

# Transfer and Flexural Bond Performance of Aramid and Carbon FRP Tendons

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*The use of non-corrosive fiber reinforced polymer (FRP) composite materials as reinforcement for concrete structures has been growing in recent years. This study, conducted at the Federal Highway Administration Laboratories, compared the transfer length and flexural bond behavior of five commercially available FRP tendons. Three of the tendons had aramid as the main reinforcement, and the other two included carbon fibers. Sixteen specimens, including a control specimen reinforced with a high strength steel tendon, were tested. It is shown that the transfer length for FRP tendons is generally shorter than that for steel. For the aramid tendons, the ACI equations result in a conservative estimation of the development length; however, this is not true for the carbon tendons examined. The efficiency of the various grips and the loss of prestress for each of the tendons is also discussed.*

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**R**esearch and development of synthetic composite fiber reinforced polymer (FRP) materials in structural applications as a potential alternative to reinforcing steel is already in an advanced stage. A major focus in the research of the Federal Highway Administration (FHWA) has been the investigation of strategies for the improvement of the service life of highway structural bridge elements, including prestressed concrete bridge components. The susceptibility of steel to corrosion has been the catalyst for FHWA-sponsored research in many directions

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in order to minimize or eliminate this problem, including consideration of the use of non-metallic reinforcement materials such as composite FRP prestressing tendons.

Material properties for the various types of FRP prestressing tendons are distinct and are dependent on fiber type, matrix types and manufacturing characteristics such as fiber geometry. Deformation of the tendon surface has a major influence on tendon performance when bonded to concrete. Although the properties required for structural design using FRP materials, including tensile strength, Young's modulus of elasticity, and bond stress limits based upon pull-out testing, are available from material manufacturers, only limited data have been produced independently on the bond behavior and transfer of force in pretensioned, prestressed concrete applications.

Under highway bridge service conditions, cracking of concrete can occur during the life of a structure. When this condition occurs on a tension face of a bonded prestressed concrete element, the internal reinforcement material may be subjected to very high strains at the location of a crack. Steel reinforcement is able to yield locally in a ductile manner to mitigate such localized high strain conditions.

All FRP prestressing tendons under consideration in this study may be characterized as nearly linear elastic to failure, with little or no inherent ductile capability when approaching their respective tensile strength limits. More information is needed on the flexural bond behavior of FRP prestressing tendons in pretensioned applications when high local stresses due to crack formation are present.

The bond behavior in prestressed concrete reinforced with pretensioned steel has been studied empirically and modeled theoretically.<sup>7-9</sup> Many variables affect the tendon-to-concrete bond behavior. These variables include tendon diameter, strand spacing and position, amount of prestress force, confinement and concrete compressive strength. Previous research into the bond of pretensioned steel strand has become characterized as "development length" research. The determination of the appropriate de-

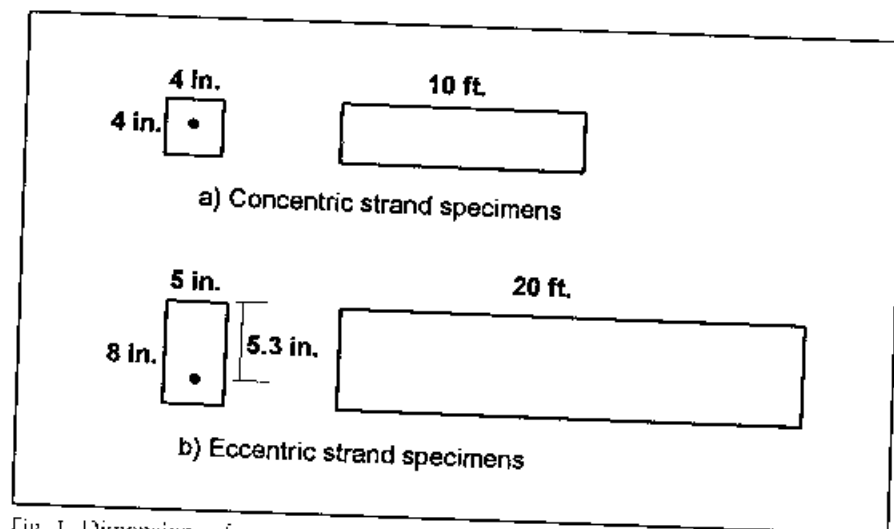


Fig. 1. Dimensions of specimens.

velopment length for a particular tendon material is considered to be a critical design parameter.

Non-metallic FRP prestressing tendons have recently become better known in structural engineering practice in the United States, Japan and Europe as a potentially viable alternative to steel strands. Mechanical properties and other behaviors of unidirectional fiber composites have been examined at length by the European FIP Commission on Prestressing Materials and Systems.<sup>10</sup> Dolan has written a summary of the role of composites in the prestressing industry, assessing potential liabilities and design considerations.<sup>11</sup> A summary overview of the materials and their anchorage systems has also been published.<sup>12</sup>

In previous research examining the bond and flexural performance, Nanni et al. demonstrated the adequate performance of the aramid tendon FIBRA and suggested development length design criteria for this material.<sup>13</sup> Design and construction experiences in Japan using FRP materials in prestressed concrete bridges and other engineered structures have also been reported.<sup>14</sup>

Development length is the total bond length required to anchor the tendon as it resists external loads applied to the member. This total required bond length has been shown in the previously referenced body of research to consist of the sum of bond lengths needed to satisfy two different stress conditions located in distinctly separate, adjacent regions along the

tendon. Release of prestressing tension introduces transfer stresses in the tendon at the free ends of a prestressed concrete member. The distance along the tendon over which these stresses occur is referred to as the transfer length.

A second tendon stress situation occurs when a pretensioned concrete member is placed under flexural load, causing an increase in tendon tension. When the member cracks under increasing load, tendon tension increases further. Although cracking may be due to either flexural loads or to shear loads, the tendon registers both as increased tension. Encased in concrete, the increase in tendon tension is resisted by the combined bond mechanisms of adhesion, Hoyer's effect and mechanical interlock. Bond between reinforcement and concrete in a structural member is the result of the successful action of these mechanisms. These three distinctly different mechanisms have been investigated by Janney,<sup>15</sup> Hanson and Kaar,<sup>16</sup> and recently by Russell and Burns.<sup>17</sup>

If a tendon is fully developed, that is, if the location of maximum moment is far enough away from the transfer zone, then the member should be able to reach its full nominal load capacity before bond is lost. When bond is lost, the tendon begins to slip, potentially being pulled from the concrete completely, through the beam end.

