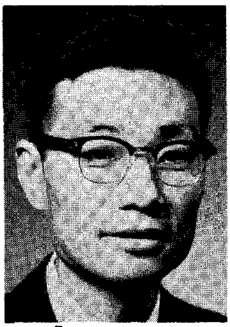
Development Length of Prestressing Strands



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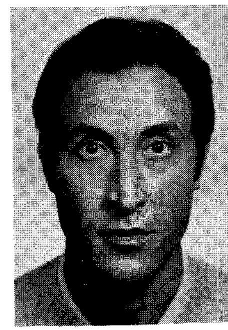

Based on an extensive literature survey of bond development, the authors propose a new equation for the transfer length of prestressing strand. This equation accounts for the effects of strand size, initial prestress, and concrete strength at transfer, and is applicable to concrete strengths ranging from 2000 to 8000 psi.

In a pretensioned member, the prestressing force imparted by the strand is transferred to the concrete by bond in the end region of the member. The distance over which the effective prestress f_{se} is developed in the strand is called transfer length.

An additional bond length is required so that a stress f_{su} may be developed in the strand at ultimate flexural strength of the member. This additional length is called flexural bond length. The sum of these two lengths is referred to as the development length of the strand.[7]*

The development length of prestressing strands specified by the current ACI Code (318-71)[26, 27] is based primarily on the work of Hanson and Kaar.[14] As illustrated in Fig. 1, the development length consists of the:

1. Transfer length $(f_{se}/3)d_b$ and
2. Flexural bond length $(f_{su} - f_{se})d_b$.

*Note that the list of references given at the end of the paper are presented in chronological order.

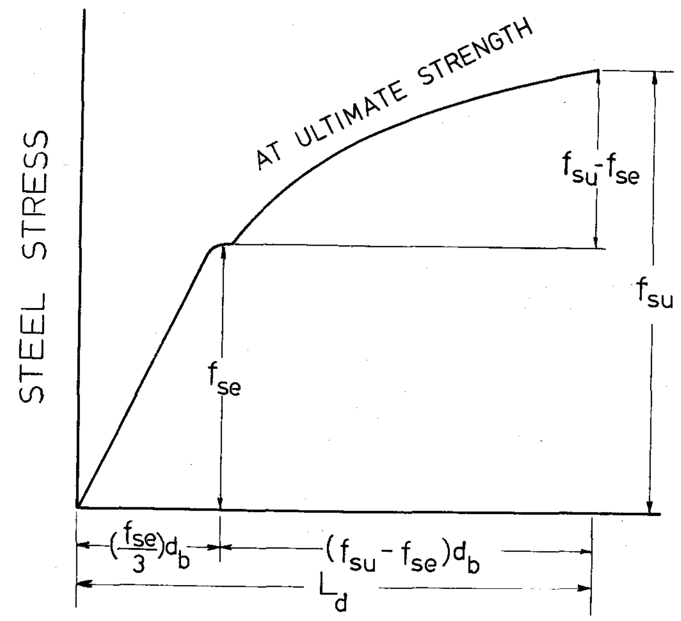

Fig. 1. Variation of steel stress with distance from free end of strand according to ACI 318-71.

It should be noted that the transfer length and the flexural bond length are given as functions of the effective steel stress f_{se} which, in turn, is dependent on the initial prestress f_{si} and the amount of prestress loss. In the expressions specified by the ACI Code, both f_{se} and f_{su} are expressed in ksi. The denominator, 3, in the expression for transfer length represents a conservative average concrete strength in ksi.

Similarly, in the expression for flexural bond length, a denominator of 1 ksi is implied, which represents a stress factor related to bond. Thus, it should be recognized that these expressions are not dimensionally inconsistent.

According to the ACI Code requirement, the transfer length would be 47 nominal strand diameters and the flexural bond length would be 110 strand diameters for 250-ksi grade strand, assuming an initial prestress of $0.7f_{su}$ and a 20 percent loss of prestress. Similarly, for 270-ksi grade strand, the transfer length would be 51 strand diameters and the flexural bond length would be 119 strand diameters. In the shear provisions of the Code, a transfer length of 50 strand diameters is specified.

The development length affects the bending and shear strengths of all pretensioned members, particularly for shallow, short beams and cantilevers. In recent years there have been reports of bond failures of such members, causing concerns among the structural engineers and within the prestressing industry.

After a reevaluation of Hanson and Kaar's test data, and noting that beams containing a lower percentage of steel are particularly vulnerable to bond failure, Martin and Scott[31] proposed a transfer length of 80 diameters for strands of all sizes, and a flexural bond length of 160, 187, and 200 diameters for the ¼, ⅜, and ½-in. diameter strands, respectively. These values are considerably higher than those specified by the current ACI Code.

