Spacing requirements of 0.7 in. (18 mm) diameter prestressing strands

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- The use of 0.7 in. (18 mm) diameter strands for pretensioned concrete girders is advantageous when increasing the flexural capacity and extending girder spans.
- This study measures transfer and development lengths and evaluates the applicability of using a strand spacing of 2.0 in. (51 mm) for 16 pretensioned, high-strength, conventional concrete or self-consolidating concrete beams using greater diameter strands.
- The experimental results indicate that the current ACI 318-14 and AASHTO LRFD specifications overestimate the measured transfer and development lengths for these beams.

Pretensioned concrete members are widely used in the construction of bridges, buildings, and parking structures. The number of prestressing strands placed in a pretensioned concrete member directly affects its flexural capacity. In fact, the number of prestressing strands that can be placed depends on the strand spacing.[1] If the prestressing strands are placed far apart, the pretensioned concrete member can only accommodate 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 be cracked. This may cause the required transfer and development lengths to be greater than the predicted values using the current specifications, producing an unsafe design. In the design of pretensioned concrete members, transfer length and development length are parameters necessary to evaluate the members' structural performance.[2–4] Transfer length is the required length for the prestressing strand to transfer the effective prestress to the concrete. Development length is the required length for the pretensioned concrete member to achieve the nominal flexural capacity at which the prestressing strands exhibit no slip.

In 1963, American Concrete Institute (ACI) Committee 318[5] proposed a minimum strand spacing of $4d_b$ (where d_b is the strand diameter) center to center for strand diameters varying from ⅜ to 0.5 in. (10 to 13 mm). For example, the minimum spacing of 0.5 in. strands was 2.0 in. (51 mm). Accordingly, transfer length and development length were predicted using Eq. (1) to (2) and Eq. (3) to (4), respectively. In 1988, the Federal Highway Administration (FHWA) issued a memorandum that prohibited the use of 0.6 in. (15 mm) diameter strands when this type of strand was first used in construction. The FHWA also included a multiplier of 1.6 in the development-length equation as a safety factor. The multiplier was added when researchers reported that the measured development lengths were greater than the predicted values for several pretensioned concrete members.[6,7] The strand spacing requirement of $4d_b$ remained unchanged until 1996, when the FHWA made a number of changes to accommodate the use of 0.6 in. diameter strand in the codes.[7] These changes included the reduction in the minimum strand spacing of 0.5 in. diameter strand to 1.75 in. (44.4 mm), which is equivalent to $3\frac{1}{2}d_b$, and the establishment of a minimum strand spacing of 2.0 in. for 0.6 in. diameter strands, which is equivalent to $3\frac{1}{3}d_b$.

These changes to strand spacing requirements were adopted by ACI 318-14[8] without modifying the transfer-length L_t (Eq. [1] and [2]) and development-length L_d (Eq. [3] and [4]) equations:

$$L_t = \frac{1}{3} f_{se} d_b \quad (f_{se} \text{ in ksi}) \tag{1}$$

$$L_t = \frac{1}{20.7} f_{se} d_b \quad (f_{se} \text{ in MPa}) \tag{2}$$

where

f_{se} = effective stress in prestressing steel after losses

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

$$L_d = \tfrac{1}{20.7} f_{se} d_b + \tfrac{1}{6.9}\left(f_{ps} - f_{se}\right) d_b \quad (f_{se} \text{ and } f_{ps} \text{ in MPa}) \tag{4}$$

where

f_{ps} = average stress in prestressing steel at the time for which the nominal flexural capacity of member is required

ACI 318-14 provides an alternative equation of $50d_b$ to estimate transfer length. The American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[9] also adopted the changes to the strand spacing requirements. However, the AASHTO LRFD specifications propose a transfer length of $60d_b$. For development length, the AASHTO LRFD specifications retained the multiplier of 1.6 in the development-length equation (Eq. [3]–[4]) for pretensioned concrete members having a depth equal to or greater than 24 in. (610 mm). Otherwise, the AASHTO LRFD specifications development-length equation is identical to the ACI 318-14 equation. A number of research projects have confirmed the adequacy of using the proposed strand spacing along with the existing transfer- and development-length equations. Cousins et al.[1] and Deatherage et al.[10] determined that the use of a strand spacing of 1.75 in. (44.4 mm) for 0.5 in. (13 mm) strands has no effect on transfer and development lengths and results in no splitting cracks. The sufficiency of using 0.6 in. (15 mm) strands at a spacing of 2.0 in. (51 mm) was confirmed by a number of studies.[11–15] In addition, Kose and Burkett[16] and Andrawes et al.[17] determined that the use of the multiplier of 1.6 in the AASHTO LRFD specifications[9] development-length equation is unnecessary when predicting development length for pretensioned concrete I-girders. The contemporary concerns are the applicability of the existing transfer- and development-length equations and a minimum strand spacing for 0.7 in. (18 mm) diameter strands.

Literature review

In the United States, 0.7 in. (18 mm) diameter, Grade 270 (1860 MPa), low-relaxation prestressing strands have been used since 2008.[22] The prestressing force of a 0.7 in. diameter strand is 35% greater than that of a 0.6 in. (15 mm) diameter strand. The use of 0.7 in. diameter strands can enhance shear strength and moment capacity, extend girder span,[22,24] or reduce the number of required prestressing strands in a pretensioned concrete member.[24] The Pacific Street Bridge and the Oxford South Bridge in Nebraska were the first two bridges in which 0.7 in. diameter prestressing strands were used in pretensioned concrete bridge girders.[4] The current ACI 318-14 and AASHTO LRFD specifications regarding transfer length, development length, and strand spacing are only valid for 0.5 in. (13 mm) diameter and 0.6 in. diameter strands. A limited number of studies[18–20] have examined these parameters along with the mechanical properties and surface conditions of the strands used for the two bridges in Nebraska and for research recommendations.

The Pacific Street Bridge consisted of twenty 98 ft 4 in. long (30.0 m) NU900 pretensioned concrete girders. Each girder contained thirty 0.7 in. (18 mm) diameter, Grade 270 (1860 MPa) prestressing strands that were tensioned to $0.64f_{pu}$ (where f_{pu} is the ultimate strength of prestressing strand) and placed at a spacing of 2.0 × 2.5 in. (51 × 64 mm).[21] Transfer and development lengths of these girders were not reported. However, one NU900 girder was tested for the Pacific Street Bridge project.[22] The tested girder contained twenty-four 0.7 in. diameter prestressing strands that were tensioned to $0.75f_{pu}$ and placed at a spacing of 2.2 × 2.25 in. (56 × 57 mm). The concrete had compressive strengths of 6.7 ksi (46 MPa) at 1 day and 8.0 ksi (55 MPa) at 28 days. 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 (4.3 m), which was predicted using the AASHTO LRFD specifications equation.

The Oxford South Bridge consisted of 20 NU1350 pretensioned concrete girders, which included 16 girders having a span of 110 ft (33.5 m) and 4 girders having a span of 140 ft (42.7 m).[4] The shorter girder contained twenty-four 0.7 in. (18 mm) diameter prestressing strands that were tensioned to $0.75f_{pu}$ and placed at a spacing of 2.0 × 2.0 in. (51 × 51 mm). These parameters are currently used for 0.6 in. (15 mm) diameter strands.[8,9] The self-consolidating concrete (SCC), which had compressive strengths of 6.0 ksi (41 MPa) at 1 day and 8.0 ksi (55 MPa) at 28 days, was used to cast the shorter girders. The average measured transfer lengths at release and 14 days for the three girder ends were 32 in. (813 mm) and 36 in. (914 mm), respectively, which were approximately equal to the predicted transfer length using the ACI 318-14 equation. The development length was not reported.

Other researchers have also evaluated the sufficiency of using 0.7 in. (18 mm) diameter strands for pretensioned concrete members. Patzlaff et al.[23] measured the transfer lengths for eight T girders in which the prestressing strands were tensioned to $0.75f_{pu}$ and placed at a spacing of 2.0 × 2.0 in. (51 × 51 mm). The average measured transfer length was 23.3 in. (592 mm), which is shorter than the predicted transfer lengths using the ACI 318-14 or AASHTO LRFD specifications equations. Several flexure tests were conducted to evaluate the development length for the eight T girders and three other NU1100 girders. The test results indicated that the AASHTO LRFD specifications equation is adequate to predict the development length of 0.7 in. diameter strands. Song et al.[24] had a similar conclusion regarding the transfer length that was measured for one AASHTO LRFD specifications Type I girder. Morcous et al.[22] and Maguire et al.[25] investigated the performance of 0.7 in. diameter strands in pretensioned concrete members in which the strands were tensioned to low prestress due to the limited capacity of the prestressing bed. This is one of the most pressing issues with using 0.7 in. diameter strands at a spacing of 2.0 × 2.0 in.

