MEASURED TRANSFER AND DEVELOPMENT LENGTHS OF 0.7 IN. (17.8 MM) STRANDS

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ABSTRACT

The use of 0.7 in. (17.8 mm), Grade 270 (1860), prestressing strands in construction is slow regardless of the engineering advantages of this type of strands. The unavailable design guidelines partially account for the slow utilization. This study measured transfer length and development length of 0.7 in. (17.8 mm) prestressing strands for 12 pretensioned concrete beams cast with two high-strength concrete mixtures. The beams contained one or two strands placed at a spacing of 2.0 in. (51 mm). The strands were tensioned to 75% of the ultimate strength prior to casting the concrete. The strand surface conditions were quantified using the Standard Test for Strand Bond. Transfer lengths at release and at 28 days were determined by measuring concrete surface strains. Development length was determined by conducting bending tests at different embedment lengths. Experimental results indicated that the increase of concrete strength can shorten transfer and development lengths. The use of a strand spacing of 2.0 in. (51 mm) had no effect on the measured transfer lengths and minimal effect on the measured development lengths. The current ACI 318 and AASHTO specifications are applicable to predict transfer and development lengths of 0.7 in. (17.8 mm) strands.

Keywords: Transfer Length, Development Length, 0.7 in. Strand; Pretensioned Concrete, Bond.

INTRODUCTION

In the United States, 0.5 in. (12.7 mm) and 0.6 in. (15.2 mm) prestressing strands are dominant while 0.7 in. (17.8 mm) prestressing strands were first used in practice in 2008 [1, 2]. The use of 0.7 in. (17.8 mm) strands has benefits over the use of 0.5 in. (12.7 mm) and 0.6 in. (15.2 mm) strands in terms of prestress force. A 0.7 in. (17.8 mm) strand carries a higher prestress force which is 35% greater than the force of a 0.6 in. (15.2 mm) strand. The increase of prestress force improves the flexural capacity, extends span length, or reduces the required number of prestressing strands. In fact, the number of bridges using 0.7 in. (17.8 mm) strands is limited. The Pacific Street Bridge and the Oxford South Bridge in Nebraska were the first two bridges in the U.S. using 0.7 in. (17.8 mm) prestressing strands for pretensioned concrete girders [3].

The number of prestressing strands used in a pretensioned concrete member (PCM) directly affects the load-carrying ability [4]. In fact, the number of prestressing strands is dependent upon the strand spacing. If the prestressing strands are placed far apart, the PCM only accommodates a limited number of prestressing strands which reduces the efficiency of the design. Otherwise, if the prestressing strands are placed too close, the concrete within the anchorage zone may crack and the required transfer length and development length are greater than the predicted values which yield an insufficient design. In the design of PCMs, transfer and development lengths are important parameters to evaluate the structural performance of the members [3, 5, 6]. Transfer length is the required length for transferring the prestress force in prestressing strands to the concrete as shown in Fig. 1. Development length is the required length at which the PCM achieves the nominal flexural capacity and the prestressing strands exhibit no slippage.

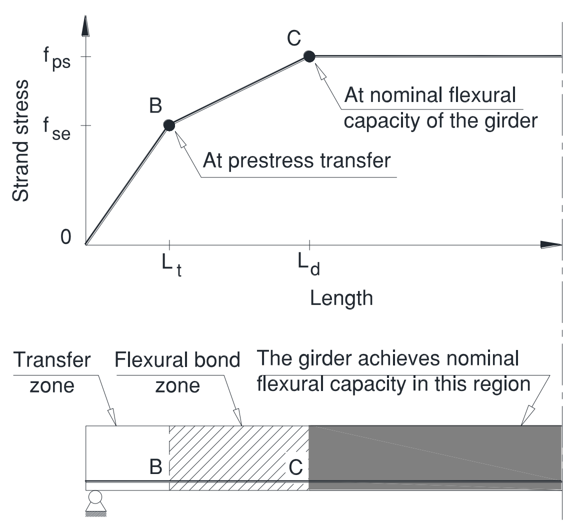

Fig. 1 Diagrams of transfer and development lengths. (Note: L_t = transfer length; L_d = development length; f_{se} = effective stress in the prestressing steel after losses; f_{ps} = is average stress in prestressing strand at the time for which the nominal flexural resistance of the member is required)

The current codes have several bonding equations to predict transfer and development lengths of 0.5 in. (12.7 mm) and 0.6 in. (15.2 mm) strands. The ACI 318 [7] development length equation shown in Eq. (1) includes two terms in which the first term represents transfer length and the second term represents flexural bond length. ACI 318 alternatively provides a simple equation of $50d_b$ (where d_b is the strand diameter) to estimate transfer length. According to AASHTO [8], transfer length can be taken as $60d_b$. The AASHTO development length equation shown in Eq. (2) is similar to the ACI 318 equation but including a multiplier κ to account for high shear effects. A κ of 1.6 is used for PCMs having a depth equal to or greater than 24 in. (610 mm), otherwise κ receives a value of 1.0. These equations are used along with the specific requirements of strand spacing. The minimum strand spacing values of 0.5 in. (12.7 mm) and 0.6 in. (15.2 mm) strands are 1.75 in. (44 mm) and 2.0 in. (51 mm) which are equivalent to $3\frac{1}{2}d_b$ and $3\frac{1}{3}d_b$, respectively. The contemporary concern is the applicability of using the existing bonding equations for 0.7 in. (17.8 mm) strands.

$$L_d = \frac{1}{3} f_{se} d_b + \left(f_{ps} - f_{se} \right) d_b \quad (f_{ps} \text{ and } f_{se} \text{ in ksi}) \tag{1}$$

$$L_d = \kappa \left(f_{ps} - \frac{2}{3} f_{se} \right) d_b \quad (f_{ps} \text{ and } f_{se} \text{ in ksi}) \tag{2}$$

where L_d = development length; f_{se} = effective stress in the prestressing steel after losses; f_{ps} = is average stress in prestressing strand at the time for which the nominal flexural resistance of the member is required; κ is a multiplier of AASHTO development length equation.

A number of tests were conducted to determine transfer length, development length, and an applicable strand spacing for the two bridges in Nebraska because of the unavailability of the design codes. One NU900 girder was tested for the Pacific Street Bridge project [2]. The tested girder contained 24 – 0.7 in. (17.8 mm) prestressing strands which were tensioned to $0.75f_{pu}$ (where f_{pu} is the ultimate strength of prestressing strand) and placed at 2.2 in. by 2.25 in. (56 mm by 57 mm) spacing. The concrete had compressive strengths of 6.7 ksi (46.2 MPa) at 1 day of age and 8.0 ksi (55.2 MPa) at 28 days of age. The reported transfer length was approximately equal to 35 in. (890 mm), and the girder achieved the nominal flexural capacity at the tested development length of 14 ft (4.27 m) predicted by the AASHTO equation. For the Oxford South Bridge, Morcous et al. [3] reported the measured transfer lengths at three ends of NU1350 girders. The NU1350 girder contained 24 – 0.7 in. (17.8 mm) prestressing strands which were tensioned to $0.75f_{pu}$ and placed at 2.0 in. by 2.0 in. (51 mm by 51 mm) spacing. These parameters are currently used for 0.6 in. (15.2 mm) strands [7, 8]. Self-consolidating concrete which had compressive strengths of 6.0 ksi (41.4 MPa) at 1 day of age and 8.0 ksi (55.2 MPa) at 28 days of age was used to cast the girders. The average, measured transfer lengths at release and at 14 days were 32 in. (815 mm) and 36 in. (915 mm), respectively, which were approximately equal to the predicted transfer length using the ACI 318 equation. The development length was not reported.

Researchers have performed a number of studies to evaluate the sufficiency of using 0.7 in. (17.8 mm) strands for PCMs. Patzlaff et al. [9] measured transfer length for 8 T-girders in which the prestressing strands were tensioned to $0.75f_{pu}$ and placed at 2.0 in. by 2.0 in. (51 mm by 51 mm) spacing. The average, measured transfer length was 23.3 in. (530 mm) which is shorter than the predicted transfer lengths using the ACI 318 or AASHTO equations. Several bending tests were conducted to evaluate development length for the 8 T-girders and three other NU1100 girders. The test results indicated the AASHTO equation is adequate to predict development length of 0.7 in. (17.8 mm) strands. Song et al. [10] and Cabage [11] had a similar conclusion regarding the transfer and development lengths which were measured for one AASHTO Type I girder. Several other studies [2, 12] investigated the performance of 0.7 in. (17.8 mm) strands in PCMs in which the strands were tensioned to a low prestress because of the limited capacity of prestressing bed.