The physical model for understanding the dynamic process of bond failure in relation to regions within a pretensioned concrete beam was first

Table 1. Tendon material properties as provided by the manufacturers.

Tendon Designation	Material	Diameter (in.)	Area (in. <sup>2</sup> )	Young's	Tensile	Elongation at rupture
				modulus (ksi)	strength (ksi)	
AA	Aramid	0.390	0.059	18,500	355	2.4 percent
AF	Aramid	0.410	0.129	7000	208	2.0 percent
AT	Aramid	0.291	0.067	9950	250	3.7 percent
CL	Carbon	0.312	0.072	21,700	287	1.3 percent
CT	Carbon	0.327	0.084	19,900	322	1.7 percent
ST	Steel	0.375	0.085	27,945	270	4.5 percent

Note: 1 in. = 25.4 mm; 1 ksi = 6.895 MPa.

suggested by Janney<sup>7</sup> using smooth or rusted steel wire and later confirmed by Hanson and Kaar<sup>8</sup> testing seven-wire steel strand. The Hanson and Kaar tests showed that a wave of high stresses proceeds outward from the load point. If the stress wave reaches the transfer zone, as determined by an increase in tendon stress in the transfer zone, a general bond failure will result.

The scope of this paper is to report a preliminary examination of transfer length of two carbon-type and three aramid-type FRP prestressing tendons. Flexural bond performance in terms of embedment length, failure mode and load vs. deflection are compared to gain an understanding of the differences in bond performance of the various materials and to approximate the development length requirements of each material. A control specimen constructed with steel tendons is also included in the study. Performance data for FRP grip systems and stressing losses for FRP tendons are also reported. Details of this investigation are also given in Ref. 15.

## PRODUCTS AND MATERIALS

Concrete for each of the seven casting sets was mixed in the FHWA laboratory. A master mixture was designed and tested, using Type I portland cement and a 0.48 water-cement ratio, to achieve a minimum 4000 psi (28 MPa) 7-day strength and a minimum 5000 psi (35 MPa) 28-day strength, with a 4 in. (100 mm) maximum slump.

The overall dimensions of the concrete beams tested are shown in Fig. 1. The primary variable in the study was the FRP material. Each of the five

FRP materials is derived from a different proprietary manufacturing process and has a unique and characteristic surface texture. The surface configuration of FRP tendons varies greatly when compared with that of steel strand. Based on the preceding discussion of mechanisms of bond, it is likely that differences in FRP tendon surface and tendon design characteristics will influence the bond performance and affect development length requirements. Trade names and a brief description of each FRP tendon are given.

The tendon material properties, including tensile strength, Young's modulus of elasticity, elongation at ultimate and coefficient of thermal expansion, were used as provided by the manufacturers. No verification of properties was undertaken in this study. The tendon material properties are summarized in Table 1. Conventional 1/8 in. (9.6 mm) low-relaxation, 270 ksi (1862 MPa) seven-wire steel strand was used in the control specimen (Specimen ST).

Most FRP prestressing grip systems contain components that are not reusable or have limited reusability. Because FRP tendons are sensitive to transverse stresses during prestressing, successful grip systems distribute the force over larger areas, and tend to have more components than the steel wedge chuck. Grip systems used in this study are shown in Figs. 2 and 3.

### Aramid Materials

**Arapree** — Originally developed in rectangular configuration by AKZO Chemicals and Hollandsche Beton Groep in The Netherlands, these tendons are now manufactured by Sireg

S.P.A., Italy. Round 0.4 in. (10 mm) tendons were used with single-tendon wedge grips supplied by Sireg. Grips consist of two inner plastic wedges and an outer steel collar. These tendons will be referred to as "AA". AA tendons contain unidirectional aramid (Twaron) fibers in an epoxy resin matrix. The AA tendon surface consists of sand impregnated epoxy.

**FIBRA** — Produced by the Mitsui Construction Company of Japan, the flexible 0.41 in. (10.4 mm) AF tendon included in these tests consists of a braided bundle of aramid fiber tows that are epoxy impregnated. The resulting surface is smooth-braided. A single tendon wedge grip system supplied by Mitsui was used, consisting of four inner steel wedges set into an outer steel collar. These tendons will be referred to as "AF".

**Technora** — Produced jointly by Sumitomo Construction Company and Teijin Corporation of Japan, the 0.29 in. (7.4 mm) Technora tendon was used with a potted anchor attached to pre-cut tendons by the manufacturer. These tendons are referred to as "AT". AT tendons have proprietary deformations that consist of vinyl-ester-impregnated aramid fiber bundles that are spirally wrapped around inner longitudinal fiber bundles.

### Carbon Materials

**Leadline** — Developed by Mitsubishi Kasei Corporation of Japan, the 0.31 in. (8 mm) Leadline tendon consists of unidirectional carbon fibers which are epoxy-impregnated. These tendons are designated as "CL". The CL tendon used has deformations that are integral with the inner FRP fiber-epoxy bundle and consists of an impressed helical surface pattern on an otherwise smooth tendon. A single tendon wedge-type grip was used, which consists of an aluminum sleeve, two inner wedges, a plastic sleeve, inner steel collar and outer steel collar.

**CFCC** — Produced by Tokyo Rope and Toho Rayon Co. of Japan, the 0.33 in. (8.3 mm) CFCC tendon used consists of seven twisted rods. Each individual rod is made up of carbon fiber in an epoxy resin matrix and is wrapped in a manufactured fiber-like protective coating of proprietary de-

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sign. A die-cast steel tube grip system was attached to pre-cut tendons by the manufacturer and used with two steel wedges and a steel collar. These tendons will be referred to as "CT".

## EXPERIMENTAL STUDY

The experimental study was conducted in the laboratories of the Federal Highway Administration in McLean, Virginia.

### Test Specimens

The rectangular, unconfined, single-tendon specimens utilized in this study were chosen to place the primary empirical emphasis of the study on the mechanisms of bond between FRP materials and concrete.

The experiment involved casting a total of 16 specimens. Five different FRP tendon materials were used. One specimen constructed with a steel tendon was included in the study. All specimens contained a single tendon. The specimen number shows the tendon type and the location of the casting bed within the laboratory. The specimen characteristics are summarized in Table 2.

