Engineering Structures 174 (2018) 111–125

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Improved prediction of long-term prestress loss in unbonded prestressed concrete members

Pablo M. Páez*, Beradi Sensale

Facultad de Ingeniería, Universidad de la República, Julio Herrera y Reissig 565, Montevideo, Uruguay

ARTICLE INFO

Keywords:
Undonded prestressing
Long-term loads
Serviceability
Prestress loss

ABSTRACT

In this paper, an approach based on the finite element method to model the behavior of concrete beams with unbonded prestressing steel over time, and an improved simplified equation for calculating the prestress losses in statically determinate prestressed concrete members with unbonded internal tendons are proposed. Both methods take into account the effects of the concrete creep, concrete shrinkage, prestressing steel relaxation and the presence of the bonded non-prestressed reinforcement. In addition, a generalization of the Step-by-Step and the Age-Adjusted Effective Modulus methods for the time cross-sectional analysis of prestressed concrete members with unbonded internal tendons is presented. The accuracy of the proposed equation is evaluated based on the results of previous studies and is contrasted with the computational implementation of the Step-by-Step Method. As the main conclusions, we mention that the results show that the proposed equation adequately predicts the prestress loss and has higher accuracy compared to simplified existing models.

1. Introduction

The term "unbonded prestressed" is used for prestressed concrete members in which there is no bonding between the concrete and the prestressing steel or, if it exists, it is so small that a perfect bond between the two materials cannot be considered. Unbonded prestressing can be divided into two different types: internal and external prestressing. In internal prestressing, the tendons are embedded in the concrete, such as in the case of beams and post-tensioned flat slabs, whereas in external prestressing, the tendons are not embedded in the concrete, such as in box girder bridges.

The behavior of the members with internal prestressing is characterized by the fact that the position of the tendon at any section does not change with the deformation of the member, whereas in external prestressing, when the element is deformed, the position of the tendon is conditioned by the displacement of both the anchor and the deviator points of the tendon.

The analysis of prestressed concrete members with unbonded prestressing tendons is inherently more complex than the analysis of members with bonded prestressing tendons, since, unlike bonded prestressing tendons, there is no strain compatibility between the tendons and the surrounding concrete, which means that the prestressing tendons and concrete can move with respect to each other. Then, the stress in unbonded tendons will depend on the deformation of the structural member as a whole. In other words, the stress in the tendon in an unbonded prestressed concrete member subjected to external loads is member-dependent instead of section-dependent [1].

Without loss of generality, we can establish that from the 1960s, different researchers have placed greater emphasis on the study of the behavior of structures with unbonded prestressing, in particular the behavior of beams and slabs [2]. Thereafter, most research has focused on predicting the behavior of these elements at ultimate strength [1–17]; however, there are relatively few research works focused on predicting the behavior of members in bending under short-term service loads [12,14–16,19] and even fewer that allow prediction of the behavior in bending under long-term service loads [11,15,18,20].

To study the time-dependent behavior of unbonded prestressed concrete members under service load, CEB-FIP [18] establishes an equation for estimating the prestress loss based on the Rate of Creep Method [21,22]. This method is based on the assumption that the rate of change of creep with time is independent of the age at loading; however, new researches show that this hypothesis is not correct [23]. Gauvreau [11] proposes a simplified equation to estimate the loss of prestress due to time effects in members with unbonded internal tendons. However, this equation does not take into account the relaxation of prestressing steel or the presence of non-prestressed reinforcement. For long-term analysis, Lou et al. [15] use a formulation based on the finite element method. Although the methodology used by the authors

* Corresponding author.
E-mail addresses: ppaez@fing.edu.uy (P.M. Páez), sensale@fing.edu.uy (B. Sensale).

https://doi.org/10.1016/j.engstruct.2018.07.038
Received 21 November 2017; Received in revised form 7 June 2018; Accepted 14 July 2018

for the time-dependent analysis can be called "step by step", meaning that it is done by dividing the time interval into small intervals, the creep compliance function used is not the one recommended by the different codes but its form has the advantage of facilitating programming with respect to the simulation of the history of applied stress. On the other hand, the use of the proposed procedure by the Finite Element Method requires a high degree of computational programming. Guo et al. [20] propose a model to predict the time-dependent losses in prestressed concrete members. This model takes into account the effect of shrinkage, creep of concrete, and relaxation of steel. However, although the authors use the method for either bonded or unbonded prestressing, the method is based on the bond hypothesis and therefore its use for unbonded prestressed members is not entirely correct.

In view of current trends of the standards based on the "Limit States Design", it is just as important to predict the behavior of the members under service load conditions, in particular under long-term service loads, as it is to predict the behavior of the unbonded prestressed members at ultimate flexural strength. It is important to estimate the prestress losses as accurately as possible, since an incorrect estimation can cause serviceability problems; for example, the tensile strength of concrete can be exceeded under service loads and/or can lead to excessive camber [24].

In most practical applications with prestressing, the members are calculated so that, under the action of long-term loads, all sections are in uncracked state (State I); that is, the tensile stress in the extreme fiber of concrete has not reached its modulus of rupture, and therefore the creep deformations of the concrete will tend to be much greater than in the case of partially prestressed concrete members. The effects of creep, shrinkage, and relaxation of the steel will cause a redistribution of stresses between the steel and concrete, which will generally result in a loss of the prestressing force and therefore an increase in the deformations.

