TOP STRAND EFFECT

Chris Carroll, Via Dept. of Civil and Env. Eng., Virginia Tech
Tommy E. Cousins, PhD, PE, Via Dept. of Civil and Env. Eng., Virginia Tech
Carin L. Roberts-Wollman, PhD, PE, Via Dept. of Civil and Env. Eng., Virginia Tech

ABSTRACT

This paper looks at the influence of the vertical casting position on transfer and development lengths of prestressing strand. This is taken into account by ACI and AASHTO for deformed bars, but neglected for prestressing strands.

Twenty pretensioned, prestressed concrete specimens have been cast to date for experimental testing. Eight of the test specimens were cast upside down, which resulted in over 12 in. of fresh concrete cast beneath the strand. This allowed for the investigation of the top strand effect. Transfer length measurements were taken at the time of transfer and 1-2 weeks following transfer and were found to have a significant increase for specimen cast upside down versus right side up. Flexural tests were also conducted for the investigation of development lengths. Beams cast upside down were also found to have an increase in development lengths.

Results-to-date have shown the top strand effect to have a significant impact on the transfer and development lengths of pretensioned, prestressed concrete specimens with more than 12 in. of fresh concrete cast beneath the prestressing strands. Based on these results, recommendations have been made for the modification of equations used to calculate transfer and development lengths.

Keywords: Transfer length, Development length, Prestressed concrete, Bond, Top strand effect

INTRODUCTION

For decades, the phenomenon known as the top bar effect has been recognized in the concrete industry. The top bar effect is defined by the American Concrete Institute (ACI) as the situation where a horizontal reinforcing bar is placed such that more than 12 in. of fresh concrete is cast below the bar.[1] Research has shown bars in this situation to have less favorable bond characteristics. ACI and the American Association of State Highway and Transportation Officials (AASHTO) have incorporated modification factors for development lengths of standard reinforcing bars, but fail to provide any such provisions for the transfer and development lengths of pretensioned prestressed concrete.

This investigation is part of a larger project involving the development of Grade 300 prestressing strand for use in industry. The purpose was to compare the effects of strand strength and casting position on the transfer and development lengths in pretensioned prestressed concrete girders. Over the course of two years, twenty, 24 ft long pretensioned prestressed concrete girders were cast for this investigation. Three different sizes of prestressing strand and two different strand strengths were also used in the investigation. Background information is provided for transfer length, development length, and top strand effect. Testing methods are described and results summarized followed by conclusions and recommendations based on the findings of the current research.

BACKGROUND

TRANSFER LENGTH

Pretensioned prestressed concrete members are fabricated by jacking strands, casting concrete around them, allowing the concrete to cure, followed by a release of the force in the strands, which is typically accomplished by flame cutting the strand. The force in the strands is instantaneously transferred to the concrete via chemical and mechanical bond between the prestressing strand and surrounding concrete. Unlike nonprestressed reinforcement, the chemical bond has a small effect, losing its adhesion with the violence during transfer; therefore the bond is primarily a result of friction and mechanical interlock. Upon transfer, prestressing strands tend to expand as a result of Poisson's Effect adding to the frictional resistance, also known as the Hoyer Effect. In addition to friction, the helical shape of the seven wire strand results in a mechanical interlock between the prestressing strand and the concrete. The bond between the strand and concrete is assumed to vary linearly from zero bond at the end of the member to full bond at a distance away from the end of the member as shown in Figure 1. The distance required to obtain full bond is referred to as the transfer length and at that point, the full amount of effective prestress is transferred to the concrete member.

Several factors have been shown to influence the bond characteristics between the prestressing strand and surrounding concrete. These factors include concrete strength, release method, top strand effect, strand surface condition, and the influence of time.[2,3]

Transfer lengths tend to decrease with increasing concrete strengths as previous research has shown. Conversely, strands exhibiting the top strand effect, more than 12 in. of fresh concrete cast beneath the strand, have shown increased transfer lengths. The surface condition of the strand may also affect the bond characteristics, with weathered surfaces typically improving the bond behavior, thus decreasing transfer lengths. The release method used at the time of transfer can have a significant impact on transfer lengths, where a sudden release likely results in longer transfer lengths than a gradual release. Time has also proven to be influential on transfer lengths. In the time period following the transfer of the prestress force, transfer lengths have a tendency to increase 10 to 20 percent, typically occurring within the first few weeks.