On the other hand, based on the results of a test program of 36 pretensioned hollow-core units, Anderson and Anderson[32] concluded that the current ACI Code requirement on the development length is adequate provided that the free end slip of the strand, upon transfer of prestress, does not exceed an empirical value which is roughly 0.2 times the strand diameter.

In an attempt to examine the question more thoroughly, a literature review of bond development studies was sponsored by the PCI Fellowship Program at North Carolina State University. This paper is a summary report on the literature survey. Based on this information a new equation for the transfer length of prestressing strand is proposed.

Theoretical Studies

Several investigators[1,7,10,18,23] have formulated theories for transfer length based on different concepts of bond between steel and concrete, such as wedging action, friction, friction plus shrinkage, or certain assumed bond-slip relations. In general, these theories underestimate the actual transfer length and can, at best, be regarded only as approximations. Their validities are questionable since they are based on the elastic concept.

Often predicted by these theories are unrealistically high localized concrete stresses within the transfer zone. However, despite these shortcomings, the theories clearly indicate that the transfer length varies directly with steel size and is also a function of steel stress and concrete strength.

Bond Development Tests

Since the bond study by Hoyer in 1939,[1] more than 30 such investigations have been reported in the literature (see References 1-32). Most of the early tests dealt with transfer length of small wires of different sizes—either plain, twisted, crimped, indented or deformed.

Only more recent bond studies in the United States and Great Britain have dealt with multi-wire strands; and it seems that, except for one study by Base[15] in England, the PCA tests[14,16,17,19] and the recent Anderson tests[32] are the principal ones that have examined the question of flexural bond. Since multi-wire strand is used almost exclusively in current practice for pretensioned beams, this paper will consider only the test results dealing with strands.

Test methods

Generally, three different methods have been used by the various investigators to determine the transfer length. These are illustrated in Fig. 2. By using the measured pull-in distance, the transfer length is determined based upon certain assumed bond-slip relations, or the transfer length can be obtained by direct measurement of the strain profile in concrete within the transfer zone. The beam test with measured end slip and strain profile along the beam, taken before and after the application of loading, will permit the determination of both the transfer length and the flexural bond region.

Effects of various parameters

The transfer length of a prestressing steel is affected by a large number of parameters. Among these are:

a. Type of steel, e.g., wire, strand
b. Steel size (diameter)
c. Steel stress level

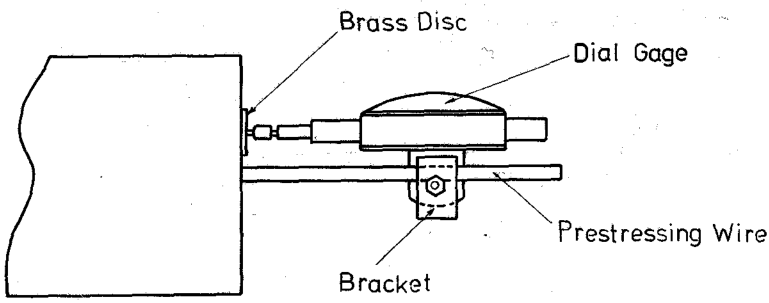

Fig. 2 (a). Pull-in measurement.

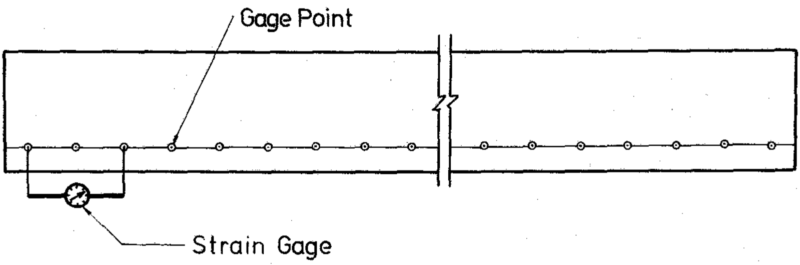

Fig. 2 (b). Strain profile measurement.

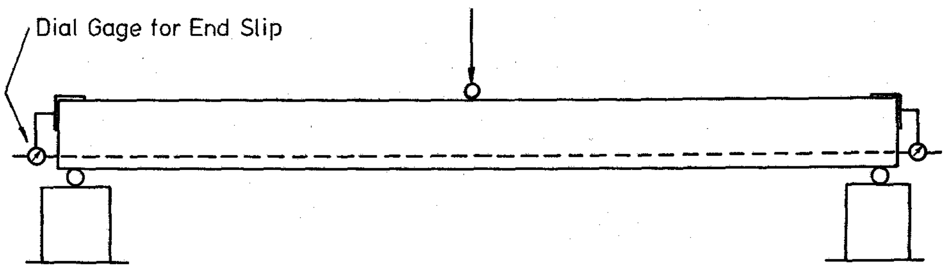

Fig. 2 (c). Beam test for end slip and strain profile measurements.

d. Surface condition of steel—clean, oiled, rusted
e. Concrete strength
f. Type of loading, e.g., static, repeated, impact
g. Type of release, e.g., gradual, sudden (flame cutting, sawing)
h. Confining reinforcement around steel, e.g., helix or stirrups
i. Time-dependent effect
j. Consolidation and consistency of concrete around steel
k. Amount of concrete coverage around steel

Except for Item k, all the parameters listed above have been examined by the various investigators, notably Items a through g. Unfortunately, since many of the parameters can not be properly and uniformly quantified, the conclusions of the various investigations can only be summarized and compared in qualitative terms.

