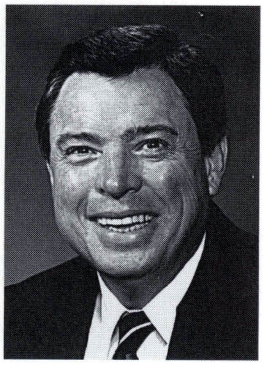
Development Length and Lateral Spacing Requirements of Prestressing Strand for Prestressed Concrete Bridge Girders



J. Harold Deatherage
Ph.D., P.E.
Associate Professor of
Civil Engineering
University of Tennessee
Knoxville, Tennessee

Edwin G. Burdette
Ph.D., P.E.
Professor of Civil Engineering
University of Tennessee
Knoxville, Tennessee

Chong Key Chew, Ph.D.
Structural Engineer
Malaysia
(Formerly, doctoral student at
University of Tennessee
Knoxville, Tennessee)

To respond to an FHWA memorandum restricting the use of certain sizes of seven-wire strand in prestressed concrete girders, the PCI sponsored a research program at the University of Tennessee at Knoxville. Twenty full-scale AASHTO Type I beams with various strand diameters were statically tested to failure. Transfer and development lengths for ½ in. (13 mm), ½ in. special (13.3 mm), $\frac{9}{16}$ in. (14 mm) and 0.6 in. (15 mm) diameter strands were determined. Also, minimum strand spacing was investigated for ½ in. (13 mm) diameter strand. Factors that affect both transfer and development length are evaluated and discussed. Based on the test data, equations for transfer and developemnt length of strand are proposed. The computed and measured moment capacities of the girder sections are compared and reasons for variations are explained. It is concluded that the use of 0.6 in. (15 mm) diameter strand should be accepted as standard practice and a center-to-center spacing of 1.75 in. (44.5 mm) should be allowed for ½ in. (13 mm) diameter strand.

In a memorandum dated October 26, 1988, the Federal Highway Administration (FHWA) imposed several restrictions on the use of seven-wire prestressing strand in prestressed concrete girders. Criteria were established for minimum strand spacing and for development length requirements of prestressing strand with varying diameters.

These restrictions stemmed primarily from the results of some research reported in Ref. 1.

Specifically, the FHWA restrictions were as follows:

1. The use of 0.6 in. (15 mm) diameter strand would be prohibited.

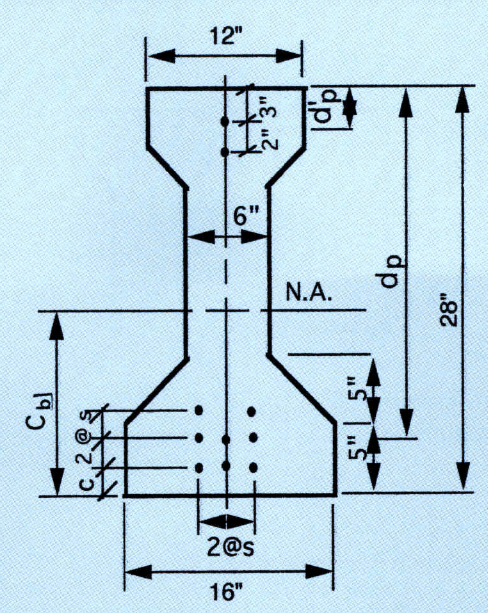
2. Minimum center-to-center strand spacing would be four times the nominal strand diameter.

3. Development length for all strand sizes would be 1.6 times the value obtained from AASHTO Eq. (9-32).

4. Where the strand is debonded (blanketed), the development length would be 2.0 times the value obtained from AASHTO Eq. (9-32).

These restrictions placed severe burdens on producers of precast, prestressed concrete bridge members. In several cases, projects had to be redesigned or alternate materials were selected for construction. Consequently, the Precast/Prestressed Concrete Institute (PCI) undertook a research program to generate additional data for comparison with the findings reported in Ref. 1.

In April 1989, an experimental research project was initiated at the University of Tennessee at Knoxville (UTK) to investigate the transfer and development length of 270 ksi (1860 MPa), low-relaxation seven-wire prestressing strand for prestressed concrete girders. This research project, which primarily involved fabrication and testing of 20 full-scale AASHTO Type I prestressed concrete bridge beams, was completed in November 1989.



AREA = 276 SQ.IN. (.178 m^2)

I = 22750 IN.^{4} (946,926 cm^4)

C_b = 12.59 IN. (320 mm)

d_p : Depth to the centroid of bottom prestressed steel strand

d'_p : Depth to the centroid of top prestressed steel strand

s: strand spacing, in.

To convert from inches to mm, multiply by 25.4.

dia (in.)	c (in.)
0.5"	2.0"
0.525"	2.0"
9/16"	2.0"
0.6"	2.5"

Fig. 1. AASHTO Type I beam cross section. Strand pattern and strand spacing.

RESEARCH OBJECTIVES

Transfer and development lengths for ½ in. (13 mm), ½ in. special (13.3 mm), $^9/_{16}$ in. (14 mm) and 0.6 in. (15 mm) diameter strands were determined. Care was taken to fabricate the specimens in accordance with standard industry practice and, at the same time, to use the practices which are considered most likely to influence the transfer and development lengths of strand.

For example, each of the specimens was detensioned using flame cutting rather than gradual detensioning. Also, strand was protected as much as possible to ensure that "mill conditions" would be simulated; i.e., weathering would not be a factor in the analysis.

Several specimens were evaluated using ½ in. (13 mm) diameter strand provided by various strand suppliers. Comparisons were made to determine whether the manufacturing process influences transfer and development lengths. The effect of reducing the strand spacing from 4.0 diameters to 3.5 was also studied.

LITERATURE REVIEW

Since 1950, much research has been reported on the transfer and development lengths of seven-wire prestressing strand. An extensive review of this literature is presented in the final report on the research reported in this paper.[2] Unfortunately, no analytical model has evolved from this research which can satisfactorily predict the bond development characteristics of prestressing strand. This inability to analytically predict the behavior of strand within its development length places a particularly high premium on test results which purport to provide some definition of transfer and development lengths and to identify and quantify some of the variables affecting them.

In 1954, Janney[3] explained the mechanism of bond between prestressing steel and concrete as consisting of adhesion, friction and mechanical resistance. This work was followed by considerable other research,[4-8] notably that by Hanson and Kaar,[4] which led to the American Association of State Highway and Transportation Officials (AASHTO) and American Concrete Institute (ACI) Code requirements which have been in use for over a decade. Then, a study reported by Cousins, Johnston and Zia[1] raised serious questions about the validity of the AASHTO/ACI equation for strand development length and led to the FHWA memorandum of October 26, 1988.

The uncertainty created in the prestressed concrete industry by the 1988 FHWA memorandum led to the initiation of several research projects,[9,10] including the one reported herein.[2] The