Criteria for transfer length calculations exist in both ACI and AASHTO. ACI provides two methods for calculating the transfer length, which is an essential element when calculating the nominal web shear strength of a member, V_{cw}. When calculating V_{cw} at a section located within the transfer zone, the prestress force should be reduced linearly from zero at the end of the member to the effective prestress force at the transfer length. The transfer length in this case is assumed to be 50 strand diameters ($50d_b$).[4]

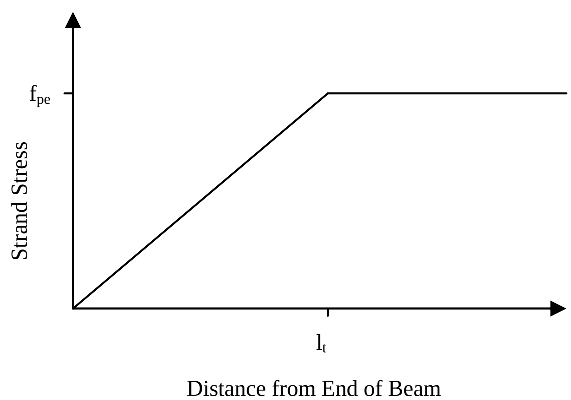


Fig. 1 Transfer Length

The second method for calculating the transfer length lies within Equation 1, which calculates the development length of prestressing strand. Development length is discussed in the following section; however, the first term of Equation 1 represents the second method of calculating the transfer length. If Grade 270 prestressing strands are stressed to 75 percent of the ultimate tensile strength (202.5 ksi) and the amount of prestress loss is assumed to be approximately 25 percent, the transfer length term will simplify to $50d_b$.[1] As compared with ACI, AASHTO recommends the transfer length to be taken as $60d_b$.[5] The 20 percent increase over the ACI recommendation accounts for higher effective prestress levels currently employed in design.[6]

$$l_d = \left(\frac{f_{se}}{3000}\right)d_b + \left(\frac{f_{ps} - f_{se}}{1000}\right)d_b \qquad \text{Eq. 1}$$

where,

l_d = development length (in.)
f_{se} = effective stress in prestressing steel (psi)
d_b = strand diameter (in.)
f_{ps} = stress in prestressing steel at nominal flexural strength (psi)

DEVELOPMENT LENGTH

Development length is defined as the length required to anchor the strand to fully develop the stress in the strand at the nominal moment capacity of a member.[5] In both ACI and AASHTO, the maximum stress in the strand, f_{ps}, can be calculated using Equations 2 and 3 from ACI and AASHTO, respectively. As previously discussed, the transfer length is understood to be the first portion of the development length equations. The remaining portion of the development length is comprised of the flexural bond length. The flexural bond length, l_{fb}, is the distance required for the stress in the strand to increase from the effective prestress, f_{se}, to f_{ps}.

$$f_{ps} = f_{pu}\left\{1-\frac{\gamma_p}{\beta_1}\left[\rho_p\frac{f_{pu}}{f_c^{'}}+\frac{d}{d_p}\left(\omega-\omega^{'}\right)\right]\right\} \qquad \text{Eq. 2}$$

where,

f_{ps} = stress in prestressing steel at nominal flexural strength (psi)
f_{pu} = specified tensile strength of prestressing steel (psi)
γ_p = factor for type of prestressing steel
β_1 = factor relating depth of equivalent rectangular stress block to neutral axis
ρ_p = ratio of A_{ps} to bd_p
f'_c = specified compressive strength of concrete (psi)
d = distance from extreme compression fiber to centroid of longitudinal tension rein. (in.)
d_p = distance from extreme compression fiber to centroid of prestressing steel (in.)
ω = tension reinforcement index
ω' = compression reinforcement index
A_{ps} = area of prestressing steel in flexural tension zone (in.^{2})
b = width of compression face of member (in.)

$$f_{ps} = f_{pu}\left(1-k\frac{c}{d_p}\right) \qquad \text{Eq. 3}$$

where,
f_{ps} = stress in prestressing steel at nominal flexural strength (psi)
f_{pu} = specified tensile strength of prestressing steel (psi)
k = factor related to type of strand
c = distance between the neutral axis and the compressive face (in.)
d_p = distance from extreme compression fiber to the centroid of the prestressing strand (in.)