Determining the required concrete compressive strength at release is one of the main concerns of using 0.7 in. (18 mm) diameter strands at a spacing of 2.0 × 2.0 in. (51 × 51 mm). Experimental results in the literature indicate that the transfer length of 0.7 in. diameter strands at release is 19.5 in. (495 mm) for pretensioned concrete members using a concrete compressive strength at release of 8.7 ksi (60 MPa).[23] The use of concrete having a compressive strength at release of 6.0 ksi (41 MPa) results in a greater transfer length of 32 in. (813 mm), which is less than the predicted values using the ACI 318-14 or AASHTO LRFD specifications equations.[4] An analytical investigation conducted by Arab,[26] however, determined that 0.7 in. diameter strands can be used at a spacing of 2.0 × 2.0 in. if the concrete compressive strength at release is equal to or greater than 10 ksi (69 MPa).

In summary, a number of transfer and development lengths of 0.7 in. (18 mm) diameter strands were reported for pretensioned concrete members having a depth equal to or greater than 24 in. (610 mm). The strand spacing varied, as did the level of prestress. In addition, researchers have come to different conclusions regarding the minimum concrete compressive strength for adequately detensioning the prestressing strands. Additional research is needed to determine the transfer and development lengths for beams having a depth less than 24 in. to address the applicability of using 0.7 in. diameter strands at a spacing of 2.0 in. (51 mm) and to determine the necessary concrete release strength.

Objectives

This study investigates the applicability of using a strand spacing of 2.0 in. (51 mm) for 0.7 in. (18 mm) diameter strands. The strand surface conditions were first evaluated using simple pull-out tests. Sixteen pretensioned concrete beams were then cast with high-strength conventional concrete or high-strength SCC. The beams contained either one or two strands using 2.0 in. spacing. Transfer lengths were measured at release and at 28 days. Development lengths were determined by conducting bending tests at different embedment lengths. A number of recommendations regarding transfer length, development length, strand spacing, and minimum concrete release strength are made.

Experimental procedures

Concrete proportioning

This study focused on using high-strength concrete (HSC), which has a compressive strength at 28 days equal to or greater than 10 ksi (69 MPa). The use of HSC would further the advantages of the large-diameter strand to make more durable bridges.[27] Two mixtures were designed: conventional HSC (specimens designated as H-CC), which had a targeted compressive strength of 12 ksi (83 MPa), and high-strength SCC (specimens designated as H-SCC), which had a targeted compressive strength of 10 ksi. In addition, the designed mixtures were developed to have a compressive strength at release equal to or greater than 7.6 ksi (52 MPa). The targeted concrete compressive strength at release was based on the AASHTO LRFD specifications. AASHTO LRFD specifications require the compressive stress limit in the concrete immediately after transfer not to exceed $0.6\, f'_{ci}$ (where f'_{ci} is the concrete compressive strength at release, which is at 1 day in this study). **Table 1** shows the mixture proportions.

Table 1. Concrete mixtures and beam designations

Material or parameter	H-CC	H-SCC
Cement, lb/yd^3	700	825
Coarse aggregate, lb/yd^3	1678	1406
Fine aggregate, lb/yd^3	1454	1392
Water, lb/yd^3	245	330
Water/cement ratio	0.35	0.4
Slump, in.	9 to 10	n/a
Slump flow, in.	n/a	22 to 25
T_{20} (T_{500}), sec	n/a	2 to 4
Slump flow: J-ring, in.	n/a	1.0 to 1.5
Visual stability index	n/a	1
Designation of the beams using section I	H-CC-S1 to H-CC-S4	H-SCC-S1 to H-SCC-S4
Designation of the beams using section II	H-CC-D1 to H-CC-D4	H-SCC-D1 to H-SCC-D4

Note: H-CC = specimens made of high-strength concrete; H-SCC = specimens made of high-strength self-consolidated concrete; n/a = not applicable; T_{20} (T_{500}) = time required to achieve slump flow of 20 in. 1 in. = 25.4 mm; 1 lb/yd^3 =0.593 kg/m^3.

The high-strength SCC mixture was selected for two reasons. First, the fresh high-strength SCC possesses advanced properties compared with conventional concrete. The fresh high-strength SCC can flow through narrow areas and congested reinforcement sections without needing mechanical vibration. The hardened high-strength SCC properties are comparable to or better than those of the conventional concrete. Second, high-strength SCC is widely used and is partially replacing conventional concrete in construction.[28] A combination of high-strength SCC and 0.7 in. (18 mm) diameter strands would offer unique benefits in bridge construction.

Several tests were conducted to evaluate the filling ability,[29] passing ability,[30] and stability[29] of the high-strength SCC. Table 1 summarizes the test results. In particular, the slump flow varied from 22 to 25 in. (560 to 640 mm), which was slightly less than the recommended range of 23.5 to 29.0 in. (600 to 740 mm) for SCC in precast, prestressed concrete applications.[31] The T_{20} (T_{500}), which is the time required to achieve a slump flow of 20 in. (500 mm), and J-ring test results showed good agreement with the recommended thresholds of 1.5 to 6.0 seconds and 0 to 3 in. (75 mm), respectively. For the segregation resistance, the visual stability index was 1, which indicates that the fresh high-strength SCC showed no evidence of segregation and little to no evidence of bleeding.

Table 2 shows concrete compressive strengths at 1 day, at 28 days, and at the time the bending tests were conducted. The concrete compressive strengths at 1 day were greater than the required compressive strength of 7.6 ksi (52 MPa) as mentioned previously. The concrete compressive strengths at 28 days were 6% to 12% and 4% to 7% greater than the targeted compressive strengths of the HSC and high-strength SCC, respectively. The bending tests were performed after the beams had aged for 28 days. The concrete compressive strengths at this time were approximately equal to or slightly greater than the concrete strengths at 28 days.

Prestressing strand testing

Strand surface condition affects the transfer and development lengths of prestressing strands.[32,33] Twelve strand specimens were cut from a 2000 ft (610 m) reel of 0.7 in. (18 mm) diameter prestressing strand to evaluate the strand surface conditions using the *Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand* (ASTM A1081).[34] Six specimens were cut prior to casting the beams using conventional HSC, and the remaining specimens were cut prior to casting the beams using high-strength SCC. The two groups of strand samples were designated 0.7-CC and 0.7-SCC, respectively. The strand samples were preserved carefully and protected from contamination by foreign substances.

The tests for strand bond were performed according to the procedures outlined in ASTM A1081.[34] The ASTM A1081 test method requires a mortar compressive strength of 4500 to 5000 psi (30.0 to 34.5 MPa). In this study, the mortar used for testing both strand groups had a compressive strength of 4580 psi (31.6 MPa). **Figure 1** presents the pull-out forces of 12 specimens. For a specific group,

Table 2. Concrete compressive strengths and strand stresses

Beam	f'_{ci}, ksi	f'_c, ksi	f'_{ct}, ksi	f_{se}, ksi	f_{ps}, ksi	M_n, kip-in.
H-CC-S1 and H-CC-S2	9.5	13.7	14.2	185.8	267.0	714
H-CC-S3 and H-CC-S4	8.9	13.2	12.8	185.4	266.8	706
Average	9.2	13.5	13.5	185.6	266.9	n/a
H-CC-D1 and H-CC-D2	9.7	12.3	13.9	175.5	264.4	1317
H-CC-D3 and H-CC-D4	9.9	13.3	13.8	175.7	264.3	1315
Average	9.8	12.8	13.9	175.6	264.4	n/a
H-SCC-S1 and H-SCC-S2	8.1	11.0	11.4	184.6	266.4	696
H-SCC-S3 and H-SCC-S4	7.8	10.4	10.7	184.3	266.3	691
Average	8.0	10.7	11.1	184.5	266.4	n/a
H-SCC-D1 and H-SCC-D2	7.7	10.2	10.6	172.6	262.3	1272
H-SCC-D3 and H-SCC-D4	8.1	10.6	10.0	173.4	261.9	1262
Average	7.9	10.4	10.3	173.0	262.1	n/a

Note: f'_c = concrete compressive strength at 28 days; f'_{ci} = concrete compressive strength at 1 day; f'_{ct} = concrete compressive strength at time of bending tests; f_{ps} = average stress in prestressing steel at the time for which the nominal resistance of member is required; f_{se} = effective stress in the prestressing steel after losses; M_n = nominal flexural capacity; n/a = not applicable. 1 ksi = 6.895 MPa; 1 kip-in. = 0.1138 kN-m.

the ASTM A1081 strand-bond value is the average pull-out force of six strand specimens. The ASTM A1081 strand-bond values for 0.7-CC and 0.7-SCC were 36.73 kip (163.4 kN) and 35.67 kip (158.7 kN), respectively. These values are not significantly different and are approximately 64% greater than those reported by Morcous et al.[18]

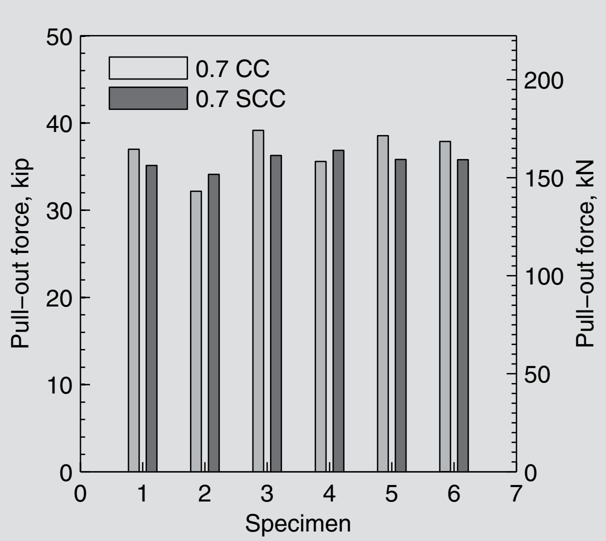

Figure 1. Results of strand bond tests for 12 strand specimens. For the 0.7-CC group, the strand-bond value, standard deviation, and coefficient of variation are 36.73, 2.56, and 0.07 kip, respectively. For the 0.7-SCC group, the strand-bond value, standard deviation, and coefficient of variation are 35.67, 0.96, and 0.027 kip, respectively. Note: CC = conventional concrete; SCC = self-consolidated concrete. 1 kip = 4.448 kN.

