

Transfer and Development Lengths of FRP Prestressing Tendons



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An experimental investigation was conducted to determine the transfer length, development length, and flexural behavior of fiber-reinforced polymer (FRP) tendons in prestressed concrete beams. Three types of nominally $\frac{5}{16}$ in. (8 mm) diameter FRP tendons were included in the study: Carbon Leadline, Aramid Technora, and a carbon fiber reference material. Thirty beams were pretensioned using a single FRP tendon. In addition, twelve control beams were pretensioned with a seven-wire steel strand (ST). The transfer length for FRP tendons was reasonably well predicted by the ACI design equation, with the modification in AASHTO providing for a minimum transfer length. The ACI equation predicts the development length very conservatively provided the tendon rupture stress is used in place of the tendon stress at nominal capacity. Therefore, it is proposed to modify the ACI equation to account for the larger bond stress developed by the FRP tendons.

In pretensioned concrete members, transfer length is the distance required to transmit the effective prestressing force from the prestressing tendon to the concrete. When a member is loaded to its ultimate flexural strength, an additional bond length beyond the transfer length is required to develop the tendon stress from the effective prestress to stress at nominal flexural strength. This additional bond length is called flexural bond length, and the development length is defined as the sum of the transfer length and the flexural bond length.

With the exception of cantilevers and short span members, strand transfer and development length seldom govern the design of pretensioned concrete members; however,

knowledge of transfer and development lengths is essential in preventing bond slip failure of the member.

OBJECTIVES AND SCOPE OF RESEARCH

The objectives of this study are to experimentally determine the transfer and development lengths of three types of fiber reinforced polymer (FRP) tendons in precast, prestressed concrete beams, and to compare the experimental results to existing models from the literature.

In this study, 30 transfer length tests, 24 development length tests and nine flexure tests were done on beams prestressed with three types of FRP tendons along with control specimens constructed with steel strands.

The primary variable studied in this investigation is the type of FRP material. Three different FRP materials were used in the study, and are fully described in the section on the experimental program.

LITERATURE REVIEW

Bond between reinforcement and concrete in a structural member is the result of three mechanisms, namely, adhesion, Hoyer's effect, or the wedge action due to transverse relaxation of the strand in the transfer zone, and mechanical interlocking. These distinctly different mechanisms have been investigated by Janney,¹ Hanson and Kaar² and by Russell and Burns,³ among other researchers.

A summary of the recommended expressions for transfer and development length for twisted, seven-wire steel strand is presented in Tables 1 and 2. The nomenclature in these tables follows ACI 318-99,⁴ with the exceptions given below.

The parameters U_t and B in Tables 1 and 2 are empirically determined coefficients of nominal bond stress and bond-stress/slip modulus, respectively. The quantity α_t , also in Table 1 and 2, is an empirically determined coefficient, which varies among tendon types and manufacturers. The quantity f_{si} is used by several authors to represent the initial prestressing.

The quantity $\kappa_b \mu_{ave}$ in Table 2 varies for different types of beams: for

Source	Equation
Current ACI ⁴ AASHTO ²² (AASHTO minimum 50 d_b)	$L_t = \frac{1}{3} f_{se} d_b$
Zia and Mostafa ¹⁷	$L_t = 1.3 \left(\frac{f_{si}}{f'_{ci}} \right) d_b - 2.3$
Cousins, Johnston and Zia ¹⁹	$L_t = 0.5 \left(\frac{U_t}{B} \right) + \frac{f_{se} A_{ps}}{\pi d_b U_t}$
Shahawy, Issa and Batchelor ²¹	$L_t = \frac{f_{si} d_b}{3}$
Russell and Burns ²⁰	$L_t = \frac{f_{se} d_b}{2}$
Mitchell, Cook, Khan and Tham ¹⁸	$L_t = \frac{f_{si} d_b}{3} \sqrt{\frac{3}{f'_{ci}}}$
Mahmoud, Rizkalla and Zaghoul ⁸	$L_t = \frac{f_{si} d_b}{\alpha_t f'_{ci}{}^{0.67}}$

Table 1.
Proposed equations for transfer length.

the slender beams used in this study, the denominator of this formula is unity, resulting in no change from the ACI equation. Also in Table 2, the value of λ increases from unity for tendons with large strains (over 1 percent) at the nominal capacity of the member.

Abdelrahman⁵ reported transfer length data for $5/16$ in. (8 mm) diameter CFRP Leadline rods. The transfer length was estimated to be 14.2 in. (360 mm) or 46 bar diameters when tendon stress after release was 137 ksi (950 MPa) and 19.7 in. (500 mm) or 64 bar diameters when the stress after release was 190 ksi (1310 MPa).

Domenico⁶ investigated the transfer length of seven-wire carbon fiber composite cable (CFCC). The CFCC diameter varied from 0.5 to 0.625 in. (12.5 to 15.2 mm). The measured transfer length was proportional to the diameter of the CFCC strand and the prestress level, and varied from 5.5 to 16.0 in. (140 to 400 mm) or 9 to 32 bar diameters.

Mahmoud and Rizkalla⁷ studied the bond characteristics of CFRP tendons in pretensioned concrete beams.

Three diameters [$7/16$, $1/2$ and $5/8$ in. (10.5, 12.5 and 15.2 mm)] were considered for the CFCC strands and $5/16$ in. (8 mm) diameter was used for Leadline. The measured transfer length varied from 21.0 to 25.5 in. (450 to 650 mm), or 56 to 81 bar diameters for Leadline rods and from 12 to 16.5 in. (300 to 425 mm), that is, 20 to 40 bar diameters, for CFCC strands. In a further elaboration of this work, Mahmoud, Rizkalla and Zaghoul⁸ present formulas for estimating the transfer and development lengths for these two types of FRP tendons.

Soudki, Green and Clapp⁹ studied the transfer length of $5/16$ in. (8 mm) spirally indented CFRP Leadline rods. The results were determined by measuring the strain in both the prestressing tendons and the concrete. The measured transfer lengths for the CFRP tendons were 26.5 to 28.5 in. (650 to 725 mm), or 80 to 90 tendon diameters.

The authors also concluded that the existing models for steel may give unconservative transfer lengths for the CFRP tendon and that the long-term transfer length of Leadline is similar

Table 2. Proposed equations for development length.

