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Transfer length in pretensioned prestressed concrete structures composed of high performance lightweight and normal-weight concrete

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ABSTRACT

This article discusses an analytical model that relates the transfer length and the prestressing strand draw-in immediately after transfer; the model is based on the elastic confinement hypothesis of the prestressing strand using concrete and/or confining reinforcement. Two expressions are proposed to estimate upper and lower bounds on the transfer length, which consider the prestressing strand draw-in and the transferred effective prestress. The analytical model and the proposed expressions are compared with the experimental results obtained at the University of La Coruña, in which precast pretensioned prestressed concrete members were fabricated from conventional concretes and lightweight concretes. Strand Y1860 S7, $d_b = 15.2$ mm, was used in this research. The tested pretensioned lightweight concrete members exhibit structural insecurity because of the splitting cracks detected after the prestress release.

1. Introduction

In pretensioned prestressed concrete structures, transfer length of a wire or prestressing strand is defined as the length over which the effective prestressing force is transferred to concrete by bond. Fig. 1 presents a graphical representation of this concept, where $\sigma_p(x)$ is the prestressing reinforcement stress after transfer at the cross section located at a distance x from the end (positive tension), $l_t(t)$ is the transfer length at time t, f_{pi} is the prestressing strand stress immediately before transfer, $f_{pe}(t)$ is the effective prestress on the pretensioned concrete element at an age t, and j is the time immediately after the prestress release.

In 1953, Guyon postulated that the transfer length is directly proportional to the prestressing draw-in and inversely proportional to the initial prestressing strand stress:

$$l_t = \alpha \cdot \delta \cdot Ep/f_{pi}. \tag{1}$$

Eq. (1) relates the transfer length l_t to the strand draw-in δ, where E_p is the modulus of elasticity of the prestressing strand. Eq. (1) was formulated by assuming that the flat sections remain flat within the transfer length, which is not completely true because most of the transfer length is affected by shear lag (Saint-Venant effect). Here, α is the Guyon coefficient, which considers the stress distribution shape of the concrete in the transfer length ($\alpha = 2$ for a constant bond stress, $\alpha = 3$ for a linear distribution of the bond stress) [1].

To estimate the transfer length, Balazs proposed Eq. (2), which relates the same variables [2]:

$$l_t = 2 \cdot \delta \cdot E_p/[f_{pi}(1 - b)], \tag{2}$$

where b is an experimental coefficient whose value is bounded between zero and one, which depends on the type of concrete and type of prestressing strand.

In a generic form, assuming the hypothesis that the prestressing stress obeys Hooke's law, the strand draw-in value immediately after transfer is calculated according to Eq. (3):

$$\delta = \int_0^{l_t} [(f_{pi} - \sigma_p(x))/E_p]dx - \int_o^{l_t} \varepsilon_c(x)dx, \tag{3}$$

where $\varepsilon_c(x)$ is the instantaneous longitudinal strain of the concrete in contact with the prestressing strand or wire due to the prestress release at x (positive compressive strain).

Several researchers have experimentally obtained different expressions that relate the transfer length to the strand draw-in immediately after transfer [3–6]. Several standards include formulations that, in general, establish a proportionality between the transfer length and the strand draw-in [7–9]. However, several researchers note the low correlation between the experimentally measured transfer length values and the draw-in values [10–12].

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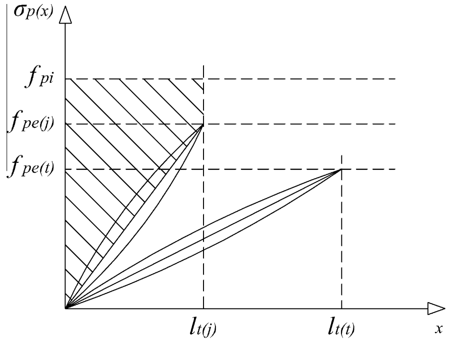

Fig. 1. Prestressing stress vs. distance to the structural member end.

Previous studies have examined the bond behavior at the development length of semi-lightweight concretes [13]. Regarding standards, Eurocode 2, Sections 1–4 “General rules on lightweight aggregate concrete with closed structure” proposes Eq. (4) [14]:

$$L_{t,LC} = 1/(0.4 + 0.6\rho/21.56) \cdot L_{t,NC}, \tag{4}$$

where $L_{t,NC}$ is the transfer length of pretensioned prestressed concrete members of normal weight concrete, $L_{t,LC}$ is the transfer length of the prestressed members of lightweight concrete with similar compressive strength to the normal weight concrete, and ρ is the specific weight of the lightweight concrete (kN/m^3).

