Influence of Concrete Strength On Strand Transfer Length

Presented at the Ninth Annual Convention of the Prestressed Concrete Institute

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SYNOPSIS

This paper reports an investigation of the influence of concrete strength on the stress transfer length of seven-wire strand at the time of transfer of prestress. Strands of ¼, ⅜, ½ and 6/10-in. diameter were used to prestress rectangular section members having concrete strengths of 1660, 2500, 3330, 4170 and 5000 psi at the time of prestress transfer. Concrete strength was found to have little influence on transfer length for strands of up to ½-in. diameter.

Periodic measurements were made of the concrete compressive strains in all specimens, beginning immediately after release of the strands and continuing for one year, to determine the initial transfer length as well as time effects. The increase in transfer length during one year was generally less than 10 percent.

In all tests except those of the specimens containing 6/10-in. diameter strand, unpitted rust-free strand was used.

BACKGROUND AND PURPOSE

Prestress transfer length is defined as the distance over which the stress in a pretensioned tendon is transferred by bond to the concrete. Transfer length has been intuitively associated with concrete strength at transfer. Low concrete strengths were thought to result in long transfer lengths, and conversely, high concrete strengths were expected to result in shorter transfer lengths. Various tests have been conducted to determine transfer length for particular conditions, but a literature search revealed no systematic investigation of the effect of concrete strength on transfer length. Janney[4] found little difference in transfer lengths of single-wire tendons determined by single comparable tests of .162-in. diameter wire prestressed in 4500 and 6500 psi concrete.

A related question is whether transfer length increases with time, and if so, whether concrete strength at transfer influences the amount of the increase. Evans[1], in his work with single-wire tendons, reported up to 100 percent increase in transfer length over a period of one year. Base[2] found smaller increases. The effect of time on the transfer length of seven-wire strand has been a matter of conjecture.

Purpose

The minimum allowable concrete strength at the time of transfer depends primarily on four factors: (a) the satisfactory transfer of prestress

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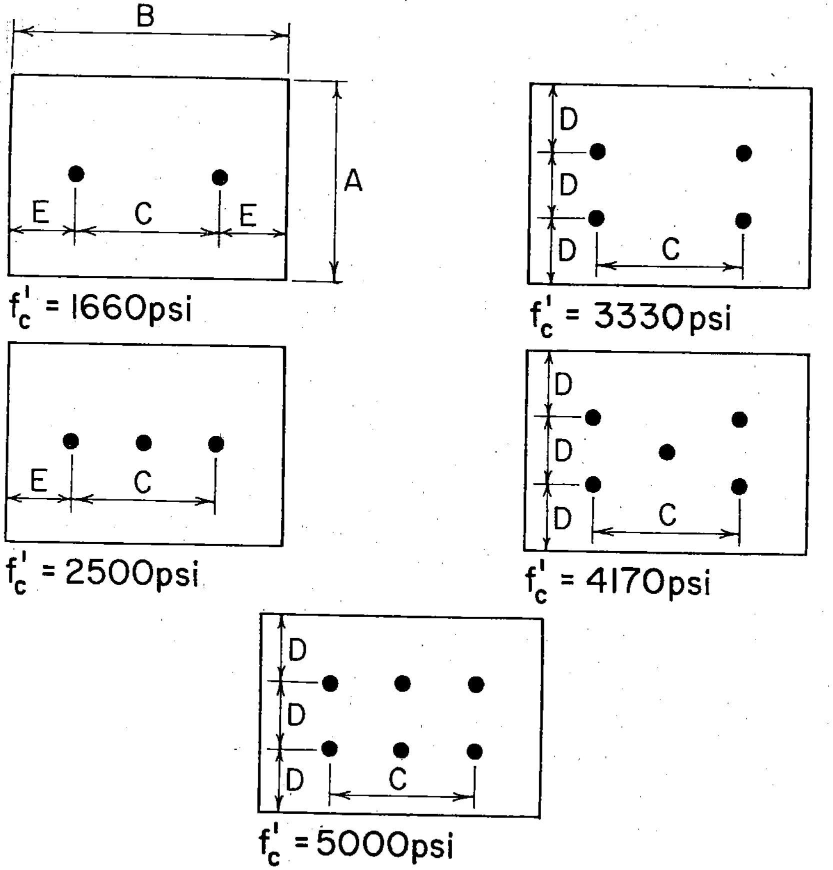

Strand Size (in.)	Strand Area (sq in.)	All dimensions given in inches					Length of Specimen (ft)
		A	B	C	D	E	
1/4	0.036	3	$4\frac{3}{16}$	$2\frac{3}{16}$	1	1	8
3/8	0.080	$4\frac{1}{2}$	$6\frac{9}{32}$	$3\frac{9}{32}$	$1\frac{1}{2}$	$1\frac{1}{2}$	8
1/2	0.144	6	$8\frac{3}{8}$	$4\frac{3}{8}$	2	2	8
6/10	0.221	$7\frac{1}{2}$	$10\frac{1}{2}$	$5\frac{1}{2}$	$2\frac{1}{2}$	$2\frac{1}{2}$	10

Fig. 1—Specimen Sizes.

from the tendons to the concrete by bond, (b) consistent control of camber and deflection of the members, (c) the level of precompression stress to which the concrete is to be subjected, and (d) effect of concrete strength on loss of prestress. Designers of pretensioned prestressed products have tended to be conservative in specifying the minimum allowable concrete strength at transfer. However, it is of considerable economic importance to the fabricator of pretensioned prestressed concrete products to be able to transfer the prestress and free his prestressing beds at as early a time as possible.

The investigation reported herein was limited to obtaining definite information on the influence of concrete strength on the transfer of prestress from the tendons to the concrete. The influence of concrete strength at transfer on the remaining three factors mentioned is also of considerable importance, but was not a part of this investigation.

SCOPE OF TEST PROGRAM

Rectangular, concentrically prestressed members of dimensions shown by Fig. 1 were fabricated utilizing five concrete strengths (1660, 2500, 3330, 4170 and 5000 psi) and four strand diameters (¼, ⅜, ½ and 6⁄10 inch). The specimens were designed in accordance with limits of stress for concrete and steel contained in the 1963 ACI Building Code Requirements for Reinforced Concrete (ACI 318-63)[3]. By this Code, temporary compression stresses immediately after transfer, before losses due to creep and shrinkage, must not exceed 0.6 of the compressive strength of the concrete at time of transfer of prestress. Also, the steel stress immediately after transfer must not exceed 0.7 of the ultimate strand stress. Using the manufacturer's nominal ultimate strand stress of 250,000 psi, the 0.7 stress value amounts to 175,000 psi. This value of effective prestress after transfer is higher than that used by most fabricators today, but it was considered advisable to design the members using the maximum stresses permitted by the Code, so that the transfer lengths determined would be the maximum likely to occur in members designed in conformance with the Code.

Measurements made along the length of each specimen determined compressive strains set up in the concrete by the prestress force transferred from the strand to the concrete by bond. From these measurements it was possible to trace the build-up of prestress from the ends of the members and so measure the transfer length for each combination of strand size and concrete strength. These measurements were repeated at intervals during the year following transfer of prestress to determine whether transfer length increased with time.