Source	Equation
Current ACI ⁴ AASHTO ²²	$L_d = \frac{1}{3} f_{se} d_b + (f_{ps} - f_{se}) d_b$
Deatherage, Burdette and Chew ²³	$L_d = \frac{f_{se} d_b}{3} + 1.5 (f_{ps} - f_{se}) d_b$
Cousins, Johnston and Zia ¹⁹	$L_d = 0.5 \left(\frac{U'_i \sqrt{f'_{ci}}}{B} \right) + \frac{f_{se} A_{ps}}{\pi d_b U'_i \sqrt{f'_{ci}}} + (f_{ps} - f_{se}) \left(\frac{A_{ps}}{\pi d_b U'_i \sqrt{f'_{ci}}} \right)$
Shahawy, Issa and Batchelor ²¹	$L_d = \frac{f_{si} d_b / 3 + (f_{ps} - f_{se}) d_b}{\kappa_b \mu_{ave}}$
Buckner ²⁴	$L_d = \frac{f_{si} d_b}{3} + \lambda (f_{ps} - f_{se}) d_b$
Mitchell, Cook, Kahn and Tham ¹⁸	$L_d = 0.33 f_{si} d_b \sqrt{\frac{3}{f'_{ci}}} + (f_{ps} - f_{se}) d_b \sqrt{\frac{4.5}{f'_c}}$
Mahmoud, Rizkalla and Zaghoul ⁸	$L_d = \frac{f_{si} d_b}{\alpha_t f'_{ci}{}^{0.67}} + \frac{(f_{pu} - f_{se}) d_b}{\alpha_f f'_{ci}{}^{0.67}}$

to the instantaneous transfer length measured at release. In these results, only slight differences in transfer length for different prestressing levels can be noted, and no differences were noted between the transfer length in the stem of a T-beam with four tendons, and in a rectangular beam with a single tendon.

Nanni, Utsunomiya, Yonekura and Tanigaki¹⁰ used concrete strain measurements and static flexural tests to determine transfer lengths of braided FiBRA AFRP tendons of nominal $\frac{5}{16}$, $\frac{1}{2}$, and $\frac{9}{16}$ in. (8, 12, and 16 mm) diameters. The reported transfer length for the tendons are approximately 15.7, 17.7, and 21.6 in. (400, 450, and 550 mm). Some increase in transfer length for increased prestressing force and some decrease for multiple strand applications can be noted. Nanni and Tanigaki¹¹ reported development lengths of less than 33.4 in. (850 mm), greater than 39.4 in. (1000 mm),

and 40.9 in. (1040 mm) for the same material.

Taerwe and Pallemans¹² used 0.3 and 0.2 in. (7.5 and 5.3 mm) diameter Arapree aramid fiber rods in their transfer length study. They suggested a transfer length of 16 times the nominal diameter of the rods for all of these Arapree rods.

Ehsani, Saadatmanesh and Nelson¹³ conducted tests on three kinds of aramid FRP tendons: Arapree 0.4 in. (10 mm), FiBRA 0.4 in. (10.4 mm) and Technora $\frac{5}{16}$ in. (7.4 mm). The transfer and development lengths were found to be 33 and 83 bar diameters for FiBRA, 43 and 117 bar diameters for Technora, and 50 and 102 bar diameters for Arapree, respectively.

Issa, Sen and Amer¹⁴ conducted a comparative study of the transfer lengths of fiberglass and twisted, seven-wire steel pretensioned members. S-2 glass epoxy tendons with $\frac{3}{8}$ in. (9.5 mm) and steel strands with $\frac{1}{2}$

in. (12.7 mm) diameter were tested. The transfer length of the fiberglass was determined to range from 10 to 11 in. (254 to 279 mm), or 28 times the nominal diameter of the tendon. The authors concluded that fiberglass had better bond characteristics than steel, in this case, due to better adhesion and interlock at transfer.

Based on previous studies for transfer length and development length of FRP materials, several conclusions can be established:

1. Transfer and development lengths increase in some nonlinear manner with tendon diameter.
2. Transfer length does not vary substantially with time.
3. Concrete strength, in the range of 5000 to 7000 psi (35 to 50 MPa), has only a moderate effect on the transfer length of FRP tendons.
4. Higher prestressing force results in slightly larger transfer and development lengths.

5. Surface finish greatly influences the bond between FRP tendons and the concrete.

6. FRP tendons develop higher bond stresses before undergoing slip than steel tendons.

EXPERIMENTAL PROGRAM

The experiments involved casting a total of 42 specimens, ten for each of the three FRP tendon materials and twelve for the seven-wire steel strand. All specimens contained a single tendon. Two specimens with a single tendon concentrically placed were used to measure transfer length only (see Fig. 1a).

Forty rectangular specimens were cast with the tendon placed eccentrically (see Fig. 1b). All specimens were fabricated by a PCI-certified producer. The specimens in this study contained no shear reinforcement or other confinement.

Materials

The concrete mix used in this project contained 750 lbs per cu yd (445 kg/m³) of Type III portland cement, 131 lbs per cu yd (78 kg/m³) of fly ash, for a total water-cementitious materials ratio of 0.36. The concrete was designed for 7.4 percent entrained air, by volume. The average compressive strength was:

- At release: 5570 psi (38.4 MPa)
- At 28 days: 6420 psi (44.3 MPa)
- At 90 days: 6550 psi (45.2 MPa)

Prestressing

A photograph illustrating the FRP tendons used in this study is shown in Fig. 2. The Leadline tendons, designated CL, are made commercially by Mitsubishi Chemical, Tokyo, Japan, using the pultrusion process with carbon fibers and an epoxy resin. The Leadline tendon surface is indented with a helical impression in the surface that spirals along the length of the tendon.

Technora tendons, designated AT, are made commercially by Teijin Company, Osaka, Japan, by the pultrusion process where straight, bundled aramid fibers are impregnated with a vinyl ester resin. Technora

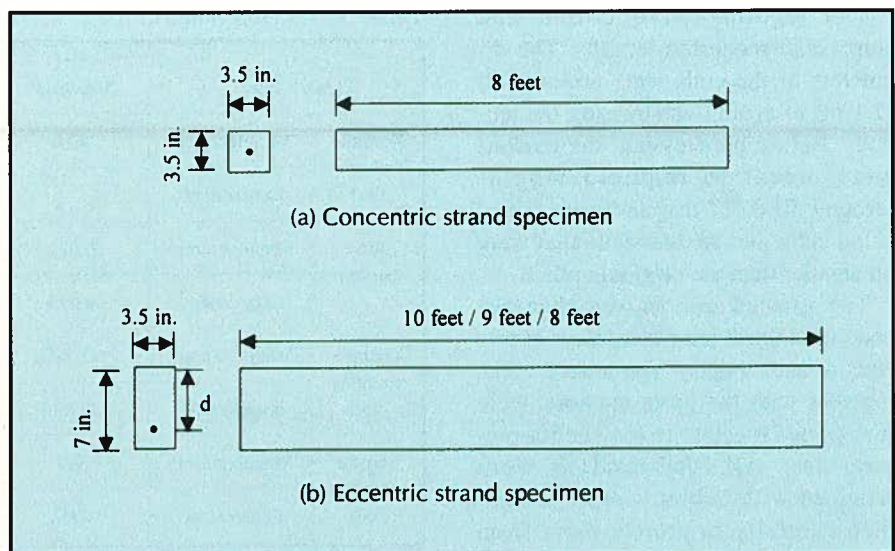


Fig. 1. Test specimen configuration.

