EFFECT OF STRAND DIAMETER ON BOND, TRANSFER AND DEVELOPMENT LENGTH PERFORMANCE OF PRESTRESSING STRANDS

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ABSTRACT

The transfer length equation presented in the ACI and AASHTO codes were developed for small diameter strands and assumes the transfer length to be linearly proportional to the strand diameter. Current industry standard is 1/2" diameter strand, but strands up to 7/10" are being introduced to the industry. The applicability of these equations to this larger strand was questioned.

Research efforts at the University of Florida concentrated on the effect of strand diameter on bond performance of prestressing strands. Forty rectangular prismatic specimens were fabricated and tested for transfer length and end-slips at transfer and for development lengths with static loading. The strand sizes ranged between 3/8" and 7/10".

The transfer lengths of small diameter strands were found to be linearly proportional to the strand diameter, but the transfer lengths for large diameter strands did not followed this trend. The large diameter strands exhibited transfer lengths shorter than those predicted by current code equations.

The current code equation was found to predict the mean and median of the experimentally measured transfer lengths, about 50 strand diameters. That is, it under-predicts approximately 50% of the transfer lengths, which could lead to unsafe designs.

A transfer length predictor equation that considered the effect of concrete strength, initial prestress, strand surface condition, method of transfer and strand diameter was developed. The transfer length estimated with the proposed equation envelopes 95% of the data in a large database.

Keywords: Prestressed, Bond Length, Development Length, Transfer Length

INTRODUCTION

Current American Concrete Institute, ACI 318-99[1] and American Association of State Highway and Transportation Officials, AASHTO[2] code provisions for transfer and development length for prestressing strands are essentially identical. These expressions were developed in the 1960's, based on data obtained from research using clean Grade 250 Stress-Relieved strand that ranged from ¼" to ½" in diameter[3, 4]. The current industry standard is 1/2" Grade 270 Low Relaxation strand, which allows for higher initial and effective prestressing stresses. Large diameter strands, 6/10" and 7/10", have already been introduced to the industry and higher grade strands, Grade 290 and Grade 300, are being tested for introduction to the industry.

The efficient use of high strength concrete demands an increase in prestressing force. The increase in prestressing force requires additional strands, or an increase in the per strand force. Sections have been developed to provide the necessary space to accommodate the additional strands. The increase in the per strand force is achieved by increasing the area of individual strands, increasing the strand's breaking strength or a combination of both.

Research efforts to investigate bond transfer and development length performance of prestressing strands at the University of Florida were initiated in December 1996. The main thrust of these efforts were focused toward improving the state of knowledge on the effect of the diameter of prestressing strands, i.e. strand size, on transfer length and flexural bond performance. To a lesser extent, the effect of the stress in the strand prior to transfer was also investigated. An extensive research program[5] was carried out to measure the transfer length and the flexural bond behavior of a variety of strand diameters mimicking current prestressed concrete industry standards.

Forty (40) specimens were fabricated and tested. With the exception of series UF13 and UF14, which were fabricated at Gate Concrete Products Jacksonville, Florida, all the specimens were fabricated and tested at the University of Florida's Civil Engineering Department Structures Research Laboratory. The fabrication and testing of these specimens was done in four (4) phases.

Measured transfer lengths, end slips and flexural test results were analyzed and discussed in light of the results obtained from published research programs. First, the effect of variables, such as concrete strength at transfer and initial prestress in the strand transfer length was individually investigated. These individual investigations were not unit-consistent or dimensionally correct, as such the information obtained was indicative of the variables qualitative influence on bond, rather than quantitative. A dimensional, or unit-consistent analysis of the data followed. Information and relationships obtained through a dimensional analysis of the data was also of qualitative nature, yet, combined with experimental procedures adequate predictor equations can be obtained.

The aforementioned analysis of the data provided the authors with a better understanding of the nature of bond and how it was influenced by parameters such as, concrete strength and strand diameter. The parameters targeted for study in this program included the effect of strand diameter and initial prestress. The exploration of the effect parameters such as concrete cover and concrete strength may have on bond was possible through a review of the published literature. An attempt was made to analytically explain the behavior observed in the effect of large diameter strands on transfer length.

A design equation to estimate the transfer length was developed, tested and presented in this paper. The knowledge and understanding of the nature of bond acquired through the analysis of the data was applied to the development of the transfer length predictor equation.

PREVIOUS RESEARCH AND CURRENT PRACTICE

FHWA MEMORANDUM

In the 1980's strand producers began to manufacture a strand 6/10" in diameter. Serious concerns were raised on the applicability of current code expressions to this strand. Research conducted at North Carolina State University found development lengths substantially longer than those computed by current code expressions[6-8], not only for the new 6/10" strand, but for the smaller diameter strands also. These findings led to a memorandum from the Federal Highway Administration, which imposed a moratorium on the use of the 6/10" strand, imposed a four strand diameter center to center spacing of the strands and increased the required development length of uncoated strands and blanketed strands by sixty (60%) and a hundred percent (100%) of the value computed by the AASHTO expression, respectively.[6-14]

Several research efforts were initiated because of the FHWA memorandum. The goal of these efforts was to improve the state of knowledge of prestressing strands bond performance in general. Some of the variables that have been studied are: the effect of the concrete cross section, strand surface condition, strand size, strand spacing and the effect of concrete strength.

LARGE DIAMETER STRANDS

The term "large diameter strand" has been re-interpreted through the years. In 1956 Thorsen[15] published his paper *Use of Large Tendons in Pre-Tensioned Concrete* in which he referred to 1/2" strands as large diameter strand. Most recently in 1993, Russell and Burns[16] referred to 1/2" and 6/10" strands as large diameter strands. For the purpose of our discussion large diameters refers to 6/10"and 7/10" diameter strands.

The move toward larger diameter strands is the result of the development of high strength concrete. Economically viable concrete mixes with compressive strengths in the 10,000-psi to 15,000-psi range are readily available. These high performance concretes allows longer spans with a given section than is possible with regular strength concrete.

In order to take advantage of higher strength concretes in an efficient manner, the level of prestress on the section must be increased. The space required to accommodate additional strands, required to achieve an increase in prestress level, is limited. Sections, such as the Texas U-beam, have been developed to allow for more space where the strands can be accommodated. Another solution to this problem was to increase the area of individual strands. The strand producers have responded with the development of, first, the 6/10" strand and recently with a 7/10" strand, which has almost twice the cross-sectional area of a 1/2" strand.

TRANSFER AND DEVELOPMENT LENGTH

In prestressed concrete applications, the strands are stressed before the concrete is poured. Once the concrete has achieved a minimum prescribed strength, typically 3,500 psi, the strands are released. The prestress force is then transferred from the steel to the concrete at the ends of the members through bond. The stress build up is gradual from zero at the ends to the effective prestress level, over a distance called the transfer length, L_t. As external loads are applied, the difference in bending moments at two adjacent sections causes the stresses in the strands to increase. While the concrete member is un-cracked, the stress increase in the strand is negligible. After cracking, the stresses in the strand increase abruptly[17]. These additional stresses are called flexural bond stresses. The flexural bond length, L_{fb}, is the additional bonded length of strand required to equilibrate the flexural bond stresses at the limit state.

The Development Length is the total length of bonded strand required to transfer the strand's design limit state force to the concrete. This required bonded length is the summation of the transfer and the flexural bond lengths.

EVOLUTION OF THE CURRENT ACI AND AASHTO CODE EXPRESSIONS

In 1993, Tabatai and Dickson[18] published a paper title titled *The History of the Pretensioning Strand Development Length Equation*, a study commissioned by the FHWA.

The ACI and AASHTO provisions for transfer and development length are identical. Current development length provisions are presented in Section 12.9 of the ACI 318-99[1]. This provision states that: Three and seven wire pretensioning strand shall be bonded beyond the critical section for development length, in inches, not less than Equation 1.

$$L_d = (f_{ps} - \tfrac{2}{3} f_{se})\, d_b \tag{1}$$

where, L_d is the development length
f_{ps} is the strand stress at the limit state
f_{se} is the strand effective stress, and
d_b is the strands nominal diameter.