TEST SPECIMENS

Design of Test Specimens

The rectangular cross section specimens were proportioned so that the prestress force from the strand, stressed to the limits defined above, would produce a stress in the concrete at transfer, f_c, equal to about 0.6 of the concrete cylinder strength, f'_c. Thus, in order to maintain this ratio of $\frac{f_c}{f'_c}$ as near as possible to 0.6, the individual specimens were prestressed with from two to six strands as f'_c was varied from 1660 psi to 5000 psi. The cross sectional

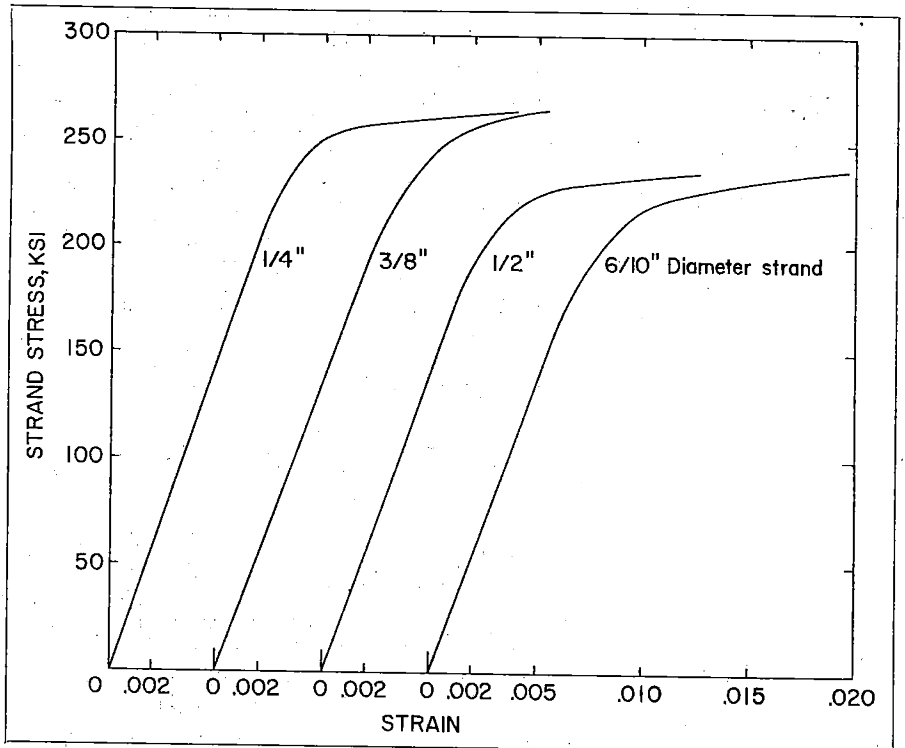

Fig. 2—Stress-Strain Curves of Strand.

dimensions of the specimens are shown in Fig. 1.

Specimen lengths for the strand diameters ¼, ⅜ and ½ in. were eight feet, while the length of the specimens containing the 6/10 in. strand was 10 ft. These lengths, determined by preliminary pilot tests, insured the existance of a zone of uniform prestress in the members in addition to the transfer lengths at each end.

Materials

All steel strand was stress relieved, and of the type commonly used for prestressed members. Stress-strain curves are shown in Fig. 2., and the nominal area and circumference values are listed in Table 1. While the ultimate stress in all cases exceeded 250,000 psi, this value, furnished by the manufacturer, was used as the ultimate stress in all calculations. The strand was clean and free of rust at time of use, except that the 6/10 in. diameter strand had been slightly rusted before cleaning in the laboratory.

The concrete used in the specimens contained 4.5 bags of Type III portland cement per cubic yard*, and ¾ in. maximum size aggregate. Curing was at 70 F, with the specimens covered by a plastic sheet for the first day, and exposed to 50 percent humidity thereafter. The concrete cylinder strengths listed in Table 2 are the average of two cylinders per batch of the specimen concrete, tested at the time of transfer

* *It should be noted that laboratory concretes are made and cured under controlled conditions. Hence, for a given cement content, higher strengths are usually obtained than those that may reasonably be expected in the field.*

Strand Size, in.	Modulus of Elasticity, E_s, 10^6psi	Ultimate Strength of Strand ksi	Nominal Cross-sectional Area, A_s sq. in.	Nominal Circumference(1) in.	Pitch of Outer Wires in.
¼	29.7	275	0.036	1.05	3.75
⅜	28.3	275	0.080	1.58	5.63
½	28.6	254	0.144	2.10	6.75
6/10	27.3	255	0.221	2.52	8.50

(1) $4\pi/3$ times diameter

Table 1—Properties of Strand.

of prestress. All cylinders were cured with the transfer bond specimens.

Fabrication

The strands were stretched between two strong-backs which were anchored to the laboratory test floor. Each strand was stressed individually using a center-hole ram, and the tension in the strand was monitored by a load cell placed under the strand grip at the "anchor" end of the prestressing bed. The initial tensioning stress in the strands was greater than the final target stress immediately after transfer by an amount equal to the anticipated losses due to (1) draw-in of the wedges of the strand grip at the tensioning end, (2) relaxation of the strand in the interval between tensioning and transfer of prestress to the concrete, (3) the elastic shortening of the concrete due to the prestress and (4) shrinkage of the concrete up to the time of transfer.

Duplicate specimens were cast end to end around the same lengths of tensioned strand. Each specimen was designated by two groups of numbers and a letter. The first number group indicates the strand diameter, while the second indicates the target value for the concrete strength at transfer. These numbers are followed by letters "A" and "B", which distinguish the duplicate specimens.

In all cases transfer of prestress was accomplished by flame cutting. The strand was severed between the adjacent ends of the duplicate specimens after a brief period of preheating. This method afforded for study two specimen ends adjacent to and two ends removed from the flame cut. These ends are referred to as the "cut end" and the "dead end" of the specimens. This method of transfer duplicated a common field procedure and produced what are probably the most severe conditions of transfer at the cut ends of the specimens, while resulting in a more gradual transfer of prestress at the dead ends.

The age of the specimens at transfer of prestress varied from one to thirty days, according to the concrete strength required. Concrete strengths were so chosen that a prestress of 1000, 1500, 2000, 2500, and 3000 psi represented 0.6 f'_c. Average ages at transfer were 1, 2, 3, 9, and 22 days for the five target strengths of 1660, 2500, 3330, 4170, and 5000 psi, respectively.

Instrumentation

Brass discs, drilled with holes to receive the legs of a 10-inch Whittemore mechanical strain gage, were attached on 2-inch centers along lines at mid-depth of two opposite sides of each specimen. These reference points extended to within one inch of both ends of each specimen. In addition, a steel angle bracket drilled for the gage leg was bolted to each specimen end. This bracket afforded support for one leg of the 10-in. long gage when measuring strains closer than 10 in. to the ends of the speci-