Five 10 ft (3.05 m) specimens with tendons concentrically placed were used to measure transfer length only [see Fig. 1(a)]. Eleven 20 ft (6.10 m) rectangular specimens were cast with the tendon placed eccentrically [see Fig. 1(b)]. The 20 ft (6.10 m) beams were long enough so that both the jack end and the dead end could be tested independently under static load, resulting in two sets of data for two different embedment lengths.

One 4 in. x 4 in. x 10 ft (102 mm x 102 mm x 3.05 m) specimen was cast for each FRP material. These specimens were monitored for transfer length and end slip periodically up to 90 days. Concentric specimens were included in the test program to represent the most simple stress case, in which force is applied uniformly over the area. The cross section dimension was chosen to provide minimum cover against splitting of concrete at prestress force release.

One to three specimens of rectangular cross section were cast for each FRP material, including one steel con-

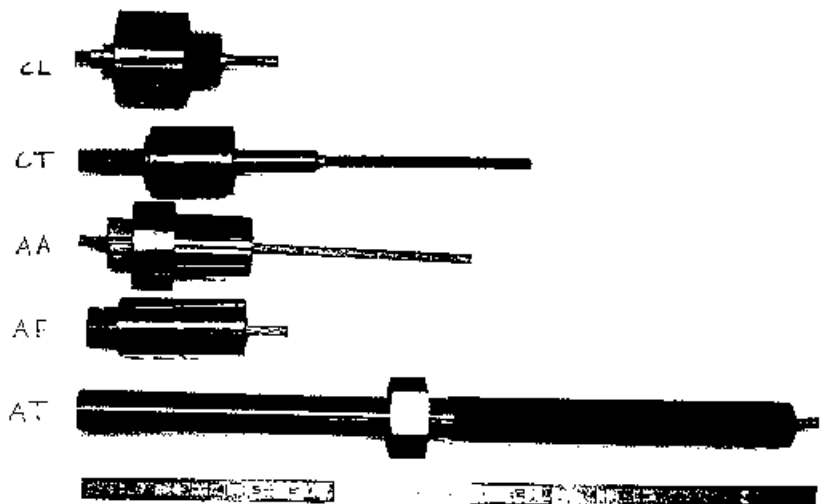


Fig. 2. Relative lengths of various gripping systems used.

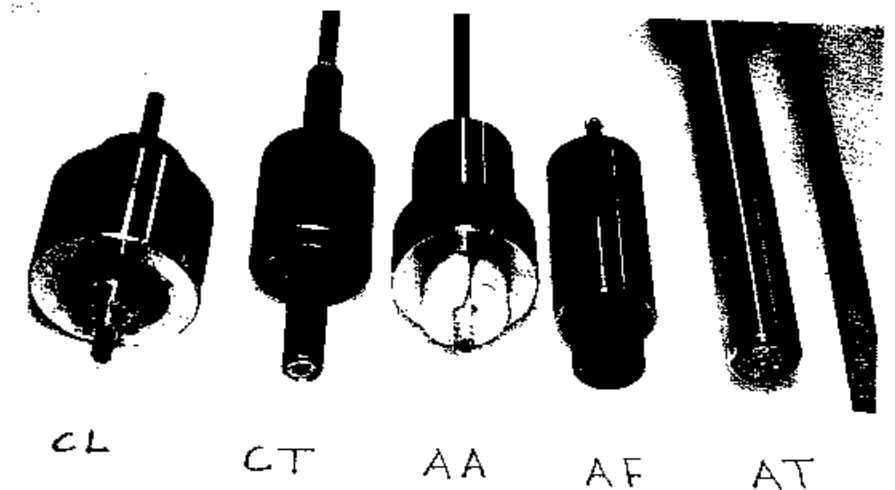


Fig. 3. End view of various FRP grips.

control specimen. Transfer length and end slip were monitored in these specimens during the first 28 days, prior to flexural testing. To facilitate comparison, the cross section was chosen as a uniform mid-size section based on first examining the nominal moment capacity of each material separately. From the range of sections thus obtained, a cross section was chosen that represents an average size within the range. Rectangular specimens contained no shear reinforcement or other confinement reinforcement.

### Prestressing FRP Tendons

A target pretensioning stressing level of  $0.60f_u$  was chosen for all FRP materials. This represents the maxi-

num recommended stressing level for most of the materials. The exceptions are that the recommended pretensioning stress for Tendon AT is  $0.70f_u$  and that the recommended prestressing level for optimum long-term performance of Tendon AA is  $0.55f_u$ . The steel control specimen was pretensioned to a target  $0.75f_u$ , which represents the maximum recommended stressing level for steel strand. Actual prestress levels attained are listed in Table 2.

Simple open box-like coupling devices made of high strength steel were fabricated in the laboratory and used to link the variously gripped FRP tendons to a hydraulic jacking system during stressing. Load cells were inserted within the linkage to monitor

Table 2. Specimen characteristics.

Beam	Length (ft)	Prestress		Concrete compressive strength (psi)			$L_r$ Transfer length (in.)	$l_c$ Load position (in.)
		Force (kip)	$P_j/P_u$	Release	28-day	On test day*		
AA-2	10	8.8	0.421	4580	6450	—	19.0	—
AI-2	10	15.1	0.561	4470	5860	—	13.0	—
AT-2	10	8.6	0.516	4365	6110	—	13.6	—
CL-2	10	11.5	0.541	4075	5090	—	37.0	—
CT-2	10	15.9	0.591	4075	5090	—	11.0	—
AA-1	20	8.9	0.424	4570	6450	6450 (J) 6450 (D)	16.0 10.5	34 40
AA-3	20	12.3	0.586	4210	6030	6080 (J) 6690 (D)	27.0 28.0	34 55
AF-3	20	15.5	0.576	4310	5860	6240 (J) 6310 (D)	15.0 12.0	40 34
AT-1	20	13.7	0.822	4370	6110	6560 (J) 7010 (D)	13.0 11.0	40 55
AT-3	20	9.5	0.571	4370	6110	6730 (J) 6830 (D)	10.0 15.0	34 34
CL-1	20	13.6	0.661	4100	5960	6050 (J) 6150 (D)	n/a n/a	40 40
2CL-1	20	12.2	0.595	4210	5930	7190 (J) 6470 (D)	12.0 15.0	55 55
CL-3	20	11.9	0.541	4100	5960	6560 (J) 6440 (D)	17.0 24.0	34 55
CT-1	20	14.3	0.529	4440	6580	6560 (J) 7020 (D)	18.0 22.0	34 40
2CT-1	20	8.3	0.309	4470	5860	6370 (J) 6180 (D)	22.0 13.0	34 40
ST-3	20	17.1	0.738	4470	5610	5540 (J) 5790 (D)	24.0 18.0	40 55

Note: 1 ft = 0.3048 m; 1 kip = 4.448 kN; 1 psi = 0.006895 MPa; 1 in. = 25.4 mm.