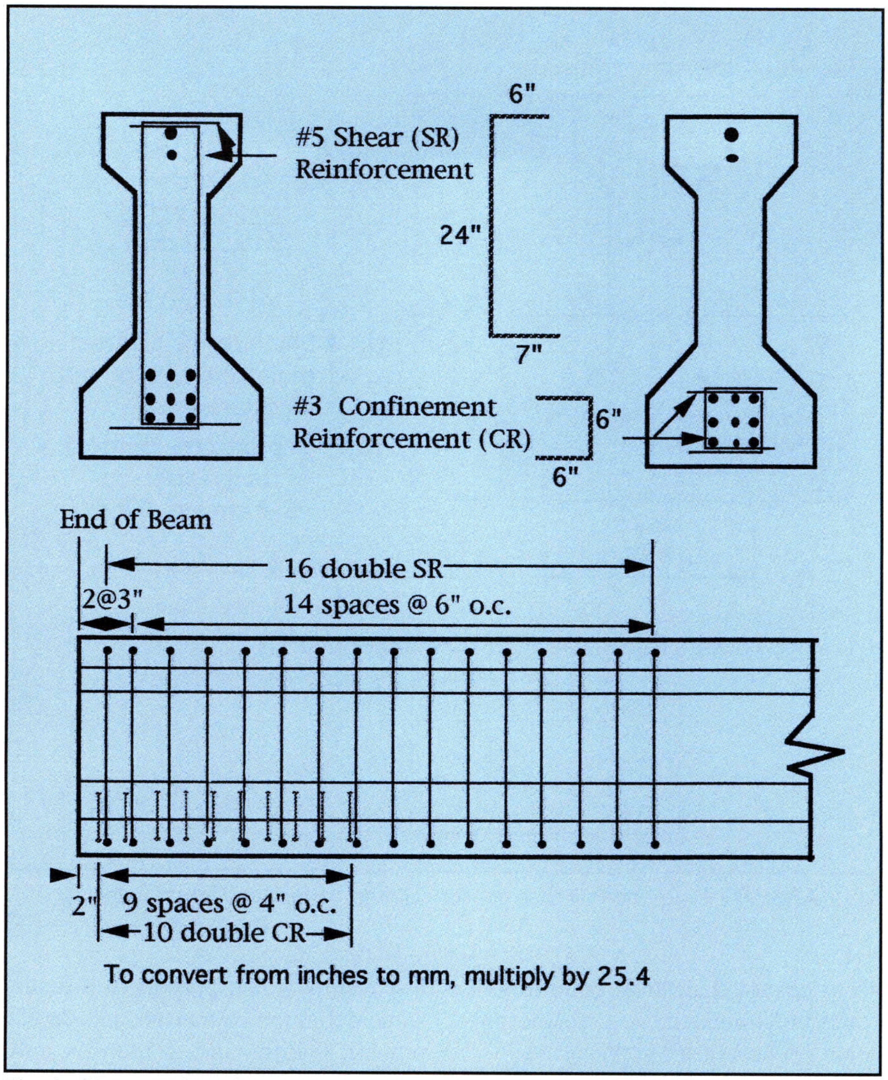


Fig. 2. Shear and confinement reinforcement in each end of beam.

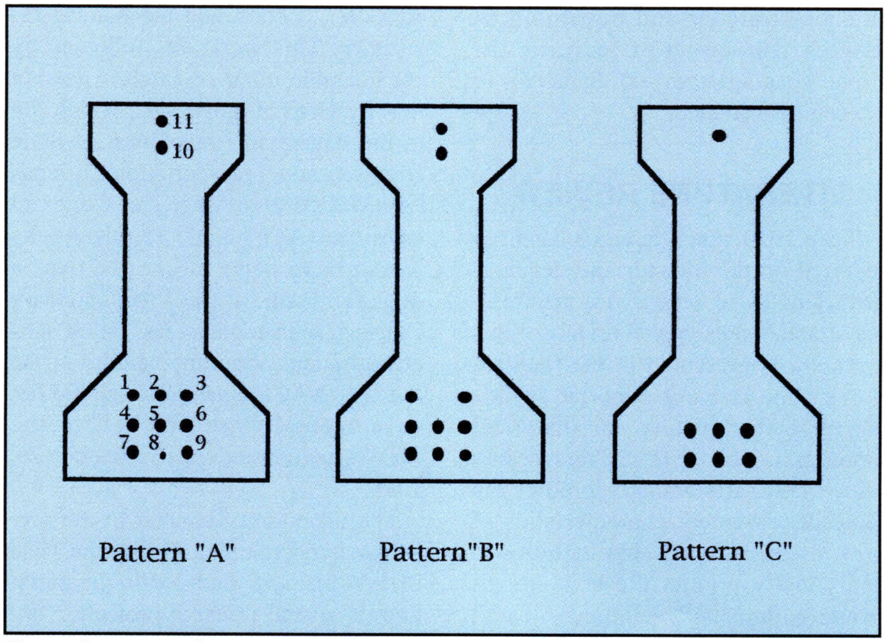


Fig. 3. Strand configuration for Patterns A, B and C.

work reported here, performed at the University of Tennessee in 1989, generated data which shed further light on the prediction of transfer and development lengths of prestressing strand.

SPECIMEN DESIGN AND DESIGNATION

All beams were 31 ft (9.45 m) long, designed to be sufficient in length for two development length tests on each beam. The beam specimens were designed so that each end of the beams provided for a set of strand end-slip measurements, a set of transfer length data and a development length test. Fig. 1 shows the cross-sectional properties and dimensions of the beams. Fig. 2 shows the details of shear and confinement reinforcement used in all beams. These details are typical of those used by the Tennessee Department of Transportation (TDOT).

Sixteen beams divided into four groups utilized strands from Florida Wire and Cable Co. (FWC) at a strand spacing of 2 in. (51 mm). Four beams in each of the four groups with 2 in. (51 mm) strand spacing were prestressed with strands of ½ in. (13 mm), ½ in. special (13.3 mm), ⁹⁄₁₆ in. (14 mm) or 0.6 in. (15 mm) in diameter. The remaining four beams in a strand manufacturer's group had 1.75 in. (44.5 mm) strand spacing, and each was prestressed with ½ in. (13 mm), 270 ksi (1860 MPa), low-relaxation strand from one of the following manufacturers: Shinko Wire America Inc. (SWAI), Union Wire Rope (UWR), FWC or American Spring Wire Corp. (ASW).

The initial prestress in all strands of the test beams was designed to be 203 ksi (1400 MPa), or 75 percent of the specified ultimate strength of the strands. Elongation measurements were used in the field to obtain this stress. The number of prestressing strands used in a beam varied with the size of the strands. Fig. 3 shows the various strand configurations used.

All strands were received encased in moisture-proof wrapping and appeared to be free of rust. These strands were shiny when prestressing was applied. The surface condition of these strands is labeled as "Milled." However, sev-

Table 1. Summary of beam properties.

Specimen designation	Strand surface	Strand pattern	Strand spacing, in.	Depth of steel, in.		Steel area, sq in.	
				Bottom	Top	Bottom	Top
5-1-EXT	MILLED	B	2.00	24.25	4	1.224	0.306
5-1-INT	MILLED	B	2.00	24.25	4	1.224	0.306
5-2-EXT	MILLED	B	2.00	24.25	4	1.224	0.306
5-2-INT	MILLED	B	2.00	24.25	4	1.224	0.306
5-3-EXT	W-1DAY	B	2.00	24.25	4	1.224	0.306
5-3-INT	W-1DAY	B	2.00	24.25	4	1.224	0.306
5-4-EXT	W-1DAY	B	2.00	24.25	4	1.224	0.306
5-4-INT	W-1DAY	B	2.00	24.25	4	1.224	0.306
5-SWAI-EAST	W-3 DAYS	B	1.75	24.47	4	1.224	0.306
5-SWAI-WEST	W-3 DAYS	B	1.75	24.47	4	1.224	0.306
5-UWR-EAST	W-3 DAYS	B	1.75	24.47	4	1.224	0.306
5-UWR-WEST	W-3 DAYS	B	1.75	24.47	4	1.224	0.306
5-FWC-EAST	W-3 DAYS	B	1.75	24.47	4	1.224	0.306
5-FWC-WEST	W-3 DAYS	B	1.75	24.47	4	1.224	0.306
5-ASW-EAST	W-3 DAYS	B	1.75	24.47	4	1.224	0.306
5-ASW-WEST	W-3 DAYS	B	1.75	24.47	4	1.224	0.306
5S-1-EXT	MILLED	A	2.00	24.00	4	1.503	0.334
5S-1-INT	MILLED	A	2.00	24.00	4	1.503	0.334
5S-2-EXT	MILLED	A	2.00	24.00	4	1.503	0.334
5S-2-INT	MILLED	A	2.00	24.00	4	1.503	0.334
5S-3-EXT	W-3 DAYS	B	2.00	24.25	4	1.336	0.334
5S-3-INT	W-3 DAYS	B	2.00	24.25	4	1.336	0.334
5S-4-EXT	W-3 DAYS	B	2.00	24.25	4	1.336	0.334
5S-4-INT	W-3 DAYS	B	2.00	24.25	4	1.336	0.334
916-1-EXT	MILLED	B	2.00	24.25	4	1.536	0.384
916-1-INT	MILLED	B	2.00	24.25	4	1.536	0.384
916-2-EXT	MILLED	B	2.00	24.25	4	1.536	0.384
916-2-INT	MILLED	B	2.00	24.25	4	1.536	0.384
916-3-EXT	W-3 DAYS	C	2.00	25.00	3	1.152	0.192
916-3-INT	W-3 DAYS	C	2.00	25.00	3	1.152	0.192
916-4-EXT	W-3 DAYS	C	2.00	25.00	3	1.152	0.192
916-4-INT	W-3 DAYS	C	2.00	25.00	3	1.152	0.192
6-1-EXT	MILLED	C	2.50	25.00	3	1.302	0.215
6-1-INT	MILLED	C	2.50	25.00	3	1.302	0.215
6-2-EXT	MILLED	C	2.50	25.00	3	1.302	0.215
6-2-INT	MILLED	C	2.50	25.00	3	1.302	0.215
6-3-EXT	MILLED	C	2.50	25.00	3	1.302	0.215
6-3-INT	MILLED	C	2.50	25.00	3	1.302	0.215
6-4-EXT	MILLED	C	2.50	25.00	3	1.302	0.215
6-4-INT	MILLED	C	2.50	25.00	3	1.302	0.215

W = Weathered

Note: 1 in. = 25.4 mm; 1 sq in. = 645 mm^2.

eral beams used strands that had been exposed to weathering in the casting bed for a few days before the concrete was cast.

