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Short communication

Simple model for time-dependent bond transfer in pretensioned concrete using draw-in data

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ABSTRACT

Time evolution of prestress loss and bond transfer length holds vital information concerning long-term performance of pretensioned prestressed concrete. In this paper, it is proposed to utilize long-term measurements of strand draw-in to extract this time-varying information, which could be more effectively obtained than concrete or strand surface strain measurements. Theoretical investigations combined with numerical studies of experimental data are carried out for this purpose. This study builds on Guyon's boundary value problem (BVP) model which quantifies draw-in for instantaneous elastic response. A one-dimensional linear viscoelastic standard solid model is employed to model the creep of concrete, which is a simple but effective model of the time-dependent response of concrete. Guyon's BVP model is generalized to include time dependence and then combined with an existing initial value problem (IVP) model for post-tensioned concrete leading to a new mixed model for time-dependent prestress loss and bond transfer in pretensioned concrete.

Analysis is undertaken in this study to (i) quantify long-term prestress loss and bond-transfer behaviors by applying the proposed model and directly utilizing measured draw-in time history data, (ii) validate the proposed quantitative analysis by using scaled pretensioned concrete beams with different types of aggregates and strengths of concrete - among other factors, and (iii) offer discussion of future work. For example, introducing concrete drying shrinkage into the proposed simple model seems promising and is necessary to provide an improved representation of the time-dependent behavior of prestressed concrete.

1. Introduction

1.1. Motivations and technical challenges

Long-term performance of pretensioned, prestressed concrete has been an active area as large numbers of pretensioned concrete bridge girders were used in construction in the fifties and sixties of the last century and have been reported to experience some aging-related issues. Prestress loss with time directly concerns the remaining load carrying capacity of both pretensioned and post-tensioned concrete members. However, bond transfer behavior is of greater interest for pretensioned concrete since the prestressing force is not fully established within the so-called bond transfer zone. This transfer zone is a region from a free end up to the end of the transfer length of a pretensioned concrete member where the effective prestress increases from zero at the free end of the transfer length. The increase in prestress is often considered to follow a straight line within the transfer zone whereas the actual distribution of stress along the transfer length is nonlinear. There are two transfer zones for each strand in a beam, one at each end. Prestress transfer behavior has the potential to affect the stress state of the beam and structural capacity near the ends. For example, the section shear capacity contribution provided by the effective prestress force within transfer zone is location-dependent, increasing from zero at the free end to the full amount at the end of the transfer length. Previous work by the authors focused on assessing actual shear capacity of pretensioned concrete girders designed according to the methods specified by previous versions of the AASHTO Bridge Design Specifications [2] when maximum shear demand was considered at the quarter-span point, and after decades in service motivate [3–6] to examine whether and how transfer length would change with time and consequently, whether and how the section properties would vary with time for a more robust long-term performance evaluation of an entire girder. Bond transfer, which is vital to the performance of pretensioned concrete members, should be carefully considered in both design and analysis because bond transfer directly affects service stresses and all section capacities directly associated with prestressing force.

The goal of this study is to understand and exploit time history of prestressing strand draw-in as a means to infer prestress loss and

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Nomenclature

A_c	cross-sectional area of concrete
A_{ps}	cross-sectional area of strand
$\frac{A_{ps}}{A_c} \triangleq p$	area ratio
d_b	strand diameter
E_c	Young's modulus of concrete in linear elastic stage
E_{ps}	Young's modulus of strand
$\frac{E_{ps}}{E_c} \triangleq m$	Young's modulus ratio
f	stress in strand as in [1]
f_{si}	initial stress in strand at the moment of release as in [1]
f_M	the maximum value of $f, f_M = \frac{f_i}{1+mp}$ from [1]
f_c'	cylindrical compressive strength of concrete in psi
$g(z,t)$	the displacement of the strand relative to the concrete along the z-axis
$g_0(t)$	the draw-in value at the free end, i.e., $g(0,t)$
$\frac{dg}{dz}$	longitudinal strain in strand at $t = 0$ as in [1]
k	as in Eq. (2)
L	total beam length
L_t	transfer length
l_0	the initial length of the post-tensioned prestressed concrete beam as in Eq. (2)
l_{0s}	the initial length of the strand in the post-tensioned prestressed concrete beam as in Eq. (2)
$P(t)$	resultant force in strand/concrete
$P(0)$	resultant force in strand/concrete at time zero
P_i	initial resultant force in strand/concrete at the moment of release, i.e., $t = 0$
P_M	the maximum value of P, $P_M = \frac{P_i}{1+mp}$
w_c	unit weight of concrete in pcf
$x(t)$	transfer length
z	abscissa of beam starting from the free end
t	time
α	coefficient accounting for bond stress variation within transfer length
η	concrete viscosity as in Eq. (2)
$\lambda(t)$	characteristic length for elastic anchorage
ξ	dummy variable of time
$\phi(t)$	creep compliance function

