Measured Transfer Lengths of 0.5 and 0.6 in. Strands in Pretensioned Concrete

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Transfer lengths were measured for both 0.5 and 0.6 in. (12.7 and 15.2 mm) diameter strands for a wide variety of research variables that included strand spacing, debonding strand, confining reinforcement, number of strands per specimen and size and shape of the cross section. Overall, the test results indicate that the transfer bond characteristics for 0.6 in. (15.2 mm) strands are very similar to the bond behavior for 0.5 in. (12.7 mm) strands. Furthermore, average measured transfer lengths for both sizes of strand are marginally predicted by current AASHTO and ACI Code provisions. These results clearly demonstrate that 0.6 in. (15.2 mm) strands can be safely employed in pretensioned concrete members with spacings of 2 in. (50.8 mm). However, the ranges of measured transfer lengths clearly indicate that a significant proportion of actual measured transfer lengths exceed the current design recommendations of either $50d_b$ *or* $f_{se}d_b/3$*. Therefore, to incorporate a more consistent level of safety, transfer lengths should be approximated by the expression* $f_{se}d_b/2$*.*

In pretensioned concrete, transfer length is the distance required to transmit the fully effective prestressing force from the strand to the concrete. Stated another way, transfer length is the length of bond from the free end of the strand to the point where the prestressing force is fully effective. The transfer zone is defined as the region of concrete spanned by the transfer length.

An idealization of steel stresses is shown in Fig. 1. Stresses in the pretensioned steel vary from zero at the free end of the strand, and increase throughout the transfer zone until the prestress force is fully effective. Increases in strand tension come about by bond stresses that restrain, or hold back, the strand. At the point of full transfer, the stress in the steel remains constant over the length. This is represented by the horizontal portion of the curve.

Concrete and steel forces must be in equilibrium at every point along the length. Tension in the steel is always balanced by equivalent compression in the concrete. Therefore, the variation of steel strain is mirrored by the variation in concrete strain. The idealization of Fig. 1 is confirmed by actual strain measurements from Specimen FCT350-3, shown in Fig. 2.

The increase in concrete strain at each end of the specimen demonstrates the transfer of prestress force into the concrete. A transfer zone is found at each end of every pretensioned element, evidenced by the increasing strains in the concrete. The strain plateau in the interior of the specimen distinguishes the region where the prestress force is fully effective.

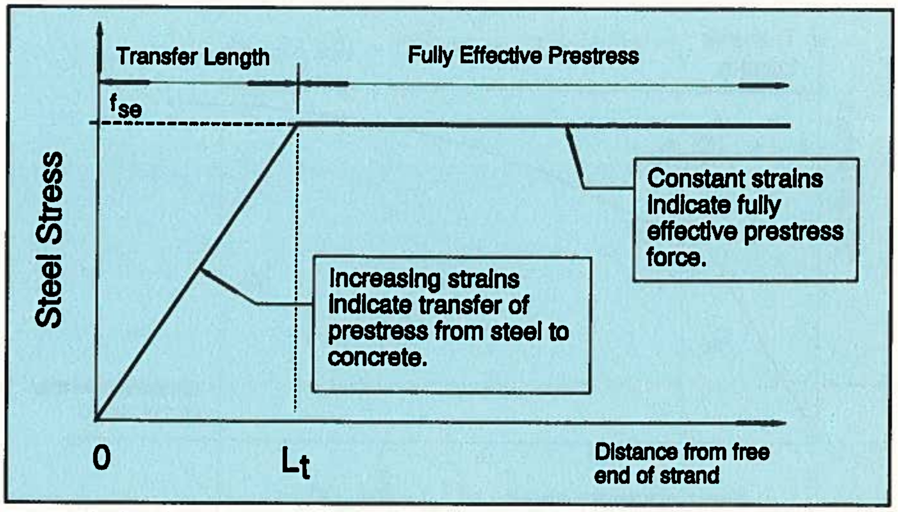

Fig. 1. Idealized steel stress vs. length for pretensioned strand.

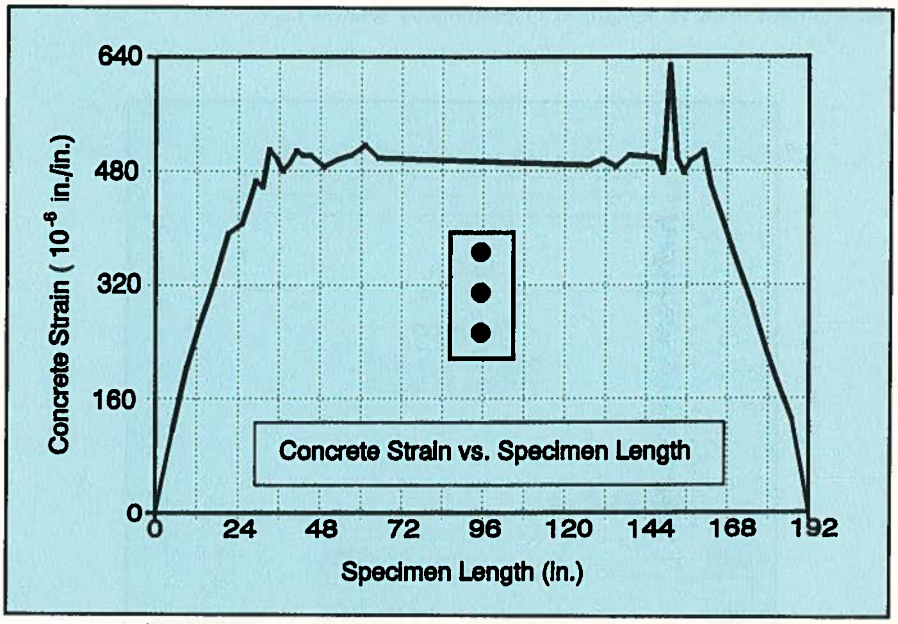

Fig. 2. Typical strain profile for pretensioned concrete, Specimen FCT350-3.

CURRENT CODE PROVISIONS

Neither the "ACI Building Code Requirements for Structural Concrete (ACI 318-95)"[1] nor the *AASHTO Standard Specifications for Highway Bridges*[2] compel a transfer length requirement. However, both codes suggest a transfer length of 50 strand diameters, or $50d_b$ (ACI Section 11.4.4 and AASHTO Article 9.20.2.4).

This recommendation is located in the shear provisions of each code. Section 12.9 of the ACI Commentary to the Building Code provides a formula for transfer length based on the effective prestressing force and strand diameter, derived from the expression for development length. The suggested transfer length is given by:

$$L_t = \frac{f_{se}}{3} d_b \qquad (1)$$

Fig. 3 shows the ACI Commentary assumption for transfer and development of stress in the strand. Steel stress is plotted vs. the "distance from the free end of strand." The transfer length is represented in the first and steeper portion of the curve.

Variations in steel stress are represented in two sections, the "transfer length" and the "flexural bond length." In the flexural bond zone, the steel stress is shown to increase beyond f_{se} as strand tension increases in response to external loads. The term "flexural bond length" shown in Fig. 3 is defined as the additional bond length required to develop the strand tension necessary to resist external loads. Summing the transfer length with the flexural bond length gives the ACI 318, Section 12.9.1 requirements for development length:

$$L_d = \frac{1}{3} f_{se} d_b + \left(f_{ps} - f_{se}\right) d_b$$
$$= \left(f_{ps} - \frac{2}{3} f_{se}\right) d_b \qquad (2)$$

Current ACI and AASHTO Code provisions for both the transfer length and development length are based on assumed values for bond stresses. These values for bond stress are empirical and are based on transfer length testing performed by Janney,[3] and Hanson and Kaar.[4] The assumed average transfer bond stress per ACI 318 can be calculated by solving equilibrium on the strand where the total bond force must equal the effective prestress force:

$$L_t u_b P_{ps} = f_{se} A_{ps} \qquad (3)$$

Substituting the ACI Commentary expression for transfer length gives the following expression:

$$L_t = \frac{f_{se}}{3} d_b = \frac{f_{se}}{u_b} \left(\frac{A_{ps}}{P_{ps}} \right) \qquad (4)$$

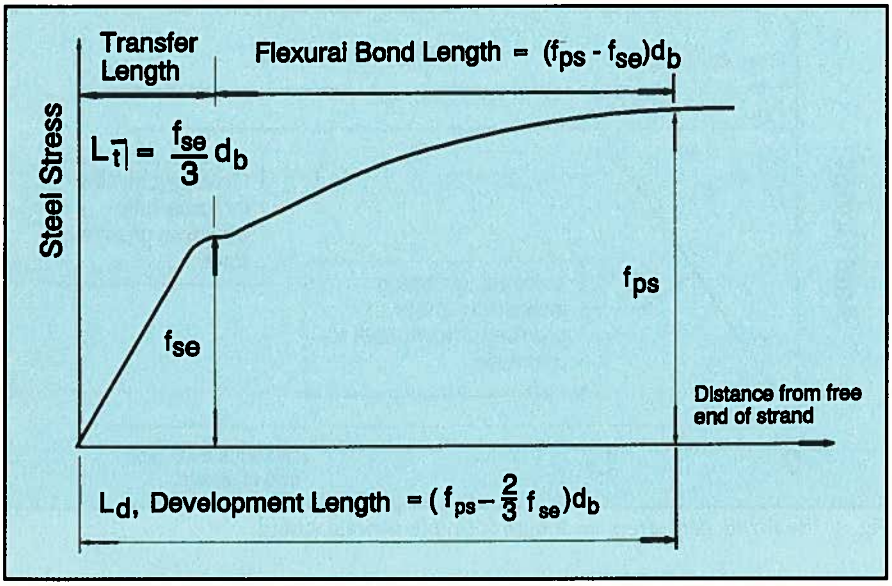

Fig. 3. Strand stress vs. length, ACI Commentary Section 12.9.

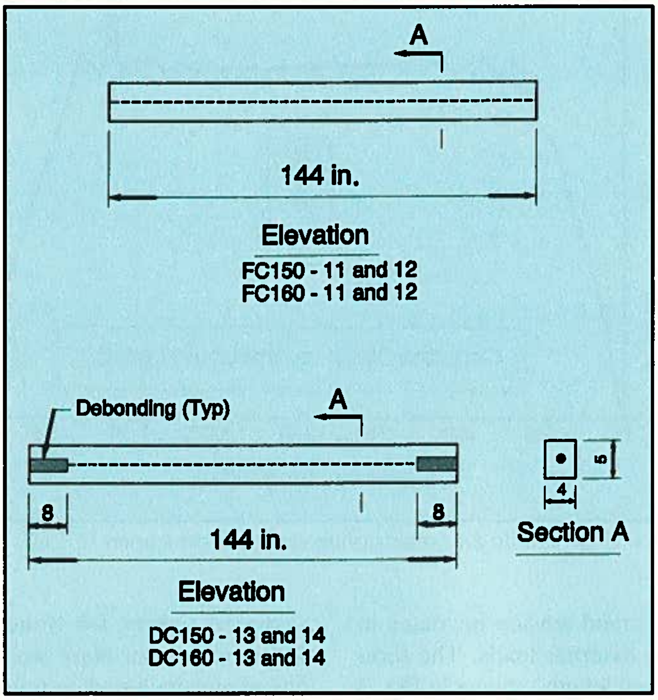

Fig. 4. Details of single-strand transfer length specimens.

If $A_{ps} = 7/36\pi d_b^2$ and $P_{ps} = 4/3\pi d_b$, then the equation can be solved directly to obtain the average transfer bond stress, u_b:

$$u_b = 438 \text{ psi} \approx 916 \text{ lbs per in. for 0.5 in. strand} \quad (5)$$

[Authors' Note: The authors suggest that bond stresses be expressed in terms of force per unit length to avoid confusion that is caused by expressing bond stress as force per unit area. Because of the irregular geometry of a seven-wire strand, one is never sure whether reported bond stress is taken over a perimeter of πd_b or $4/3\pi d_b$.]

The code treats flexural bond in a similar manner, but its assumed average value is lower by a factor of three. Average flexural bond stresses were derived empirically from flexural bond tests.[4] Using the same method described above, the empirical value for the average flexural bond stress, u_f, that is used in the ACI development length expression is:

$$u_f = 146 \text{ psi} \approx 305 \text{ lbs per in.} \quad (6)$$

The average flexural bond stress is less than transfer bond stresses largely because flexural cracking occurs within the flexural bond length and disturbs bonding between steel and concrete, thereby reducing bond strength.

The ACI Commentary acknowledges other factors that may affect transfer length, such as low slump concrete and the strand's surface condition. Low slump concrete may cause longer transfer lengths if the concrete is not properly consolidated. Additionally, the importance of surface condition is recognized. Strands that are slightly rusted have been shown to have shorter transfer lengths.[1,4,5,6,7,8]

Conversely, strands that are lubricated demonstrate significantly longer transfer lengths. In fact, surface condition of the strand has been shown to be the single biggest variable in estimating the transfer length of pretensioned strand.[7,9] As such, the strand surface condition should be of primary concern for designs when transfer length is critical to structural performance.