The duration of weathering for these strands is indicated in Table 1 under the heading "Strand surface." Table 1 also summarizes the strand configuration used in various beam specimens, including the areas of both the top and bottom strands, and the distances to the centroids of the top and bottom strands measured from the top of each beam.

A three-part designation is used to identify an end of a beam, as illustrated by "5S-1-EXT." The first part refers to the diameter of the strands used in a beam where:

5 = ½ in. (13 mm) strand, nominal diameter of 0.5 in. (12.7 mm)
5S = ½ in. special strand, nominal diameter of 0.5224 in. (13.3 mm)
916 = $\frac{9}{16}$ in. (14 mm) strand, nominal diameter of 0.5625 in. (14.3 mm)
6 = 0.6 in. (15 mm) strand, nominal diameter of 0.6 in. (15.2 mm)

The second part of the designation refers to one of the beams prestressed with the strands, and the third part refers to a specific end of this beam. The INT or EXT refers to the interior or exterior end of a beam as defined in Fig. 4. For the beams from the strand manufacturers' group, the second part of the designation refers to the name of the manufacturer and the third part refers to an end of the beam.

MATERIALS

All prestressing steel used was seven-wire, low-relaxation strand with a specified ultimate tensile strength of 270 ksi (1860 MPa). Strands of four different sizes supplied by FWC were ½ in. (13 mm), ½ in. special (13.3 mm), $\frac{9}{16}$ in. (14 mm), and 0.6 in. (15 mm) diameter strands. Additional ½ in. (13 mm) diameter strands were furnished by three other manufacturers: SWAI, UWR and ASW.

Nominal diameter (d_b), cross-sectional area (A_{ps}) and pitch of twist of the outer wires of the strands are listed in Table 2. The pitch of twist is the distance along the length of the strand over which a wire of the strand makes a complete revolution.

All shear and confinement reinforcement used in the bridge girders was of ASTM A-615, Grade 60 reinforcing steel. The configuration was consistent with current (TDOT) specifications. A TDOT mix design for 28-day concrete compressive strength of 5000 psi (34.5 MPa) was used. The concrete mix design is provided in Table 3.

FABRICATION OF SPECIMENS

All test specimens were fabricated by a local producer in accordance with the generally accepted production practices approved by the PCI Plant Certification

Table 2. Properties of prestressing strand.

Strand size	Diameter (in.)	Area of prestressing steel, A_{ps} (sq in.)	Pitch of outer wires (in.)
½ in.	0.5	0.153	7
½ in. special	0.5224	0.167	7
⁹⁄₁₆ in.	0.5625	0.192	8.38
0.6 in.	0.6	0.217	9

Note: 1 in. = 25.4 mm; 1 sq in. = 645 mm^2.

Table 3. Concrete mix design.

Quantity	Description
752 lb	Type I cement (Signal Mountain)
1920 lb	No. 67 coarse aggregate (American Limestone Co.)
1326 lb	Fine aggregate manufactured sand (American Limestone Co.)
21.2 oz.	Low range pozzolin 300 (Master Builders Inc.)
35 gal.	Water

Note: 1 lb = 0.454 kg; 1 oz. = 30 ml; 1 gal. = 3.8 l.

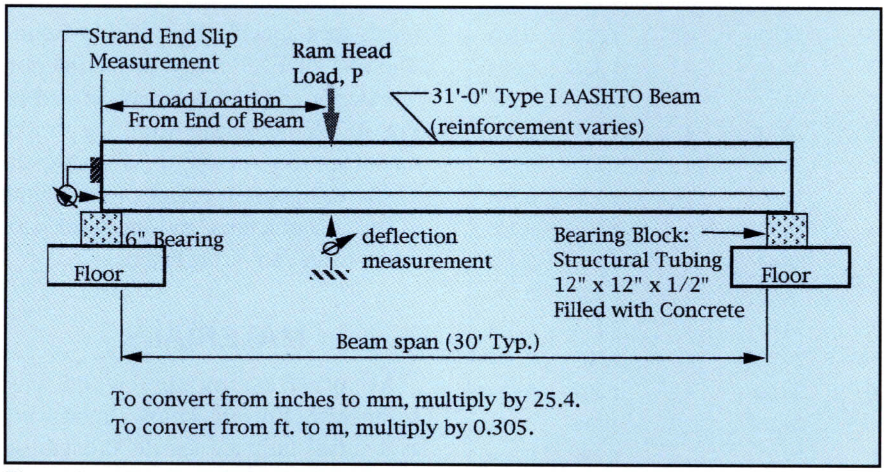


Fig. 4. Loading arrangement for development length tests.

Program. Two beams from each of the strand diameter groups were cast simultaneously, end to end, in a 123 ft 4 in. (37.6 m) long prestressing bed. The four beams having 1.75 in. (44.5 mm) strand spacing were cast individually, each with strands solely from one of the four manufacturers. All strands were initially stressed to a tension of 203 ksi (1400 MPa).

Specimens were steam cured for approximately 16 hours. The transfer of the prestress force was made when the concrete compressive strength reached a minimum of 4000 psi (27.6 MPa), except for two cases in which the prestress was transferred when the compressive strengths were 3350 and 3750 psi (23.1 and 25.8 MPa). Transfer of the prestress force was achieved by simultaneously flame cutting the strands at both ends of each beam, one strand at a time.

INSTRUMENTATION AND TEST PROCEDURE

After all the strands in each beam had been tensioned to 5 kips (22.2 kN) each in the casting bed, electrical resistance strain gauges were bonded parallel to the longitudinal axis of the helical individual outer wires of the twisted strands to monitor any changes in strain. These gauges were then waterproofed and mechanically protected.

The gauges were located from the end of each beam at a distance equal to the estimated development length. Strain readings were zeroed before additional tensile force was applied to the strands, and the changes in strain were monitored before casting of concrete, just before and just after prestress transfer, and before the static test to failure.

Transfer Length Measurements

Transfer length measurements were made on both ends of each beam using the following method. After the forms were removed, mechanical gauge points were affixed to both sides of the beam, using an appropriate adhesive. Starting from each end of the beam, 15 gauge points were equally spaced at about 4.92 in. (125 mm).

The gauge points were located along the neutral axis (NA) of the beam and along the center of gravity of the steel (CGS). A mechanical strain indicator, having a nominal gauge length of 9.82 in. (250 mm) and a precision of 0.0001 in. (0.0025 mm) was used to measure the precise lengths between the gauge points immediately before and after detensioning of all the strands.

The total deformation on the concrete surface over a gauge length is the algebraic difference in two respective readings. The average strain is the total deformation divided by the gauge length, and it is assumed to occur at the middle point of the gauge length. The average of the average strains of the corresponding middle points on both sides of the beam was calculated and plotted against the longitudinal distance of the middle points from the end of the beam. Such a plot of transfer length strain distributions was made for the NA and for the CGS on each end of the beam.

Development Length Tests

Bearing 6 in. (152 mm) at each end onto two supporting steel tubes filled with concrete, all test beams were individually loaded using a hydraulic ram as illustrated in Fig. 4. The displacement at the top of each beam at the load point was monitored by a linear variable differential transformer (LVDT).

The displacement measured by the LVDT was used to control the movement of the hydraulic ram head. A load cell attached to the ram head monitored the applied force of the ram. Dial gauges were mounted on all the bottom strands at the loaded end of each beam to measure any strand end slippage during the test.