It is generally agreed that transfer length is longer for larger steel sizes, higher prestress levels, and lower concrete strengths. Sudden release of prestress by flame cutting or sawing prestressing steel also leads to in-

Table 1. Measured transfer length versus $(f_{si}/f'_{ci})d_b$.

d_b in.	f_{si} ksi	f'_{ci} psi	L_t, in. Cut End	L_t, in. Dead End	$\frac{f_{si}}{f'_{ci}} d_b$ (in.)	Reference	Notes
1/4	194.1	1720	13	10.5	28.20	Kaar, Lafraugh and Mass[19]	
1/4	192.5	2470	15	11.0	19.48		
1/4	194.1	3560	12	8.5	13.63		
1/4	193.6	4150	10	10.5	11.66		
1/4	195.7	4430	12.5	11.5	11.04		
1/4	150	4000[a]	--	13[a]	9.38	Hanson and Kaar[14]	
1/4	175	4230	11.15	--	10.34	Marshall and Mattock[16]	
3/8	191.7	1690	24.5	20.0	42.54	Kaar, Lafraugh and Mass[19]	
3/8	191.1	3400	28.5	25.5	21.08		
3/8	186	5000	25.5	21.5	13.95		
3/8	167.5	3150	33.0	23.0	19.94		
3/8	187.3	3250	32.0	21.0	21.61		
3/8	166.1	3450	26.0	15.0	18.05		
3/8	144.9	3400	23.0	12.0	15.98		
3/8[b]	167.5	3150	27.0	21.0	19.94		
3/8	150.0	4000[a]	--	19[a]	14.06	Hanson and Kaar[14]	
3/8	165	3232[a]	8.0[a]	--	19.14	Base[15]	4 results
3/8	165	4696[a]	8.0[a]	--	13.18		
3/8[c]	250	7536[a]	14.7[a]	--	12.44	Mayfield, et al.[25]	8 results
3/8[d]	250	7536[a]	17.4[a]	--	12.44		
5/16	183.8	3700	23	24.0	15.52	Kaar, Lafraugh and Mass[19]	
5/16[e]	173.5	3550	22	18.00	15.27		
1/2	177.4	1580	40.5	32	56.14	Kaar, Lafraugh and Mass[19]	
1/2	175.4	2790	43.5	35.5	31.43		
1/2	175.6	3525	43.5	36	24.91		
1/2	173.7	4350	37.5	36	19.97		
1/2	171.1	4930	41	33.5	17.35		
1/2	150	4000[a]	--	26[a]	18.75	Hanson and Kaar[14]	
1/2	175	4000[a]	12[a]	--	21.88	Base[14]	4 results
1/2	175	5856[a]	8[a]	--	14.94		4 results
1/2	175	4000	30	--	21.88	Janney[17]	
1/2	200	4000	30	--	25.0	Janney[17]	
1/2[f]	197.6	9520	46.3	29.6	10.38	Swamy and Anand[29]	
1/2[f]	197.6	11225	33.5	29.0	8.80		
1/2[g]	217.3	11190	28.0	24.8	9.71		
1/2[g]	172.9	9114	15.0	12.0	9.49		
1/2[h]	214.0	10112	50.0	23.0	10.58		
1/2[h]	192.6	8395	20.0	18.0	11.47		
1/2[h]	192.6	9277	19.2	16.0	10.38		
1/2[h]	214.2	9497	28	27.7	11.28		
1/2[i]	190	8480[a]	11.0[a]	--	11.20	Mayfield, et al.[25]	8 results
1/2[d]	190	8480[a]	16.7[a]	--	11.20		8 results
1/2[d]	250	8480[a]	22.1[a]	--	14.74		12 results
1/2[j]	250	6600[a]	33[a]	--	18.94		3 results
5/8	182.0	2220	51.5	33.5	51.24	Kaar, Lafraugh and Mass[19]	
5/8	179.7	2410	52	41.5	46.60		
5/8	181.3	3180	49	42.5	35.63		
5/8	191.8	4070	36	29	29.45		
5/8	177.7	5465	39.5	27.5	20.32		
5/8[i]	190	7120[a]	16.73[a]	--	16.68	Mayfield, et al.[25]	7 results
5/8[d]	190	7120[a]	26.07[a]	--	16.68		8 results
5/8[d]	250	6120[a]	29.53[a]	--	25.53		9 results
0.7[k]	175	4000[a]	20[a]	--	30.63	Base[15]	4 results
0.7[k]	175	5190[a]	20[a]	--	23.60		4 results
0.7[k]	175	4625[a]	20[a]	--	26.49		4 results
0.7[i]	190	7096[a]	21.15[a]	--	18.74	Mayfield, et al.[25]	8 results
0.7[d]	250	6480[a]	27.75[a]	--	27.01		7 results
0.7[c]	250	6480[a]	26.55[a]	--	27.01		
3/4	101	3600	21.2	--	21.04	Rusch and Rehm[18]	