Concrete strength is reported as a non-factor in transfer length under current design codes. Tests performed by Kaar, LaFraugh and Mass[6] indicated that concrete strength did not affect the transfer length. However, more recent research suggests that concrete strengths do affect transfer lengths.[10,11] These tests indicate that stronger concrete results in shorter transfer lengths.

TRANSFER LENGTH: ITS IMPORTANCE AND USE

Transfer length is a structural requirement only in that the transfer of prestressing force is essential to maintain the integrity of the structure. However, small variations in transfer length will not normally control the design or alter the performance of pretensioned concrete structures. Consequently, an exact value for transfer length may not be necessary to design and build safe concrete structures.

AASHTO and ACI suggest a trans-

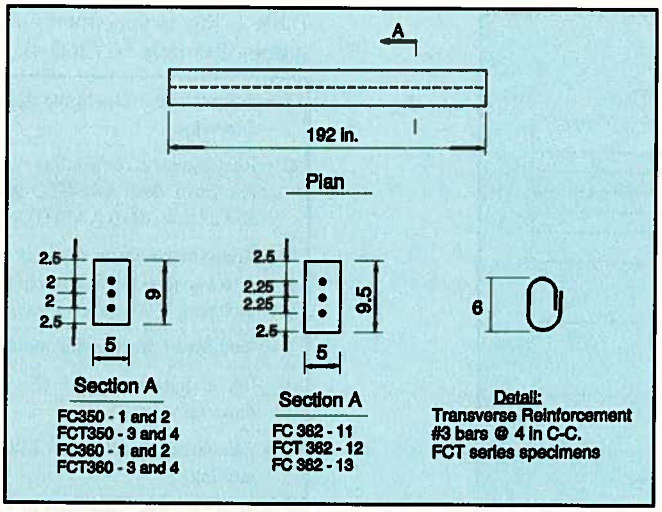

Fig. 5. Details of fully bonded three-strand transfer length specimens.

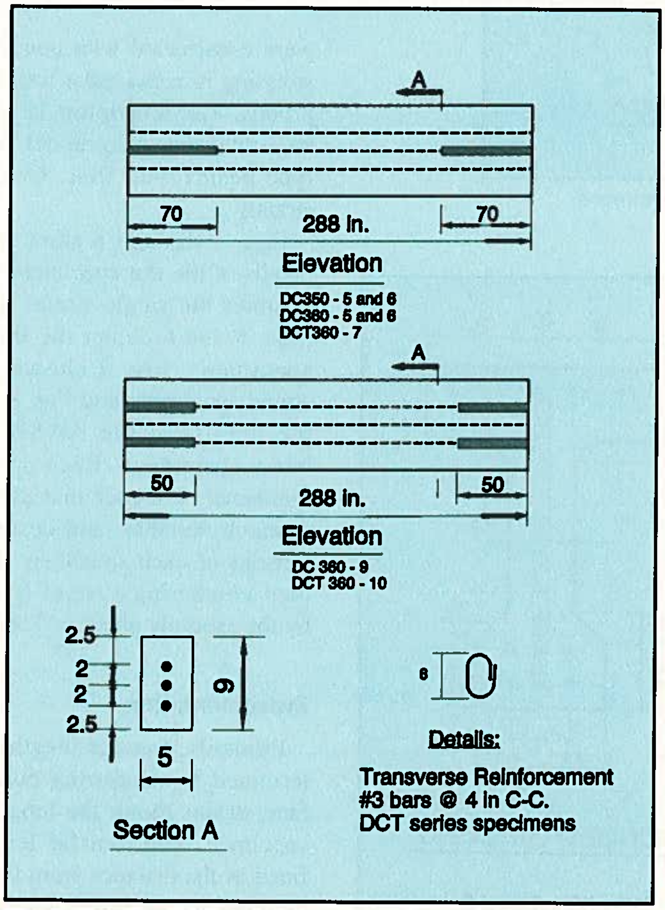

Fig. 6. Details of debonded three-strand transfer length specimens.

fer length of 50 strand diameters ($50d_b$). They also recommend the assumption that the effective prestress force varies linearly from zero at the free end of the strand to the maximum prestress force over the transfer length. These suggestions are provided so that the designer can calculate the concrete's contribution to shear strength, V_c, which is, in current design, either the web cracking shear (V_{cw}) or inclined cracking shear (V_{ci}).

One problem with this approach is that shear cracking has been shown to cause anchorage failure of the strand. Flexural tests demonstrate that when anchorage failure occurs, not only is the concrete contribution to shear strength lost, but the tension required from prestressing strand is also lost. A simple truss model for shear demonstrates that loss of the bottom tension chord will result in a shear failure of the structure. Consequently, current code provisions for shear may not preclude bond/shear failures in some pretensioned members. This behavior is discussed in greater detail in Ref. 12.

Tests performed at the University of Texas at Austin[12] and at the University of Oklahoma[13] demonstrate that transfer length is very important in accurately predicting strand development failures. In the ultimate limit state for highway girders, both the flexural capacity and shear capacity of pretensioned beams are affected by the transfer length.

Testing consistently demonstrates that if a crack propagates through or near the transfer zone of a pretensioned strand, then that crack can be expected to generate general bond slip. Because either flexural cracking or shear cracking can occur in the transfer zone of a strand, it is important to predict and/or prevent both types of cracks within the transfer zone. Therefore, to prevent cracking within the transfer zone, a reliable transfer length is important to accurately predict cracking loads and the location of cracking.

In summary, transfer length has been shown to significantly affect structural behavior in many design cases, indicated by testing where the interaction between cracking through or near the transfer zone caused failure of strand anchorage. Therefore, it is important to understand the design cases where transfer length can control behavior, and to adjust structural design and detailing accordingly.

TRANSFER LENGTH TESTS

Transfer lengths were measured on a wide variety of research variables and on different sizes and types of cross sections. The variables included:

1. Number of strands (1, 3, 4, 5, and 8)

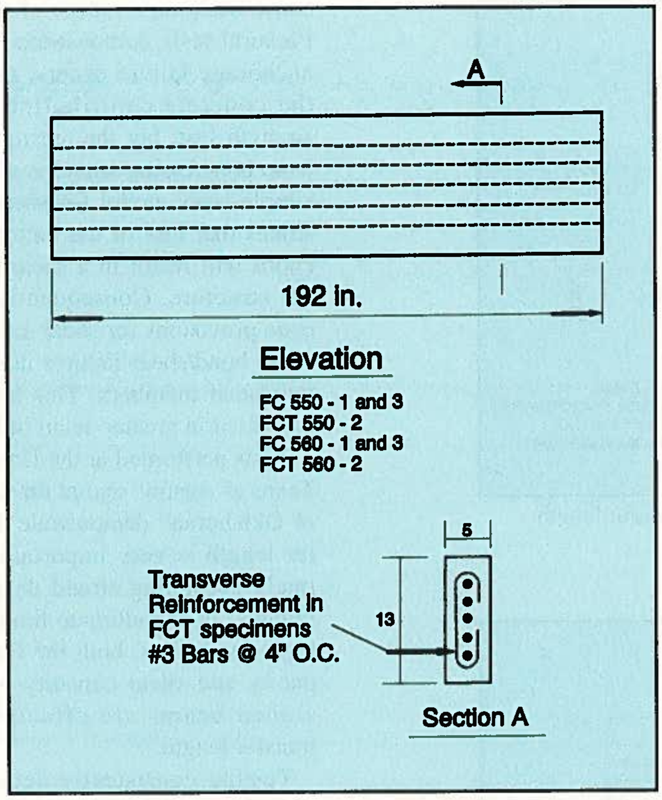

Fig. 7. Details of five-strand transfer length specimens.

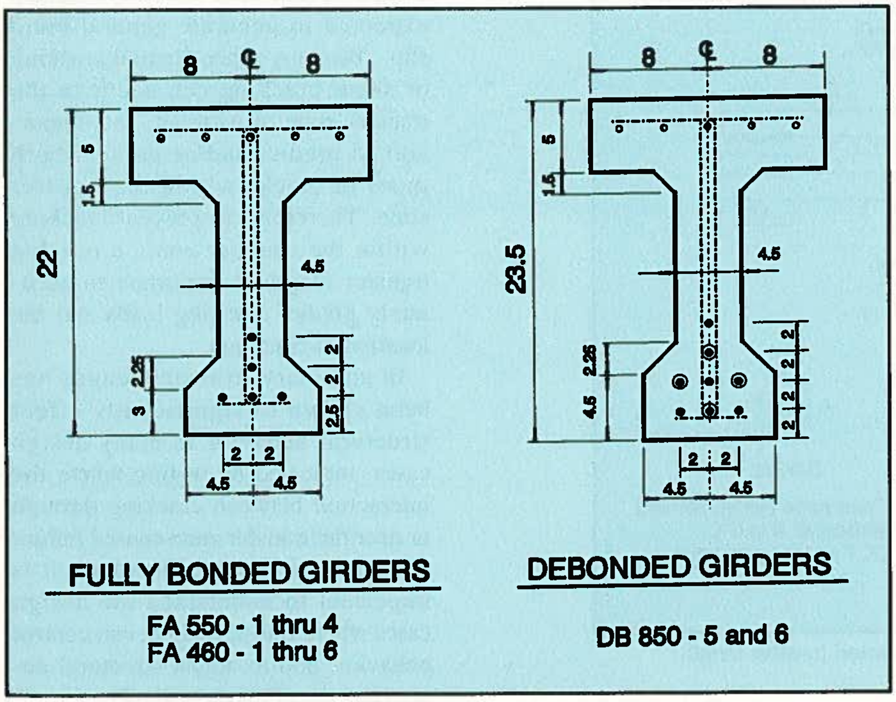

Fig. 8. Details of AASHTO-type beams.

2. Size of strand [0.5 and 0.6 in. (12.7 and 15.2 mm) diameter]

3. Debonding (fully bonded or debonded strands)

4. Confining reinforcement (with or without)

5. Size and shape of the cross section

The number of specimens and the variables included in the testing represent one of the largest bodies of transfer length data taken from a single research project. Altogether, transfer lengths were measured on each end of 44 specimens. Of these specimens, 32

Table 1. Key to specimen numbering system (Example FCT360-4).

F = Fully bonded (D = Some strands are debonded)
C = Rectangular cross section A = 22 in. deep AASHTO-type beam B = 23.5 in. deep AASHTO-type beam
T = Transverse reinforcement is included (if transverse reinforcement is not included, T does not appear)
3 = Number of prestressing strands
6 = 0.6 in. diameter strands (5 = 0.5 in. diameter strands)
0 = 2 in. strand spacing (2 = 2.25 in. strand spacing)
4 = Number of the specimen in a particular series

Note: 1 in. = 25.4 mm.

were constructed with concentric prestressing in rectangular transfer length prisms. The remaining 12 specimens were built as scale model AASHTO-type beams with four, five, or eight strands.

Figs. 4 through 8 show the design details of the test specimens. Fig. 4 illustrates the single-strand specimens, Figs. 5 and 6 depict the three-strand specimens, Fig. 7 shows the five-strand specimens and Fig. 8 illustrates the details of the AASHTO-Type beam specimens. Each specimen is numbered by a code that identifies the research variables and design characteristics of each specimen. The specimen numbering system is explained by the example given in Table 1.

Instrumentation

Primarily, transfer lengths were determined by measuring concrete surface strains along the length of each specimen. The transfer length is defined as the distance from the end of a member to the point where the prestress force is fully effective. By measuring the concrete strains and plotting the strains with respect to length, transfer length can be determined from the resulting strain profile. These data were collected:

1. Strains on the outside surface of the concrete

2. End slips

3. Electrical Resistance Strain Gauges (ERSGs) attached to the strand wires

4. Visual inspection of the specimens

Concrete strains were measured with detachable mechanical strain gauges (DEMEC© gauges), used in conjunction with DEMEC© target points. Essentially, this gauge measures the change in length between targets. The gauge and targets are shown in Fig. 9. The gauges used in this research were manufactured by Hayes Manufacturing Company in the United Kingdom. The gauges proved to be accurate within 20 to 30 microstrains (±20 to ±30 × 10^{-6} in./in.). The gauge length was 200 mm (7.87 in.).

Electrical Resistance Strain Gauges (ERSGs) were mounted on the prestressing strands before the concrete was cast. Ideally, the change in strain over the strand's length would measure transfer length. However, the ERSGs proved to be unreliable for several reasons. First, each wire of the seven-wire strand experiences a slightly different strain condition.[10] As the strand is detensioned and relative displacements between the strand and concrete take place, relative displacements between wires are also probable.