Specimen No.	Steel stress, f_{si}, before transfer ksi	Steel stress, f_{se}, immediately after transfer ksi	Ratio $\frac{f_{se}}{f'_s}$	Prestress in Concrete $f_c = \frac{n_s \, x \, f_{se} \, x \, A_s}{A_c}$ psi	Concrete Cylinder Strength, f'_c psi	Ratio $\frac{f_c}{f'_c}$	Measured modulus of elasticity of concrete, E_c 10^6 psi	Theoretical Concrete strain at transfer $\epsilon_{c(theo)} = \frac{f_{si} A_s}{A_s E_s + A_c E_c}$ 10^{-4} in./in.	Actual concrete strain at transfer $\epsilon_{c(meas.)}$ 10^{-4} in./in.	$\frac{\epsilon(meas.)}{\epsilon(theo.)}$
¼—1660A	194.1	178.8	.72	1020	1720	.59	2.03	5.06	5.14	1.02
¼—1660B	194.1	179.8	.72	1030	1720	.60	2.03	5.06	4.83	0.95
¼—2500A	192.5	175.4	.70	1510	2470	.61	2.67	5.66	5.74	1.01
¼—2500B	192.5	174.1	.70	1500	2470	.61	2.67	5.66	6.20	1.10
¼—3330A	194.1	172.4	.69	1980	3560	.56	2.72	7.27	7.30	1.00
¼—3330B	194.1	174.2	.70	2000	3560	.56	2.72	7.27	6.69	0.92
¼—4170A	193.6	168.6	.67	2420	4150	.58	2.90	8.34	8.40	1.01
¼—4170B	193.6	167.7	.67	2400	4150	.58	2.90	8.34	8.71	1.04
¼—5000A	195.7	167.0	.67	2870	4430	.65	3.04	9.48	9.68	1.02
¼—5000B	195.7	166.7	.67	2870	4430	.65	3.04	9.48	9.80	1.03
⅜—1660A	191.7	177.1	.71	1000	1690	.59	1.91	5.24	5.16	0.98
⅜—1660B	191.7	176.4	.71	1000	1690	.59	1.91	5.24	5.43	1.04
⅜—3330A	191.1	169.7	.68	1920	3400	.56	2.81	6.90	7.64	1.11
⅜—3330B	191.1	167.4	.67	1890	3400	.56	2.81	6.90	8.38	1.21
⅜—5000A	186.0	158.2	.63	2680	4680	.57	3.39	8.15	9.82	1.20
⅜—5000B	186.0	159.4	.64	2700	5350	.50	3.40	8.13	9.39	1.15
½—1660A	172.5	161.3	.65	920	1550	.59	2.15	4.27	3.75	0.88
½—1660B*	182.3	172.1	.69	990	1610	.61	2.66	3.70	3.59	0.97
½—2500A	175.4	159.9	.64	1370	2740	.50	2.32	5.88	5.42	0.92
½—2500B	175.4	160.4	.64	1380	2840	.49	2.42	5.65	5.24	0.93
½—3330A	175.6	155.0	.62	1780	3480	.51	2.15	8.12	7.19	0.89
½—3330B	175.6	155.6	.62	1780	3570	.50	2.29	7.69	6.98	0.91
½—4170A	173.7	152.1	.61	2180	4480	.49	3.27	6.71	7.73	1.15
½—4170B	173.7	150.3	.60	2150	4220	.51	3.23	6.78	8.16	1.20
½—5000A	171.1	146.9	.59	2530	5060	.50	3.39	7.58	8.47	1.12
½—5000B	171.1	146.2	.58	2510	4800	.52	3.34	7.68	8.72	1.14
6/10—1660A	182.0	172.7	.69	970	2330	.42	2.44	3.96	3.43	0.87
6/10—1660B	182.0	170.8	.68	960	2110	.45	2.20	4.35	4.10	0.94
6/10—2500A	179.7	163.8	.66	1380	2520	.55	2.00	6.80	6.02	0.89
6/10—2500B	179.7	161.2	.64	1360	2300	.59	1.88	7.18	6.80	0.95
6/10—3330A	181.3	159.2	.64	1790	3180	.56	2.44	7.43	8.12	1.09
6/10—3330B	181.3	159.4	.64	1790	3180	.56	2.41	7.51	8.03	1.07
6/10—4170A	191.8	170.6	.68	2400	4000	.60	2.94	8.11	7.76	0.96
6/10—4170B	191.8	169.3	.68	2380	4140	.57	2.83	8.39	8.23	0.98
6/10—5000A	177.7	153.8	.62	2590	5560	.47	3.34	7.89	8.75	1.11
6/10—5000B	177.7	153.1	.61	2580	5370	.48	3.48	7.61	9.03	1.19

* Cast separately from specimen ½—1660A

Table 2—Strand and Concrete Stress and Strain at Prestress Transfer.

mens. Since the bracket was unstrained, any difference in readings using the bracket for the support of one strain gage leg would indicate strain in that part of the concrete spanned by that particular gage length. Use of the bracket is illustrated by Fig. 3.

The strand tension immediately before transfer was measured by taking readings on the SR4 gage load cells under the strand grips before and after cutting the strand.

All testing was at a controlled temperature of 70 F.

TEST METHODS AND DATA REDUCTION

Method of Test

Immediately before transfer, readings were taken on all the Whittemore gage lengths and on the load cells beneath the strand grips at the dead end of the prestressing bed. The strands were then flame cut between the adjacent ends of the duplicate specimens. Immediately after cutting the strands the specimens were lifted from the prestressing bed to eliminate frictional restraint along the bottom of the specimen, and a second complete set of readings was taken using the strain gage and the load cells. The specimens were then placed on racks where they were supported at close intervals on Styrofoam pads. Similar complete sets of strain gage readings were subsequently taken at ages after transfer of 1, 3, 7, 14, 28, 56, 90, 180 and 365 days. Using the initial set of readings as a reference, it was then possible to obtain the average strain in each gage length immediately after transfer as well as at the later ages.

Immediately after transfer of prestress, two 6 by 12-in. cylinders made from the same concrete as the transfer bond specimen were tested in compression to determine the modulus of elasticity of the concrete. The values of modulus of elasticity listed in Table 2 (averages of the two tests in each case) are the secant modulus at 0.6 f'_c measured on the first loading of the cylinders.

Reduction of Data

The Whittemore strain gage measured the average strain over a 10-in.

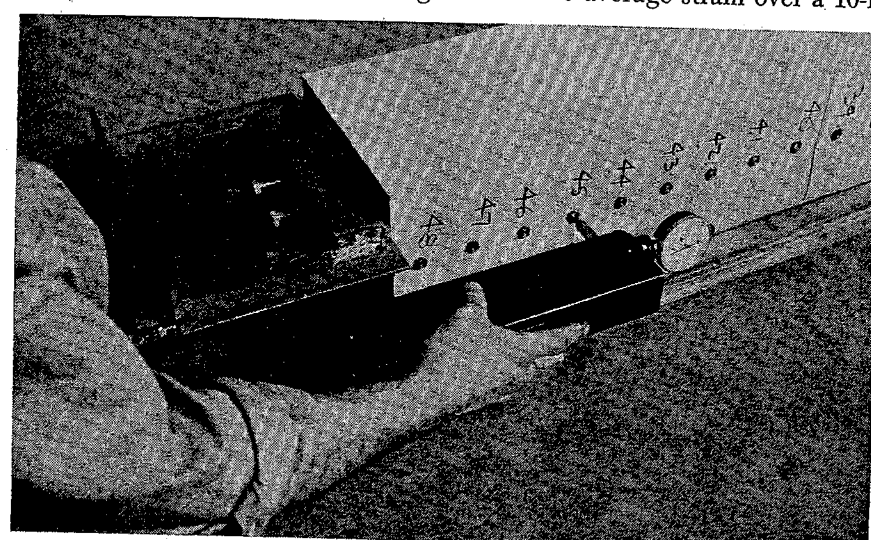

Fig. 3—Method of Measuring Strains at Specimen End.

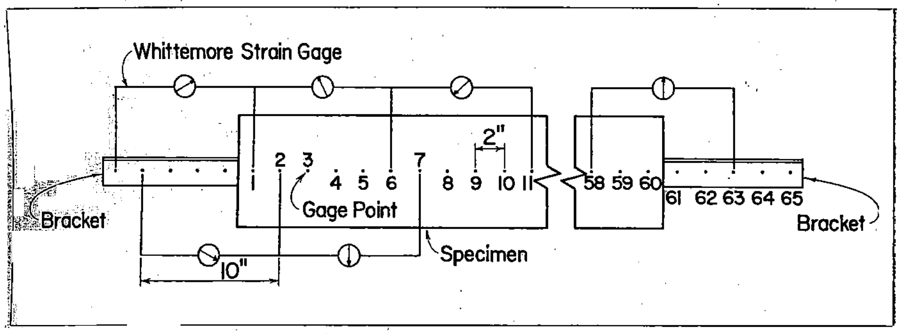

Fig. 4—View of Specimens Showing Strain Gage Positions.

gage length. In view of the rapid change in strain which occurs near the end of a pretensioned prestressed member it was necessary to evaluate the strain at each point along the length of the member. The actual strain at particular points can be obtained from the average strains measured by the 10-in. gage by plotting the cumulative strain from the end of the member and then measuring the slope of the curve at the points in question. The actual strain at any particular point will then be equal to the slope of the cumulative strain curve at that point.

The procedure used in each case was as follows. The cumulative strains were first obtained by addition of the differences in the 10-in. gage readings for each successive gage length. Fig. 4 shows a representative 10-ft. long specimen with attached brackets, each bracket being drilled for five Whittemore gage points at two-inch centers. Also shown in this figure are representations of the strain gage in reading position. The cumulative strain for gage point location 11 consists of the change in reading at gage point 1 plus that at point 6 plus that at point 11*. An example of such a curve of cumulative strains is shown in Fig. 5. The procedure for determining cumulative strains in the 8-ft. long specimens is similar to that described above. All such cumulative curves were of the same general shape—an inclined straight line gradually changing to a nearly horizontal line at each end. The tangents to this cumulative curve clearly define strains starting near zero at each end and increasing throughout the prestress transfer region to uniform prestress strain in the fully prestressed region of the specimen. Such a curve of prestress strain determined from tangents drawn to the cumulative curve of Fig. 5 is shown in Fig. 6. The distance from the end of the member to the point at which the tangents drawn to the cumulative curve deviate from the straight-line portion of the curve is the transfer length. These transfer length determinations were made for each specimen from large scale plots of the cumulative strain data.

