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Correct Prediction of Transfer Lengths in Pretensioned Prestressed Concrete Structures

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ABSTRACT

The current ACI design code considers only the prestress intensity and the diameter of prestressing steels to calculate the transfer length of steels. Other important parameters, however, including concrete strength and concrete cover may affect the transfer length significantly. To this end, a comprehensive experimental program has been set up. The principal test variables considered were strand diameter, concrete strength, concrete cover size and strand spacing. The results of present study indicate that the current code equation for transfer length overestimates the actual measured transfer length. This overestimation is particularly significant for high strength concrete with larger concrete cover, which are not covered by the ACI code. The present study shows that the transfer length decreases with an increase of concrete strength and also decreases with an increase of concrete cover. These important parameters must be, therefore, included reasonably in the current design codes. The strand spacing also affects the transfer length and the increase of strand spacing results in a decrease of transfer length. The present study also shows that the end slip values can be efficiently used to determine the transfer length of pretensioned concrete members. The theoretical determination of transfer length based on slip agrees very well with test data. The present study provides valuable test data for the realistic and accurate determination of transfer length, which can be efficiently used for improving the design equation of transfer length in pretensioned prestressed concrete members.

INTRODUCTION

In recent years, the importance of transmission of prestress within concrete has been re-emphasized and current practices have been questioned.[1-5] In pretensioned beams, transfer length is the distance required to transfer the fully effective prestressing force from the strand to the concrete. Stated another way, transfer length is the length of bond from the free end of the strand to the point where the prestressing force is fully effective. Stresses in the pretensioned steel vary from zero at the free end of the strand to the fully effective value at a certain point within the member. At the point of full transfer, the stress in the steel remains constant over the length. The bond between a steel tendon and concrete depends on stress states around the interface region, which are governed by material and geometric properties surrounding the tendon. The general research trend in pretensioned prestressed concrete members has been to establish transfer lengths based on relationships between steel geometric properties and concrete material properties. Those studies have been confined to the qualitative assessment rather than quantitative assessment.

There appears to be general agreement that strand diameter, level of prestress, shape of tendon, concrete strength, concrete cover around steel and time dependent effects (creep and shrinkage) affect the bond and transfer length [1-14]. However, it is not clear how these parameters affect the transfer length and consensus has not been reached yet as to the most significant parameters on the transfer length. The current ACI code provides the design equation for transfer length only in terms of prestress intensity and strand diameter, and other important parameters are neglected [15]. The purpose of the present study is, therefore, to explore the bond behavior and to determine realistically the transfer lengths of prestressing steel in pretensioned prestressed concrete members. To this end, a comprehensive experimental program has been set up and several important test variables have been studied, including the diameter of steel, concrete strength, concrete cover and spacing of prestressing steel.

EXPERIMENTS ON PRETENSIONED PRESTRESSED CONCRETE MEMBERS

Test Variables

An experimental program was undertaken to investigate the transfer length of seven-wire prestressing strands in pretensioned concrete members. The scope of the experimental program includes fabrication and testing of thirty-six pretensioned prestressed concrete beams. The major test variables include the number and nominal diameter of prestressing strands, concrete compressive strength, bottom cover, and spacing of prestressing strands. The main variables can be summarized as follows.

(1) Number of prestressing strands; Single (Mono), Double (Twin) strands
(2) Nominal diameter of prestressing strand; 12.7mm, 15.2mm
(3) Concrete compressive strength at transfer; 35MPa, 45MPa

(4) Clear bottom cover; 3cm, 4cm, 5cm

(5) Center to center spacing of prestressing strands; $3d_b$, $4d_b$, $5d_b$

Test Beam Description

To simulate the actual pretensioned beam produced by the industry, strands were located below the centroid of the cross section. All the specimens have the same total depth of 200mm and overall length of 3000mm. The beam lengths were designed to fully encompass the transfer zones at both ends. The beams for transfer length test consist of 24-series as follows. Thirty-six beams were made for transfer length tests.