ACI gives the equation for the calculation of development length, previously shown as Equation 1. Figure 2 shows the idealized relationship between steel stress and the distance away from the end of the beam. AASHTO also provides an equation for the calculation of the development length shown in Equation 4, when rearranged and having a κ factor equal to one results in the same equation provided by ACI. In addition to Equation 4, AASHTO also provides a plot of strand stress as a function of the distance away from the end of the beam as shown in Figure 3 for the determination of the effective prestress at any location within the development length.

$$l_d = \kappa\left(f_{ps} - \frac{2}{3} f_{pe} \right) d_b \qquad \text{Eq. 4}$$

where,
l_d = development length (in.)
f_{pe} = effective stress in prestressing steel after losses (ksi)
d_b = strand diameter (in.)
f_{ps} = average stress in prestressing steel at the time for which the nominal resistance of the member is required strength (ksi)
κ = 1.0 for pretensioned members with a depth of less than or equal to 24.0 in.
κ = 1.6 for pretensioned members with a depth greater than 24.0 in.

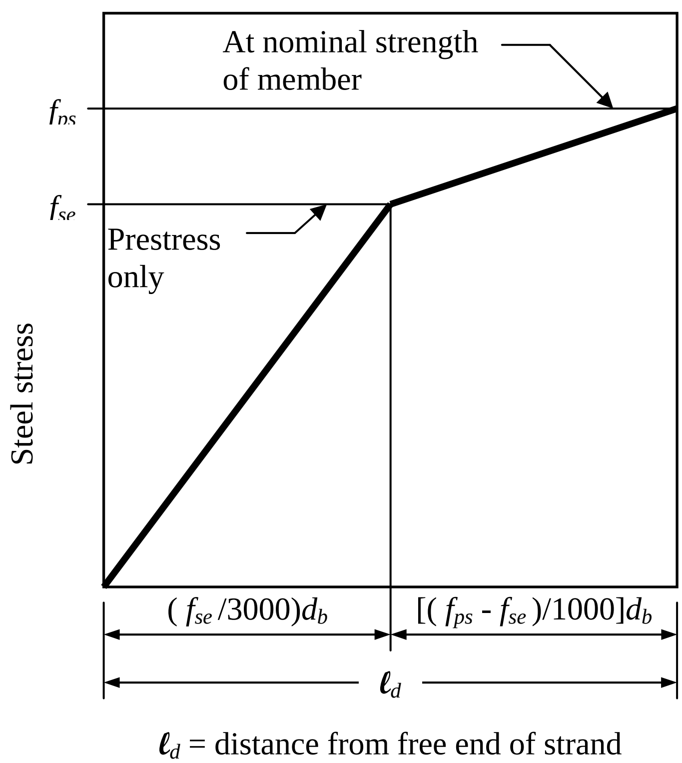


Fig. 2 ACI development length plot[1]