* *By this method there are five independent determinations of total shortening or total strain along the length of the specimen; these were the cumulative strains between gage readings ending at points 1 and 61, 2 and 62, 3 and 63, 4 and 64, 5 and 65. These values of total length change from one steel bracket to another should be identical and thereby serve as a check of accuracy.*

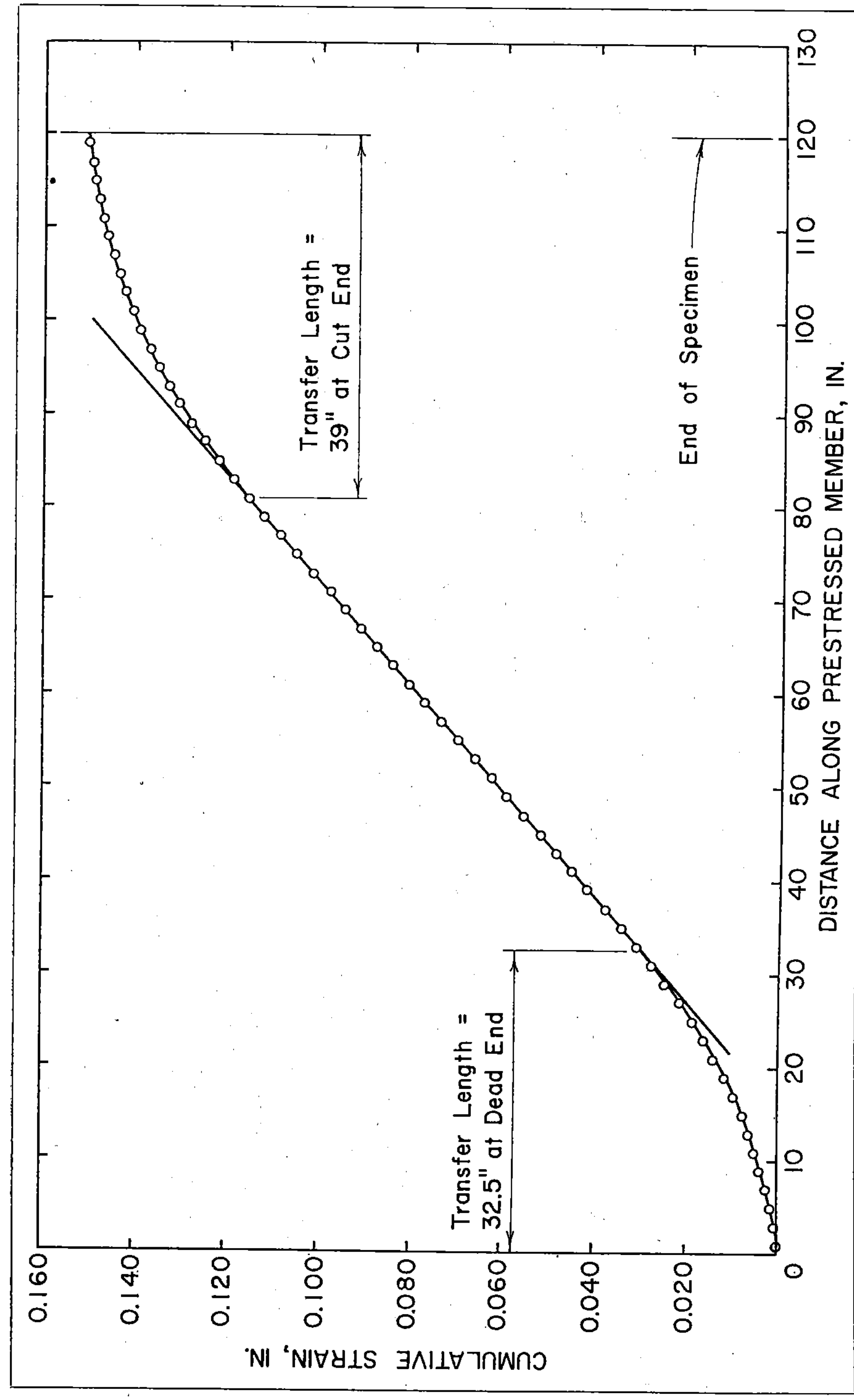

Fig. 5—Cumulative Prestress Concrete Strain-Specimen 6/10—4170 at 56 Days.

TEST RESULTS

General Considerations

The essential characteristics of the test specimens, strand tension, concrete strength, and concrete strain are listed in Table 2. As stated earlier, target values for the steel stress and concrete stress immediately after transfer were 70 percent of the nominal ultimate strand strength, f'_s, and 60 percent of the concrete cylinder strength at transfer, f'_c. Actual values of strand and concrete stress are shown in Table 2, along with the ratios of these measured stresses to f'_s and f'_c.

The loss of prestress due to initial elastic shortening of the concrete is equal to $\epsilon_c E_s$, the reduction of strain in the strand being equal to the corresponding increase in concrete strains, ϵ_c, providing no slip occurs between the steel and concrete. In Table 2, the concrete strain $\epsilon_{c(meas.)}$, was taken equal to the slope of the straight-line portion of the cumulative strain curve which represents the average concrete strain in the zone of fully transferred prestress. The theoretical value of the concrete compressive strain due to elastic shortening is:

$$\epsilon_{c(theo.)} = \frac{f_{si} A_s}{A_s E_s + A_c E_c}$$

The measured and theoretical values of concrete strain, ϵ_c, compared in Table 2 generally show good agreement. Janney, in his investigation of single-wire transfer lengths[4] makes a similar comparison, with similar agreement between theoretical and observed concrete strains.

Transfer lengths are listed in Table 3 and are also shown in Fig. 7 for the cut and dead ends of the prestressed members at various ages after transfer of the prestress. These values represent the average of the transfer lengths at the corresponding ends of the duplicate specimens.

To facilitate comparison, all transfer lengths shown in Table 3 and Fig. 7 were adjusted to correspond

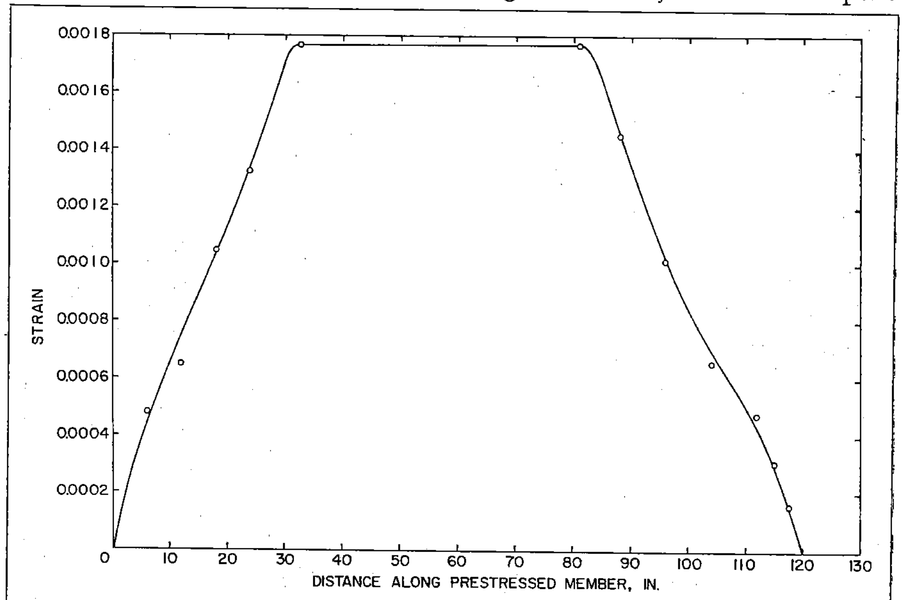

Fig. 6—Prestress Strain Obtained from Cumulative Strain Curve for Specimen 6/10—4170 at 56 Days.