Pretensioned beam fabrication

Sixteen pretensioned concrete beams were cast using the two concrete mixtures. Each beam had an identical cross section of 6.5 × 12 in. (165 × 305 mm) and a length of 18 ft (5.5 m). The selection of this beam section was based on the capacity of the available equipment, and so that the possible effect of girder geometry could be ignored. To examine strand spacing, two different reinforcing details were used in this study (**Fig. 2**).

Section I contained one 0.7 in. (18 mm) diameter strand and used two no. 5 (16M) reinforcing bars as the top reinforcement to control the anticipated cracking in the top fiber of the beam. Shear reinforcement consisted of 0.25 in. (6.4 mm) diameter smooth bars spaced at 6 in. (150 mm) along the entire beam length. Section II contained two 0.7 in. diameter strands that were placed at a spacing of 2.0 in. (51 mm). This type of section used two no. 6 (19M) reinforcing bars as the top reinforcement and 0.25 in. diameter smooth bars spaced at 3 in. (75 mm) as the shear reinforcement. Section I was used for the H-CC-S and H-SCC-S beams in which *S* represents a single prestressing strand. Section II was used for the H-CC-D and H-SCC-D beams in which *D* represents two prestressing strands. Table 1 shows the beam designations.

Prior to casting, the prestressing strands were anchored at the dead end using chucks and tensioned to $0.75f_{pu}$ (202.5 ksi [1396 MPa]) at the live end using a hydraulic system.

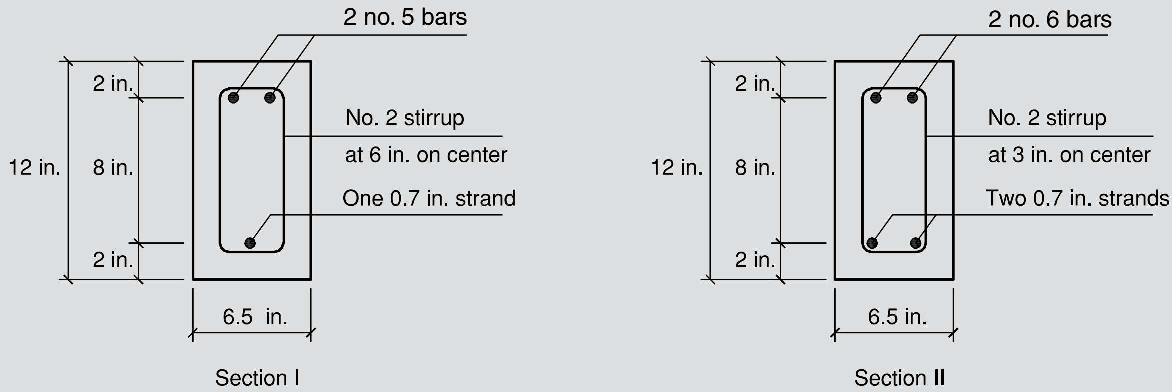

Figure 2. Two types of beam sections. Note: no. 2 = 6M; no. 5 = 16M; 1 in. = 25.4 mm.

Two beams were simultaneously cast on a 50 ft (15 m) prestressing bed using one batch of concrete. Nine 4 × 8 in. (100 × 200 mm) cylinders were cast and cured adjacent to the beams to evaluate the concrete strengths at 1 day, at 28 days, and at the time the bending tests were performed. After casting, the beams were covered with a plastic sheet to prevent moisture loss while the concrete cured in the forms. The forms were removed approximately 20 hours after casting.

Transfer-length measurement

After removing the forms, target points were attached to the beam surface at the level of the 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. (1500 mm) from the beam end. The initial reading was conducted approximately 2 hours after removing the forms. Three cylinders were tested to verify the concrete compressive strength before release. The prestressing strands were gradually detensioned 24 to 26 hours after casting by releasing the pressure in the hydraulic system. The subsequent readings were taken immediately after release and at 28 days.

All beams were examined for cracking periodically from strand release until 28 days. After prestress transfer, there were no signs of cracks at the ends or in the vicinity around the prestressing strands. At 28 days, several hairline cracks were observed on the top fiber of the H-SCC-D beams. The cracks were most likely caused by the prestressing force of the two 0.7 in. (18 mm) diameter prestressing strands and concrete shrinkage. The remaining beams had no cracks.

The measured concrete strains were smoothed using a three-point moving average technique to attain the concrete strain profile. A detailed explanation regarding the use of this technique is presented by Gross and Burns[14] and Russell and Burns.[3] Transfer length was determined using the concrete strain profile for each beam end along with the 95% average maximum strain method.[12] The following steps were used to determine transfer length:

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

2. Determine the constant strain plateau to calculate the average maximum strain value.

3. Draw the 95% average maximum strain line. This is the horizontal line passing through the 95% average maximum strain value and represents the constant strand stress beyond the transfer zone.

4. Draw the initial linear trend line. The initial linear trend line passes through the origin and is the best-fit trend line of target points within the transfer zone. The initial linear trend line represents the linear strand stress in the transfer zone.

5. Determine the intersection of the 95% average maximum strain line and the initial linear trend line. Transfer length is the distance from the beam end to the intersection point.

Figure 3 shows the measured transfer lengths at release and at 28 days for the live end of the H-CC-S1 beam. Previous studies used the distance from the beam end to the intersection of the concrete strain profile with the 95% average maximum strain line as the defined transfer length.[11,12,32,35,36] This technique is slightly different from the technique presented in Fig. 3.

The advantage of using the initial linear trend line in determining transfer length is to reduce the effect of strain fluctuation near the end of the transfer zone[37] and to provide more precise and consistent measurements.[38] Each target point within the transfer zone has an identical contribution in determining the initial linear trend line. Therefore, the use of the intersection of the 95% average maximum strain line and the initial linear trend line has been implemented in several studies[4,21,39–41] and in this study to estimate transfer lengths of prestressing strands.

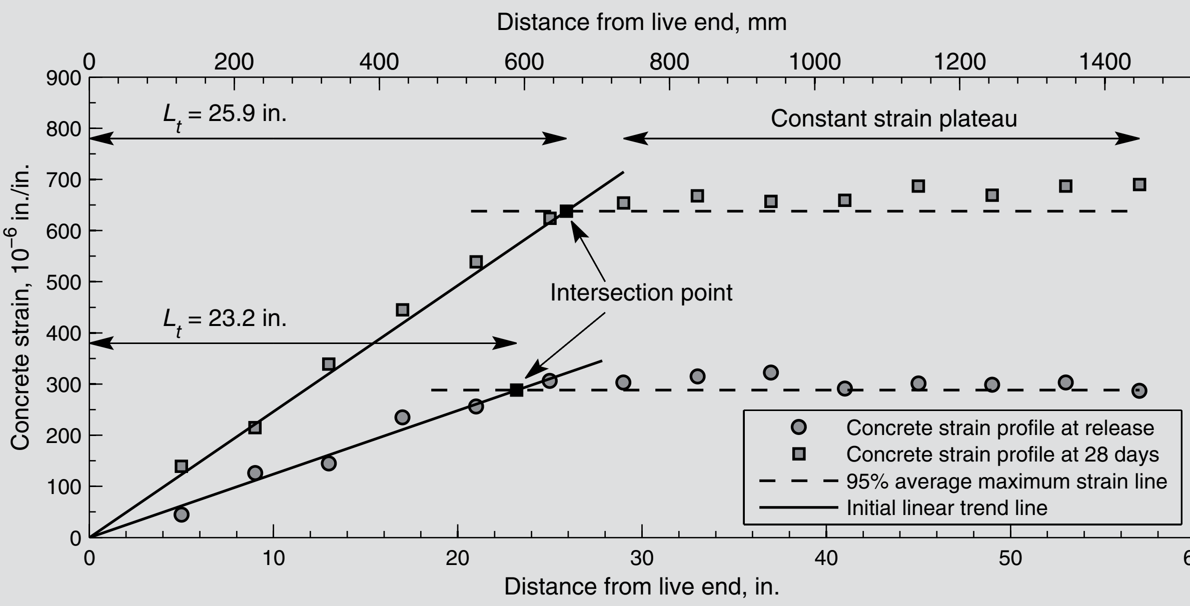

Figure 3. Determination of transfer lengths at release and at 28 days of H-CC-S1 beam. Note: L_t = transfer length. 1 in. = 25.4 mm.