Secondly, a large percentage of the gauges in the transfer zone were destroyed at transfer. Either the changes in strain exceeded the capacity of the ERSG or the relative displacement between the steel and concrete destroyed the gauge. Thirdly, the ERSG's presence on the strand may interfere with bond, at least locally. The adverse effect of too many ERSGs mounted on a strand would prejudice the test result.

Lastly, the gauges proved difficult to protect during casting because they are susceptible to damage from vibration and/or moisture while casting the concrete. All of these factors compound to render ERSGs ineffective in measuring transfer length of pretensioned strand.

Strand end slips were also measured. In earlier tests on single-strand specimens, a dial gauge was clamped to the strand at the end of the specimen to measure the amount of strand that slipped into the concrete upon release of the pretensioning force. However, release of the strands proved to be too violent and several dial gauges were damaged. End slips were then measured by placing a tape marker on the strand, and measuring the distance the tape slipped toward the concrete upon release of the strand. These measurements were made with a steel rule. Measurements with this method were accurate to about ±1/32 in. (±0.8 mm).

Fig. 9. DEMEC© gauge used in research program.

Test Procedure

Test procedures were adopted to duplicate actual pretensioned concrete plant construction as much as possible. Accordingly, procedures for the fabrication of the specimens followed industry standards for plant construction.

The procedures for fabrication and testing can be summarized by a few simple steps:

1. Stress the prestressing steel to 75 percent f_{pu}, about 202.5 ksi (1396 MPa)

2. Place the mild steel reinforcement

3. Set the forms

4. Cast the concrete

5. Cure the concrete (approximately 48 hours)

6. Remove the formwork

7. Take initial measurements

8. Detension the strands (by flame cutting)

9. Take final measurements (The difference between initial and final gauge measurements produced the concrete strains that are plotted along the length of each specimen. From these strain plots, the transfer lengths are determined.)

Strands were tensioned using an hydraulic actuator and an electric hydraulic pump. Hydraulic pressure was continuously monitored as a measure of strand tension. Strands were initially tensioned to approximately 1600 lbs (7.11 kN) of tension, and ERSGs were attached to the strands in their proper locations. Strands were then tensioned incrementally until the correct initial prestress was reached.

Strand elongations were also measured on all strands as a check against the hydraulic pressure. Strand elongations and pretension stresses are listed in Tables 2 and 3. Elongations were measured over a gauge length of about 71.5 ft (21.8 m). Some small variations in initial strand tension are noted. However, the variation in the transfer length data exceeds the differences that possibly result from variation in pretension stress. The differences in strand tension do not significantly affect the test results.

After the strands were tensioned, the mild steel reinforcement was tied in place. Debonding material, if required, was placed on the strands. Concrete was cast into wooden forms. During casting, the concrete was internally vibrated to ensure proper consolidation.

Strand tension was released approximately 48 hours after casting, with

Table 2. Transfer length data for 0.5 in. diameter, fully bonded strands.

Specimen	Strand stress		Concrete strengths		Transfer lengths		End slips	
	Elongation (in.)	f_{si} †,‡,§ (ksi)	f'_{ci} (psi)	f'_c (psi)	North end (in.)	South end (in.)	North end (in.)	South end (in.)
FC150-11	5.933	195	4480	6710	27.0	34.0	0.125	0.125
FC150-12	5.933	195	4480	6710	28.5	28.0	0.125	0.125
FC350-1	6.026	198	4320	6630	32.5	27.5	—	—
FC350-2	6.026	198	4320	6630	27.5	27.5	—	—
FCT350-3	6.026	198	4320	6630	30.5	30.0	—	—
FCT350-4	6.026	198	4320	6630	29.0	32.0	—	—
DC350-5	5.941	195	4200	6250	26.5	28.0	0.063	0.063
DC350-6	5.941	195	4200	6250	28.5	30.5	0.063	0.063
FC550-1	5.929	195	3850	5400	39.5	36.5	0.031	0.031
FCT550-2	5.929	195	3850	5400	36.0	39.5	—	—
FC550-3	5.929	195	3850	5400	33.0	44.0	—	—
FA550-1*	5.976	196	4640	5110	18.0	16.0	0.075	—
FA550-2*	5.976	196	4640	5110	20.5	21.0	0.088	—
FA550-3*	5.976	196	4040	5280	21.5	22.0	0.056	0.063
FA550-4*	5.976	196	4040	5280	21.0	21.0	0.081	0.069
DB850-5*	5.761	193	5580	7220	30.5	44.0	0.125	0.176
DB850-6*	5.865	196	5150	6880	36.5	33.5	0.250	0.125
Average		195			28.6	30.3		

Note: 1 in. = 25.4 mm; 1000 psi = 6.895 MPa.
* AASHTO-type beams.
† f_{si} = strand tensile stress prior to release.
‡ E = 28,200 ksi for Specimens FC150, FC350, DC350, FC550 and FA550.
E = 28,700 ksi for Specimens FA550 and DB850.
§ Elongations were measured over 71.5 ft gauge length.

few exceptions. Factors such as student work schedules precluded the release of prestressing within 24 hours. In only one casting series, release was performed on the third day because of low concrete strength. The timing of the release was held as an important parameter because of its importance in the pretensioned concrete industry. In typical precast concrete plants, quick turnarounds are driven by an extremely competitive marketplace. Therefore, the most important concrete parameter is the strength at release. Conversely, concrete strengths at 28 days are not usually critical. Concrete strengths at release and at 28 days are listed in Tables 2 and 3.

Two different release methods were used to detension the strands. Using one method, the strands were flame cut at full tension in order to create a worst case for release of the prestressing force. Several past researchers had noted that transfer lengths on the "cut" end were much longer than transfer lengths on the "dead" end.[5,6,8] However, when the initial single-strand specimens (not reported in this paper) were flame cut at full tension, moderate damage was inflicted on some of the specimens. Additionally, the data showed relatively wide variation, raising doubts about the release procedure.

With the testing of the multiple strand rectangular specimens, a moderated flame cutting release procedure was adopted. Instead of flame cutting at full tension, the strands were detensioned gradually to about 70 percent of their full pretension, and then flame cut. The moderated flame cutting method was employed on the FC1, FC3, DC3 and FC5 series specimens.

The larger AASHTO-type beam cross sections were flame cut at 100 percent tension without any detensioning beforehand. The specimens that were flame cut at 100 percent tension include the FA550, FA460 and the DB850 series specimens. Interestingly, the moderated method resulted in transfer lengths that closely matched the transfer lengths that were measured on larger specimens where strands were cut at 100 percent tension.

The moderated flame cutting method is justified when considering the damage caused at strand release to a small cross section when compared to the damage caused to a large cross section. Because of their larger mass and multiple strands, large cross sections possess greater ability to absorb and distribute the energy at release than small cross sections. Furthermore, larger cross sections usually contain a greater number of strands that are flame cut one at a time.

The progressive release of each additional strand increases the overall precompression of the pretensioned member, and the effect improves the release conditions for members with multiple strands over smaller cross sections with only a few strands. The conclusion from this argument is that larger specimens with multiple strands should suffer less cumulative damage at release than smaller specimens (with fewer strands). As a result,

Table 3. Transfer length data for 0.6 in. diameter, fully bonded strands.

Specimen	Strand stress		Concrete strengths		Transfer lengths		End slips	
	Elongation (in.)	f_{si} †,‡,§ (ksi)	f'_{ci} (psi)	f'_c (psi)	North end (in.)	South end (in.)	North end (in.)	South end (in.)
FC160-11	5.882	195	3850	5400	—	—	—	—
FC160-12	5.882	195	3850	5400	48.0	46.0	0.031	0.063
FC360-1	5.880	195	4200	6250	42.0	40.5	0.094	0.135
FC360-2	5.880	195	4200	6250	37.0	48.0	0.094	0.156
FCT360-3	5.880	195	4200	6250	39.5	45.5	0.073	0.135
FCT360-4	5.818	193	4790	7300	50.5	42.0	0.146	0.115
DC360-5	5.901	196	4790	7300	42.0	36.0	0.094	0.125
DC360-6	5.901	196	4790	7300	34.5	41.0	0.125	0.125
DCT360-7	5.818	193	4790	7300	40.5	34.5	0.156	0.109
DC360-9**	5.943	197	4760	7530	—	—	—	—
DCT360-10**	5.943	197	4760	7530	—	—	—	—
FC362-11	5.464	182	4760	7530	46.0	44.0	0.125	0.146
FCT362-12	5.464	182	4760	7530	44.0	42.0	0.125	0.146
FC362-13	5.464	182	4760	7530	44.0	40.0	0.135	0.146
FC560-1	5.865	195	4480	6600	45.5	47.0	0.163	0.156
FCT560-2	5.865	195	4480	6600	48.0	51.5	0.169	0.144
FC560-3	5.865	195	4480	6600	48.0	48.0	0.169	0.150
FA460-1*	5.867	195	4880	6360	29.5	37.0	0.102	0.094
FA460-2*	5.945	198	4460	6570	34.0	37.0	—	—
FA460-3*	5.945	198	4460	6570	33.0	32.5	—	—
FA460-4*	5.995	199	4840	6460	27.5	28.5	0.125	0.133
FA460-5*	6.219	207	4660	7020	31.5	31.0	0.125	0.117
FA460-6*	6.219	207	4660	7440	31.5	31.0	0.117	0.086
Average		195			39.8	40.2		

Note: 1 in. = 25.4 mm; 1000 psi = 6.895 MPa.
* AASHTO-type beams.
† f_{si} = strand tensile stress prior to release.
‡ E = 28,500 ksi for all 0.6 in. strands.
§ Elongations were measured over 71.5 ft gauge length.
** Specimens contained two debonded strands with a debond length of 50 in. (1.27 m) and one fully bonded strand; the transfer lengths of fully bonded strands were not discernible from the data.

shorter transfer lengths could be expected for larger cross sections.

Before release, initial measurements were taken. The initial measurements included electrical resistance strain gauges, initial strain readings on the external faces of the concrete, and the initial end slip readings. After release, these measurements were repeated. Strains in the concrete and steel are given by the difference between initial and final readings from the strain data. Strand end slip is also given by the difference between the initial and final readings.

To minimize strain reading errors, a specific procedure for obtaining strain measurements was adopted. All strain readings were taken by teams of two persons. Each person would take measurements independently of the other. Once the measurements were taken, readings were compared. If the readings from the two individuals differed by more than 0.000032 in./in., measurements were retaken until the difference was resolved. Strain measurements from the two individuals were then averaged together with the average measurements from the opposite side of each specimen. In effect, the "bare" strain measurements are actually the average of four sets of readings, collected by two individuals from both sides of each specimen.

Measurement of concrete strains with the strain gauges proved to be an effective and reliable method to measure transfer length. Strain measurements were taken on the outside surface of the concrete along both sides of the specimen. By averaging strain readings from both sides of the specimen, the effects from eccentric prestressing were negated. The repeatability and reliability of the strain measurements was proven over many different trials with several different student researchers.

DATA ANALYSIS

The strain profile taken from Specimen FCT350-3 is illustrated in Fig. 2 where measured concrete strains are plotted vs. the length of the specimen. These strains are labeled "bare strains"

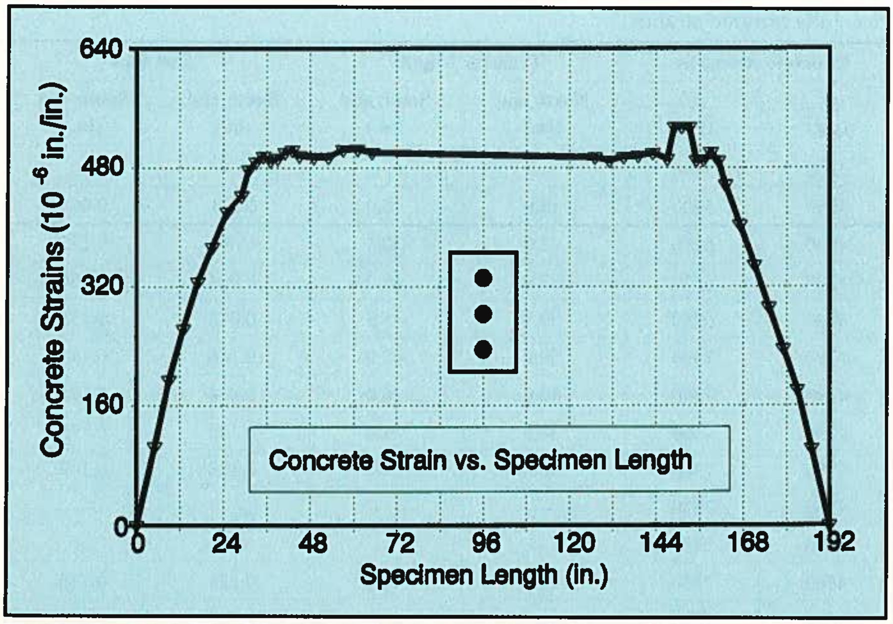

Fig. 10. Strain profile of "smoothed" strains, Specimen FCT350-3.

