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Time-dependent behavior of concrete beams prestressed with bonded AFRP tendons

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ABSTRACT

This paper presents a numerical study on the long-term performance of bonded aramid fiber reinforced polymer (AFRP) prestressed concrete beams. A computer model capable of predicting the service load long-term response of prestressed concrete beams with AFRP and steel tendons is developed. Model predictions agree well with the results of long-term tests on prestressed concrete beams. The time-dependent behavior of AFRP prestressed concrete beams is evaluated and the results are compared with those of steel ones. It is indicated that, when tendon relaxation is considered, AFRP tendons register a higher long-term prestress loss than steel tendons although the prestress loss contributed by concrete creep and shrinkage is significantly lower in AFRP tendons than in steel ones. As a consequence, AFRP tendons mobilize a lower prestressing camber and a higher downward load deflection compared to steel tendons. The analysis also shows that the influence of bottom nonprestressed steel on the time-dependent performance can be important or not so important, depending on the level of loading.

1. Introduction

The deterioration of traditional prestressed concrete structures due to corrosion of steel tendons is a major concern for designers and engineers. An effective solution to corrosion control of prestressed concrete is to replace steel tendons with fiber reinforced polymer (FRP) composites, which have noncorrosive, nonmagnetic and high-strength properties [1,2]. Glass FRP (GRRP) composites are usually employed as reinforcing bars rather than prestressing tendons because they can only sustain a low stress without suffering from creep rupture [3,4]. On the other hand, aramid FRP (AFRP) and carbon FRP (CFRP) are typically available for prestressing applications [4]. In market, the cost of AFRP composites is much lower than that of CFRP composites. From economical consideration, AFRP composites may be preferred in prestressed concrete structures in practice.

Many researches have been carried out regarding the short-term behavior of prestressed concrete members with FRP tendons [5–15] or strips [16–18], including deflection, deformability and moment redistribution. The authors have recently performed a series of numerical studies on prestressed concrete beams with bonded or unbonded FRP tendons [10–13], but these works did not take into account time-dependent effects such as concrete creep, shrinkage and tendon relaxation. The assessment of the long-term behavior of FRP prestressed concrete beams is practically important, since creep and relaxation of common FRP tendons are much more significant than those of steel ones. However, few studies have addressed the topic related to long-term performance of concrete beams prestressed with FRP tendons. Pisani [19] developed a general computer model for time-dependent analysis of simply-supported concrete beams prestressed with AFRP tendons. He also proposed a simplified analysis based on the age-adjusted effective modulus method for AFRP prestressed concrete beams under long-term sustained loads [20]. Youakim and Karbhari [21] presented an analytical approach to predict the long-term response of FRP prestressed concrete members. They concluded that the long-term prestress loss in FRP tendons is much lower than that in steel tendons due to lower modulus of elasticity of FRP composites. This conclusion seems to be correct when the tendon relaxation is neglected as will be confirmed in the present study. When the tendon relaxation is considered, however, the present study leads to a different finding.

The literature review shows that research on FRP prestressed concrete members under long-term loading is very limited. Further

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study is necessary to better understand the time-dependent behavior of concrete members prestressed with FRP tendons. In this paper, a computer model for time-dependent analysis of concrete beams prestressed with bonded AFRP and steel tendons is proposed. This model is an extension of a finite element model previously developed for predicting the long-term behavior of steel prestressed concrete girders [22]. A numerical investigation is conducted to evaluate the time-dependent performance of concrete beams prestressed with bonded AFRP tendons. The main investigation variables include the type of tendons, the level of initial prestress, the level of applied loads and the amount of bottom nonprestressed steel.

2. Concrete creep and tendon relaxation

2.1. Concrete creep

The concrete strain at time t, $\varepsilon_c(t)$, is assumed to comprise the following components

$$\varepsilon_c(t) = \varepsilon_c^m(t) + \varepsilon_c^{cr}(t) + \varepsilon_c^{sh}(t) \tag{1}$$

in which $\varepsilon_c^m(t)$ is the immediate or mechanical strain due to short-term loading; $\varepsilon_c^{cr}(t)$ is the creep strain and $\varepsilon_c^{sh}(t)$ is the shrinkage strain.

