The use of Grade 300 prestressing strand in pretensioned, prestressed concrete beams

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- Current code provisions are based on years of experimental research and are used with the traditional 270 ksi (1860 MPa) prestressing strand.
- Recent developments have resulted in a higher-strength strand with an ultimate tensile strength of 300 ksi (2070 MPa).
- This paper presents the results of an experimental investigation looking at the behavior of pretensioned, prestressed concrete members containing 300 ksi (2070 MPa) prestressing strands.

Grade 270 (1860 MPa) prestressing strand is the industry standard for use in pretensioned, prestressed concrete members. Current code provisions in the American Concrete Institute's (ACI's) *Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)*[1] and the American Association of State Highway Transportation Officials' (AASHTO's) *AASHTO LRFD Bridge Design Specifications*[2] predict member behavior through various empirical formulas. While research validates the use of these equations for use with Grade 270 strand, little validation exists for other strand types. The purpose of this study was to investigate the use of Grade 300 (2070 MPa) prestressing strand in pretensioned, prestressed concrete beams and compare member behavior both to counterpart beams containing Grade 270 strand and to predicted values calculated using the current code provisions. The study included a variety of T-beam test specimens resulting in 35 transfer zones and 35 flexural tests. Included is an evaluation of influential factors and comparisons of the results for Grade 300 and Grade 270 strands for transfer and flexural bond lengths along with flexural capacity. Also included is an evaluation of the results with respect to the current code provisions.

Current code provisions

ACI 318-14 and the AASHTO LRFD specifications provide empirical formulas for the calculation of transfer length, development length, stress in the strand at flexural strength, and flexural strength of pretensioned, prestressed concrete members. Numerous research projects confirm the reliability of those equations, but the majority of that research includes the industry standard, Grade 270 (1860 MPa), prestressing strand. Each of the formulas depends on the strength of the strand in some form, either directly with respect to the ultimate tensile strength or indirectly with respect to the jacking or effective prestress, which is some percentage of the ultimate tensile strength. Equation (1) gives the expression for the development length l_d of prestressing strand found in ACI 318-14 and the AASHTO LRFD specifications. This equation takes into consideration the effective prestress f_{se}, the stress in the strand at the nominal moment capacity f_{ps}, and the diameter of the strand d_b made up of two parts (**Fig. 1**). The first term represents the transfer length l_t (Eq. [2]), and the second term represents the flexural bond length l_{fb} (Eq. [3]).

ACI 318-14 defines the transfer length as the distance over which the strand should be bonded to the concrete to develop the effective prestress in the prestressing steel. Code provisions assume that the stress in the strand varies linearly from zero at the end of the member to the effective prestress f_{se} at the transfer length. Both ACI 318-14 and the AASHTO LRFD specifications have criteria for calculating transfer length with only slight variations between the two. The expression for transfer length currently used in the determination of development lengths for both ACI 318-14 and the AASHTO LRFD specifications is given in Eq. (2), which is based on research conducted in the late 1950s and early 1960s.[3–6] Furthermore, within the shear provisions of both codes, a value of 150 ksi (1030 MPa) is assumed for the effective prestress f_{se} after all losses, reducing Eq. (2) to $50d_b$. This assumption provides designers with a simplified method for obtaining the force in the strand at any distance within the transfer zone. The AASHTO LRFD specifications increased this distance to $60d_b$ to account for the higher jacking stresses typically used in industry.[7]

The flexural bond length is the additional distance required to sufficiently increase the stress in the strand from the effective prestress to the stress in the strand at the nominal moment capacity. Similar to transfer length, code provisions assume that the stress in the strand varies linearly from the effective prestress at the end of the transfer length to the stress in the strand at the nominal moment capacity at the end of the flexural bond length. Equation (3) gives the expression used to calculate the flexural bond length for both ACI 318-14 and the AASHTO LRFD specifications. Like the expression for transfer length, Eq. (3) was also based on research performed in the late 1950s and early 1960s.[3–6] ACI 318-14 and the AASHTO LRFD specifications also provide empirical formulas for the calculation of the stress in the strand at the nominal moment capacity (Eq. [4] and [5]), respectively. Each equation includes both the ultimate tensile strength of the strand and the yield stress of the strand, typically taken as 90% of the ultimate tensile strength. While research validates the use of the code provisions for the predicted behavior of members containing Grade 270 (1860 MPa) prestressing strand, little research exists on the use of current code provisions in conjunction with Grade 300 (2070 MPa) prestressing strand.

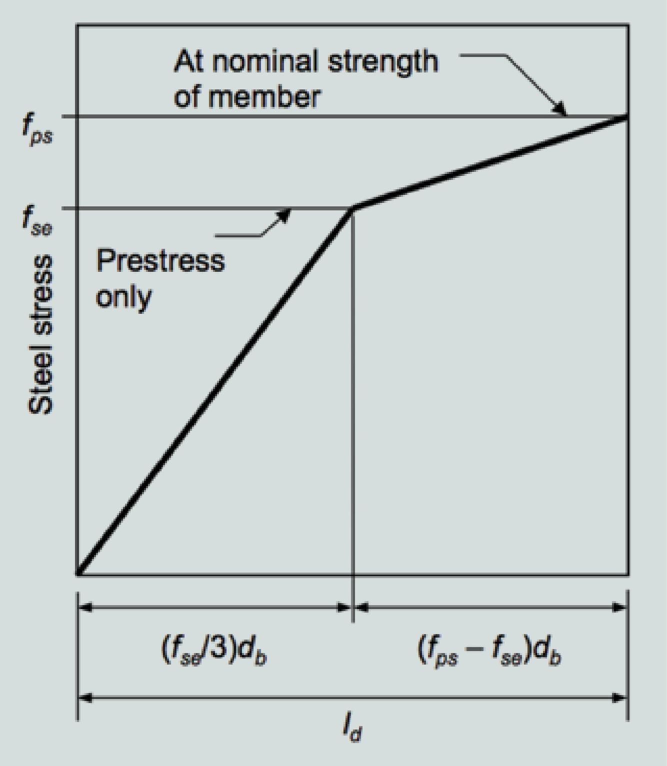

Figure 1. Idealized bilinear steel stress relationship at strength. Note: d_b = strand diameter; f_{ps} = stress in the prestressing strand at nominal moment capacity; f_{se} = effective stress in the strand after all losses; l_d = development length.

$$l_d = \left(\frac{f_{se}}{3}\right)d_b + \left(f_{ps} - f_{se}\right)d_b \quad (1)$$

$$l_t = \left(\frac{f_{se}}{3}\right)d_b \quad (2)$$

$$l_{fb} = \left(f_{ps} - f_{se}\right)d_b \quad (3)$$

$$f_{ps} = f_{pu}\left\{1 - \frac{\gamma_p}{\beta_1}\left[\rho_p \frac{f_{pu}}{f_c'} + \frac{d}{d_p}\frac{f_y}{f_c'}\left(\rho - \rho'\right)\right]\right\} \quad (4)$$

where

f_{pu} = specified minimum tensile strength of prestressing strand

γ_p = factor for type of prestressing steel based on the ratio of f_{py}/f_{pu}

β_1 = factor relating depth of equivalent rectangular compressive stress block to neutral axis depth