1) Mono strand series (2 beams/series):
    2 strand size × 2 concrete strength × 3 bottom cover (=12 series)
2) Twin strand series (1 beams/series):
    2 strand size × 2 concrete strength × 3 strand spacing (=12 series)

Fig. 1 and 2 shows the details and dimensions of each beam in the testing program. Each beam is identified by a numbering system containing a code to help identify the characteristics of that beam. The beam numbering system is explained in Fig. 3.

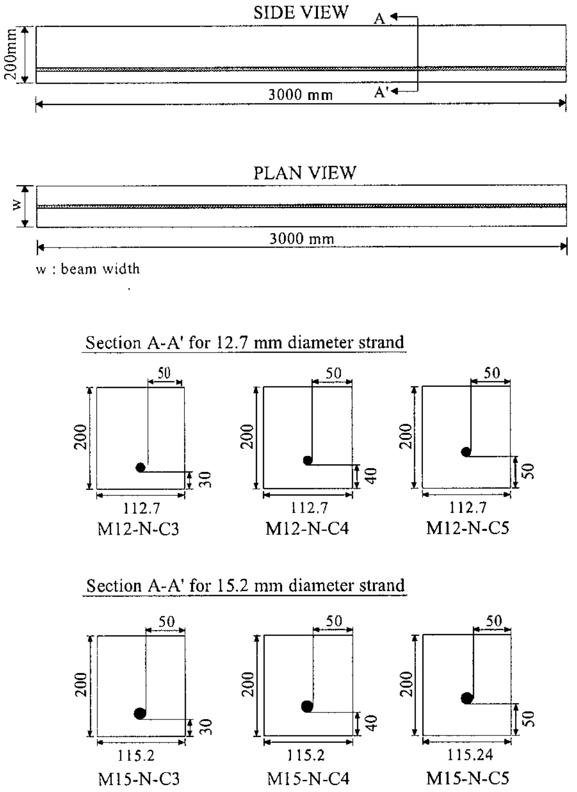

Fig. 1 Details of mono strand test beams

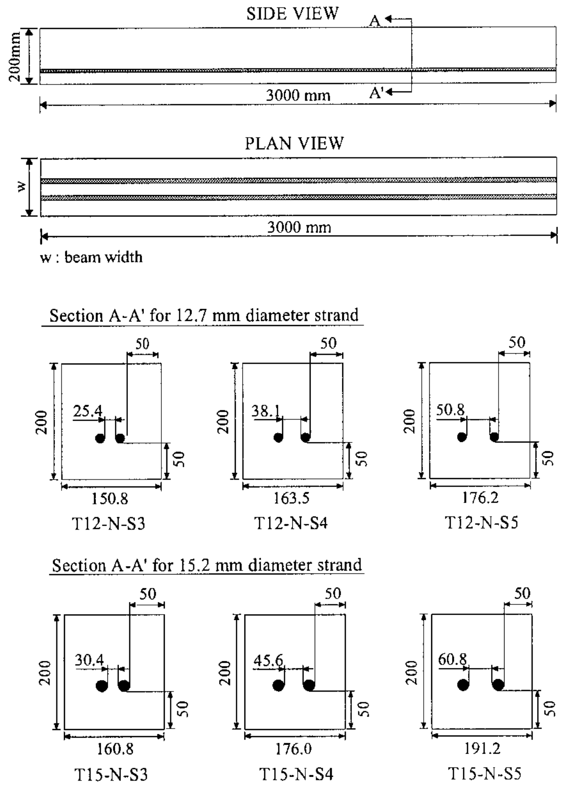

Fig. 2 Details of twin strand test beams

Material Properties

Two different concrete mixes were designed to study the effects of compressive strength on the bond behavior of pretensioned beam. The target compressive strengths at transfer were 35MPa for N-series and 45MPa for H-series, respectively. Twelve 10cm × 20cm cylinders were cast and cured along with the beams under similar environmental conditions to monitor concrete strength. The cylinders were tested to obtain compressive strengths at prestress transfer and at 28 days. All prestressing steels used for this study were uncoated, low-relaxation, stress-relieved, seven-wire strands, which are becoming the industry standard. Two different sizes, 12.7mm and 15.2mm nominal diameter, were used. The strand was not treated in any special manner such as wiping or cleaning with acid before casting. Care was taken not to drag the strand on the floor. The strands were free of rust at time of casting and the surface condition of all strand used was that of bright mill condition.