In summary, most of studies in the literature were conducted for the PCMs having a depth equal to or greater than 24 in. (610 mm) which include a multiplier of 1.6 for the development length equation. This study represents the members having a depth less than 24 in. (610 mm) in which the development length equation would not include the multiplier. The measured transfer lengths for these members may be longer than for the members having a depth equal to or greater than 24 in. (610 mm) [6, 13] which would increase the conservativeness in evaluating transfer length.

OBJECTIVES

This study investigated the applicability of using a strand spacing of 2.0 in. (51 mm) for 0.7 in. (17.8 mm) strands. Twelve pretensioned concrete beams which had cross-section of 6.5 in. by 12 in. (165 mm by 305 mm) and a length of 18 ft (5500 mm) were cast using two high-strength concrete mixtures. The strand surface conditions were evaluated using the Standard Test for Strand Bond (STSB) in which the testing procedures are adopted from ASTM A1081 [14]. The beams contained one or two prestressing strands which were tensioned to $0.75f_{pu}$ prior to casting the concrete. Transfer lengths were measured at release and 28 days. Development lengths were determined by conducting bending tests at different embedment lengths after the beams had reached 28 days of age. A number of recommendations regarding transfer length, development length, and an applicable strand spacing were made.

EXPERIMENTAL PROCEDURES

PRESTRESSING STRAND TESTING

Strand surface is a significant factor affecting the performance of prestressing strands in PCMs [15-18]. The strand surface may vary for different strand manufacturers and cycles of production. In the current practice, ASTM A1081 [14] is used to quantify the strand surface conditions for 0.5 in. (12.7 mm) and 0.6 in. (15.2 mm) strands using the STSB tests. However, ASTM A1081 does not specify the acceptance criteria for the prestressing strands used in precast/prestressed concrete applications. For 0.5 in. (12.7 mm) strands, Ramirez and Russell [16] proposed a minimum STSB value (the average pull-out force of six specimens) of 10.5 kips (46.7 kN) and a minimum the pull-out force of 9.0 kips (40.0 kN) for an individual specimen as the acceptance criteria. These proposed acceptance criteria were based on the correlation of the STSB values and the predicted transfer length using the ACI 318 equation. Polydorou [19], however, proposed higher acceptance criteria in which the strands should have a STSB value equal to or greater than 14.6 kips (64.9 kN).

The acceptance criteria of 0.7 in. (17.8 mm) strands were established based on the proportion of strand diameters. Based on the acceptance criteria proposed by Ramirez and Russell [16], Morcous et al. [20] proposed the STSB value of 0.7-in. (17.8-mm) strands is equal to or greater than 14.7 kips (65.4 kN), and no individual specimen exhibits a pull-out force less than 12.6 kips (56.1 kN). If the acceptance criteria proposed by Polydorou [19] are adopted, 0.7 in. (17.8 mm) strands should have a minimum STSB value of 20.4 kips (90.9 kN) and a minimum pull-out force of 17.5 kips (77.8 kN) for an individual specimen to use in precast/prestressed concrete applications. However, there are no experimental data for validating these proposed acceptance criteria.

In this study, six strand specimens were cut from a 2000 ft (610 m) reel of 0.7 in. (17.8 mm) prestressing strand for evaluating the strand surface conditions using the STSB test. The strand specimens were obtained in the as-received condition. These samples were then preserved with great care and protected from getting contaminated by foreign substances. The tests were performed at 22 to 26 hours after casting the STSB specimens. ASTM A1081 requires a mortar compressive strength of 4500 (30.0 MPa) psi to 5000 psi (34.5 MPa) at the time the STSB tests were conducted to reduce the variation of the pull-out forces [16, 21]. The mortar strengths at the beginning and at the finishing of the STSB tests were 4520 psi (31.2 MPa) and 4650 psi (32.1 MPa), respectively. The average mortar strength was 4580 psi (31.6 MPa) which met the requirements of ASTM A1081 as mentioned previously.

The measured pull-out forces of the 6 strand specimens were: 36.99 kips (164.5 kN), 32.17 kips (143.1 kN), 39.16 kips (174.2 kN), 35.6 kips (158.4 kN), 38.55 kips (171.5 kN), and 37.88 kips (168.5 kN) which resulted in a STSB value of 36.73 kips (163.4 kN) with standard deviation of 2.56 kips (11.4 kN). The relationships of the pull-out force measured at the loaded-end and the strand slippage measured at the free-end of the 6 strand specimens are shown in Fig. 2. The measured STSB value was 150% and 80% greater than the acceptance critiaria proposed by Morcous et al. [20] and those adopted from Polydorou [19], respectively, and 64% greater than the experimental results reported by Morcous et al. [20].

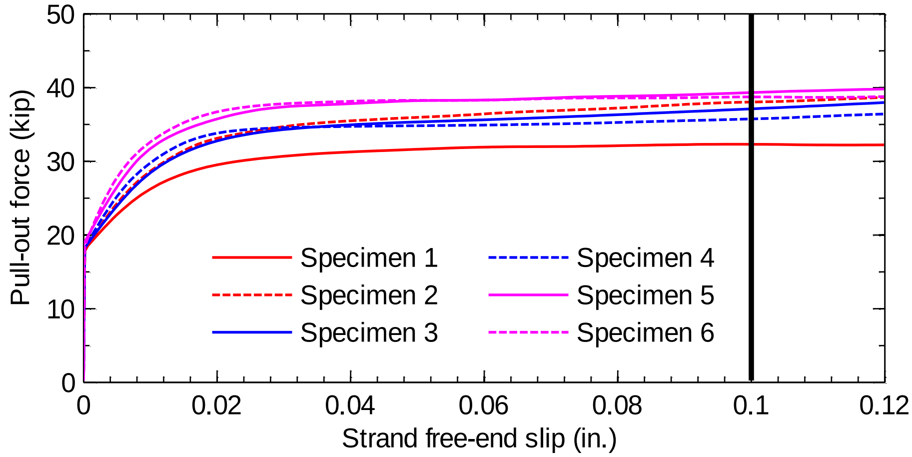

Fig. 2 Pull-out forces of the 6 strand specimens. (Note: 1 in. = 25.4 mm; 1 kip = 4.448 kN)

CONCRETE PROPORTIONING

High-strength concrete has been widely used for pretensioned concrete bridge girders. The use of high-strength concrete would further the advantages of using 0.7 in. (17.8 mm) prestressing strands [9, 10, 12, 22] while normal-strength concrete has been employed in a number of studies in the literature [1-3]. It was recommended that the concrete compressive strength used for bridge girders should be greater than 8 ksi (55.2 MPa) [23] and extend to 10 ksi (69.0 MPa) [24]. Two high-strength concrete mixtures which had compressive strengths equal to or greater than 10 ksi were designed in this study. The M10 and M12 mixtures had targeted compressive strengths of 10 ksi (69.0 MPa) and 12.0 ksi (82.7 MPa), respectively. Table 1 shows the mix proportions of the two concrete mixtures and the beams cast with each mixture. For example, M10-S1 is the first in a set of 4 beams which were cast with the M10 mixture and used one 0.7 in. (17.8 mm) prestressing strand.

Table 1 Concrete mixture proportions

Material	M10	M12
Cement (lb/yd^3)	700	700
Coarse aggregate (lb/yd^3)	1678	1678
Fine aggregate (lb/yd^3)	1363	1454
Water (lb/yd^3)	280	245
Water/ Cement ratio	0.40	0.35
High range water reducer (fl oz/cwt)	5 to 6	5 to 6
Targeted compressive strength at 28 days of age (ksi)	10	12
Designation of the beams using Section I*	M10-S1 to M10-S4	M12-S1 to M12-S4
Designation of the beams using Section II*	n.a.	M12-D1 to M12-D4

(Note: * = see Fig. 3; n.a. = not applicable; 1 yd^3 = 0.765 m^3; 1 lb = 0.454 kg; 1 cwt (hundred weight) = 100 lb; 1 fl oz = 29.57 mL; 1 ksi = 6.895 MPa)

The concrete compressive strengths at release of the prestressing strands, at 28 days of age, and at the time the bending tests were conducted are summarized in Table 2. In particular, the concrete strengths at release varied from 6.3 ksi to 9.8 ksi (43.4 MPa to 67.6 MPa). The concrete compressive strengths at 28 days of age were -5% to 12% greater than the targeted strengths for all concrete mixtures. At the time the bending tests were conducted, the concrete compressive strengths were 1% to 8% greater than those at 28 days of age.

