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Slip distribution model along the anchorage length of prestressing strands

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ABSTRACT

An analytical model to predict strand slips within both transmission and anchorage lengths in pretensioned prestressed concrete members is presented. This model has been derived from an experimental research work by analysing the bond behavior and determining the transmission and anchorage lengths of seven-wire prestressing steel strands in different concrete mixes. A testing technique based on measuring the prestressing strand force in specimens with different embedment lengths has been used. The testing technique allows measurement of free end slip as well as indirect determination of the strand slip at different cross sections of a member without interfering with bond phenomena. The experimental results and the proposed model for strand slip distribution have been compared with theoretical predictions according to different equations in the literature and with experimental results obtained by other researchers.

1. Introduction

The prestressing force is transferred from the prestressing strands to concrete by bond during the prestress transfer operation. Afterwards, bond mechanisms allow force variations in the prestressing strands ranging from zero at the free end of the member to the full prestressing strand force which is achieved at a distance defined as transmission length [1] – or transfer length [2].

Also, when a pretensioned prestressed concrete member is loaded by externals actions, higher forces in the prestressing strands are activated. This increase in prestressing strand force is developed only if bond between concrete and prestressing strands allows it, and a bond length (complementary bond length [3] – or flexural bond length [2]) beyond the transmission length is required. The sum of the transmission length and this complementary bond length is defined as anchorage length [1] – or development length [2]. Fig. 1 shows the idealized prestressing strand force profile according to the aforementioned lengths.

Variation in prestressing strand force along both transmission and anchorage lengths involves bond stresses which are activated by the relative displacement (slips) of the prestressing strand into concrete cross-sections [4,5]. After prestress transfer, the maximum strand slip occurs at the free ends of the member, and the strand slip will be zero when the full prestressing strand force is achieved and compatibility of strains between the prestressing strand and concrete exists [6]. In addition to the definition of anchorage length in [1], Buckner [7] indicates that the overloading force must be developed without additional strand end slip at the free ends of the member.

The prestressing strand-to-concrete bond is a function of a large number of factors [8,9]. A literature review of the factors influencing bond and transmission and anchorage lengths of prestressing reinforcement has been presented in [1]. Several equations to calculate both transmission and anchorage lengths have been proposed [3,10,11]. However, knowledge on the slips of prestressing strands is generally limited to free end slip measurements which are used to obtain the transmission length by means of the Guyon's theory [12].

Consequently, the purpose of this research is to develop an analytical bond model to predict the slip distribution along both the transmission and anchorage lengths of seven-wire 13 mm prestressing steel strands. An experimental program has been carried out to determine the force-slip relationships along the transmission and anchorage lengths for twelve different concrete proportionings by means of the ECADA test method [13].

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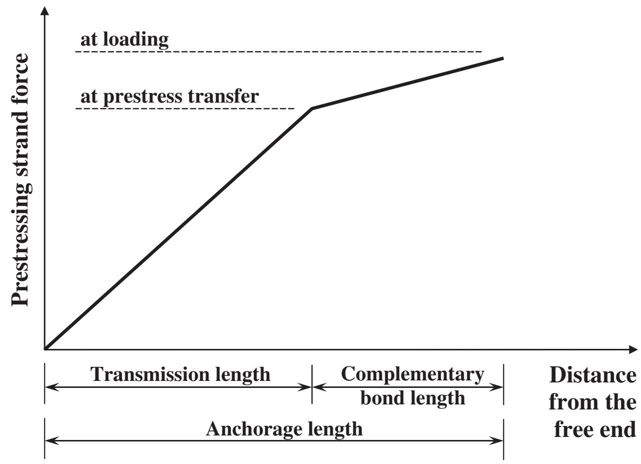

Fig. 1. Prestressing strand force profile along the anchorage length.

2. Background

The measurement of the free strand end slip is a traditional indirect method to determine the transmission length in pretensioned prestressed concrete members. This method has been proposed as a simple non-destructive assurance procedure by which the quality of bond can be monitored within precasting plants [14,15]. Most experimental standards [16–18] are based on this method along with the analysis of the strains profile on the concrete surface after release, but it provides no information on the anchorage length or on the slips along the transmission length.