\* J designates the jacking end and D designates the dead end.

the applied force. FRP tendons were placed in grips. The grips were then set using the manufacturer's recommended procedure, if any, and a load of approximately 300 lbs (1.3 kN) was applied. This load was sufficient to hold the tendons in slight tension for attachment of tendon strain gauges.

Full prestressing took place 3 days later. In addition to monitoring of load during tensioning, the total elongation of the tendon was recorded at the face of the jack-end grip as well as movement of the tendon at the face of the dead end grip, which represents the dead end grip slip during tensioning. The actual elongation is the total elongation minus dead end grip slip. Both the target load and target elongation criteria were established for each tendon.

Although most tendons were tensioned without difficulty, two tension-

ing efforts were unsuccessful. A CL tendon slipped out of the jack end grip at about 80 percent of target load, shattering in a brittle manner against the dead end anchor block. One CT tendon broke just in front of the die-cast sleeve at 53 percent of target load. In both instances, tendon fragments were scattered widely about the laboratory despite formwork covering, underscoring the importance of implementing safety procedures in pretensioning FRP tendons. In addition, three tensioning efforts (AA-1, AA-2, 2CT-1) were stopped before attaining target load levels when loud ping/pop noises were heard accompanied by a 500 lb (2.2 kN) drop in load.

Two specimens, AA-3 and 2CL-1 in casting Set 7, were rapidly preloaded to 2 kips (8.9 kN) for 2 hours the day before full tensioning, then unloaded to 300 lbs (1.3 kN) overnight. Though

not specifically recommended by respective manufacturers, this practice led to an apparent reduction in grip slip during tensioning. Both preloaded tendons achieved full target loads without the grip slip-out or tendon ping/pop behavior encountered in tensioning Tendons CL and AA.

### Transfer Length

Gradual release of prestress force in two stages, 50 and 100 percent release, was used for all materials including the steel. The observations reported are based on the concrete strain measured at the tendon level on the specimen surface and from the tendon strain obtained from a limited number of electrical resistance strain gauges attached directly to the FRP tendon surface. The tendon end slip data and observation of cracking behavior dur-

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ing flexural testing contribute additional insight.

Transfer lengths are determined by measurement of concrete strain on the surface of the specimen using the Whittemore gauge point system. This method requires the attachment of gauge points to the specimen. As an alternative to gluing the contact points to each specimen by hand, contact point inserts were screwed to the inside surface of the fiberglass formwork before placement of the concrete. The screws were removed before the formwork was removed so that the inserts remained cast-in-place. This system is shown in Fig. 4.

A gauge length of 8 in. (200 mm) was used. Using a handset and data logger, readings were taken to 0.001 mm resolution. As measurements were taken, the measured gauge length was compared against a standard gauge length made of invar steel every 20 or 50 data points, so that corrections could be made for a change in measured length due to temperature effects on the Whittemore handset. The laboratory temperature was also recorded at the time of each reading so that an account could also be made of the change in strain of the prestress material due to the laboratory temperature variation between the baseline reading and  $t = t_i$ . The coefficient of thermal expansion of the individual materials was used in making this correction.

The gauge contact point intervals were varied from 2, 4 or 8 in. (50, 100 or 200 mm), with a closer contact point spacing near the specimen ends. The Whittemore gauge length was 8 in. (200 mm); therefore, the strain data for a given measured length was assigned to the midpoint location of the gauge length. Measuring from the specimen ends, with a first contact point located as near to the end as practical, the position of the first strain reading became 5 in. (127 mm) from the specimen end. The position of contact points was symmetrical along each side of the specimen, so that the concrete strain at a given location along the beam was an average of two readings from the opposite faces of the specimen.

Baseline Whittemore and end slip readings were taken for each specimen

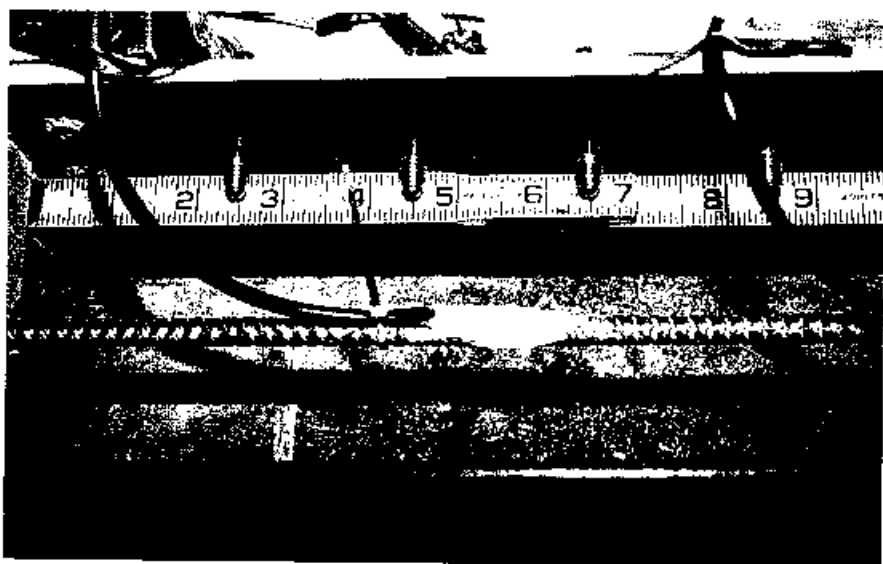


Fig. 4. Whittemore gauge and tendon strain gauge instrumentation.

prior to release of the tendon from its prestressing grips. These readings were taken when the concrete had attained a minimum strength of 4000 psi (28 MPa) based on cylinder test results, which varied from Day 7 to Day 10 for the seven casting sets. Subsequent readings were taken for all specimens at 50 percent release, 100 percent release, at 1 day after release, at 14 days after casting and at 28 days after casting. Concentric specimens were read again at Days 45, 60, 75 and 90. Rectangular specimens were read again on the day of flexural testing.