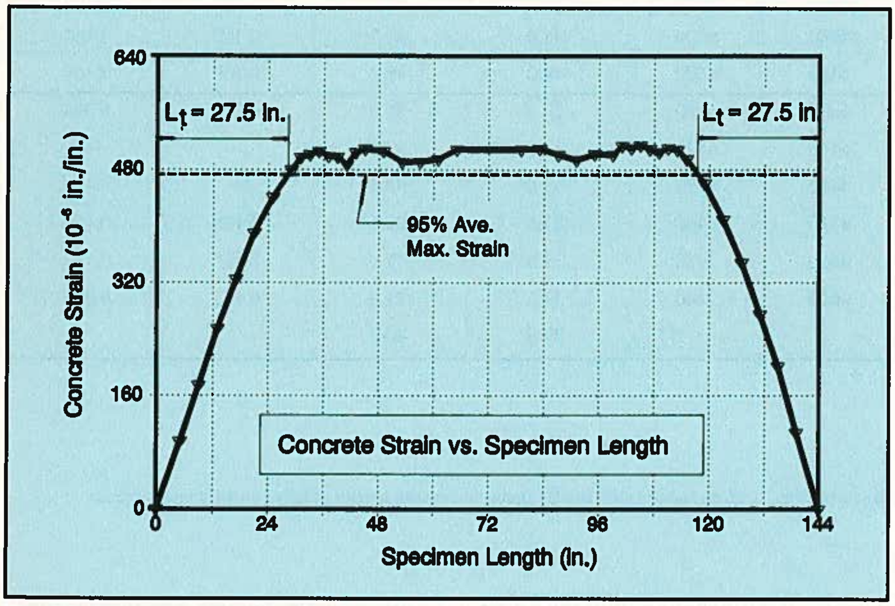

Fig. 11. 95 percent average maximum strain method.

although each strain profile is constructed from the average readings of four sets of strain measurements: two research assistants by two sides of each specimen. To further reduce anomalies in the data, the "bare" strain profiles were smoothed by averaging the data over three gauge lengths. Fig. 10 illustrates the same strain profile of Fig. 2, but with smoothed values. The smoothing technique can be summarized by the following equation:

$$(\text{Strain})_x = \frac{(\text{Strain})_{x-1} + (\text{Strain})_x + (\text{Strain})_{x+1}}{3} \tag{7}$$

Determination of Transfer Length: The 95 Percent Average Maximum Strain Method (95 percent AMS)

Transfer lengths for each specimen were determined by evaluating the concrete strain profiles. The method used has been labeled the "95 Percent Average Maximum Strain" method and was conceived by personnel from this research project.[12,14] Its execution is very simple:

1. Plot the "smoothed" strain profile.

2. Determine the "Average Maximum Strain" for the specimen by computing the numerical average of all the strains contained within the strain plateau of the fully effective prestress force.

3. Calculate 95 percent of the "Average Maximum Strain" and construct a line corresponding to this value.

4. Transfer length is determined by the intersection of the 95 percent line with the "smoothed" strain profile.

This procedure is illustrated in Fig. 11 for Specimen FC350-2. The average maximum strain is computed by averaging all the strains contained on or near the plateau of the fully effective prestress force. The average may include all of the points above the 95 percent line, but generally, only the points clearly within the strain plateau are included in the average.

The method gives a transfer length value that is free from arbitrary interpretation because the "Average Maximum Strain" will not change significantly if one or two data points are either included or excluded from the average. Current variations in analysis methods leave data open to arbitrary interpretation. Its "inherent objectivity" is the major advantage derived by using the "95 percent AMS" method.

On the other hand, this method has drawn criticism because it does not use the fully effective concrete strain to determine the transfer length. Precedent does exist for using 95 percent of the maximum stress or strain. Kaar and Hanson used 95 percent of the maximum strain in their transfer and development length study for pretensioned concrete railroad ties.[8]

Overall, the 95 Percent Average Maximum Strain (95 percent AMS) method represents an accurate value for determining the transfer length. If on the one hand, the reported transfer lengths are too short because only 95 percent of the maximum strain is used to define transfer length, then it must also be recognized that the use of mechanical strain gauges combined with the technique of "smoothing" the data artificially lengthens the measured transfer lengths. Additionally, if 100 percent of the average maximum strain (100 percent AMS) is employed, it could prove difficult to determine an exact intersection between the strain profile and the 100 percent AMS because the strain profile can approach the 100 percent AMS asymptotically.

MEASURED STRAND TRANSFER LENGTHS

All reported measured transfer lengths were obtained using the "95 percent AMS" method. Fig. 12 illustrates the strain profile for Specimen FCT350-3, containing three 0.5 in. (12.7 mm) diameter strands that were enclosed within confining reinforcement. The transfer lengths on both ends of Specimen FCT350-3 were measured at about 30 in. (762 mm). For specimens with fully bonded strands, the transfer length at each end of the specimen is evidenced by the ascending and descending portions of the strain profile. Strain profiles for all of the specimens are included in Appendix A of Ref. 12.

Fig. 13 depicts the strain profile for Specimen FC362-13. This specimen contained three 0.6 in. (15.2 mm) strands spaced at 2.25 in. (57 mm). The transfer lengths measured on Specimen FC362-13 were 44 and 40 in. (1.118 and 1.016 m). Typically, 0.6 in. (15.2 mm) strands required longer transfer lengths than 0.5 in. (12.7 mm) strands.

Fig. 14 illustrates concrete strains taken from Specimen DC350-5, where the middle of three strands was debonded for a distance of 70 in. (1.78 m). The strain profile clearly depicts four separate and distinct transfer zones, two at each end. Transfer of the two fully bonded strands are represented by the initial transfer zone at each end. An intermediate plateau occurs between the transfer zone of the two fully bonded strands and the transfer zone of the single debonded strand. This clearly demonstrates that blanketing effectively eliminated bond between the prestressing strand and the concrete. Also, note that the slope in the fully bonded transfer zone is steeper than the slope of the debonded strand, corroborating two fully bonded strands vs. a single debonded strand.

Measured transfer lengths are reported in Tables 2 through 6. Table 2 lists the measured transfer length for 0.5 in. (12.7 mm) diameter strands, fully bonded from the end of the specimen. Table 2 also includes data from the FA550 and DB850 AASHTO-type beams whose strands were flame cut at 100 percent tension. For specimens labeled "DC", these data refer to measured transfer lengths on the fully bonded strands, even though the specimen may have contained one or more debonded strands.

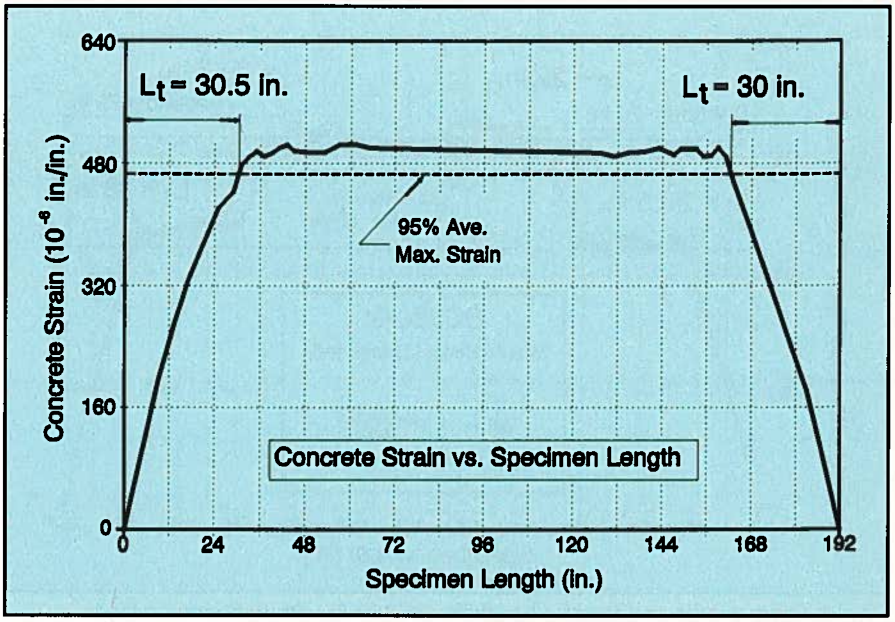

Fig. 12. Strain profile and transfer length for Specimen FCT350-3.

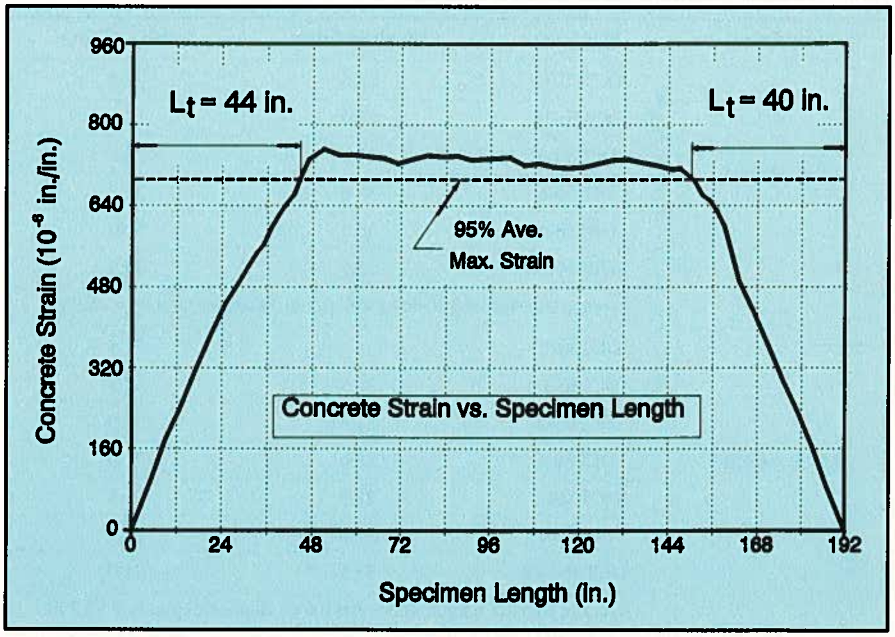

Fig. 13. Strain profile and transfer length for Specimen FC362-13.

Measured transfer lengths on specimens containing 0.6 in. (15.2 mm) strands, fully bonded from the end of the member, are listed in Table 3. Transfer lengths are also reported for the specimens in the FA460, AASHTO-type beam series that were flame cut at 100 percent tension.

Table 4 lists the transfer lengths measured for strands that were debonded, or blanketed. These strands were debonded a distance of 8 in. (203 mm) in the DC150 and DC160 series, 70 or 50 in. (1.78 or 1.27 m) in the DC350/DC360 series, and 78 in. (1.98 m) in the DB850 series.

Strand end slips were also measured at each end of each transfer length specimen. End slips are also reported in Tables 2 and 3. The reported end slip values are derived from the average value of end slip measured for all

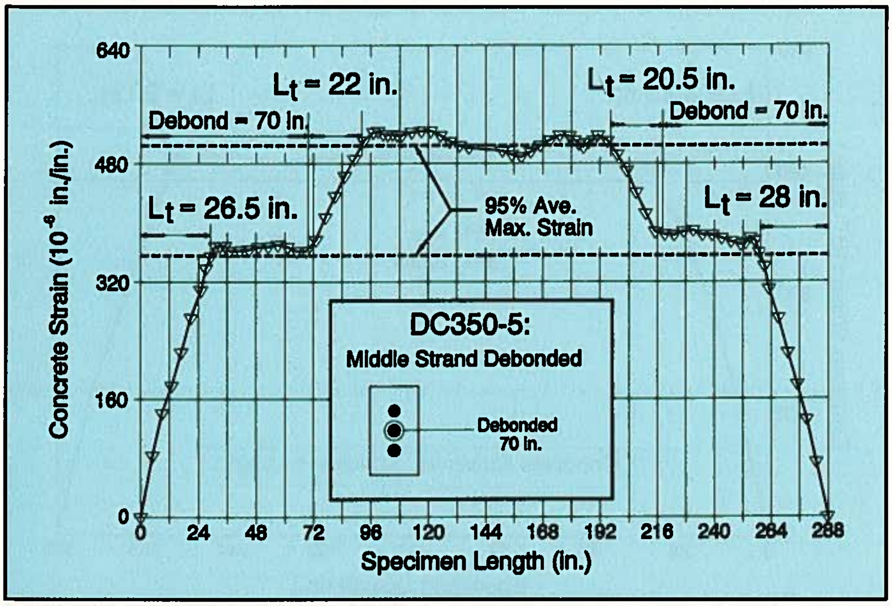

Fig. 14. Strain profile and transfer length for DC350-5, with debonded strand.