About transfer length, neither ACI 318-99, nor AASHTO Standards, has explicit provisions for a minimum or maximum length over which the prestress must become effective. The

ACI 318-99 Commentary provides an expression to estimate transfer length by re-writing Equation 1 as the sum of transfer length and flexural bond length, see Equation 2.

$$L_d = \frac{f_{se}}{3} d_b + (f_{ps} - f_{se})\, d_b \tag{2}$$

ACI 318-99 Section 11.4.3 and AASHTO 9.20.2.4 suggests that a transfer length of fifty strands diameter ($50d_b$) and a linear distribution be assumed for shear design consideration.

ACI transfer length provisions, derived by Alan Mattock, are based on tests conducted in the 1950's and early 1960's with clean Grade 250 Stress Relieved Strands[3,4]. In deriving an expression to predict transfer length, Mattock noted that the average transfer bond strength of 400 psi reported by Hanson and Kaar seemed reasonable[18]. With this information and the equilibrium equation for prestressing steel force and bond force a transfer length expression, Equation 3, was derived.

$$L_t = \frac{f_{se}}{3} d_b \tag{3}$$

Regarding ACI 318-99 Section 11.4.3 provision for transfer length, it should be noted that: The effective prestress in Hanson and Kaar's tests never exceeded 150 ksi. Evaluating Equation 3 for this level of effective prestress resulted in a simplified expression for transfer length in the form of $50d_b$. This expression applicability should be limited to a maximum level of prestress of 150 ksi.[3,18] If the derivation of Equation 3 is done for a 1/2", Grade 270, strand and is evaluated for an effective prestress of 168 ksi (See Example 4.7.1 of the PCI Design Manual[19]) the simplified expression for transfer length would be $61.3d_b$ instead of $50d_b$, or 22.6% longer.

EXPERIMENTAL TESTING PROGRAM

TEST SPECIMENS FABRICATION

The experimental program consisted of four phases, each consisting of two parts, measurement of transfer length and flexural bond test. In the first two phases, Phase I and Phase II, the strands used were 1/2" in diameter Grade 270 - Low Relaxation. Since this strand, 1/2" Grade 270 – Low Relaxation, is the current industry standard, these first two phases served to set a benchmark to which the following phases were compared.

The effect of strand size, or diameter, was investigated in Phase III. The strand diameters studied were 3/8", 1/2" special, 6/10" and 7/10". Phase IV dealt with the effect of initial prestress level on transfer length and bond performance in general. The following strands were investigated: 3/8" Grade 270 and Grade 300, 1/2" Grade 300 and 1/2" special Grade 290. All the strands were Low Relaxation strands.

MATERIALS PROPERTIES

The prestressing steel used conformed to the specifications put forth by the American Society of Testing and Measurements, ASTM A 416/A 416M – 94a, *Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete.* The strands used were seven-wire strands in as-received condition.

Compression reinforcement consisted of two (2) deformed reinforcing Grade 60 bars in accordance with ASTM A 615. Shear reinforcement consisted of #2 smooth wire and #3 deformed bars, bent into a closed U-shaped stirrup.

The concrete mix was designed to mimic current prestressed concrete industry standards. The design slump ranged between 4 1/2" and 7 1/2". The design compressive strength for the mix used is 6200 psi and 7900 psi at 7 days and 28 days, respectively. Typical values for the measured slump ranged between 3" and 4 1/2". The concrete strength twenty-four (24) hours after casting ranged between 3500 psi and 4300 psi. The 28-day compressive strengths ranged between 7200 psi and 9000 psi.

EXPERIMENTAL PROCEDURES AND INSTRUMENTATION

The transfer lengths were determined from deformations measured with a digital Whittemore-Type De-mountable Mechanical (DEMEC) Strain Gage, precise to 0.00005", along each beam at the strand's level. DEMEC target points, stainless steel discs ⅜" in diameter with a hole milled in the center, were attached to the specimen's sides at the level of the strand along the specimen. The instrument and target points are shown on Figure 1.

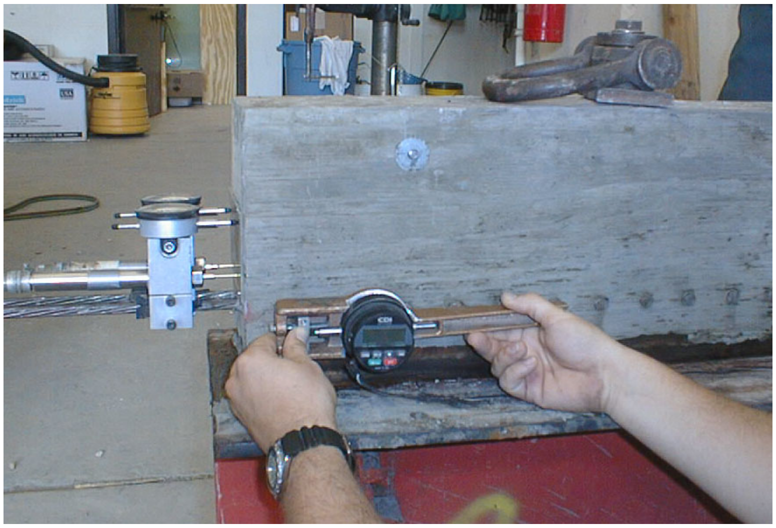

Figure 1 Picture of the Demountable Mechanical Strain Gauge and Target Points.

The concrete surface strain were computed from the deformation measurements and corrected for the strain induced by the weight of the specimen acting on the cambered specimen. Concrete surface strains were plotted and the transfer length estimated using the

Slope-Intercept Method with the intercept at 95% of the maximum average strain and the 95% Average Maximum Strain Method.

End slips were measured with Linear Voltage Differential Transducers, LVDTs, and dial gauges accurate to 0.001". The instruments were mounted on an aluminum block clamped to the protruding portion of the strands. A plexiglass plate, at the end face of each specimen, provided a smooth surface for the instrument probes to rest against. Figure 2 shows a schematic of the instrumentation setup.

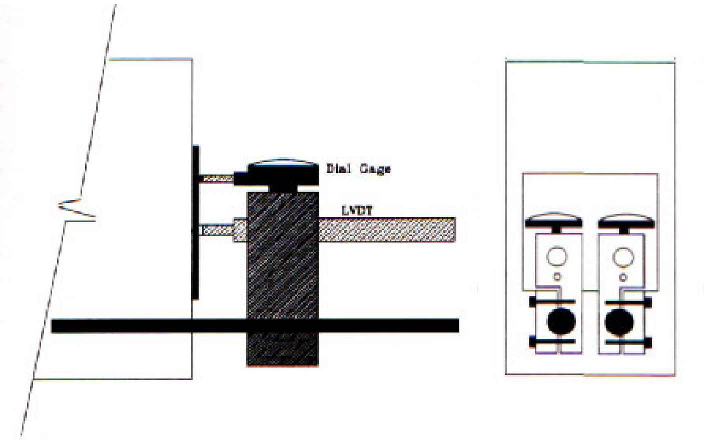

Figure 2 Schematic of Instrumentation Setup

To measure the internal concrete strains, the free ends of each specimen of series UF12 through UF14 was instrumented with electronic strain gages. The strain gages were attached to Fiber Reinforced Polymers (FRP) reinforcing bars. Slots were milled to mid-depth of each bar. Five (5) Vishay Measurements Group, Inc. CEA-06-500UW-120 strain gages were attached to each bar. The strain gages were attached at 10", 20" 50", 60" and 70" from one end of the bar.

The specimens were tested in flexure in a two-point load configuration using a manually activated 60-Ton jack. The loads were measured with a 200 kip load cell. The vertical displacements were measured by two LVDT's placed under the resultant load. Vertical displacement, end-slips and load were plotted as the test progressed and recorded on a personal computer through a Data Acquisition System.

