Experimental Study of Transfer and Development Length of Fiber Reinforced Polymer Prestressing Strands

by Z. Lu, T. E. Boothby, C. E. Bakis, and A. Nanni

Synopsis:

An experimental study was conducted to determine the transfer length, development length and flexural behavior of fiber-reinforced polymer (FRP) tendons in prestressed concrete beams. Three kinds of nominally 5/16 in (8 mm) diameter FRP tendons were included in the study: Carbon Leadline, Aramid Technora and Carbon Strawman. Thirty beams were pretensioned using a single FRP tendon. In addition, twelve control beams were pretensioned with a seven-wire steel strand (ST).

Transfer length observations from this study were based on concrete strain measurements with a DEMEC gage system. Development length observations were based on three-point flexural tests. Four-point flexure tests were also performed on each material to gain additional understanding of the bond behavior between concrete and the PC reinforcing materials.

The "95% average plateau strain" method of using concrete strain results was shown to be an effective way to determine transfer length. By using an appropriate flexural model and extrapolating results from over-reinforced tests to situations where the tendon would actually fail, it was possible to determine development length in this investigation. Despite differences in tendon material properties and prestressing forces, both the measured transfer lengths and the development lengths were almost identical for all tendon materials tested. The development length for FRP tendons was reasonably predicted by the ACI design equation, although transfer length appears to be underestimated.

Keywords: bond; development; fiber reinforced polymers; flexure; length; prestressing; strength

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INTRODUCTION

In pretensioned concrete, transfer length is the distance required to transmit the effective prestressing force from the prestressing to the concrete. When a member is loaded to the ultimate flexural strength of the member, an additional bond length beyond the transfer length is required to develop the tendon stress from the effective prestress to ultimate stress. 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 length and development length seldom govern the design of pretensioned concrete members. However, the knowledge of transfer and development length are essential to maintain the integrity of the structure and to prevent bond slip failure of the member.

Objectives and Scope of the Research

The objectives of this study are to experimentally determine the transfer and development length of three types of fiber reinforced polymer (FRP) tendons in precast prestressed concrete beams, to compare the experimental results with existing models from the literature, and to propose rules for the determination of the components of development length for FRP prestressing. In this study, 30 transfer length tests, 24 development length tests and 9 flexure tests were done on beams prestressed with three types of FRP tendons along with control specimens constructed with steel strands.

The primary variable in the study is type of FRP material. Each of the three FRP materials is produced by a different proprietary manufacturing process and has a unique and characteristic surface texture. The Leadline tendons, designated CL, are made commercially by Mitsubishi using the pultrusion process with carbon fibers and an epoxy resin. The Leadline tendon surface is indented with two helical impressions in the surface that spiral in opposite directions down the length of the tendon. Technora tendons, designated AT, are made commercially by Teijin by the pultrusion process where straight, bundled aramid fibers are impregnated with a vinylester resin. Technora aramid yarns are wound spirally and placed axially around the bundle of straight fibers to provide a rough surface capable of achieving adequate bond strength. A noncommercial tendon developed especially for this project as a reference material is designated CS. 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.

Previous work carried out on the transfer and development length of steel and FRP prestressing, which is summarized in Lu (1), or in Ehsani, Saadatmanesh, and Nelson (2), has found that transfer and development lengths increase in some nonlinear manner with tendon diameter, transfer length does not vary much with time, the concrete strength has little effect on the transfer length of FRP tendons, higher prestress force results in slightly larger transfer and development lengths, and that surface finish greatly influences the bond between FRP tendons and the concrete.

EXPERIMENTAL PROGRAM

The experiments involved casting a total of forty-two 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. Forty rectangular specimens were cast with the tendon placed eccentrically. All specimens were cast by a PCI-certified producer. The specimens in this study contained no shear reinforcement or other confinement.

The concrete mix used in this project contained of 445 kg/m^3 of Type III Portland Cement, 78 kg/m^3 of fly ash, for a total water/cement ratio of 0.36. The concrete was designed for 7.4% entrained air, by volume. The average compressive strength at release was 38.4 MPa, at 28 days, 44.3 MPa, and at 90 days, 45.2 MPa.

Tendon properties are given in Table 1. Manufacturer's data given in Table 1 are guaranteed values--all other data are mean values. A grouted FRP single-tendon anchorage system was developed and tested (3). 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. Coupling devices with thread on the outer face 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 conventional steel can also be used for FRP tendons. Details of the experimental procedure are available in Lu (1).

Transfer length was measured using DEMEC gage readings before and after release, with data processed according to the procedure detailed in Ehsani, Saadatmanesh, and Nelson (2).