Development-length measurement

Two bending tests were conducted for each beam at different embedment lengths. Embedment length is the distance from the beam end to the point at which a concentrated load was applied. During a bending test, the magnitude of concentrated load, beam deflection at the loading position, and strand slip were continuously monitored using a data-acquisition system. Hydraulic pressure was monitored using a pressure transducer connected to the hydraulic system. Beam deflection was measured using a linear cable encoder (LCE) or a steel ruler, and the strand slip was quantified using a linear variable differential transformer (LVDT). Strand slip was the distance that the prestressing strand slipped into the pretensioned concrete beam when the beam resisted external load. These devices were connected to the data-acquisition system, which transferred the received data to a computer.

Table 2 shows the concrete compressive strength before conducting the bending tests. The strain compatibility method was used to calculate the average stress in prestressing steel f_{ps} at the time for which the nominal flexural capacity of the member is required. This value varied from $0.970f_{pu}$ to $0.989f_{pu}$ (Table 2). The AASHTO LRFD specifications[9] refined method was used to predict prestress losses at 28 days. The effective strand stress ranged from $0.639f_{pu}$ to $0.688f_{pu}$. These stress values were used to calculate the predicted transfer and development lengths using the ACI 318-14 or AASHTO LRFD specifications equations and the nominal flexural capacity (Table 2).

The failure mode of a bending test determined whether the tested embedment length was greater than the required development length. If the bending test exhibits a flexural failure, the tested embedment length is equal to or greater than the required development length. The flexural failure is characterized by two requirements in terms of strength and ductility. For the strength requirement, the maximum measured moment M_{max} is equal to or greater than the nominal flexural capacity M_n, and the prestressing strand does not slip before the specimen achieves the nominal flexural capacity. For the ductility requirement, the specimen exhibits significant deflection at failure. If the specimen exhibits a bond failure, the tested embedment length is shorter than the required development length. The bond failure is determined when the prestressing strand slips before the specimen achieves the nominal flexural capacity. Strand slip is the sign of degradation in the bond strength within the transfer zone, which can lead to catastrophic failure of a pretensioned concrete member.

Testing results and discussion

Transfer-length results

Figure 4 shows the measured transfer lengths at release of the beams containing one prestressing strand (H-CC-S1–S4 and H-SCC-S1–S4) and two prestressing strands placed at 2.0 in. (51 mm) spacing (H-CC-D1–D4 and H-SCC-D1–D4). There was no significant difference in the measured transfer lengths at the live ends and at the dead ends. The similarity in transfer lengths is most likely because of gradually detensioning the strands, which minimizes the damage to the bond between the prestressing strand and the adjacent concrete at the live end. The gradual detensioning technique is suitable for small pretensioned concrete members, but it does not yield the worst

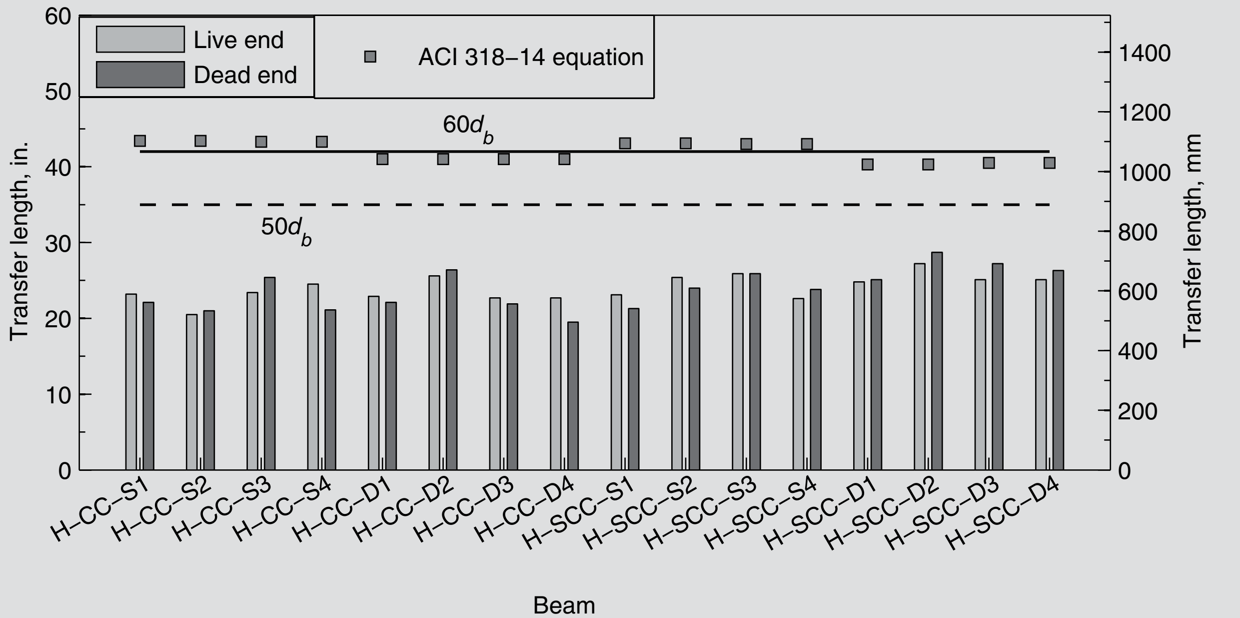

Figure 4. Measured transfer lengths at release of 16 pretensioned concrete beams. For a specific beam, the left and the right columns represent the measured transfer lengths at the live end and dead end, respectively. Note: d_b = strand diameter.

case scenario for transfer lengths. A flame-cut technique is more appropriate for large members and creates the worst case scenario for prestress transfer and required transfer length.[35,36,42] As shown in the figure, the measured transfer lengths varied from 19.5 to 28.7 in. (500 to 730 mm). These values are shorter than the predicted transfer lengths using the ACI 318-14 equation (50d_b equals 35 in. [890 mm]), the AASHTO LRFD specifications equation (60d_b equals 42 in. [1070 mm]), or Eq. (1) and (2).

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 in this study with a confidence interval of 95% (**Fig. 5**). This figure shows that the ACI 318-14 and AASHTO LRFD specifications equations are applicable to predict transfer lengths of 0.7 in. (18 mm) diameter strands for the concrete mixtures, prestressing strands, and testing procedures used in this study.

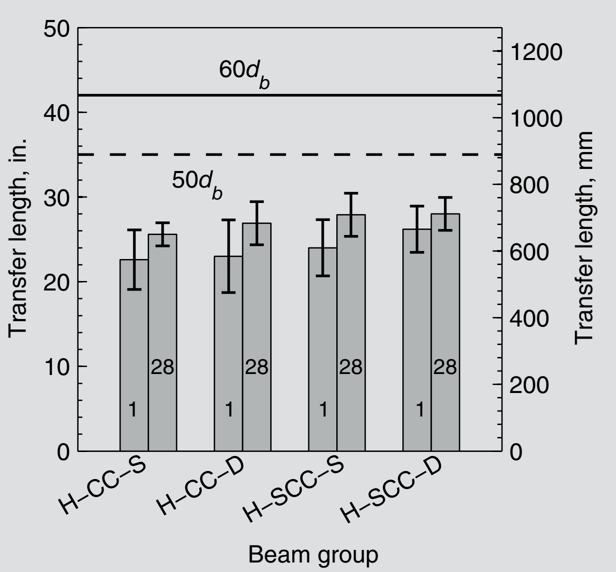

Figure 5. Statistical analysis of the measured transfer lengths at release (1 day) and 28 days. The columns represent the average values, and the error bars represent the upper bounds and the lower bounds of the measured transfer lengths. The number in each column indicates the time at which transfer lengths were measured. Note: d_b = strand diameter.

Figure 5 also indicates that the measured transfer lengths increased over time. Barnes et al.[43] determined that this increase varied from 10% to 20% on average and was significant for the first four weeks after release. In this study, the observed increase varied from 7% to 17%, which was slightly less than the reported thresholds. There was no trend to define the variability in transfer lengths over time. The increase was likely to be independent of concrete compressive strength, concrete type, and the number of prestressing strands. The measured transfer lengths of the H-CC-S and H-CC-D beams increased by 13% and 17%, respectively, while the measured transfer lengths of H-SCC-S and H-SCC-D beams increased by 16% and 6%, respectively.