The two-point load configuration was intended to produce a constant moment region, neglecting the effect of the weight of the specimen. For the flexural tests of Phase I and most of the specimens of Phase II, the span was fixed at one-hundred-forty-four-inches (144"), effectively negating the constant moment region for the specimens tested at short embedment length. The remaining specimens on Phase II were tested symmetrically or with one-point load configuration in an attempt to force the critical section to concur with the embedment length. The specimens of Phase III and Phase IV were tested symmetrically and the span was changed accordingly. Figure 3 depicts a schematic of the Flexural Bond Test setup.

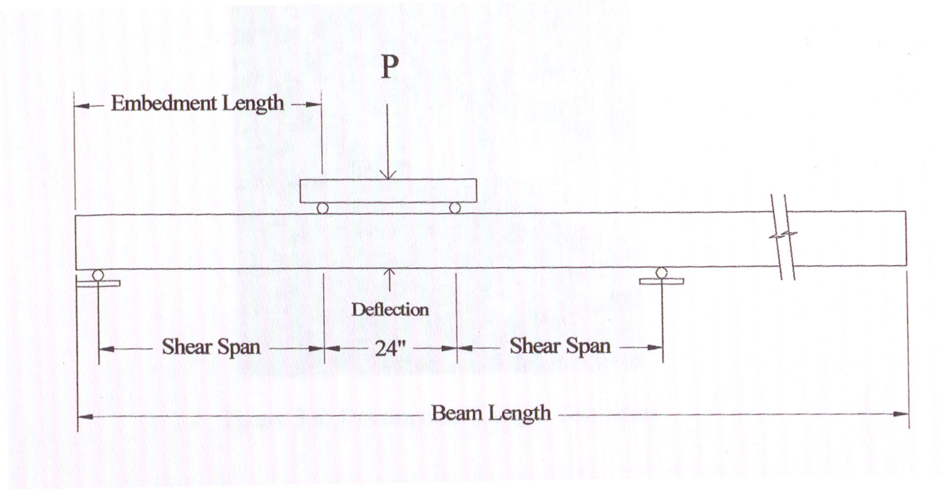

Figure 3 Schematic of Flexural Bond Test Setup

TEST RESULTS

Transfer lengths were estimated following the 95% Average Maximum Strain Method and the Slope-Intercept Method. These methods are based on the evaluation of the concrete surface strain profiles. A third estimate of the transfer length was obtained by means of end-slip measurements.

The 95% Average Maximum Strain Method was developed at the University of Texas[17], and recently endorsed by the Federal Highway Administration as the preferred method to estimate transfer length. This method is considered to yield an upper-bound value of the transfer length[13].

The Slope-Intercept Method is based on the bi-linear idealization of the strain profile. This idealization assumes that the strain profile consist of a linearly increasing portion followed by a plateau region. The linearly increasing portion is described by the equation of a straight-line, $y = \boldsymbol{m}x + \boldsymbol{b}$. An horizontal line describes the plateau region. The transfer length is determined as the intercept of these two lines.

In light of the fact that the data obtained during the experimental program at the University of Florida had been analyzed following the Slope-Intercept Method, with intercept at 95% of the maximum average strain, the data was re-analyzed following the procedure endorsed by the Federal Highway Administration. The strain profiles were re-evaluated following the 95% Average Maximum Strain Method and the Slope-Intercept Method with intercept at 100% of the average maximum strain. A descriptive statistical analysis was performed on the data, totaling 65 measured transfer lengths. The transfer lengths were normalized with respect to the strand diameter. The results of this analysis are presented on Table 1.

Table 1 Descriptive Statistical Analysis of Transfer Length Determination Methods

Parameters in Terms of Number of Strand Diameters	95% Slope Intercept	100% Slope Intercept	95% Average Maximum Strain
Mean Transfer Length	46.8	49.3	50.0
Median Transfer Length	47.5	50.0	52.0
Standard Deviation	10.1	10.6	11.0
Range of Transfer Lengths	26.2 – 69.2	27.6 – 72.8	27.6 – 76.9
95% Confidence Interval	43.9 – 49.8	46.3 – 52.8	47.0 - 53.0

Tables 2 and 3a-d presents a summary of the transfer length, flexural test and development length results. The coefficient of variation [COV], computed as the sample standard deviation divided by the mean, is also presented on Table 2. The range of values presented for each strand is based on the transfer lengths estimated using the Slope-Intercept Method.

Table 2 Summaries of Transfer Length Results

Strand	Average transfer length [COV] (in.)			Range (in)
	Slope Intercept	95% AMS	End Slip	
3/8” Grade 270 Phase III	17.6 (22.1%)	17.7 (20.5%)	17.5 (13.8%)	15.0 – 23.7
3/8” Grade 270 Phase IV	13.9 (17.3%)	16.2 (17.9%)	16.8 (5.2%)	12.2 – 15.6
3/8” smooth Grade 270 ALL	16.1 (24.9%)	17.6 (18.3%)	16.9 (13.5%)	12.2 – 23.7
3/8” Grade 300	19.0 (16.0%)	18.7 (20.4%)	21.8 (13.5%)	14.5 – 21.1
3/8” indented Grade 270	13.7 (7.2%)	13.4 (7.8%)	16.7 (26.8%)	11.8 – 14.2
1/2" Grade 270 Phase I	26.8 (10.7%)	28.8 (11.5%)	22.1 (9.9%)	19.2 – 31.8
1/2" Grade 270 Phase II	22.6 (18.8%)	24.4 (19.3%)	17.2 (25.9%)	14.2 – 27.9
1/2" Grade 270 Phase I & II	24.0 (20.6%)	25.4 (21.7%)	18.9 (21.2%)	14.2 – 31.8
1/2" Grade 300	33.1 (4.1%)	34.0 (4.0%)	30.1 (14.0%)	31.9 – 34.6
1/2" special Grade 270	26.0 (23.7%)	27.5 (13.8%)	25.5 (27.6%)	21.6 – 30.3
1/2" special Grade 290	28.3 (7.6%)	31.6 (6.1%)	27.9 (13.2%)	31.9 – 34.6
6/10” Grade 270	25.7 (13.5%)	25.1 (8.5%)	17.5 (21.4%)	20.1- 27.8
7/10” Grade 270	22.2 (24.0%)	23.7 (15.3%)	17.9 (12.3%)	18.3 – 28.7

Table 3.a Summary Flexural Test and Development Length Data (Phase I)

Specimen ID	End	Span (in.)	Development Length (in.)			Cracking Moment (kip-in)	Nominal Capacity (kip-in)	Maximum Moment (kip-in)	Flexural Capacity Ratio	Failure Mode
			ACI [1]	Embedment	% ACI					
UF 1-1-1/2-270	Cut End	144	70.8	66.0	82.5 %	441	705	798	113 %	Flexure
UF 1-2-1/2-270	Cut End	144	78.2	62.0	79.3 %	452	707	787	111 %	Flexure
UF 1-3-1/2-270	Cut End	144	79.5	58.0	72.9 %	452	708	778	110 %	Flexure
UF 1-4-1/2-270	Cut End	144	80.0	66.0	82.5 %	441	705	768	109 %	Flexure
UF 1-5-1/2-270	Cut End	144	78.3	66.0	84.3 %	452	707	780	110 %	Flexure
UF 1-6-1/2-270	Cut End	144	79.6	56.0	70.3 %	452	708	802	113 %	Flexure

Table 3.b Summary Flexural Test and Development Length Data (Phase II)

Specimen ID	End	Span (in.)	Development Length (in.)			Cracking Moment (kip-in)	Nominal Capacity (kip-in)	Maximum Moment (kip-in)	Flexural Capacity Ratio	Failure Mode
			ACI	Embedment	% ACI					
UF 2-1-1/2-270	Cut End	144	72.8	45.0	62.8 %	442	709	755	107 %	Flexure
	Free End	144	72.8	36.0	49.4 %	445	720	815	113 %	Flexure
UF 2-2-1/2-270	Cut End	144	72.8	37.0	50.8 %	442	709	786	111 %	Flexure
	Free End	144	72.8	28.0	38.5 %	445	720	887	123 %	Flexure
UF 3-1-1/2-270	Cut End	144	73.6	26.0	35.3 %	448	725	751	104 %	Flexure

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[1] The development length was computed using the effective prestress level estimated following the procedure outlined by Zia, Preston, Scott and Workman[20]. When computed using the estimated prestress level at the time of testing the computed development length was 72.5” for UF1-1 and UF1-4, and 70.8” for the other specimens.