ρ_p = ratio of prestressed longitudinal tension reinforcement

f_y = specified yield strength for nonprestressed reinforcement

f_c' = concrete compressive strength

d = distance from extreme compressive fiber to centroid of longitudinal tension reinforcement

d_p = distance from extreme compressive fiber to centroid of prestressing steel

ρ = ratio of nonprestressed tension reinforcement

ρ' = ratio of nonprestressed compression reinforcement

$$f_{ps}=f_{pu}\left(1-k\frac{c}{d_p}\right) \quad (5)$$

where

c = distance from extreme compressive fiber to neutral axis

k = coefficient for type of prestressing steel

$= 2\left(1.04-\frac{f_{py}}{f_{pu}}\right)$

f_{py} = yield stress of prestressing steel

Bond characteristics and influential factors

Existing research shows that a number of factors affect the bond characteristics of prestressing strand, including strand stress, strand diameter, surface condition, concrete strength, location relative to release, as-cast vertical location and spacing, and cover and confinement. An increase in strand stress generally leads to an increase in transfer and development lengths.[3,8–10] Likewise, the general consensus is that transfer and development lengths increase with an increase in strand diameter.[4,11,12] However, two studies found that transfer length and development lengths decrease for 0.6 in. (15 mm) diameter strands.[13,14] While the current code provisions only consider the stress in the strand and the strand diameter, various studies show all of the aforementioned factors to be influential. The surface condition of the strand can influence the frictional resistance between the prestressing strand and surrounding concrete. Slightly rusted strand has a positive effect on bond, while various coatings result in a negative effect on bond.[3,12,15,16] Transfer and development lengths decrease as concrete strength increases, significantly in the case of high-strength concrete.[4,5,11,14,17–22] Furthermore, a sudden release is, for the most part, the industry standard among precast concrete manufacturers, but differences in transfer length exist with respect to the location of the strand relative to the release location.[5,10,11,16,18,19] The as-cast vertical location can also significantly affect transfer length, especially in the case of mixtures with high fluidity. Transfer and development lengths of top-cast strands consistently exceed the transfer and development lengths of bottom-cast strands, with the most recent studies concluding that this phenomenon is more dependent on the amount of concrete cast above the strand than below the strand.[7,20,21,23–26] Last, the spacing, cover, and confinement of prestressing strands can affect the bond characteristics. The industry standard is a 2 in. (50 mm) center-to-center spacing, but studies show that smaller spacing has no significant effect on transfer and development length of ½ in. (13 mm) diameter strands.[13,16] However, one study showed a reduction in cover to result in longer transfer lengths.[19]

Experimental investigation

Test specimens

This study included 18 T-beam test specimens cast throughout the duration of the project. The T beams were 24 ft (7.3 m) long and had two different cross sections corresponding to the size of prestressing strand used. The small and large beams each contained ½ in. (13 mm) diameter regular strands and ½ in. diameter super strands, respectively. Each cross section contained three strands, placed 2 in. (50 mm) from the base of the stem with a lateral center-to-center spacing of 2 in., which is typical in the prestressing industry. Each beam also contained no. 4 (13M) single-leg stirrups for shear reinforcement spaced at 4 in. (100 mm) on center over a distance of 8 ft (2.4 m) from each end. In the middle 8 ft, the small beams contained no. 3 (10M) single-leg stirrups spaced at 8 in. (200 mm) on center, while the large beams contained no. 4 single-leg stirrups spaced at 8 in. on center. Previous research shows that the development length of prestressing strand depends on the strain in the strand at the time of failure.[7] Thus, the objective of the cross-section design was to ensure that the strain in the strand at the ultimate flexural capacity was greater than the minimum required elongation of 3.5%.[27] The selected size and shape of each cross section took into consideration the strand size and desired flexural behavior at the time of failure, which ensures similar be-

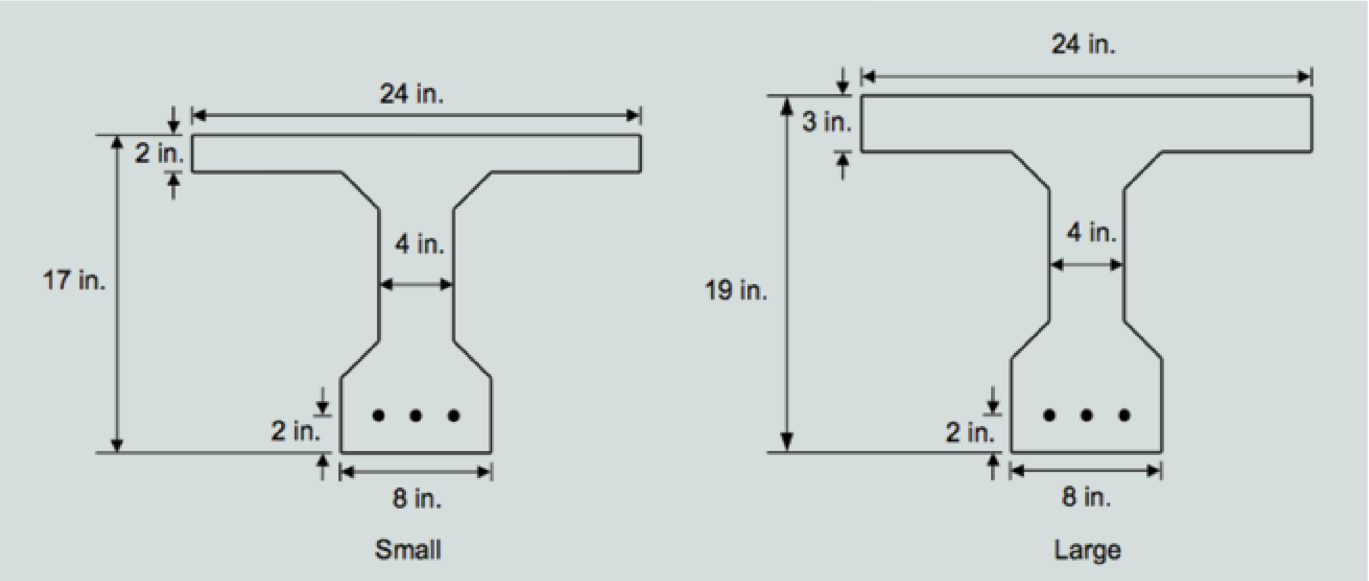

Figure 2. T-beam test specimens. Note: 1 in. = 25.4 mm.

havior to larger sizes of pretensioned, prestressed concrete beams. **Figure 2** shows the cross sections of the T beams.

Seven of the T-beam test specimens were cast upside down (inverted) to observe the influence of the vertical casting position as part of a secondary study.[26] The inverted casting orientation resulted in more than 12 in. (300 mm) of fresh concrete below the strand, categorizing each strand as a "top strand" based on the ACI 318-14 definition for top reinforcing bars. Inverted orientations of the small and large beams resulted in respective depths of concrete cast below the strands of 15 and 17 in. (380 and 430 mm), while maintaining a constant depth of 2 in. (50 mm) of concrete cast above the strand. Each beam cast with an inverted orientation was on the same line of strands in succession with a counterpart beam having a normal orientation, ensuring a better comparison of beams cast with normal and inverted orientations.

Previous research shows that the level of prestress affects both transfer and development lengths of prestressing strand. A number of studies use jacking stress values ranging from $0.60f_{pu}$ to $0.80f_{pu}$, resulting in an increase in transfer length corresponding to an increase in the resulting level of prestress at transfer. While the industry standard is to use a jacking stress equal to $0.75f_{pu}$, the jacking stress levels used in this study were $0.67f_{pu}$ and $0.75f_{pu}$ to evaluate the effect of the resulting levels of prestress. The T-beam test specimens in groups 1 through 4 used a jacking stress of $0.67f_{pu}$, while those in groups 5 and 6 used a jacking stress of $0.75f_{pu}$. The concrete mixture used in the study was a normalweight concrete provided by a local ready-mix plant with a target compressive strength of 4500 psi (31 MPa) at transfer and 6000 psi (41 MPa) at 28 days. **Table 1** lists the slump, compressive strength at transfer, and compressive strength at the time of testing for each mixture. Values for slump and compressive strength were determined in accordance with ASTM C143[28] and ASTM C39[29], respectively. In addition to the strand sizes used throughout the study, the study includes both 270 ksi (1780 MPa) and 300 ksi (2070 MPa) prestressing strands. **Figure 3** illustrates the naming convention for the test specimens.