Table 2 Concrete compressive strengths

Beam	Concrete compressive strengths		
	f'_{ci} (ksi)	f'_{c} (ksi)	f'_{ct} (ksi)
M10-S1 and M10-S2	5.9	9.3	9.7
M10-S3 and M10-S4	6.6	9.7	10.5
M10-S (Average)	*6.3*	*9.5*	*10.1*
M12-S1 and M12-S2	9.5	13.7	14.2
M12-S3 and M12-S4	8.9	13.2	12.8
M12-S (Average)	*9.2*	*13.4*	*13.5*
M12-D1 and M12-D2	9.7	12.3	13.9
M12-D3 and M12-D4	9.9	13.3	13.8
M12-D (Average)	9.8	12.8	13.9

(Note: f'_{ci} = concrete compressive strength at 1 day of age; f'_{c} = concrete compressive strength at 28 days of age; f'_{ct} = concrete compressive strength at time the bending tests were conducted; 1 ksi = 6.895 MPa)

PRETENSIONED BEAM FABRICATION

Twelve pretensioned concrete beams were cast using the two concrete mixtures. The beam had a rectangular cross-section of 6.5 in. by 12 in. (165 mm by 305 mm) and a length of 18 ft (5500 mm). The beam sections were classified as two types because of the difference in the number of pressing strands and amount of top steel and shear reinforcement as shown in Fig. 3. Section I contained one 0.7 in. (17.8 mm) strand and used two No.5 (16 mm) reinforcing bars as the top reinforcement to control the anticipated tensile stress at the top fiber of the beam. Shear reinforcement consisted of 0.25 in. (6.4 mm) smooth bars spaced at 6 in. (150 mm) along the entire beam length. Section II contained two 0.7 in. (17.8 mm) strands which were placed at a spacing of 2.0 in. (51 mm). This type of section used two No.6 (19 mm) reinforcing bars as the top reinforcement and 0.25 in. (6.4 mm) smooth bars spaced at 3 in. (75 mm) as the shear reinforcement.

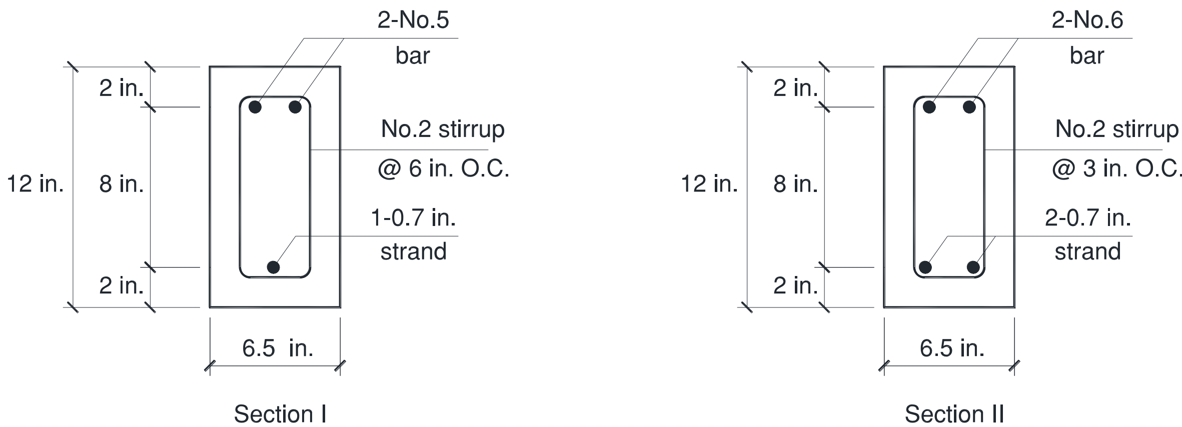

Fig. 3 Beam sections. Section I was used to cast 8 beams using the two concrete mixtures (M10-S1 to M10-S4 and M12-S1 to M12-S4), and section II was used to cast 4 beams using the M12 mixture (M12-D1 to M12-D4) as presented in Table 1. (Note: 1 in. = 25.4 mm; No.2 = 6.4 mm; No.5 = 16 mm; No.6 = 19 mm; 0.7 in. strand = 17.8 mm strand)

The prestressing strands were tensioned to $0.75f_{pu}$ (202.5 ksi or 1396 MPa) prior to casting the concrete. Two 100 ton (890 kN) hydraulic rams were used to tension the strands at the live-end while the strands were anchored using chucks at the dead-end. The ram movement was monitored to properly achieve the specified prestress. The tensioning of prestressing strands was accomplished few hours prior to casting, so the relaxation loss was ignorable. The strand stress was held constantly until the concrete reached the desired age to detension.

Two beams were simultaneously cast on a 50 ft (15.24 m) prestressing bed using one batch of concrete; therefore, the concrete compressive strengths were identical for each pair of beams (see Table 2). Nine cylinders (4 in. by 8 in. [100 mm by 200 mm]) were additionally cast and cured adjacent to the beams to evaluate the concrete strengths at 1 day of age, 28 days of age, and at the time the bending tests were conducted as discussed previously. After casting, plastic sheets were used to cover the beams to prevent the loss of moisture while the concrete was cured in the wooden forms. The forms were removed at approximately 20 hours after casting.

TRANSFER LENGTH MEASUREMENT

Transfer length was determined by quantifying the variation of strand stresses (see Fig. 1). The strand stress is proportional with the strand strain according to the Hooke's law because the strands were tensioned to a prestress lower than the yield strength. The variation of strand strains along the transfer zone was indirectly quantified by measuring concrete surface strains as shown in Fig. 4. After removing the forms, a set a target points were attached to the beam surface at the level of prestressing strands. The first point was placed at 1 in. (25 mm) from the beam end and the subsequent points were spaced at 4 in. (100 mm) for the first 60 in. (1524 mm). The target points were affixed at the both beam ends and at the both beam sides. The initial reading was conducted at approximately 2 hours after removing the forms. Three cylinders were tested to verify the concrete compressive strength before release of the prestressing strands.

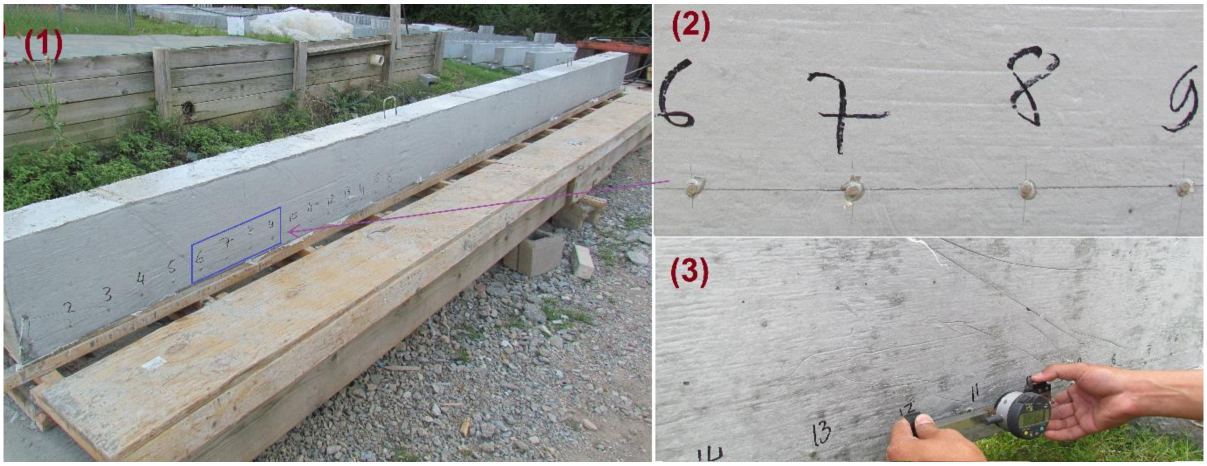

Fig. 4 (1) The attachment of a set of target points on the surface of a pretensioned concrete beam after removing the form; (2) A set of target points at a spacing of 4 in. (100 mm); (3) The use of mechanical strain gauge to measure concrete strains.

The prestressing strands were detensioned at approximately 24 hours after casting. The detensioning was accomplished by gradually releasing the pressure in the hydraulic systems which brought the strand stress from full tension to no tension. The prestressing strands were then saw-cut. The subsequent readings were conducted immediately after release and at 28 days. The concrete strains were the difference between a particular reading after release of the strands and the initial reading.