Attempts were made to determine iteratively the full development length of the beams. Load was applied on a beam at a distance from the end of

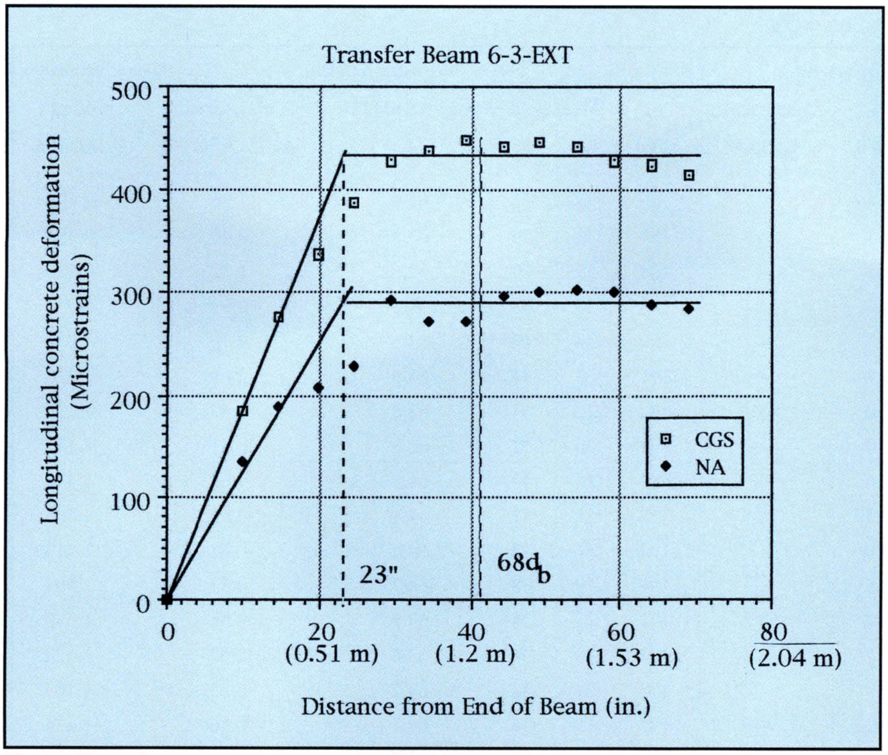


Fig. 5. Transfer length strain distribution diagram for beams.

beam equal to the estimated full development length for the type of strands in the beam. If end slip (bond failure) of any of the strands occurred before reaching the ultimate flexural compression failure, then subsequent tests of the beams with the same strands were made with the load located at a longer distance from the end of the beam. Conversely, if flexural compression failure occurred without any strand slippage, subsequent tests were conducted with the load at a shorter distance from the end of the beam.

TEST RESULTS

Considerable experimental data have been gathered in the UTK test program. At each end of the test beams, a set of measurements of transfer length, strand end slip and steel strain was obtained at strand release during the fabrication process, and load vs. deflection and load vs. steel strain relationships were acquired during the development length test. The ends of strands were gauged during the test and any end slips detected were recorded. The ultimate mode of failure for each test, either shear or flexure, was identified.

Out of the total of 20 full-scale AASHTO Type I prestressed concrete bridge beams, 39 development length tests were successfully performed and 40 sets of transfer length strain distribution data were obtained. These test results and data are presented in the following subsections, with interpretation of each type of data.

Transfer Length

Fig. 5 presents a typical transfer length concrete strain distribution diagram upon prestress transfer. Two subsets of data points are plotted in the figure. Each data point represents the average of the corresponding strain measurements from both side faces of the end of each beam. The subset with the larger strains relates to the data from the CGS, while the one with the smaller strains relates to the data from the NA.

The transfer length is defined as the distance required to transfer the fully effective prestressing force from the strand to the concrete. In other words, transfer length is the length of bond from the free end of the strand to the point where the prestressing force is fully effective. The bond resistance that exists at the ends of a beam immediately after prestress transfer is specifically called the transfer bond.

Because multiple layers of strands were used in the beam, the measured concrete strain was the average effect of the transfer bond of all the strands. Since the concrete strain is linearly proportional to the compressive force at any section for low concrete stress, the average steel stress gradient (or the transfer bond) of the strands can be calculated from the slope of the concrete strain vs. transfer length curve in Fig. 5.

Ideally, the strains in the concrete would remain nearly constant beyond the transfer length unless the beam is subjected to transverse loadings. The constant concrete strains imply that a horizontal line can be constructed for the portion of the beam beyond the transfer length. Some random deviations in the data points from the supposedly horizontal portion of the strain distribution diagram are apparent. The deviations are probably due to the nonhomogeneous nature of concrete and the limited precision of the measurements. It is reasonable to assume that such random errors also exist within the transfer length, thereby making the reconstruction of the actual concrete strain distribution diagram there less definitive.

Careful interpretation of the data points obtained is essential to reconstruct the actual strain distribution diagram correctly and determine the transfer length. Previous studies[4-6] on the bond characteristics of prestressing strands have consistently demonstrated that the bond behavior of the strands is characterized by small elasticity and large plasticity. The bond behavior implies that the transfer bond is mostly constant over the transfer length. Therefore, a straight line fitting the data points can be drawn that makes a constant slope in the transfer length portion of the strain distribution diagram. The intersection of this line with the horizontal line previously drawn as the average strain on the concrete with full effective prestress is approximately the end of the transfer bond zone.

Due to the type of instrument used which measures the average change of strain within a nominal gauge length of 9.82 in. (250 mm), a sharp change in slope of the actual strain distribution diagram near the end of the trans-

Table. 4. Summary of transfer length data of specimens.

Specimen designation	f'_{ci} (psi)	f_{si} (ksi)	Elastic shortening			f_{se} (ksi)	Transfer length, L_t				Bond strength
			Mechanical		Electrical		Measured		ACI/AASHTO	$\frac{\text{Measured}}{\text{ACI/AASHTO}}$	
			$\mu\varepsilon$	D_{fs} (ksi)	d_{fs} (ksi)		in.	d_b	d_b		U_t (kips/in.)
5-1-EXT	3780	203	580	16.4	18	186	36	72	62.0	1.16	0.791
5-1-INT	3780	203	550	15.5	18	187	30	60	62.3	0.96	0.954
5-2-EXT	4170	203	525	14.8	18	188	35	70	62.6	1.12	0.820
5-2-INT	4170	203	520	14.7	18	188	29	58	62.6	0.93	0.991
5-3-EXT	4775	203	450	12.7	–	190	23	46	63.3	0.73	1.263
5-3-INT	4775	203	420	11.8	–	191	22	44	63.6	0.69	1.326
5-4-EXT	5235	203	390	11.0	–	192	22	44	63.8	0.69	1.332
5-4-INT	5235	203	390	11.0	–	192	26	52	63.8	0.81	1.127
5-SWAI-EAST	5129	203	340	9.6	11	193	20	40	64.3	0.62	1.476
5-SWAI-WEST	5129	203	330	9.3	11	193	21	42	64.4	0.65	1.408
5-UWR-EAST	5553	203	305	8.6	–	194	21	42	64.6	0.65	1.413
5-UWR-WEST	5553	203	300	8.5	–	194	19	38	64.7	0.59	1.563
5-FWC-EAST	4775	203	380	10.7	–	192	18	36	63.9	0.56	1.630
5-FWC-WEST	4775	203	415	11.7	–	191	18	36	63.6	0.57	1.622
5-ASW-EAST	5154	203	350	9.9	–	193	21	42	64.2	0.65	1.403
5-ASW-WEST	5154	203	365	10.3	–	192	18	36	64.1	0.56	1.634
5S-1-EXT	5340	203	440	12.2	13	190	33	63	63.4	1.00	0.963
5S-1-INT	5340	203	410	11.4	13	191	33	63	63.7	0.99	0.967
5S-2-EXT	4950	203	430	11.9	13	191	34	65	63.5	1.02	0.936
5S-2-INT	4950	203	415	11.5	13	191	30	57	63.7	0.90	1.063
5S-3-EXT	5410	203	430	11.9	12	191	31	59	63.5	0.93	1.027
5S-3-INT	5410	203	455	12.6	12	190	36	69	63.3	1.09	0.881
5S-4-EXT	5300	203	450	12.5	12	190	35	67	63.3	1.06	0.907
5S-4-INT	5300	203	440	12.2	12	190	22	42	63.4	0.66	1.445
916-1-EXT	3360	203	680	19.9	18	183	42	75	60.9	1.23	0.835
916-1-INT	3360	203	640	18.8	18	184	32	57	61.2	0.93	1.102
916-2-EXT	3750	203	580	17.0	18	186	36	64	61.8	1.04	0.989
916-2-INT	3750	203	580	17.0	18	186	28	50	61.8	0.81	1.272
916-3-EXT	5060	203	390	11.4	16	191	30	53	63.7	0.84	1.223
916-3-INT	5060	203	390	11.4	16	191	23	41	63.7	0.64	1.595
916-4-EXT	4950	203	400	11.7	16	191	30	53	63.6	0.84	1.221
916-4-INT	4950	203	390	11.4	16	191	27	48	63.7	0.75	1.359
6-1-EXT	4100	203	450	12.6	19	190	25	42	63.3	0.66	1.634
6-1-INT	4100	203	450	12.6	19	190	27	45	63.3	0.71	1.513
6-2-EXT	4280	203	490	13.7	19	189	30	50	62.9	0.79	1.353
6-2-INT	4280	203	490	13.7	19	189	24	40	62.9	0.64	1.692
6-3-EXT	5230	203	430	12.0	12	191	23	38	63.5	0.60	1.781
6-3-INT	5230	203	405	11.3	12	191	21	35	63.7	0.55	1.958
6-4-EXT	5450	203	450	12.6	12	190	22	37	63.3	0.58	1.856
6-4-INT	5450	203	425	11.9	12	191	23	38	63.5	0.60	1.782