This paper is motivated by the need to predict the behavior of prestressed concrete members with unbonded internal tendons under long-term loads. The main objective of this work is to propose a simplified equation to calculate the prestress losses in statically determinate prestressed concrete members with unbonded internal tendons, taking into account the effects of concrete creep, concrete shrinkage, prestressing steel relaxation, and the presence of the bonded non-prestressed reinforcement. The second objective of this work is to develop the formulation of the Step-by-Step Method (SSM) and the Age-Adjusted Effective Modulus Method (AAEM) for long-term analysis of prestressed beams with unbonded internal tendons; to date, there is no literature or research work that has developed such a formulation. Finally, an approach based on the finite element method (FEM) to model the behavior of concrete beams with unbonded prestressing steel over time is proposed. The originality of this technique lies in its treatment of long-term effects. Also in this paper, a computational algorithm based on the Step-by-Step Method from the basic principles of the Strength of Materials will be implemented (without using Finite Element Method). The accuracy of the proposed equation was evaluated based on the results of previous studies and was contrasted with the computational implementation of the Step-by-Step Method. The results show that the proposed equation adequately predicts the prestress loss and has higher accuracy compared to existing simplified formulations.

2. Constitutive equations of materials: instantaneous and time-dependent behavior

2.1. Concrete

For normal strength concretes, that is, for concretes whose characteristic compressive cylinder strength at 28 days is less than 50 MPa, a linear elastic behavior in compression can be considered for stress levels below about 40% of the characteristic cylinder strength. Therefore, the stress–strain relationship for concrete in compression can be expressed as Eq. (1):

$$\sigma_c = E_c \varepsilon_e \tag{1}$$

where σ_c is the concrete stress produced by a compression strain ε_e and E_c is the modulus of elasticity of concrete. The modulus of elasticity of concrete can be calculated from the models provided in the different standards, for example, that provided by the MC10 [25].

The total concrete strain at time t in an uncracked concrete member uniaxially loaded at constant temperature may be expressed as the sum of the instantaneous strain, $\varepsilon_e(t)$, the creep strain between the times t_0 and t, $\varepsilon_{cr}(t, t_0)$, and the shrinkage strain between the time t_s and t, $\varepsilon_{sh}(t, t_s)$, with t_0 the age of concrete at loading and t_s the age of the concrete at the beginning of drying [26] (Eq. (2)):

$$\varepsilon(t) = \varepsilon_e(t) + \varepsilon_{cr}(t, t_0) + \varepsilon_{sh}(t, t_s) \tag{2}$$

Shrinkage strain in concrete can be defined as the time-dependent strain of a concrete specimen in a given environment, where displacement of the specimen is not restricted and the specimen is not subject to external load [27]. Shrinkage strain can be calculated from the model provided by MC10 [25].

If a concrete specimen is subjected to a compressive stress at time $t = t_0$, $\sigma_c(t_0)$, which is kept constant in time, the creep strain at time $t > t_0$ is given by Eq. (3):

$$\varepsilon_{cr}(t, t_0) = \varphi(t, t_0)\frac{\sigma_c(t_0)}{E_c(t_0)} \tag{3}$$

where $\varphi(t, t_0)$ is the creep coefficient and $E_c(t_0)$ is the modulus of elasticity of concrete at time $t = t_0$. The value of the creep coefficient can be calculated from the model proposed by MC10 [25].

If the magnitude of stress varies with time, which is usual in concrete structures, creep strain can be obtained from the *principle of superposition*. The principle of superposition was applied to concrete for the first time by McHenry [28] and requires the fulfillment of certain hypotheses to obtain sufficiently accurate results. These hypotheses are often referred to as linearity assumptions [29] and can be stated as follows: (*a*) the stress in the concrete is less than 40% of the characteristic compressive strength, f_{ck}; (*b*) ε is not decreasing; that is, strain of decreasing magnitude does not take place; (*c*) there is no significant change in moisture content; and (*d*) there are no sudden changes in stress. In most practical applications of civil engineering, these assumptions are fulfilled, so the principle of superposition is usually accepted in most analyses and calculations. The strain in concrete at time t caused by a given stress history is obtained from Eq. (4):

$$\varepsilon(t) = \frac{\sigma_c(t_0)}{E_c(t_0)}(1 + \varphi(t, t_0)) + \int_{\tau=t_0}^{\tau=t} \frac{1 + \varphi(t, \tau)}{E_c(\tau)} d\sigma_c(\tau) + \varepsilon_{sh}(t, t_s) \tag{4}$$

If the change in stress between t_0 and t, $\Delta\sigma_c(t)$, is known, Eq. (4) can be written in simplified form [30–32] as Eq. (5):

$$\varepsilon(t) = \frac{\sigma_c(t_0)}{E_c(t_0)}(1 + \varphi(t, t_0)) + \frac{\Delta\sigma_c(t)}{\overline{E}_c(t, t_0)} + \varepsilon_{sh}(t, t_s) \tag{5}$$

where $\overline{E}_c(t, t_0)$ is the *age-adjusted effective modulus*, whose expression is given by Eq. (6):

$$\overline{E}_c(t, t_0) = \frac{E_c(t_0)}{1 + \chi(t, t_0)\varphi(t, t_0)} \tag{6}$$

$\chi(t, t_0)$ is the *aging coefficient*, whose expression is given by Eq. (7) [31]:

$$\chi(t, t_0) = \frac{\sigma_c(t_0)}{\sigma_c(t_0) - \sigma_c(t)} - \frac{1}{\varphi(t, t_0)} = \frac{E_c(t_0)}{E_c(t_0) - E_R(t, t_0)} - \frac{1}{\varphi(t, t_0)} \tag{7}$$

where $E_R(t, t_0)$ is the relaxation function of the concrete, defined as the stress at time t due to a unit strain applied at time t_0 and kept constant throughout the period t_0 to t. Values for the relaxation function can be calculated by applying Eq. (4) to the case of a constant unit strain history beginning at t_0 or they can be calculated from the approximate