The measured concrete strains at the both sides of a specific beam end were averaged and smoothed using a three-point moving average technique to attain the concrete strain profile [6, 25]. Transfer length was determined using the concrete strain profile at each beam end along with the 95% Average Maximum Strain (AMS) method [26]. Previous studies used the distance from the beam end to the intersection of the 95% AMS line with the concrete strain profile as the defined transfer length [15, 26-28]. The study used the intersection point of the 95% AMS line with the initial linear trend (ILT) line as shown in Fig. 5 to determine transfer length. The advantages of using the ILT line are to reduce the effect of strain fluctuation near the end of the transfer zone [29] and increase the precision and consistency of the measurements [30].

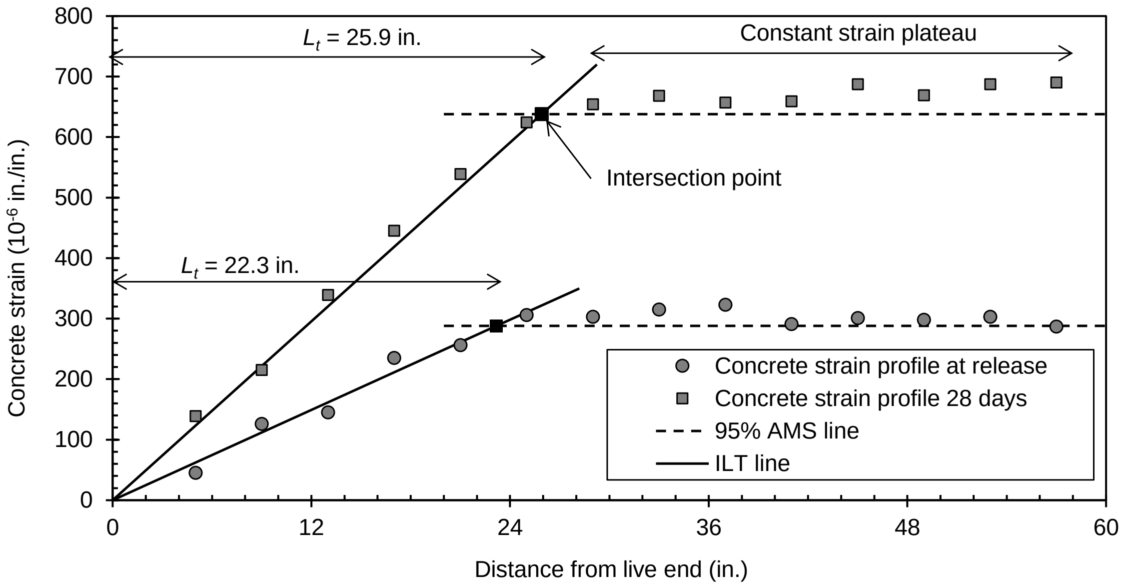

Fig. 5 Determination of transfer lengths at release and at 28 days of the M12-S1 beam. (Note: L_t = transfer length; AMS = Average Maximum Strain; ILT = initial linear trend; 1 in. = 25.4 mm)

The following steps were used to determine transfer lengths at release and at 28 days.

Step 1: Plot the concrete strain profile along the beam length.

Step 2: Determine the constant strain plateau to calculate the AMS value.

Step 3: Draw the 95% AMS line. This is the horizontal line passing through the 95% AMS value and represents the constant strand stress beyond the transfer zone.

Step 4: Draw the ILT line. The ILT line passes through the origin and is the best-fit trend line of the target points within the transfer zone. The ILT line represents the linear strand stress in the transfer zone (see Fig. 1).

Step 5: Determine the intersection of the 95% AMS line and the ILT line. Transfer length is the distance from the beam end to the intersection point.

DEVELOPMENT LENGTH MEASUREMENT

Table 3 summarizes the predicted transfer and development lengths using the ACI 318 equations and the nominal flexural capacity of 12 pretensioned concrete beams. The AASHTO [8] Refined method was used to predict prestress losses at 28 days. The effective strand stress ranged from $0.650f_{pu}$ to $0.688f_{pu}$ or 175.5 ksi to 185.8 ksi (1210 MPa to 1281 MPa). The strain compatibility method [31] was used to calculate f_{ps} (where f_{ps} is the average stress in prestressing strand at the time for which the nominal flexural resistance of the member is required). This value varied from $0.979f_{pu}$ to $0.989f_{pu}$ or 264.3 ksi to 267.1 ksi (1822 MPa to 1841 MPa). These stress values were used to calculate the predicted transfer and development lengths and the nominal flexural capacity.

Table 3 Strand stresses, predicted transfer and development lengths, and nominal moment capacity

Beam	f_{se} (ksi)	f_{ps} (ksi)	L_t *(in.)*	L_d *(in.)*	M_n (kip-in)
M10-S1 and M10-S2	181.6	266.0	42.4	101.4	683
M10-S3 and M10-S4	182.8	266.2	42.7	101.1	690
M10-S (Average)	*182.2*	*266.1*	*42.5*	*101.3*	*n.a.*
M12-S1 and M12-S2	185.8	267.0	43.4	100.2	714
M12-S3 and M12-S4	185.4	266.8	43.3	100.2	706
M12-S (Average)	*185.6*	*266.9*	*43.3*	*100.2*	*n.a.*
M12-D1 and M12-D2	175.5	264.4	41.0	103.1	1317
M12-D3 and M12-D4	175.7	264.3	41.0	103.0	1315
M12-D (Average)	175.6	264.4	*41.0*	*103.0*	*n.a.*

(Note: f_{se} = effective strand stress; f_{ps} = average stress in prestressing strand at the time for which the nominal flexural resistance of the member is required; L_t = transfer length; L_d = development length; M_n = nominal flexural capacity; n.a. = not applicable; 1 kip-in = 113 N-m; 1 ksi = 6.895 MPa)

Bending tests were used to determine development length of prestressing strands. A concentrated load was applied to the beam at a given distance from the beam end and the beam was testing until failure. This distance is defined as the embedment length of the prestressing strand. The determination of development length is an iterative procedure in which the beams are tested at different embedment lengths. During a bending test, the strand slippage, beam deflection at the loading position, and hydraulic pressure were continuously monitored as shown in Fig. 6. The bending test was stopped when the tested beam would not resist additional load.

The failure mode of a bending test is used to determine whether the tested embedment length is greater than the required development length. For the specimen which exhibits a flexural failure, the tested embedment length is equal to or greater than the required development length. The flexural failure is characterized by three requirements: (1) the maximum measured moment (M_{max}) is equal to or greater than the nominal flexural capacity (M_n) or $M_{max}/M_n \geq 1$, (2) the prestressing strand experiences no slippage before the specimen achieves the nominal flexural capacity or $M_{slip}/M_n \geq 1$ (where M_{slip} is the measured moment at which the prestressing strand exhibits an amount of slippage recorded using a linear variable differential transformer [LVDT]), and (3) the specimen shows a great deformation at failure. For the specimen which displays a bond failure, the tested embedment length is shorter than the required development length. The bond failure occurs when the prestressing strand begins slipping prior to the specimen achieves the nominal flexural capacity or $M_{slip}/M_n < 1$.