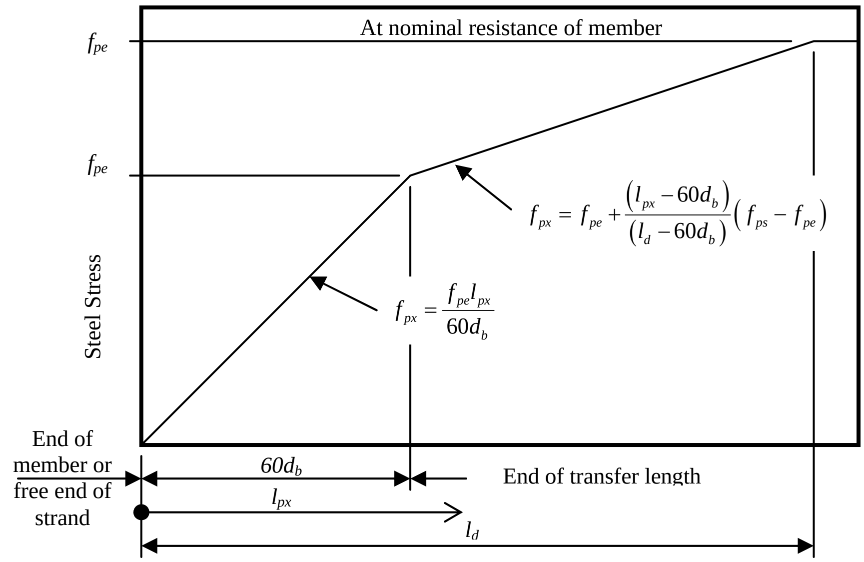


Fig. 3 AASHTO development length plot[5]

TOP STRAND EFFECT

The phenomenon known as the top bar effect has been recognized since 1913 with modification factors first implemented in the 1951 ACI building code.[7] Figure 4 shows the typical situation that would allow a bar to exhibit the top bar effect, which was used by Jeanty to further investigate the need for development length modification factors. ACI requires a modification factor of 1.3 be applied to the development length of bars categorized as top bars, while AASHTO requires a modification factor of 1.4. The modification factor is applied to the calculated development length for nonprestressed reinforcement during these conditions and is understood to incorporate the effect bleed water and concrete settlement have on the bond of horizontally placed top bars and the surrounding concrete.[8]

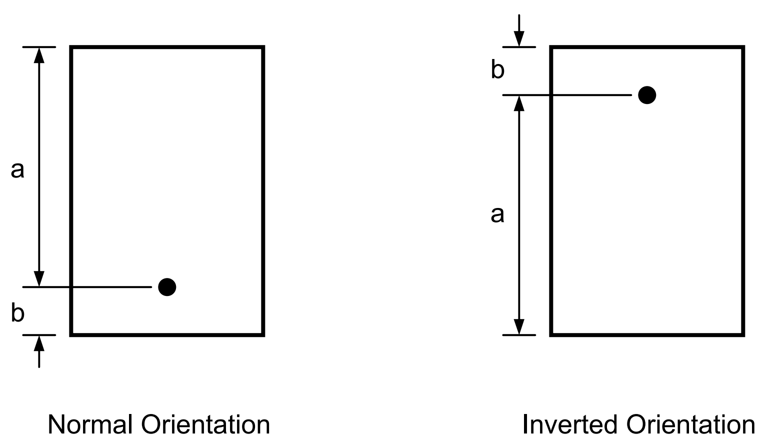


Fig. 4 Typical "Top Bar" Effect Condition

Top strand effect is understood to be the same as the top bar effect only applied to prestressing strand rather than standard reinforcing bars. As both ACI and AASHTO have modification factors for top bar effect, neither have modification factors for any aspect of the top strand effect; therefore it is imperative to determine the applicability of these modification factors to pretensioned prestressed concrete.

Current research by Larson et al., has shown beams containing strands placed such that more than 12 in. of concrete cast beneath them have had increased transfer and development lengths.[9] In addition to the research by Larson, Peterman has also proposed a new hypothesis stating that the top strand effect is not only a factor of the amount of concrete cast beneath the strand, but also a factor of the amount of concrete cast above it.[8] In an effort to verify this hypothesis for the top strand effect, rectangular blocks were cast as shown in Figure 5 to monitor the behavior of transfer length as a factor of both the concrete above and beneath the strand.