Table 4. Transfer lengths for debonded strands.

Strand size	Specimen	North end (in.)	South end (in.)
0.5 in. strand	DC150-13	23.0	23.5
	DC150-14	27.0	17.0
	DC350-5	22.0	20.5
	DC350-6	30.0	26.5
	DB850-5	35.5	30.0
	DB850-6	25.5	29.0
	Average transfer length: debonded 0.5 in. diameter strands = 25.8 in.		
0.6 in. strand	DC160-13	—	31.5
	DC160-14	37.5	37.5
	DC360-5	31.5	20.0
	DC360-6	28.0	21.0
	DCT360-7	29.5	26.5
	DC360-9	32.0	26.5
	DCT360-10	31.5	41.0
	Average transfer length: debonded 0.6 in. diameter strands = 32.7 in.		

Note: 1 in. = 25.4 mm.

fully bonded strands. End slips on 0.5 in. (12.7 mm) diameter strands ranged from 0.031 to 0.25 in. (0.8 to 6.4 mm), although end slips greater than 0.125 in. (3.2 mm) were uncommon. For 0.6 in. (15.2 mm) diameter strands, measured end slips ranged from 0.031 to 0.25 in. (0.8 to 6.4 mm), but most of the end slip values were in the range of 0.09 to 0.16 in. (2.3 to 4.1 mm).

Strand end slips were also measured on debonded strands, and generally, these strand slips were much greater than end slips measured on fully bonded strands. The larger end slips on debonded strand suggest that the prestressing strand was unrestrained over the length of debonding.

DISCUSSION OF TEST RESULTS

Discussed below are the effects of strand diameter, cross section size and strand spacing on strand transfer length. Also discussed are transfer lengths for debonded strands, confining reinforcement, strand surface condition, strand end slip and comparisons with other research data.

Transfer Length vs. Strand Diameter

The measured transfer lengths for fully bonded 0.5 in. (12.7 mm) diameter strands are summarized by the histogram in Fig. 15. The histogram charts the incidence of measured transfer lengths by plotting the transfer length vs. the number of ends measured for specific transfer length values. Measured transfer lengths are grouped in ranges of 4 in. (102 mm). For example, the histogram in Fig. 15 illustrates that 11 specimen ends had measured transfer lengths of 28.0 ±2.0 in. (711 ±51 mm), and the incidence of measured transfer lengths between 30.0 and 34.0 in. (762 and 864 mm) was eight.

For fully bonded 0.5 in. (12.7 mm) diameter strands, the average measured transfer length was 29.5 in. (749 mm) with a standard deviation of 6.85 in. (174 mm), or 24.0 percent. The average transfer length and the standard deviation are indicated on the plot. Transfer lengths were measured on a total of 34 ends of specimens containing fully bonded 0.5 in. (12.7 mm) strands.

The histogram in Fig. 16 illustrates the incidence of measured transfer lengths for fully bonded, 0.6 in. (15.2 mm) diameter strands. These data include transfer lengths measured on each end of 19 specimens for 38 measurements. The average transfer length for 0.6 in. (15.2 mm) strands was 40.0 in. (1.02 m) with a standard deviation of 6.80 in. (171 mm), or 17.0 percent.

Clearly, the measured transfer lengths for 0.6 in. (15.2 mm) diameter strand are longer than those for 0.5 in. (12.7 mm) strand. These data reinforce transfer length as a function of strand diameter.

The current expressions of either $50d_b$ or $f_{se}d_b/3$ suggest that transfer length varies proportionately with strand diameter. The linear relationship between the transfer length and strand diameter is also supported by the simplified bond model where transfer length is proportional to the ratio of strand area to strand perimeter, A_{ps}/P_{ps}. This ratio is a linear function of d_b.

The histogram in Fig. 17 normalizes and plots all 74 transfer lengths by the strand diameter. By normalizing 0.5 and 0.6 in. (12.7 and 15.2 mm) strand diameter data, 74 transfer length measurements are compared on the same histogram. The transfer lengths of 0.5 in. (12.7 mm) strand are shown with the solid bars and the transfer lengths of 0.6 in. (15.2 mm) strand are indicated by the hatched bars. For all data, the average transfer length is given by $63.1d_b$ with a standard deviation of $13.1d_b$, or 20.8 percent.

However, when the transfer lengths of 0.5 in. (12.7 mm) strand are compared to the transfer lengths of 0.6 in. (15.2 mm) strands, the data indicate that the transfer lengths cannot be normalized by the strand diameter. In other words, these data demonstrate that the measured transfer length of pretensioned strands is not directly proportional to the strand diameter. Whereas the ratio of the strand diameters would predict only a 20 percent increase in transfer lengths for 0.6 in. (15.2 mm) strands compared to 0.5 in. (12.7 mm) strands, these data indicate that the ratio of measured transfer lengths is greater than 1.2. The actual ratio of the average transfer lengths for 0.6 in. (15.2 mm) strands compared to 0.5 in. (12.7 mm) strands is 1.36.

By their unmatched transfer length distributions, Fig. 17 shows that 0.6 in. (15.2 mm) diameter strands require more strand diameters to transfer prestressing forces when compared to 0.5 in. (12.7 mm) strands. Transfer lengths for 0.6 in. (15.2 mm) strands average almost $67d_b$ whereas the transfer lengths for 0.5 in. (12.7 mm) strands average about $59d_b$.

Considering these data, the transfer length distributions indicate the transfer lengths cannot be normalized by the strand diameter. Instead, the data suggest the following form for the relationship between transfer length and strand diameter:

$$L_t = K d_b^{\alpha} \quad (8)$$

where K equals a constant and α equals 1.68 for these data.

Table 5. Average transfer lengths vs. strand size and specimen series.

Tests series (cross section dimensions)	Average transfer lengths (in.) (number of ends tested)		Ratio
	0.5 in. strands	0.6 in. strands	$L_{t(0.5)}/L_{t(0.6)}$
Single strand specimens (5 x 4 in.)	29.4 (4)	47.0 (2)	1.60
Three strand specimens (5 x 9 in.)	29.1 (12)	41.6 (20)	1.43
Five strand specimens (5 x 13 in.)	38.1 (6)	48.0 (6)	1.26
AASHTO-type beams (I-beams)	25.5 (12)	32.0 (12)	1.25
Average	29.5	40.0	1.36
Standard deviation	6.9	6.8	

Note: 1 in. = 25.4 mm.

Table 6. Transfer lengths vs. strand spacing; 0.6 in. strands spaced at 2.0 and 2.25 in.

Specimen	Transfer lengths (in.)	
	North end	South end
FC362-11	46	44
FCT362-12	44	42
FC362-13	44	40
Average transfer lengths: Specimens with strands at 2.25 in. spacings = 43.3 in. Standard deviation = 2.0 in.		
Average transfer lengths: All specimens with 0.6 in. strands = 40.0 in. Standard deviation = 6.8 in.		

Note: 1 in. = 25.4 mm.

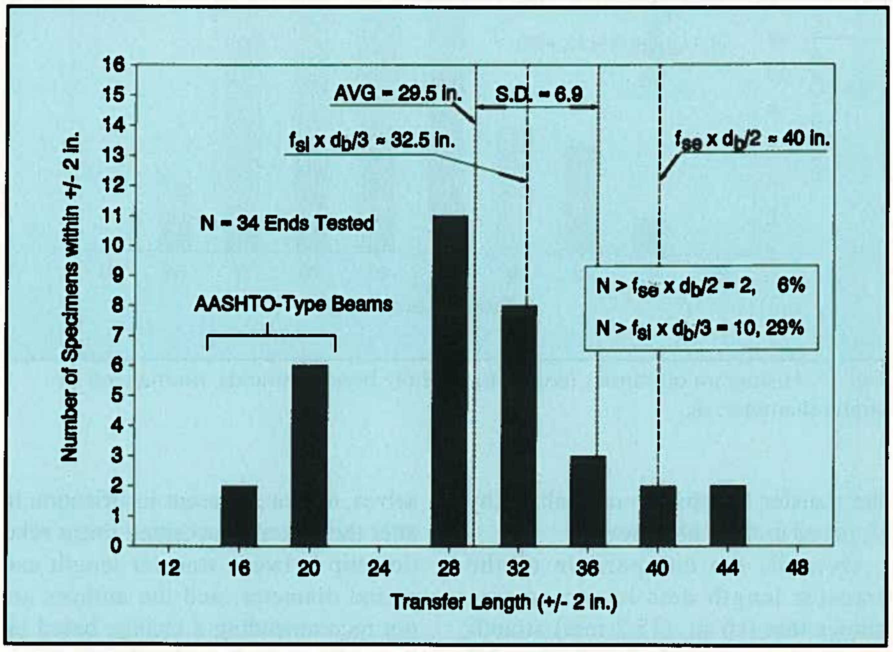

Fig. 15. Histogram of transfer lengths for 0.5 in. (12.7 mm) fully bonded strands.

The histogram in Fig. 18 shows all of the transfer length data normalized against the bar diameter raised to the 1.68 power, $d_b^{1.68}$. This histogram shows that data from the 0.6 in. (15.2 mm) transfer lengths closely match the data from the 0.5 in. (12.7 mm) strands and their pattern of distribution, when

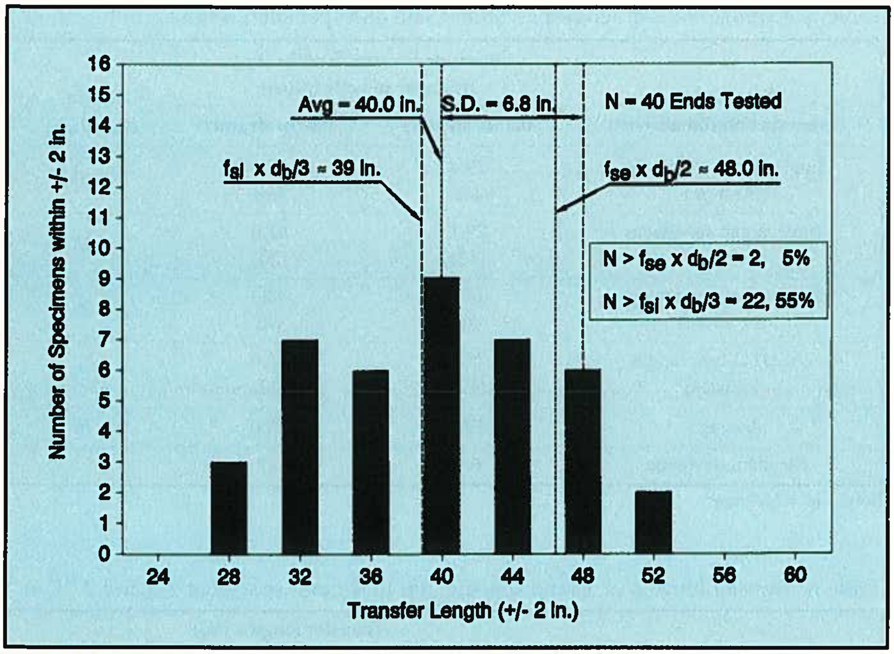

Fig. 16. Histogram of transfer lengths for 0.6 in. (15.2 mm) fully bonded strands.

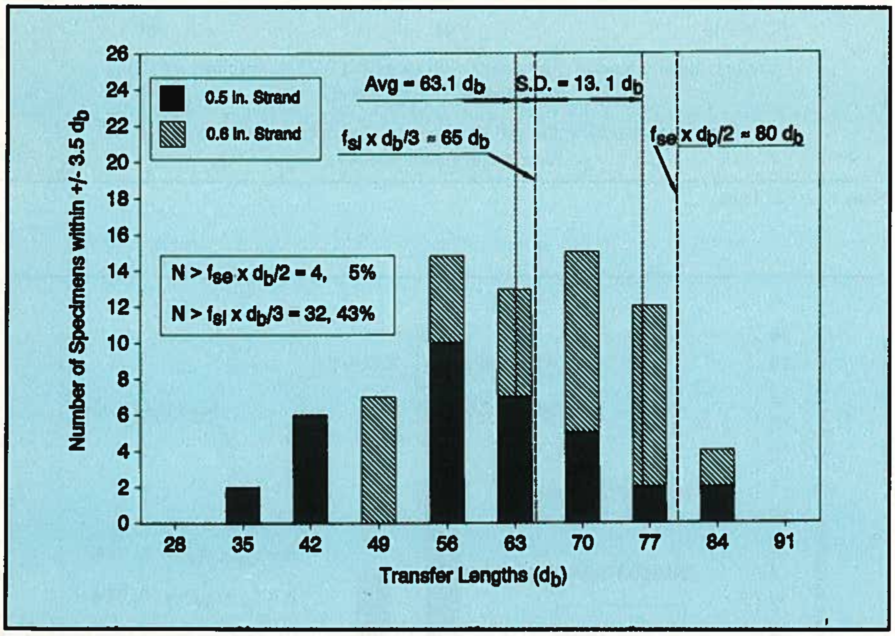

Fig. 17. Histogram of transfer lengths for all fully bonded strands, normalized by strand diameter, d_b.

the transfer lengths are normalized by d_b raised to the 1.68 power.