Strand properties

The standard material properties were determined for each type of strand, including yield stress, ultimate tensile strength, modulus of elasticity, and ultimate elongation in accordance with ASTM A416[30] and A370.[31] **Table 2** shows a summary of the results for each strand type. Each value shown is the average of at least four experimental tests. The total average yield stress and ultimate tensile strength for Grade 270 (1860 MPa) strand were 241 and 273 ksi

Table 1. Material properties summary for concrete

Group	Slump, in.	f'_{ci}, psi	f'_c, psi
1	2.75	4900	6500
2	7.5	5300	6400
3	6.5	6000	8200
4	7.5	4900	6300
5	6.25	5000	6500
6	11.5	6400	8300

Note: f'_c = concrete compressive strength; f'_{ci} = concrete compressive strength at time of transfer. 1 in. = 25.4 mm; 1 psi = 6.895 kPa.

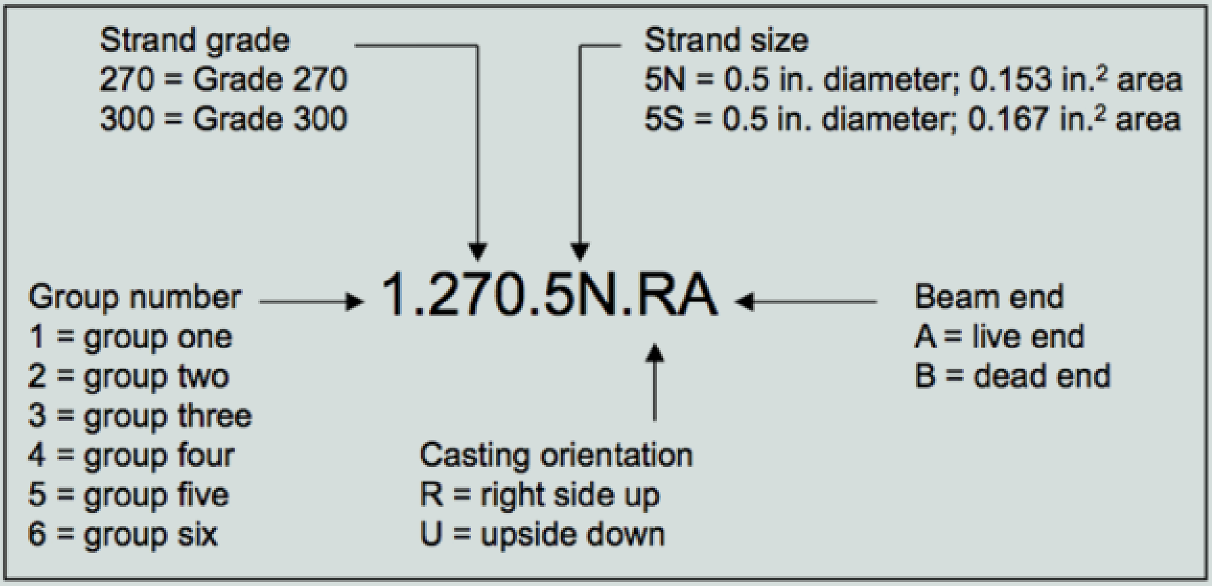

Figure 3. Specimen naming convention. Note: 1 in. = 25.4 mm; Grade 270 = 1860 MPa; Grade 300 = 2070 MPa.

(1660 and 1880 MPa), respectively. The average yield stress was just under the ASTM A416 minimum of $0.90f_{pu}$, while the average ultimate tensile strength was satisfactory. Although the ½ in. (13 mm) diameter Grade 270 strands had satisfactory behavior, the ½ in. diameter super strand had the lowest yield stress and ultimate strength. The total average yield stress and ultimate tensile strength for the Grade 300 (2070 MPa) strand were 270 and 299 ksi (186 and 2060 MPa), respectively. The yield stress for Grade 300 strand satisfies the requirements of ASTM A416,[30] but the average ultimate tensile strength was just under the minimum of 300 ksi (2070 MPa).[32]

The average modulus of elasticity for Grade 270 (1860 MPa) strand was 28,500 ksi (197 GPa), consistent with standard values used in industry. However, the average modulus of elasticity for Grade 300 (2070 MPa) strand was 29,500 ksi (203 GPa), 3.51% higher than the Grade 270 strand. Furthermore, the average ultimate elongations for Grade 270 strand and Grade 300 strand were 7.4% and 7.1%, respectively. Differences in elasticity are apparent based on materials testing, which may affect member behavior. First, higher modulus values may result in higher jacking stresses during member fabrication if not taken into consideration. Second, higher modulus values will result in greater loss of prestress from creep and shrinkage. Last, the ultimate elongation was comparable.[32]

The relaxation properties were determined for each strand type in accordance with ASTM A416[30] and E328.[33] The ASTM standards specify a maximum relaxation of 2.5% for low-relaxation strands stressed to 70% of the ultimate tensile strength and 3.5% when stressed to 80% of the ultimate tensile strength. Efforts were made to stress each strand to at least 70% of the ultimate tensile stress. However, seating losses resulted in stresses just under

Table 2. Material properties summary for prestressing strands

Strand type	Average yield stress, ksi	Average ultimate stress, ksi	Modulus of elasticity, ksi	Average elongation, %	Average relaxation, %
½ in. regular Grade 270	248	279	29,200	7.5	1.51
½ in. regular Grade 300	270	301	30,000	7.1	1.34
½ in. super Grade 270*	239	268	28,600	7.2	1.30
½ in. super Grade 270†	236	273	27,400	7.4	n/a
½ in. super Grade 300	270	296	28,900	7.2	1.80

Note: n/a = not applicable. Grade 270 = 1860 MPa; Grade 300 = 2070 MPa; 1 ksi = 6.89 MPa.
* Groups 3 and 4
† Groups 5 and 6

70% in most cases. The average losses for all strand types were less than the maximum allowable relaxation losses of 2.5%, and the Grade 300 strands had comparable relaxation properties with respect to the Grade 270 strands.[34]

Bond quality

Large block pull-out tests and the North American Strand Producers (NASP) tests were performed on each strand type used, including Grade 270 (1860 MPa) and Grade 300 (2070 MPa) ½ in. (13 mm) diameter regular strands and Grade 270 and Grade 300 ½ in. diameter super strands. Large block pull-out test specimens for each strand type were cast individually in groups of four strands in a single 24 in. (610 mm) cube. Logan[35] recommends a minimum pullout capacity of 36 kip (160 kN) for ½ in. diameter strands, while recommendations were not given for other strand sizes. A minimum capacity of 39 kip (174 kN) was selected for ½ in. diameter super strands based on the ratio of strand area. NASP test specimens were also cast for each strand type to investigate the bond characteristics of each. Six test specimens were cast for each strand type for a total of 30. Ramirez and Russell[36] recommend a minimum average NASP bond test value of 10.5 kip (46.7 kN) for ½ in. diameter strands with no individual test result below 9.0 kip (40 kN). A minimum average NASP bond test value for ½ in. diameter super strand of 11.5 kip (51.2 kN) and no single test result below 9.8 kip (44 kN) were used based on a ratio of strand areas. All strand types performed with satisfactory results, each exceeding the minimum recommended values, except one set of the ½ in. diameter super strand, which fell slightly below the minimum required average pull-out force of 39 kip for large block pull-out tests and the minimum required value of 11.5 kip for the NASP tests. However, the strand had satisfactory behavior for transfer length, development length, and flexural capacity of the test specimens used in this study.[32]

Transfer-length measurements

A total of 35 transfer lengths were calculated based on concrete surface strain measurements. Concrete surface strains are typically measured using a demountable mechanical (DEMEC) strain gauge and surface-mounted gauge points. The DEMEC gauge had a gauge length of 7.87 in. (200 mm), and the gauge points were approximately ¼ in. (6 mm) in diameter with a small, fine point indentation at the approximate center. The points were placed on the test specimens at the level of the strands at spacings of 1.97 and 3.94 in. (50.0 and 100 mm) and attached using a five-minute epoxy. The points located in the anticipated transfer zone had a spacing of 1.97 in., ensuring a defined ascending branch of the strain plot, while the remaining points located beyond the anticipated transfer zone, corresponding to the strain plateau, had a spacing of 3.94 in. Just prior to the transfer process, initial measurements were obtained by taking the average of three successive measurements. Immediately following the transfer process, the gauge points were measured once more. The difference between the two readings at any one location provides the change in length from when zero prestress force exists to the point at which the entire prestress force is present. The average strain across the gauge length for that location is the change in length divided by the gauge length. All initial transfer-length measurements were completed following a period of moist curing to minimize shrinkage losses. Based on each set of concrete surface strains, strain profiles were created for each transfer zone and the 95% average maximum strain method used to estimate the transfer lengths.[37]