a Average value.
b Reinforcing spirals around the strand in the transfer region.
c Dyform with end stirrups and U bars.
d Dyform with end stirrups, U bars and helices.
e 3-wire strand.
f Stirrups (end reinforcement).
g Helices and two stirrups.
h Helices and shear reinforcement in the one-third length of each end.
i End stirrups, U bars and helices.
j Dyform, no end requirements.
k 19-wire strand.

Table 2. Comparison of Eq. (1) with ACI Code requirement for transfer length L_t (in.).

Strand Size, in.	250-K Grade f_{si} = 175 ksi, f_{se} = 140 ksi			270-K Grade f_{si} = 189 ksi, f_{se} = 151 ksi		
	Eq. (1)		ACI	Eq. (1)		ACI
	f'_{ci} = 3500 psi	f'_{ci} = 4000 psi		f'_{ci} = 3500 psi	f'_{ci} = 4000 psi	
1/4	14	12	12	16	13	13
5/16	19	16	15	21	18	16
3/8	24	20	18	26	22	19
7/16	28	24	21	31	26	22
1/2	33	28	24	36	31	25

Table 3. Experimental results obtained by Hanson and Kaar[14] on embedment length.

Beam No.	Strand Size in.	Embed-ment Length in.	f_{su} ksi	f_{si} ksi	f_{se} ksi	f'_{ci} psi	p %	f'_c psi	$p\frac{f_{su}}{f'_c}$	L_t, in. Eq. (1)	L_b in.	u_{ave} psi Eq.(4)
1-4	1/4	48	278	150	141	4500	0.274	6040	0.126	8	40	214
1-9	3/8	90	268	150	129.7	4500	0.462	5730	0.215	14	76	170
2-2R	3/8	60	266	150	119.4	4500	0.632	5420	0.310	14	46	298
1-17	1/2	90	258	150	132	4500	0.543	5090	0.275	20	70	225
3-11	1/2	80	260	150	135	4500	0.631	6050	0.272	20	60	260
											Ave	233

creased transfer length. Since strands provide a certain amount of mechanical resistance in addition to friction, their transfer length is shorter than that of smooth wires of comparable size. Under repeated loading, if applied outside of the transfer zone, no significant effect on the transfer length was observed. However, if applied within the transfer zone, repeated loading could cause early bond failure if a crack developed within or near the transfer length.

The use of reinforcement to resist the bursting stress near the end of prestressing steel reduced slightly the transfer length, although the effect was not significant.

In several test programs, the transfer length was observed to increase with time, to the extent of 100 percent for some small size wires. However, other tests have shown that there was virtually no change in transfer length with time.

Transfer length of strands

Tabulated in Table 1 are measured transfer lengths L_t as reported by the various investigators. Under the heading of "cut end" are the transfer lengths corresponding to sudden release of strands by flame cutting. (The effect of sudden release may be minimized by gradual heating of the strand in a sufficient length before actual cutting.) Those corresponding to gradual release of strands by slow detensioning are given under the heading of "dead end." Also tabulated are the corresponding values of strand diameter d_b, initial prestress f_{si}, and concrete strength at transfer f'_{ci}.