Specimen Designation	Days after Transfer: At Transfer	1	3	7	14	28	56	90	180	365
	Dead End									
¼–1660	10.5	9	10	10	10	10	10	10.5	10.5	10.5
¼–2500	11	9.5	10	9.5	9.5	9.5	9	9.5	10	9
¼–3330	8.5	7.5	7	7.5	7	7	8	9.5	9	9
¼–4170	10.5	10	10.5	10.5	11.5	11	11.5	11.5	11.5	12
¼–5000	11.5	10.5	10.5	11	11.5	11.5	12	11.5	11.5	12.5
⅜–1600	20	20.5	20	20	20	19.5	21.5	19.5	20.5	20
⅜–3330	25.5	26	25.5	25.5	25.5	27	26.5	26.5	26	26
⅜–5000	21.5	20	20.5	22	23.5	23	25	25	24	25.5
½–1600	32	33	31.5	30.5	34	..	..	33	35.5	33
½–2500	35.5	35.5	36	37	36.5	36.5	37	37	37	37
½–3330	36	38	38.5	36.5	38	41	38.5	39.5	40.5	40.5
½–4170	36	34	36.5	38	36.5	34	36	36	39	38
½–5000	33.5	34	33	35	36.5	36.5	35.5	36.5	33.5	37.5
6/10–1660	33.5	34	33	34.5	34.5	33	34.5	34	32.5	33.5
6/10–2500	41.5	43	42.5	43	43	43	43.5	42.5	44	44
6/10–3330	42.5	42	40	42	41.5	43.5	42	42	41	43.5
6/10–4170	29	31.5	31	32	34	32.5	32.5	32.5	32	33.5
6/10–5000	27.5	28.5	28.5	28.5	28.5	30	29.5	29	29	32
	Cut End									
¼–1660	13	12.5	12.5	12	11.5	11.5	10.5	11.5	12.5	13
¼–2500	15	15.5	15.5	15	15	16	17	18	17	17
¼–3330	12	12	12.5	11.5	12	12	12	11.5	12	12.5
¼–4170	10	10	9.5	9.5	10	9.5	10.5	11.5	10.5	11.5
¼–5000	12.5	12	13	14.5	15	13	13.5	13	14.5	14.5
⅜–1660	24.5	26	26.5	25	26.5	26	27	27	24.5	25
⅜–3330	28.5	27.5	27	27.5	28	28.5	28	27.5	28	28
⅜–5000	25.5	25.5	25	26	26.5	26	26.5	27.5	27.5	27.5
½–1660	40.5	41	40.5	39	41.5	..	..	42	43.5	45.5
½–2500	43.5	43.5	44.5	43	45	45	45	44	44	43.5
½–3330	43.5	44.5	45	43.5	47	47.5	46	45.5	45	46
½–4170	37.5	37	37.5	36.5	38	35.5	37	36	38	37.5
½–5000	41	41	40.5	43	43.5	42	43	45	43.5	44
6/10–1660	51.5	51.5	52	51.5	51.5	51	52	52	50	51
6/10–2500	52	53	53	54	53	54	54	54	54.5	52.5
6/10–3330	49	50	49.5	50	47.5	50.5	49.5	50	49.5	50
6/10–4170	36	39	38	38	39	38.5	39	39	39	40.5
6/10–5000	39.5	39.5	39	39	40	40.5	40	39.5	40	39

Table 3—Prestress Transfer Length in Inches.

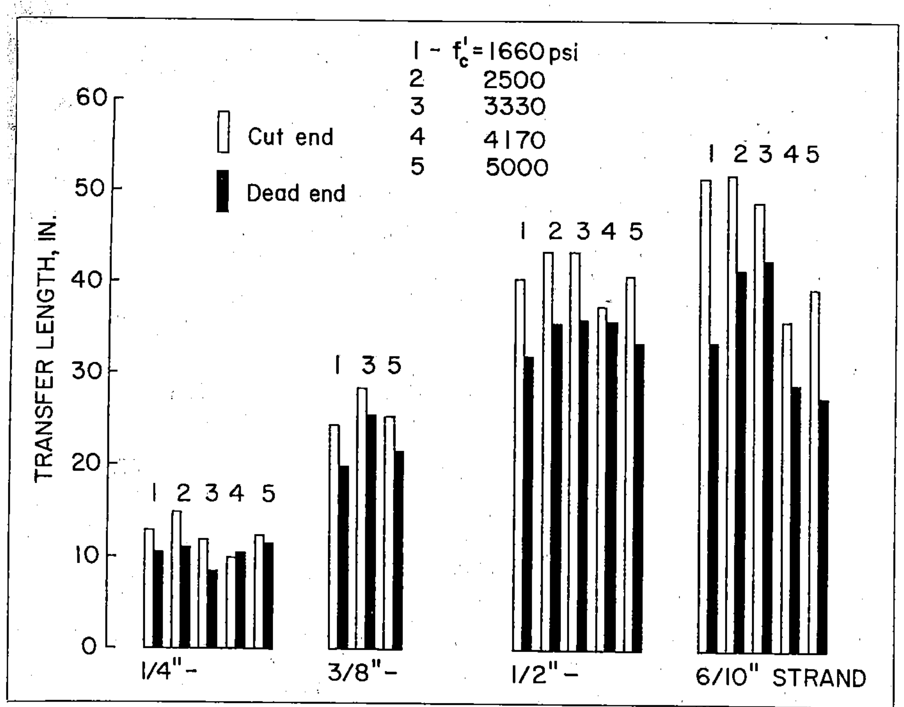

Fig. 7—Prestress Transfer Lengths Immediately After Transfer.

to the target strand stress immediately after transfer of 175,000 psi. This adjustment was made on the basis of tests reported in the Appendix. These auxiliary tests indicate that transfer length is closely proportional to effective prestress in the strand tension range of 120,000 to 175,000 psi.

Summary of Test Results

As may be seen in Fig. 7, there is no systematic variation of transfer length with concrete strength for strand up to ½ in. diameter. In the case of the 6/10 in. diameter strand, transfer length did reduce with increase in concrete strength at the cut end, but did not show a clear-cut relationship for the dead end. This will be discussed more fully in the paragraphs which follow.

The variation of transfer length with strand diameter and with time is summarized in Table 4.

It can be seen that the average transfer length at the cut ends of the specimens was approximately 20 percent greater than at the dead ends for strands of ¼, ⅜ and ½ in. diameter, and 30 percent greater for the 6/10 in. diameter strand. The amount of increase in transfer length with time does not appear to be related to the concrete strength at the time of transfer. The concrete strength in the specimens showing the greatest increase in transfer length ranged from 2500 psi to 5000 psi for the different diameters of strand.

DISCUSSION OF TEST RESULTS

Influence of Concrete Strength

Typical curves are shown in Fig. 8 which illustrate the way in which concrete strain varied along the length of the specimens after transfer of prestress. The curves for Specimens 6/10-1660 and 6/10-3330 show zero or near-zero strain for a distance of 5 to 12 inches from the cut ends of the specimens. This same unstrained region also occured in Specimen 6/10-2500, not shown in Fig. 8. Apparently the strand slipped locally through the concrete in the end regions of these specimens, and no precompression exists there.

It is interesting to note, however, that the length of specimen over which prestress is transferred, measured from the point at which the concrete strains first rise above zero, is almost the same for all specimens prestressed with the 6/10 in. diameter strand. At the dead end of the specimens the concrete strain commenced to increase immediately, indicating that no slip occurred in the end regions where the prestress was transferred to the concrete gradually. The local slip of the strand at the cut ends of the specimens was therefore apparently due to the sudden transfer of prestress associated with flame cutting of the strand.

It was also observed that local spalling occurred around each strand on the end face at the cut ends of the specimens prestressed with 6/10 in. strand. No such spalling occurred at the dead end of the specimens where the prestress was transferred more gradually.