The averaged values of concrete strain were plotted vs. distance along the length of each specimen to generate a strain profile for each specimen at each time interval. Each profile was examined and a judgment was made concerning the points that formed inclusively the plateau region of the profile. These points were then averaged and multiplied by 0.95 to obtain the 95 percent average strain value for the specimen for the given time interval.

The measured transfer length is the distance from the free end of the specimen to the location where the rising strain profile intersects with the plateau strain value as determined by the 95 percent average method. A representative strain profile is shown in Fig. 5. The transfer zone is the region near the end of the prestressed beam and, for a given specimen, is equivalent to the transfer length,  $L_T$ , as deter-

mined using 28-day concrete strain data for that specimen.

### End Slip

The end slip of the prestressing tendon was determined by measuring the distance from a fixed metal U-shaped bracket to the end surface of the concrete specimen using an extensometer. U-shaped brackets were fabricated in the laboratory machine shop. Two small alignment holes were drilled in the upper legs of the bracket to serve as guides for the extensometer, which rests against the outer leg of the bracket during the measurement. Before release of the prestress force, brackets were attached securely with hose clamps to the tendon at both ends of the specimen, approximately 2 in. (50 mm) from the end of the concrete surface. Readings were obtained to an accuracy of 0.01 mm.

### Flexural Testing Procedure

The rectangular specimens were tested in flexure using a hydraulic jack to apply a point load to the specimen at the designated embedment length. The beam loading arrangement is shown in Fig. 6. Embedment length, designated with the small letter  $e$  in Fig. 6, is the distance from the free end of a specimen to the location of the point of application of the external load. Two tests were made for each beam with the load always applied between the two supports.

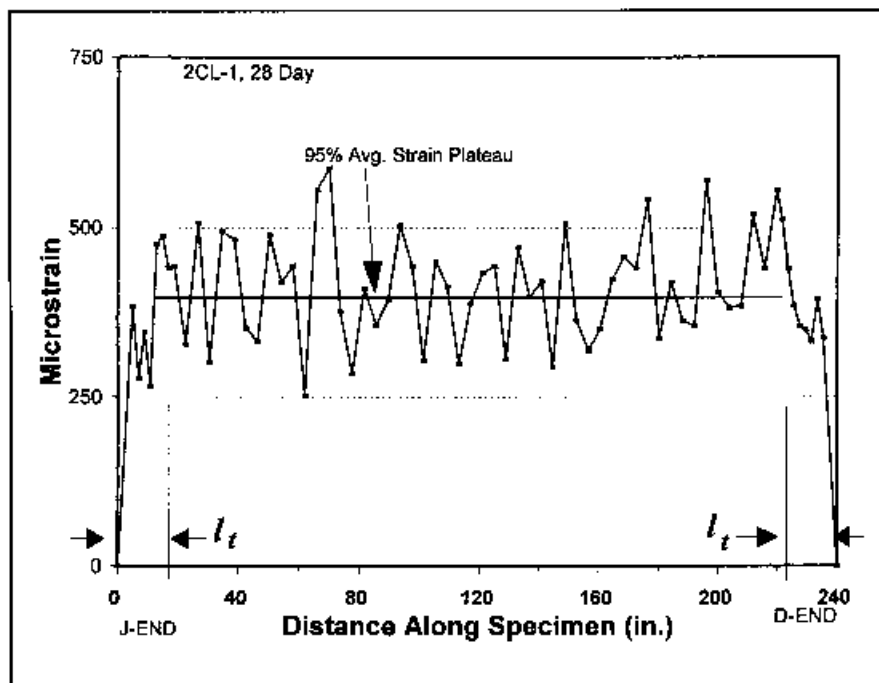


Fig. 5. Representative concrete strain profile showing 95 percent average strain plateau and determination of transfer length.

In each flexural test in this study, the embedment length was either 34, 40 or 55 in. (864, 1016 or 1397 mm). All the tests were carried out with a span of 12 ft (3.66 m) between reaction supports. At the beam end not undergoing external loading, the unsupported cantilever length varied from 55 to 90 in. (1.40 to 2.29 m). It is noted that the support locations shown in Fig. 6 are valid only for the case when  $P_1$  is applied; none of the beams were tested as cantilevers.

In addition to baseline concrete and tendon strain and end slip, increments of applied load, deflection at the load point and concrete strain at the top

surface of the specimen at the location  $e + 6$  in. (150 mm) were also monitored during the testing. Load was applied in increments rather than continuously, with frequent pauses in loading to monitor crack formation. End slip during flexural loading was measured using an extensometer described previously. During pauses in loading, the hydraulic jack was locked off to maintain the applied load.

#### Failure Modes

Three failure modes are used to classify the way in which a specimen fails in static load testing.

**Bond Slip Failure** — In this case, flexural cracking has occurred, but before the occurrence of flexural-shear failure tendon end slip into the beam equal to or greater than 0.01 in. (0.254 mm) is recorded. This is the same slip failure criterion used in previous development length studies conducted by Cousins<sup>11</sup> and by Lane.<sup>12</sup>

**Tendon Rupture Failure** — In this case, either partial or complete rupture of the FRP tendon has occurred. In most instances, rupture occurs at tendon stress levels near  $f_b$ . Tendon end slip, if any, is less than 0.01 in. (0.254 mm). Prior to rupture, flexural-shear cracks had not penetrated through the top surface of the beam.

**Flexure Failure** — Flexural-shear cracks penetrate through the top surface of the beam. There is no significant tendon end slip and no evidence of partial FRP tendon rupture.

## TEST RESULTS

The experimental data were analyzed to determine the transfer and development length of the various tendons. In addition, the flexural behavior, loss of prestress and the performance of the grips were evaluated.

#### Transfer Length

Transfer length,  $l_t$ , at 28 days is listed for each specimen in Table 2. Fig. 7 summarizes the average 28-day transfer length of FRP tendons comparatively with steel tendons and with experimentally determined development lengths for the FRP materials.