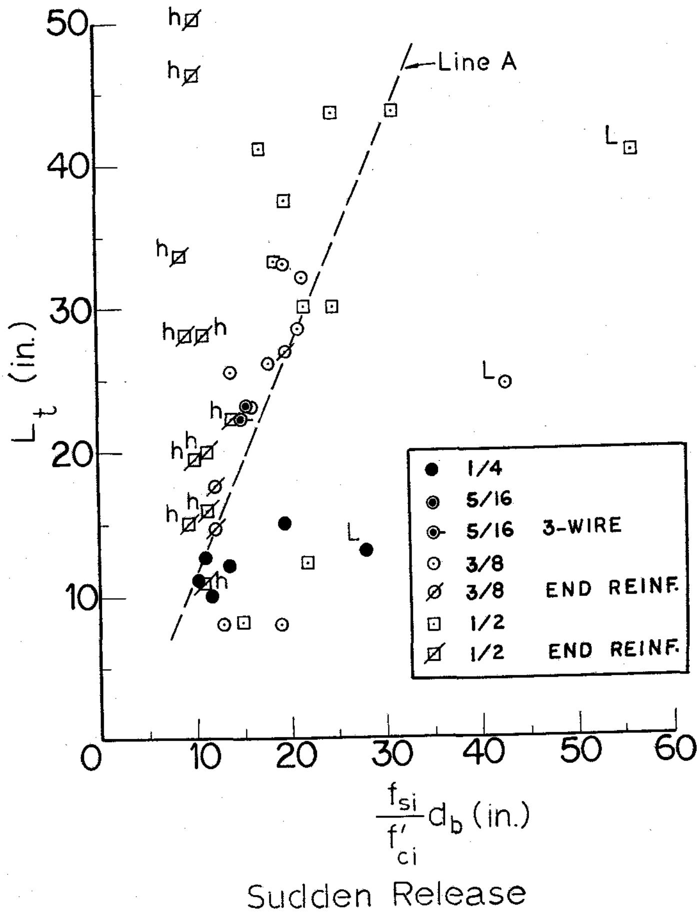

Fig. 3. Transfer length versus $f_{si}d_b/f'_{ci}$ (sudden release).

Fig. 3 shows a plot of transfer length L_t versus the quantity $(f_{si}/f'_{ci})\,d_b$ for different sizes of strand up to ½ in. diameter. By excluding the data for low strength concrete ($f'_c < 2000$ psi) marked by "L" and those for high strength concrete ($f'_c > 8000$ psi) marked by "h", the remaining data can be represented by Line A based on a linear regression analysis. Similarly, for the test data obtained with gradual release, Line B is obtained as shown in Fig. 4. Lines A and B can be expressed as follows:

$$\text{Line A: } L_t = 1.5\frac{f_{si}}{f'_{ci}}d_b - 4.6 \quad (1)$$

$$\text{Line B: } L_t = 1.3\frac{f_{si}}{f'_{ci}}d_b - 2.3 \quad (2)$$

It is noted that the transfer length represented by Line A is slightly more conservative than that represented by Line B.

In Figs. 5 and 6, the transfer lengths for strands larger than ½ in. diameter are compared with Line A and it is seen that Line A is on the conservative side. Therefore, it seems reasonable that, as a design criterion, the transfer length may be taken as:

$$L_t = 1.5\frac{f_{si}}{f'_{ci}}d_b - 4.6$$

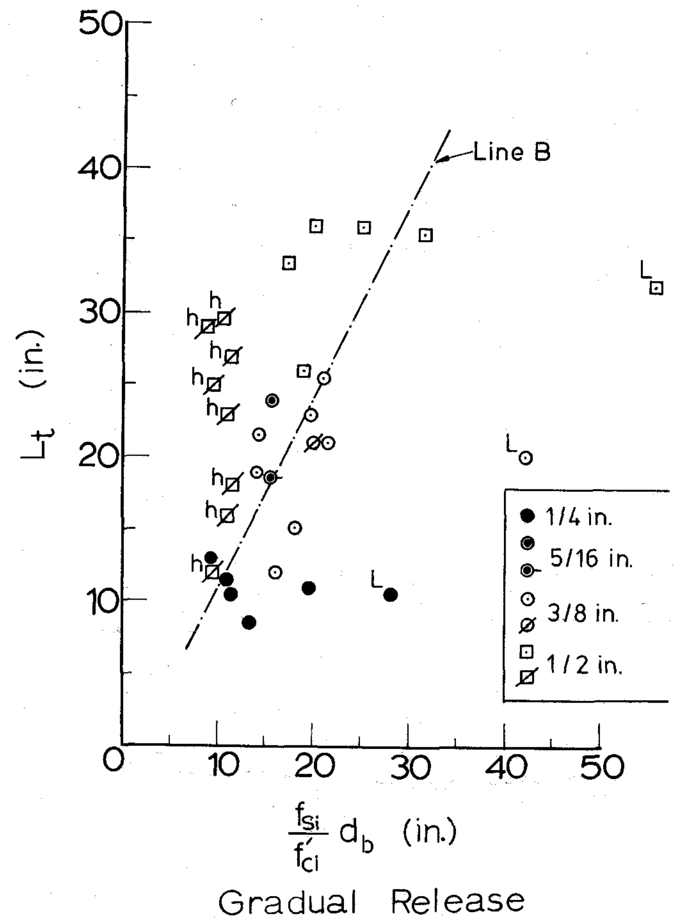

Fig. 4. Transfer length versus $f_{si}d_b/f'_{ci}$ (gradual release).

A comparison of Eq. (1) with the current ACI requirement is given in Table 2. It can be seen that Eq. (1) is more conservative than the current ACI Code requirement. While the difference between the two criteria is quite small for the small size strand, it becomes appreciable for the large size strand, especially if the concrete strength at transfer is relatively low.