The curves of concrete strain in Fig. 8 also show that a more rapid build-up of concrete strain occurs near the ends of the specimens made from the higher strength concretes than occurs near the ends of the lower strength specimens. The strain curves at the ends of the 1660-psi specimens are generally concave with respect to the horizontal axis, while the corresponding curves for the 5000-psi specimens are generally convex.

The distances from the end of each specimen to the point at which 75 percent and 85 percent of the full prestress strain was developed at transfer are recorded in Table 5, together with the corresponding transfer lengths. In this same table these distances are also expressed as proportions of the transfer length. It can be seen that the ratios of these distances to the transfer length tend to decrease as the concrete strength increases. This

Strand Diameter—in.		¼	⅜	½	6/10
Dead Ends of Specimens	Minimum Transfer Length at Transfer—in.	8.5	20	32	27.5
	Maximum Transfer Length at Transfer—in.	11.5	25.5	36	42.5
	Average Transfer Length at Transfer—in.	10.5	22.5	34.5	35
	Maximum Increase in Transfer Length in One Year—percent	14	19	13	16
	Average Increase in Transfer Length in One Year—percent	6	7	6	8
Cut Ends of Specimens	Minimum Transfer Length at Transfer—in.	10	24.5	37.5	36
	Maximum Transfer Length at Transfer—in.	15	28.5	43.5	52
	Average Transfer Length at Transfer—in.	12.5	26	41	45.5
	Maximum Increase in Transfer Length in One Year—percent	16	8	12	12
	Average Increase in Transfer Length in One Year—percent	10	3	5	3

Table 4—Variation of Transfer Length with Strand Diameter.

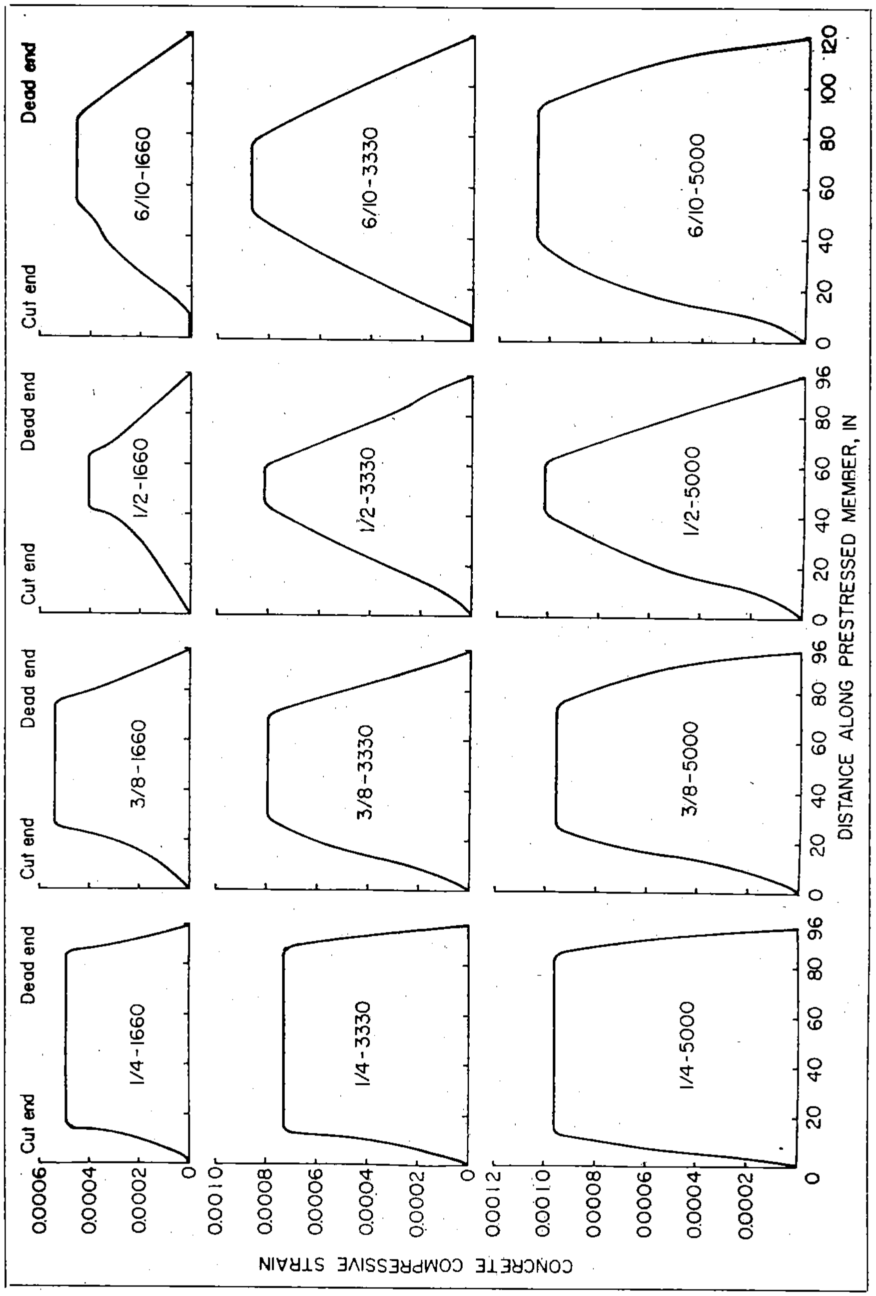

Fig. 8—Prestress Strain Curves at Transfer.

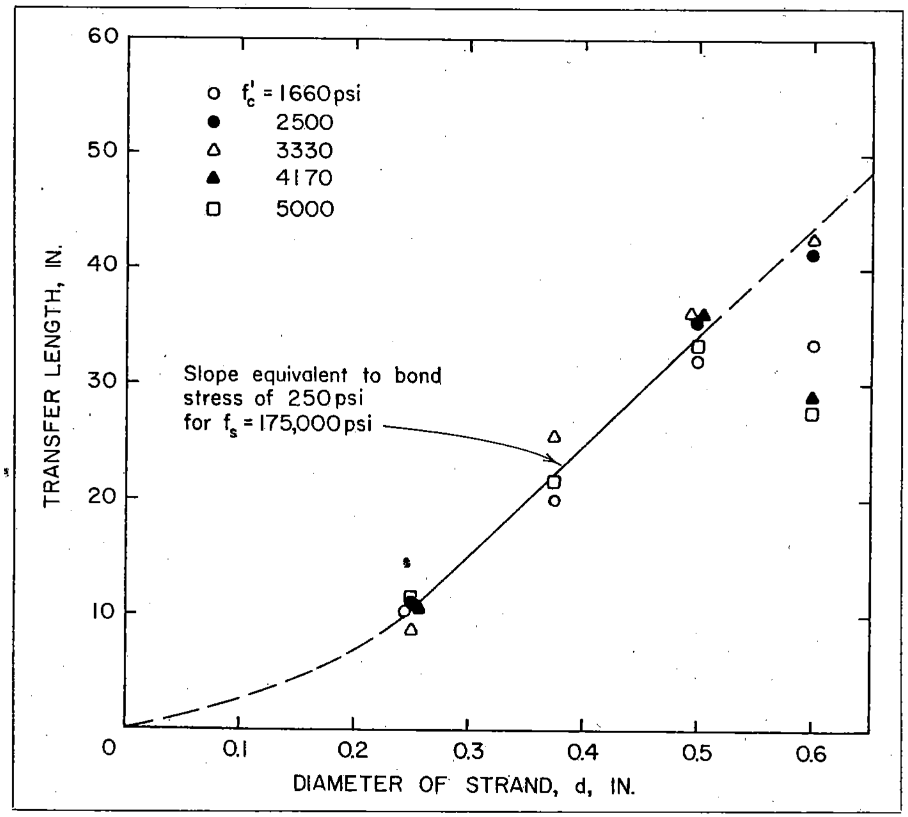

Fig. 9—Relation of Prestress Transfer Length at Dead End to Strand Diameter.

also demonstrates the more rapid build-up of prestress close to the ends of specimens made from the higher strength concretes, even though the distance to achieve full prestress did not vary systematically with concrete strength.