The use of 0.7 in. (18 mm) diameter strands at a spacing of 2.0 in. (51 mm) had minimal effect on the measured transfer lengths. As shown in Fig. 5, the measured transfer lengths at release and at 28 days of the H-CC-D beams were marginally longer than those of the H-CC-S beams. For the beams using high-strength SCC, the average measured transfer length at release of the H-SCC-D beams was 10% greater than that of the H-SCC-S beams. At 28 days, however, the average measured transfer lengths of the

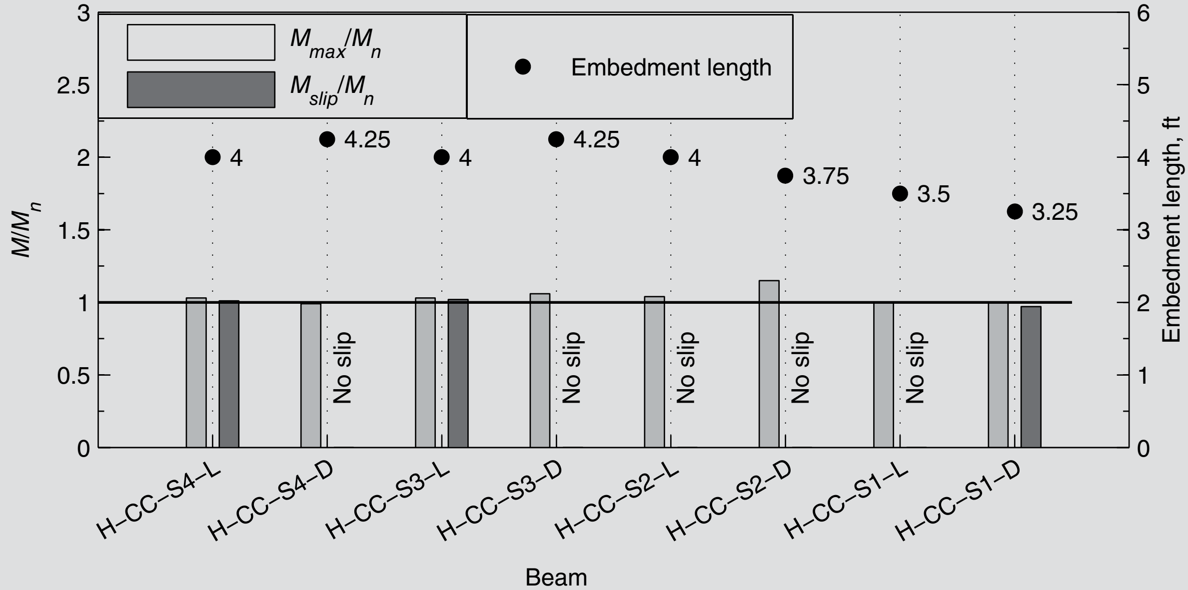

Figure 6. Bending-test results of the H-CC-S beams. Note: M = measured moment; M_{max} = maximum measured moment; M_n = nominal flexural capacity; M_{slip} = measured moment at which prestressing strands began slipping. 1 ft = 0.305 m.

H-SCC-S and H-SCC-D beams were approximately equal to 28 in. (710 mm). This was mostly because of the strand-interaction effects in the H-SCC-D beams at early ages. At early ages, the cement paste is a primary contributor to concrete compressive strength.

Determination of development length for H-CC-S beams

Figures 6 to **9** summarize the bending-test results of the four beam groups, and **Fig. 10** shows the typical relationships of the measured moment with beam displacement and strand slip. Figure 6 presents the bending-test results of the H-CC-S beams. In the figure, three parameters are presented for each bending test. The first column represents the M_{max}/M_n ratio. The second column represents the M_{slip}/M_n ratio (where M_{slip} is the measured moment at which the prestressing strand exhibits slip recorded by the LVDT). If the prestressing strand had no slip, "no slip" was entered in the second column. The final parameter is the tested embedment length, which is shown as a solid dot in the figure. For the specimen name, the bending test

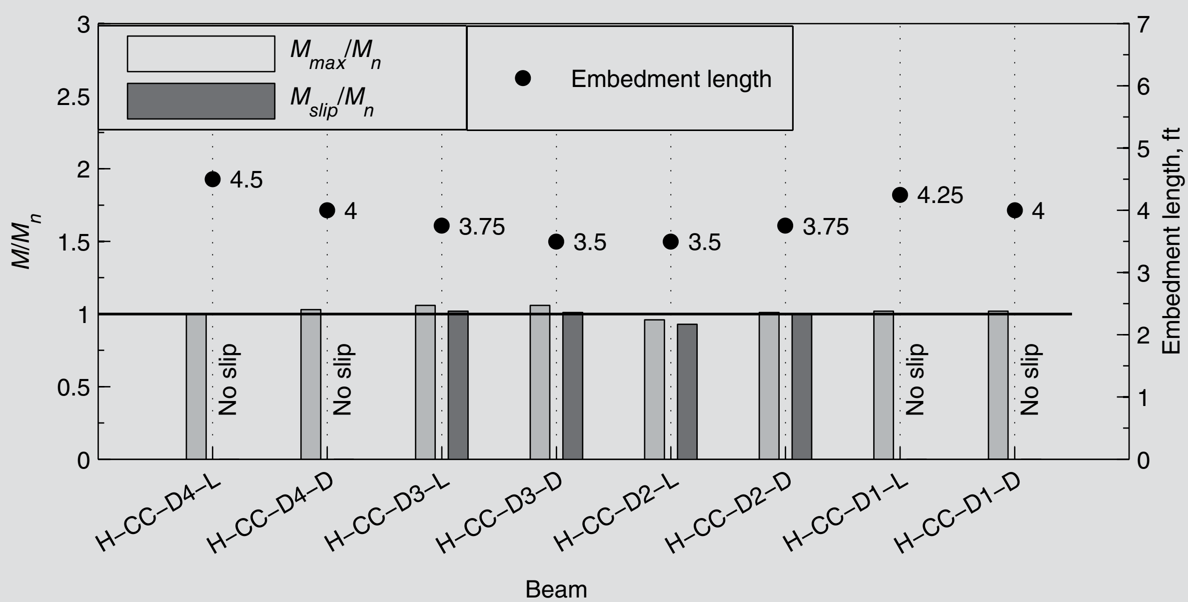

Figure 7. Bending-test results of the H-CC-D beams. Note: M = measured moment; M_{max} = maximum measured moment; M_n = nominal flexural capacity; M_{slip} = measured moment at which prestressing strands began slipping. 1 ft = 0.305 m.

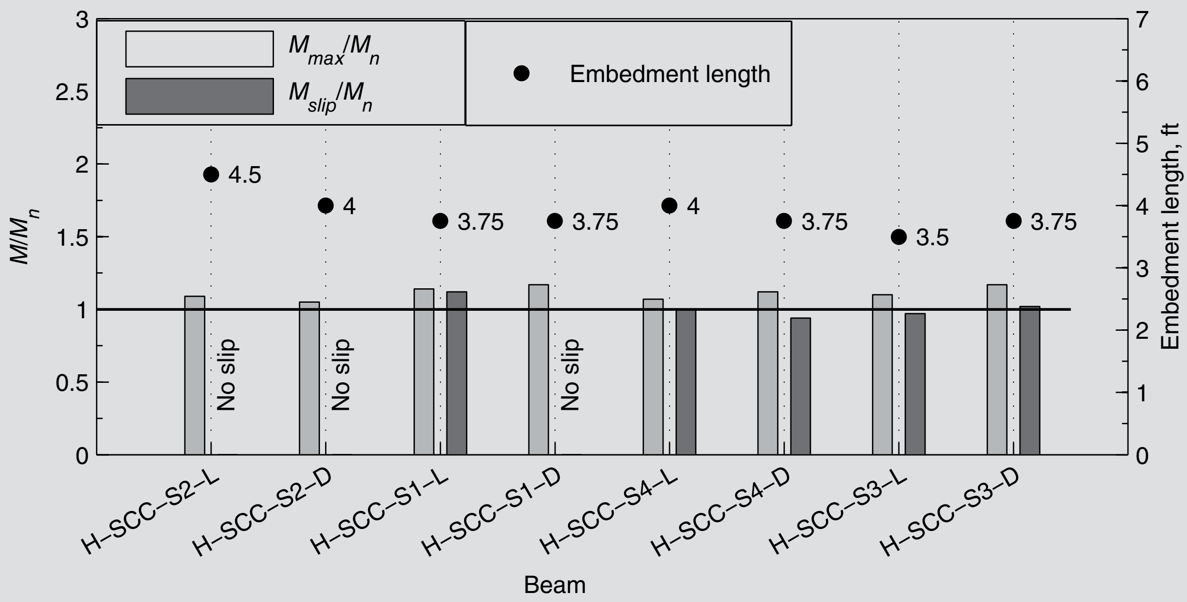

Figure 8. Bending-test results of the H-SCC-S beams. Note: M = measured moment; M_{max} = maximum measured moment; M_n = nominal flexural capacity; M_{slip} = measured moment at which prestressing strands began slipping. 1 ft = 0.305 m.

performed at the live end was identified as *L* and at the dead end as *D*.

The bending tests of the H-CC-S beams were conducted at embedment lengths varying from 3.25 to 4.25 ft (0.915 to 1.30 m). Two specimens (H-CC-S4-D and H-CC-S3-D), which were tested at an embedment length of 4.25 ft, exhibited flexural failures without strand slip. Three other specimens (H-CC-S4-L, H-CC-S3-L, and H-CC-S2-L) were tested at a shorter embedment length of 4 ft (1.2 m). All of the specimens presented flexural failures. Specimens H-CC-S4-L and H-CC-S3-L failed at 103% of M_n, and the prestressing strands began slipping when the measured moment reached 101% and 102% of M_n, respectively. These results indicate that the required development length may be close to the tested embedment length of 4 ft.