Specimen ID	End	Span (in.)	Development Length (in.)			Cracking Moment (kip-in)	Nominal Capacity (kip-in)	Maximum Moment (kip-in)	Flexural Capacity Ratio	Failure Mode
			ACI	Embedment	% ACI					
	Free End	144	73.6	44.0	59.8 %	448	725	779	107 %	Flexure
UF 3-2-1/2-270	Cut End	144	73.6	36.0	48.9 %	448	725	872	120 %	Flexure
	Free End	144	73.6	46.0	62.5 %	448	725	537	74 %	Shear
UF 4-1-1/2-270	Cut End	144	72.0	40.0	55.6 %	444	706	820	114 %	Flexure
	Free End	144	72.0	30.0	41.7 %	444	706	777	110 %	Flexure
UF 4-2-1/2-270	Cut End	144	72.0	50.0	69.4 %	444	706	747	106 %	Flexure
	Free End	144	72.0	40.0	55.6 %	444	706	795	113 %	Flexure/Slip
UF 5-1-1/2-270	Cut End	144	72.2	40.0	55.4 %	440	701	736	105 %	Flexure/Slip
	Free End	96	72.2	40.0	55.4 %	440	701	623	89 %	Bond[2]
UF 5-2-1/2-270	Cut End	144	72.2	34.0	47.1 %	440	701	799	114 %	Flexure
	Free End	84	72.2	34.0	47.1 %	440	701	349	50 %	Shear[3]
UF 6-1-1/2-270	Cut End	144	72.3	38.0	52.6 %	445	709	703	99 %	Flexure/Slip
	Free End	144	72.3	38.0	52.6 %	445	709	646	91 %	Bond[4]
UF 6-2-1/2-270	Cut End	144	72.4	38.0	52.6 %	445	709	860	121 %	Flexure/Slip
	Free End	144	72.4	38.0	52.6 %	445	709	620	87 %	Bond[5]
UF 7-1-1/2-270	Cut End	144	72.0	50.0	69.4 %	449	701	780	111 %	Flexure

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[2] Flexural concrete compression failure was observed at 98%.

[3] Failure was sudden. A large crack formed from the support to the point load.

[4] Loaded with one-point load.

[5] Loaded with one-point load.

Specimen ID	End	Span (in.)	Development Length (in.)			Cracking Moment (kip-in)	Nominal Capacity (kip-in)	Maximum Moment (kip-in)	Flexural Capacity Ratio	Failure Mode
			ACI	Embedment	% ACI					
	Free End	144	72.0	40.0	55.6 %	449	701	832	119 %	Flexure
UF 7-2-1/2-270	Cut End	144	72.0	38.0	52.8 %	449	701	725	103 %	Bond
	Free End	144	72.0	39.0	54.2 %	449	701	606	86 %	Bond[6]

Table 3.c Summary Flexural Test and Development Length Data (Phase III)

Specimen ID	End	Span (in.)	Development Length (in.)			Cracking Moment (kip-in)	Nominal Capacity (kip-in)	Maximum Moment (kip-in)	Flexural Capacity Ratio	Failure Mode
			ACI	Embedment	% ACI					
UF 8-1-3/8i-270	Free End	106	56.5	45.0	79.6 %	196	295	326	111 %	Flexure
	Cut End	106	56.5	45.0	79.6 %	196	295	164	56 %	Shear
UF 8-2-1/2-270	Free End	106	56.5	45.0	79.6 %	196	295	332	113 %	Flexure
	Cut End	106	56.5	45.0	79.6 %	196	295	267	90 %	Flexure
UF 9-1-3/8i-270	Free End	104	55.5	44.0	79.3 %	198	295	328	111 %	Flexure
	Cut End	104	55.5	44.0	79.3 %	198	295	330	112 %	Shear
UF 9-2-3/8-270	Free End	104	55.5	44.0	79.3 %	198	295	276	94 %	Flexure
	Cut End	104	55.5	44.0	79.3 %	198	295	266	90 %	Flexure
UF 10-1-3/8i-270	Free End	88	55.3	36.0	65.1 %	198	295	275	93 %	Flexure
	Cut End	104	55.3	44.0	79.6 %	198	295	326	111 %	Flexure
UF 10-2-3/8-270	Free End	96	55.3	40.0	72.3 %	198	295	266	90 %	Flexure
	Cut End	104	55.3	44.0	79.6 %	198	295	254	86 %	Shear

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[6] Loaded with one-point load.

Specimen ID	End	Span (in.)	Development Length (in.)			Cracking Moment (kip-in)	Nominal Capacity (kip-in)	Maximum Moment (kip-in)	Flexural Capacity Ratio	Failure Mode
			ACI	Embedment	% ACI					
UF 11-1-1/2s-270	Free End	134	73.9	59.0	79.8 %	521	788	797	101 %	Flexure
	Cut End	126	73.9	55.0	74.3 %	521	788	499	63 %	See Note[7]
UF 11-2-1/2s-270	Free End	134	73.9	59.0	79.8 %	521	788	777	99 %	Flexure
	Cut End	134	73.9	59.0	79.8 %	521	788	764	97 %	Flexure
UF 12-1-3/8i-270	Free End	102	53.7	43.0	80.0 %	246	344	435	126 %	Flexure
	Cut End	102	53.7	43.0	80.0 %	246	344	409	119 %	Flexure
UF 12-2-3/8-270	Free End	102	53.7	43.0	80.0 %	246	344	444	129 %	Flexure
	Cut End	102	53.7	43.0	80.0 %	246	344	409	119 %	Flexure
UF 13-1-6/10-270	Free End	134	90.1	71.0	78.8 %	830	1287	1204	94 %	Flexure
	Cut End	134	90.1	71.0	78.8 %	830	1287	1231	96 %	Flexure
UF 13-2-6/10-270	Free End	134	90.1	71.0	78.8 %	830	1287	1176	91 %	Flexure
	Cut End	134	90.1	71.0	78.8 %	830	1287	1242	97 %	Flexure
UF 14-1-7/10-270	Free End	140	106.9	74.0	69.2 %	1309	2077	2169	104 %	Flexure
	Cut End	112	106.9	48.0	44.9 %	1309	2077	1663	80 %	Shear/Bond
UF 14-2-7/10-270	Free End	140	106.9	84.0	78.6 %	1309	2077	2125	102 %	Flexure
	Cut	156	106.9	80.0	74.8 %	1309	2077	1867	90 %	Flexure

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[7] Shear cracks appeared in the shear span being tested. No slip was recorded. Load-deflection chart demonstrated a marked loss of stiffness and ductile behavior. The Deflection-Span ratio was 1%, the test was stopped.