Influence of Strand Diameter

In Figs. 9 and 10 the transfer lengths measured at the time of transfer are plotted for the four strand diameters and five concrete lengths considered. Fig. 9 relates to the transfer length at the dead end of the specimens, i.e. where the prestress was transferred gradually, and Fig. 10 relates to the cut ends where the prestress was transferred suddenly.

It can be seen that in both figures the data from the specimens prestressed with ¼, ⅜ and ½ in. diameter strand can be represented quite closely by straight lines. The slope of these lines is equivalent to uniform bond stresses of 250 and 210 psi for gradual and sudden transfer of prestress, respectively, when the effective prestress in the strand is 175,000 psi. The dashed lines in Figs. 9 and 10, in the region below ¼ in. and above ½ in. diameter strand, indicate a possible relationship at the extremes of strand sizes.

The results obtained from the specimens prestressed with the 6⁄10 in. diameter strand fall below the proposed lines of equivalent uniform bond stress. The reason for the relatively shorter transfer lengths obtained with this strand probably lie in the slightly different surface condition of this strand as compared to

Specimen Designation	Transfer Length at Maximum concrete strain, L_t (inches) dead	cut	Length from end to 85% maximum concrete strain, L_{85} (inches) dead	cut	Length from end to 75% maximum concrete strain, L_{75} (inches) dead	cut	$\frac{L_{85}}{L_t}$ dead	cut	$\frac{L_{75}}{L_t}$ dead	cut
¼–1660	10.5	13	9.5	12.5	8.5	12	.90	.96	.81	.92
¼–2500	11	15	10.5	14.5	9.5	13.5	.95	.97	.86	.90
¼–3330	8.5	12	7	11.5	6	11	.82	.96	.71	.92
¼–4170	10.5	10	9.5	9	7	7.5	.90	.90	.67	.75
¼–5000	11.5	12.5	9.5	11.5	7.5	10	.83	.92	.65	.80
⅜–1660	20	24.5	19.5	24	18.5	23	.98	.98	.93	.94
⅜–3330	25.5	28.5	23	24	19	21	.90	.84	.75	.74
⅜–5000	21.5	25.5	16	21	14	17.5	.74	.82	.65	.69
½–1660	32	40.5	31	40	28	38.5	.97	.99	.88	.95
½–2500	35.5	43.5	34	41.5	31.5	39.5	.96	.95	.89	.91
½–3330	36	43.5	33	38	29.5	34.5	.92	.87	.82	.79
½–4170	36	37.5	30	32	26.5	29.5	.83	.85	.74	.79
½–5000	33.5	41	29.5	33	23.5	27.5	.88	.80	.70	.67
6/10–1660	33.5	51.5	27.5	45.5	25.5	38.5	.82	.88	.76	.75
6/10–2500	41.5	52	40	46	37	41.5	.96	.88	.89	.80
6/10–3330	42.5	49	35.5	43	30	38	.84	.88	.71	.78
6/10–4170	29	36	25	32.5	21	29.5	.86	.90	.72	.82
6/10–5000	27.5	39.5	21	30	17	25.5	.76	.76	.62	.65

NOTE: Above data taken from specimens immediately after transfer.

Table 5—Length from Ends of Specimens to Points of 85% and 75% of Full Prestress.

the other strands used. Whereas the ¼, ⅜ and ½ in. diameter strands were entirely clean and free from any sign of rust when received at the laboratory, the 6/10 in. diameter strand had been exposed to rain in transit and consequently there were rust spots on the strand when received.

Although this rust was removed as thoroughly as possible, it is thought that the surface of the strand was slightly pitted from the rusting, and that as a result of this a better bond was achieved between the concrete and this strand than was possible in the case of the other strands which were perfectly smooth and clean.

CONCLUSIONS

Study of the test data in this investigation lead to the following conclusions:

1. For concrete cylinder strengths of 1500 to 5500 psi, concrete strength at transfer of prestress has little influence on the transfer length of clean seven-wire strands of up to and including ½ in. diameter. (Other factors which govern the minimum allowable concrete strength of time of transfer are listed in the section *Purpose.)*

2. For strands of 6/10 in. diameter slip occurred over a distance of from 5 to 12 inches at the end of members adjacent to the flame-cutting process when concrete strength at transfer was less than 3000 psi, and the total transfer length was increased correspondingly.

3. For strands of up to ½ in. dia-

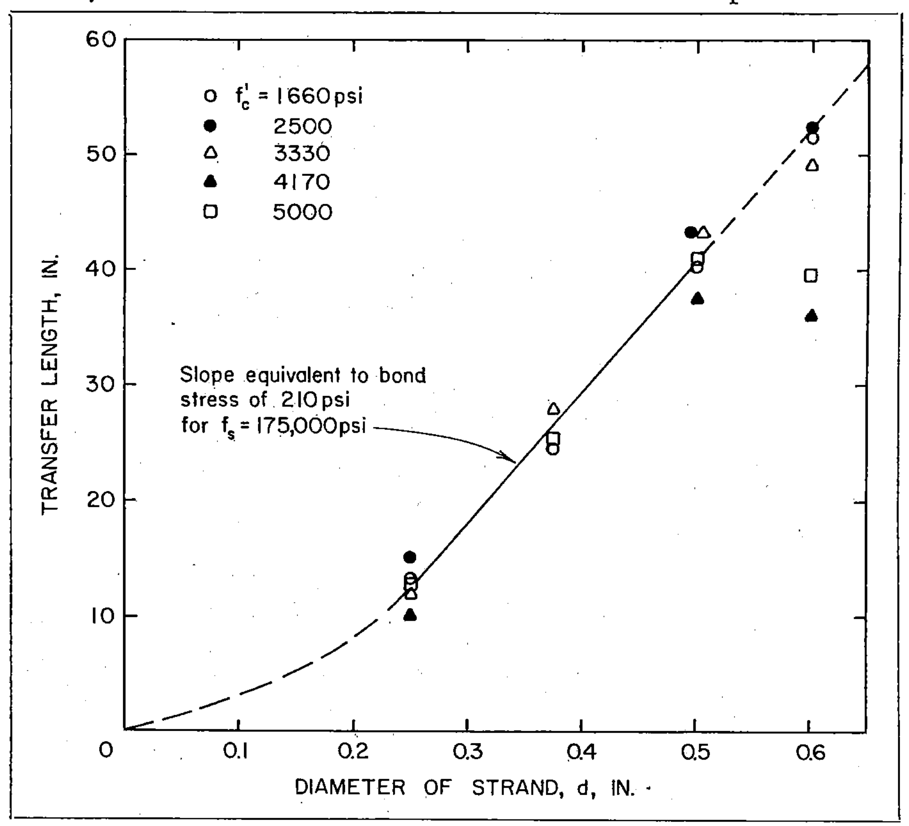

Fig. 10—Relation of Prestress Transfer Length at Cut End to Strand Diameter.

meter, the transfer lengths measured at the ends of the specimens adjacent to the flame-cutting operation were approximately 20 percent greater than the transfer lengths measured at the opposite ends of the specimens. For 6/10 in. diameter strand, the increase was 30 percent.

4. The average increase in transfer length over a period of one year following prestress transfer was 6 percent for all sizes of strand. The maximum increase in transfer length in this same period was 19 percent. The increase in transfer length with time was apparently independent of the concrete strength at the time of transfer.

NOTATION

A_c = cross sectional area of specimen
A_s = area of strand
d = diameter
E_c = modulus of elasticity of concrete
E_s = modulus of elasticity of strand
f_c = compressive prestress in concrete
f'_c = strength in compression of 6 by 12-in. concrete cylinders
f'_s = ultimate strand strength
f_{se} = stress remaining in strand immediately after transfer
f_{si} = stress in strand just before transfer
n_s = number of strands in specimen
$\epsilon_{c(meas.)}$ = measured compressive strain in concrete after transfer
$\epsilon_{c(theo.)}$ = theoretical compressive strain in concrete after transfer

ACKNOWLEDGMENTS

The investigation reported herein was carried out in the Structural Laboratory of the Portland Cement Association and contributions were made by several members of the laboratory staff. Particular credit is due to B. W. Fullhart and Arne G. Aabey for the contributions to the testing and instrumentation work involved.