Note: 1 psi = 6.89 kPa; 1 ksi = 6.89 MPa; 1 kip = 4.445 kN; 1 in. = 25.4 mm.

fer length gives the average strain measurements there that appear to fit a transitionally smooth curve. The point right at the end of the transfer length has the maximum concrete strain equal to that beyond the transfer bond zone, but the measured average strain over the gauge length centered at the point would be less than the maximum. Failure to recognize this fact can lead to the identification of transfer lengths from the same data that, on second look, appear to be too large.

The method of data interpretation just presented, which might be termed a "slope-intercept" method, is a reasonable and consistent method for determining the length required to transfer steel stress to concrete. However, when the results are finally translated to a design equation for transfer length, a multiplier greater than unity may need to be applied to ensure a conservative design.

Table 5. Development length test results of specimens.

Specimen designation	f'_c (psi)	Load location L_p (in.)	Strain gauge location L_g (in.)	Ultimate load P_u (kips)	Mode of failure	Maximum shear V_u (kips)	Moment (kip-ft)			f_{se} (ksi)	f_{sb} (ksi)	f_{su} (ksi)	f_{sm} (ksi)	Load at strand slippage Load (kips) [Strand No.] (Fig. 3)
							M_{cr}	M_b	M_u					
5-1-EXT	5476	92	92	114.0	B-F	91.2	396	611	645	191	259	265	268	108[1]; 110[6,7,8,9]
5-1-INT	5476	69.6	69.6	125.0	B-S	107.0	469	550	564	191	234	240	–	122[1,6,7,8,9]
5-2-EXT	6746	77.4	77.4	124.0	B-S	104.0	444	612	612	191	259	259	262	124[1,3,5,7,8,9]
5-2-INT	6746	85	58	120.0	B-F	98.1	415	623	639	191	234	242	257	117[5,7,8,9]
5-3-EXT	6858	85.1	93	127.0	F	103.0	388	–	675	191	–	–	–	No slip
5-3-INT	6858	77.4	81	138.0	B-F	115.0	408	645	679	191	262	265	270	131[7,8]; 135[9]; 138[1,3,5]
5-4-EXT	7600	81.25	67	132.0	F	109.0	410	–	676	191	260	260	–	No slip
5-4-INT	7600	77.4	86	135.0	B-F	112.0	453	644	664	191	n/a	–	–	131[n/a]
5-SWAI-EAST	5553	81	84	125.3	F	104.0	430	–	641	200	–	269	273	No slip
5-SWAI-WEST	5553	69.6	87	147.0	F-B	125.0	485	660	660	200	269	270	274	147[n/a]
5-UWR-EAST	5989	77.4	–	138.0	B-F	115.0	463	630	679	–	–	–	–	128[n/a]
5-UWR-WEST (S)	5989	69.6	–	177.0	B-F	134.0	459	611	707	–	–	–	–	153[n/a]
5-FWC-EAST	5341	72.5	–	137.5	B-F	117.0	419	624	640	–	–	–	–	134[n/a]
5-FWC-WEST	5341	77.4	–	134.0	F	112.0	448	–	660	–	–	–	–	No slip
5-ASW-EAST	5400	73.5	–	134.3	F	114.0	429	–	633	–	–	–	–	No slip
5-ASW-WEST	5400	69.6	–	142.0	F	121.0	463	–	638	–	–	–	–	No slip
5S-1-EXT	6624	69	69	127.0	B-S	109.0	466	565	569	199	232	232	–	126[4]
5S-1-INT (LC)	6624	81	50	142.0	F-B	117.0	449	719	724	199	217	217	–	141[7,8,9]; 138.5[4]
5S-2-EXT	–	84	90	–	–	–	–	–	–	199	–	–	–	
5S-2-INT (S)	6800	82.5	82.5	161.0	F-B	100.0	408	692	692	199	260	260	–	161[n/a]
5S-3-EXT	5967	81	66	125.0	F-B	103.0	471	–	640	200	–	253	261	125[1,4,6,7,8,9]
5S-3-INT	5967	75	75	122.0	B-S	103.0	457	587	587	200	245	245	–	122[1,4,6,7,8,9]
5S-4-EXT	6181	68	66	130.0	B-S	112.0	442	530	574	200	241	243	–	120[1]; 130[5]
5S-4-INT	6181	72	111	144.0	B-F	122.0	472	601	666	200	241	255	–	130[5]; 144[7,8,]
916-1-EXT	5533	106	106	110.0	B-F	83.9	488	682	688	185	240	240	248	109[7,8]
916-1-INT	5533	87	87	130.0	B-F	105.0	476	633	703	185	222	242	258	117[1]; 122[7,8]
916-2-EXT	5921	96	65	114.0	B-F	90.0	455	642	665	185	210	–	–	110[7,8,9]; 112[4,6]; 114[1,3]
916-2-INT	5921	87	87	126.0	B-F	102.0	465	677	682	185	n/a	203	–	125[1,3,4,6,8,9]
916-3-EXT	6119	95.5	114	114.0	B-F	90.1	419	628	663	187	220	218	–	95[7]; 108[8]; 110[9]; 113[4]
916-3-INT	6119	104.4	105	109.0	F	83.7	390	–	675	187	–	–	–	No slip
916-4-EXT	6237	104.4	87.5	108.0	B-F	82.9	390	601	669	187	222	246	248	97[n/a]
916-4-INT (LC)	6237	108	95.5	108.0	F	81.9	429	–	688	187	–	251	–	No slip
6-1-EXT	5126	116	116	99.0	F	73.2	412	–	658	184	232	–	–	No slip
6-1-INT (S)	5126	93	66	155.0	F	95.3	335	–	682	184	217	–	–	No slip
6-2-EXT	5285	83.5	83.5	126.0	B-F	103.0	398	660	660	184	232		–	126[n/a]
6-2-INT	5285	74.4	92	138.0	B-F	116.0	462	609	657	184	226	244	–	128[n/a]
6-3-EXT	7463	83.52	85.5	134.0	B-F	110.0	424	696	701	191	n/a	–	–	133[n/a]
6-3-INT	7463	88.16	93	129.0	F	104.0	426	–	704	191	–	268	–	No slip
6-4-EXT	7984	85.84	89	130.0	F	106.0	406	–	695	191	–	262	–	No slip
6-4-INT	7984	85.84	95.5	133.0	F	108.0	428	–	711	191	–	265	–	No slip

Note: 1 in. = 25.4 mm; 1 kip = 4.445 kN; 1 kip-ft = 1.36 kN-m; 1 ksi = 6.895 MPa.