Table 3.d Summary Flexural Test and Development Length Data (Phase IV)

Specimen ID	End	Span (in.)	Development Length (in.)			Cracking Moment (kip-in)	Nominal Capacity (kip-in)	Maximum Moment (kip-in)	Flexural Capacity Ratio	Failure Mode
			ACI	Embedment	% ACI					
UF 15-1-3/8-270	Cut End	102	53.8	43.0	80.0 %	250	370	357	97 %	Flexure
	Free End	102	53.8	43.0	80.0 %	250	370	377	102 %	Flexure
UF 15-2-3/8-270	Cut End	88	53.8	36.0	66.7 %	252	373	352	94 %	Flexure
	Free End	80	53.8	32.0	59.3 %	252	373	356	95 %	Flexure
UF 16-1-1/2-300	Cut End	140	82.2	62.0	75.4 %	519	788	696	88 %	Bond[8]
	Free End	126	82.2	56.0	68.1 %	519	788	698	89 %	Bond
UF 16-2-1/2-300	Cut End	146	82.2	65.0	79.1 %	519	786	686	87 %	Flexure
	Free End	148	82.2	66.0	80.3 %	519	786	776	99 %	Flexure
UF 17-1-3/8-300	Cut End	112	59.4	48.0	80.8 %	259	392	392	100 %	Flexure
	Free End	110	59.4	47.0	79.1 %	259	392	388	99 %	Flexure
UF 17-2-3/8-300	Cut End	104	59.4	44.0	74.1 %	259	392	418	107 %	Flexure
	Free End	96	59.4	40.0	67.3 %	259	392	392	100 %	Flex/Slip
UF 18-1-1/2s-290	Cut End	148	83.0	66.0	79.5 %	540	811	741	91 %	Bond
	Free End	152	83.0	68.0	81.9 %	540	811	758	93 %	Flexure
UF 18-2-1/2s-290	Cut End	148	83.0	66.0	79.5 %	540	811	797	98 %	Flexure
	Free End	140	83.0	62.0	74.7 %	540	811	720	89 %	Flexure

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[8] Flexural concrete compression failure observed after test was completed.

DISCUSSION OF EXPERIMENTAL TEST RESULTS

TRANSFER LENGTH ESTIMATE METHODOLOGY

On average, the transfer lengths estimated following the procedure endorsed by the FHWA were 6.8% longer than those determined with the slope –intercept method, with intercepts at 95% the maximum average strain. The mean of these transfer lengths was also longer, by 1.4%, than those estimated by the Slope-Intercept Method with intercept at 100% of the average maximum strain. The transfer lengths estimated with the Slope-Intercept Method, with intercept at 100% of the maximum average strain, were 5.3% longer than those estimated with the intercept at 95% of the average maximum strain.

The coefficients of variation for the transfer lengths estimated following the Slope-Intercept Methods were 21.6% and 21.5% for intercepts at 95% and 100% of the average maximum strain, respectively. The coefficient of variation for the transfer lengths estimated following the 95% Average Maximum Strain Method was 22%. Figure 4 presents a graph of the transfer lengths estimated using the three different methods described before.

The Slope-Intercept Method with intercept at 95% of the average maximum strain and the 95% Average Maximum Strain Method yielded the upper and lower-bound mean transfer length values. Best-fit lines, or trendlines, for the transfer lengths estimated with these two methods are included on Figure 4. The slope of these lines, which were not forced through the origin, differs by less than half-percent, 0.5%. Hence, these lines are essentially parallel with the intercept of the lines shifted by 1.8 strand diameters, or about 3.6%. Had the intercept of these lines been forced through the origin, the slope of these lines would have differed by less than 7%.

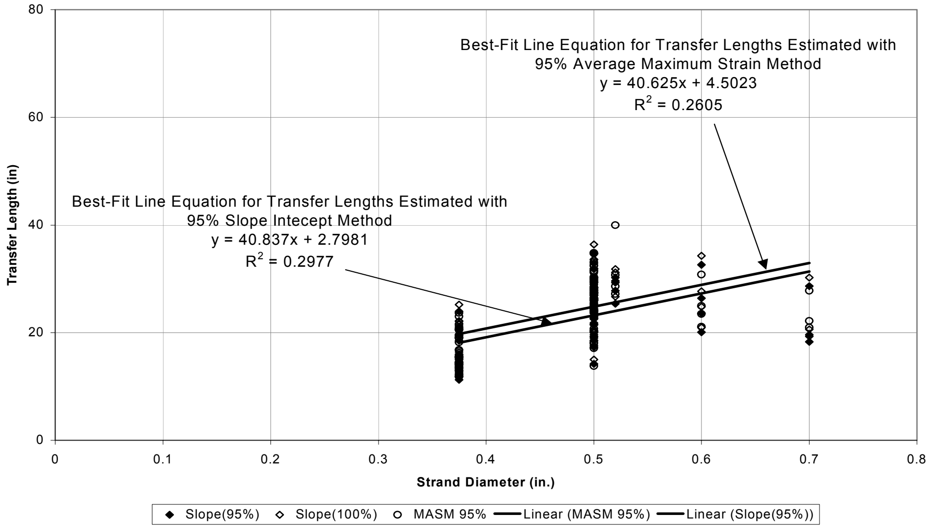

Figure 4 Comparison of Method Used for Determining the Transfer Length

The variation in the transfer lengths, as estimated by each of these methods, is more than three times the maximum difference of the mean transfer lengths when estimated following the different procedures. This large scatter in the data relative to the small difference in the transfer lengths determined by the different methods indicates that concerns over which method is used when determining the transfer length are not warranted.

EFFECT OF CONCRETE STRENGTH

The predictor equations presented by AASHTO and ACI for transfer length does not consider the effect of the concrete strength at transfer[1,2]. Research programs conducted by Sozen and Stoker and, most recently, by Mitchell et al. have found that the concrete strength does affect the strand bond behavior.

Figure 5 shows a graph of the transfer length, normalized with respect to the strand diameter, versus the concrete strength at transfer. From visual inspection, the transfer length appears to be independent of the strength of the concrete at time the prestressing force is transferred from the strand to the concrete section. A linear regression analysis of the data indicated that this is not so. The regression analysis yielded a negative sloped line. The negative slope obtained from this analysis indicates that the transfer length is reduced as the concrete strength at transfer increases.

The transfer of the prestressing force at the University of Florida occurred at concrete strengths in the 3500 psi to 4300 psi range. For this range of concrete strengths, the transfer length measured at the University of Florida decreased approximately 4.2% per 1000-psi increase in concrete strength at transfer.

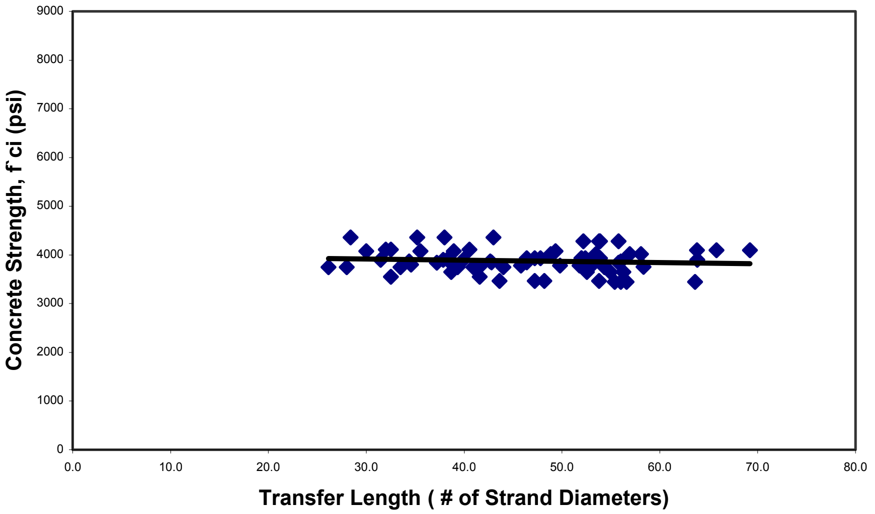

Figure 5 Effect of Concrete Strength on Transfer Length (University of Florida Data)

Two regression analyzes, similar to the analysis performed on the transfer lengths measured at the University of Florida, were performed. One of these analyses was performed on the entire population included on the transfer length database. The second regression analysis was done on a population that excluded the data reported by Cousins et al.[8,11,21] Both regression analyses yielded results similar to those observed at the University of Florida. In both instances, a reduction of 5.1% in the transfer length could be expected for a 1000-psi increase in concrete strength at transfer. The coefficient of determination, R, improved when the transfer lengths reported by Cousins et al. were excluded.