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APPENDIX

A limited number of specimens were fabricated to investigate the influence on transfer length of the following variables:

1. strand tension,
2. reinforcing spirals around the strand in the transfer region, and
3. the use of three-wire strand as compared to seven-wire strand of the same nominal diameter and cross sectional area.

The concrete strength chosen for all test specimens was 3330 psi. The strand diameter used for 1 and 2

Stand Size (in.)	Strand Area, (sq. in.)	All Dimensions in Inches					Length of Specimens (ft)
		A	B	C	D	E	
5/16	0.058	3¾	5¼	2¾	1¼	1¼	8
3/8	0.080	4½	6 9/32	3 9/32	1½	1½	8

Table 1A—Auxiliary Test Specimen Dimensions. (See Fig. 1)

above was 3/8 inch; 5/16 inch diameter strand was used for item 3 above.

Description of Test Specimens

The specimens used in investigating the influence of strand tension on transfer length, and the effect of end spiral reinforcement, were dimensioned as shown in Fig. 1 for the 3/8 in. diameter strand. The cross sectional dimensions of the specimens used to compare the transfer length of three-wire strand and seven-wire strand are shown in Tabel 1A. The dimensions of the specimens containing 3/8 in. diameter strand are repeated for comparison.

The methods of fabrication of these specimens were the same as for the specimens of the main investigation, with the exception that the specimens used to study items 1 and 3 were cast singly. Designation of the specimens was consistent with the system outlined previously. Table 2A shows the designations and the description of the specimens in terms of the chief variable.

The spiral reinforcing for Specimen 3/8-3330f was fabricated in the laboratory. A single wire from a length of 3/8 in. strand was used to form each spiral. The diameter of each spiral was approximately 2.5 inches, the pitch was also 2.5 inches, and the length 30 inches. A spiral was placed concentrically around each strand at both ends of the specimen.

Materials

All data pertinent to the 3/8 in. diameter strand will be found in the main body of the report. Stress-strain curves for the 5/16 in. diameter strand are shown in Fig. 1A. The concrete mix and proportions for the test specimens were the same as described in the main body of the report.

Test Results

Table 3A shows the characteristics of the auxiliary test specimens. The transfer lengths for these specimens are shown in Table 4A.

Effect of Strand Tension—Specimens 3/8-3330c to e were tested to investigate the influence on transfer length of the magnitude of effective prestress. It can be seen from Table 4A and Fig. 2A that the transfer length is essentially proportional to prestress for both cut and dead ends, for values of prestress between 120 ksi and 175 ksi.

Effect of Spirals—Specimens 3/8-3330f and 3/8-3330g were tested to study the effect on transfer length of

Designation	Description of Variable
3/8—3330 c	strand tension, 165 ksi after transfer
3/8—3330 d	strand tension, 140 ksi after transfer
3/8—3330 e	strand tension, 120 ksi after transfer
3/8—3330 f	with spiral end reinforcement about strand
3/8—3330 g	without spiral end reinforcement about strand
5/16—3330 a	specimen prestressed with three-wire strand
5/16—3330 b	specimen prestressed with seven-wire strand

Table 2A—Designation and Description of Auxiliary Test Specimens.

Table 3A—Characteristics of Auxiliary Test Specimens.

Specimen No.	No. of Strands	Steel Stress, f_{st}, before transfer (ksi)	Steel Stress, f_{se}, immediately after transfer (ksi)	Ratio $\frac{f_{se}}{f'_s}$	Prestress in Concrete $f_c = n_s x f_{se} \frac{A_s}{A_c}$ (psi)	Concrete Cylinder Strength f'_c (psi)	Ratio $\frac{f_c}{f'_c}$	Measured Modulus of Elasticity of Concrete, E_c millions of psi
⅜—3330c	4	187.3	164.8	0.66	1860	3250	.57	2.53
⅜—3330d	5	166.1	141.5	0.57	2000	3450	.58	2.67
⅜—3330e	6	144.9	119.1	0.48	2020	3400	.59	2.42
⅜—3330f	4	167.5	146.7	0.59	1660	3150	.53	2.66
⅜—3330g	4	167.5	146.0	0.58	1650	3150	.52	2.66
5⁄16—3330a	4	173.5	154.9	0.62	1830	3550	.52	2.63
5⁄16—3330b	4	183.8	161.3	0.65	1900	3700	.51	2.69

Table 4A—Auxiliary Test Prestress Transfer Lengths (in inches).

Specimen	At Transfer	Days after transfer 7	Days after transfer 28
Dead End			
⅜—3330c (f_{se} = 165 *ksi*)	21	22	23
⅜—3330d (f_{se} = 140 *ksi*)	15	16	17
⅜—3330e (f_{se} = 120 *ksi*)	12	13	12
⅜—3330f (spiral)	21	21	23
⅜—3330g (no spiral)	23	23	23
5⁄16—3330a (3-wire strand)	18	20	19
5⁄16—3330b (7-wire strand)	24	25	27
Cut End			
⅜—3330c (f_{se} = 165 *ksi*)	32	32	31
⅜—3330d (f_{se} = 140 *ksi*)	26	26	26
⅜—3330e (f_{se} = 120 *ksi*)	23	23	23
⅜—3330f (spiral)	27	27	25
⅜—3330g (no spiral)	33	33	33
5⁄16—3330a (3-wire strand)	22	23	22
5⁄16—3330b (7-wire strand)	23	23	22

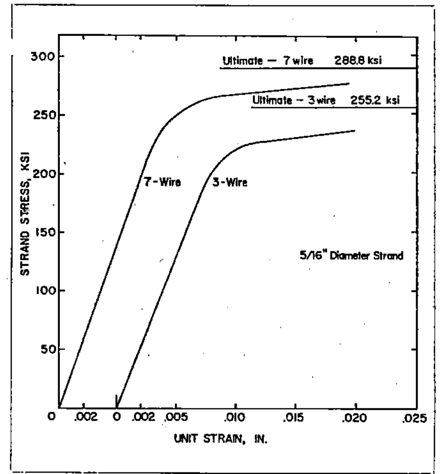

Fig. 1A—Stress-Strain Curves of 5/16 in. Diameter Strand.

a smooth wire spiral placed concentrically about each strand. Referring to Table 4A, Specimen 3/8-3330f, having the spirals about the strand shows a slightly shorter transfer length at transfer, at the dead end. The difference is greater at the cut end, the spirals producing a 15 percent transfer length reduction.

Effect of Strand Type—The specimens containing the 5⁄16 in. diameter strand were tested to study the influence of the number of wires in the strand on the transfer length. From the data presented in Tables 3A, and 4A, it is seen that both specimens had similar concrete cylinder strengths, similar initial effective prestress, and the strand was of the same nominal cross section. However, in one case the strand was made up of seven wires and in the other of three wires.

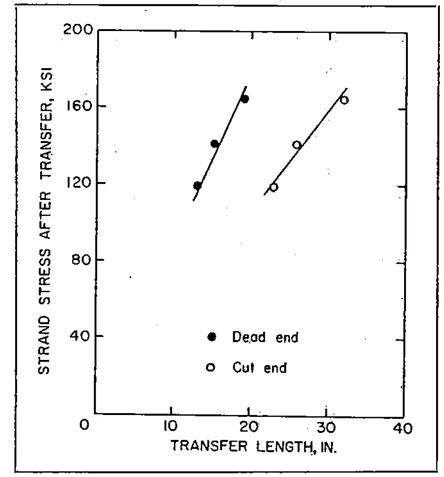

Fig. 2A—Effect of Strand Tension on Transfer Length for Specimens Prestressed with ⅜ in. Diameter Strand.

The transfer length of the three-wire strand was 25 percent less than that of the seven-wire strand at the dead end but no significant difference was found at the cut end. The difference at the dead end may have been due to the strand pitch which was 4¹¹⁄₁₆ in. for the seven-wire strand, 2⅝ in. for the three-wire strand.