Instrumentation and Measurements

Transfer length can be determined by measuring strains in the concrete and strand along the length of the specimen. In view of the importance of the interface of strand, a method that does not interfere with the bonding is preferred. Hence, the measurement of concrete strains was chosen in the present study. Since in all cases the clear side cover to the tendon was small (50mm), strain measurements on the surface at the tendon level are appropriate. To verify the applicability of the concrete strain measurements it was considered desirable to attach a few strain gauges to the steel to determine the strains of prestressing steel [Fig. 4].

Concrete strains were measured with detachable mechanical strain gages (Demec gages). The Demec gages are used in conjunction with Demec points. The Demec points, or targets, are stainless steel discs (ϕ =6.3mm), each with a small hole (ϕ =1.0mm) in the center designed to fit the Demec strain gage as shown in Fig. 6. The change in length is measured between the holes in the center of the targets. The accuracy of the Demec gage readings proved to be satisfactory. Two sets of readings were taken for concrete strains by two different individuals both before and after transfer. All individual readings, which did not agree with each other, were retaken to maintain a high degree of accuracy.

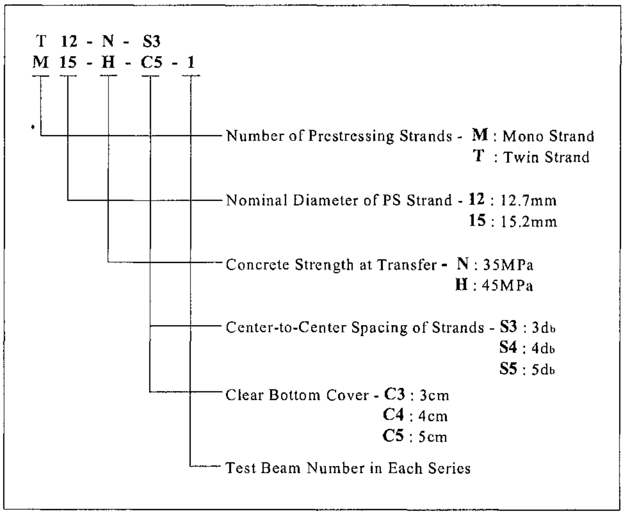

Fig. 3 Key to beam numbering system

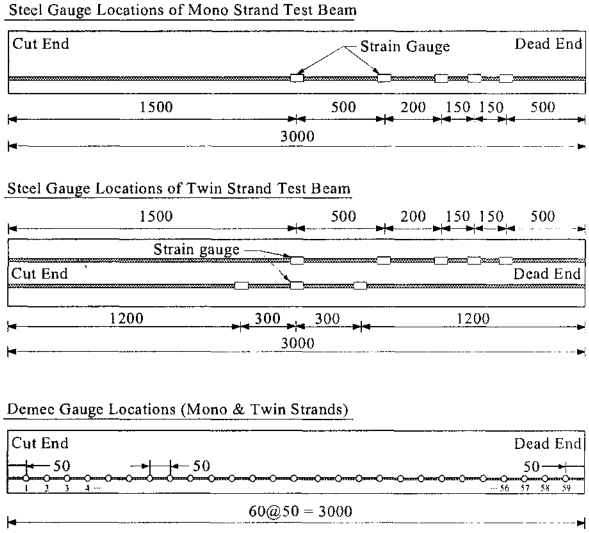

Fig. 4 Locations of ERSG and Demec gage points

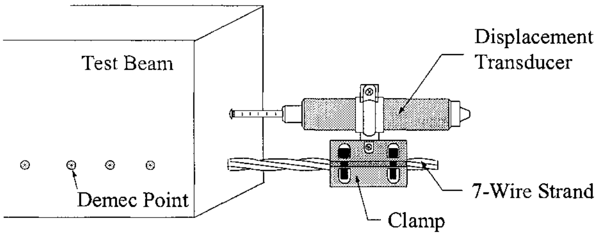

Fig. 5 Instrumentation scheme for slip measurements

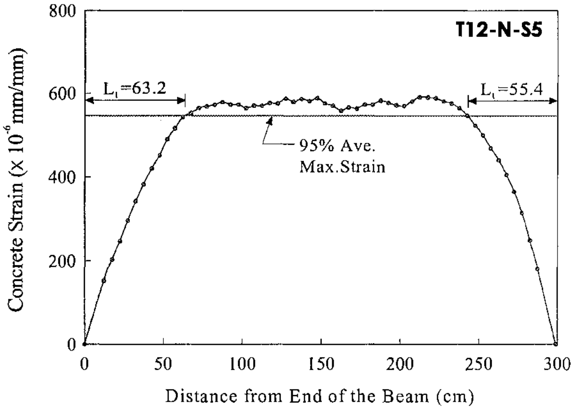

Fig. 6 Determination of transfer length

Demec gauge points were attached using rapid adhesive glue along the length of the beam on both sides at the same level as the strands. Gage length of the Demec gage was 150 mm and the gauge points were set at 50mm intervals. The locations of Demec gage points are shown in Fig. 4. Also shown in Fig. 4 are the locations of Electrical Resistance Strain

Gages (ERSG) mounted on the prestressing strands. Prior to prestress transfer, clamps were attached to the strand at the beam end to fix displacement transducers as shown in Fig. 5. A displacement transducer was clamped to the strand at the end of the specimen to measure the amount of slip upon release of the pretensioning force. In order to assure the correct measurement of slip, the end slips were also measured by placing a tape marker on the strand and measuring the distance the tape slipped toward the concrete upon release of the strand.

DETERMINATION OF TRANSFER LENGTH: 95% AVERAGE MAXIMUM STRAIN METHOD