EFFECT OF INITIAL PRESTRESS

The current code philosophy, with respect to the effect the stress in the strand has on transfer length, assumes the transfer length to be linearly proportional to the effective stress in the strand. Recently, several researchers have proposed the transfer length to be proportional to the initial stress in the strand, f_{pi}.

Attempting to correlate the transfer length to the initial stress in the strand seems reasonable for two reasons. First, the initial stress in the strand is always higher than the effective prestress, ensuring that the correlation obtained is for the worst-case scenario. Second, most of the reported transfer lengths were measured soon after transfer of the prestressing force took place, as is the case of the project conducted at the University of Florida. The stress in the strand at this point is the initial prestress minus the elastic shortening loss, since losses due to creep, shrinkage and strand relaxation have not taken place, yet. The initial prestress – transfer lengths pairs, measured at the University of Florida, are plotted on Figure 6.

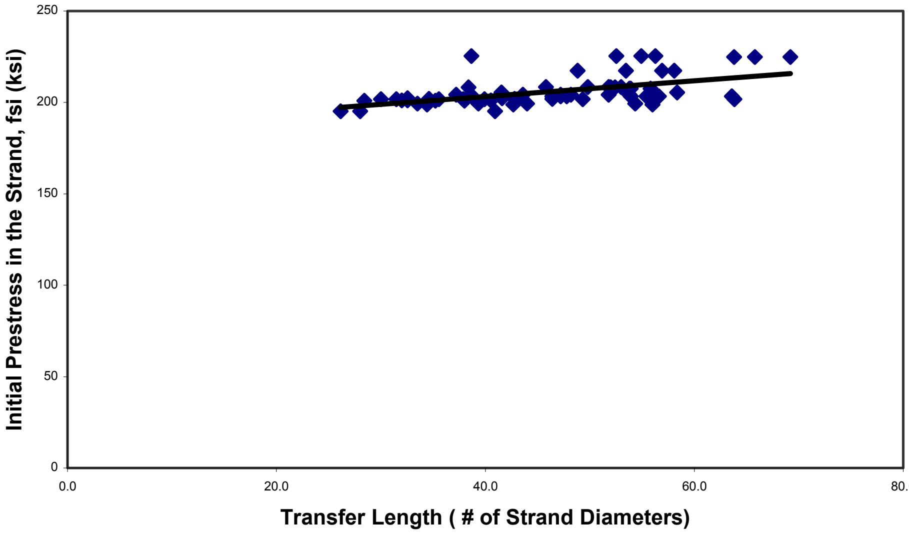

Figure 6 Effect of Initial Prestress on Transfer Length (University of Florida Data)

A regression analysis demonstrated an increase in initial stress in the strand, f_{pi}, was corresponded by an increase in transfer length. Transfer lengths increased 1.6% per one ksi increase in stress in the strand, when evaluated in a range of initial prestress of 190 ksi to 220 ksi.

Similarly, the initial prestress transfer length pairs reported in the literature, and included in the database were plotted. A linear regression analysis was performed on the data. The best-fit line obtained from this analysis had a negative slope, indicating a reduction in transfer length corresponding to an increase in the initial stress in the strand. This behavior is contrary to what theoretical developments indicate.

Figure 7 presents a plot of the transfer length – initial prestress pairs reported by the University of Texas, the University of Tennessee, McGill University, Hanson and the University of Florida. A linear regression analysis yielded a positively sloped line, indicating an increase in transfer length following an increase in the initial prestress. The increase in transfer length was in the order of a quarter of a percent (0.25%) per ksi increase in stress in the strand.

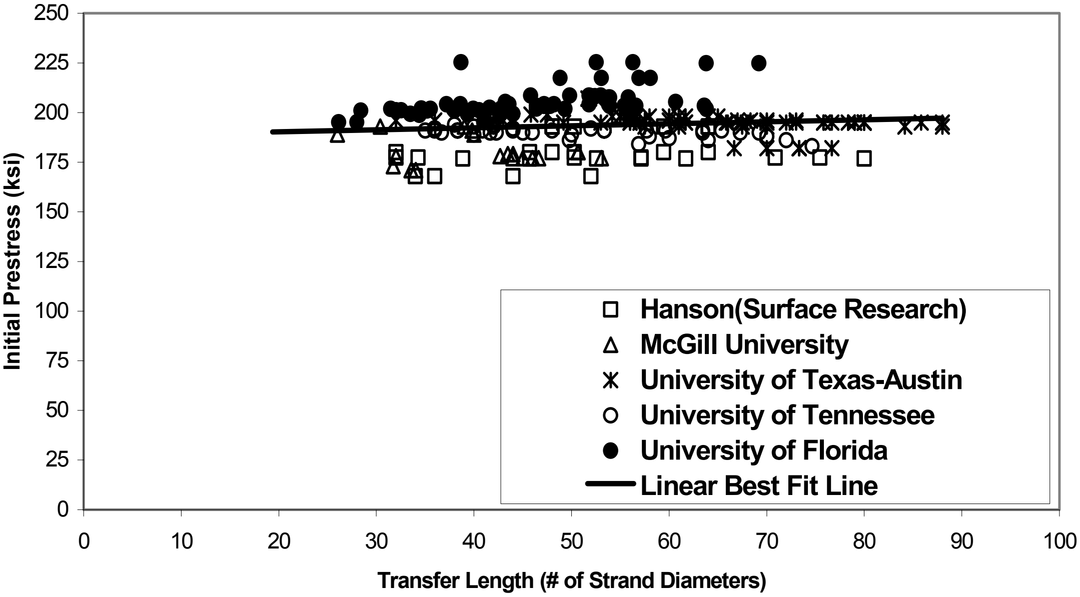

Figure 7 Effect of Initial Prestress on Transfer Length

Figure 6 shows a clear trend where an increase in the initial stress is corresponded by an increase in transfer length. This trend is not clear in Figure 7. Furthermore, had all the data in the database had been included this trend would have been reversed. Such divergence could be attributed to the fact that the research at the University of Florida systematically investigated the effect of initial prestress. Meanwhile, for most research programs, by setting a constant target initial prestress level and using a single grade of strand, the range for the initial prestress for any particular research program is relatively narrow and statistically insignificant. By using three different grades of strands, the researchers at the University of Florida were able to obtain three distinct initial prestress levels, 202 ksi, 218 ksi and 225 ksi. This was done, while variables such as concrete strength, section size and shape, specimen age and other variables identified as affecting transfer length and bond performance were kept constant. By doing so, the effect of the initial prestress on the transfer length was isolated.

EFFECT OF STRAND DIAMETER

Current code philosophy on bond and transfer length of prestressing strands assumes a linearly proportional relation with the strand diameter. Transfer lengths measured on large diameter strands at the University of Florida did not conformed to this philosophy. As other researchers found before, the author found the smaller diameter strands to follow this linear-proportionality philosophy. Transfer lengths for strand diameters up to the 1/2" special strand, with a nominal strand diameter of 0.52", appeared to be proportional to the strand diameter. The transfer lengths for 6/10" and 7/10" diameter strand did not followed this trend, as depicted on Figure 8.