Overall, the comparison of the transfer length data by strand size shows that 0.6 in. (15.2 mm) strands require longer transfer lengths than 0.5 in. (12.7 mm) strands. Furthermore, these data indicate that the relationship between transfer length is not linear, but rather the transfer length is an exponential function of strand diameter.

However, these data, taken by themselves, do not represent justification to alter the currently accepted linear relationship between transfer length and strand diameter, and the authors are not recommending a change based on these data. On the other hand, this is an interesting result and other researchers should continue to investigate the possibility that strand transfer length and/or flexural bond length may not be linear functions of strand diameter.

Effects of the Cross Section's Size on Measured Transfer Length

Much of the earlier transfer length research was performed on small rectangular prisms with a single strand.[3,5,6,7,8,10] Fewer transfer length measurements have been taken on multi-strand specimens such as the three- and five-strand specimens tested as part of this research program. Even fewer transfer length studies have been performed on beams with cross sections as large as the AASHTO-type beams in this research. Intuitively, data from larger test specimens should match more closely the transfer lengths of real pretensioned concrete members, particularly test specimens with multiple strands.

Figs. 19 and 20 compare the transfer lengths from each series of transfer length specimens. The range of transfer lengths are portrayed separately for each type of cross section, depicting the high, low and average values of measured transfer lengths. The data are grouped according to cross section dimensions and numbers of strands. For both 0.5 and 0.6 in. (12.7 and 15.2 mm) strands, the figures illustrate that larger specimens tend to possess shorter transfer lengths.

Considering specimens with 0.5 in. (12.7 mm) strands and illustrated in Fig. 19, the transfer lengths for the AASHTO-type beams are almost 40 percent less than transfer lengths from the FC3 series. (The FC5 series results could be slightly skewed because of low concrete strength.) This result is made more remarkable by the cutting techniques. The FC1, FC3, DC3, and the FC5 series were flame cut after slight detensioning whereas the AASHTO-type beams were flame cut at 100 percent of tension.

The same trend is demonstrated with 0.6 in. (15.2 mm) strands in Fig. 20 where the transfer lengths for AASHTO-type beams were 28 percent shorter than other cross sections. This trend is also described numerically in Table 5 where average transfer length values are reported for each specimen series. For both 0.5 and 0.6 in. (12.7 and 15.2 mm) strands, the transfer lengths for AASHTO-type beams were markedly shorter than the transfer lengths of the other test specimens.

These data indicate that test specimens with larger cross sections and multiple strands possess significantly shorter transfer lengths. Transfer length measurements on the different cross sections were performed with consistent procedures using the same prestressing strand and under similar laboratory conditions. The results also indicate that transfer lengths measured on relatively small, single-strand specimens may not simulate transfer lengths of real pretensioned concrete members.

Perhaps the most striking illustration of this effect is found in Fig. 15, the histogram of transfer lengths for 0.5 in. (12.7 mm) strands. In this histogram, the data fall into two distinct regions separated by a significant gap in the data. Eight data points are indicated with transfer lengths less than 22 in. (0.56 m). All of these points were generated from the tests on the larger, AASHTO-type beams whereas the longer transfer lengths were measured on rectangular prisms.

Several factors can explain the shorter transfer lengths measured in larger cross sections. First, if flame cutting is the method of release, then strands are cut one at a time. As each strand is detensioned, the larger masses of concrete will be less affected by the sudden release of each individual strand because the larger mass has more capacity to withstand localized damage from sudden release.

Secondly, in larger cross sections with multiple strands, the release of each individual strand acts to further precompress the cross section. Consequently, a cross section becomes increasingly precompressed as tension from each successive strand is released. Lastly, multiple strands also act as reinforcement to the cross section, helping to distribute the energy and stress from the release of a single strand.

Typical pretensioned beams, with larger cross sections and multiple strands, could be expected to register shorter transfer lengths when compared to many of the typical research specimens. Researchers should also be cautioned that small rectangular prisms may not represent "real" pretensioned structures.

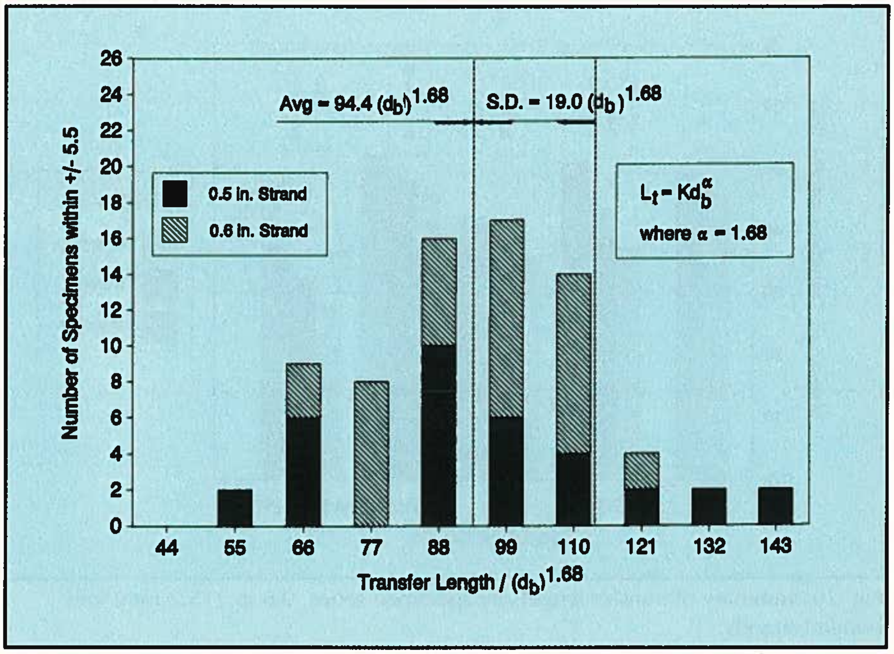

Fig. 18. Histogram of transfer lengths for all fully bonded strands, normalized by strand diameter raised to the 1.68 power, $d_b^{1.68}$.

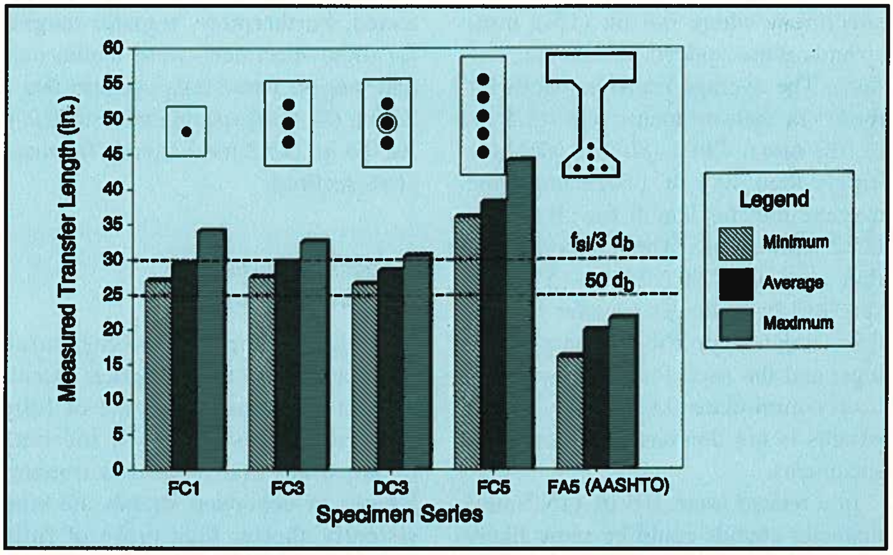

Fig. 19. Summary of transfer lengths by specimen series, 0.5 in. (12.7 mm) fully bonded strands.

Effects of Strand Spacing on Pretensioned Transfer

Current practice dictates that center-to-center spacing of strands should be at least four times the strand diameter. Although this "rule of thumb" is based on very little experimental data, it has served the industry well, primarily because the industry standard used 0.5 in. (12.7 mm) strands at 2.0 in. (51 mm) spacings. Now, with the approved use of 0.6 in. (15.2 mm) strand for pretensioned applications, the standard spacing should be investigated to determine if the "rule of thumb" should be maintained as a standard. Strong economic impetus for these studies exists because the structural efficiency of 0.6 in. (15.2 mm) strands is nullified if 2.4 in. (61 mm) spacings are required. Therefore, tests were performed to determine what effects, if any, strand spacing would have on pretensioned transfer.

The data for transfer lengths of 0.6 in. (15.2 mm) strand with 2.0 and 2.25 in. (51 and 57 mm) spacings are com-

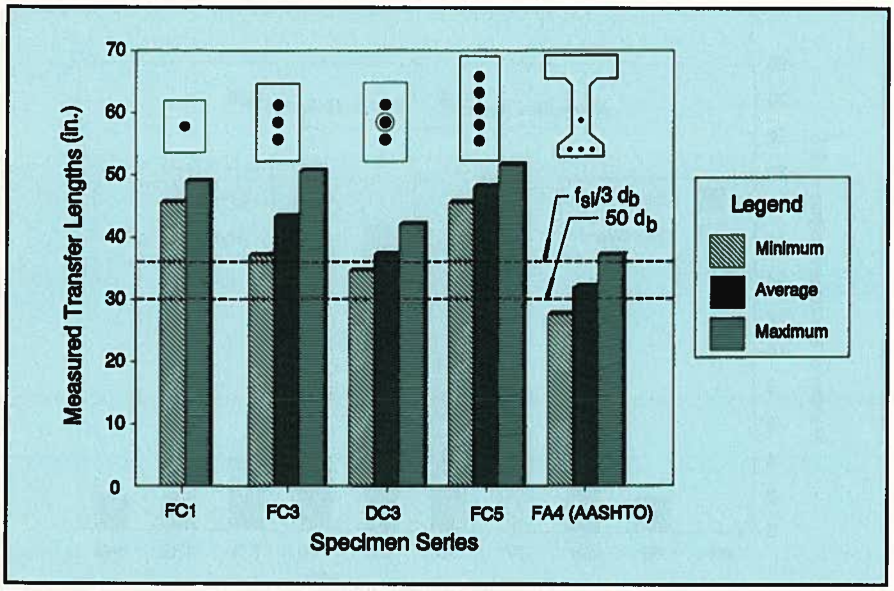

Fig. 20. Summary of transfer lengths by specimen series, 0.6 in. (15.2 mm) fully bonded strands.

pared in Table 6. The table lists the transfer lengths from each end of three specimens where 0.6 in. (15.2 mm) strands were spaced at 2.25 in. (57 mm). The average transfer length for these six measurements was 43.3 in. (1100 mm). This value is slightly longer than 40.1 in. (1019 mm), the average transfer length for all 0.6 in. (15.2 mm) strands. These data indicate that strands with 2.25 in. (57 mm) spacings have longer transfer lengths than strands with 2 in. (51 mm) spacings, and the need for wider spacings to accommodate 0.6 in. (15.2 mm) strands is not demonstrated for these specimens.

In a related issue, 0.6 in. (15.2 mm) diameter strands could be more likely to cause splitting upon pretensioning release because the larger size can cause larger bursting stresses around the strand. Current standard box girder shapes in the State of Texas are made with 5 in. (127 mm) thick bottom flanges and 6 in. (152 mm) wide webs. Tests were performed to study the reliability of transferring fully bonded 0.6 in. (15.2 mm) strands on 2.0 in. (51 mm) spacings in a 5 in. (127 mm) wide concrete member. Three specimens were fabricated 5 in. (127 mm) wide and 13 in. (330 mm) deep with five 0.6 in. (15.2 mm) strands each, FC(T)560-1, 2, and 3.

After pretensioned transfer, these specimens were inspected for splitting cracks and measured for transfer length. No signs of splitting were detected. Furthermore, transfer lengths for these specimens were within normal ranges. These tests confirm that a 2.0 in. (51 mm) spacing was sufficient for 0.6 in. (15.2 mm) strands for these cross sections.

Transfer Lengths for Debonded Strands

Table 4 compares the measured transfer lengths for debonded strands against the transfer lengths of fully bonded strands. Overall, the data demonstrate that measured transfer lengths of debonded strands are consistently shorter than those of fully bonded strands. Debonded 0.5 in. (12.7 mm) strands were transferred in an average of 25.8 in. (655 mm) length while their fully bonded counterparts were transferred in 29.5 in. (749 mm) length.