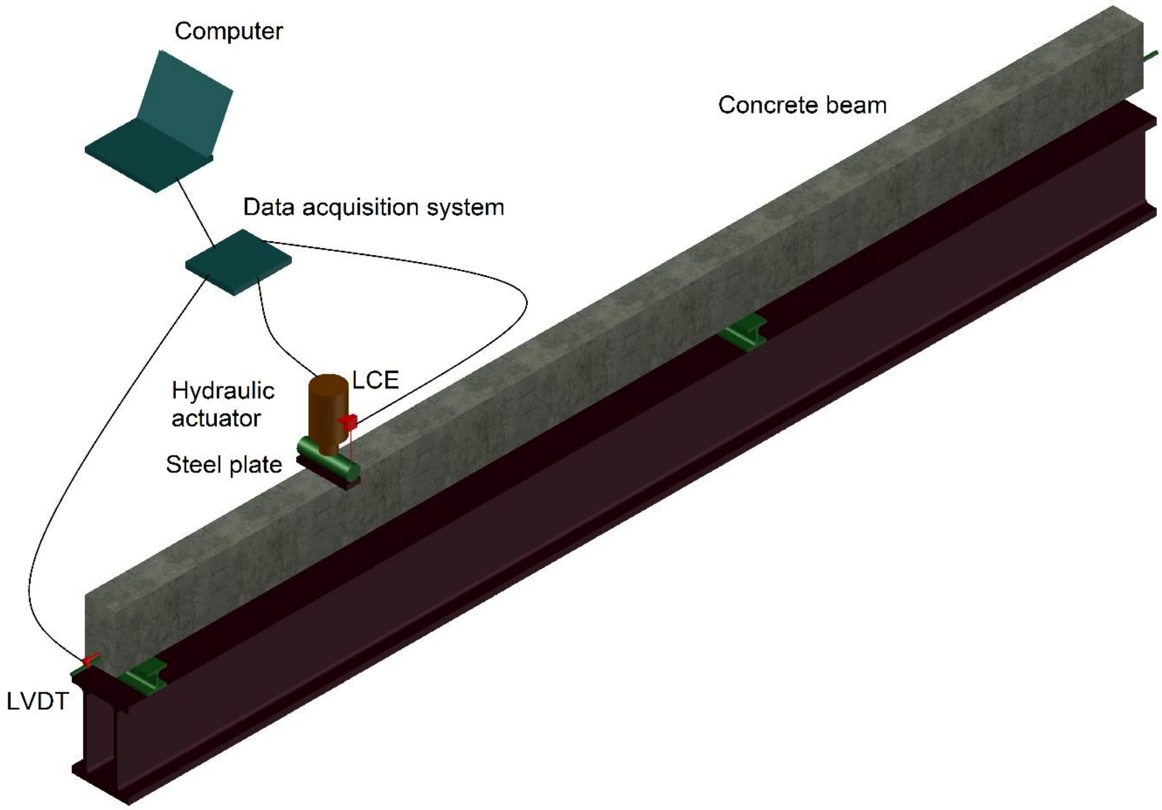

Fig. 6 Bending test frame. In this figure, the strand slippage is quantified using a LVDT. The beam deflection is measured automatically using a linear cable encoder (LCE) and manually using a steel ruler. The hydraulic pressure is monitored using a pressure transducer connected to the hydraulic system. These devices are connected to a data acquisition system which transferred the received data to a computer. (Note: LVDT = linear variable differential transformer)

Two bending tests were conducted at the two ends of a specific beam. The bending test performed at the live-end was identified as *L* and at the dead-end was identified as *D*. For a specific bending test, the relationships of the measured moment, strand slippage, and specimen deflection were plotted in one graph to determine the failure mode. Fig. 7 shows a typical bond failure of the M10-S1-D specimen. The measured moment reached 107% of M_n at failure, but the prestressing strand began slipping when the specimen achieved 93% of M_n. The figure indicates that the M10-S1-D specimen gained 14% of M_n after the prestressing strand began slipping. However, this was not representative of all the tested specimens. Several specimens were unable to resist additional load after the prestressing strand slipped while the others failed instantly when the strand began slipping. In summary, after the prestressing strand had slipped, the behaviors of the specimens were dependent upon the location at which cracks occurred and propagated.

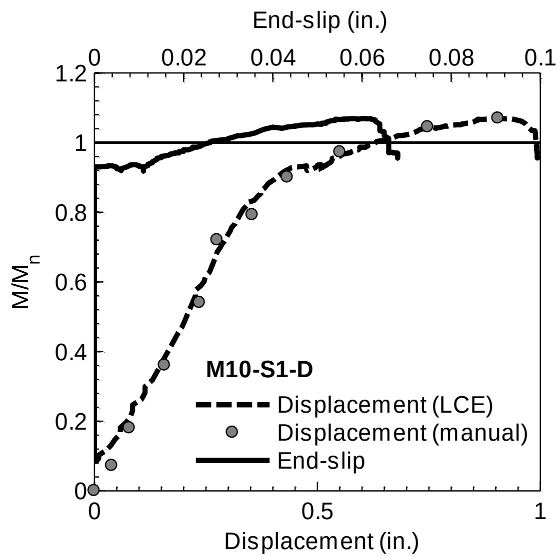

Fig. 7 Bending test results of the M10-S1-D specimen when tested at an embedment length of 3.25 ft (990 mm). In this figure, the dashed-line represents the relationship of M/M_n and the specimen deflection measured using the LCE. The gray dots are similar to the dashed-line, but the deflection was measured using a steel ruler. The solid-line represents the relationship of M/M_n and strand slippage. (Note: M = measured moment; M_n = nominal flexural capacity; 1 in. = 25.4 mm)

TESTING RESULTS AND DISCUSSION

TRANSFER LENGTH RESULTS

Fig. 8 presents the measured transfer lengths of the three beam groups: M10-S (a group of four beams cast with the M10 concrete mixture and one prestressing strand), M12-S (a group of four beams cast with the M12 concrete mixture and one prestressing strand), and M12-D (a group of four beams cast with the M12 concrete mixture and two prestressing strands). There was no significant difference in the measured transfer lengths at the live-end and at the dead-end. The use of gradually detensioning technique was the most likely reason for the similarity in the measured transfer lengths. The detensioning process involved reducing the pressure in the hydraulic system, and consequently the prestress was gradually transferred to the concrete. This technique reduces the shock of prestress transfer and minimizes the damage to the bond strength at the live-end of the pretensioned concrete beams. Researchers have determined that the gradually detensioning technique is suitable for small PCMs while the flame-cut technique is more appropriate for large PCMs [13, 27].

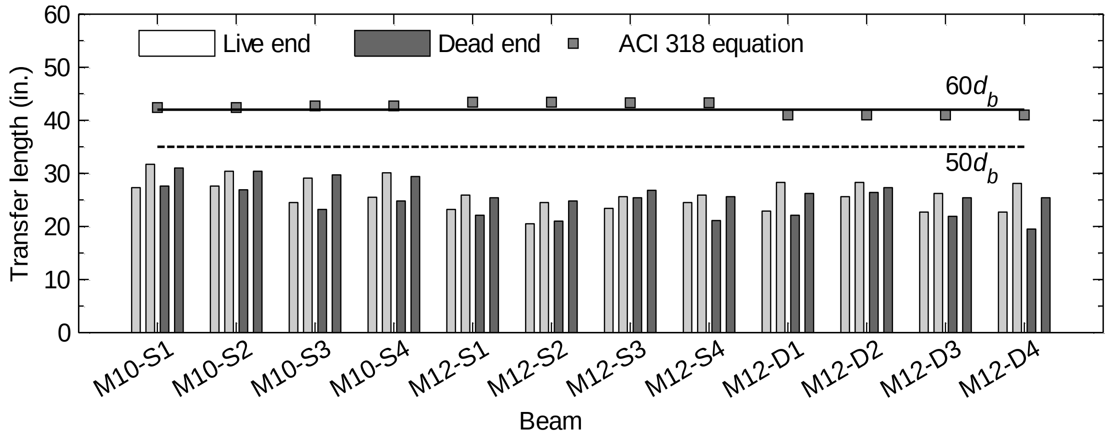

Fig. 8 Measured transfer lengths at release and at 28 days. For a specific beam, the first two columns represent the measured transfer lengths at the live-end, and the remaining two columns represent the measured transfer lengths at the dead-end. For a specific beam end, the first and the second columns represent the measured transfer lengths at release and at 28 days, respectively. The solid- and dashed- lines represent the ACI equation of 50d_b and the AASHTO equation of 60d_b, respectively. (Note: d_b = strand diameter; 1 in. = 25.4 mm)

In Fig. 8, the measured transfer lengths at release varied from 19.5 in. to 27.6 in. (500 mm to 700 mm) and those at 28 days varied from 24.5 in. (625 mm) to 31.7 in. (805 mm). These values are shorter than the predicted transfer lengths using the ACI 318 equation of 50d_b (35 in. [890 mm]), the AASHTO equation of 60d_b (42 in. [1070 mm]), or the first term of Eq. (1). The predicted transfer lengths using the first term of Eq. (1) are similar to those using the AASHTO equation because the effective strand stresses at 28 days are approximately equal to 180 ksi (1242 MPa). It was determined at the ACI 318 equation of 50d_b provides a better prediction than the other equations.

For each beam group, the measured transfer lengths at release and at 28 days were assumed to be normally distributed. Least squares estimation was used to calculate the lower bounds and upper bounds of the measured transfer lengths with a confidence interval of 95%. Fig. 9 indicates that the ACI 318 and AASHTO equations are applicable to predict transfer lengths of 0.7 in. (17.8 mm) at release and at 28 days with a confidence interval of 95%. In addition, the use of 0.7 in. (17.8 mm) strands at a spacing of 2.0 in. (51 mm) had no effect on the measured transfer lengths. As shown in Fig. 9, the measured transfer lengths at release and at 28 days for the M12-S and M12-D beams have no significant difference.