Of the three aramid FRP tendons tested, Tendons AT and AF had the shortest average transfer lengths of 12.6 and 13.4 in. ( $43d_b$  and  $33d_b$ ), respectively. Tendon AA recorded a longer average transfer length of 20 in. ( $50d_b$ ). The average value for Tendon AA includes results of both high and low prestressed specimens. When averaged separately,  $l_t$  for high prestress (Tendon AA) was 28 in. ( $70d_b$ ), and it was 16 in. ( $41d_b$ ) for low prestress (Tendon AA). Two carbon FRP tendons were tested. Both returned similar average transfer lengths of 17 in. ( $54d_b$ ) for the CI tendons and 16.3 in. ( $50d_b$ ) for the CT tendon.

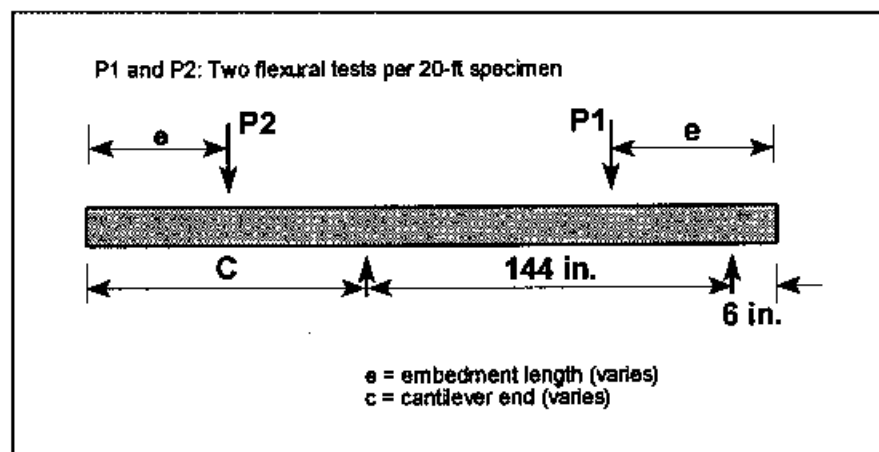


Fig. 6. Diagram of beam loading arrangement.

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Most of the FRP tendons tested displayed average transfer lengths shorter than that of the steel. The average  $L_t$  for the steel control specimen was 21 in. ( $56d_b$ ), which is a typical value for steel strand of the diameter tested. Transfer lengths of aramid FRP tendons were 60 to 94 percent of the average steel  $L_t$ . Transfer lengths of carbon FRP tendons tested were 78 to 80 percent of the steel transfer length. No bursting or splitting of concrete at release of prestress force occurred despite the short transfer lengths recorded.

### Development Length

The required development length can be approximated for each FRP material tested using the load point embedment length and failure mode results. The results depicted comparatively in Fig. 7 provide a minimum development length for each material.

For each material tested, the development length shown represents the shortest embedment length tested that developed the flexural capacity of the bonded tendon without the occurrence of bond slip. For this determination, the flexural capacity is taken to be  $M_{fail}/M_n$  greater than or equal to 1.0. The nominal moment capacity,  $M_n$ , was calculated following the strain compatibility method given in ACI 318-95, utilizing the manufacturer-suggested data for the FRP tendons. The steel Specimen ST-3-D was tested at an embedment length of 40 in. ( $106d_b$ ) and experienced bond slip after attaining a moment ratio of 1.05. The results of this test are used in Fig. 7 for comparison of FRP prestressing tendon requirements with those of steel tendons.

The aramid Tendon AA required a minimum development length of 40 in. (1016 mm) to meet the flexural capacity criteria without bond slip, based on performance data for Specimen AA-1-D. The aramid Tendon AF experienced bond slip at an embedment length of 34 in. (864 mm); however, the failure moment for this specimen (AF-3-I) was  $1.28M_n$  when slip occurred. Therefore, this embedment length is considered adequate to attain the full flexural capacity of the AF tendon. Thus, AF tendons require a development length of 34 in. ( $83d_b$ ).

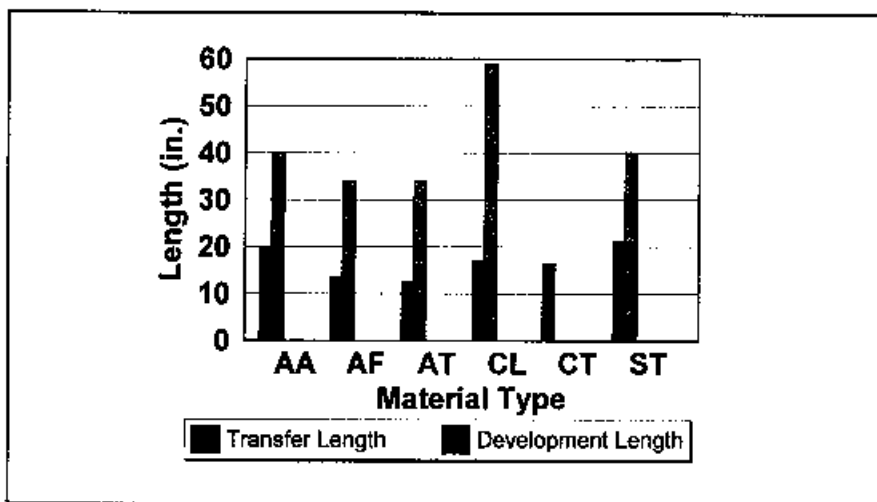


Fig. 7. Comparison of transfer and development length results for materials tested.

The aramid Tendon AT was tested twice at the shortest embedment length utilized in this study. At an embedment of 34 in. (864 mm), Specimen AT-3-D ruptured at a failure moment of  $1.10M_n$  and Specimen AT-3-I experienced bond slip at a failure moment of  $1.32M_n$ . Because both the rupture and slip outcomes occurred at moments above  $M_n$ , AT tendons require a minimum development length of 34 in. ( $112d_b$ ).

Three specimens of the carbon Tendon CL exhibited bond slip failures at moment ratios less than 0.82. Only when the embedment was increased to 55 in. (1397 mm) did CL tendons repeatedly reach moment ratios greater than 1.0 without slip failure. It is concluded that the CL tendons require a minimum development length of 55 in. ( $175d_b$ ).