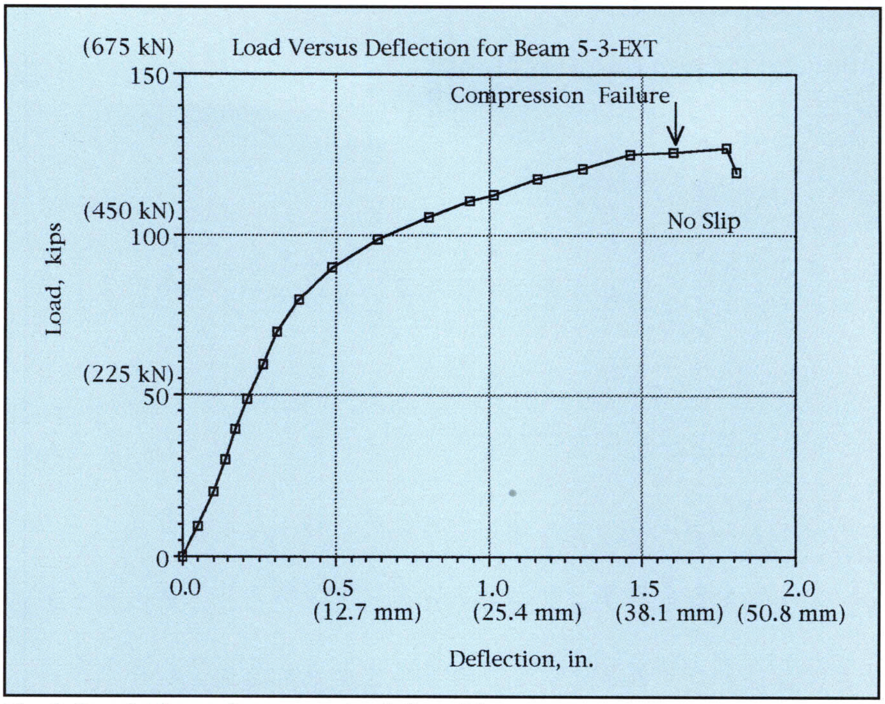


Fig. 6. Typcial flexural compression failure (F).

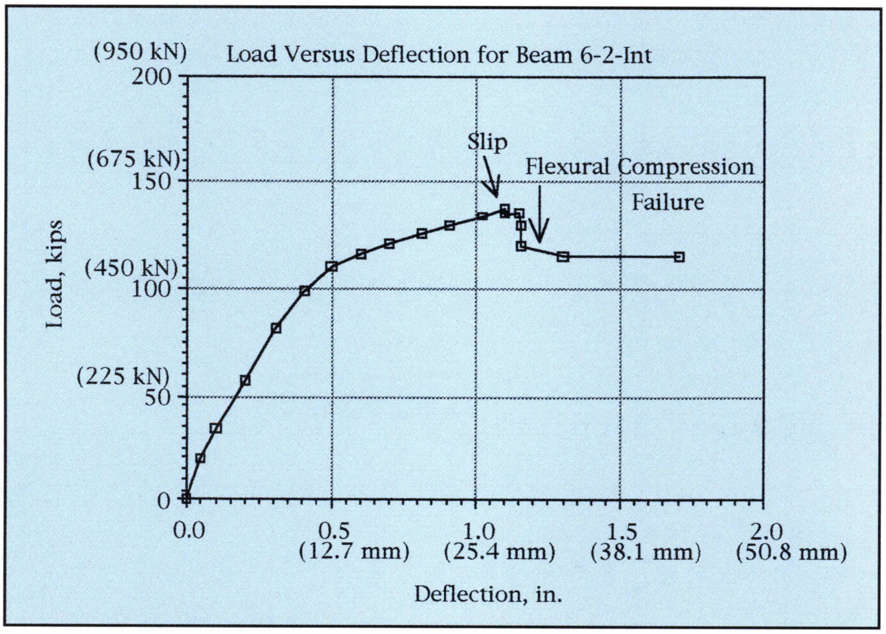


Fig. 7. Typical slip and flexural compression failure (B-F).

Table 4 lists the concrete strength at transfer, f'_{ci}, the specified initial prestress, f_{si}, elastic shortening (ES) as measured from the change in strain on the concrete surface of each specimen in the unit of microstrains ($\mu\varepsilon$) and the corresponding steel stress loss, D_{fs}, the effective prestress, f_{se}, and the transfer length, L_t, obtained immediately after transfer according to the slope-intercept method. The f_{se} is obtained by subtracting the D_{fs} from the f_{si}.

For comparison with the measured transfer length, Table 4 also lists the transfer length calculated as $f_{se}/3$ times the nominal diameter of the strand. The term $(f_{se}/3)D$ is not specifically identified in the AASHTO Specifications or ACI Code, but it is a part of the AASHTO and ACI development length equations. The effective prestress multiplied by the area of an individual strand gives the effective prestress force in the strand. The average transfer bond strength, U_t, is calculated by dividing the effective prestress force in the strand by the transfer length.

Development Length Tests

The development length test results for all the beams are summarized and presented in Table 5. For each test, these data are tabulated: the concrete strength at the time of test, f'_c, the point from the nearer end of the beam where load is applied, L_p, the location of the electrical strain gauges from the end of the beam, L_g, the maximum measured load, P_u, and the corresponding shear force, V_u, the mode of failure of the beam, and the measured flexural moments at the load point and steel stresses at the gauge point at different important stages during the test.

The effective prestress at the time of test was determined from readings of electrical resistance gauges. The values listed in Table 5 are not perfectly consistent with those in Table 4, which were obtained using a mechanical strain gauge.

The flexural moments at the load point are calculated from the measured applied load on each beam with the assumption of simple supports at the beam ends. The cracking moment, M_{cr}, is, on the average, about 66 percent of the ultimate moment, M_u. The moment at which the first strand slippage is detected, M_b, is also calculated and tabulated for beams with bond failure.

The effective prestress, f_{se}, in the strands was measured with electrical strain gauges just before each development length test. Listed in Table 5 are the observed steel stresses at the gauge point at first slippage of the strands, f_{sb}, and at the maximum applied load, f_{su}, during the development length tests. Some higher steel stresses in the strands were also observed in a few of the beams when the beams were deflected beyond their ultimate loads and plastic hinges were forming beneath the load points. These maximum steel stresses observed are tabulated as f_{sm}.

Due to a malfunction in the controller of the hydraulic loading equipment, data on the very first development length test were not acquired. Of the 39 development length tests performed, end slip was not detected in 13 tests, four showed "slight" end slips after flexural compression failures were developed, 17 experienced end slips but did eventually fail in flexural compression, and five exhibited shear failure immediately after a bond failure.

Beam Behavior and Mode of Failure

The behavior of the test beams can be generally categorized into four different modes of failure, which are explained briefly here with reference to the typical load vs. deflection plot. The load vs. deflection plot for each test can be found in the final project report.[2]

Fig. 6 shows a typical load vs. deflection plot for a flexural failure denoted in Table 5 by "F." This plot is for Test 5-3-EXT. The beam exhibited linear behavior up to cracking; then the stiffness rapidly decreased with increasing deflection and, ultimately, concrete crushing occurred at the maximum moment. The failure is typical of a beam with adequate development length and, thus, without any strand slippage.

Typical load vs. deflection plots for tests with bond failure are shown in Figs. 7 and 8. Beams showed the typical linear behavior up to cracking load and then nonlinear behavior until a bond failure, indicated by end slip, occurred. The bond failure occurred prematurely, before the ultimate flexural strength. Losses in bond were subsequently accompanied by premature flexural compression failure or shear failure, denoted as "B-F" or "B-S," respectively.

When a bond failure is detected only at loads very near to the flexural compression failure or just after the compressed concrete fiber begins to crush, the beam is evidently loaded at a point very close to the full development length. This mode of failure is denoted as "F-B," and a typical load vs. deflection plot for this is shown in Fig. 9.

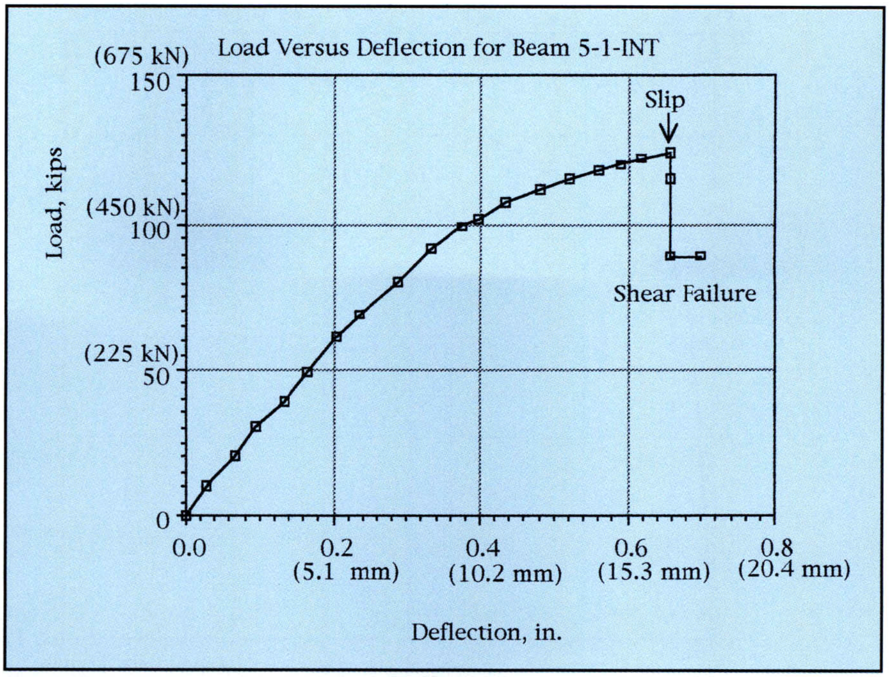


Fig. 8. Typical slip and shear failure (B-S).