The embedment lengths were further reduced to determine the requireed development length. The bending test of specimen H-CC-S2-D failed without strand slip at an embedment length of 3.75 ft (1.14 m). The bending test of specimen H-CC-S1-L displayed similar results when

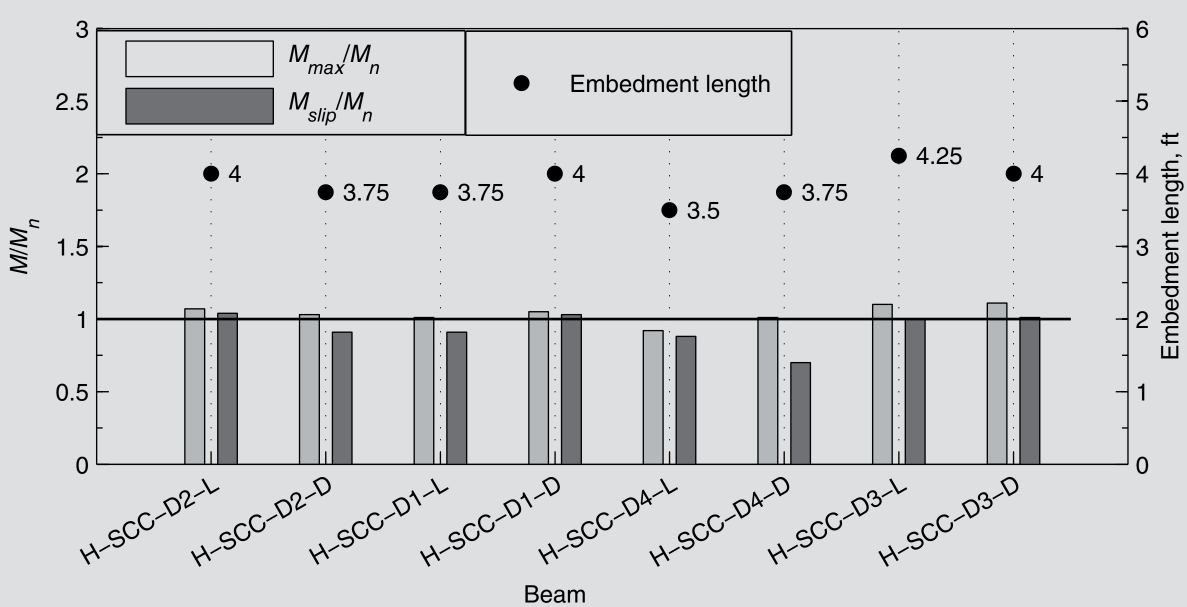

Figure 9. Bending-test results of the H-SCC-D beams. Note: M = measured moment; M_{max} = maximum measured moment; M_n = nominal flexural capacity; M_{slip} = measured moment at which prestressing strands began slipping. 1 ft = 0.305 m.

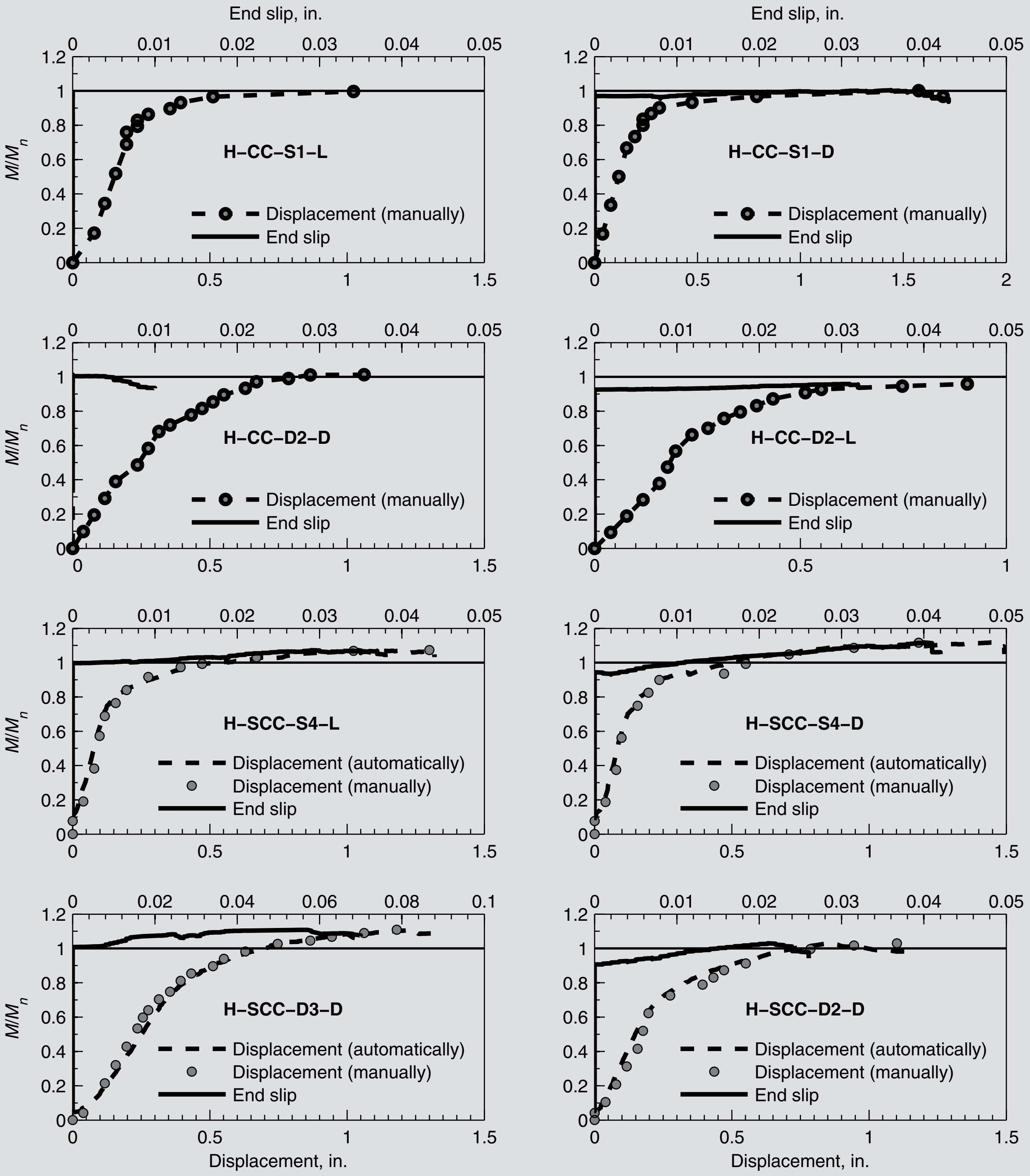

Figure 10. Relationship of the measured moment with specimen displacement and strand slip. Note: M = measured moment; M_n = nominal flexural capacity. 1 in. = 25.4 mm.

conducted at an embedment length of 3.5 ft (1.1 m). This specimen failed at 100% of M_n, with several cracks occurring within the flexural-bond zone. Figure 10 shows the relationships of the measured moment with specimen deflection and strand slip for specimen H-CC-S1-L. A shorter embedment length of 3.25 ft (0.990 m) was used for the bending test of specimen H-CC-S1-D. A bond failure occurred; however, the specimen achieved M_n before failure, and slip occurred when the measured moment reached 97% of M_n. This specimen showed ductile behavior, but it was unable to resist additional load after the prestressing strand slipped (Fig. 10).

The required development length for a beam group is the shortest tested embedment length at which the specimens exhibited flexural failures. Therefore, the required development length of the H-CC-S beams was 3.5 ft (1.1 m), which is approximately 42% of the predicted development length using the ACI 318-14 equation.

Determination of development length for H-CC-D beams

The bending tests of the H-CC-D beams were conducted at embedment lengths varying from 3.5 to 4.5 ft (1.1 to 1.4 m) (Fig. 7). In the figure, all of the specimens that were tested at embedment lengths equal to or greater than 4 ft (1.2 m) exhibited flexural failures, where M_{max}/M_n ranged from 1.00 to 1.03. These specimens included H-CC-D4-L, H-CC-D4-D, H-CC-D1-L, and H-CC-D1-D. The test results indicate that the required development length may be shorter than the tested embedment length because the prestressing strands did not slip in any of the bending tests.

Four other specimens were tested at shorter embedment lengths. An embedment length of 3.75 ft (1.14 m) was used for the bending tests of specimens H-CC-D3-L and H-CC-D2-D. Both specimens exhibited flexural failures. Specimen H-CC-D3-L failed at 106% of M_n, and the prestressing strands began slipping when the measured moment reached 102% of M_n. For specimen H-CC-D2-D, the prestressing strands slipped instantly when the specimen achieved M_n, and this specimen failed at 101% of M_n (Fig. 10). These results indicate that the required development length was close to the tested embedment length of 3.75 ft. The embedment length was reduced to determine whether the required development length was 3.75 ft.