Development length and flexural strength test procedure

A single-point bending test was performed on each end of the 24 ft (7.3 m) long T-beam test specimens with a test span of 16 ft (4.9 m), resulting in one of three types of failure. In this study, a flexural failure was a beam exceeding the calculated nominal moment capacity with less than 0.01 in. (0.25 mm) of average end slip. A hybrid failure was a beam with more than 0.01 in. of average end slip occurring after exceeding the nominal moment capacity, and a bond failure was a beam having more than 0.01 in. average end slip prior to reaching the calculated nominal moment capacity. **Figure 4** shows the test setup for one of the single-point bending tests. The initial location of the point load P and the embedment length l_e from the end of the beam were based on the calculated development length. While one previous study included a length of unbounded strand directly beneath the load point to accentuate cracking and to better estimate the remaining prestress force,[25] the selected embedment lengths used in this study were based on the resulting transfer lengths of each beam end and could not be predetermined. Thus, the test method followed the same procedure used in a number of previous studies.[3,4,11,13,14,17,18,38]

A test resulting in a flexural failure indicated that the selected embedment length was longer than the actual development length, in which case the subsequent test of a new specimen would incorporate a different embedment length corresponding to a shorter flexural bond length. A test resulting in a bond failure indicated that the selected embedment length was shorter than the actual development length, in which case the subsequent test of a new specimen would incorporate a different embedment length corresponding to a longer flexural bond length. This process was repeated for each strand type with the intention of determining the minimum flexural bond length to result in flexural failure. Upon the completion of each test, the tested flexural bond length was taken as the tested embedment length minus the corresponding transfer length ($l_e - l_t$).

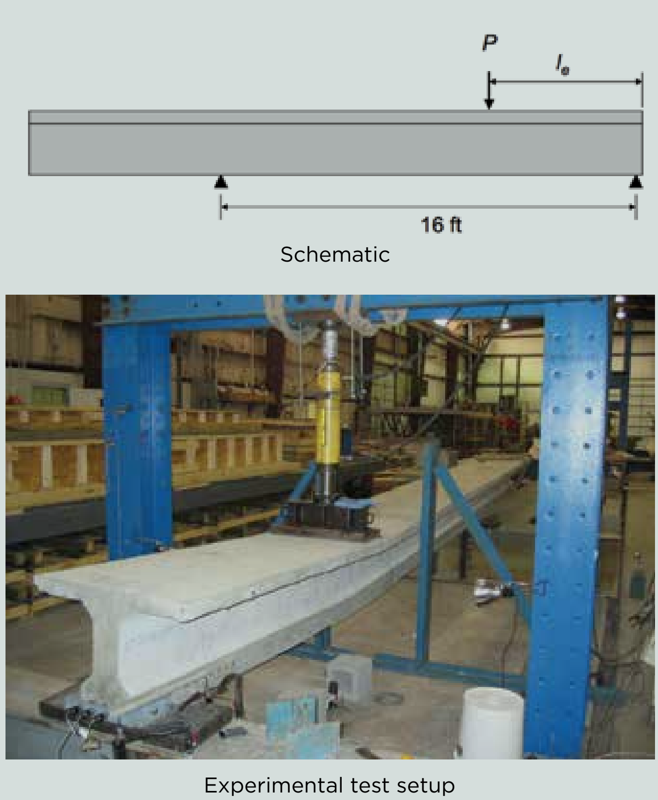

Figure 4. Single-point bending test. Note: l_e = embedment length; P = point load. 1 ft = 0.305 m.

Experimental test results

Transfer length

This study included transfer lengths for 35 transfer zones calculated using measurements of concrete surface strains. Transfer-length measurements for beams containing Grade 270 (1860 MPa) and Grade 300 (2070 MPa) strands were evaluated with respect to location relative to release, strand grade, initial and effective prestress, concrete strength, and vertical casting position and were compared with the current code provisions in ACI 318-14 and the AASHTO LRFD specifications. **Table 3** lists a summary of the transfer-length results, including average, standard deviation, and coefficient of variation.

A number of researchers have shown that the transfer lengths of strands released by and adjacent to a flame cutting process (live end) are longer than those located away from the flame cutting process (dead end). The increases between the average live- to dead-end transfer lengths for beams cast with a normal orientation containing Grade 300 (2070 MPa) and Grade 270 (1860 MPa) strands were 43.3% and 37.4%, respectively. Likewise, the increase between the average live- to dead-end transfer lengths for beams cast with an inverted orientation containing Grade 300 strands was 70.0%, while beams containing Grade 270 strands had an increase of 25.9%. The substantial increase for Grade 300 strands was specific to beams 2.300.5N.U and 3.300.5S.U, which may be the result of the vertical casting position.[26] Otherwise, the results show typical increases in transfer lengths at the live ends with respect to transfer lengths at the dead ends. The results are comparable for the two strand strengths.

In addition to a direct comparison of locations relative to release, a direct comparison was made with respect to strand strength for companion transfer lengths (for example, Grade 300 [2070 MPa] live end compared with Grade 270 [1860 MPa] live end and Grade 300 dead end compared with Grade 270 dead end). The increases between average transfer lengths for Grade 300 strands compared with Grade 270 strands cast with a normal orientation were 5.8% and 1.4% at the live and dead ends, respectively. The increases between average transfer lengths between Grade 300 strands compared with Grade 270 strands for beams cast with an inverted orientation were 40.3% and 3.9% at the live and dead ends, respectively.

A direct comparison was also made of transfer lengths of beams cast with normal and inverted orientations. The average transfer lengths for Grade 300 (2070 MPa) strands at the live ends of inverted beams were 79.2% longer than the average transfer lengths at the live ends of beams cast with a normal orientation. The same comparison at the dead end showed a 51.1% increase. Likewise, average transfer lengths for Grade 270 (1860 MPa) strands were 35.1% and 47.5% longer in beams cast with an inverted orientation at the live and dead ends, respectively. The vertical casting position of the strand appears to have a significant effect on transfer length. A related study by Carroll et al.[26] provides a complete summary of the effect of vertical casting position on transfer and development length.

The effective prestress f_{se} has been used in the calculation of transfer length since the implementation of Eq. (2) in ACI 318. However, previous research shows that transfer lengths may depend more on the stress in the strand just before transfer, or initial prestress f_{si}, than on the effective prestress.[7,9,11,13,17] **Figure 5** shows the relationship of the experimental transfer lengths with respect to effective prestress and initial prestress, which does not reveal any definitive trends. Although the current code provisions do not account for concrete strength, past research shows that transfer length decreases with an increase in concrete strength, especially for strengths in excess of 10,000 psi (69 MPa). The concrete strengths in this study ranged from 4800 to 6400 psi (33 to 44 MPa) at the time of transfer. The transfer-length results were normalized with respect to concrete strength at the time of transfer, but there was no observable effect on the general trend, given the small range of compressive strengths. Therefore, the data were left in their raw form for comparisons. Figure 5 also shows the re-