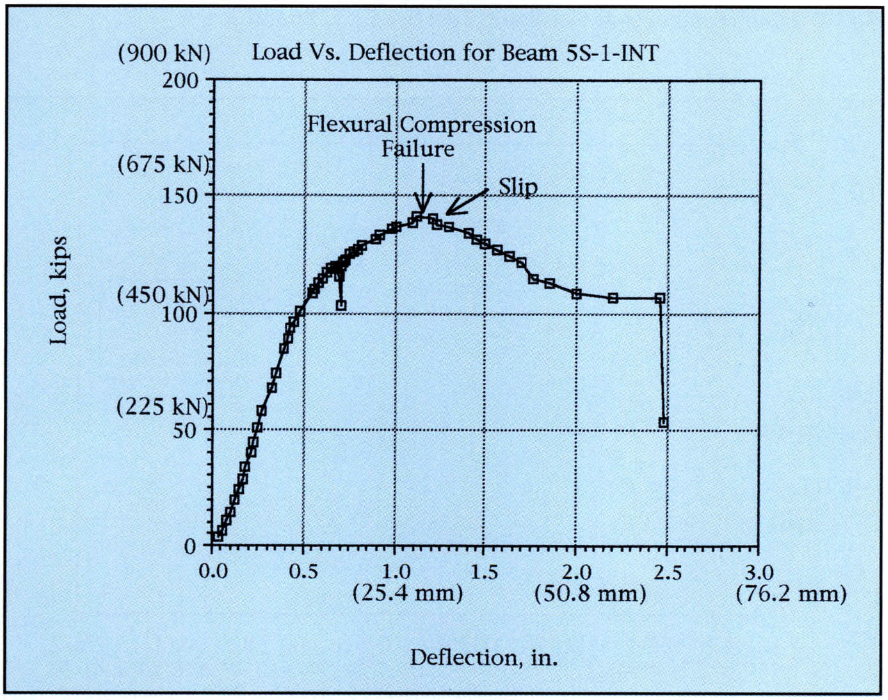


Fig. 9. Typical flexural compression and slip failure (F-B).

Stress increase in the steel above the effective prestress is relatively small up to cracking of the section. These stress ranges, however, are typical of service conditions; service loads in pretensioned slabs and beams are usually below the cracking loads. As indicated by the strain gauges, steel strains below the load point increased abruptly at the initial flexural crack and continued to increase until failure of the beam occurred. A measured load vs. steel strain, plotted in Fig. 10, clearly illustrates this behavior.

DISCUSSION OF TEST RESULTS

The results of the development length tests are discussed at some length herein in the section where those results are presented. Development length consists of transfer length plus flexural bond length and is related to the overall beam behavior.

Development length is difficult to

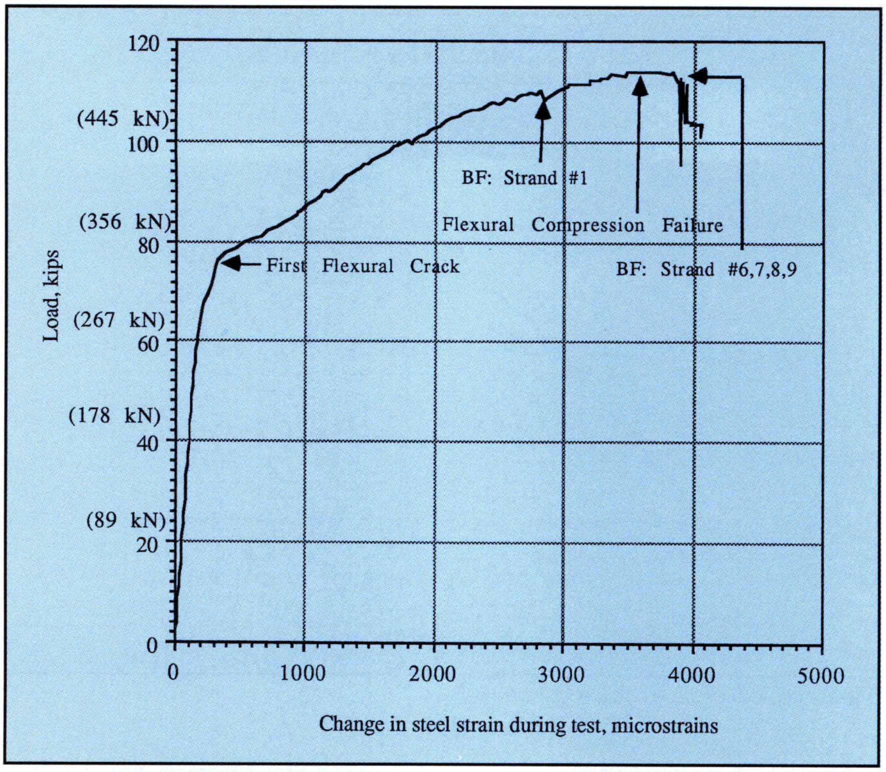


Fig. 10. Load vs. steel strain for Beam Test 5-1-EXT, Strand 3.

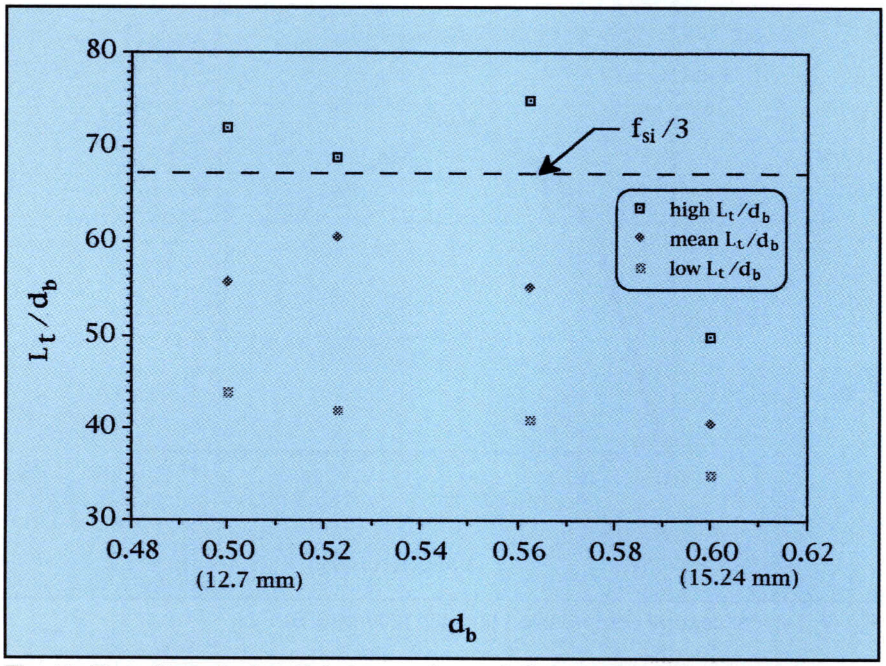


Fig. 11. Plot of transfer length in terms of strand diameter for different strand sizes.

Table. 6. Average transfer lengths of beams.

	Average transfer length, d_b		
Strand	**Milled**	**Weather 1-day**	**Weather 3-day**
½ in.	64.5	46.5	39.0
½ in. special	62.2	–	59.3
9/16 in.	62.2	–	48.9
0.6 in.	40.6	–	–

Note: 1 in. = 25.4 mm.

measure precisely and the variables affecting it are difficult to quantify. On the other hand, transfer length is much easier to quantify. In the following sections some of the variables that affect transfer length are discussed. All conclusions are based on tests of strands in mill condition unless otherwise noted.

Effects of Strand Diameter

The perimeter of seven-wire prestressing strand is approximately equal to $4/3\pi d_b$. Adhesion force, which is directly proportional to the amount of adhered surface, is therefore directly proportional to the strand diameter. Friction may be affected by strand diameter due to the difference in normal force from different wire sizes. Because the grooves between the outer wires of a strand get larger with increasing strand diameter, mechanical bond strength would tend to increase with strand diameter.