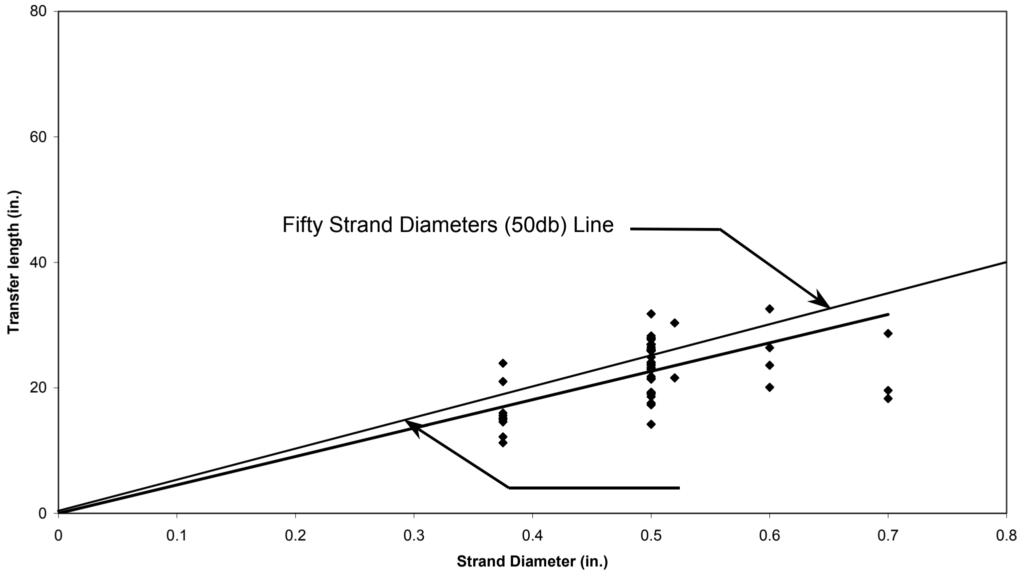

Figure 8 Transfer Length versus Strand Diameter Chart

The measured transfer lengths for the 6/10" and 7/10" strands averaged 25.7 inches and 22.2 inches, respectively. These transfer lengths are comparable to those measured on 1/2" Grade 270 strands during Phase I and Phase II of this research project (Lt = 24.0"). Transfer lengths measured on indented wire strand and higher grade, i.e. Grade 290 and Grade 300, strands were not included, so the only variable affecting the transfer lengths is the strand diameter. We should recall that the initial stress in the strand and concrete strength at transfer were kept relatively constant. The initial prestress is approximately 75% of the strand guaranteed strength and the concrete strength is in the 3700 psi to 4300 psi range.

A review of the literature revealed that Kaar, LaFraugh and Mass observed a similar behavior. They disregarded this observation because the 6/10" strand they tested was slightly rusted. Yet, the rust in the strands by self, cannot explain the difference in bond and transfer length behavior. Figure 9 presents a transfer length versus strand diameter chart reported by Kaar, LaFraugh and Mass.

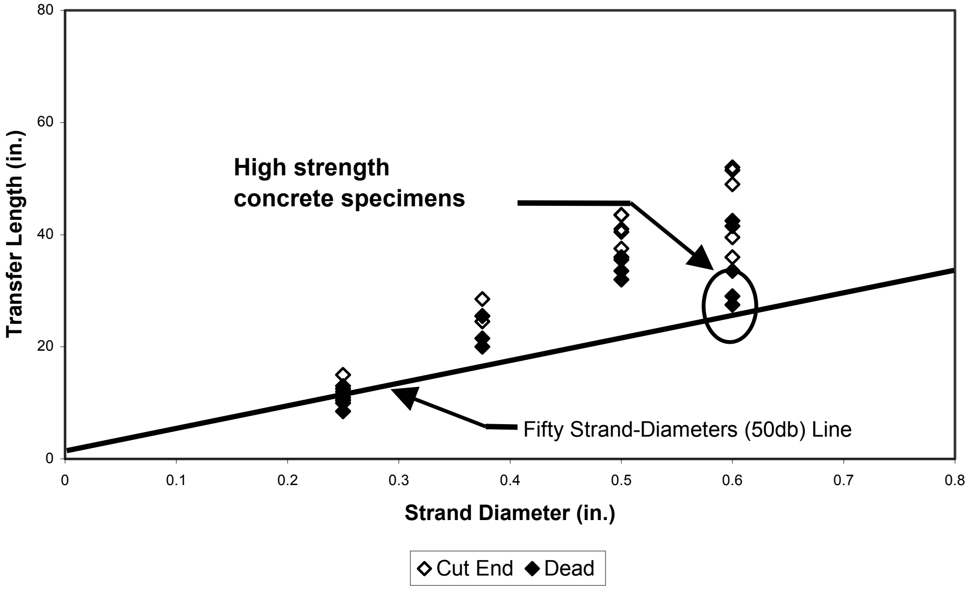

Figure 9 Transfer Length versus Strand Diameter Chart (Kaar, LaFraugh and Mass)

Transfer lengths measured on the cut ends of specimens with low concrete strength at transfer followed the linear proportionality trend of the smaller diameter strands for all strand diameters. Yet, on the free ends of these specimens, an improved transfer length performance was observed. It appears that due to the impact at transfer and the low concrete strength the mechanical interlocking was destroyed, reducing the transfer mechanism to mostly frictional.

A marked improvement in transfer length performance was observed for transfer lengths measured on specimens with high concrete compressive strengths at transfer. This improvement in transfer length performance points toward an enhanced mechanical bonding capability that is independent of the strand surface condition but dependent on the diameter of the strand and the concrete strength at transfer.

The disproportionate distribution in the population of transfer lengths forces any regression type analysis to describe the behavior of the smaller diameter strands. Since, currently the industry standard is 1/2" Grade 270 strand, nearly half the entries on the database correspond to this size of strands. Yet, a clear trend can be observed for the larger diameter strands. All the transfer lengths reported for strands with strand diameter in excess of 6/10” fall below the regression analysis line and the ACI $50d_b$ line. Further research is desirable to increase the population of transfer lengths measured on large diameter of strands, before the development of empirical equations is attempted. Figure 10 depicts a transfer length versus strand diameter graph for all the entries on the database compiled from published literature.

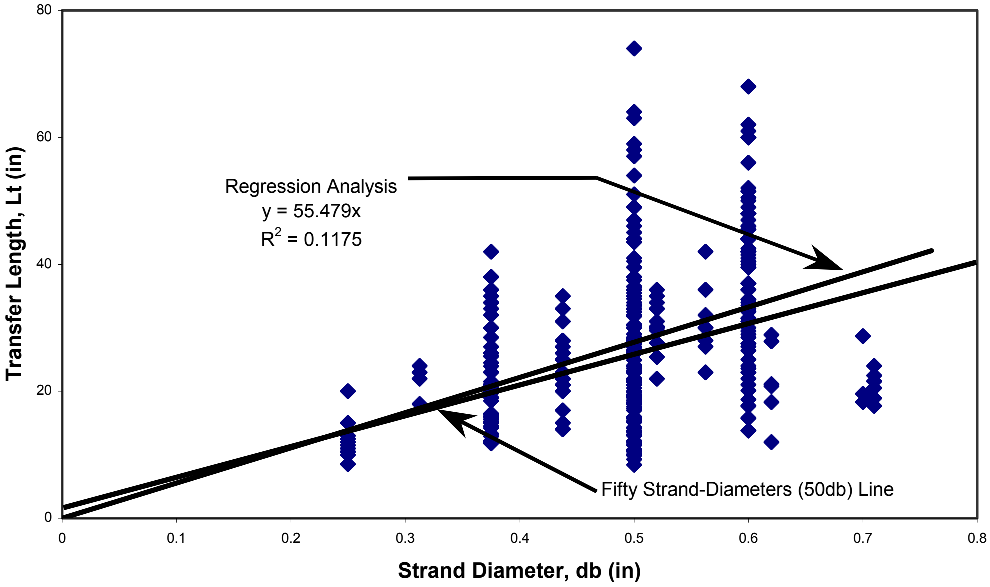

Figure 10 Transfer Length versus Strand Diameter Chart (All entries on the Database)

END-SLIP

The end-slip, or draw-in, is the distance the strand slips into the concrete section when the prestressing force is transferred. The draw-in occurs under the same bond conditions as the prestressing force is transferred, that is, the same initial prestress in the strand, strand surface condition and concrete strength at transfer, among other variables identified as affecting bond. As such, the measurement of end-slip has been proposed as an *in-situ* bond indicator.

