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A higher-order equation for modeling strand bond in pretensioned concrete beams

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ABSTRACT

In pretensioned concrete members, the bond between prestressing strands and concrete in the transfer zone is necessary to ensure the two materials can work as a composite material. This study develops a computer program based on the Thick-Walled Cylinder theory to predict the bond behavior within the transfer zone. The bond was modeled as the shearing stress acting at the strand-concrete interface, and this generated a normal stress to the surrounding concrete. The stresses developed in the concrete often exceeded its tensile strength, which resulted in radial cracks at the strand-concrete interface. These cracks reduced the concrete stiffness and redistributed the bond strength along the transfer zone. The developed program was able to determine the bond stress distribution, degree of cracking, and transfer length of the prestressing strands. The program was validated using a data set of transfer lengths measured at the University of Arkansas and a data set collected from the literature.

1. Introduction

Pretensioned concrete has been used extensively in buildings and bridge structures since the 1950s. In the design of pretensioned members, determining the transfer length is needed for calculating concrete stresses at release and quantifying shear strength at the ultimate state. Transfer length is the required length to transfer the prestress in the prestressing strands to the concrete. The prestressing force is transferred to the concrete by the bond between the two materials. The bond is a fundamental factor, which enables the strands and concrete to work as a composite material [1]. Studies have shown that bond strength is affected by many factors [1–8], including strand surface conditions [9], size of the strands [10], concrete compressive strength [11], type of release [4], concrete cover [12], cement content and water to cement ratio [8], and strand configuration [8,13,14]. The effects of these factors on strand bond have been validated by analytical and experimental studies [15]. While most studies have determined that the transfer length of prestressing strands is an indicator of strand bond, the number of studies that directly quantifies the bond-strength modeling at the strand-concrete interface is limited [16–21]. That existing numerical models and programs propose complex procedures to quantify the nonlinear interaction between the prestressing strands and concrete. Therefore, more research is needed to develop a simple a reliable technique to efficiently quantify the interaction and precisely predict the transfer length.

Prestressing steel can be considered as a homogeneous material in an analytical analysis, and its properties are generally well defined by ASTM-A416/A416M-15 [22]. Concrete, on the other hand, is a heterogeneous material consisting of cement mortar and aggregates. Concrete properties depend on many variables and are difficult to define accurately. However, concrete can be assumed to be a homogeneous material for general applications in many civil engineering structures, and this assumption is commonly accepted in the literature [23,24]. The stress-strain relationship of concrete is nonlinear, and it is different in compression versus in tension. Prestressing steel is used exclusively in tension, and its stress-strain relationship is represented by a nonlinear curve [25].

The bond at the strand-concrete interface is dependent upon the properties of prestressing steel and concrete. The properties of the prestressing steel depend on the strain state of the material [25–27]. The concrete exhibits a high nonlinear behavior at higher compressive-stress levels and at the tensile state because of cracking, yielding and crushing [24]. Several investigations have assumed a perfect bond between the concrete and the prestressing