Table 4 and Fig. 11 illustrate that the average transfer lengths for the ½ in. (13 mm), ½ in. special (13.3 mm) and 9/16 in. (14 mm) strands of milled surface condition are approximately proportional to the strand diameter, but this relationship does not hold for the 0.6 in. (15 mm) strands. The shorter transfer length for 0.6 in. (15 mm) strands may be attributed to the increase in mechanical bond.

Effects of Strand Surface Condition

The wires of all stress-relieved and low-relaxation strands have residual surface lubricants, usually stearates, resulting from the wire drawing process. These residuals result in less adhesion between the concrete paste and the wire than would be provided by clean, bare wire. Weathering, which is not sufficient to create visible rust, causes microscopic roughness which considerably improves bond. From Table 6, the average improvement in the transfer length for one-day weathering of ½ in. (13 mm) diameter strand was about 27.9 percent, while that for three-day weathering of the same strand appears to be about 40 percent.

This reduction in transfer length is due to increased adhesion of the concrete and an increased coefficient of friction between the concrete and the strand. Because the strands of all manufacturers were in the group that weathered, no definite conclusions can be drawn as to relative bond characteristics of the different strands in the milled condition.

Transfer Length

The method used to determine the transfer length from measured data is described herein and referred to as the slope-intercept method. It is the opinion of the authors that the slope-intercept method best represents the data obtained during the research and that it is logically based on the mechanical strain gauge method of determining transfer length.

Based on this interpretation of the data from the transfer length tests, the conclusion is drawn that, consistent with ACI and AASHTO, the length required to transfer a particular steel stress to concrete is approximately equal to the stress in ksi divided by three and multiplied by the diameter of the strand in inches. As the stress being transferred initially is f_{si}, a reasonable expression for calculating transfer length is $L_t = (f_{si}/3)d_b$. This equation is consistent with the test results and is somewhat more conservative than the ACI and AASHTO requirements.

The plot in Fig. 11, which shows mean transfer lengths as well as upper and lower transfer lengths measured in the tests, clearly demonstrates that calculating L_t as one-third the stress at transfer times the bar diameter is reasonable and conservative for the ½ in., ½ in. special and 9/16 in. (13, 13.3 and 14 mm) strand sizes. As noted earlier, the transfer length for 0.6 in. (15 mm) diameter strand is somewhat less than for the other sizes.

Development Length

The development length data obtained from the static tests to failure lead to the conclusion that the ACI and AASHTO provisions for calculating development length are somewhat unconservative. The development length equation given by these two codes is in the following form:

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

The right-hand side of the equation can be split into two parts:

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

in which the first term, $(f_{se}/3)d_b$, represents the transfer length and the second term, $(f_{ps} - f_{se})\, d_b$, represents the flexural bond length.

The other symbols are:

L_d = development (in.)
f_{ps} = stress in prestressed reinforcement at nominal strength (ksi)
f_{se} = effective stress in prestressing steel after losses (ksi)
d_b = nominal diameter of prestressed reinforcement (in.)

The results of a number of research efforts, including the work reported herein, were reviewed by Chew[10] in terms of the flexural bond strength obtained. He found that the flexural bond strength, which appeared to be justified by tests, is approximately 42 percent higher than the value implied by the ACI and AASHTO equations. In other words, the flexural bond length required by the code equations is approximately 42 percent lower than that justified by the tests.

Consistent with Chew's findings and with the earlier discussion on transfer length, the following equation for development length is proposed:

$$L_d = (f_{si}/3)d_b + 1.50\,(f_{ps} - f_{se})\, d_b$$

The proposed equation increases the calculated development length (1) through increasing the transfer length portion of the equation by using f_{si} rather than f_{se}, and (2) through multiplying the flexural bond length portion by 1.5. For a case with f_{si} = 180 ksi (1240 MPa), f_{se} = 160 ksi (1100 MPa) and f_{ps} = 260 ksi (1790 MPa), L_d increases from 153.3 d_b to 210 d_b, a 37 percent increase.

Obtaining accurate values of development length from tests is not a well-defined, straightforward procedure. While the equation just presented gives values of development length which compare reasonably well with the data presented in Table 5, further work to refine this prediction is clearly necessary.

FHWA Memorandum

Since the October 26, 1988, FHWA memorandum created the need for this research, it is appropriate to formulate comments on the various restrictions imposed by the subject memo. The data obtained during this research supports the following conclusions:

1. The use of 0.6 in. (15 mm) diameter strands *should not* be prohibited. In fact, 0.6 in. (15 mm) diameter strands have shorter transfer lengths in relation to their diameters than any of the other three sizes tested. The measured development lengths were comparable to the other strand sizes, and the ultimate moments were substantially higher than those predicted by either the ACI or AASHTO equations.

2. Based on these data, the authors see no need to restrict the use of 0.6 in. (15 mm) diameter seven-wire prestressing strand.[2] Spacings of less than four times the diameter were only tested using ½ in. (13 mm) diameter strand. As the authors understand it, this is a fairly common practice for West Coast manufacturers of prestressed concrete beams. Eight test beams were constructed with strand spacings of 1.75 in. (44.5 mm). There was no significant difference between the moment capacities of beams with this spacing and those with 2.0 in. (51 mm) spacing, and in every case the measured moment capacity was at least 10 percent greater than that predicted by ACI and AASHTO.

The beams with 1.75 in. (44.5 mm) spacing were the beams with weathered strands, a condition quite likely to occur in practice. In view of the excellent performance of these beams, with no observed splitting, there appears to be no valid reason not to use this spacing. Based on these data and the fact that extensive field use has produced no adverse effects, it is recommended that the spacing requirement for ½ in. (13 mm) diameter prestressing strand be reduced to 3.5 strand diameters.

3. Increasing the development length for all strand sizes to 1.6 times the value obtained from the AASHTO equation is not justified. The authors would recommend the equation proposed under the discussion on development lengths, which would result in an increase of about 35 percent for most cases.

4. This research did not investigate the effects of debonding; therefore, no conclusions can be drawn relative to this restriction.

RECOMMENDATIONS

The following recommendations are based on the research presented in this paper:

1. The transfer length for ½ in., ½ in. special and ⁹⁄₁₆ in. (13, 13.3 and 14 mm) strand sizes should be calculated as:

$$L_t = (f_{si}/3)d_b$$

2. Further work should be done to develop an expression for transfer length of 0.6 in. (15 mm) diameter strand. In the meantime, the equation recommended for other strand sizes, which is clearly conservative, may be used.

3. The use of 0.6 in. (15 mm) diameter strand should be accepted as standard practice.

4. A center-to-center spacing of 1.75 in. (44.5 mm) should be permitted for ½ in. (13 mm) diameter strands.

5. The development length of all strand sizes should be calculated as:

$$L_d = f_{si}/3 + 1.50\,(f_{ps} - f_{se})\,d_b$$

ACKNOWLEDGMENT

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Ross Prestressed Concrete in Knoxville built the prestressed concrete beams that were tested and thus played a key role in the research. Their special efforts and flexible cooperation are much appreciated.

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Any opinions, findings, conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the Precast/Prestressed Concrete Institute.

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APPENDIX — NOTATION

A_{ps} = area of prestressed reinforcement

C_v = distance from bottom of member to neutral axis

D_{fs} = loss of prestress due to elastic shortening (mechanical gauge)

d_{fs} = loss of prestress due to elastic shortening (electrical gauge)

CGS = center of gravity of strand

d_b = nominal diameter of prestressing strand

E_s = modulus of elasticity of steel

f'_c = concrete compressive strength at time of test

f_{ci} = concrete compressive strength at transfer of prestress

f_{ps} = steel stress at nominal beam strength

f_{sb} = stress in strand at bond slip

f_{su} = stress in strand at ultimate moment

f_{se} = effective stress in prestressing steel after losses

f_{si} = initial prestress in steel reinforcement

f_{sm} = maximum stress in strand measured during test

I = moment of inertia of beam section

L_b = flexural bond length of strand

L_d = development length of strand

L_g = distance of electrical strain gauges from end of beam

L_t = transfer length of strand

L_p = distance of load point from nearest end of beam

M_b = moment at bond failure

M_{cr} = cracking moment of section

M_u = ultimate moment capacity of section

NA = neutral axis of beam

P_u = maximum measured load

U_t = average transfer bond length

V_u = maximum shear force

$\mu\varepsilon$ = elastic shortening, microstrains