The flexure test is a four-point bending test, as shown in Figure 1. This test establishes the static flexural behavior of the specimens. In this test, the specimen is symmetrically loaded by two point forces. Two methods were used to measure the curvature in the constant moment zone: the first was by measuring concrete strains at beam top and beam bottom; the second was by measuring beam deflection at different points along the constant moment zone. Tendon end slips at both ends were monitored. Deflection at the center of the specimen was measured using potentiometers

The development length test is a three-point flexural test. A point load was applied for the designated embedment length, which varied for each test. In addition to increments of applied load measured using a load cell, end slip of the prestress 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 LVDT's. End slip at each end was taken as the average readings of the three LVDT's. During development length testing, deflection at the load point was measured using potentiometers. Crack width of the first detected crack was measured at the level of the tendon using a crack gauge.

RESULTS AND DISCUSSION

Five CL beams, three AT and three CS beams were tested for transfer length. The results are presented in Table 2 and compared to the prediction based on ACI 12.9. The strains reported in Table 2 were measured on the surface of the concrete at the depth of the prestressing.

Three specimens for each of the three FRP materials and two steel specimens were tested for flexure. In these tests, flexural-shear cracks penetrated through the top surface of the beams. Crushing of the concrete in the compression zone at the point of maximum moment was observed. There was no significant slip of the tendon at either end (tendon end slip less than 0.254 mm) up to failure. The flexure test results are summarized in Table 2 In the tables, the failure mode is presented for each specimen, as well as maximum moment obtained (M_{max}), ratio of maximum moment to nominal moment (M_{max}/M_n), maximum deflection at center of beam (Δ_{max}), and maximum measured curvature of the constant moment zone (ϕ_{max})

A simple flexural model, based on linear strain distribution, linearly elastic stress-strain law in the tendons, and trapezoidal stress strain law in the concrete can be used to predict curvatures of the specimens. The measured and the calculated curvatures are compared for specimens CL-8, AT-8, CS-8 and ST-10 at five different loading stages: 25%M_{max} (uncracked concrete), 50%M_{max} (cracked elastic concrete), 75%M_{max} (cracked elastic-plastic concrete), 90%M_{max} (close to ultimate stage) and 100%M_{max} (ultimate stage), where M_{max} was the maximum moment attained during the test. The measured curvatures used for the comparison were determined from the first method for specimens CL-8 and ST-10 and from both of the two methods for specimens AT-8 and CS-8. The comparison is shown in Table 4.

The development length, being the embedment length required to develop the length of the strand, a direct experimental determination of the development length would require that the strand rupture during one of the tests. For the embedment lengths realizable in this study, all of the specimens failed by tendon slip, or concrete crushing. A linear trend line was used to predict the required development length at tendon rupture. For each of the embedment lengths investigated in this study, the force in the tendon was estimated using the flexural model validated by the flexural tests (see Lu[1]). 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 a magnitude of 2 to 3 MPa for fully developed tendons.

In Table 5, the measured development length is compared with the predicted development length predicted by applying ACI 12.9 (4), and equations developed by other investigators. The measured development length appears to be very little different for the different materials studied, and can be tentatively considered to be a function of tendon diameter only. The various prediction models, which incorporate factors such as initial prestress and concrete strength predict variations among the different material types that were not borne out in the experimental findings. The ACI equation appears to predict development length adequately, for the range of tendon types, initial prestress levels, and concrete strengths in this study.

CONCLUSIONS

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.

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 transfer length for FRP tendons is very little influenced by prestress level. Since the f_{se} was lower for AT and CS in this study, the transfer lengths of these two materials were poorly predicted by the ACI equation. Use of a formula that solely based on tendon diameter may give better predictions, especially for materials with lower initial prestress levels.

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

The development lengths of the three FRP tendons were reasonably predicted by the ACI design equation, which only includes three parameters: effective prestress f_{se}, tendon stress at failure f_{ps} and tendon diameter. The use of other parameters in other recommended models in the literature does not appear justifiable. These models give wide-ranging development length results, most of which are over-estimations compared to the ACI equation.

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TABLE 1—TENDON MATERIAL PROPERTIES.

Tendon Type		CL	AT	CS	ST
Nominal Diameter (mm)	Manufacturer[1]	8	8	8	8
	Experiment[2]	--	--	--	--
Area (mm^2)	Manufacturer[1]	46.1	50.2	50.0	37.4
	Experiment[2]	47.2	50.7	50.0	-
Young's Modulus (GPa)	Manufacturer[1]	147	53	160.8	200.6
	Experiment[2]	171	44.9	161	-
Tensile Strength (MPa)	Manufacturer[1]	2256	1714	1834	1724
	Experiment[2]	2900	n/a[3]	1890	--

1. guaranteed values.
2. mean values
3. All specimens slipped in grips before rupture

TABLE 2—TRANSFER LENGTH RESULTS.

tendon type	ACI Prediction	at 100% release				at 28 days			
		n[1]	μ[2]	σ[3]	ε_{avg}	n	μ	σ	ε_{avg}
			mm	mm	$\mu\varepsilon$		mm	mm	$\mu\varepsilon$
CL	416	10	422	23	276	10	410	19	609
AT	300	6	368	26	197	6	375	27	503
CS	328	6	408	20	218	6	414	13	446
ST	380	12	486	28	189				

1. number of repetitions
2. mean
3. standard deviation

TABLE 3—FLEXURE TEST RESULTS.