Table 3. Summary of transfer length results

Beam	Strand grade	Strand size	Orientation	f_{si}, ksi	f_{se}, ksi	f'_{ci}, psi	d_{cast}, in.	l_t, in.	
								Live	Dead
1.270.5N.R	270	½ in.	Normal	179.4	157.8	4900	15	16.7	12.3
2.270.5N.R	270	½ in.	Normal	179.1	162.3	5300	15	18.1	12.5
3.270.5S.R	270	½ in. S	Normal	179.0	158.6	6000	17	21.1	13.6
4.270.5S.R	270	½ in. S	Normal	179.2	157.1	4900	17	17.5	15.5
5.270.5S.R	270	½ in. S	Normal	199.7	162.5	5000	17	20.2	12.8
6.270.5S.R	270	½ in. S	Normal	199.7	174.2	6400	17	20.7	16.7
Average								**19.1**	**13.9**
Standard deviation								**1.8**	**1.8**
Coefficient of variation								**9.6%**	**13.2%**
1.300.5N.R	300	½ in.	Normal	199.4	175.8	4900	15	n/a	14.6
2.300.5N.R	300	½ in.	Normal	199.0	180.0	5300	15	21.2	14.2
3.300.5S.R	300	½ in. S	Normal	198.9	176.3	6000	17	20.8	13.5
4.300.5S.R	300	½ in. S	Normal	199.1	175.1	4900	17	18.4	14.1
5.300.5S.R	300	½ in. S	Normal	221.8	181.1	5000	17	20.6	13.9
Average								**20.2**	**14.1**
Standard deviation								**1.3**	**0.4**
Coefficient of variation								**6.2%**	**2.8%**
2.270.5N.U	270	½ in.	Inverted	179.1	161.9	5300	2	30.2	24.5
3.270.5S.U	270	½ in. S	Inverted	179.0	157.5	6000	2	25.6	19.8
5.270.5S.U	270	½ in. S	Inverted	199.7	162.3	5000	2	26.3	19.9
6.270.5S.U	270	½ in. S	Inverted	199.7	173.5	6400	2	21.3	17.8
Average								**25.8**	**20.5**
Standard deviation								**3.6**	**2.8**
Coefficient of variation								**14.1%**	**13.9%**
2.300.5N.U	300	½ in.	Inverted	199.0	179.1	5300	2	43.3	23.6
3.300.5S.U	300	½ in. S	Inverted	198.9	175.1	6000	2	41.1	21.1
5.300.5S.U	300	½ in. S	Inverted	221.8	180.8	5000	2	24.3	19.2
Average								**36.2**	**21.3**
Standard deviation								**10.4**	**2.2**
Coefficient of variation								**28.7%**	**10.3%**

Note: d_{cast} = depth of concrete cast above strand; f'_{ci} = concrete compressive strength at time of transfer; f_{se} = effective stress in the strand after all losses; f_{si} = stress in the strand just before transfer; l_t = transfer length; n/a = not applicable; S = super. 1 in. = 25.4 mm; 1 psi = 6.895 kPa; 1 ksi = 6.895 MPa.

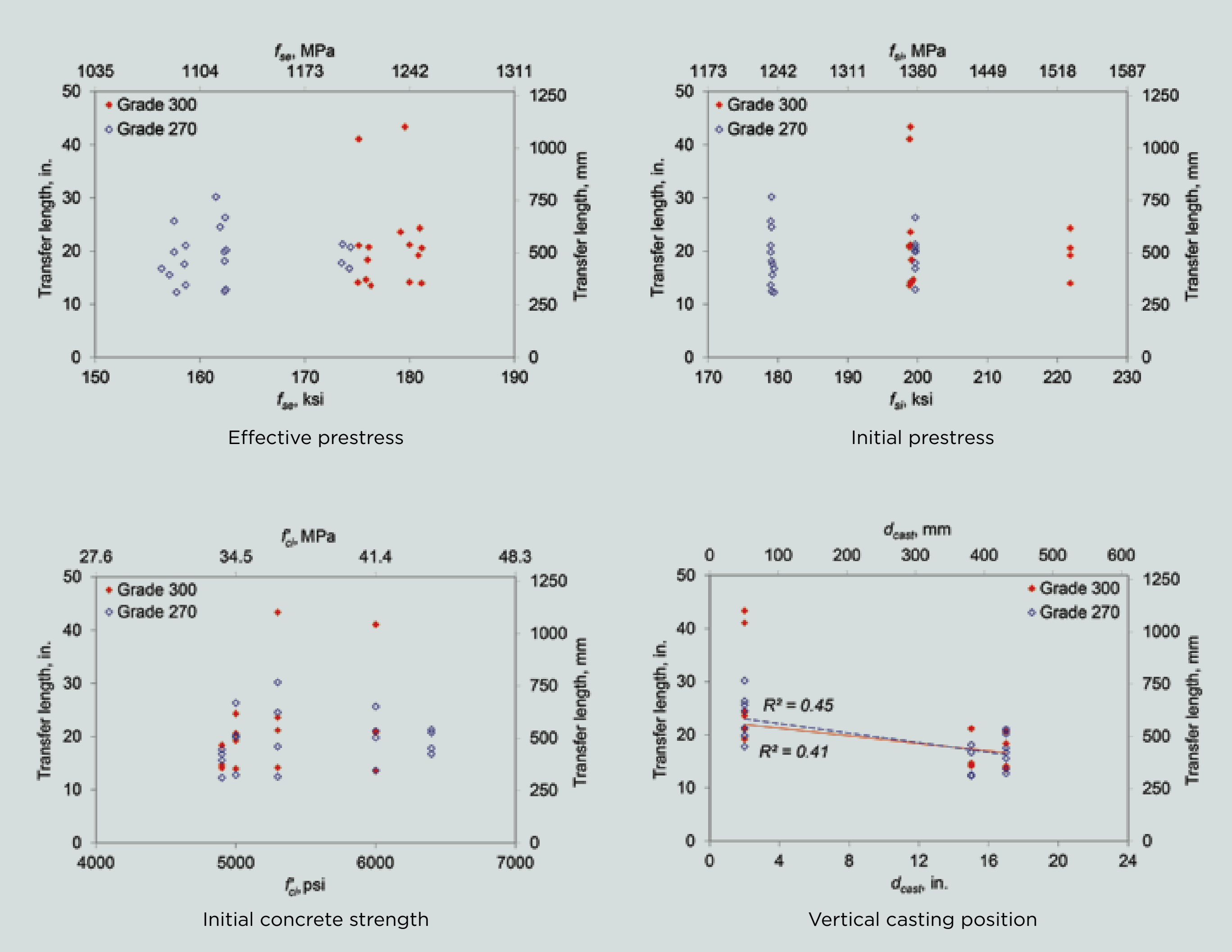

Figure 5. Effect of selected influential factors on transfer length. Note: d_{cast} = depth of concrete cast above strand; f'_{ci} = concrete compressive strength at time of transfer; f_{se} = effective stress in the strand after all losses; f_{si} = stress in the strand just before transfer. Grade 270 = 1860 MPa; Grade 300 = 2070 MPa.

lationship of each experimental transfer length with respect to the concrete strength at the time of transfer but shows no observable trend for transfer lengths of Grade 300 (2070 MPa) strands or those of Grade 270 (1860 MPa) strands.

In addition to strand stress and concrete strength, transfer lengths for both Grade 300 (2070 MPa) strands and Grade 270 (1860 MPa) strands were compared with the vertical casting position. Previous studies show transfer lengths depend more on the amount of concrete cast above the strand than the amount cast below the strand. Therefore, each of the experimental transfer lengths was evaluated with respect to the amount of concrete cast above the strand d_{cast} (Fig. 5). Both Grade 300 and Grade 270 showed good correlation with respect to other comparisons. Excluding the two data points with excessive transfer lengths, the data showed a decrease in transfer length of roughly ½ in. (13 mm) for every 1 in. (25 mm) increase in the amount of concrete cast above the strand.

Furthermore, the experimental transfer lengths were compared with the current code provisions for estimating transfer length. Only one transfer-length measurement for Grade 270 (1860 MPa) strands exceeded the predicted value based on Eq. (2), while two transfer-length measurements for Grade 300 (2070 MPa) strands exceeded the predicted value. Similarly, when compared with the assumed value of $50d_b$, three transfer-length measurements for Grade 270 strands and two transfer-length measurements for Grade 300 strands exceeded the predicted value of 25 in. (635 mm). When compared with the increased value of $60d_b$, one transfer-length measurement for Grade 270 strand slightly exceeded the predicted value of 30 in. (762 mm), while two transfer lengths for the Grade 300 strands exceeded the predicted value of 30 in. Thus, the current code provisions appear to provide consistent estimates for transfer lengths of both Grade 270 and Grade 300 prestressing strand with the exception of the two data points with excessive transfer lengths.