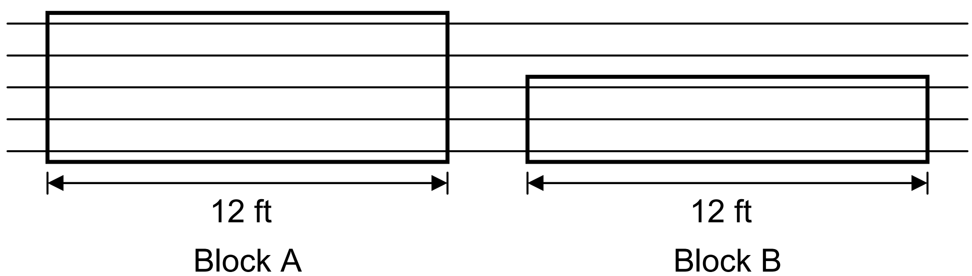


Fig. 5 Peterman Test Setup[8]

This setup allowed for a head-to-head comparison of the effect the amount of concrete above and below the strand had on transfer length. Transfer lengths were calculated for each strand based on end slip measurements and when evaluated, strands with the same amount of concrete above the strand tended to show a better correlation than those with the same amount of concrete beneath the strand.[8] This hypothesis is recognized and is of interest to the authors, but is beyond the scope of this paper.

METHODOLOGY

TEST SPECIMENS

Throughout the duration of the project, a total of twenty, 24 ft long T-shaped specimens were cast, with a transfer zone at each end of each specimen, providing a total of 40 transfer zones, one of which was lost due to a flash setting of the concrete while casting the specimen. Of the twenty specimens, the size of the cross section varied with strand type. Strand types included low relaxation ½ in. diameter regular, ½ in. diameter super, and 0.6 in. diameter strands each having a cross sectional area of 0.153 in.^{2}, 0.167 in.^{2}, and 0.217 in.^{2} respectively. With an increase in cross sectional area, also comes an increase in the initial prestress force, therefore, the prestress force in beams containing 0.6 in. diameter strands would be significantly higher than in those containing ½ in. diameter super strands and the prestress force in beams containing ½ in. diameter super strands would be significantly higher than in those containing ½ in. diameter regular strands. For this reason, the size of the cross section varied with the strand type. The three cross sections used throughout the project are shown in Figure 6. The small, medium, and large beams each contained ½ in. diameter regular, ½ in. diameter super, and 0.6 in. diameter strands, respectively.

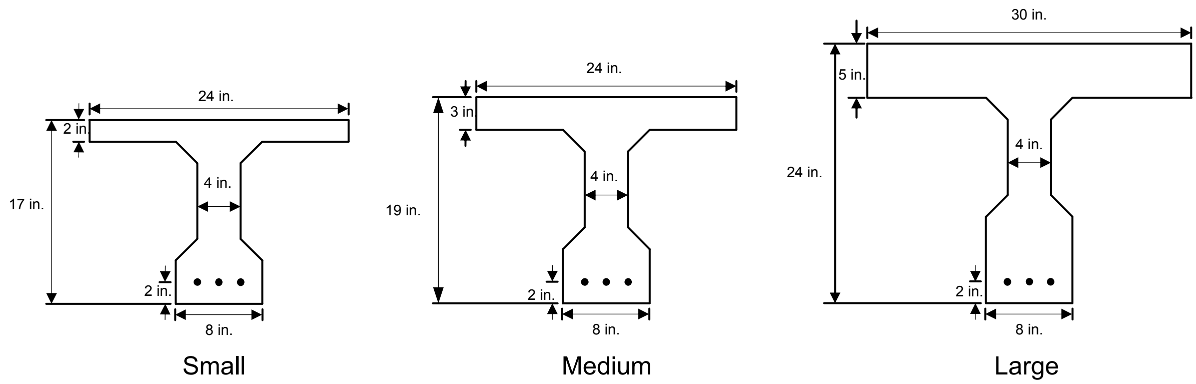


Fig. 6 Beam Cross Sections

Each cross section had a web width of 4 in., a web height of 11in. and a bottom flange width of 8 in. These dimensions were chosen, which required only slight modifications of the formwork to accommodate each of the three cross sections. The top flange of the small beams was 24 in. wide and 2 in. deep. The bottom flange height was adjusted such that the overall depth of the cross section was 17 in. The top flange of the medium beams was also 24 in. wide, but had a depth of 3 in. and the overall depth of the cross section was 19 in. The large cross section had an overall depth of 24 in. and a flange thickness and depth of 30 in. and 5 in., respectively. In each cross section, three strands were placed 2 in. from the bottom of the formwork with a lateral center-to-center spacing of 2 in.