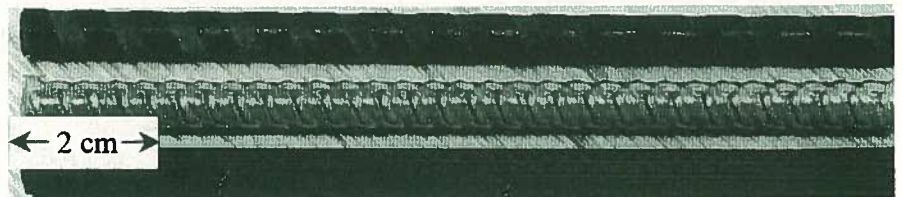


Fig. 2. FRP tendons used in this study. (From top to bottom: CL, AT, CS.)

aramid yarns are wound spirally around the bundle of straight fibers to provide a rough surface capable of achieving adequate bond strength.

A non-commercial tendon developed especially for this investigation is designated CS. This tendon is not intended to achieve optimal results compared to the other materials used in the research; however, it is a generic, non-proprietary type of tendon that could be produced by any manufacturer and represents a reference specimen for comparison in this and any further studies.

As opposed to the commercial tendons used in this and other studies, the exact composition of the CS tendon has been disclosed by the manufacturer. The tendon consists of a nominal volume fraction of 65 percent T650 carbon fibers, with a tensile strength of 650 ksi (4480 MPa), and a tensile modulus of 34,000 ksi (234 GPa).

The matrix material consists of 100 parts Shell 9405 resin, 28 parts Shell 9470 curing agent, five parts ASP-400P filler, 0.65 parts Axel 1846 mold release, and 1.5 to 2 percent by weight Shell 537 curing agent accelerator.

The matrix has a tensile strength of 9.3 ksi (64 MPa), and a tensile modulus of 396 ksi (2.73 GPa).

The surface of this tendon is roughened by applying a cloth-like peel ply during processing that, when removed, results in indentations to the tendon. Tendon properties are given in Table 3. Manufacturer's data given in Table 3 are guaranteed values – all other data are mean values of three tests.

A grouted FRP single-tendon anchorage system was developed and tested.¹⁵ The system consists of a hollow steel tube filled with expansive grout, into which the end of the tendon is embedded. The volume expansion is delayed until after the grout partially sets.

The resulting grip minimizes axial and shear stress concentrations. Coupling devices with thread on the outer diameter were used to couple an FRP tendon to a conventional steel strand, which was then anchored to the hydraulic jacking system with a conventional steel wedge chuck. In this way, the same jacking system that is used for a conventional steel tendon can also be used for FRP tendons.

The tendons were coiled and shipped in requested lengths. The diameters of the coils were around 7 ft (2.1 m) to avoid overstressing the tendons. Before prestressing, the tendons were precut to required lengths [around 50 ft (17 m)] and were coiled using cable ties to diameters that were no smaller than the original coils.

Two grouted anchors were then cast and cured for at least three days at two ends of each tendon. The tendon coils, together with the grout anchors, were transported together to the site for prestressing. All FRP tendons were wrapped with bubble wrap and handled carefully to protect them from scraping, kinking, notching or crushing during handling.

The three days required for the expansive grout to cure can result in inefficient use of the prestressing bed for FRP materials; however, these anchors were applied in advance to the FRP prestressing, with the assembly of the coupler only done in the prestressing bed. Since the couplers are located within the prestressing area, their use resulted in the loss of up to 5 ft (1.52 m) of prestressing bed.

The jacking force at the live end of the bed was monitored with a pressure cell connected to the hydraulic jack. An electronic load cell was used at the dead end of one of the two prestressing lines to verify the applied force. Load at full prestress was locked

Table 3. Tendon material properties.

Tendon type		CL Leadline	AT Technora	CS Reference	ST Steel
Nominal diameter (in.)	Manufacturer*	5/16	5/16	5/16	5/16
	Experiment†	—	—	—	—
Area (sq in.)	Manufacturer*	0.071	0.078	0.078	0.058
	Experiment†	0.073	0.078	0.078	—
Young's modulus (ksi)	Manufacturer*	21,300	7700	23,300	29,000
	Experiment†	24,800	6500	23,300	—
Tensile strength (ksi)	Manufacturer*	327	248	266	250
	Experiment†	435§	N/A‡	274§	—

Note: 1 in. = 25.4 mm; 1 sq in. = 645 mm²; 1 ksi = 6.89 MPa.

* Manufacturer's values are guaranteed values.

† Experimental values are mean values of three tests.

‡ All specimens slipped in grips before rupture.

§ Tendon is linearly elastic to rupture.

down using a steel chuck at the live end anchor plate.

In addition to monitoring of load during tensioning, elongation of the FRP tendon plus steel strand and anchorages at the live end were recorded at the face of the hydraulic jack. Target load and target elongation criteria were established for each tendon. Tensioning was stopped at the target load criterion. The FRP tendons were jacked to 62 to 64 percent of the strength using the same type of anchor, determined by laboratory testing

as part of this study. Tendons were de-tensioned gradually by releasing the hydraulic jack.

Characteristics, including concrete strength and prestress force at various load stages are given in Table 4. Further details of the experimental procedure are available in Lu's thesis.¹⁶

Transfer Length Measurement

Demec gauge readings [a mechanical measurement using metal targets] spaced on 4 in. (102 mm) centers were

Table 4. Characteristics of specimens.

Specimen material	CL Leadline	AT Technora	CS Reference	ST Steel	
Length, ft (number of beams)	10 (10)	10 (8) 8 (2)	10 (10)	9 (9) 8 (1)	8 (2)
Cross section, in. x in.	3.5 x 7	3.5 x 7	3.5 x 7	3.5 x 7	3.5 x 3.5
Concentric (C) or Eccentric (E) (Eccentricity, in.)	E (1.75)	E (1.75)	E (1.75)	E (1.75)	C (0)
Concrete strength, psi					
At release (1 day)	5800	6250	5150	5100	
At 28 days	6500	6700	6100	6350	
At 90 days	6580	6830	6400	6420	
Prestress					
f_{sj} (jacking stress) (ksi)	198	153	170	190	
f_{si} (initial prestress) (ksi)	180	132	146	169	
f_{sj}/f_{pu} (percent)	62	62	64	76	
f_{si}/f_{sj} (percent)	91	87	86	89	

Note: 1 in. = 25.4 mm; 1 ft = 305 mm; 1 psi = 6.89 kPa; 1 ksi = 6.89 MPa.

taken for each specimen prior to release of the tendon. Considering that these initial readings are especially important, these measurements were repeated at least six times by the same operator.

Subsequent readings were taken for all specimens at 50 percent release, 100 percent release, 28 days after release (CL, AT, CS), and also 90 days after release (AT). The measurements during and after release were repeated at least twice by the same operator.

Transfer length observations resulting from this study are based on concrete strain measured on both sides of the specimen at the level of the tendons. Release of the prestressing force, which was accomplished by slow release of pressure on the jack, occurred in two stages for all specimens, 50 and 100 percent release. The specimens remained on the prestressing bed while concrete strains were measured at these two stages. At 100 percent release, the tendons were cut completely.