Development length

This study also includes the results of 35 single-point bending tests performed on the T-beam test specimens, each test resulting in one of three types of failure: flexural, hybrid, or bond, as previously defined. The development length of prestressing strand consists of two components: transfer length and flexural bond length. Analogous to transfer length, various contributing factors may affect the flexural bond length, such as the required increase in strand stress, the concrete strength, and vertical casting position. The tested flexural bond length is taken as the embedment length minus the respective measured transfer length ($l_e - l_t$). The tested flexural bond length and corresponding types of failure were compared with each of these factors. **Table 4** shows a summary of the flexural bond length results and flexural test results, including failure type, ultimate capacities, and displacement ductility.

The influence of strand strength was first evaluated. For test specimens containing ½ in. (13 mm) diameter Grade 300 (2070 MPa) strands, the minimum tested flexural bond length resulting in a flexural failure was 45.9 in. (1170 mm), while the minimum tested flexural bond length resulting in a flexural failure for test specimens containing ½ in. diameter Grade 270 (1860 MPa) strands was 47.6 in. (1210 mm), showing relatively no difference in flexural bond length. For test specimens containing ½ in. diameter super Grade 300 strands, the minimum flexural bond length resulting in flexural failure was 45.4 in. (1150 mm), while the minimum flexural bond length resulting in flexural failure for test specimens containing ½ in. diameter super Grade 270 strands was 46.1 in. (1170 mm). Overall, the Grade 300 strand performed very similarly to the Grade 270 strand.

The difference in the stress in the strand at the nominal moment capacity f_{ps} and the effective prestress f_{se} is part of Eq. (3) used for the calculation of the flexural bond length in the current code provisions and is an influential factor in numerous proposed equations for the calculation of flexural bond length. **Figure 6** shows each tested flexural bond length and corresponding type of failure with respect to $f_{ps} - f_{se}$. Although studies show that $f_{ps} - f_{se}$ is a known influential factor for flexural bond length, neither an increase nor decrease was observed for the tested flexural bond lengths in this study. Like transfer length, the current code provisions do not account for the strength of concrete in the calculation of flexural bond length. The concrete strengths in this study ranged from 6300 to 8300 psi (43.5 to 57.3 MPa) at the time of testing. Figure 6 also shows the tested flexural bond lengths and corresponding type of failure with respect to concrete strength, but again, there is no apparent relationship between flexural bond length and the given range of concrete strengths. Flexural bond lengths appear constant regardless of concrete strength. As previously discussed, research shows that transfer length depends more on the amount of concrete cast above the strand than the amount of concrete cast below the strand. Therefore, the tested flexural bond length from each test was compared with the amount of concrete cast above the strand. Figure 6 shows the relationship of the tested flexural bond length with corresponding type of failure and the amount of concrete cast above the strand. There is no apparent correlation between the tested flexural bond lengths resulting in flexural failures and the amount of concrete cast above the strand.

Historically, development length is calculated by Eq. (1) taking into consideration the effective prestress in the strand after all losses, stress in the strand at the nominal moment capacity, and the diameter of the strand. The second part of Eq. (1) estimates the flexural bond length required to increase the stress in the strand from the effective prestress to the stress in the strand at the nominal moment capacity. The tested flexural bond lengths were compared with the predicted flexural bond lengths based on the current code provisions. **Figure 7** shows the comparison. All of the tested flexural bond lengths resulting in a hybrid or bond failure for both Grade 300 (2070 MPa) and Grade 270 (1860 MPa) strands fall below the line of perfect correlation. On the contrary, all of the tested flexural bond lengths resulting in a flexural failure for both Grade 300 and Grade 270 strands fall near the line of perfect correlation. The tested flexural bond lengths appear to increase, while the predicted flexural bond lengths remain relatively constant. Although there is no definitive trend, Eq. (3) provides sufficient values for the prediction of flexural bond length for both Grade 300 and Grade 270 strands.

Flexural strength

The flexural strength of a prestressed concrete member is its ability to resist externally applied moment with equal and opposite internal forces. The current code provisions estimate the flexural strength of prestressed concrete members using the equivalent rectangular stress block method. The tensile force is taken as the product of the stress in the strand at flexural strength and the total area of prestressed tensile reinforcement. The current code provisions estimate the stress in the strand at flexural strength using Eq. (4) and (5). The stress in the strand at flexural strength and the nominal moment capacity were calculated for each beam based on the actual material properties and levels of effective prestress. The experimental flexural strength was determined for each beam through single-point bending tests. However, only the results of beams having a flexural failure with less than 0.01 in. (0.25 mm) of slip are included in the comparisons.

The average experimental flexural strength was 184 and 164 kip-ft (249 and 222 kN-m) for beams containing ½ in. (13 mm) diameter Grade 300 (2070 MPa) and Grade 270 (1860 MPa) strands, respectively. The beams containing

Table 4. Summary of flexural bond length results

Beam	Strand grade	Strand size, in.	Orientation	$f_{ps} - f_{se}$, ksi	f_c', psi	d_{cast}, in.	$l_e - l_t$, in.	Failure type	M_{ACTUAL}, kip-ft	M_{ACTUAL}/M_{AASHTO}	μ
1.270.5N.RA	270	½	Normal	107	6500	15	61.3	Flexural	171	1.19	2.79
2.270.5N.RA	270	½	Normal	101	6400	15	47.9	Flexural	181	1.26	3.72
3.270.5S.RA	270	½ S	Normal	106	8200	17	38.9	Hybrid	201	1.11	4.65
4.270.5S.RA	270	½ S	Normal	105	6300	17	36.5	Bond	176	0.98	n/a
5.270.5S.RA	270	½ S	Normal	101	6500	17	39.8	Bond	197	1.10	2.76
6.270.5S.RA	270	½ S	Normal	90	8300	17	33.3	Hybrid	206	1.10	3.52
1.300.5N.RA	300	½	Normal	116	6500	15	n/a	n/a	n/a	n/a	n/a
2.300.5N.RA	300	½	Normal	112	6400	15	26.8	Bond	142	0.89	n/a
3.300.5S.RA	300	½ S	Normal	117	8200	17	39.3	Hybrid	226	1.13	1.95
4.300.5S.RA	300	½ S	Normal	116	6300	17	47.6	Bond	208	1.05	n/a
5.300.5S.RA	300	½ S	Normal	111	6500	17	45.4	Flexural	222	1.13	2.74
1.270.5N.RB	270	½	Normal	106	6500	15	53.7	Flexural	165	1.15	2.35
2.270.5N.RB	270	½	Normal	101	6400	15	47.6	Flexural	138	0.96	3.87
3.270.5S.RB	270	½ S	Normal	106	8200	17	58.4	Flexural	211	1.17	3.93
4.270.5S.RB	270	½ S	Normal	107	6300	17	50.5	Flexural	206	1.16	3.17
5.270.5S.RB	270	½ S	Normal	101	6500	17	41.2	Hybrid	200	1.12	3.86
6.270.5S.RB	270	½ S	Normal	90	8300	17	43.3	Hybrid	204	1.13	4.30
1.300.5N.RB	300	½	Normal	116	6500	15	63.4	Flexural	181	1.14	2.76
2.300.5N.RB	300	½	Normal	112	6400	15	45.9	Flexural	188	1.18	2.71
3.300.5S.RB	300	½ S	Normal	117	8200	17	58.5	Flexural	230	1.15	2.95
4.300.5S.RB	300	½ S	Normal	117	6300	17	63.9	Flexural	237	1.20	2.41
5.300.5S.RB	300	½ S	Normal	111	6500	17	40.1	Bond	198	1.00	n/a
2.270.5N.UA	270	½	Inverted	102	6400	2	35.8	Hybrid	181	1.26	3.75
3.270.5S.UA	270	½ S	Inverted	107	8200	2	34.4	Bond	182	1.01	n/a
5.270.5S.UA	270	½ S	Inverted	101	6500	2	39.7	Bond	189	1.06	2.06
6.270.5S.UA	270	½ S	Inverted	91	8300	2	50.7	Hybrid	205	1.14	2.97
2.300.5N.UA	300	½	Inverted	113	6400	2	34.7	Bond	190	1.20	2.58
3.300.5S.UA	300	½ S	Inverted	118	8200	2	18.9	Bond	153	0.76	n/a
5.300.5S.UA	300	½ S	Inverted	111	6500	2	35.7	Bond	219	1.11	1.88
2.270.5N.UB	270	½	Inverted	102	6400	2	35.5	Hybrid	167	1.16	1.67
3.270.5S.UB	270	½ S	Inverted	107	8200	2	52.2	Flexural	203	1.13	4.17
5.270.5S.UB	270	½ S	Inverted	102	6500	2	46.1	Flexural	202	1.13	4.23
6.270.5S.UB	270	½ S	Inverted	91	8300	2	36.2	Bond	185	1.03	n/a
2.300.5N.UB	300	½	Inverted	113	6400	2	36.4	Hybrid	193	1.21	1.91
3.300.5S.UB	300	½ S	Inverted	118	8200	2	50.9	Flexural	225	1.13	2.51
5.300.5S.UB	300	½ S	Inverted	112	6500	2	34.8	Bond	197	1.00	n/a