All four flexural tests of specimens

containing the carbon Tendon CT exhibited a complete or nearly complete rupture of the tendon at moment ratios varying from 0.65 to 0.85 at embedment lengths of either 34 or 40 in. (864 or 1016 mm). Although no slip occurred at the shortest embedment length attempted, neither did these trials demonstrate that bonding mechanisms could be sustained to the full anticipated capacity of the section. No recommendation is made, therefore, regarding minimum development length requirements for CT tendons.

### Flexural Performance

A comparison of flexural performance for the three aramid and two carbon FRP tendons tested is summarized in Fig. 8 and in Table 3. All specimens selected for comparison were tested at a load point embedment length of 40 in. (1016 mm). Fig. 8 shows a

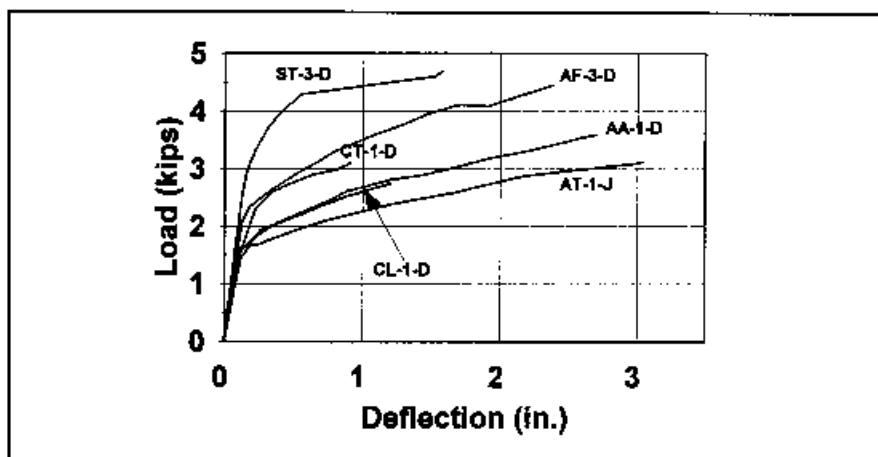


Fig. 8. Comparison of load vs. deflection to failure for all materials tested at an embedment length of  $e = 40$  in. (1016 mm).

Table 3. Comparison of mode of failure of all materials at an embedment length of  $e = 40$  in. (1016 mm).

Specimen	Mode of failure	$M_{fail}/M_n$
AA-1-D	Rupture	1.16
AF-3-D	Flexure-shear	1.30
AT-1-J	Rupture	1.17
CT-1-D	Rupture	0.85
2CT-1-D	Rupture	0.75
CL-1-J	Bond slip	0.82
CL-1-D	Bond slip	0.76
ST-3-D Steel control	Bond slip	1.05

comparison of the load vs. deflection at the load point. Table 3 provides moment ratio and modes of failure. The performance of the steel control specimen is included for comparison.

At failure, the aramid AA tendon exhibited a deflection 1.8 times that of steel while carrying 80 percent of the load carried by steel. Specimen AA exceeded the full predicted flexural capacity by 16 percent. When the AA tendon ruptured, the beam failure was sudden and the specimen broke apart, whereas in the case of the steel tendon, when bond slip failure occurred, the specimen remained intact.



Fig. 9. Failure of specimen reinforced with AF tendon.

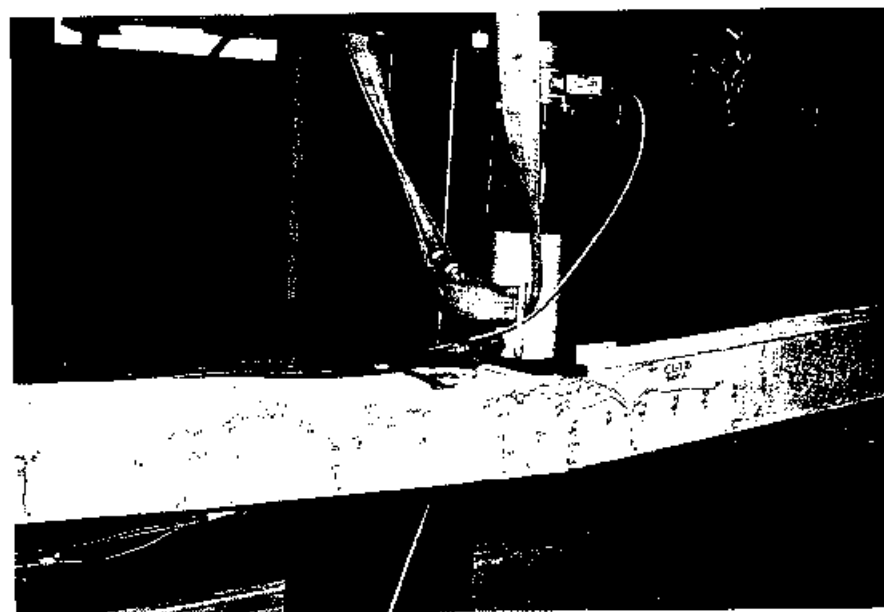


Fig. 10. Failure of specimen reinforced with CL tendon.

The aramid AF exhibited a deflection 1.5 times that of the steel tendon while carrying 95 percent of the load carried by the steel tendon. Tendon AF exceeded the predicted flexural capacity by 30 percent. When the flexural-shear cracks reached the top surface of the beam, the AF tendon did not rupture and the specimen remained intact.

The aramid AT exhibited a deflection 1.9 times that of the steel tendon while carrying 67 percent of the load carried by the steel tendon. Tendon AT exceeded the predicted flexural capacity by 17 percent. When the AT tendon ruptured, the beam failure was sudden and the specimen broke apart (see Fig. 9).

The carbon CL exhibited a deflection 0.65 times that of the steel tendon while carrying 60 percent of the load carried by the steel tendon. At bond slip failure, the CL tendons exhibited 18 to 24 percent less flexural capacity than predicted. At failure, the specimen remained intact (see Fig. 10).

The carbon CT exhibited a deflection 0.55 times that of the steel tendon while carrying 67 percent of the load carried by the steel tendon. At failure, the CT tendons exhibited 15 to 25 percent less flexural capacity than predicted. When the CT tendons ruptured, the beam failure was sudden and the specimen broke apart.