Flexural bond length

Within the flexural bond region, the strand stress varies from f_{se} to f_{su}. This increase in stress induces the flexural bond stress. By representing the strand as a circular element of same nominal diameter, it can be shown from the condition of equilibrium that the flexural bond length:

$$L_b = \frac{f_{su} - f_{se}}{4\,u_{ave}} d_b \qquad (3)$$

$$u_{ave} = \frac{f_{su} - f_{se}}{4\,L_b} d_b \qquad (4)$$

where u_{ave} is average bond stress within L_b. In the current ACI Code, it is implied that u_{ave} = 250 psi.

According to Hanson and Kaar,[14] if the ultimate strength of the strand is

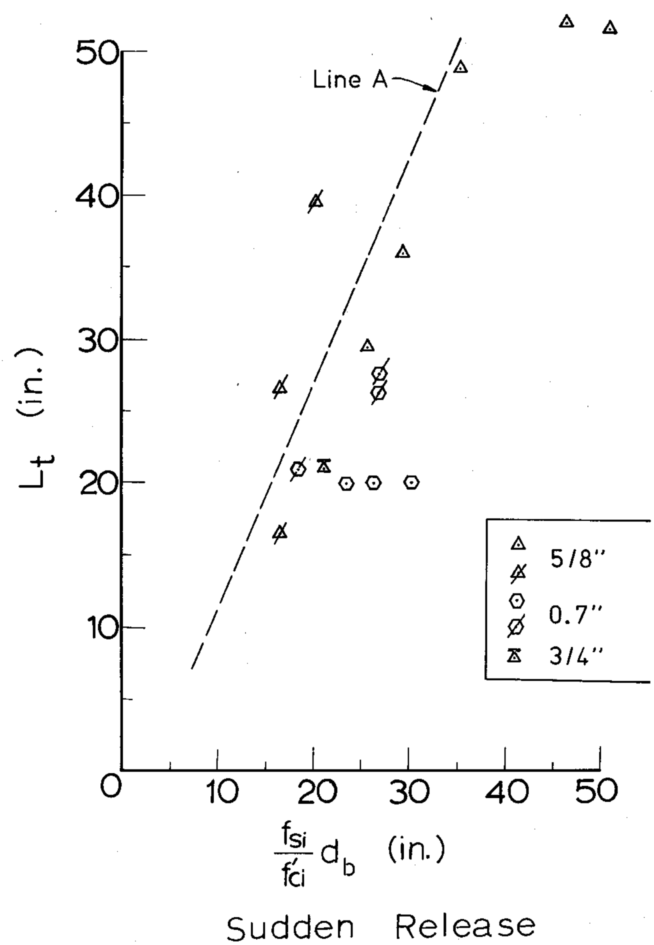

Fig. 5. Transfer length versus $f_{si}d_b/f'_{ci}$ (sudden release).

to be developed by beam flexure before general bond slip occurs, the minimum required embedment lengths are approximately 70, 106, and 134 in. for ¼, ⅜, and ½-in. diameter strands, respectively. However, these values were obtained based on the flexural bond stress wave immediately prior to a general bond slip which was conservatively deduced from the experimental results.

A close examination of Hanson and Kaar's test data reveals that the actual embedment lengths for the strands which developed the ultimate strength before a general bond slip were considerably shorter than indicated above. Their experimental values are tabulated in Table 3. Also listed in Table 3 are the computed values of L_t from Eq. (1) for the specimens in question.

Knowing the actual embedment length and the computed L_t, the flexural bond length L_b is then calculated for each specimen, from which the average bond stress u_{ave} is computed using Eq. (4). It is noted that the average bond stress u_{ave} is lower for beams with lower reinforcement index pf_{su}/f'_c. The average value of computed u_{ave} is 233 psi which is

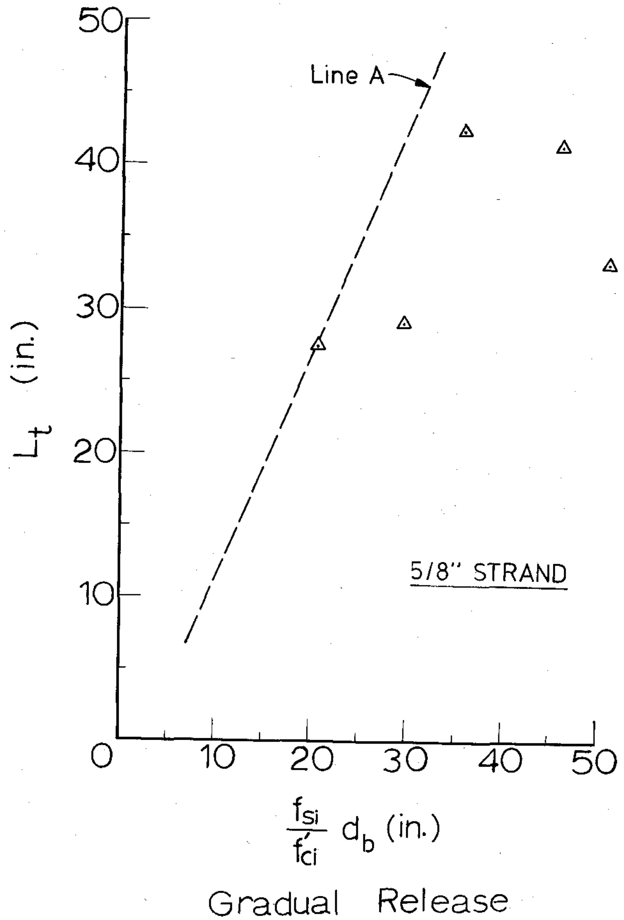

Fig. 6. Transfer length versus $f_{si}d_b/f'_{ci}$ (gradual release).

somewhat lower than what is implied by the current ACI Code.