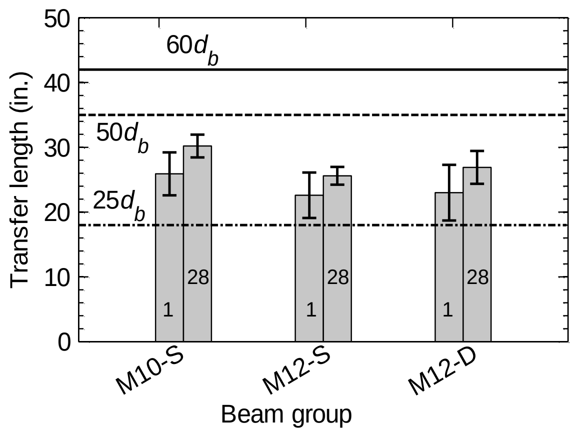

Fig. 9 Statistical analysis of the measured transfer lengths at release (1 day) and 28 days. In the figure, the columns represent the average values, and the error bars represent the upper bounds and the lower bounds of the measured transfer lengths. The number in each column indicates the time at which transfer lengths were measured. The solid- and dashed- lines represent the ACI and AASHTO equations, respectively. The dash-dot line represents the proposed lower limit of transfer length. (Note: d_b = strand diameter; 1 in. = 25.4 mm).

Fig. 9 shows that the ACI equation of 50d_b provides a conservative prediction for the upper bounds of the measured transfer lengths. While an upper limit of transfer length is essential to compute shear strength and moment capacity, a lower limit is necessary for preventing unexpectedly high stresses near the end of the transfer zone at release of the prestressing strands [3, 5]. As shown in the figure, a transfer length of 25d_b adequately predicts the lower bounds of the measured transfer lengths with a confidence interval of 95%. While it is not necessary to propose a new equation for predicting transfer length of 0.7 in. (17.8 mm) strands, the researchers propose to adopt a lower limit of transfer length of 25d_b for checking allowable stresses at release.

DEVELOPMENT LENGTH RESULTS

M10-S Beams

The bending test results of the M10-S beams are shown in Fig. 10. The M10-S4-L specimen exhibited a flexural failure without strand slippage when tested at an embedment length of 4 ft (1220 mm). Three other specimens including M10-S4-D, M10-S3-L, and M10-S3-D were tested at a shorter embedment length of 3.5 ft (1070 mm). The first specimen exhibited a bond failure while the two latter specimens experienced flexural failures. The relationship of strand slippage and moment of the M10-S4-D specimen shown in Fig. 11 indicates that the prestressing strand slipped as the specimen achieved 92% of M_n. The specimen was able to gain 10% of M_n after the prestressing strand began slipping and failed when the strand slippage reached 0.05 in. (1.3 mm). This specimen failed because of a shear crack which developed from the end of the transfer zone and went toward to the concentrated load.

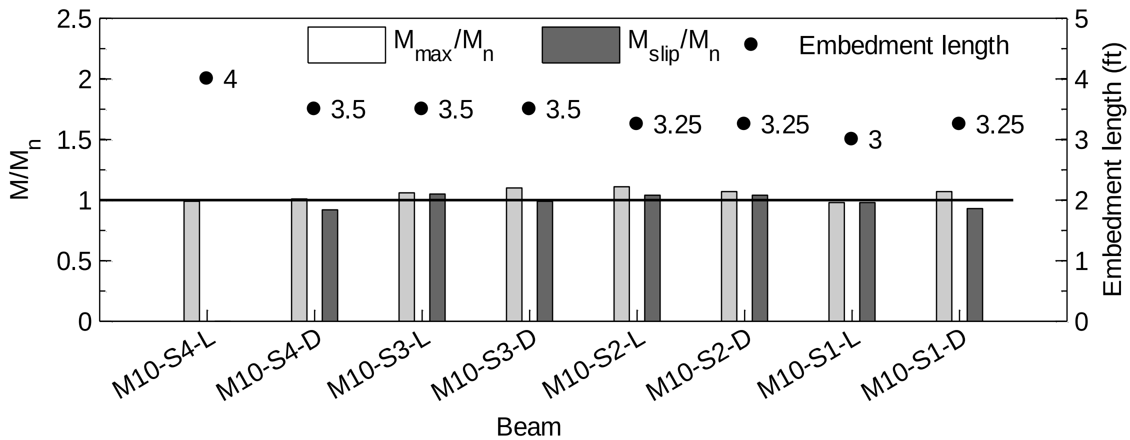

Fig. 10 Bending test results of the M10-S beams. (Note: M_{max} = maximum measured moment; M_{slip} = measured moment at which the prestressing strands began slipping; M_n = nominal flexural capacity; 1 ft = 305 mm).

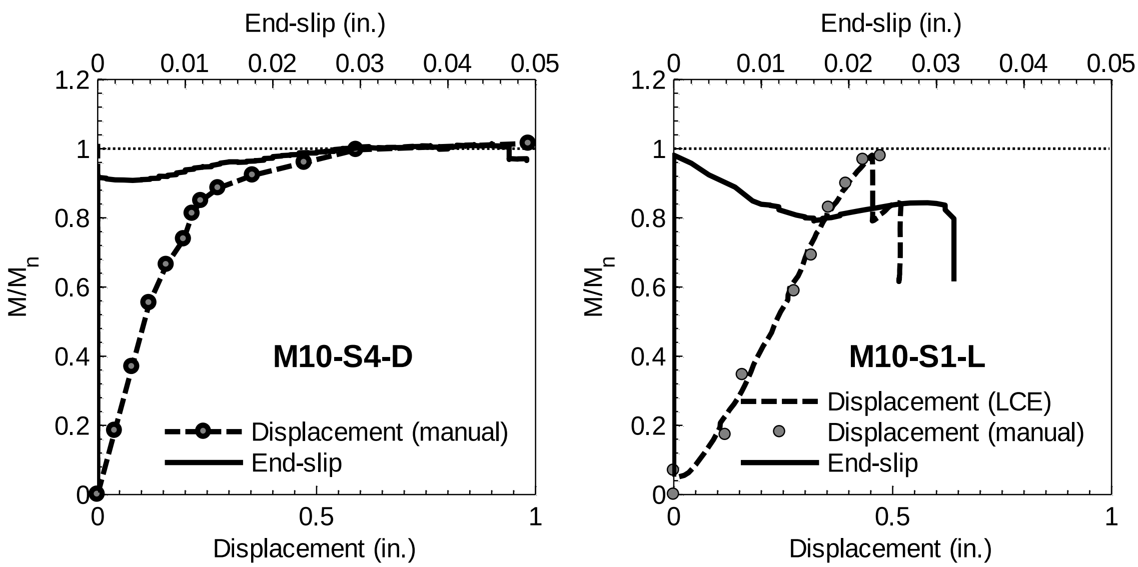

Fig. 11 Bending test results of the M10-S4-D and M10-S1-L specimens when tested at embedment lengths of 3.5 ft (1070 mm) and 3 ft (915 mm), respectively. (Note: 1 in. = 25.4 mm).

Three other specimens including M10-S2-L, M10-S2-D, and M10-S1-D were tested at a shorter embedment length of 3.25 ft (990 mm). These specimens showed similar results to the specimens tested at an embedment length of 3.5 ft (1070 mm). In particular, two out of three specimens exhibited flexural failures, and one specimen showed a bond failure. In addition, the M10-S1-L specimen almost met the flexural failure requirements excluding the ductile behavior when tested at an embedment length of 3 ft (915 mm). This specimen reached 98% of M_n at failure, and the prestressing strand also began slipping at 98% of M_n as shown in Fig. 11. However, the moment curve rapidly dropped when a shear crack that occurred within the transfer zone. The occurrence of this crack locally increases the tensile stress in the prestressing strand at the cracking position and consequently reduces the bond strength generated by the Hoyer's effect [6]. Therefore, the M10-S1-L specimen was unable to exhibit a ductile behavior and resist additional load.

In summary, the required development length was possibly in the range of 4.0 ft to 3.5 ft (1220 mm to 1070 mm). The specimen which was tested at an embedment length of 4 ft (1220 mm) exhibited a flexural failure without strand slippage. One out of three specimens which were tested at an embedment length of 3.5 ft (1070 mm) displayed a bond failure. Therefore, it was determined that the required development length of the M10-S beams was 4 ft (1220 mm).

M12-S Beams

The bending tests of the M12-S beams shown in Fig. 12 displayed similar results when tested at different embedment lengths. The M12-S4-D and M12-S3-D specimens experienced flexural failures without strand slippage when tested at an embedment length of 4.25 ft (1295 mm). For a shorter embedment length of 4 ft (1220 mm), three other specimens including M12-S4-L, M12-S3-L, and M12-S2-L also exhibited flexural failures. In particular, the bending test of the M12-S4-L specimen achieved M_{max}/M_n ratio of 1.03, and the prestressing strand slipped at 102% of M_n as shown in Fig. 13. These results indicated that the required development length was close to the tested embedment length of 4 ft (1220 mm). The M12-S4-L specimen failed because of a major flexural crack occurring beneath the concentrated load, and there was no visible crack within the transfer zone.