### Grip Performance

Table 4 provides a comparison of the performance of the five FRP tendon-grip systems with steel. The comparison is expressed in terms of an efficiency factor  $\kappa$ . The factor  $\kappa$  is found for each specimen by dividing the slip measured in units of inches

Table 4. Relative grip efficiency of FRP prestressing systems tested.

Material	Grip type	$\kappa_{avg}$
AA	Wedge chuck	0.119
AF	Wedge chuck	0.040
AT	Bonded	0.014
CL	Wedge chuck	0.044
CT	Die-cast sleeve plus chuck	0.012
ST Steel control	Wedge chuck	0.014

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by the final jacking load. The average value is listed in the table for each material tested. Using this measure, the potted or die-cast type grips used with FRP Tendons AT and CT performed with efficiency similar to that of the wedge chuck used with the steel tendons. Wedge type grips used with FRP Tendons AF and CL allowed three times more slip during tensioning. The wedge grip used with the AA tendon was the least efficient gripping mechanism and allowed 8.5 times more slip than that used in the steel control specimen.

### Prestress Losses

Information concerning the prestress loss characteristics for FRP materials is needed to determine the stress in the material which is available after losses have occurred. The effective stress,  $f_{se}$ , is used in the nominal capacity and development length design equations. The concrete strain in the beam specimens was monitored over time. The strains were recorded before tensioning and at regular time intervals after tensioning, until the beams were tested in flexure.<sup>12</sup> The figures presented in Table 5 summarize average prestress losses observed for each material tested. It is clear that at least in the early stages of prestressing, all FRP tendons exhibit higher losses than steel tendons.

## DISCUSSION OF TEST RESULTS

Although this investigation was not intended to be a definitive investigation of development length requirements for each type of FRP prestressing tendon, the results herein can be a useful design guide which parallels the ACI 318-95 development length criteria for steel tendons. Table 6 lists the required development length for each FRP tendon calculated according to the ACI 318-95 design equation:

$$L_d = (f_{ps} - \frac{1}{3}f_{se})d_b$$

where

$f_{ps}$  = stress in prestressed reinforcement at nominal strength calculated from Eq. (18-3) of ACI 318-95

$f_{se}$  = effective stress in prestressed reinforcement after all losses

Table 5. Comparison of prestress losses for FRP materials based on concrete strain data.

Material	Average initial loss (percent)	Average 28-day loss (percent)	Average 90-day loss (percent)
AA	5.1	9.0	12.2
AF	9.5	12.4	13.8
AT	8.2	10.4	14.4
CL	4.5	10.6	17.5
CT	1.4	5.4	8.4
ST	0.1	4.9	—
Steel control			

Note: Average of high prestress specimen only.

Table 6. Comparison of total development length required for FRP prestressed tendons based on current ACI Code vs. test program recommendations.

Material	$d_b$ (in.)	$f_{ps}$ (ksi)	$f_{se}$ (ksi)	$L_d$ (ACI) (in.)	$L_d$ (Exp.) (in.)	$L_d$ (ACI) / $L_d$ (Exp.)
AA	0.390	333	154	90	40	2.24
AF	0.410	190	104	50	34	1.45
AT	0.291	237	122	45	34	1.33
CL	0.312	268	147	53	55	0.96
CT	0.327	296	121	70	n/a	n/a
ST	0.375	249	191	45	40	1.13

Note: 1 in. = 25.4 mm; 1 ksi = 6.895 MPa

$d_b$  = nominal diameter of prestressing strand

The value used in Table 6 for the tendon effective stress after prestress losses is the average value based on 28-day concrete strain measurements from this study. A comparison is made with the minimum development length recommendations made above for each FRP material.

The results of this test program suggest that the ACI 318-95 development length equation is conservative when applied to the three aramid FRP tendons included in this study. The results suggest that for the carbon FRP Tendon CL the present design equation may be adequate but provides no margin of safety. In this test program, the carbon Tendon CT exhibited a rupture failure at embedment lengths less than 60 percent of that required for development using the ACI equation. Therefore, no conclusion can be drawn concerning the adequacy of the ACI 318-95 development length when applied to CT tendons.

All five FRP prestressing tendons used in this test program have linear-

elastic behavior to failure. Four of the five materials tested have demonstrated sufficient bond performance to avoid bond slip when the ACI 318-95 development lengths are utilized. However, the likelihood of a sudden brittle fracture of the FRP tendon under nominal moment stress or concentrated localized stress conditions is high and warrants imposition of higher factors of safety on these materials.

## CONCLUSIONS

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

1. FRP prestressing tendons displayed average transfer lengths shorter than those of steel tendons. Transfer lengths of aramid FRP tendons were 60 to 94 percent those of steel tendons. Transfer lengths of carbon FRP tendons were 78 to 80 percent of steel tendons.

2. The ACI 318-95 development length requirements are conservative for aramid FRP Tendons AA, AF and AT by factors of at least 2.2, 1.5 and

1.3, respectively. However, due to the limited scope of this study with respect to tendon diameter, tendon spacing, and confinement, no reduction in the ACI 318 development length requirements is recommended at this time. The ACI 318-95 development length requirements may not be adequate for the carbon prestressing Tendon CL. Therefore, it is recommended that a safety factor of 1.2 be applied to the ACI 318 development length requirements for design using CL tendons. Testing of the carbon Tendon CT was inadequate to relate its development length to the ACI 318-95 requirements.

3. All FRP tendons except Tendon AF exhibited a complete or nearly complete rupture of the tendon under very high moment stress conditions. Additional research is needed to establish the safe upper flexural moment

bounds when using FRP prestressing tendons.

4. In the absence of additional test results, the maximum loading should be limited to  $0.9M_n$  for aramid FRP materials and  $0.7M_n$  for carbon FRP materials.

## RECOMMENDATIONS

The use of fiber composites in the construction industry is rapidly growing. The present investigation is among several projects undertaken by the U.S. Federal Highway Administration and demonstrates the interest of this organization in the use of these materials. It must be noted, however, that field application of FRPs in the United States is lagging behind that of other nations, such as Japan, Canada, and some European countries.

Sufficient information on the behavior of these materials is available to warrant their use in demonstration projects. While research on FRPs will inevitably continue for years to come, it is hoped that the American construction industry will take a deeper interest in the utilization of these materials so that it will remain competitive in this emerging field.

## ACKNOWLEDGMENT

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