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Assessment of transmission length of prestressing strands according to *fib* Model Code 2010

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A B S T R A C T

The use of 18-mm prestressing strands is advantageous in the construction of long-span bridges. Transmission length is a significant parameter in the design of pretensioned concrete members. This study provides a unique set of experimental data to validate the applicability of using the *fib* Model Code 2010 to predict the transmission length and strand draw-in of 18-mm strands. Twelve pretensioned concrete beams were cast with high-strength concrete. Transmission lengths were measured at prestress transfer and at 28-day of age. The experimental results indicated the lower and upper bounds of transmission length specified by the code adequately predict the measured values.

1. Introduction

Pretensioned concrete is widely used in the construction of long-span bridges. These bridges are often constructed in the locations having traffic and geometrical restrictions or in water-crossing areas. The use of large diameter strands can increase the prestressing force in pretensioned concrete bridge girders, which results in the extension of bridge span lengths, reduction in construction costs, and improvement in long-term durability. A 18-mm, Grade 1860, prestressing strand can carry a high prestressing force, which is 35% and 96% greater than the corresponding forces of a 15.2-mm and 12.7-mm strand, respectively. In the United States, 18-mm prestressing strands have been used to fabricate pretensioned concrete girders in several bridge projects since 2008 [1–3].

Transmission length is a significant parameter in the design of pretensioned concrete members. According to the *fib* Model Code for Concrete Structures 2010 (herein referred as MC 2010) specifications [4], transmission length is the required length for prestressing strands to develop the full effective prestress force after release. As stated in the Article 6.1.8.4, the lower bound and upper bound of the transmission length of 7-wire prestressing strands can be estimated using Eqs. (1) and (2), respectively. The lower bound is used to verify transverse stresses in concrete while the upper bound is used to calculate shear strength and flexural resistance. These provisions are based on the fact that a short transmission length is important for checking allowable stresses at release of prestressing strands, and a long transmission length is significant for the calculation of the anchorage length in the ultimate state.

$$l_{bpt,0.05} = 0.25\alpha_{p1}\frac{\sigma_{pi}}{f_{ptd}}l_{bp} \quad (1)$$

$$l_{bpt,0.95} = 0.5\alpha_{p1}\frac{\sigma_{pi}}{f_{ptd}}l_{bp} \quad (2)$$

where $l_{bpt,0.05}$ = lower bound of transmission length; $l_{bpt,0.95}$ = upper bound of transmission length; α_{p1} = a coefficient considering the type of release (α_{p1} = 1.0 for gradual release and 1.25 for sudden release); σ_{pi} = strand stress just after release; f_{ptd} = design strand strength; l_{bp} = basic anchorage length.

The lower bound and upper bound of transmission length can be simplified by substituting the basic anchorage-length equation shown in Eq. (3) into Eqs. (1) and (2). The simplified

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Notation

A_{sp}	cross-sectional area of prestressing strand
E_p	modulus of elasticity of prestressing strand
E_{ct}	modulus of elasticity of concrete at release
α_{p1}	a coefficient considering the type of release
d_b	nominal strand diameter
f_{ctd}	lower design concrete tensile strength
f_{ctm}	concrete tensile strength at release
f_{ptd}	design strand strength
f_{cki}	concrete compressive strength at release
f_{ck}	concrete compressive strength at 28 days of age
f_{pj}	jacking stress
l_{bpt}	transmission length
$l_{bpt,0.05}$	lower bound of transmission length
$l_{bpt,0.95}$	upper bound of transmission length
l_{bp}	basic anchorage length
η_{p1}	1.2 for 7-wire prestressing strands
η_{p2}	1.0 for all the strands which are up to 250 mm from the bottom fiber of pretensioned concrete members
σ_{pi}	strand stress just after release
δ_e	measured strand draw-in
Δ_t	distance from the reference point to the beam end just after release
Δ_0	distance from the reference point to the beam end before release
Δf_{pES}	elastic shortening loss
f_{cgp}	concrete stress at the center of gravity of prestressing strands due to the prestressing force immediately after transfer and the self-weight of the member at the section of maximum moment

transmission-length equations are shown in Eqs. (4) and (5). In these equations, the design bond strength shown in Eq. (6) is a function of concrete tensile strength as shown in Eq. (7). According to the MC 2010 specifications, the tensile strength can be derived from compressive strength as presented in Eqs. (5.1-3a) and (5.1-3b) in Article 5.1.5.1 of the code.