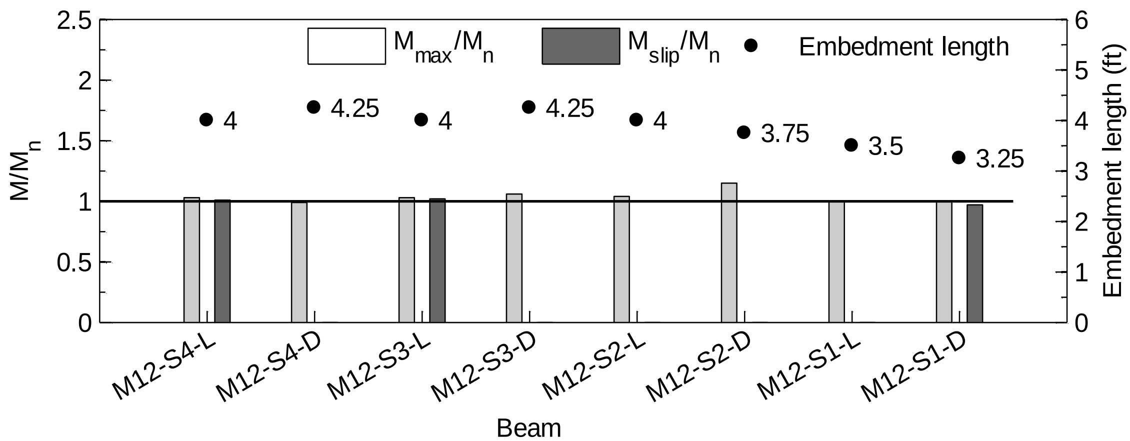

Fig. 12 Bending test results of the M12-S beams. (Note: M_{max} = maximum measured moment; M_{slip} = measured moment at which the prestressing strands began slipping; M_n = nominal flexural capacity; 1 ft = 305 mm.).

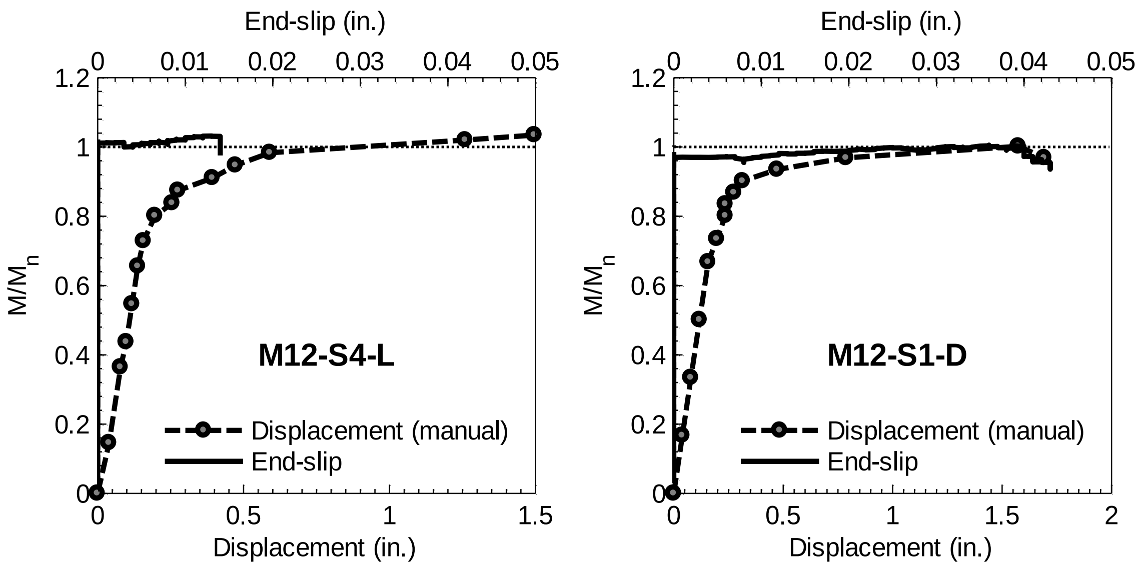

Fig. 13. Bending test results of the M12-S4-L and M12-S1-D specimens when tested at embedment lengths of 4 ft (1220 mm) and 3.25 ft (990 mm), respectively. (Note: 1 in. = 25.4 mm).

The following bending tests were conducted at shorter embedment lengths to determine the required development length for the M12-S beams. The M12-S2-D and M12-S1-L specimens experienced flexural failures without strand slippage when tested at embedment lengths of 3.75 ft (1145 mm) and 3.5 ft (1070 mm), respectively. In addition, the bending test of the M12-S1-D specimen showed similar results to the M10-S1-L specimen when tested at an embedment length of 3.25 ft (990 mm). This specimen was able to achieve M_n at failure, and the prestressing strand slipped at 97% of M_n as shown in Fig. 13. Although this specimen almost reached the three requirements of a flexural failure, its failure mode was identified as a bond failure for conservatism in determining the required development length.

In summary, all the specimens which were tested at an embedment length of 3.5 ft (1070 mm) or greater met the flexural failure requirements. Therefore, the required development length for the M12-S beams was 3.5 ft (1070 mm).

M12-D Beams

The bending tests of the M12-D beams shown in Fig. 14 were conducted at embedment lengths varying from 4.5 ft (1370 mm) to 3.5 ft (1060 mm). As shown in the figure, all the specimens which were tested at embedment lengths equal to or greater than 4 ft (1220 mm) exhibited flexural failures. These specimens included M12-D4-L, M12-D4-D, M12-D1-L, and M12-D1-D. The test results of these specimens indicated that the required development length was possibly shorter than the tested embedment length of 4 ft (1220 mm) because the prestressing strands had no slippage in all bending tests.

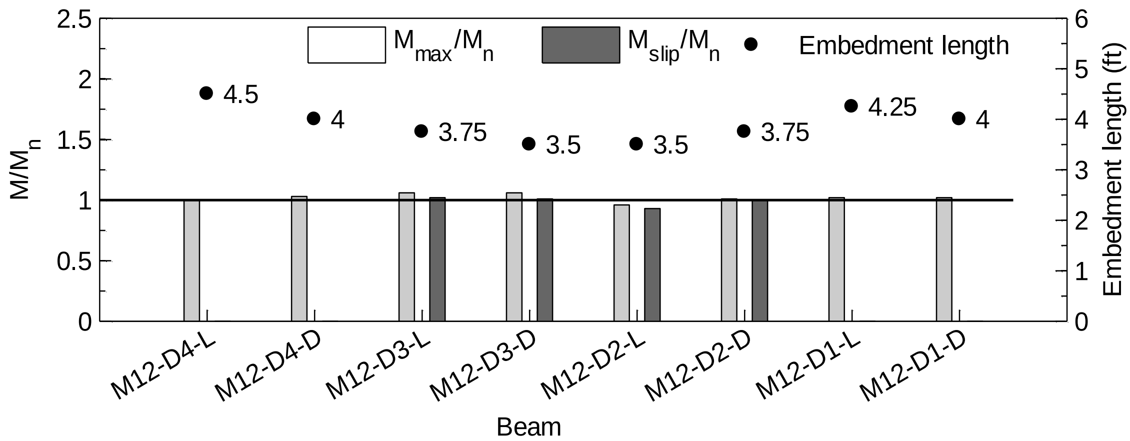

Fig. 14 Bending test results of M12-D beams. (Note: M_{max} = maximum measured moment; M_{slip} = measured moment at which the prestressing strands began slipping; M_n = nominal flexural capacity; 1 ft = 305 mm).

Four other specimens were tested at shorter embedment lengths. The M12-D3-L and M12-D2-D specimens experienced flexural failures when tested at an embedment length of 3.75 ft (1145 mm). The M12-D3-L specimen failed at 106% of M_n, and the prestressing strands began slipping when the measured moment reached 102% of M_n. For the M12-D2-D specimen, the prestressing strands slipped instantly when the specimen achieved M_n, and the specimen failed at 101% of M_n as shown in Fig. 15. These results indicated the required development length was very close to the tested embedment length of 3.75 ft (1145 mm).