Differences were even greater for 0.6 in. (15.2 mm) diameter strands. Measured transfer lengths of debonded strands were 32.2 in. (818 mm) compared to 40.1 in. (1.02 m) for fully bonded, 0.6 in. (15.2 mm) strands. While it has been argued that the bond of debonded strands could be adversely affected because their anchorage is not aided by confining stresses developed at the support, these data indicate that the transfer bond stresses of debonded strands exceed the bond stresses for fully bonded strands.

The transfer zone of a debonded strand is positioned in regions of the specimen that are subject to precompression from strands that are fully bonded. While the difference in transfer lengths is significant, the differences do not appear large enough to warrant special provisions for the transfer length of debonded strands. Again, variations in transfer length between debonded strands and fully bonded strands do not greatly exceed the general variation observed throughout the transfer length testing.

Confining Reinforcement

Confining reinforcement is analogous to hoop ties in a column. In a column, the hoop ties prevent the longitudinal reinforcement from buckling outward. The ties also help to confine the concrete within the core by resisting lateral deformations. In the pretensioned transfer zone, the transfer of pretensioned strands causes bursting stresses in the surrounding concrete. Presumably, confining reinforcement surrounding the concrete and pretensioned strand would improve strand anchorage and shorten the transfer length. However, these data do not support this theory.

Transfer lengths measured on specimens containing confining reinforcement are presented in Table 7. The table reports that the average transfer lengths for specimens made with confining reinforcement are 32.8 in. (833 mm) for 0.5 in. (12.7 mm) strands and 45.4 in. (1.15 m) for 0.6 in. (15.2 mm) strands. Also listed in the table are the average transfer lengths for all strands. In comparison, specimens containing confining reinforcement possessed slightly longer transfer lengths than specimens where confining reinforcement was omitted. These tests demonstrate that confining reinforcement did not contribute significantly to prestress transfer for these tests.

It is postulated that the confining reinforcement remained largely ineffective because the concrete remained relatively free from cracking throughout the transfer zone. Even though confining reinforcement necessarily must increase each member's elastic stiffness in the circumferential direction, this effect is apparently small compared to the elastic stiffness of concrete. Indeed, fundamental mechanics prove that small radial cracking must occur locally at the interface of strand and concrete.[3] However, these cracks do not usually become large enough to activate confining forces in the reinforcement hoops. Therefore, the confining reinforcement exerts little or no influence on the prestress transfer.

On the other hand, for the general design case, pretensioned concrete members must be detailed to prevent propagation of splitting cracks that can occur at transfer. In cases where splitting does occur at transfer, confining and/or transverse reinforcements are the only elements that maintain integrity of the concrete if splitting cracks should occur. Therefore, transverse reinforcement should not be eliminated from standard detailing.

Table 7. Effects of confining reinforcement on measured transfer lengths.

Specimen	Measured transfer length (in.)			
	0.5 in. strands		0.6 in. strands	
	North end	South end	North end	South end
FCT350-3	30.5	30.0	—	—
FCT350-4	29.0	32.0	—	—
FCT550-2	36.0	39.5	—	—
FCT360-3	—	—	39.5	45.5
FCT360-4	—	—	50.5	42.0
FCT362-12	—	—	44.0	42.0
FCT560-2	—	—	48.0	51.5
Average transfer lengths: Strands confined by hoops	32.8 (Standard deviation = 4.1 in.)		45.4 (Standard deviation = 4.3 in.)	
Average transfer lengths: All test specimens	29.5 (Standard deviation = 6.9 in.)		40.0 (Standard deviation = 6.8 in.)	

Note: 1 in. = 25.4 mm.

Strand Surface Condition

The impact of strand surface condition on transfer length has been established by many researchers.[1,3,4,5,6,7,8] Strands that are rusted or weathered, even in limited amounts, generally possess measurably shorter transfer lengths compared to bare, bright strand. A coating of light rust improves the frictional restraint between concrete and strand. Conversely, transfer lengths can become very long if the strand is lubricated or otherwise contaminated with oil.

The strand used in this study was furnished with a bright, mill condition surface. During testing, the strand was protected from contamination and corrosion by storing it in a dry warehouse. Throughout specimen fabrication, the strands were handled carefully to avoid contaminating the strand surface. Additionally, no form release oils nor lubricants of any kind were allowed near the bare strand at any stage of fabrication.

Efforts were made to eliminate the strand surface condition as a variable, yet the data demonstrate significant variations in measured transfer lengths with standard deviations on the order of 20 percent of the average values. None of the research variables can account for this variation in data, leaving the unknown variations in surface condition as a possible cause. Other research studies noted similar variations in transfer lengths in their studies. However, no quality assurance or quality control procedures currently exist to monitor or control the surface condition of strands.

To summarize, the strand surface condition is probably the most important variable affecting transfer length of strand, yet it is the least predictable. Large degrees of scatter in the data exist not only from researcher to researcher, but within an individual research project, as exhibited here.

Strand End Slips vs. Transfer Lengths

At prestress release, at the ends of a pretensioned member, the pretensioned strands slip into the surrounding concrete and relative displacement occurs throughout the transfer zone. At the ends of the pretensioned members, the relative slip between the concrete and the strand can be measured; it is generally referred to as "strand end slip" and the designation L_{es} is used in this paper.

Where prestress transfer is fully accomplished, no slip occurs between steel and concrete and concrete strains are compatible with strand strain. In other words, in regions not including the transfer zone, steel strains are compatible with the concrete strain and no relative displacement occurs between the concrete and the steel.

A theoretical relationship has been developed that relates the transfer length as a function of strand slip.[12,15,16] The equation is derived from a mechanistic relationship integrating steel strains over the transfer length and subtracting the concrete strains over that same length. Assuming linear variation of steel and concrete strains within the transfer zone yields the expression:

$$L_t = \frac{2E_{ps}}{f_{si}}(L_{es}) \qquad (9)$$

where E_{ps} is the elastic modulus of the steel strand, f_{si} is the strand stress immediately before release, and L_{es} is the measured end slip. Note that this theoretical relationship is independent of strand size. For these tests, the equation is simplified to the following:

$$L_t = 290L_{es} \qquad (10)$$

Strand end slips were measured on every strand at each end of all transfer length specimens. End slips were averaged for each end of each specimen and listed in Tables 2 and 3. In some cases, the end slip measuring devices were disturbed during detensioning and accurate measurements were not available.

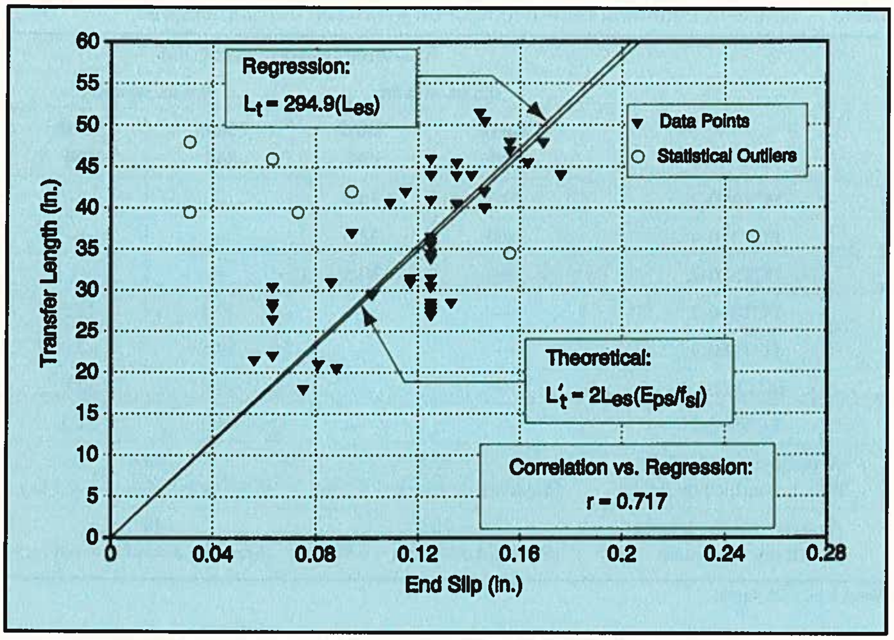

Fig. 21. Measured transfer lengths vs. measured end slips for all strands.

In Fig. 21, strand end slips are plotted vs. the measured transfer lengths. Each data point represents one end of one transfer length specimen. There are a total of 54 data points for strand end slips vs. transfer lengths. Fig. 21 combines and depicts data from 0.5 and 0.6 in. (12.7 and 15.2 mm) strands.

The figure shows that the data are arrayed around the theoretical relationship, $L_t = 290L_{es}$, indicating that the data tend to corroborate the theoretical, mechanistic relationship between transfer length and strand end slips. A regression analysis was performed to determine the line that represented the data with the least error. This line, constrained through the origin, is given by $L_t = 294.9L_{es}$. The reported correlation of $r = 0.717$ indicates that a statistical correlation does exist between transfer length and strand end slips, and suggests that end slips may reliably predict transfer length.

Comparison With Other Research

Some recent transfer length research is summarized in Table 8. The test results from Cousins et al. were first reported in 1986,[18] spurring the Federal Highway Administration (FHWA) to restrict the use of 0.6 in. (15.2 mm) diameter strands from pretensioned application, and to increase the development length provisions for other sizes of strand. Cousins et al. found the transfer lengths of uncoated 0.5 in. (12.7 mm) strands to exceed current code recommendations for transfer lengths by over 100 percent, with average transfer lengths measured at 49.7 in. (1.26 m).[18,19,20]

The transfer lengths reported by Deatherage et al. from the University of Tennessee at Knoxville (UTK) were performed under research sponsored by PCI in response to the FHWA moratorium.[16,17] Shahawy et al. also conducted transfer length research at the Florida Department of Transportation (FDOT).[21,22]

The UTK and FDOT tests are particularly related to this research because AASHTO girders were used as transfer length specimens. UTK measured transfer lengths on AASHTO Type I girders and FDOT measured transfer lengths on AASHTO Type II girders. The tests performed by FDOT were conducted at a prestressing plant.

It should be mentioned that results from these other researchers should be tempered because their analysis techniques differed from the technique reported here. In some cases, analysis techniques are susceptible to arbitrary interpretation that can significantly influence the research results. The data reported in Table 8 summarize the data as it is reported in the literature.

Researchers at FDOT employed a plateau intercept method that is subject to arbitrary interpretation. In using the plateau intercept method, transfer lengths are defined by the intersection of the parabolic portion of the concrete strain with the strain plateau. The transfer length is poorly defined using this technique because the parabolic portion of the strain profile approaches the strain plateau asymptotically. UTK utilized a bilinear intersection method that requires two arbitrary lines be drawn from the transfer length data.

Table 8. Results of concurrent transfer length research.

Specimen	0.5 in. strands: Number of ends tested	0.5 in. strands: Measured transfer lengths (in.): Maximum	Average	Minimum	Standard deviation	0.6 in. strands: Number of ends tested	0.6 in. strands: Measured transfer lengths (in.): Maximum	Average	Minimum	Standard deviation
NCSU*	20	74	49.7	32	10.7	10	68	56.5	44	8.0
FDOT†	12	32	30.1	29.5	0.7	7	36	34.7	32	1.5
UTK‡	8	36	27.9	22	5.6	8	30	24.4	21	2.9

Note: 1 in. = 25.4 mm.
* Method for data analysis is not reported.
† Transfer length data were analyzed using a plateau intercept method that may allow arbitrary interpretation of results.
‡ Transfer length data were analyzed using a bilinear intersection method that may allow arbitrary interpretation of results.

DEVELOPMENT OF DESIGN GUIDELINES FOR TRANSFER LENGTH

In reviewing the transfer length data collected in this and other research projects, the data are most remarkable for their relatively wide variation. Certainly, if one includes data from other research projects, the transfer length data do not converge to a single value. Cousins et al. report a maximum transfer length for 0.5 in. (12.7 mm) diameter strands of 74 in. (1.88 m) with an average value of 49.7 in. (1.26 m). On the other hand, Shahawy reports transfer lengths for 0.5 in. (12.7 mm) strand to be tightly grouped around 30 in. (762 mm).

Transfer lengths measured in this research appear to distribute somewhat normally around an average value. The average transfer length for 0.5 in. (12.7 mm) diameter strands is 29.5 in. (749 mm) and the average transfer length for 0.6 in. (15.2 mm) strands is 40.0 in. (1.02 m). The only significant, identifiable variable that affected transfer lengths measured in this research was strand diameter. All other variables, i.e., confining reinforcement, debonded strands and strand spacing affected transfer lengths to a smaller degree. Concrete strength was not a research variable in this testing program and no recommendations can be made in that regard.

Figs. 15 and 16 present the data in histograms based upon the measured transfer lengths from this research project. The histograms are helpful in that they illustrate the distribution of measured transfer lengths by plotting the number of specimen ends vs. their measured transfer lengths. The transfer lengths are grouped in ranges of ±2 in. (±51 mm).