Note: d_{cast} = depth of concrete cast above strand; f_c' = concrete compressive strength; f_{ps} = stress in the prestressing strand at nominal moment capacity; f_{se} = effective stress in the strand after all losses; l_e = embedment length; l_t = transfer length; M_{ACTUAL} = tested flexural strength; M_{AASHTO} = nominal flexural strength (AASHTO LRFD specifications); n/a = not applicable; S = super; μ = displacement ductility ratio. 1 in. = 25.4 mm; 1 kip-ft = 1.356 kN-m; 1 psi = 6.895 kPa; 1 ksi = 6.895 MPa.

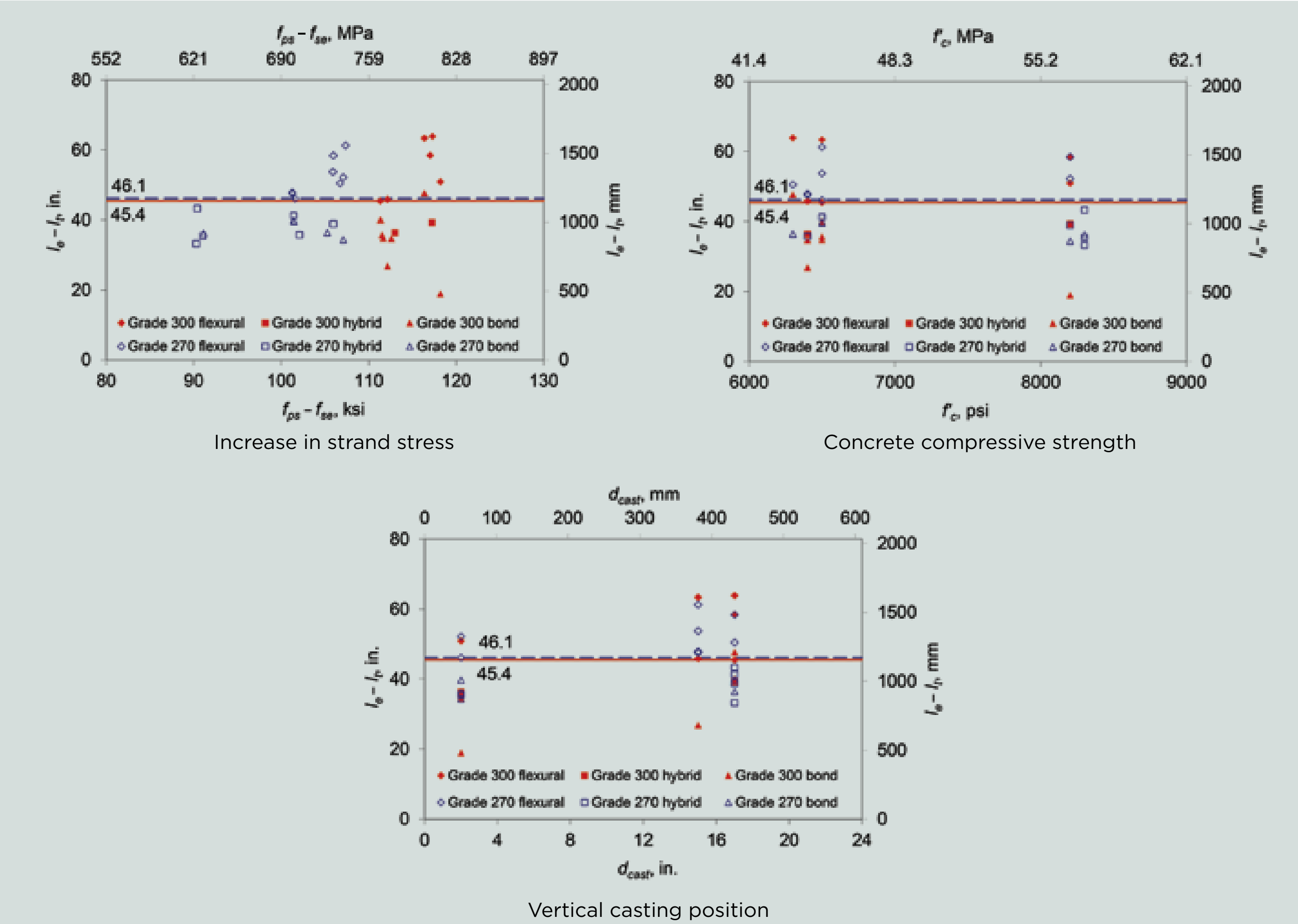

Figure 6. Effect of selected influential factors on flexural bond length. Note: d_{cast} = depth of concrete cast above strand; f_c' = concrete compressive strength; f_{ps} = stress in the prestressing strand at nominal moment capacity; f_{se} = effective stress in the strand after all losses; l_e = embedment length; l_t = transfer length. Grade 270 = 1860 MPa; Grade 300 = 2070 MPa.

Grade 300 strands had a 12.6% higher flexural strength than those containing Grade 270 strands. The average experimental flexural strength was 228 and 206 kip-ft (310 and 279 kN-m) for beams containing ½ in. diameter super Grade 300 and Grade 270 strands, respectively. The beams containing Grade 300 strands had an 11.1% higher flexural strength than those containing Grade 270 strands.

The experimental flexural strengths for each beam were compared with the nominal moment capacities calculated using the current AASHTO LRFD specifications. Beams containing Grade 300 (2070 MPa) strands had 15.3% higher experimental flexural strengths than the nominal moment capacity estimated by the current code provisions. Likewise, beams containing Grade 270 (1860 MPa) strands had 14.2% higher experimental flexural strengths than the nominal moment capacity estimated by the current code provisions. Like the current code provisions for transfer and development length, the current code provisions for the calculation of flexural strength produce satisfactory values.

Last, the displacement ductility ratio μ was calculated for each T-beam specimen when possible using Eq. (6), but only those beams having a flexural failure were compared. The average displacement ductility ratio for beams containing Grade 300 strands was 2.68, while the average displacement ductility ratio for beams containing Grade 270 strands was 3.53. Beams containing Grade 300 strands appear to be 24.1% less ductile than beams containing Grade 270 strands, but there were a limited number of data points available for the comparison. Ductility tends to increase with an increase in concrete compressive strength through a reduction in the depth to the neutral axis.

However, this trend is not definitive for the T beams evaluated in this study. **Figure 8** shows the displacement ductility ratios plotted with respect to concrete compressive strength. The displacement ductility ratios for beams containing both Grade 300 and Grade 270 strands appear to be relatively constant, regardless of concrete strength.