The average values of measured concrete strain were plotted versus distance along the length of each specimen to generate a strain profile for each specimen at each time interval. To further reduce anomalies in the data, the raw strain profiles were smoothed by averaging the data over three gauge lengths. The smoothing technique can be summarized by the following equation:

$$(Strain)_i = \frac{(Strain)_{i-1} + (Strain)_i + (Strain)_{i+1}}{3} \quad (1)$$

where the i , $i-1$, and $i+1$ measurements proceed from one pair of Demec points to the next, in sequence.

Transfer lengths for each specimen were determined by evaluating the concrete strain profiles. The method used in this study is as follows:

1. Plot the smoothed strain profile versus longitudinal position in the beam.

2. Determine the average maximum strain for the specimen by computing the numerical average of all the strains contained within the strain plateau. The plateau is determined by visual inspection. Calculate 95 percent of the

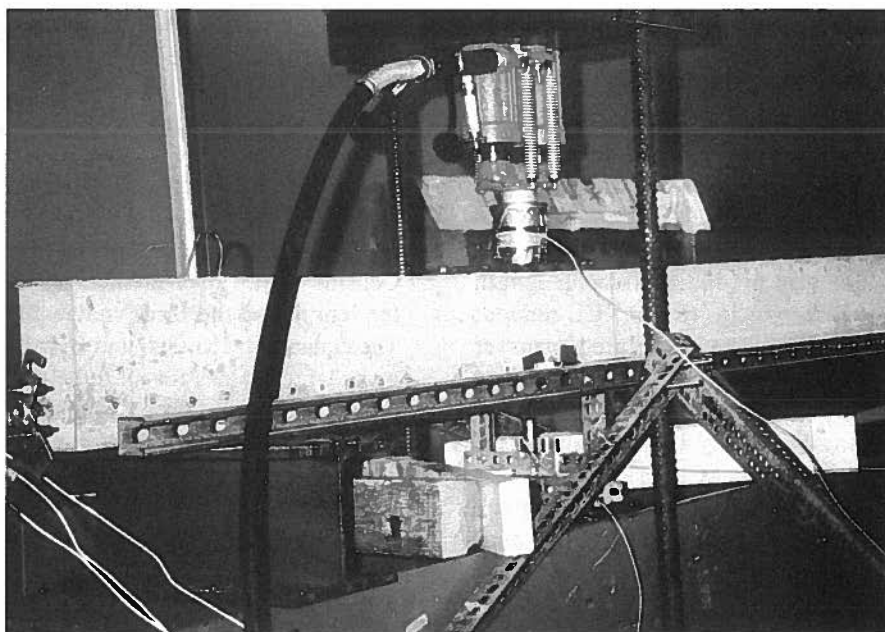


Fig. 3. Development length test apparatus.

average maximum strain and construct a horizontal line through the data corresponding to this value.

3. The transfer length at each end of the beam is determined by the intersection of the 95 percent line with the smoothed strain profile. Reported values of transfer length are the average values from the two ends of the beam. The average maximum strain is computed by averaging all the strains contained on the plateau of the fully effective prestressing force. This procedure is identical to that employed by Ehsani, Saadatmanesh, and Nelson¹³ and similar to that employed by Mahmoud, Rizkalla, and Zaghoul,⁸ who chose to use 100 percent of the average strain.

Development Length Measurement

The development length test is a three-point flexural test. A hydraulic jack and a hand pump were used to apply a point load at the designated embedment length, which varied for each test. In addition to increments of applied load measured using a load cell, the end slip of the prestressing tendon was determined by measuring the distance from a metal bracket, which is fixed on the tendon, to the end surface of the concrete specimen using LVDTs (Linear Variable Differential Transformer). The metal bracket can hold three LVDTs, evenly dis-

tributed around a circle 120 degrees apart.

Different embedment lengths were attained by applying load at varying distances from one of the supports. The test apparatus is shown in Fig. 3.

TEST RESULTS

Discussed below are the results from the experimental determination of transfer and development lengths.

Transfer Length Results

Five CL beams, three AT and three CS beams were tested for transfer length. The results are summarized in Table 5. In Table 6, based on concrete strain data, the measured transfer length from the end of the beam required to achieve maximum effective prestressing force (i.e., distance to the strain plateau) is compared to the predicted transfer lengths, which are determined using the equations listed in Table 1.

Transfer length values in this study were based on the 95 percent average plateau strain method determined using concrete strain results. The transfer length results for the CL and the AT tendons were verified to be close to values reported by Ehsani, Saadatmanesh, and Nelson,¹³ who obtained values of 17 in. (430 mm) for the CL tendon and 12.3 in. (312 mm) for the AT tendon, using the same measurement method.

The following observations can be made based on Table 6:

- There is little change in transfer length with time for all four materials, although it should be noted that the test was conducted over a relatively short time period.
- The ACI design equation is adequate in predicting transfer length for the $5/16$ in. (8 mm) CL tendon; however, the calculated transfer length from the ACI equation is very close to the measured transfer lengths, barely leaving any safety margin. The ACI design equation is unconservative in predicting the transfer length for the $5/16$ in. (8 mm) AT tendon. The measured transfer lengths are 20 to 25 percent larger than that predicted by the ACI Code. The ACI design equation is unconservative in predicting the transfer length for the $5/16$ in. (8 mm) CS tendon, simply because the initial prestress is smaller than that of the CL tendon. The measured trans-

fer lengths are 25 to 28 percent larger than that predicted by the ACI Code.

- The equation suggested by Zia and Mostafa¹⁷ and the equation by Mitchell et al.¹⁸ give smaller transfer lengths than the measured values for all four materials. The equation by Cousins et al.¹⁹ over-predicts transfer length for the three materials. The equation by Russell and Burns²⁰ gives larger values for all three materials. The equation by Shahawy, Issa, and Batchelor²¹ gives a close prediction of transfer length for all three materials.
- When applying the models to the three tendons tested, the only variable is the prestressing force. For a given model, the differences in predicted transfer lengths for the three materials are only a reflection of the differences in prestressing forces.
- The lack of variation in transfer length among the materials, and the unconservative predictions of trans-

fer length for some of the materials appears to be resolved by the adoption of a minimum value of transfer length, such as in the AASHTO Specifications.²²

Development Length Results

Based on the usual assumption that plane cross sections of a beam remain plane as bending moment is applied, the concrete strains at any loading stage vary linearly. Using strain compatibility from the appropriate linear strain distribution and force equilibrium from the appropriate stress distribution, flexural analysis can be done for any loading stage.

For each of the embedment lengths investigated in this study, the force in the tendon was estimated using a simple flexural model of a prestressed concrete beam.

Details of this procedure are given by Lu.¹⁶ In the cases where tendon slip was recorded, the nominal bond stress (tendon force divided by bonded surface area) decreases with increasing embedment length, and is of maximum magnitude of 300 to 600 psi (2 to 4 MPa) for fully developed tendons.