Specimen	M_{max} (kN-m)	M_{max} / M_n	Δ_{max} (mm)	ϕ_{max} (10-6/mm)
CL-8	14.85	1.217	30.93	77.82
CL-9	14.51	1.189	34.98	84.61
CL-10	13.59	1.114	34.39	82.80
AT-8	8.78	0.964	42.13	100.80
AT-9	8.88	0.976	41.13	106.67
AT-10	8.93	0.981	36.14	110.56
CS-8	11.95	0.913	31.88	96.48
CS-9	11.19	0.855	33.21	87.11
CS-10	12.84	0.981	28.45	104.89
ST-9	6.04	0.805	24.50	118.25
ST-10	6.91	0.921	28.41	122.04

TABLE 4—COMPARISON OF MEASURED AND CALCULATED CURVATURE (UNIT: 10-6/MM).

Loading Stages			$25\%M_{max}$	$50\%M_{max}$	$75\%M_{max}$	$90\%M_{max}$	$100\%M_{max}$
CL-8	Measured Curvature (Method I)		0.52	2.38	31.12	52.62	77.82
	Calculated Curvature		0.83	3.44	35.74	54.77	86.19
AT-8	Measured Curvature	Method I	0.58	20.21	64.93	85.80	100.80
		Method II	0.71	28.28	74.41	94.21	122.17
	Calculated Curvature		0.69	20.88	71.07	94.00	120.36
CS-8	Measured Curvature	Method I	1.42	10.00	36.90	68.66	96.48
		Method II	1.88	14.06	48.64	80.66	100.10
	Calculated Curvature		1.67	13.63	43.75	78.98	101.73
ST-10	Measured Curvature (Method I)		2.75	43.70	76.19	92.99	122.04
	Calculated Curvature		2.82	41.63	85.88	104.38	139.05

TABLE 5—COMPARISON OF MEASURED AND PREDICTED DEVELOPMENT LENGTH.

	CL	AT	CS	ST
Measured Development Length	1116	1220	1190	1174
Current ACI (4)]	1525	1226	1274	1109
Model by Cousins, Johnston and Zia (5)	3028	2633	2860	1787
Model by Deatherage et al. (6)	2080	1689	1747	1473
Model by Shahawy, Issa and Batchelor (7)	1598	1279	1332	1176
Model by Buckner (8)	1773	2017	1348	1120
Model by Mitchell, Cook and Khan (9)	1270	1003	1106	956

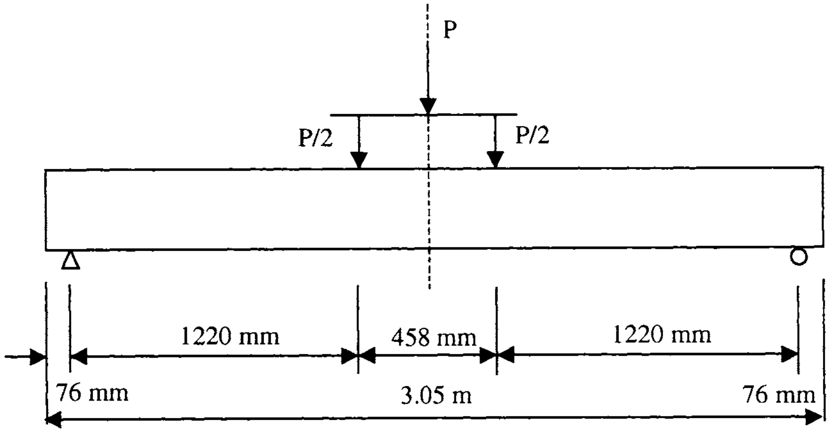

Fig. 1—Flexure test setup.

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Modeling Stress State Dependency of Bond Behavior of Fiber Reinforced Polymer Tendons

by J. V. Cox and J. Guo

Synopsis:

The bond behavior of carbon FRP tendons for concrete is characterized with an interface model. In particular tendons with a surface structure that produce significant mechanical interlocking with the adjacent concrete are considered. This type of mechanical interaction can produce damage in the adjacent concrete and within the surface structure of the reinforcing element. The combination of these mechanisms is characterized with an elastoplasticity model that fully couples the longitudinal and radial response; the model calibration is based upon a series of bond tests under differing stress states. The model does not provide a detailed description of the underlying mechanics associated with the progressive bond failure, and it will generally require recalibration when applied to significantly different FRP bars or tendons. However, using a calibration for a GFRP bar, the model gives acceptable estimates of the bond strength for several tests of a particular CFRP tendon, even though the specimens have significantly different attributes. Additional validation tests (using data with measures of the experimental scatter) are needed to define the predictive limits of the model; nonetheless the transfer length problem further demonstrates the potential application of the model to help predict and understand the behavior of FRP-reinforced structural components.

Keywords: bond model; carbon fiber reinforced polymers; elastoplasticity; finite element method; numerical model