatigue (materials); shrinkage; structural design; volume change.

Some decades ago, interest in the creep, shrinkage and temperature effects on concrete structures was almost totally confined to the work of researchers, in spite of the well-documented list of failures attributed to these volumetric changes.

At that time, the concrete structural design techniques that were borrowed from the well-established design techniques for steel structures assumed elastic concrete behavior. Later, the non-elastic properties of concrete and its volume changes were accounted for almost entirely by experience and judgment.

Most experiences were gained the hard way; that is, from failures and unexpected behavior, which, perhaps, could have been anticipated in the original design, with greater knowledge of concrete behavior. The inexperienced designer and those who tried to extrapolate the state-of-the-art were and are usually the most affected by the lack of data on design for these effects.

The construction of large, mass concrete structures and the development and subsequent use of prestressed concrete increased interest of the designers in this subject; however, in both cases, the interest from the designer standpoint was confined to the designers and designer-researchers directly involved with those types of structures. It is interesting to mention that structures like these were extreme cases that pointed out the limitations of the design techniques, the lack of designers' experience and judgment and the limitations of our knowledge on concrete volume changes. Two types of solutions were developed for these extreme cases. One solution deals basically with the material properties; that is, avoid or reduce the effects by reducing the causes. Mass concrete technology, as developed for the construction of big dams, is the best example. The second solution is basically analytical. Where the effects cannot be avoided, they must be considered. Analytical techniques combined with empirical formulation and "expansion" joints have been applied successfully to a wide range of prestressing problems, regardless of the actual concrete properties.

The large research projects on columns, started in the early 30's at the University of Illinois and at Lehigh University, indicated clearly the dependency of steel and concrete stresses on the amount of shrinkage and creep in the concrete and the loading history. The early abandonment of the elastic method for design of columns initiated the slow switch in emphasis from service loads to ultimate strength loads in the ACI 318 Building Code. At the same time, shrinkage and creep effects began to be incorporated into the code, either in a hidden form, that is, as part of the non-elastic coefficient and provisions, or in "motherhood" statements cautioning the designer that concrete volume changes shall be properly accounted for, but without being specific as to how this is to be accomplished.

This approach had worked out fairly well for most structures designed under ACI 318, UBC and AASHTO Codes; however, the designer has been confronted with the fact that even up to a few years ago, only a general qualitative analysis was possible in most cases and only recently, rigorous quantitative analysis techniques became available. Moreover, these techniques are not accepted unanimously and, hence, are not found in the textbooks and manuals used by most designers. The designer has difficulty locating recommended solutions and sorting these out to find the one that best suits his situation. In general, these are simplified methods of analysis which yield reasonably good but not precise results, especially when compared with the method of analysis used for the applied loads.

Special structures, such as nuclear reactor containments, bridges and shells of record spans, require more complex and sophisticated techniques of analysis which are still in the process of development.

Let's consider, for example, the case of prestressed nuclear containments. Because of their dimensions, loading, discontinuities and reinforcement, they do not fit into the definition of mass concrete as generally accepted. At the same time, they also do not fit into the definition of common prestressed structures. Those structures are generally thinner, geometrically simpler and designed for simpler loading. Containments are pressure-tested (structural integrity test at 115% of the design pressure) and the ungrouted tendons are periodically inspected in service, tested and the losses are determined. Prototype containments are fully instrumented to measure strains, stresses and deformations at critical sections and, of course, the results are to be compared with the theoretically predicted values at different stages of the pressure test. It is easy to figure out that the long-term concrete volume changes are no longer a secondary problem, as considered in most other structures. Since no prediction is better than the assumptions, the analysis techniques, the material parameters versus time, the loading and environmental histories used, it is not difficult to imagine the complexity of the predictions and the importance of the creep, shrinkage and temperature effects on these predictions.

As designers, we have to develop analytical techniques consistent not only with the design requirements but with the long-term data. Also, elaborate concrete long-term test programs are being performed for each one of the containments under design and construction. The abundant data from the actual determination of prestressing losses, the structural integrity tests and the inservice surveillance of the tendons are used as feedback data to further refine the techniques used in the design and predictions. At the same time, provisions in specifications are enforced to minimize the effects by minimizing the causes.