In Table 7, the measured development lengths are compared to the predicted development lengths, which are determined using the equations in Table 2. The further equations of Deatherage et al.²³ and Buckner²⁴ are also compared to the experimental results. Measured development lengths of 58 in. (1473 mm) for the CL tendon and 34 in. (865 mm) for the AT tendon were previously reported by Ehsani, Saadatmanesh, and Nelson.¹³

The Cousins, Johnston, and Zia¹⁹ model, and the Mahmoud, Rizkalla, and Zaghoul⁸ models explicitly incorporate material properties, while the Buckner²⁴ model, in increasing the development length for higher strain at nominal flexural strength implicitly incorporates material properties.

Two values of the measured development length are reported in Table 7 for each material. The first value of development length reported is the development length determined in the testing program. A value of f_{ps} calculated from the flexural model at failure is inserted into the formulas for the

Table 5. Strand transfer length results of specimens.

Tendon type	At 50 percent release				At 100 percent release			
	n^*	$\mu^\dagger$ (in.)	$\sigma^\ddagger$ (in.)	ϵ_{avg} ($\mu\epsilon$)	n^*	$\mu^\dagger$ (in.)	$\sigma^\ddagger$ (in.)	ϵ_{avg} ($\mu\epsilon$)
CL (Leadline)	—	—	—	—	10	16.6	0.91	276
AT (Technora)	6	14.1	0.75	105	6	14.5	1.0	197
CS (Reference)	6	16.6	0.51	118	6	16.1	0.79	218
ST (Steel)	12	18.1	1.6	111	12	19.1	1.1	189
Tendon type	At 28 days				At 90 days			
	n^*	$\mu^\dagger$ (in.)	$\sigma^\ddagger$ (in.)	ϵ_{avg} ($\mu\epsilon$)	n^*	$\mu^\dagger$ (in.)	$\sigma^\ddagger$ (in.)	ϵ_{avg} ($\mu\epsilon$)
CL (Leadline)	10	16.1	0.75	609	—	—	—	—
AT (Technora)	6	14.8	1.1	503	6	14.8	1.3	816
CS (Reference)	6	16.3	0.51	446	—	—	—	—
ST (Steel)	—	—	—	—	—	—	—	—

Note: 1 in. = 25.4 mm.

* Number of repetitions.

† Mean.

‡ Standard deviation.

Table 6. Comparison of measured strand transfer length with predicted strand transfer length.

Model (units in in.)		CL (Leadline)	AT (Technora)	CS (Reference)	ST (Steel)
Measured transfer length	50 percent	—	14.2	16.6	18.2
	100 percent	16.6	14.5	16.0	19.1
	28 days	16.1	14.8	16.3	—
	90 days	—	14.8	—	—
Current ACI ⁴ /AASHTO ²²		16.4/18.8	11.8/18.8	12.9/18.8	15.0/18.8
Model by Zia and Mostafa ¹⁷		10.7	6.4	9.2	11.2
Model by Cousins, Johnston and Zia ¹⁹ *		23.6	18.1	21.4	18.8
Model by Shahawy, Issa and Batchelor ²¹ *		19.3	13.9	15.2	17.6
Model by Russell and Burns ²⁰		24.6	17.7	19.4	22.4
Model by Mitchell, Cook and Khan ¹⁸		13.7	9.6	19.4	22.4
Model by Mahmoud, Rizkalla and Zaghoul ⁸		17.6	—	—	13.3

Note: 1 in. = 25.4 mm.

* Published values of material parameters for steel used in calculations.

least embedment length at which a flexural failure occurred.

For the embedment lengths attained in this study, all of the specimens failed by tendon slip, or concrete crushing. Hence, a linear trend line

was used to predict the required development length at tendon rupture. Embedment length versus tendon force at failure are plotted for each material, based on which the maximum development length of the material was de-

termined, as shown in Figs. 4a through 4d. This is reported as a maximum development length in Table 7.

Discrepancies between the measured and maximum development length appear because the maximum

Table 7. Comparison of measured and predicted strand development lengths.

Model	CL (Leadline)	AT (Technora)	CS (Reference)	ST (Steel)
Measured development length (in.)	42.1	37.4	45.1	51.0
Nominal bond stress at failure (psi)	585	454	465	287
Maximum development length (in.)	43.0	44.2	45.9	46.2
Current ACI ⁴ /AASHTO ²² (in.)	68.5	35.6	62.1	48.5
Current ACI ⁴ /AASHTO ²² (in.), using rupture strength in place of f_{ps}	68.5	54.6	62.1	48.5
Proposed modified ACI ⁴ /AASHTO ²² (in.)	57.6	43.9	48.4	—
Model by Cousins, Johnston and Zia ¹⁹ (in.)*	153	73.6	140	77.8
Model by Deatherage et al. ²³ (in.)	99.4	47.5	86.7	65.2
Model by Shahawy, Issa and Batchelor ²¹ (in.)*	68.5	35.6	62.1	48.5
Model by Buckner ²⁴ (in.)	77.7	75.4	65.7	58.0
Model by Mitchell, Cook, Khan and Tham ¹⁸ (in.)	59.6	29.1	54.2	39.5
Model by Mahmoud, Rizkalla and Zaghoul ⁸ (in.)	42.7	—	—	—

Note: 1 in. = 25.4 mm; 1 psi = 6.89 kPa.

* Published values of material parameters for steel used in calculations.

development length is based on guaranteed values of rupture strength, or the nominal value of the yield strength in the case of the ST tendons, which can be exceeded by individual specimens.

Calculated values of the development length, using the formulas in Table 2, are also provided in Table 7. All of the models predict the development length of the AT tendon very

poorly. This is due to the exceptionally low longitudinal modulus of elasticity of this material, which results in a very slight difference between the stress at the nominal strength of the member, f_{ps} , and the effective prestress f_{se} .

The approach used by Mahmoud, Rizkalla, and Zaghoul,⁸ of using the rupture strength of the tendon in place of f_{ps} addresses this issue, al-

though it results in conservative estimates of the development length for FRP tendons. The development length calculated by the ACI formula, with this substitution, is also shown in Table 7.

It can be noted that the nominal bond stress of the FRP tendons is considerably higher than that of the steel. The result is that the development length for the FRP material is consid-