In addition to the consideration of strand size on the cross section development, a T-shaped cross section was selected in an effort to maximize the tensile strain in the prestressing strands at the time of failure during flexural testing. By using a T-shaped cross section, the depth to the neutral axis was minimized, resulting in more curvature and increased strains in the prestressing strands.

In order to investigate the effect the amount of concrete cast beneath a strand has on transfer and development lengths, a number of the specimens were cast up-side-down, also referred to as inverted. By casting a specimen with an inverted orientation, it allows for more than 12 in. of fresh concrete to be placed beneath the strand as previously defined for the top strand effect. To ensure a direct head-to-head comparison of a beam cast with a normal orientation and a beam cast with an inverted orientation, the beam must be cast along the same line of prestressing strands and contain the same concrete.

The twenty test specimens were cast in six groups of beams. Each group is designated by pour, from Pour 1 to Pour 6. Pours 1 and 4 included only two beams both of which were cast with a normal orientation while the remaining pours included both normal and inverted beams. In addition to the three strand sizes, a higher strength, Grade 300, strand was also used with the small and medium cross sections. The Grade 300 strand was not used with the large cross section because 0.6 in. Grade 300 strand was not available. In order to distinguish each individual transfer measurement location, a unique identification scheme was created. Figure 7 gives a description of the naming convention.

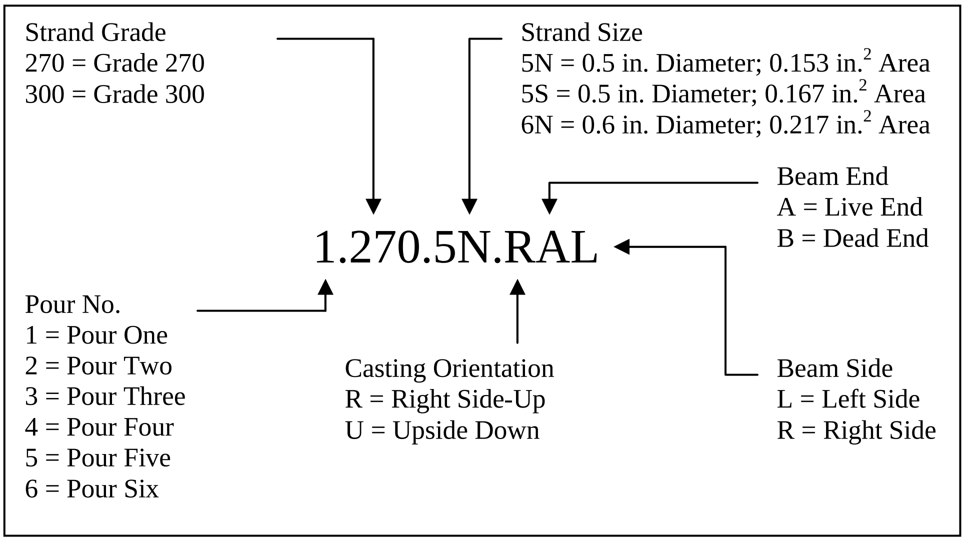


Fig. 7 Identification Scheme

The test specimens were cast in the Structural Engineering Laboratory at Virginia Tech. Two small prestressing beds were created on a portion of the reaction floor inside the lab. The reaction floor consists of eight, 60 ft long wide flange steel girders fully embedded in concrete, two of which were used for the prestressing beds. At each end of the two floor beams, a steel abutment shown in Figure 8, was bolted to the floor beams.

When casting beams with both normal and inverted orientations, special care was given to ensure each normally oriented beam has an identical inverted beam. Each pour consisted of two different types of strands, typically one line of Grade 270 strands and one line of Grade 300 strands excluding Pour 6. Each type of strand accompanied its own temporary prestressing bed on a corresponding floor beam. Figure 9 shows the plan view layout of a typical pour along with the sections of both beam orientations. Note that the beam with a normal orientation must be elevated to allow for simultaneous casting of both beams along the same line of strands.