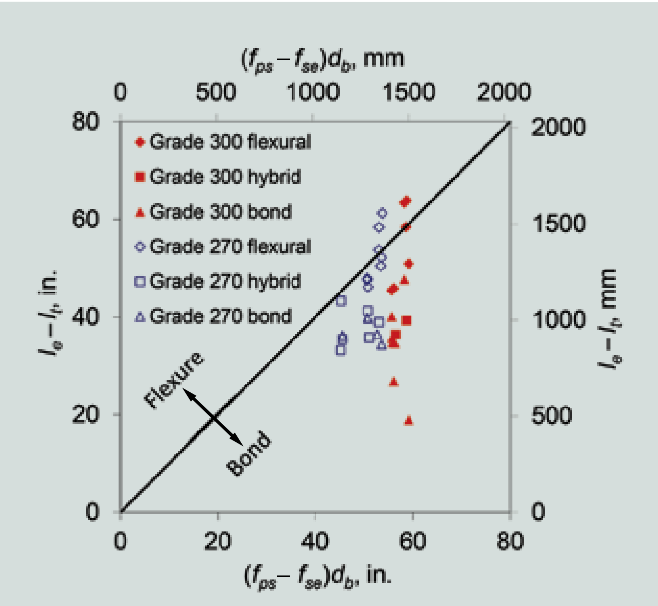

Figure 7. Tested flexural bond length versus predicted ACI/AASHTO flexural bond length. Note: d_b = strand diameter; f_{ps} = stress in the prestressing strand at nominal moment capacity; f_{se} = effective stress in the strand after all losses; l_e = embedment length; l_t = transfer length.

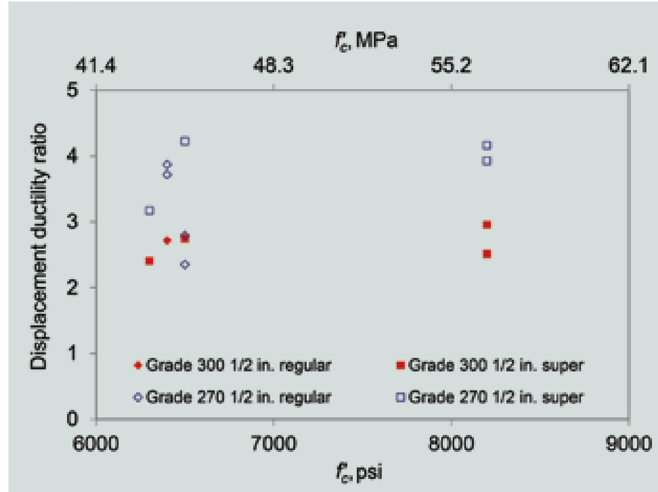

Figure 8. Displacement ductility ratio compared with concrete compressive strength. Note: f'_c = concrete compressive strength. 1 in. = 25.4 mm; Grade 270 = 1860 MPa; Grade 300 = 2070 MPa.

$$\mu = \frac{\delta_u}{\delta_y} \tag{6}$$

where

δ_u = deflection corresponding to ultimate moment

δ_y = deflection corresponding to yield moment

Conclusion

The use of Grade 300 (2070 MPa) prestressing strand in pretensioned, prestressed concrete beams was investigated. The study included a total of 35 transfer zones and 35 flexural tests, resulting in transfer-length measurements and the determination of minimum flexural bond lengths required for flexural strength and the flexural strength for beams containing Grade 300 and Grade 270 (1860 MPa) strands. Included was an evaluation with respect to selected known influential factors along with direct comparisons for Grade 300 and Grade 270 strands. The results show slight increases in transfer lengths for Grade 300 strands compared with Grade 270 strands, except for those cast near the top of a specimen at the live end, which showed a greater increase. Among the known influential factors, the vertical casting position appears to have a greater influence on transfer length. The minimum flexural bond length resulting in flexural failures for beams containing Grade 300 strands was 45.4 in. (1150 mm), while the minimum flexural bond length resulting in a flexural failure for beams containing Grade 270 strands was 46.1 in. (1170 mm). The results for flexural bond length had no apparent correlation to any of the influential factors investigated. Beams containing Grade 300 strands had more than 10% higher flexural strengths than beams containing Grade 270 strands, as expected. However, beams containing Grade 300 strands appear to be less ductile than beams containing Grade 270 strands.

Also included was an evaluation of the current code provisions for use with the Grade 300 (2070 MPa) strand in pretensioned, prestressed concrete members. The current code provisions provide estimates for transfer length, most of which were higher than the experimental values, with the exception of a few data points. Likewise, code provisions for flexural bond length produce consistent values with respect to all tested flexural bond lengths. Furthermore, the experimental values consistently exceeded the flexural strengths predicted by the current code provisions for flexural strength, which were 15% and 14% higher than predicted values for beams containing Grade 300 and Grade 270 (1860 MPa) strands, respectively. Overall, the current code provisions produce acceptable values for the estimation of transfer length, flexural bond length, and flexural strength of pretensioned, prestressed concrete members containing Grade 300 and Grade 270 strands. The current code provisions appear adequate for use with Grade 300 prestressing strand, with the exception of the transfer length of strands cast near the top of a section. Furthermore, the results show an apparent decrease in ductility for beams containing Grade 300 strands compared with counterpart beams containing Grade 270 strands. Although ultimate elongations were satisfactory with regard to ASTM standards, the observable decrease in ductility is worth further investigation.

In conclusion, Grade 300 (2070 MPa) strands had behavior similar to Grade 270 (1860 MPa) strands when used in pretensioned, prestressed concrete beams. The use of Grade 300 strands in lieu of Grade 270 strands would increase flexural capacities and has the potential to reduce the number of beams required to resist a given load. While the small range of concrete strengths in this study had no apparent effect on the overall behavior, using Grade 300 strands coupled with higher-strength concrete would likely be the most efficient use of materials to produce the highest flexural strengths and potentially increase the ductility by increasing the strain in the strand at the time of failure.

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Notation

c = distance from extreme compressive fiber to neutral axis

d = distance from extreme compressive fiber to centroid of longitudinal tension reinforcement

d_b = strand diameter

d_{cast} = depth of concrete cast above strand

d_p = distance from extreme compressive fiber to centroid of prestressing steel

f_c' = concrete compressive strength

f_{ci}' = concrete compressive strength at time of transfer

f_{ps} = stress in the prestressing strand at nominal moment capacity

f_{pu} = specified minimum tensile strength of prestressing strand

f_{py} = yield stress of prestressing steel

f_{se} = effective stress in the strand after all losses

f_{si} = stress in the strand just before transfer

f_y = specified yield strength for nonprestressed reinforcement

k = coefficient for type of prestressing steel

l_d = development length

l_e = embedment length

l_{fb} = flexural bond length

l_t = transfer length

M_{AASHTO} = nominal flexural strength (AASHTO LRFD specifications)

M_{ACTUAL} = tested flexural strength

P = point load

β_1 = factor relating depth of equivalent rectangular compressive stress block to neutral axis depth

γ_p = factor for type of prestressing steel based on the ratio of f_{py}/f_{pu}

μ = displacement ductility ratio

δ_u = deflection corresponding to ultimate moment

δ_y = deflection corresponding to yield moment

ρ = ratio of nonprestressed tension reinforcement

ρ' = ratio of nonprestressed compression reinforcement

ρ_p = ratio of prestressed longitudinal tension reinforcement

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Abstract

The current editions of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications* and ACI 318-14 are based on years of experimental research and use the traditional 270 ksi (1860 MPa) prestressing strand. Recent developments have resulted in a higher-strength strand with an ultimate tensile strength of 300 ksi (2070 MPa). This paper presents the results of an experimental investigation looking at the behavior of pretensioned, prestressed concrete members containing 300 ksi prestressing strands. Eighteen T-beam test specimens were fabricated and used to evaluate the effects of using the higher-strength strand on transfer and development lengths as well as flexural capacity and ductility. The results from 35 transfer zones and 35 flexural tests are compared with a variety of known influential factors and the current code provisions for transfer and development length and nominal moment capacity. The results are also evaluated with respect to the tensile strength of the strand.

Keywords

Code, development length, ductility, flexural strength, Grade 300, high-strength strand, prestressing strand, T beam, tensile strength, transfer length.

Review policy

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

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