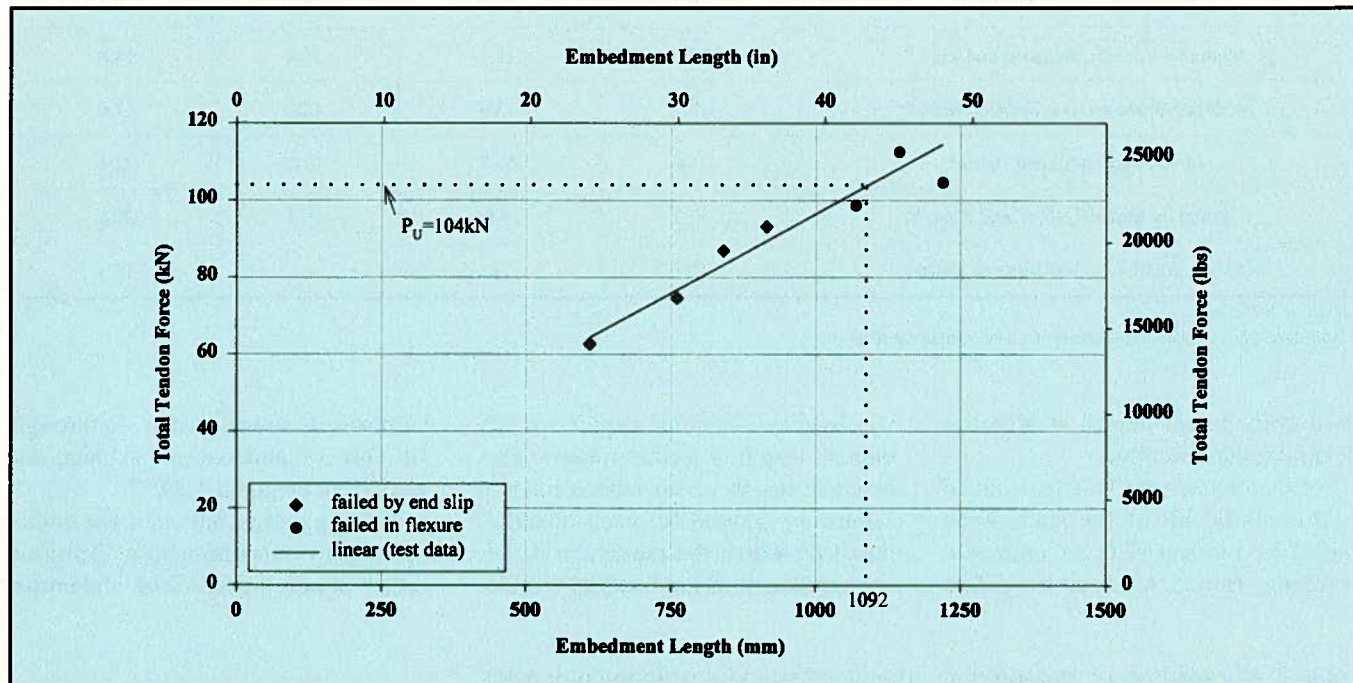


Fig. 4(a). Development length test results for Leadline tendons (CL).

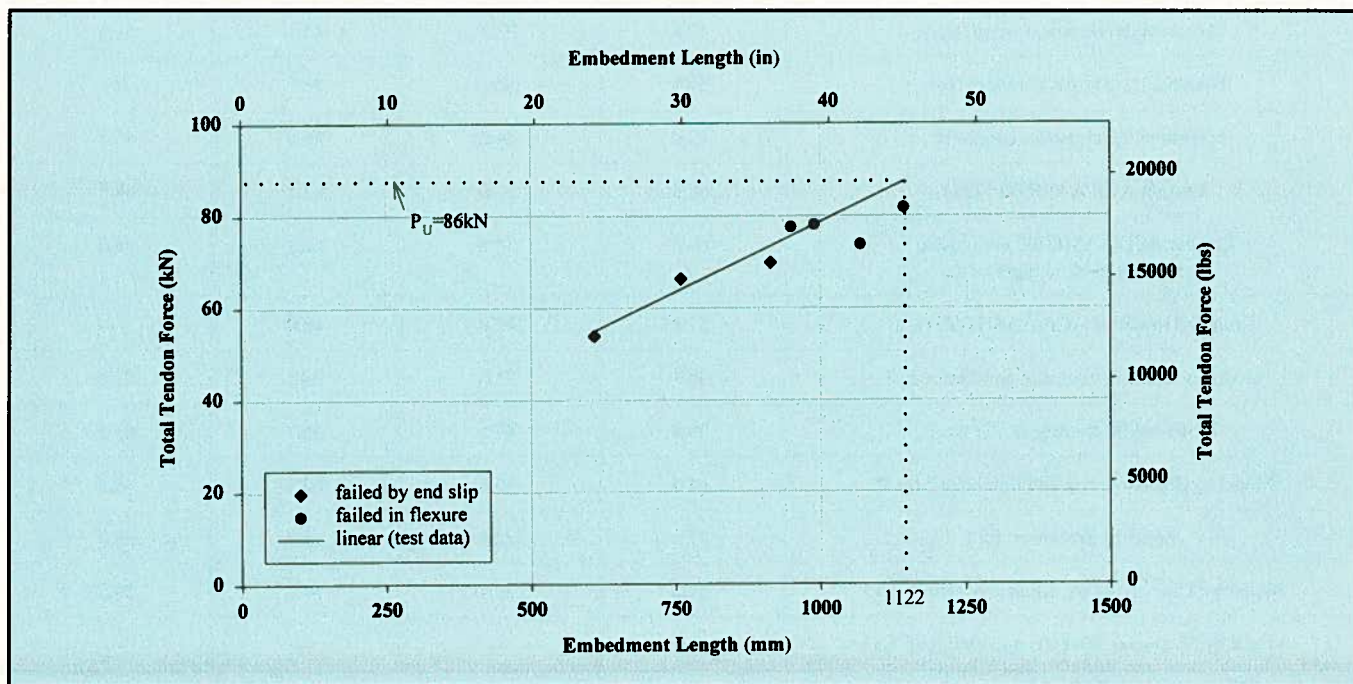


Fig. 4(b). Development length test results for Technora tendons (AT).

erably lower than predicted by any formula developed for steel tendons, when the rupture strength is substituted for f_{ps} .

The development length can be conservatively calculated for FRP tendons by modifying the ACI formula to reflect the larger nominal bond stress. Based on a nominal bond stress of 333 psi (2.30 MPa), the ACI formula can be modified to:

$$L_d = \frac{1}{3} f_{se} d_b + \frac{3}{4} (f_r - f_{se}) d_b \quad (2)$$

for FRP tendons only, in which:

d_b = diameter of tendon

f_r = rupture strength of tendon

f_{se} = effective prestress of tendon

This modified formula, which is also applied in Table 7, results in closer but conservative predictions for all tests noted in the literature review and this

study, including Ehsani, Saadatmanesh, and Nelson's¹³ finding of a development length of 58 in. (1473 mm) for $5/16$ in. (8 mm) diameter Leadline.