As the development of mass concrete and prestressed concrete types of solutions contribute to the better design and construction techniques for concrete structures in general, the present effort on containment designs is and will be extremely useful in expanding our knowledge of the effects of creep, shrinkage and temperature on concrete structures.

ACI Committee 209 which sponsored sessions and symposiums in 1956, 1964 and 1970, made substantial contributions to the design for volume changes on concrete structures. Today, as a designer, I would like to thank all the participants in this symposium for their contribution in making our work easier and for adding credibility to our results.

SP 76-2

New Model for Practical Prediction of Creep and Shrinkage

By Zdenek P. Bazant and Liisa Panula

Synopsis: A new model for the prediction of creep and shrinkage (which is presented in full detail elsewhere), along with a large scope verification by test data, is outlined in simple terms, explained and illustrated in this paper. In this model, the total creep strain is separated into the basic and drying creep components, but not into "reversible" and "irreversible" creep components. The effect of environmental relative humidity is modeled by vertical scaling of the drying creep term. The effect of specimen size is modeled by a horizontal shift of the drying creep term in the logarithmic time scale, and the basic creep term is unaffected by humidity and specimen size. The effects of humidity and size upon the drying creep are modeled completely analogously to those on shrinkage.

The dependence of shrinkage as well as drying creep on the size of the cross section is introduced by means of shrinkage-square halftime, which is the same for both shrinkage and drying creep. Finally, the basic creep component of total creep strain is characterized by double power law.

Keywords: building codes; concretes; creep properties; deformation; humidity; mathematical models; shrinkage; strains; structural analysis; structural design; volume change.

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INTRODUCTION

With the exception of creep buckling of thin shells, a poor prediction of creep and shrinkage does not cause structural collapse, but produces cracking, damage, excessive deflections, i.e., endangers serviceability and economy. The question of optimum creep and shrinkage prediction is, therefore, of great interest for the formulation of building codes and standard recommendations.

However, what is the optimum model for creep and shrinkage? This is a difficult question which has been during the past eight years the subject of lively polemics, the source of which has been the lack of quantitative argument.

Creep is a phenomenon of great variability, influenced by many factors which can hardly be considered in a deterministic way. Quantitative evaluation of test data, therefore, requires that many, essentially all, available test data be considered. An exhaustive program aimed at collecting, organizing and evaluating usable creep and shrinkage data that exist in the literature has been launched at Northwestern and it led to a formulation of new model which allows a greatly improved prediction of creep and shrinkage compared to the existing models (see in detail references 1 and 2). The theoretical structure of this model was based on previous work in Ref. 3, 4, and 5 in which the mechanics and mathematical aspects of the model were analyzed in depth.

The purpose of this brief paper is to present, in simple terms, an instructive explanation of how the model works and what are the reasons behind its structure, as well as the advantages compared to the existing models.

CREEP FUNCTION

Let ϵ be the uniaxial strain of concrete, t the time, t' the instant of load application, $t = t - t'$ = duration of load, Δ_d the delay of the time of loading after the start of drying, and h the relative humidity of the ambient air. Considering a unit normal stress applied at time t' and constant in time, the strain ϵ at time t, or th ed according to the new mo

$$\varepsilon = \underbrace{\frac{1}{E_o}}_{\text{(Constant)}} + \underbrace{A(t')F(\bar{t})}_{\substack{=\varepsilon_{b.c.}\\ \text{(Basic Creep)}}} + \underbrace{H(h)B(t')P(\Delta_d)\bar{S}\left(\frac{\bar{t}}{\tau_{sh}}\right)}_{\substack{=\varepsilon_{d.c.}\\ \text{(Drying Creep)}}} \tag{1}$$

Here the first term represents the elastic deformation, the second term represents the basic creep and the third term represents the drying creep. A,F,H,B,P,$\bar{S}$ are functions of the variables indicated, and τ_{sh} is called shrinkage-square half time.