Fig. 8 Stressing Abutment

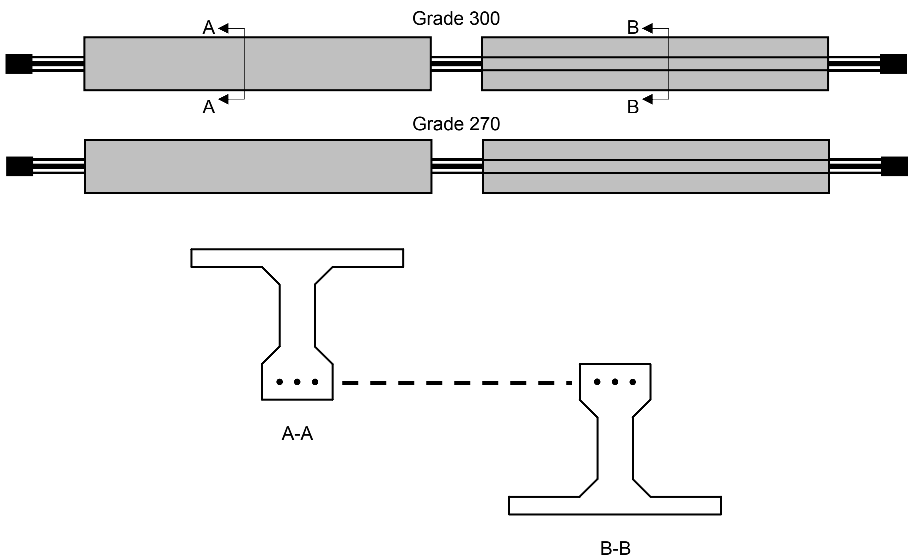


Fig. 9 Plan View of Typical Pour Layout

When casting the beams in a laboratory setting, an effort was made to replicate as close as possible the casting process typically used in industry. The industry casting procedure usually entails stressing of the strands during the first part of the day, followed by the addition of mild reinforcement, and finally formwork prior to actual casting on the same day. In the laboratory setting, this process is not feasible due to time constraints and lack of manpower; therefore, slight modifications were made to the casting process. The formwork was first assembled followed by the addition of mild reinforcement. The prestressing strands were then initially stressed. Following initial stressing, mild reinforcement was tied and final adjustments made to the formwork. These modifications were mainly due to the presence of the inverted beams. For the duration of final adjustments and tying of mild reinforcement, the prestressing strands would experience some losses due to relaxation. To compensate for these losses, just prior to casting, the prestressing strands were restressed and aluminum spacers placed in between the chuck and abutment bearing plate. The thickness of the spacer was determined based upon the amount of prestress loss which had occurred up to that point. Concrete was then placed and the beams were moist cured with wet burlap and covered with plastic up to the point of transfer. During that time, the formwork was removed and preparations made for transfer length measurements.

INITIAL PRESTRESS

The maximum allowable initial prestress is $0.75*f_{pu}$, which is viewed as the industry standard for prestressed concrete. Each strand in Pours 1 through 4 were stressed to $0.67*f_{pu}$, while each strand in Pours 5 and 6 were stressed to the maximum allowable stress of $0.75*f_{pu}$. Having strands with two levels of prestress enabled the researchers to compare not only the influence of casting position, but also the influence the initial prestress may have on transfer and development lengths.

MATERIAL PROPERTIES

The concrete mixture used in this project was designed to be a normal weight concrete with a target compressive strength of 4500 to 5000 psi at transfer and a 28 day compressive strength of 6000 psi. A 3/8 in. maximum aggregate was specified because of the tight spacing of reinforcement. The concrete was batched at a local ready mix plant and delivered to the laboratory. Following a flash set during the first Pour, the initial mix design was slightly modified for the remaining pours, both of which are shown in Table 1. The revised concrete mixture had a slightly larger water to cement ratio as well as the addition of retarder. Superplasticizer was included in the mix design, but was not used with Pours 2 through 5.