$$l_{bp} = \frac{A_{sp}}{\pi d_b}\frac{f_{ptd}}{f_{bpd}} \tag{3}$$

$$l_{bpt,0.05} = 0.25\alpha_{p1}\frac{\sigma_{pi}}{f_{bpd}}\frac{7d_b}{36} \tag{4}$$

$$l_{bpt,0.95} = 0.5\alpha_{p1}\frac{\sigma_{pi}}{f_{bpd}}\frac{7d_b}{36} \tag{5}$$

$$f_{bpd} = \eta_{p1}\eta_{p2}f_{ctd} \tag{6}$$

$$f_{ctd} = \frac{0.7f_{ctm}}{1.5} \tag{7}$$

where $A_{sp}/(\pi d_b)$ = $7d_b/36$ for 7-wire prestressing strands; η_{p1} = 1.2 for 7-wire prestressing strands; η_{p2} = 1.0 for all the strands which are up to 250 mm from the bottom fiber of pretensioned concrete members; f_{ctd} = lower design concrete tensile strength; f_{ctm} = concrete tensile strength at release.

Alternatively, transmission length can be estimated from the draw-in of prestressing strands [5–10]. Strand draw-in is the distance for which the prestressing strands slip into the concrete member when the strands are released. Instead of directly stating the correlation between transmission length and strand draw-in, MC 2010 specifies the allowable draw-in of prestressing strands as shown in Eq. (8). For a specific prestressing strand, the measured transmission length is considered to be less than the upper bound value [see Eq. (5)] if the measured strand draw-in satisfies Eq. (8).

$$\delta_e < 0.5\frac{\sigma_{pi}}{E_p}l_{bpt,0.95} \tag{8}$$

where δ_e = measured strand draw-in; E_p = modulus of elasticity of prestressing strands.

There are two common techniques used to measure the transmission length of prestressing strands. The first technique involves using electrical resistance strain gauges attached to the prestressing strands to quantify the variation in strand stress along the pretensioned concrete members [11,12]. This technique provides a direct variation in strand stress, but the strain gauges are easily damaged during concrete placement, particularly when vibrated concrete is used, which may lead to unreliable results [13,14]. The second technique involves using a DEMEC gauge in conjunction with DEMEC target points to measure the change in the distance between the target points before and after detensioning the prestressing strands [7,13]. This technique provides reliable results in the determination of transmission length of prestressing strands [7,15,16].

The measurement of strand draw-in is quick and easy. A number of studies [5–10] have addressed the relationship of the strand draw-in and transmission length of prestressing strands. This relationship, however, is based on an assumed variation in strand stress along the transmission length. Most of specifications [4,17,18] assume a linear strand stress along the transmission length while researchers [19] determined that the strand stress nonlinearly increases along the transmission length. The allowable draw-in of prestressing strand shown in Eq. (8) was derived based on the linear strand stress assumption.

2. Review of previous research

The properties of 18-mm prestressing strands can be nominally classified as two categories: mechanical properties and bond properties. The mechanical properties are significant for the prestressing strands to resist the tensile stresses generated by external loads. The bond properties are important for transferring the prestressing force in the strands to the concrete [20–23]. The bond properties typically depend on the surface condition of prestressing strands [8,20], the properties of the concrete adjacent to the prestressing strands [24–26], and strand diameters [7,13]. Pretensioned concrete members tend to show premature failures prior to the prestressing strands achieving the design strength if bond properties are inadequate.

The mechanical properties of 18-mm prestressing strands are specified in the American Society for Testing and Materials (ASTM) A1081 [27]. A 18-mm strand has a cross-section area (A_{sp}) of 190 mm^2, the modulus of elasticity (E_p) of 196 GPa, a minimum elongation of 3.5%, a minimum yield strength of 1674 MPa, and a minimum breaking strength (f_{pu}) of 1860 MPa. Based on the tension test results of 102 strand specimens collected from two strand manufacturers, Morcous et al. [28] determined that all of the specimens complied with the requirements of elongation and breaking strength, but several specimens did not meet the requirement of yielding strength.

The bond behavior of 18-mm prestressing strands can be assessed by conducting simple bond tests [21,28,29], measuring transfer and development lengths [2,3,30–39], and using