Shrinkage is defined as the change in concrete volume, occurring independently of applied stresses. Creep is defined as the increase in concrete strain under sustained stresses. At service loads, the creep strain due to the applied stress which is subject to change with time can be calculated by applying the linear creep law and the principle of superposition.

$$\varepsilon_c^{cr}(t) = \sigma_c(t_0)C(t,t_0) + \int_{t_0}^{t} C(t,\tau)\frac{\partial \sigma_c(\tau)}{\partial \tau}d\tau \tag{2}$$

in which t_0 is the age at which the initial stress is applied; $\sigma_c(\tau)$ is the concrete stress at age τ; and $C(t,\tau)$ is the creep compliance defined as the creep strain at time t caused by a unit stress applied at time τ. The form of $C(t,\tau)$ proposed by Zienkiewicz and Watson [23] is adopted here.

$$C(t,\tau) = \sum_{k=1}^{m} \phi_k(\tau)\left[1 - e^{-r_k(t-\tau)}\right] \tag{3}$$

where m, $\phi_k(\tau)$ and r_k are coefficients which can be determined by test data. The modified Zhu [24] coefficients are used in this study: $m = 2$; $\phi_1(\tau) = 0.46(1+9.2\tau^{-0.45})/E_0$, $r_1 = 0.1$; $\phi_2(\tau) = 1.04(1+1.7\tau^{-0.45})/E_0$, $r_2 = 0.005$. E_0 is related to the time-dependent modulus of elasticity of concrete by: $E_c(\tau) = E_0(1-e^{-0.4\tau^{0.34}})$.

The concrete stress is computed from the mechanical strain according to the stress-strain law. At service loading, the concrete in compression can be considered to be linearly elastic. The concrete in tension is assumed to be elastic up to cracking, followed by linear tension-stiffening.

2.2. Tendon relaxation

Creep of prestressing tendons is usually evaluated by relaxation tests. When a tendon is stretched and maintained a constant strain, the tendon stress is subject to loss due to creep effects, referred to as intrinsic relaxation σ_{pr}. An equation that has been widely used for the intrinsic relaxation of prestressing steel is as follows [25]:

$$\frac{\sigma_{pr}}{\sigma_{p0}} = -\frac{\log(\tau - t_0)}{k}\left(\frac{\sigma_{p0}}{f_{py}} - 0.55\right) \tag{4}$$

in which $(\tau - t_0)$ is the relaxation time in hours; σ_{p0} is the initial tendon stress at which the relaxation starts; f_{py} is the yield stress of prestressing steel; and k is a coefficient, equal to 10 for normal-relaxation steel tendons and 30 for low-relaxation steel tendons.

On the other hand, the relaxation of AFRP tendons is very different from that of steel tendons. Saadatmanesh and Tannous [26] conducted an experimental study to explore the relaxation behavior of AFRP tendons. Test results of 12 specimens in air at temperatures of −30, 25 and 60 °C as well as 24 specimens in three different solutions (i.e., alkaline, acidic and salt) at temperatures of 25 and 60 °C were reported. Based on their test data, Saadatmanesh and Tannous [26] proposed an equation for predicting the intrinsic relaxation of AFRP tendons.

$$\frac{\sigma_{pr}}{\sigma_{p0}} = -\frac{\lambda - [a - b\log(\tau - t_0)]}{\lambda} \tag{5}$$

in which $\lambda = \sigma_{p0}/\sigma_{pu}$ where σ_{pu} is the ultimate tensile strength of AFRP tendons; a and b are constants determined from test data by the regression analysis. The values of a and b depend on the initial prestress level, temperature and the solution type. For prestressing AFRP in air at temperature of 25 °C, the values of a and b are 0.37 and 0.0058, respectively, for the initial prestress level of 40%, and are 0.5684 and 0.0145, respectively, for the initial prestress level of 60%.

In prestressed concrete members, creep and shrinkage of concrete would interact with relaxation of prestressing tendons and this interaction would lead to an additional stress loss in tendons. Therefore, when computing tendon relaxation of prestressed concrete beams, the value of σ_{p0} in Eqs. (4) and (5) should be appropriately modified at each time interval in accordance with the change in tendon stress due to concrete creep and shrinkage as well as some other causes such as prestress transfer and load application [22].

3. Numerical model

Fig. 1 shows a two-node plane beam element in the local coordinate system (x, y). The cross section of the element is assumed to be symmetric with respect to the y axis. In order to describe different material properties over the section depth, a layered approach is applied in the analysis. The prestressing tendon with each element is idealized to be parallel to the x axis. Both the prestressing tendon and nonprestressed steel are assumed to perfectly bond with the surrounding concrete. The element nodal displacements $\boldsymbol{r}^e$ are written as

$$\boldsymbol{r}^e = \left\{ \boldsymbol{u}^T \quad \boldsymbol{v}^T \quad \boldsymbol{\theta}^T \right\}^T \tag{6}$$

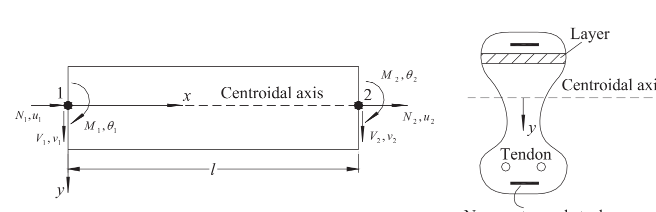

Fig. 1. Beam element and layered section.