The relationship between the transmission length and the strand end slip can be expressed as [12]:

$$L_t = \alpha \frac{\delta_f}{\varepsilon_{pi}} \tag{1}$$

where L_t is the transmission length, δ_f is the strand end slip at the free end of a pretensioned prestressed concrete member, ε_{pi} is the initial strand strain, and α represents the shape factor of the bond stress distribution (α = 2 for uniform bond stress and α = 3 for linear descending bond stress distribution). Several experimental and theoretical studies subsequent to Guyon's theoretical analysis have reported α values ranging from 1.5 to 4, as it has been reviewed in [19]. Also a value of α = 2.44 for Guyon's equation has been proposed in [19].

A modification of Guyon's expression was proposed by Balazs [4,20] which takes into account a nonlinear bond stress-slip relationship over the transmission length considering the strand diameter and concrete compressive strength. As a result, the following equations for calculating the transmission length of 13 mm seven-wire prestressing steel strand were developed [4,20]:

$$L_t = 105 d_b \sqrt[4]{\frac{\delta_f^{3/2}}{f_{ci}}} \tag{2}$$

$$L_t = \frac{111\delta_f^{0.625}}{f_{ci}'^{0.15} \cdot \left(\frac{f_{pi}}{E_p}\right)^{0.4}} \tag{3}$$

where d_b is the diameter of prestressing strand, f_{ci} is the concrete compressive strength at the time of prestress transfer, f_{pi} is the strand stress immediately before release and E_p is the modulus of elasticity of the prestressing strand.

An equation to obtain directly the strand slip at the free end as a function of the initial prestress was also proposed by Balazs [4]:

$$\delta_f = 1.23 \left(\frac{f_{pi}^2}{E_p \sqrt{f_{ci}}}\right)^{0.8} \tag{4}$$

Another equation that relates the transmission length to the strand free end slip of a pretensioned prestressed concrete member was proposed in [21] (K = 0.00035 mm^{-1} for 12.7 mm seven-wire strand):

$$L_t = \sqrt{\frac{\delta}{K}} \tag{5}$$

Regarding the anchorage length, the test methods are based on pull-out tests [22] or full size beams [23]. The former does not reproduce the previous prestress transfer stage, and the latter requires an iterative beam testing process. In this iterative process, there are intrinsic disadvantages due to the size and cost of the members. Other procedures for bond strength determination such as the pushpullout test [24] or the use of cylindrical [25] or prismatic specimens [26] have been used in some cases.

To measure slips, Mains [27] devised a technique based on determining the reinforcement strain. This technique involves attaching strain gauges inside specially prepared hollow reinforcement. A large diameter is required, and therefore this technique is not applicable to the wires and strands for pretensioned concrete.

In an experimental study conducted by Ratz et al. [28] on the wire displacements into the concrete along the transmission zones, prestressed concrete specimens were made with holes at various distances at the upper side of specimens. The holes allowed researchers to observe the wires in the specimens. Marks on the wire surface were made. Wire movements relative to concrete at various stages of the prestress transfer were measured using microscopes provided with micrometers eye-glass. The microscopes were attached to the concrete and focused on the holes. From this study, an empirical relationship between the stress in the wire and its displacement within the transmission zone was determined. However, this method has the disadvantage of removing concrete from the surface of the wires by the holes with the consequent destruction of bond.

An experimental application of air-gage devices to detect small linear movements (slips) of reinforcement in concrete slabs and to convert these slips into changes in air-flow rates was developed by Lewis and Moore [29]. In this procedure, a stainless-steel pin is driven into a hole drilled into the reinforcement. A plastic block is then placed over this pin, and the entire assemblage is cast into the concrete. Consequently, the bond phenomenon and the concrete confinement of the reinforcement are distorted.

Therefore, the measurement of slips in prestressing reinforcement mothered the application of sophisticated measurement procedures that do not disturb the bond phenomenon.

The radiographic strain-measuring technique was applied to measure slips along the transmission length in wires [30]. This technique involves placing small lead markers in slots formed in the reinforcement. The positions of the markers are recorded on an X-ray photograph. Wire slip relative to the concrete may be measured directly as the distance between the portions of a marker embedded in the wire and in the concrete. However, the conditions for obtaining a satisfactory film are critical and this technique has not been developed sufficiently.

Sophisticated techniques for instrumentation and measurement procedures based on fiber optic sensors are being used in some cases [31], but have not been used for strand-concrete bond.

Recently, an experimental methodology based on the measurement and the analysis of the force supported by the prestressing strand in specimen series with different embedment lengths has