Specimens H-CC-D3-D and H-CC-D2-L were tested at a shorter embedment length of 3.5 ft (1.1 m). Specimen H-CC-D3-D displayed a flexural failure. Specimen H-CC-D2-L, however, exhibited a bond failure in which the prestressing strands slipped when the measured moment achieved 93% of M_n (Fig. 10). This result indicates that the required development length was greater than the tested embedment length of 3.5 ft.

In summary, all of the bending tests that were conducted at embedment lengths equal to or greater than 3.75 ft (1.14 m) exhibited flexural failures. Accordingly, it was determined that the required development length of the H-CC-D beams is 3.75 ft, which is equivalent to 44% of the predicted development length using the ACI 318-14 equation. The required development length of the H-CC-D beams is slightly greater than that of the H-CC-S because of the effect of placing prestressing strands at a spacing of 2.0 in. (51 mm). Therefore, the use of 0.7 in. (18 mm) diameter strands at a spacing of 2.0 in. had little effect on the measured development lengths.

Determination of development length for H-SCC-S beams

Figure 8 shows M_{max}/M_n and M_{slip}/M_n for the H-SCC-S beams. For all embedment lengths, M_{max}/M_n was greater than 1.0. The tested embedment lengths ranged from 3.5 to 4.5 ft (1.1 to 1.4 m). Specimen H-SCC-S2-L displayed a flexural failure without strand slip when tested at an embedment length of 4.5 ft. The bending tests of specimens H-SCC-S2-D and H-SCC-S4-L were conducted at a shorter embedment length of 4 ft (1.2 m). Specimen H-SCC-S2-D exhibited a flexural failure without strand slip. Specimen H-SCC-S4-L also exhibited a flexural failure in which the specimen failed at 107% of M_n, but the prestressing strands slipped instantly when the measured moment reached M_n (Fig. 10). These results indicate that the required development length was close to the tested embedment length of 4 ft.

Five bending tests were conducted at shorter embedment lengths to evaluate the previous assessment regarding the required development length. Four specimens (H-SCC-S1-L, H-SCC-S1-D, H-SCC-S4-D, and H-SCC-S3-D) were tested at an embedment length of 3.75 ft (1.14 m). Three out of the four specimens exhibited flexural failures without strand slip prior to achieving M_n. Specimen H-SCC-S4-D displayed a bond failure because the prestressing strands began slipping when the measured moment reached 94% of M_n (Fig. 10). One bending test (H-SCC-S3-L), which was performed at a shorter embedment length of 3.5 ft (1.1 m), almost met the requirements for a flexural failure. This specimen achieved 110% of M_n before failure, but the prestressing strands began slipping when the measured moment reached 97% of M_n.

For the H-SCC-S beams, the required development length was between 3.75 and 4.0 ft (1.14 and 1.2 m). However, one out of the four specimens that were tested at an embedment length of 3.75 ft experienced a bond failure. Therefore, the required development length of the H-SCC-S beams was determined as 4 ft. This length is approximately equal to 48% of the predicted development length using the ACI 318-14 equation.

Determination of development length for H-SCC-D beams

The bending tests of the H-SCC-D beams were performed at embedment lengths that varied from 3.5 to 4.25 ft (1.1 to 1.30 m) (Fig. 9). The prestressing strands slipped in all bending tests. Specimen H-SCC-D3-L, which was tested at the longest embedment length of 4.25 ft, exhibited a flexural failure. Bending tests were conducted at a shorter embedment length of 4 ft (1.2 m) for three other specimens (H-SCC-D2-L, H-SCC-D1-D, and H-SCC-D3-D). All of the specimens displayed flexural failures. These specimens failed at 105% to 111% of M_n, and the prestressing strands slipped when the measured moment reached 101% to 104% of M_n. The results indicate that the required development length is close to the tested embedment length. Figure 10 shows the relationships of the measured moment with the specimen deflection and strand slip for specimen H-SCC-D3-D.

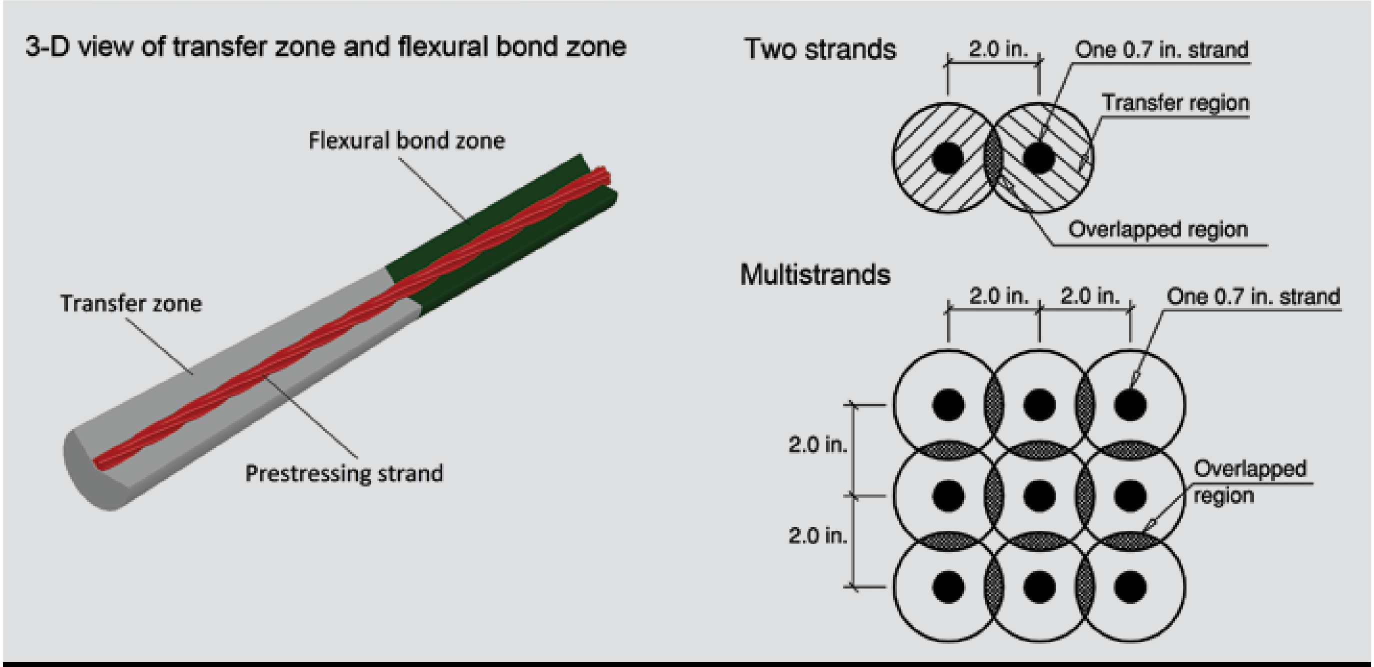

Figure 11. Prestress transferring of a 0.7 in. diameter strand and the effect of placing the strands at 2.0 × 2.0 in. spacing. Note: 1 in. = 25.4 mm.

Four other specimens were tested at shorter embedment lengths to determine the required development length. The bending tests of three specimens (H-SCC-D2-D, H-SCC-D1-L, and H-SCC-D4-D) resulted in bond failures when tested at an embedment length of 3.75 ft (1.14 m). All of these specimens achieved M_n before failure, but the prestressing strands slipped when the measured moment reached 70% to 91% of M_n. The prestressing strands of specimen H-SCC-D2-D began slipping at 91% of M_n due to the occurrence of several shear cracks within the transfer zone. The remaining specimen (H-SCC-D4-L), which was tested at an embedment length of 3.5 ft (1.1 m), also displayed a bond failure. This specimen was unable to achieve M_n before failure, and the prestressing strands slipped when the measured moment reached 88% of M_n because of shear cracks that were similar to those of specimen H-SCC-D2-D.

The results of eight bending tests indicate that the required development length of the H-SCC-D beams was 4 ft (1.2 m), which is approximately equal to 47% of the predicted development length using the ACI 318-14 equation. All of the specimens exhibited flexural failures when tested at embedment lengths equal to or greater than 4 ft. In addition, the identical development lengths of the H-SCC-S and H-SCC-D beams indicate that the use of a strand spacing of 2.0 in. (51 mm) had no effect on the measured development lengths.

Applicability of ACI 318-14 and AASHTO LRFD specifications

Several studies have investigated transfer length, development length, and applicable spacing of 0.7 in. (18 mm) diameter strands as discussed in the literature review. Most of these studies were conducted on members having a depth equal to or greater than 24 in. (610 mm), which includes the safety factor of 1.6 for the development-length equation. This study presents the results for the members less than 24 in. deep, for which the development-length equation would not include the multiplier. In addition, the measured transfer lengths for these members may be longer than those for members having a depth equal to or greater than 24 in., which would increase the conservativeness in evaluating transfer length.[3,42]

Figure 11 shows the mechanism of prestress transfer and the effect of using a strand spacing of 2.0 in. (51 mm). As shown in the three-dimensional view, a prestressing strand transfers the tensile stress to the adjacent concrete through the transfer zone and flexural-bond zone. The strand transfers the prestress f_{se} (where f_{se} is the effective strand stress) within the transfer zone, and develops f_{ps} within the flexural-bond zone when the pretensioned concrete beam resists external loads. The radii of these zones represent the concrete regions stressed by Hoyer's effect and mechanical interlock. The radius of the transfer zone is largest at the end of the beam due to the maximum influence of the Hoyer's effect[3] and reduces along the transfer zone. Using finite element modeling, Jiang[44] determined that the largest radius of the transfer zone is approximately equal to 1.0 in. (25 mm). The finite element modeling conducted by Jiang and the experimental investigation performed in this study are comparable because the strand stresses prior to release in both studies are identical.