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Nomenclature

A_s	nominal strand area
A_b	nominal area of strand
A_g	cross-section area of concrete member
A_p	total area of strand
A_c	cross-sectional area of concrete
c_y	clear concrete cover
d_b	strand diameter
e_c	eccentricity of the prestressing force
E	elastic modulus
E_c	elastic modulus of concrete
E_p	elastic modulus of strand
E_{pr}	elastic modulus of strand in the transversal direction
f_{si}	initial prestress in strand
f_{se}	effective prestress in strand after losses
f'_{ci}	concrete's compressive strength at release of strand
f'_c	concrete's compressive strength
f_t	concrete's tensile strength
f_{cz}	concrete compressive stress due to effective prestress
f_{pu}	ultimate tensile strength of prestressing strand
f_{py}	yield strength of prestressing strand
f_{pi}	initial prestress of prestressing strand
I_g	moment of inertia of concrete section
v	Poisson's ratio
v_p	Poisson's ratio of strand
v_c	Poisson's ratio of concrete
$\eta = E_p/E_c$	modular ratio
n	integer number (2 for second-order equation and 3 for third-order equation)
λ_b	bond factor
λ_{sp}	strand perimeter factor (1 is for solid strand and 4/3 for seven-wire strand)
λ_{uscE}	factor of unit system conversion for elastic modulus
λ_{uscT}	factor of unit system conversion for tensile strength
L_t	transfer length of prestressing strand in pretensioned concrete members
w	unit weight of concrete
μ	coefficient of friction between prestressing steel and concrete
σ_i	interface pressure
σ_r	radial stress at concrete and strand interface
σ_θ	hoop stress
σ_z	longitudinal stress
ε_r	radial strain
ε_θ	hoop strain
ε_z	longitudinal strain
ε_{sh}	drying shrinkage coefficient
K_f	constant factor
k_t	radial stress
k_{ii}	constant factor (ii = 1, 2, 3,...,7)
k_{bi}	bond surface stiffness
r_p	nominal radius of strand
$r_{c,1}$	internal radius of concrete cylinder which equals to radius of strand after prestressing
$r_{c,2}$	external radius of concrete cylinder
r	radius in the radial direction
R_1	inner radius
R_2	outer radius
R_{cr}	crack radius
R_{fr}	fracture radius
τ	bond stress
(r, θ, z)	polar coordinates stresses
(u, v, w)	polar coordinates displacements
Δ^p_{fp}	increase in radius of strand due to reduction in longitudinal stress from initial prestress f_{si} to effective prestress f_{se}
$\Delta^p_{\sigma i}$	reduction in radius of strand due to the uniform radial compression at interface σ_i
$\Delta^c_{\sigma i}$	increase in inner radius of the thick-walled concrete cylinder due to the interface pressure σ_i
Δ^c_{fcz}	increase in inner radius of the thick-walled concrete cylinder due to the longitudinal compressive stress at the level of strand f_{cz}
Δ^c_{sh}	reduction in inner radius of the thick-walled concrete cylinder due to drying shrinkage ε_{sh}
Δ^c_{cr}	deformation of the real crack zone
Δ^c_{fr}	deformation of the fracture zone
$u^c_{R_{fr}}$	radial displacement at $r = R_{fr}$
Δx	incremental of transfer zone
Δf_{bi}	bond force around the strand surface
Δf_{pxi}	strand stress incremental
w_{cr}	crack width at any point
w_a	crack width
w_o	initial crack width at the shear plane

steel since there is no slip at the contact surface of the concrete and strand. This assumption is used to simplify the calculation in pretensioned concrete structures using numerical methods, but it does not reflect the actual behavior of the materials.

For simplification, the design aspects related to strand bond are often solved without considering the bond stress distribution [7]. In this paper, the bond acting at the strand-concrete interface was modeled using the principles of solid mechanics. Previous studies determined that the stress level in the concrete after release often exceeds the concrete's tensile strength [28,29], which is responsible for the concrete cracking within the transfer zone. Therefore, this study considered both cracked and uncracked regions adjacent to the strand within the transfer zone.

The research aims at predicting the bond behavior within the transfer zone using the Thick-Walled Cylinder theory. A second-order equation that represents the relationship of post-peak stress and crack width [30] was upgraded to a third-order equation. A computer program used to predict the transfer length and bond behavior was developed to analyze the cracked and fracture zone. The accuracy of the developed program was validated using a data set of transfer lengths measured at the University of Arkansas and a data set collected from the literature.

2. Background

A thick-walled cylinder, which is shown in Fig. 1, is widely used for estimating the transfer length in pretensioned concrete beams [12,28,30]. The cylinder thickness is constant and subjected to a uniform internal pressure p_1, a uniform external pressure p_2, and an axial load P. In 1939, Hoyer and Friedrich [32] idealized a pretensioned concrete beam as a thick-walled cylinder as shown in Fig. 2. The researchers considered the anchorage to be a result of swelling of the prestressing steel or wires that were caused by Poisson's ratio and proposed an equation to predict the transfer length of prestressing strands as shown in Eq. (1).

$$L_t = \frac{d_b}{2\mu}(1 + v_c)\left(\frac{\eta}{v_p} - \frac{f_{si}}{E_c}\right)\frac{f_{se}}{2f_{si} - f_{se}} \quad (1)$$

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