According to Eurocode 2 for structural concrete [14] and Model Code 2010 [7,15], to guarantee the structural security of the pretensioned prestressed concrete members, the following conditions must be met:

- A lower bound for the transfer length must be considered in the design of passive confining reinforcement so as to eliminate the possibility of cracking by splitting and/or bursting.
- An upper bound for the transfer length (and, in general, for the development length) must be estimated so as to enable assessment of the ultimate limit states of bending and shear, as well as to design the D zones of the supports of the pretensioned prestressed concrete members with structural security.

2. Research significance

The objectives of this article are as follows:

- To gain insights into the relationship between the transfer length and the prestressing strand draw-in immediately after transfer by explaining the significant dispersion of prestressing draw-in values measured by various researchers.
- To develop a procedure to establish the upper and lower bounds for the transfer length through measurements of the prestressing strand draw-in after transfer in the precast plants. These bounds would permit the design of the confining reinforcement, the assessment of the structural security against the ultimate limit states of bending and shear, and the design of the D support zones of the pretensioned prestresed concrete girders.
- To validate the proposed procedure with the experimental results obtained in the research conducted at the University of La Coruña and in a precast plant for conventional and lightweight concretes with characteristic design strengths of 50 MPa.

3. Theory

If the equilibrium of a differential element after transfer in a prestressing strand embedded in the concrete is considered, the differential Eq. (5) is obtained:

$$d\sigma p(x) \cdot A_p(x) - \tau(x) \cdot U(x)dx = 0, \tag{5}$$

where $A_p(x)$ is the prestressing strand cross-sectional area at the cross section x, $\tau(x)$ is the bond stress at section x, and $U(x)$ is the prestressing strand perimeter at the cross section x.

An analytical model has been developed to study the prestress release along the transfer length by considering the following hypotheses [16,17]:

- Axial symmetry is considered such that the strand is modeled as a cylinder with the apparent diameter of the strand (strand or wire), surrounded by the concrete’s zone of influence, with a determined diameter, which is conditioned by the lining and the presence of the neighboring strands.
- The equilibrium situation immediately after transfer is considered such that the concrete time-dependent strains and the prestressing reinforcement relaxation are not considered.
- The superposition principle is applied such that elastic linear behavior of the longitudinal and transversal stress–strain diagram is assumed for the concrete and steel.
- The flat cross sections are considered to remain flat along the transfer length after the prestressing force is applied.
- The compatibility of radial strains between the concrete and steel is applied because contact between both materials occurs along the entire transfer length due to the Hoyer effect [6]. The exerted confinement by the concrete on the prestressing strand is considered to be linear-elastic.
- According to Eq. (6), the transversal geometry variation of the strand is ignored (it is proven that the radius variation is less than 0.3% of the initial radius [16]):

$$dA_p(x)/dx = 0; \quad dR(x)/dx = 0, \tag{6}$$

where $R(x)$ is the prestressing strand radius at the cross section x.

If the differential Eq. (5) is solved with the aforementioned hypotheses and boundary conditions, Eqs. (7)–(9) are obtained, where α is the Guyon coefficient of Eq. (1):

$$\alpha = 1/\{1/ln[f_{pi}/(f_{pi} - Bf_{pe}) - f_{pi}/(Bf_{pe})] + 1\} \tag{7}$$

$$B = 1 + \nu_c \cdot c_2/\nu_p \tag{8}$$

$$c_2 = A_p \cdot E_p/(A_c \cdot E_c), \tag{9}$$

where ν_c is the Poisson’s modulus of the set {concrete-confining reinforcement}, ν_p is the Poisson’s modulus of the prestressing strand or wire, A_p is the cross-sectional area of the prestressing strand, A_c is the concrete area of the prestressing strand’s zone of influence, and E_c is the concrete modulus of elasticity at the time of transfer. The experimental determination of ν_c and ν_p is complex for seven-wire prestressing strands, particularly in elements with confining reinforcement. Therefore, α will be determined from the experimental results as a function of the prestressing reinforcement, the type of concrete, and the amount of confining reinforcement.

According to Eqs. (7)–(9), the value of α depends on the initial stress of the tensioning, on the effective stress transferred to the pretensioned element (and therefore, considers the prestress losses due to elastic shortening, conditioned by the concrete’s modulus of elasticity), and on the concrete and Poisson’s effect on the prestressing strand, which generates circumferential tensile stresses on the concrete, even at the central zone of the element.