transfer length as functions of time, noting that strand draw-in is a quantity that can be more conveniently measured than other quantities (i.e., strand strain, concrete surface strain). Studying time-dependent behavior of bond-transfer is considered rational according to pp. 191 in [1] Chapter VII, which reads: "When the wires are released from their temporary anchorages the force to be anchored is equal to the total tension in the wires at that moment less a certain component due to the instantaneous shortening of the concrete. Later the stress in the wires in the body of the beam (i.e., outside the anchorage zones) decreases owing to the delayed strains of concrete; the magnitude of the force anchored by bond adhesion therefore decreases." This decrease in stress, typically referred to as prestress losses, is important for service level properties of a beam such as deflection and camber and to strength level shear capacity.

1.2. Intended contributions

This study intends to make a contribution to the mathematical modeling of bond transfer in pretensioned concrete. In addition to Guyon [1], [7] is another source for mathematical modeling of bond transfer in pretensioned concrete. Other relevant publications include [8–20], a number of which are summarized in Section 2.

The first time derivative is necessary to capture the well-established phenomenon of concrete creep and to utilize time-dependent draw-in data. Indentations on the strand and their period affect the bond substantially [12], which is known to affect λ (the characteristic length of elastic anchorage) and, hence, draw-in. In this sense, surface roughness of the strand will be implicitly treated.

Another intended contribution of this study is to demonstrate the power of a simple linear time-dependent model in capturing time-dependent behavior of prestressed concrete. Nonetheless, more complicated and advanced creep models – together with shrinkage models – can be considered in future work.

1.3. Structure of this paper

After introducing the motivation of this study in Section 1.1, the intended technical contributions are specified in Section 1.2. Under literature review in Section 2, the initial value problem (IVP) method for modeling post-tensioned concrete is first presented before highlighting important concepts and formulas from [1] based on Guyon's boundary value problem (BVP) formulation. These two concepts will be combined to form the basis of a model for time-dependent deformation behavior of a pretensioned concrete member. Section 3.1 shares a physical insight into the proposed model. Key assumptions, problem formulas and governing equations are presented systematically in Section 3.2 by leveraging and integrating the two methods reviewed in Section 2, including the connection of a model for post-tensioned concrete to pretensioned concrete. Section 3.3 outlines the data-based strategy, mostly because of the unmodeled error – concrete shrinkage – that is not insignificant, and for insights into the solution. To validate the proposed model and data-based solution, Section 4 details all aspects involved in a numerical investigation of applying the proposed method to the data obtained from an experimental study. Discussions for future work are given there as well. Conclusions are drawn in Section 5.

2. Literature review

It is generally well known that prestress transfer length can be related to measured strand draw-in at the end of a prestressed member. The expression shown in Eq. (1) is a simplified version of the relationship derived based on an examination of the stress and strain relationships within the prestressed transfer length originally proposed by [1] and further investigated by other researchers [21,22,7,8,23].

$$L_t = \frac{\alpha E_{ps} g_0}{f_{si}} \tag{1}$$

where L_t is the transfer length (in.), E_{ps} is the Young's modulus of the prestressing steel, g_0 is the measured draw-in (in.), f_{si} is the initial stress in the strand due to the prestress (ksi), and α corresponds to the bond stress variation. An α value of 2 corresponds to a constant bond stress variation (linear steel stress distribution), while an α value of 3 corresponds to a linear bond stress variation (parabolic steel stress distribution). There is some disagreement among researchers as to the exact value of α, but it is generally agreed to be between 2 and 3 [21,22,7,8,23,24]). A number of α values have been determined using experimentally measured transfer lengths for prestressing strands cast in conventional concrete including 2.86 [7], 2.44 [23], and 2.61 [25]. Others have been determined based on theoretical studies such as [8] who proposed a value varying based on the specific bond-stress slip relationship (2.67 for 0.5 in. (12.7 mm) strands). Additional equations based on theoretical and empirical relationships have been proposed to relate strand end slip and transfer length taking into account the effects of strand diameter, concrete compressive strength at time of prestress release, and strand diameter (e.g. [14,8,17]). Cousins et al. [16]