CONCLUSIONS AND RECOMMENDATIONS

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

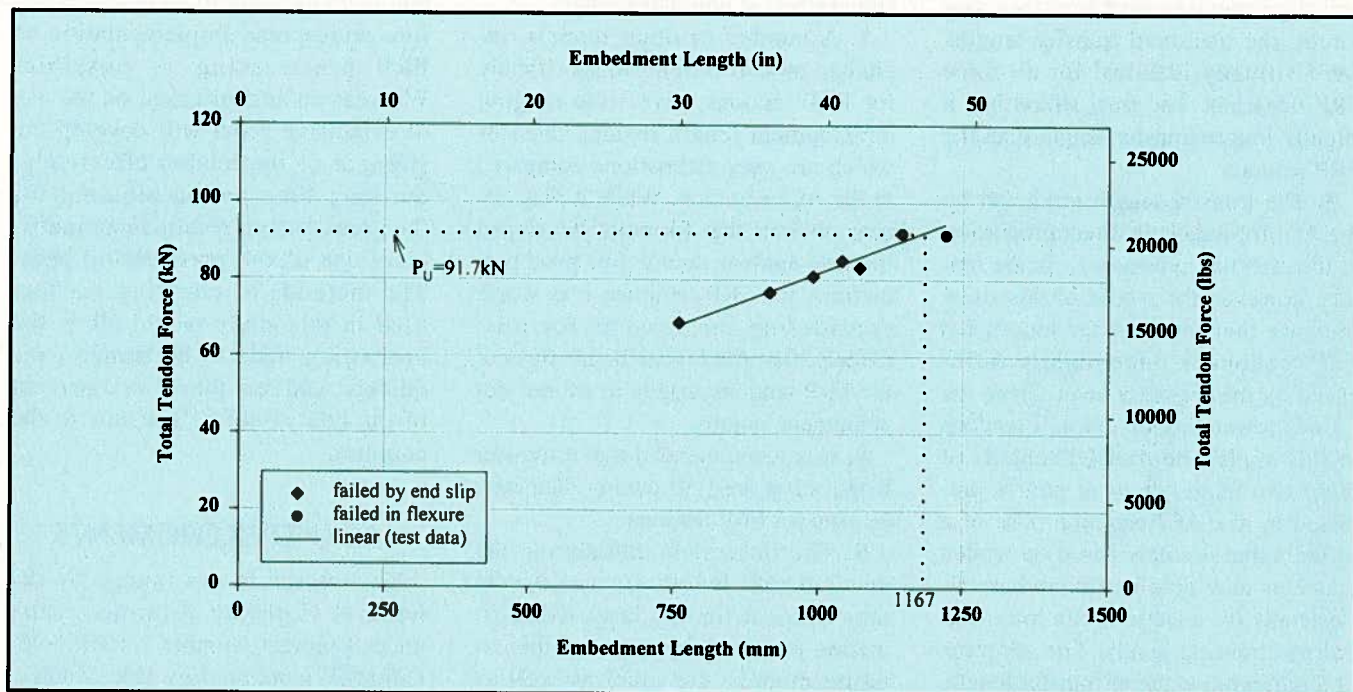


Fig. 4(c). Development length test results for non-commercial carbon/epoxy tendons (CS).

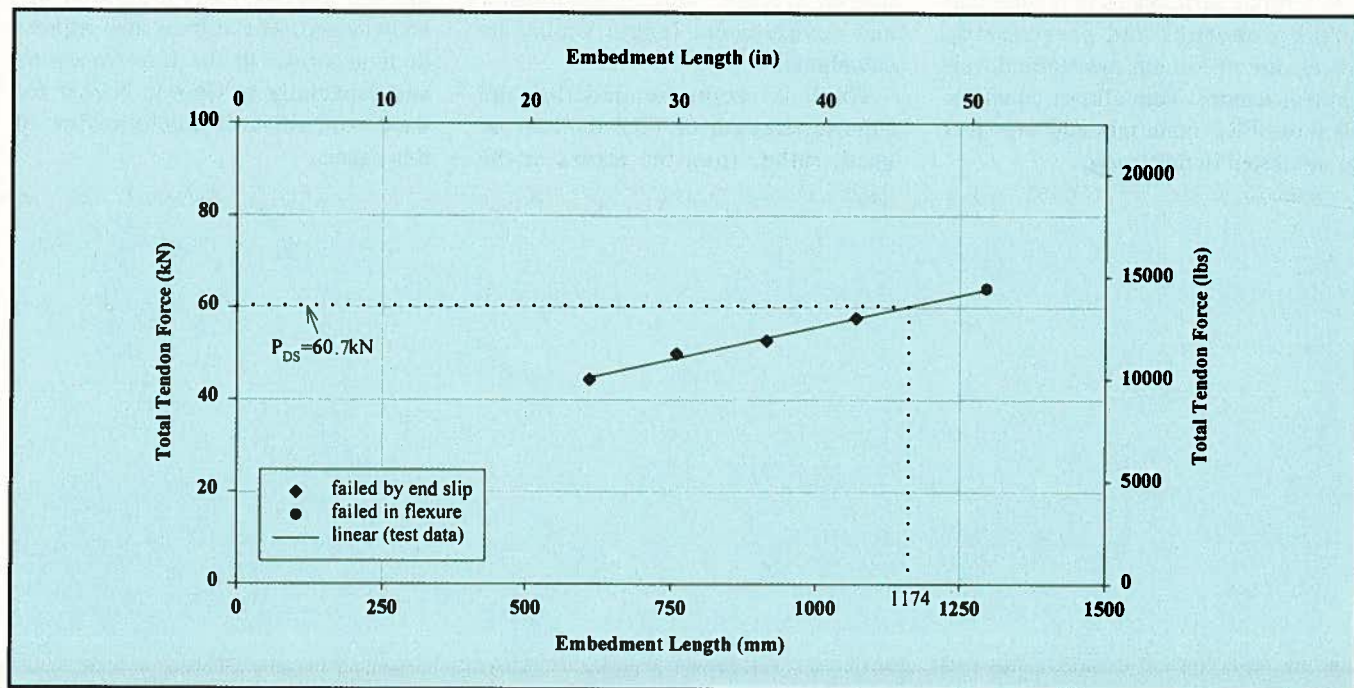


Fig. 4(d). Development length test results for steel strand (ST).

1. Transfer length values in this study were based on the 95 percent average plateau strain method determined using concrete strain results. The transfer length results for the CL and AT tendons used in this study were verified to be close to values reported by Ehsani, Saadatmanesh, and Nelson¹³ and Mahmoud, Rizkalla, and Zaghoul⁸ using the similar measurement methods.

2. Despite differences in tendon material properties and prestressing forces, the measured transfer lengths were virtually identical for all three FRP materials. The steel strand had a slightly longer transfer length than the FRP tendons.

3. The transfer length predicted by the ACI formula is in direct proportion to the effective prestress f_{se} in the tendon; however, the results of this study indicate that the transfer length for FRP tendons is only slightly influenced by the prestress level. Since the f_{se} was lower for AT and CS tendons in this study, the transfer lengths of these two materials were poorly predicted by the ACI equation. Use of a formula that is solely based on tendon diameter may give better predictions, especially for materials with lower initial prestressing levels. The adoption of a minimum value of transfer length, as given in the AASHTO Specifications,²² improves this result.

4. Despite differences in tendon material properties and prestressing forces, the maximum measured development lengths were almost equal for all three FRP materials and the steel strand tested in this study.

5. The FRP materials consistently had a nominal bond stress (pull-out force divided by nominal surface area) over 450 psi (3.10 MPa) at their development length, considerably higher than the nominal bond stress of steel tendons.

6. The development lengths of the three FRP tendons were very conservatively predicted by the ACI design equation, provided that the strand rupture strength is substituted for f_{ps} , the strand stress at nominal strength.