Transfer lengths for each specimen were determined from the results of the measured strain profiles. The method employed here is called the "95% Average Maximum Strain Method". The procedure to determine the transfer length can be summarized as follows.

(1) Plot the "smoothed" strain profile diagram from the measured strain values.

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

(3) Take 95% of the "Average Maximum Strain" and construct a horizontal line corresponding to this value in the strain profile diagram (see Fig. 6).

(4) The transfer length is determined by the intersection of the 95% AMS line with the smoothed strain profile diagram. This procedure is illustrated in Fig. 6. This method yields realistic and reasonable values for the transfer length that eliminate arbitrary interpretation of test data, which is the major advantage of this method

ANALYSIS OF TEST RESULTS

The transfer length of prestressing strands may be influenced by many important variables including the strand diameter, concrete strength, strand spacing, and concrete cover, etc. Discussed below are the effects of each different variable on the strand transfer length.

Table 1. Transfer length according to strand size for various test

Test Series		Average Transfer Lengths (cm)		$l_{t(15.2)}/l_{t(12.7)}$
		d_b =12.5mm	d_b =15.2mm	
Mono Strand	N-Series*	65.1	82.2	1.26
	H-Series**	54.8	68.1	1.24
Twin Strand	N-Series	66.1	82.7	1.25
	H-Series	57.7	71.7	1.24
Average		60.6	75.8	1.25
Standard Deviation		10.5	14.6	

* N-series : f'_{ci} = 35MPa, ** H-series : f'_{ci} = 45MPa

Effect of Strand Diameter on the Transfer Length

The ratio of area to perimeter is approximately 18% greater for 15.2mm diameter strand than for 12.7mm strand. Therefore, it follows that 15.2mm strand should have a longer transfer length than the 12.7mm strand. Table 1 compares transfer lengths for the two different sizes of strands. Clearly, the measured transfer lengths for 15.2mm strand are longer than those for 12.7mm strand. The results in Table 1 reveal that the average transfer length of 15.2mm strand is 25% longer than that of 12.7mm strand. This is mainly due to the difference of the relative ratio of area to perimeter of the two strands. While the 15.2mm strand has 42% greater cross sectional area, and likewise a larger prestressing force, it has only about 20% more surface area to develop bond. The current code expressions for transfer length [Eq. (1)] suggest that the transfer length varies linearly with the strand diameter. The ratio of the strand diameters would induce 20% longer transfer length for 15.2mm strand (i.e., the ratio of d_b). However, the present study shows a little bit larger increase in transfer length according to strand diameter as shown in Table 1.