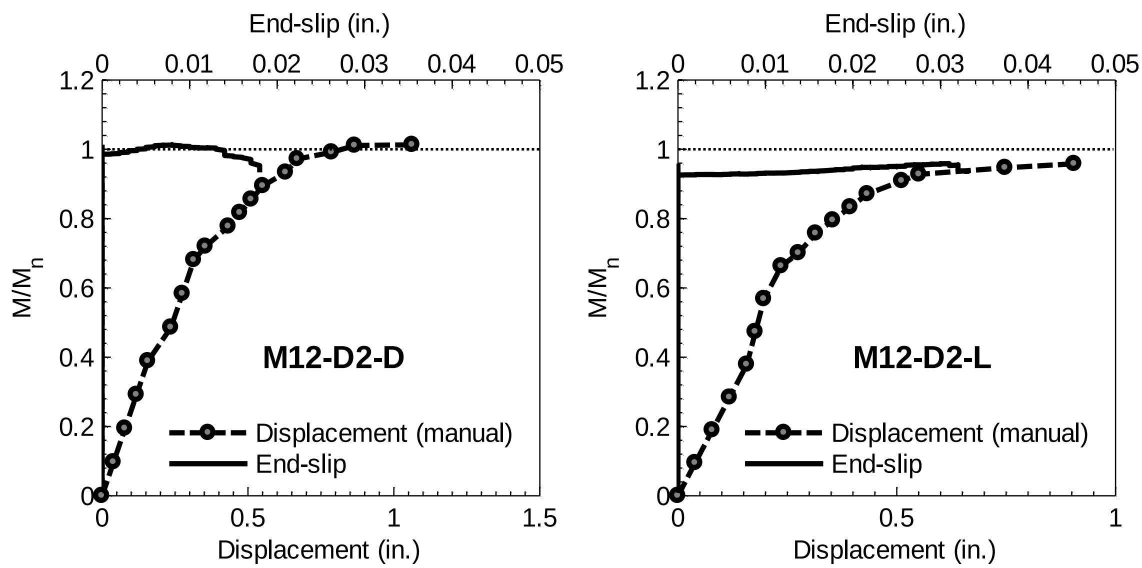

Fig. 15 Bending test results of the M12-D2-D and M12-D2-L specimens when tested at embedment lengths of 3.75 ft (1145 mm) and 3.5 ft (1070 mm), respectively. (Note: 1 in. = 25.4 mm).

The embedment length was reduced to determine whether the required development length was 3.75 ft (1145 mm). The M12-D3-D and M12-D2-L specimens showed different results when tested at a shorter embedment length of 3.5 ft (1060 mm). The M12-D3-D specimen displayed a flexural failure while the M12-D2-L specimen exhibited a bond failure in which the prestressing strands slipped when the specimen achieved 93% of M_n as shown in Fig. 15. These results indicated the required development length was greater than the tested embedment length of 3.5 ft (1060 mm). After the prestressing strands had slipped, the specimen was unable to resist additional load and failed when the strand slippage reached 0.03 in. (0.8 mm).

In summary, all bending tests which were conducted at embedment lengths equal to or greater than 3.75 ft (1145 mm) exhibited flexural failures. Accordingly, it was determined that the required development length of the M12-D beams was 3.75 ft (1145 mm) which is equivalent to 44% of the predicted development length using the ACI 318 equation. The required development length of the M12-D beams was slightly greater than the M12-S beams because of the effect of using a strand spacing of 2.0 in. (51 mm). Therefore, the use of 0.7 in. (17.8 mm) strands at a spacing of 2.0 in. (51 mm) had minimal effect on the measured development lengths.

SUMMARY AND CONCLUSIONS

This study measured transfer and development lengths of 0.7 in. (17.8 mm) strands for 12 pretensioned concrete beams cast with two high-strength concrete mixtures. The M10 mixture had average compressive strengths of 6.3 ksi (43.4 MPa) at 1 day of age and 9.5 ksi (65.5 MPa) at 28 days of age. The M12 mixture had average compressive strengths of 9.5 ksi (65.5 MPa) at 1 day of age and 13.1 ksi (90.3 MPa) at 28 days of age. The STSB tests were used to quantify the strand surface conditions according to ASTM A1081. The measured STSB value was 36.73 kips (163.4 kN) which is 150% and 80% greater than the acceptance critiaria proposed by Morcous et al. [20] and those adopted from Polydorou [19], respectively.

Four pretensioned concrete beams (M12-D beams) which consisted of two 0.7 in. (17.8 mm) strands placed at a spacing of 2.0 in. (51 mm) were cast using the M12 mixture. This concrete mixture was used to cast another 4 beams (M12-S beams) which contained one 0.7 in. (17.8 mm) strand to create the comparable data with the first 4 beams. The last four beams (M10-S beams) were similar to the M12-S beams but these beams were cast using the concrete having a lower compressive strength. Through this experimental program, the researchers investigated the effects of strand spacing and concrete compressive strength on transfer length and development length. Based on the experimental results, the following conclusions were made:

1. The STSB value of 0.7 in. (17.8 mm) strands used in this study was significantly greater than existing acceptance criteria proposed or adopted from different researchers. This confirmed that the strands are suitable for use in precast/prestressed concrete applications.
2. The use of high-strength concrete can shorten transfer and development lengths. The average, measured transfer lengths at release and at 28 days of the M12-S beams were 14%

and 18% less than the M10-S beams, respectively. The measured development length of the M12-S beams was 0.5 ft (150 mm) less than the M10-S beams.
3. The average, measured transfer lengths varied from 22.6 in. to 26.2 in. (575 mm to 665 mm) at release and from 25.6 in. to 28.0 in. (650 mm to 710 mm) at 28 days. Transfer lengths increased from 13% to 17% for the first 28 days after casting concrete.
4. The ACI equation of $50d_b$ provides a conservative prediction for the upper bounds of the measured transfer lengths. It was proposed to adopt a transfer length of $25d_b$ as the lower limit for preventing unexpectedly high stresses at the end of the transfer zone.
5. The measured development lengths for the three beam groups varied from 3.5 ft to 4 ft (1060 mm to 1220 mm) which are approximately by 42% to 48% of the predicted development length using the ACI 318 equation. The use of high-strength concrete and the prestressing strands having a high STSB value accounts for the overestimation of the ACI 318 equation.
6. The use of 0.7 in. (17.8 mm) strands at a spacing of 2.0 in. (51 mm) which is equivalent to $2\frac{7}{8}d_b$ had no effect on the measured transfer lengths and minimal effect on the measured development lengths. There was no significant difference in the measured transfer lengths of the M12-S and M12-D beams at release and at 28 days. The measured development length of the M12-D beams was slightly greater than the M12-S beams.
7. The ACI 318 and AASHTO specifications are applicable to predict transfer length and development length of 0.7 in. (17.8 mm) strands placed at a spacing of 2.0 in. (51 mm) for pretensioned concrete beams using high-strength concrete.

RECOMMENDATIONS

The following recommendations are drawn from the experimental results in this study:
1. More research is needed to evaluate the strand bond performance of 0.7 in. (17.8 mm) strands. This is a critical factor affecting the applicability of current bonding equations and the safety of using 0.7 in. (17.8 mm) strands in bridge construction. The STSB is a reliable test to assess the strand bond, and the proposed acceptance criteria in the literature should be further validated.
2. The applicability of using a strand spacing of 2.0 in. (51 mm) should be further investigated. The testing of full-scale girders which contain a number of prestressing strands and different amounts of confinement reinforcement would provide useful data for evaluating the strand spacing.
3. Further testing is needed to investigate the suitability of using 0.7 in. (17.8 mm) strands with normal-strength concrete. It is necessary to determine the concrete release strength for properly detensioning 0.7 in. (17.8 mm) strands without compromising the structural performance of the pretensioned concrete members.

ACKNOWLEDGEMENTS

The authors would like to thank Insteel Industries Inc. for providing the strands and the RJ Peterman & Associates, Inc. for conducting the STSB tests for this research. The authors would like to thank Mr. Don Logan for providing the financial support to conduct the STSB tests. The authors are also very thankful to Richard Deschenes Jr., Cameron Murray, Joseph Daniels III, William Phillips, Doddridge Davis, Alberto Ramirez, and Ryan Hagedorn for helping cast the beams at the Engineering Research Center at the University of Arkansas.

NOTATION

The following symbols are used in this paper:

d_b = strand diameter;
L_t = transfer length;
L_d = development length;
f_{se} = effective stress in the prestressing steel after losses;
f_{ps} = is average stress in prestressing steel at the time for which the nominal flexural resistance of the member is required;
f_{pu} = ultimate strength of prestressing strand;
f'_{ci} = concrete compressive strength at 1 day of age;
f'_c = concrete compressive strength at 28 days of age;
f'_{ct} = concrete compressive strength at the time of conducting bending tests;
M = measured moment;
M_n = nominal flexural capacity;
M_{max} = maximum measured moment; and
M_{slip} = measured moment at which the prestressing strands began slipping

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