Accordingly, for the purpose of design, it would seem appropriate to choose u_{ave} = 200 psi. Thus, returning to Eq. (3), one obtains:

$$L_b = \frac{f_{su} - f_{se}}{4(0.2)} d_b = 1.25(f_{su} - f_{se})d_b \quad (5)$$

Acknowledgment

The support of the PCI Fellowship Program for this study is gratefully acknowledged.

Conclusions

Based on a review of available research information, a new expression Eq. (1) for the transfer length of prestressing strands is proposed, which is applicable for concrete strength ranging from 2000 to 8000 psi.

This expression accounts for the effects of the strand size, the initial prestress and the concrete strength at transfer. The proposed equation for transfer length gives comparable results as the current ACI Code requirement for the small size strands, but is more conservative than the ACI Code, particularly for cases where the concrete strength at transfer is low.

A review of the test data obtained by Hanson and Kaar[14] suggests that the flexural bond length specified by the current ACI Code should be increased by about 25 percent as given by Eq.(5).

Combining Eq.(1) and Eq.(5), the total development length for prestressing strands may, therefore, be represented as:

$$L_d = 1.5\frac{f_{si}}{f'_{ci}}d_b - 4.6 + 1.25(f_{su} - f_{se})d_b$$

For the purpose of design, the stress in the strand may be assumed to vary linearly from zero to f_{se} within the transfer region as given in Eq.(1) and from f_{se} to f_{su} within the flexural bond region as given by Eq.(5).

Notation

d_b = nominal diameter of prestressing strand, in.

f'_c = compressive strength of concrete, ksi

f'_{ci} = compressive strength of concrete at time of initial prestress, ksi

f_{se} = effective stress in prestressing strand, after losses, ksi

f_{si} = initial stress in prestressing strand, before losses, ksi

f_{su} = ultimate strength of prestressing strand, ksi

L_b = flexural bond length, in.

L_d = development length, in.

L_t = transfer length, in.

p = ratio of prestressed reinforcement to beam cross section

u_{ave} = average bond stress, ksi

References

1. Hoyer, E., and Friedrich, E., "Beitrag zur Frage der Nalftspannung in Eisenbeton-bauteinten," *Beton und Eisen* (Berlin), 1939, V. 38, No. 6, pp. 107-110.
2. Ros, M., "Vorgerpannter Beton," Zurich, Eidgenossische Materialprufungs und versuchsanstalt fur Industrie, *Bauwesen und Gewerbe*, 1946, pp. 96 (EMPA), Reprint No. 155.
3. Marshall, G., "End Anchorage and Bond Stress in Prestressed Concrete," *Magazine of Concrete Research* (London), V. 1, December 1949, pp. 123-127.
4. Ros, M., "Die Materialtechnischen Grundlagen und Problem des Eisenbetons im Hinblick auf die Zukunflige Gestaltung der Stahlbeton-Bauweise," Eidgenossische Materialprufungsanstalt, Bericht, No. 162, Zurich, 1950, Chapter 8, "Prestressed Concrete."
5. Evans, R. H., "Research and Developments in Prestressing," *Journal*, Institute of Civil Engineers, V. 35, No. 4, February 1951, pp. 231-261.
6. Guyon, Y., *Prestressed Concrete*, Contractors Record and Municipal Engineering, London, 1953.
7. Janney, J. R., "Nature of Bond in Pretensioned Prestressed Concrete," *ACI Journal*, Proceedings V. 50, No. 9, May 1954, pp. 717-736.
8. Abeles, P. W., Hajnal-Konyi, K., Hanson, N. W., and Janney, J. R., discussion of the paper "Nature of Bond in Pretensioned Concrete," *ACI Journal*, Proceedings V. 50, Dec. 1954, Part 2, p. 736-1.
9. Evans, R. H., and Robinson, G. W., "Bond Stresses in Prestressed Concrete From X-ray Photographs," *Proceedings*, Institution of Civil Engineers, V. 14, March 1955, Part 1, pp. 212-235.
10. Cowan, H. J., *The Theory of Prestressed Concrete Design*, St. Martin's Press, New York, N.Y., 1956, pp. 158-166.
11. Base, G. D., "Some Tests on the Effects of Time on Transmission Length in Pretensioned Concrete," *Magazine of Concrete Research* (London), V. 9, No. 26, August 1957, pp. 73-82; Reprint No. 41, Cement and Concrete Association.
12. Base, G. D., "An Investigation of Transmission Length in Pretensioned Concrete," Research Report No. 5,