$$l_t = \frac{1}{3} f_{pe} d_b \tag{1}$$

Effect of Concrete Strength at Transfer on the Transfer Length

There have been different observations about the effect of concrete compressive strength on transfer length in the past. Considering these conflicting observations, the concrete strength has been selected as a prime variable in this study. Table 2 compares the transfer lengths for the two different concrete strengths at time of transfer. Also shown are the average transfer lengths predicted by the ACI code equations using the average f_{pe} values of corresponding series. Clearly, the measured transfer lengths for high concrete strength were shorter than the beams made with lower strength concrete. This shows clearly the beneficial effect of higher strength concrete in transferring the prestress force. Test results show the reduction of the average transfer lengths with increasing concrete strength at transfer. In these plots, the transfer length has been divided by f_{pe} in order to account for the different stress levels of prestressing strand. There is a clear trend of reduction in transfer length as concrete strength increases. However, the current code equations do not contain concrete strength as a main variable affecting transfer length and thus give constant value of transfer length irrespective of concrete strength.

Effect of Concrete Cover on the Transfer Length

Like the effects of tendon spacing, the influence of concrete cover has not been fully examined previously on the transfer length. Therefore, there is a need to incorporate concrete cover as a major variable in the transfer length tests. The influence of clear cover on transfer length was examined in mono strand series. The clear bottom cover was varied (c_b= 3cm, 4cm, 5cm) while maintaining clear side cover constant (c_b = 5cm). The influence of clear bottom cover can be seen in Table 3. There exists a clear trend that transfer lengths increase with a reduction of clear bottom cover. The results also show that the transfer lengths of the normal strength concrete beams with (c_b = 3cm) are no longer conservative compared to those predicted by the present code equations.

Table 2. Transfer length according to concrete strength

Test Series		Average Transfer Lengths (cm)		ACI Transfer Length
		f'_{ci} = 35MPa	f'_{ci} =45MPa	
d_b = 12.7mm	M-Series*	65.1	54.8	84.2
	T-Series**	66.1	57.7	81.4
d_b = 15.2mm	M-Series	82.2	68.1	92.4
	T-Series	82.7	71.7	97.1

* M-series: Mono strand, ** T-series: Twin strands

Table 3. Transfer length according to bottom clear cover

Test Series		Average Transfer Lengths (cm)			ACI Transfer Length
		c_b = 3cm	c_b = 4cm	c_b = 5cm	
d_b = 12.7mm	N-Series*	78.1	61.9	55.4	84.2
	H-Series**	59.1	52.3	48.6	
d_b = 15.2mm	N-Series	100.6	79.3	66.5	92.4
	H-Series	82.5	67.5	54.4	

* N-series: f'_{ci}= 35MPa, ** H-series: f'_{ci}= 45MPa

Influence of Time Dependent Effect on the Transfer Length

The transfer length measurements were made up to 7 days after prestress force release for all test beams. It can be seen from test results that the transfer length increases with the age after prestress transfer. The increase of transfer length is about 2 to 3 percent at the age of seven days after prestress release.

For several test beams, the measurements were made periodically up to 90 days after prestress release. As shown in Fig. 7, axial concrete strains increase with time due to creep and shrinkage. The time dependent effects shift the strain build-up profiles, but do not influence the transfer length very much. The variation of transfer length according to the ages up to 90 days is summarized in Table 8. The increase of transfer length at 90 days after prestress release is about 5 percent.