Several equations have been derived to correlate the transfer length to the end-slip, known as slip-theory. Currently two slip-theory based transfer length expressions are generally accepted. In the United States, the generally accepted expression assumes a linear profile, Equation 5. One proposed by the International Federation of Concrete[22] assumes a parabolic strain profile, Equation 6.

$$L_t = \lambda * L_{es}/\varepsilon_{pi} \qquad (4)$$

$$L_t = 2 * L_{es}/\varepsilon_{pi} \qquad (5)$$

$$L_t = 3 * L_{es}/\varepsilon_{pi} \qquad (6)$$

Polish researchers found λ to be 2.86. De Uijl[23,24], through simulations, found that the value of λ to lie between 2.4 and 2.7 with an average of 2.56.

The research project at the University of Florida measured end-slips. These end-slip measurements helped verify the transfer lengths measured by means of surface strain measurements. Measurements on the cut ends were often lost due to the impact received by the instrumentation at transfer. Most of the research projects included in the database did not measured end-slip at transfer. A graph of the transfer length - end slip pair measured at the University of Florida is presented on Figure 11.

Equations 5 and 6 have been consistently proven by research work done in various laboratories. Equation 5 coincides with the average of the available data, while Equation 6 envelops 90% of the data points. Eighty-percent (80%) of the pairs measured at the University of Florida are enveloped by Equation 4 with a coefficient λ equal to 2.6. Yet, if the end slips measured on the higher strength strands are excluded then Equation 6 and Equation 4 envelops 95% and 90% of the data points, respectively. This does not means that Equation 4, Equation 5 and Equation 6 do not apply to the higher grade strands. It denotes that the lines drawn on Figure 11 were computed for an initial prestress, f_{si}, of 202.5 ksi.

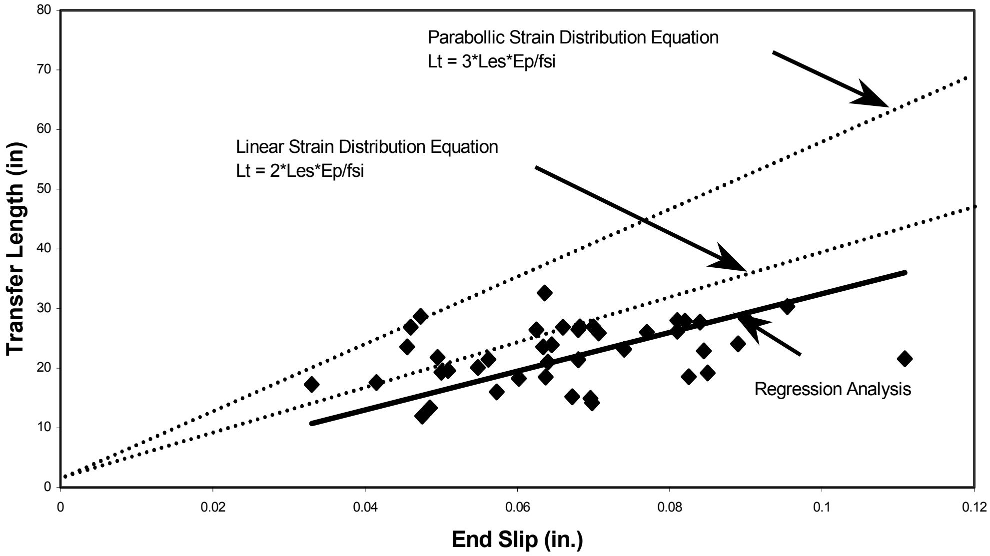

Figure 11 End Slip versus Transfer Length Chart (University of Florida Data)

CONCLUSIONS AND DESIGN RECOMMENDATIONS

For an extensive literature review and analytical and experimental studies presented in this paper, the following conclusions can be drawn.

1. Transfer lengths on specimens reinforced with small diameter strands, i.e. diameter smaller than 6/10", are proportional to the strand diameter. Transfer lengths on specimens with large diameter strands, that is $d_b \geq 6/10"$, are not proportional to the strand diameter.
2. The transfer length provisions presented in the Commentary to ACI 318 adequately predict the mean transfer length for small diameter strands. For large diameter strands, the Commentary on ACI transfer length provisions overestimated the transfer lengths.

The ACI 318 Section 11.4.3, $L_t = 50d_b$, also provided a good estimate of the mean transfer length. Inclusion of 95% of the data required 75 to 80 strand diameters.

3. Transfer lengths were found to be inversely proportional to the compressive strength of the concrete at transfer, f'_{ci}, and directly proportional to the initial prestress, f_{pi}. That is, the transfer lengths decreased as the concrete strength at transfer increased and increased as the initial presstress in the strand increased.
4. A good correlation was found between the transfer lengths estimated from end-slip measurements and the transfer lengths estimated from measured deformations. A best-fit analysis of the data coincided with the transfer lengths estimated assuming linear strain profile. The transfer length estimated, from end-slip measurements, assuming a parabolic strain profile enveloped most of the data, about 90%.
5. A fifty percent (50%) improvement in the transfer lengths estimated from measured deformations was observed on the 3/8" Grade 270 indented wire strand compared to the 3/8" Grade 270 smooth wire strand. The improved bond performance of the indented wire was corroborated by the measured end-slips. Simple pull-out tests, Moustafa type test, could not reproduce the improved bond performance of the indented wire strand.
6. All the specimens loaded at embedment lengths in excess of 80% of the ACI 318 development length estimate, where adequate shear reinforcement was provided, were able to achieve ductile, flexure type, failures.
7. As presented in the literature, the formation of cracks crossing the level of the strand within the transfer region led to bond failures. In addition, the results seen on series UF17, 1/2" Special Grade 290 strand, where bond and flexural type failures were observed at identical embedment lengths on ends with different transfer lengths, indicated that the development length appears to be proportional to the transfer length. Yet, it is not possible to reach a conclusion, with some degree of certainty, because the data available is insufficient.
8. A transfer length predictor equation was successfully developed. The predictor equation is based on the thick-walled hollow cylinder solution presented by Timoshenko. Frictional and mechanical interlocking bond mechanisms are present in the transfer bond mechanism of large diameter strands, while the transfer bond mechanism for small diameter strand is, predominantly, frictional.
9. As developed by Alcaraz, Fagundo and Cook[5], the transfer length can be reasonably computed using the following simplified equation

$$L_t = \alpha_{rm}\alpha_1\alpha_2\alpha_3\alpha_4\, f_{si}\frac{A_p}{\Sigma_o}\left[\frac{1}{\dfrac{\varphi\, \upsilon_s f_{si}}{1+(1+\upsilon_c)n}+f_{mi}}\right]$$

where f_{si} is the initial prestress in the strand

A_p is the strand nominal area

Σ_o is the perimeter of the strand, $1.33\,\pi\, d_b$

n is the modular ratio, Eps/Ec

φ is the friction coefficient of the steel, 0.3.

ν_s and ν_c are the Poisson ratios for the steel and concrete, respectively.

f_{mi} is the mechanical interlocking bond strength, zero for $d_b < 6/10"$ and $2\sqrt{f'_{ci}}$ for $d_b \geq 6/10"$.

α_{rm} is the release method correction factor, 1.0 for gradual release and 1.3 for flame-cut, or sudden release.

α_1 is the strand surface condition correction factor, 1.0, 0.8 and 0.7, for shiny, rusted and deformed strands, respectively

α_2 is the initial prestress correction factor, $\left[\dfrac{f_{pi}}{202.5\ \text{ksi}}\right]^{\frac{4}{3}}$

α_3 is the concrete strength correction factor, $\sqrt[3]{\dfrac{4000\ \text{psi}}{f'_{ci}}}$

α_4 is a constant that assume a value of 2 for stress verification and 3.3 for shear and moment strength verification.

The adequacy of the equation is limited to elements where sufficient concrete cover and confinement steel is provided to preclude the formation of splitting cracks, that is concrete cover greater than four strand diameters, concrete compressive strengths in a 3500 psi to 8000 psi range and initial prestress in a 190 ksi to 225 ksi range. The equation is valid for strand diameters ranging from 3/8" to 7/10".

ACKNOWLEDGEMENTS

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