7. A number of other models, including models developed specifically for FRP tendons, give wide-ranging development length results, most of which are over-estimations compared to the ACI equation. While it may appear obvious that formulas developed for steel tendons do not give good predictions for FRP tendons, it is worth considering the reasons for this, namely, that the higher bond stress of the FRP tendons results in shorter development lengths.

8. It is recommended that a transfer length of at least 50 tendon diameters be used for FRP tendons.

9. The interest in calculating the development length conservatively may account for the large overestimation produced by many of the existing models, for steel as well as FRP strands; however, the existing code philosophy appears to suggest that an average value of the transfer and development length should be calculated.

10. It is recommended that the rupture strength of FRP tendons be used, rather than the stress at the

nominal flexural strength of the cross section f_{ps} , in calculating the flexural bond length of FRP tendons. It is further recommended that the development length formula take into account the higher bond stress developed by FRP tendons, so that development length is not calculated excessively conservatively.

11. The experience of fabricating the specimens has indicated that the anchorage of the prestressing tendon is a key issue to be resolved before widespread implementation of FRP prestressing is possible. Whereas an anchor based on the use of expansive grout will develop the strength of the tendon effectively, the long time period required for the grout to cure results in an inefficient use of the prestressing beds. The methods of coupling anchors used in this study would allow the precasting beds to be turned over quickly, and less than 2 to 3 percent of the bed would be lost due to the coupling.

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REFERENCES

1. Janney, J. R., "Nature of Bond in Pre-Tensioned Prestressed Concrete," *ACI Journal*, V. 25, May 1954, pp. 717-736.
2. Hanson, N. W., and Kaar, P. H., "Flexural Bond Tests of Pre-Tensioned Prestressed Beams," *ACI Journal*, V. 30, January 1959, pp. 783-802.
3. Russell, B. W., and Burns, N. H., "Design Guidelines for Transfer, Development and Debonding of Large Diameter Seven-Wire Strands in Pretensioned Concrete Girders," Research Report No. 1210-5F, Center for Transportation Research, University of Texas at Austin, TX, 1993, 286 pp.
4. ACI Committee 318, "Building Code Requirements for Reinforced Concrete (ACI 318-99)," American Concrete Institute, Farmington Hills, MI, 1999.
5. Abdelrahman, A. A., "Serviceability of Concrete Beams Prestressed by Fiber Reinforced Plastic Tendons," Ph.D. Thesis, Department of Civil Engineering, University of Manitoba, Winnipeg, Manitoba, Canada, 1995, 365 pp.
6. Domenico, N. G., "Bond Properties of CFCC Prestressing Strands in Pretensioned Concrete Beams," M. S. Thesis, Department of Civil Engineering, University of Manitoba, Winnipeg, Manitoba, Canada, 1996, 179 pp.
7. Mahmoud, Z. I., and Rizkalla, S. H., "Bond of CFRP Prestressing Reinforcement," *Advanced Composite Materials in Bridges and Structures (ACMBS-II)*, Montreal, Quebec, Canada, August, 1996, pp. 877-884.
8. Mahmoud, Z. I., Rizkalla, S. H., and Zaghoul, E. R., "Transfer and Development Lengths of Carbon Fiber Reinforced Polymer Prestressing Reinforcement," *ACI Structural Journal*, V. 96, No. 4, July-August 1999, pp. 594-602.
9. Soudki, K. A., Green, M. F., and Clapp, F. D., "Transfer Length of Carbon Fiber Rods in Precast Pretensioned Concrete Beams," *PCI JOURNAL*, September-October, 1997, pp. 78-87.
10. Nanni, A., Utsunomiya, T., Yonekura, H., and Tanigaki, M., "Transmission of Prestressing Force to Concrete by Bonded Fiber Reinforced Plastic Tendons," *ACI Structural Journal*, V. 89, No. 3, May-June 1992, pp. 335-344.
11. Nanni, A., and Tanigaki, M., "Pretensioned Prestressed Concrete Members with Bonded Fiber Reinforced Plastic Tendons: Development and Flexural Bond Lengths (Static)," *ACI Structural Journal*, V. 89, No. 4 July-August 1992, pp. 433-441.
12. Taerwe, L., and Pallemans, I., "Force Transfer of AFRP Bars in Concrete Prisms," *Proceedings of the Second International RILEM Symposium*, Ghent, Belgium, 1995, pp. 154-163.
13. Ehsani, M. R., Saadatmanesh, H., and Nelson, C. T., "Transfer and Flexural Bond Performance of Aramid and Carbon FRP Tendons," *PCI JOURNAL*, V. 42, No. 1, January-February 1997, pp. 76-86.
14. Issa, M., Sen, R., and Amer, A., "Comparative Study of Transfer Length in Fiberglass and Steel Pretensioned Concrete Members," *PCI JOURNAL*, V. 38, No. 6, November-December 1993, pp. 52-63.
15. Bakis, C. E., Nanni, A., and Dye, W. K., "Behavior of FRP Tendon/Anchor Systems Under Accelerated Sustained Loading," *Proceedings of The International Composites Exposition '98*, Society of the Plastics Industry, New York, NY, 1998, pp. 16B.1-16B.8.
16. Lu, Z., "Flexural Performance of Fiber Reinforced Polymer Prestressing Tendons," M.S. Thesis, The Pennsylvania State University, University Park, PA, 1998.
17. Zia, P., and Mostafa, T., "Development Length of Prestressing Strands," *PCI JOURNAL*, V. 22, No. 5, September-October, 1997, pp. 54-65.
18. Mitchell, D., Cook, W. D., Khan, A. A., and Tham, T., "Influence of High Strength Concrete on Transfer and Development Length of Pretensioning Strand," *PCI JOURNAL*, V. 38, No. 3, May-June, 1993, pp. 52-66.
19. Cousins, T. E., Johnston, D. W., and Zia, P., "Transfer and Development Length of Epoxy Coated and Uncoated Prestressing Strands," *PCI JOURNAL*, V. 35, No. 4, July-August 1990, pp. 92-103.
20. Russell, B. W., and Burns, N. H., "Measured Transfer Lengths of 0.5 and 0.6 in. Strands in Pretensioned Concrete," *PCI JOURNAL*, V. 41, No. 5, September-October, 1996, pp. 44-65.
21. Shahawy, M. A., Issa, M., and Batchelor, B., "Strand Transfer Lengths in Full Scale AASHTO Prestressed Concrete Girders," *PCI JOURNAL*, V. 37, No. 3, May-June 1992, pp. 84-96.
22. AASHTO, *Standard Specifications for Highway Bridges, LRFD. US Customary Units*, Second Edition, American Association of State Highway and Transportation Officials, Washington, D. C., 1998.
23. Deatherage, J. H., Burdette, E. G., and Chew, C. K., "Development Length and Lateral Spacing Requirements of Prestressing Strand for Prestressed Concrete Bridge Girders," *PCI JOURNAL*, V. 39, No. 1, January-February 1994, pp. 70-83.
24. Buckner, C. D., "A Review of Strand Development Length for Pretensioned Concrete Members," *PCI JOURNAL*, V. 40, No. 2, March-April 1995, pp. 84-99.