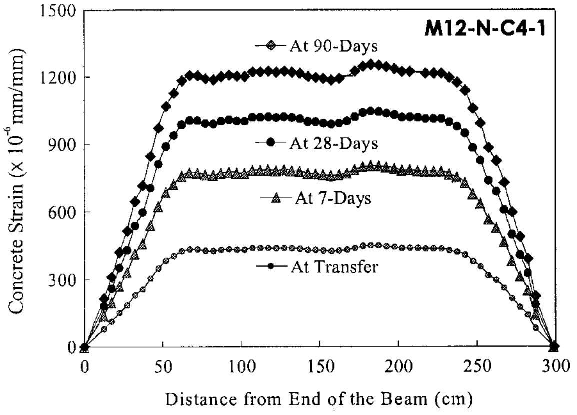

Fig. 7 Variation of concrete strain with time

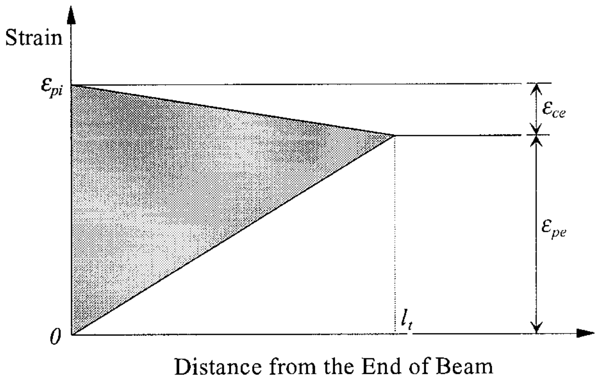

Fig. 8 Linear variation of strains over transfer length

Table 4. Measured end slip values at both ends of beams

Specimen	End Slip (mm)		Specimen	End Slip (mm)	
	Cut	Dead		Cut	Dead
M12-N-C3-1	2.690	2.270	M15-H-C3-1	3.156	2.161
M12-N-C3-2	N/A*	1.926	M15-H-C3-2	N/A	2.235
M12-N-C4-1	1.864	1.746	M15-H-C4-1	N/A	1.864
M12-N-C4-2	2.214	1.750	M15-H-C4-2	2.265	1.617
M12-N-C5-1	2.132	1.967	M15-H-C5-1	1.960	1.496
M12-N-C5-2	2.396	2.182	M15-H-C5-2	1.934	1.645
M12-H-C3-1	N/A	2.082	T12-N-S3	2.354	1.938
M12-H-C3-2	2.473	2.231	T12-N-S4	N/A	1.634
M12-H-C4-1	1.865	1.734	T12-N-S5	1.476	1.674
M12-H-C4-2	1.912	1.756	T12-H-S3	2.189	1.845
M12-H-C5-1	1.564	1.745	T12-H-S4	2.231	1.840
M12-H-C5-2	1.542	1.632	T12-H-S5	1.932	1.840
M15-N-C3-1	N/A	2.840	T15-N-S3	N/A	2.26
M15-N-C3-2	N/A	2.061	T15-N-S4	2.491	2.076
M15-N-C4-1	2.800	2.432	T15-N-S5	2.610	2.175
M15-N-C4-2	2.228	1.857	T15-H-S3	3.240	2.146
M15-N-C5-1	2.037	1.958	T15-H-S4	1.980	1.702
M15-N-C5-2	2.365	2.144	T15-H-S5	1.695	1.643

* N/A : Not available due to disturbance of measuring device.

Prediction of Transfer Length from Strand End Slip

The pretensioned strands tend to slip into the concrete at the ends of the member upon prestress release, and thus relative displacements occur throughout the transfer zone. At the ends of the pretensioned members, the relative slip between the concrete and the strand can be measured during the tests and it is generally referred to as "strand end slip". The end slips have been measured in the present tests and summarized in Table 9. The slip values are slightly larger at cut ends than at dead ends, which has the same nature as transfer length shown previously in this paper. The strain distributions of pretensioned members along the member length are linear as shown in Fig. 6 and 7. It is, therefore, reasonable to assume that the strain distribution of strand varies linearly from zero at the ends to the maximum value at the location of fully developed prestress [see Fig. 8]. Theoretically, the amount of slip is obtained from the summation of strain release of strand over the transfer length. Therefore, the slip δ can be obtained by getting the area of the shaded triangle in Fig. 8:

$$\delta = \frac{\varepsilon_{pi}\, l_t}{2} = \frac{f_{pi}\, l_t}{2E_p} \quad \text{or} \quad l_t = \frac{2E_p \delta}{f_{pi}} \tag{2}$$

where E_p is the elastic modulus of the steel strand, f_{pi} is the strand stress immediately before release, and δ is the end slip. The transfer length, l_t, may be calculated from Eq. (2) by using the present test data, i.e.,

$$l_t = \frac{2 \times 196{,}000}{0.70 \times 1862}\, \delta = 301\delta \tag{3}$$

The strand end slips were measured on every strand at each end of all test beams. The end slips of all 36 beams at both ends of strand are listed in Table 4. The predicted transfer length values by Eq. (2) are plotted as a function of end slip value in Fig. 9. Also shown in Fig. 9 are the measured values of transfer length and end slip for all test beams in the present study. It can be seen that the theoretical line correlates very well with test data. Therefore, the transfer lengths in pretensioned prestressed concrete members can be predicted reasonably once the end slip values are measured after prestress release.

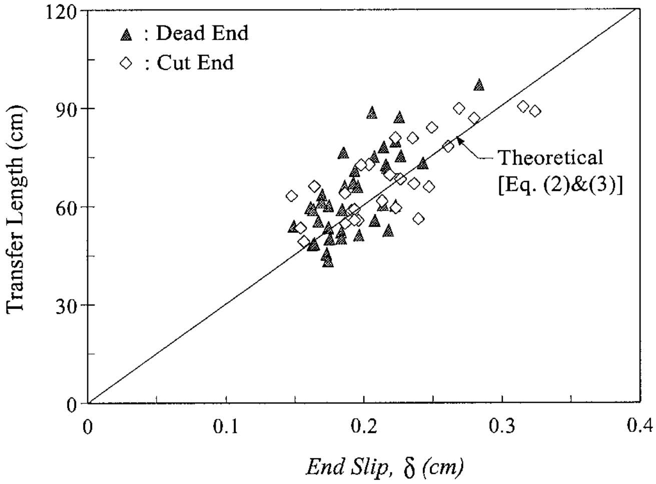

Fig. 9 Relationship between Transfer Length and End Slip

CONCLUSIONS

From the experimental observations reported in this paper, the following conclusions can be drawn:

(1) The current ACI code equation for transfer length overestimates the actual measured transfer length. This discrepancy is particularly significant when concrete strength is high and concrete cover is large, which are not currently considered in the ACI code expression.

(2) The present study indicates that the transfer length in pretensioned concrete members decreases with an increase of concrete strength and increases with a decrease of concrete cover. These important parameters should be included appropriately in the transfer length provisions of design codes.

(3) The transfer length increases with an increase of strand diameter. However, the increase in transfer length is not perfectly linear with the diameter of strand, while the current ACI code assumes a linear relation between transfer length and strand diameter.

(4) It is seen that the end slip values can be used reasonably to calculate the transfer length of pretensioned concrete members. The theoretical prediction of transfer length based on slip values correlates fairly well with measured test data.

(5) The transfer length tends to increase slightly with time due to creep effects. The amount of increase of transfer length is about five percent at 90 days after prestress transfer.

(6) The present study provides valuable test data which can be used as the basis for improving the design equations for transfer length of pretensioned prestressed concrete members.

NOMENCLATURE

c_b = clear bottom cover
c_s = clear side cover
d_b = nominal diameter of prestressing steel
E_p = modulus of elasticity of prestressing steel
f'_c = compressive strength of concrete at 28 days
f'_{ci} = compressive strength of concrete at transfer
f_{pe} = effective stress in prestressing steel
f_{pi} = strand stress immediately before release
f_{pu} = ultimate strength of prestressing steel
l_t = transfer length
s = clear strand spacing
δ = end slip
ε_{ce} = concrete strain after prestress transfer
ε_{pe} = strain of prestressing steel after prestress transfer
ε_{pi} = strain of prestressing steel at initial prestress

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