When placing two strands at 2.0 in. (51 mm) spacing, the transfer zones of the strands may overlap (Fig. 11). The concrete stress in the overlapped region is intensified, which can lead to concrete cracking. However, the

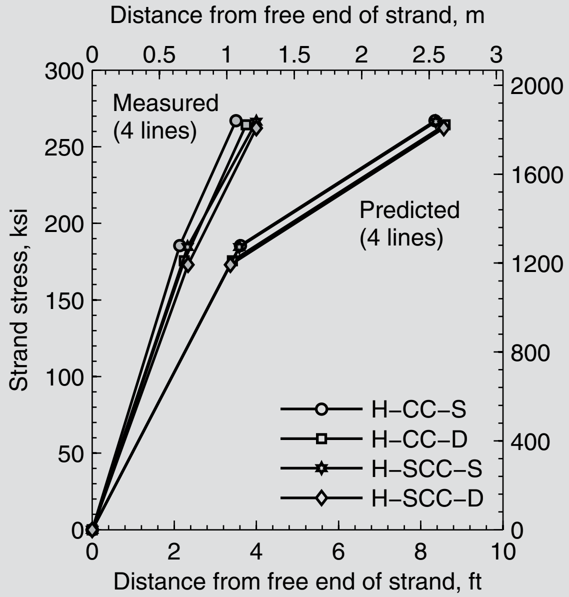

Figure 12. Measured and predicted transfer lengths and development lengths.

experimental results of the H-CC-D and H-SCC-D beams showed no sign of cracking in this region. In addition, the average transfer lengths of the beams containing two strands (H-CC-D and H-SCC-D beams) were slightly longer than those of the beams containing one strand (H-CC-S and H-SCC-S beams) (Fig. 5). Therefore, the overlapped region had minimal effect on the measured transfer lengths. This experimental observation can be applied for a pretensioned concrete member containing multiple strands. For example, a full-scale pretensioned concrete beam may contain several strands placed at 2.0 × 2.0 in. spacing. This beam may contain some overlapped regions (Fig. 11). The effect of these regions on the measured transfer lengths is insignificant if the concrete release strengths are equal to 7.7 ksi (53 MPa) or greater. This threshold was based on the experimental results of the H-SCC-D1 and H-SCC-D2 beams.

The flexural-bond zone may not overlap. Within the flexural-bond zone, the bond generated by the mechanical interlock is dominant, while that generated by the Hoyer's effect is minimal.[3] The flexural-bond lengths of H-CC-S, H-CC-D, H-SCC-S, and H-SCC-D were 19.4 in. (490 mm), 22.0 in. (560 mm), 24.0 in. (610 mm), and 21.8 in. (555 mm), respectively. The flexural-bond length of the H-CC-D beams was 2.6 in. (65 mm) greater than that of the H-CC-S beams, while flexural-bond length of the H-SCC-D beams was 2.2 in. (55 mm) less than that of the H-SCC-S beams. These deviations were attributed to the nature of determining the development length. During the testing, all bending tests exhibited flexural failures when tested at embedment lengths equal to or longer than the development length. Therefore, the measured development lengths in this study are applicable for full-scale pretensioned concrete beams if the effects of shear are adequately considered.[45]

Figure 12 summarizes the measured transfer and development lengths of the four beam groups. On average, the predicted transfer lengths ($50d_b$, $60d_b$, and Eq. [1] and [2]) were greater than the measured transfer lengths by 29%, 55%, and 55%, respectively. The predicted development lengths using the ACI 318-14 equation overestimated the measured data by 122%. The use of high-strength concrete and prestressing strands having high strand-bond values according to the ASTM A1081 test method partially accounts for the overestimation. Regardless of the overprediction, for the materials and testing procedures used in this study, the ACI 318-14 and AASHTO LRFD specifications for transfer length and development length are applicable for 0.7 in. (18 mm) diameter strands with a spacing of 2.0 in. (51 mm).

Conclusion

This study measured the transfer and development lengths of 0.7 in. (18 mm) diameter strands for 16 pretensioned concrete beams cast with two high-strength concrete mixtures. Based on the experimental results, the following conclusions were made:

- The ASTM A1081 test method is suitable to evaluate the surface conditions of 0.7 in. (18 mm) diameter, untensioned prestressing strands. The strands that were tested in this study had high pull-out forces that were 64% greater than the results reported in the literature.

- On average, the measured transfer lengths at release varied from 22.6 to 26.2 in. (575 to 665 mm). For the beams using high-strength concrete, the transfer length of the H-CC-D beams was marginally longer than that of the H-CC-S beams. For the beams using high-strength SCC, the transfer length of the H-SCC-D beams was 10% greater than that of the H-SCC-S beams. These results indicated that the use a strand spacing of 2.0 in. (51 mm) in the H-CC-D and H-SCC-D beams had minimal effect on the measured transfer lengths.

- All of the measured transfer lengths at 28 days were shorter than the predicted values using the ACI 318-14 and AASHTO LRFD specifications equations. The average transfer lengths of the four beam groups were from 73% to 80% and 61% to 67% of those predicted using equations of $50d_b$ and $60d_b$, respectively.

- The measured transfer lengths of the 0.7 in. (18 mm) diameter strands increased 6% to 17% for the first 28 days after casting the concrete. The current codes have no coefficient to account for the increase of transfer length over time, but they adequately serve as the upper bound in predicting transfer length of prestressing strands.

- The measured development lengths of the four beam groups ranged from 42% to 48% of the predicted development lengths using the ACI 318-14 equation. The development length of the H-CC-D beams was marginally longer than that of the H-CC-S beams. For the beams using high-strength SCC, however, the development lengths of the beams using one and two strands were identical. Therefore, the use of 0.7 in. (18 mm) diameter strands at 2.0 in. (51 mm) spacing had little to no effect on the measured development lengths of the H-CC-D and H-SCC-D beams.

- The concrete region around the prestressing strands of the H-SCC-D and H-CC-D beams showed no sign of cracking when the strands were placed at 2.0 in. (51 mm) spacing, tensioned to $0.75f_{pu}$ prior to release, and gradually detensioned at a concrete compressive strength of 7.7 ksi (53 MPa) or greater.

Additional research is needed to incorporate the use of 0.7 in. (18 mm) diameter strands into the current codes. The measurement of transfer and development lengths on full-scale pretensioned concrete beams, which contain different amounts of confinement reinforcement and use various types of concrete, would provide useful data. Both normal-strength and high-strength concrete should be employed in the investigation. The research, which confirms the applicability of using a strand spacing of 2.0 in. (51 mm) and determines the required concrete release strength, is needed. The investigations, which use analytical methods or finite element modeling, would further the understanding regarding the bond behaviors in the transfer zone and flexural-bond zone.

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Notation

d_b = strand diameter

f_c' = concrete compressive strength at 28 days

f_{ci}' = concrete compressive strength at 1 day

f_{ct}' = concrete compressive strength at time of bending tests

f_{ps} = average stress in prestressing steel at the time for which the nominal flexural capacity of member is required

f_{pu} = ultimate strength of prestressing strand

f_{se} = effective stress in the prestressing steel after losses

L_d = development length

L_t = transfer length

M = measured moment

M_{max} = maximum measured moment

M_n = nominal flexural capacity

M_{slip} = measured moment at which prestressing strands began slipping

T_{20} (T_{500}) = time required to achieve slump flow of 20 in. (500 mm)

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Abstract

The use of 0.7 in. (18 mm) diameter strands for pretensioned concrete girders is advantageous when increasing the flexural capacity and extending girder spans. The current codes have no design guidelines for predicting transfer length, development length, and minimum strand spacing for this greater-diameter strand. This study measures transfer and development lengths and evaluates the applicability of using a strand spacing of 2.0 in. (51 mm) for 16 pretensioned concrete beams with 0.7 in. diameter strands. These beams were fabricated with high-strength, conventional concrete or self-consolidating concrete. The *Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand* (ASTM A1081) was used to quantify the strand surface conditions. The experimental results indicate that the current ACI 318-14 and AASHTO LRFD specifications overestimate the measured transfer and development lengths for the beams. Transfer and development lengths of the beams containing two strands placed at 2.0 in. spacing were equal to or slightly greater than those of the beams containing one strand. Finally, the concrete region around the strands showed no sign of cracking.

Keywords

Bond, bridge, development length, high-strength concrete, strand, surface condition, transfer length.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

Reader comments

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