Shahawy et al. suggested that the transfer length could be predicted by $f_{si}d_b/3$. This expression yields transfer lengths of approximately 32.5 in. (826 mm) for 0.5 in. (12.7 mm) diameter strands and 39 in. (991 mm) for 0.6 in. (15.2 mm) strands. This expression has also been recommended by Buckner in his recent summary of strand bond research.[23] However, this recommended expression predicts a shorter transfer length rather than a large percentage of the measured transfer lengths that are reported in this and other literature.

On the histograms in Figs. 15 through 18, the transfer lengths corresponding to $f_{si}d_b/3$ are shown. The data indicate that the expression $f_{si}d_b/3$ roughly predicts the average values of transfer lengths measured in this research. However, the recommended expression would be unconservative to much of the transfer length data. For transfer lengths measured on 0.5 in. (12.7 mm) diameter strands, 10 transfer lengths of 34 measured exceed 32.5 in. (826 mm). Considering 0.6 in. (15.2 mm) strands, 21 transfer lengths out of 40 measured transfer lengths exceed 39 in. (991 mm). Overall, the recommended expression, $f_{si}d_b/3$, predicts shorter transfer lengths than 43 percent of the data (shown in Fig. 17).

Considering the sudden and violent nature of failures that can result from strand anchorage failure, it seems inappropriate to recommend an expression that predicts the average value for transfer length. Because flexural tests have shown that strand development is directly related to the transfer length,[7,8,12,13,24] the expression predicting transfer length must be conservatively chosen. Accordingly, it would seem more appropriate to select a value or an expression that provides an upper limit for a greater percentage of the test results. By choosing a more conservative expression for transfer length, the expression could be used confidently in a wide variety of applications. The following expression is suggested by the data and recommended for use in design applications:

$$L_t = \frac{f_{se}}{2} d_b \qquad (11)$$

This expression would predict transfer lengths of 40 in. (1.02 m) for 0.5 in. (12.7 mm) diameter strands and 48 in. (1.22 m) for 0.6 in. (15.2 mm) strands, assuming an effective prestress of 160 ksi (1100 MPa). Corresponding values for $f_{se}d_b/2$ are shown on each of the histograms (see Figs. 15 through 18). Alternatively, transfer lengths could be predicted by setting transfer length equal to 80 strand diameters, or $80d_b$ (as long as Grade 270, low relaxation strands are employed).

There are two primary advantages in using $f_{se}d_b/2$:

First, this expression exceeds the measured transfer length from most of the data, which is important as transfer length relates to strand development. As development length testing has consistently shown, successful strand anchorage depends upon the prevention of cracking through or near the transfer zone. Therefore, an undisturbed transfer zone is essential to strand development.

Secondly, the expression relates transfer length to both strand diameter and to the prestressing force, using the same variables currently employed in the expression from the ACI Commentary. This expression would allow evolution to new strand sizes and higher strand strengths. [However, transfer lengths do not appear to be directly proportional to strand diameter. Introduction of strand sizes larger than 0.6 in. (15.2 mm) will require additional testing.]

In developing an expression for transfer length, one must consider the importance of transfer length and the manner in which transfer length is used for design. For some designers, transfer length will be important only as it relates to predicting the elastic properties in the end regions of a pretensioned member. Primarily, this concern focuses most specifically in calculating the shear strength of concrete, V_c.

In the early and mid 1980s, many testing programs focused on developing reliable design guidelines for the shear design of pretensioned concrete. Tests performed in these research programs consistently demonstrated a direct interaction between shear failures and bond failures. In fact, the failure modes are difficult to distinguish and failures were labeled shear/bond failures. Significantly, these shear/bond failures were sudden, violent and would represent catastrophic failures in real structures.

Similarly, in the late 1980s and into the 1990s, strand bond issues of transfer length and development length became the focus of new testing programs. In the development length research that followed, research programs at Tennessee (UTK), FDOT, and Austin tested I-shaped beams for strand development. In many of those tests, violent and catastrophic failures were observed that resulted directly from bond failure precipitated by web shear cracking. These failures were labeled bond/shear failures and closely matched the shear/bond failures that were observed in shear testing. A brief summary of the test results is included in a recent issue of the PCI JOURNAL.[25]

From the development length testing, it is imperative to recognize that the transfer length can directly and adversely affect the strength and ductility of a pretensioned member. Typical shear/bond failures have not only been recorded in research laboratories, but also during the Northridge earthquake.[26] These failures highlight the need for the industry to collectively acknowledge the importance of transfer length in the safe design of pretensioned beams.

Accordingly, the expression for transfer length must be conservatively chosen, and must encompass a large percentage of the data to prevent unexpected and non-ductile failures. (Also, acceptance criteria should be established to control and limit the extreme values for transfer length.) Therefore, the more conservative expression for transfer length is recommended:

$$L_t = \frac{f_{se} d_b}{2} \qquad (12)$$

[Authors' note: The essential criteria that control strand anchorage failures are the interaction between the anchorage failure and cracking that propagates through or near the transfer zone of a pretensioned strand, thereby causing anchorage failure. Failure to recognize the importance of the interaction between cracking and bond failures has led to ultra-conservative recommendations for the development length equation by Shahawy et al. and by Buckner. By conservatively choosing a transfer length provision (and by requiring acceptance criteria limiting the maximum strand transfer length), pretensioned strand anchorage should be assured for a wide variety of applications without resorting to extremely conservative equations for development length. It is imperative to note that the longer design transfer length given in Eq. (11) directly reflects the wide variation in measured transfer lengths and the need for a design value to exceed a large percentage of the possible transfer lengths. At some point in the future, if a standardized bond performance test is implemented that significantly reduces the degree of scatter in pretensioned bond, then a less conservative design expression for transfer length could be adopted without reservation.]

CONCLUSIONS

Based on the results of this investigation, the following conclusions can be made:

1. The average measured transfer length for 0.5 in. (12.7 mm) diameter strands was 29.5 in. (749 mm) with a standard deviation of 6.9 in. (175 mm), or 23 percent. Transfer lengths were measured on 34 ends of pretensioned specimens.

2. The average measured transfer length for 0.6 in. (15.2 mm) strands was 40.0 in. (1.02 m) with a standard deviation of 6.8 in. (170 mm), or 17 percent. Transfer lengths were measured on 40 ends of pretensioned specimens.

3. The transfer lengths for debonded strands were measurably shorter than those of the fully bonded strands. Transfer lengths for debonded strands were, on average, 16 percent shorter than transfer lengths for fully bonded strands. For 0.5 in. (12.7 mm) debonded strands, the average transfer length was 25.8 in. (655 mm). For 0.6 in. (15.2 mm) debonded strands, the average transfer length was 32.7 in. (831 mm).

4. Overall, confining reinforcement had little or no effect in improving the transfer lengths of 0.5 or 0.6 in. (12.7 or 15.2 mm) diameter strands. In fact, the measured transfer lengths for strands confined by mild steel reinforcement were marginally longer than strands where confining reinforcement was not provided. For strands enclosed by confining reinforcement, the average transfer length was about 12 percent longer than for strands without confining reinforcement. These results indicate that confining, or transverse, reinforcement is not activated until splitting cracks occur at prestress transfer. The authors recommend that standard detailing continue to include transverse reinforcement to prevent loss of anchorage due to the splitting cracks that can occur at release of pretensioning.

5. The 0.6 in. (15.2 mm) diameter strands were found to adequately and reliably transfer prestressing forces into the concrete. Therefore, the 0.6 in. (15.2 mm) strands should be allowed for regular use in pretensioned concrete. Furthermore, although the 0.6 in. (15.2 mm) strands required longer transfer lengths than 0.5 in. (12.7 mm) strands, the transfer of forces from 0.6 in. (15.2 mm) strands was similar to the transfer of forces from 0.5 in. (12.7 mm) strands.

6. The 0.6 in. (15.2 mm) diameter strands required measurably longer transfer lengths than 0.5 in. (12.7 mm) strands. On average, the 0.6 in. (15.2 mm) strands required 36 percent longer transfer lengths to adequately transfer prestressing forces into the concrete when compared to 0.5 in. (12.7 mm) strands. Therefore, strand diameter, d_b, should continue to be part of the transfer length expression.

7. Results from these transfer length tests indicate that the transfer length may not vary linearly with strand diameter, d_b. Instead, these data indicate that the expression, $L_t = K d_b^{\alpha}$, would be more accurate (for these data, α = 1.68). However, the authors do not suggest that these data alone provide sufficient evidence to recommend adoption of an exponential equation. Therefore, additional research is required to evaluate the transfer length as a nonlinear function of the strand diameter, d_b.

8. The anchorage of 0.6 in. (15.2 mm) diameter strands was adequately and reliably accomplished by spacing strands at 2.0 in. (51 mm) center-to-center spacings. Narrow specimens with 0.6 in. (15.2 mm) strands spaced at 2.0 in. (51 mm) centers reliably transferred prestressing forces, without evidence of splitting cracks or other adverse effects. Furthermore, specimens with 0.6 in. (15.2 mm) strands spaced at 2.0 in.

(51 mm) spacings had essentially identical transfer lengths. Therefore, 0.6 in. (15.2 mm) strands should be allowed for use in pretensioned concrete on 2.0 in. (51 mm) center-to-center spacings.

9. Larger cross sections containing multiple strands had measurably shorter transfer lengths than the smaller transfer length specimens. The larger AASHTO-type beam specimens had measured transfer lengths that were 25 percent shorter than the smaller rectangular transfer length prisms, on average.

10. The data indicate that correlation does exist between transfer length and strand end slips. Linear regression of the data, transfer length vs. end slip, generated a "best fit" line described by $L_t = 294.9L_{es}$, with a coefficient of correlation, $r = 0.717$. This "best fit" line is nearly identical to the theoretical relationship, $L_t = 2L_{es}(E_{ps}/f_{si}) = 290L_{es}$. Significantly, the relationship between end slip, L_{es}, and transfer length is independent of strand size, concrete strength and all other variables that are recognized to affect strand transfer length.

11. From the data, a rational and safe expression for transfer length is determined:

$$L_t = \frac{f_{se}d_b}{2}$$

It should be emphsized that the conservative nature of this recommended design equation is a direct reflection of the wide variation in measured transfer lengths.

RECOMMENDATIONS

1. The expression for transfer length should be changed to protect against the potentially dangerous failures if transfer length is underestimated. The recommended expression is:

$$L_t = \frac{f_{se}d_b}{2}$$

2. The transfer length for debonded strands should be assumed to match the transfer length for fully bonded strands, and is also given by the expression above.

3. The 0.6 in. (15.2 mm) diameter strands should be allowed for use in pretensioned concrete at an allowable center-to-center spacing of 2.0 in. or 50 mm. Designers of pretensioned concrete must also be aware that 0.6 in. (15.2 mm) strands require longer transfer lengths and adjust designs accordingly.

AUTHORS' POSTSCRIPT

In recent testing conducted at the University of Oklahoma beginning in 1994, at the University of Texas at Austin and at Stresscon Corporation in Colorado Springs, Colorado, it is becoming increasingly clear that transfer lengths for some strands can be quite shorter than the transfer lengths measured in the research described in this paper. Additionally, the authors recognize ongoing efforts to implement quality control procedures that should help control the bond properties of prestressing strands.

If the transfer lengths of strands are measurably shortened from these efforts, or if the variations in measured transfer lengths are significantly reduced, then a less conservative design expression for transfer length may be more appropriate. Therefore, if appropriate quality assurance can be enacted to ensure the reliability of bond of strands used in pretensioned applications, then it may be possible for these authors to acknowledge that transfer lengths could remain at the current expression, $L_t = f_{se}d_b/3$.

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APPENDIX — NOTATION

A_{ps} = area of prestressing strand, $7/36\pi d_b^2$

d_b = diameter of prestressing strand

E_{ps} = modulus of elasticity of prestressing strand

f_c' = concrete compressive strength at 28 days (ASTM C 39)

f_{ci}' = concrete compressive strength at release of prestressing

f_{ps} = stress in prestressed reinforcement at nominal strength

f_{se} = effective stress in prestressed reinforcement (after allowance for all prestress losses)

f_{si} = stress in prestressed reinforcement before release and transfer

L_b = length of debonding, or length of blanketing

L_d = development length

L_{es} = amount of strand slip into concrete on release of prestressing strands

L_t = transfer length

P_{ps} = perimeter of prestressing strand, $4/3\pi d_b$

u_b = average transfer bond stress

u_f = average flexural bond stress

V_c = nominal shear strength provided by concrete

V_{ci} = nominal shear strength provided by concrete when diagonal cracking results from combined shear and moment

V_{cw} = nominal shear strength provided by concrete when diagonal cracking results from excessive principal tensile stress in web