The most important aspect of the model is that the basic creep strain and the drying creep strain are separated, as is illustrated in Fig. 2c. An essential point to note is that the basic creep term involves no effect of humidity and no effect of the size of the cross-section of specimen. These effects are involved only in the second, drying creep term and they enter through function H and function $\bar{S}$, respectively.

For comparison it is useful to indicate the expressions for the strain due to long time loading according to Branson's Model adopted by ACI Committee 209, and according to the 1978 CEB-FIP Model Code (7-9):

ACI 209:

$$\varepsilon = \frac{1}{E_c(t')}\,(1 + \underset{\substack{\uparrow\\ \text{hum.}}}{c_1}\,\underset{\substack{\nwarrow\\ \text{size}}}{c_2}A(t')F(\bar{t})) \tag{2}$$

CEB-FIP:

$$\varepsilon = \underbrace{\frac{1}{E_c(t')}}_{\text{("Elastic")}} + \underbrace{\frac{\beta_a(t')}{E_{c_{28}}}}_{\text{("Rapid Irr.")}} + \underbrace{\frac{\varphi_d\beta_d(t,t')}{E_{c_{28}}}}_{\text{("Reversible")}} + \underbrace{\frac{\varphi_{f_1}\varphi_{f_2}[\beta_f(t) - \beta_f(t')}{E_{c_{28}}}}_{\text{("Irreversible")}} \tag{3}$$

We see that the ACI model is given by a considerably simpler equation, whereas the CEB model is about equally involved as the present model (the reader should note that the numerous graphs which are used to define the functions in the CEB model would require involved mathematical expressions if they should be described by formulas).

In the ACI model the humidity effect enters through coefficient c_1 and the size effect enters through coefficient c_2. In the CEB model these effects are introduced by coefficients φ_{f_1} and φ_{f_2}, respectively. Here we see an essential difference.

These models made no distinction between the basic creep and the drying creep and the coefficients introducing the humidity and size effects multiply a term which is supposed to represent both the drying and basic creeps. This is not justified by the present understanding of the humidity effects in creep.

The CEB model does separate the total strain in several parts; the third term in equation (3) represents the so-called "reversible" strain, the fourth term represents the so-called "irreversible" strain, and the second term represents the so-called "rapid irreversible initial" creep strain. But there exists no good reason for the humidity effect and the size effect not entering the third, "reversible", term and at the same time applying to the last, "irreversible", term that involves both the basic and drying creeps.

The drying creep term in equation (1) is characterized by function $\bar{S}$ which is a shrinkage-like function and depends on τ_{sh}, the shrinkage-square half time, which brings in the size effect.

The fact that the creep strain is made dependent on the shrinkage corresponds to what experimentalists have been saying all the time. The shrinkage and creep of concrete are not simply additive (10); shrinkage affects creep. It is for this reason that the shrinkage-like function $\bar{S}$ is included in equation (1).

SHRINKAGE

As has been said, drying creep cannot be properly described without reference to shrinkage. The formula giving the shrinkage strain ϵ_{sh} at time t is:

$$\epsilon_{sh} = k_h S\left(\frac{\hat{t}}{\tau_{sh}}\right) \qquad (4)$$

$$\tau_{sh} = \frac{D^2}{C_1(t_o)} \qquad (5)$$

Here $\hat{t}$ represents the duration of drying, i.e., $\hat{t} = t - t_o$, where t_o is the age at the start of drying. Coefficient k_h depends on relative humidity h, as sketched in Fig. 1e.

According to diffusion theory, which is the governing physical model for the drying process of concrete, the shrinkage-square half time τ_{sh} must be proportional to the square of cross-section thickness D (or a characteristic dimension of the cross-section of specimen).

Furthermore, also according to the diffusion theory, τ_{sh} should be inversely proportional to moisture diffusivity C_1, which itself is a function of the age of concrete at the start of drying t_o as illustrated in Fig. 1f. This introduces the effect of the age of concrete at the start of drying.