Cement and Concrete Association, London, August 1958.
13. Ratz, E. H., Holmjanski, M. M., and Kolner, V. M., "The Transmission of Prestress to Concrete by Bond," Paper 10, Third Congress of the Fédération Internationale de la Précontrainte, Berlin, 1958. Cement and Concrete Association, London, 1958, pp. 624-640.
14. Hanson, N. W., and Kaar, P. H., "Flexural Bond Tests of Pretensioned Prestressed Beams," *ACI Journal*, Proceedings V. 55, No. 7, January 1959, pp. 783-803. Also, Development Department Bulletin D28, Portland Cement Association, Skokie, Illinois.
15. Base, G. D., "An Investigation of the Use of Strand in Pretensioned Prestressed Concrete Beams," Research Report No. 11, Cement and Concrete Association, London, January 1961.
16. Marshall, W. T., and Mattock, A. H., "Control of Horizontal Cracking in the Ends of Pretensioned Prestressed Concrete Girders," PCI JOURNAL, V. 7, No. 5, October 1962, pp. 56-74.
17. Janney, J. R., "Report of Stress Transfer Length Studies on 270K Prestressing Strand," PCI JOURNAL, V. 8, No. 1, February 1963, pp. 41-43.
18. Rusch, H., and Rehm, G., "Tests for Determining the Transmission Length of Prestressing Wires," Translation No. CJ 120, Cement and Concrete Association, London, 1963.
19. Kaar, P. H., Lafraugh, R. W., and Mass, M. A., "Influence of Concrete Strength on Strand Transfer Length," PCI JOURNAL, V. 8, No. 5, October 1963, pp. 47-67. Also, Development Department Bulletin D71, Portland Cement Association, Skokie, Illinois.
20. Aurther, P. D., and Ganguli, S., "Tests on End Zone Stresses in Pretensioned Concrete I-Beams," *Magazine of Concrete Research* (London), V. 17, June 1965, pp. 85-96.
21. Over, S., and Au, Tung, "Prestress Transfer Bond of Pretensioned Strands in Concrete," *ACI Journal*, Proceedings V. 62, No. 11, November 1965, pp. 1451-1459.
22. Kaar, P., and Magura, D., "Effect of Strand Blanketing on Performance of Pretensioned Girders," PCI JOURNAL, V. 10, No. 6, December 1965, pp. 20-34. Also, Development Department Bulletin D97, Portland Cement Association, Skokie, Illinois.
23. Marshall, W. T., "A Theory for End Zone Stresses in Pretensioned Concrete Beams," PCI JOURNAL, V. 11, No. 2, April 1966, pp. 45-51.
24. Marshall, W. T., and Krishnamurthy, O., "Transmission Length of Prestressing Tendons from Concrete Cube Strengths at Transfer," *The Indian Concrete Journal* (Bombay), V. 43, July 1969, pp. 244-253 and 257.
25. Mayfield, B., Davis, G., and Kong, F. K., "Some Tests on the Transmission Length and Ultimate Strength of Pretensioned Concrete Beams Incorporating Dyform Strand," *Magazine of Concrete Research* (London), V. 22, No. 73, December 1970, pp. 219-226.
26. ACI Committee 318, "Building Code Requirements for Reinforced Concrete (ACI 318-71)," American Concrete Institute, Detroit, Michigan, 1971, p. 44.
27. ACI Committee 318, "Commentary on Building Code Requirements for Reinforced Concrete (ACI 318-71)," American Concrete Institute, Detroit, Michigan, 1971, p. 61.
28. Krishnamurthy, D., "A Theory for the Transmission Length of Prestressing Tendons," *The Indian Concrete Journal* (Bombay), V. 47, February 1973, pp. 73-80.
29. Swamy, R. N., and Anand, K. L., "Transmission Length and Prestress Losses in High Strength Concrete," Paper Presented at the Seventh International Congress of the Fédération Internationale de la Précontrainte, New York, N.Y., May-June, 1974.
30. Kaar, P. H., and Hanson, N. W., "Bond Fatigue Tests of Beams Simulating Pretensioned Concrete Crossties," PCI JOURNAL, V. 20, No. 5, September-October, 1975, pp. 65-80.
31. Martin, L. D., and Scott, N. L., "Development of Prestressing Strand in Pretensioned Members," *ACI Journal*, Proceedings, V. 73, No. 8, August 1976, pp. 453-456.
32. Anderson, A. R., and Anderson, R. G., "An Assurance Criterion for Flexural Bond in Pretensioned Hollow Core Units," *ACI Journal*, Proceedings V. 73, No. 8, August 1976, pp. 457-464.