The concrete supplier provided batch information with each delivery, to allow for on-site manipulation of the concrete to more accurately control the water to cement ratios. Throughout the duration of the project, there was little correlation between slump measurements and compressive strengths of the concrete. The provided batch information is based on moisture contents for coarse and fine aggregates calculated by the concrete supplier. It is believed by the researchers that these moisture contents lack a high level of accuracy and overestimate the amount of water in each mix. When manipulating each batch of concrete, water to cement ratios were adjusted to match those shown in Table 1, providing a constant water to cement ratio of 0.40 throughout the project with the exception of Pour 1 where a water to cement ratio of 0.38 was used. Again, the adjustments were made based on provided batch information and the accuracy of this information is uncertain. Table 2 lists the final slump values along with the compressive strength at transfer and the average compressive strength at the time of testing for each pour.

Table 1 Concrete Mix Proportions

Component	Quantity (per yd^3) Initial	Quantity (per yd^3) Revised
No. 78 Stone	1443 lb	1443 lb
Natural Sand	1083 lb	1083 lb
Portland Cement	600 lb	600 lb
Fly Ash	150 lb	150 lb
Water	34 gal	36 gal
Air Entrainment	3-5%	3-5%
Super Plasticizer	19 oz.*	19 oz.*
Retartder	None	19 oz.#
W:C Ratio	0.38	0.40

*Not used in Pours 2-5
#Used in Pours 2-6

Table 2 Concrete Properties

Pour	Final Slump (in.)	HRWR Used (oz)	f'_{ci} (psi)	f'_c (psi)
1	2.75	76	4900	6500
2	7.5	NA	5300	6400
3	6.5	NA	6000	8200
4	7.5	NA	4900	6300
5	6.25	NA	5000	6700
6	11.5	128*	6600	8300

*Mid-way through casting an additional 28 oz was added

TRANSFER LENGTH

Transfer length measurements were taken at the live and dead ends of each beam. The live end of the beam is the end at which the strand is torch cut (in between the two beams), while the dead end of the beam is the end at which the strand is anchored to the supporting abutments. Transfer lengths were measured using two techniques. The primary method used was to measure the concrete surface strains at the level of the strand in each member, while the secondary method used was to measure end slip of the strand with relation to the end of the beam.

Concrete surface strains were measured using a DEmountable MECanical (DEMEC) strain gauge and surface mounted gauge points. The DEMEC gauge had a gauge length of 7.874 in. (200 mm) and the gauge points are approximately ¼ in. in diameter with a small fine point indention located at the approximate center. These points are placed on the beam at the level of the strands at a spacing of 1.969 in. (50 mm) and 3.937 in. (100 mm). A spacing of 1.969 in. was used in areas expected to be at or below the anticipated transfer lengths, ensuring a defined ascending branch of the transfer plot. The remaining points located beyond the transfer length, corresponding to the strain plateau were spaced at 3.937. Each individual strain reading was based on the total gauge length of 7.874 in., so adjacent strain readings would overlap aiding in the development of a smooth strain plot.

The initial distance between each point was measured three times and then averaged to ensure a secure starting point for all future measurements. During initial measurements, the standard deviation of each set of measurements was also examined to allow for the elimination for any outlying measurements. In the situation that a spurious measurement existed, a fourth measurement was taken to provide a more accurate starting point. Subsequent to the initial readings, the strands were cut using an acetylene torch, cutting the middle strand first followed by each of the two outer strands. DEMEC points were again measured and recorded. The difference between the two readings at any one location provided the change in strain from the point at which zero prestress force is applied to the point at which the entire prestress force is applied. The transfer process typically occurred after a seven day moist cure. The measurements taken on the day of transfer are considered to be the initial transfer lengths. Transfer lengths tend to increase approximately 10 percent with time, which typically occurs within the first few weeks. In order to confirm the transfer lengths for each specimen, measurements were again taken 1-2 weeks after transfer. These measurements are considered to be the final transfer lengths.

In addition to measuring changes in concrete surface strains, the strand tends to pull into the end of the beam upon transfer, which is referred to as end slip. Figure 10 shows the idealized strain distribution for both the concrete and the steel as a function of the distance from the end of the beam. Research by Guyon has shown end slip to be an accurate predictor of transfer length which resulted in the development of Equation 5.[10] However, Equation 5 neglects the effect of the concrete strain shown in Figure 10; therefore, Equation 6 was used for transfer length calculations.

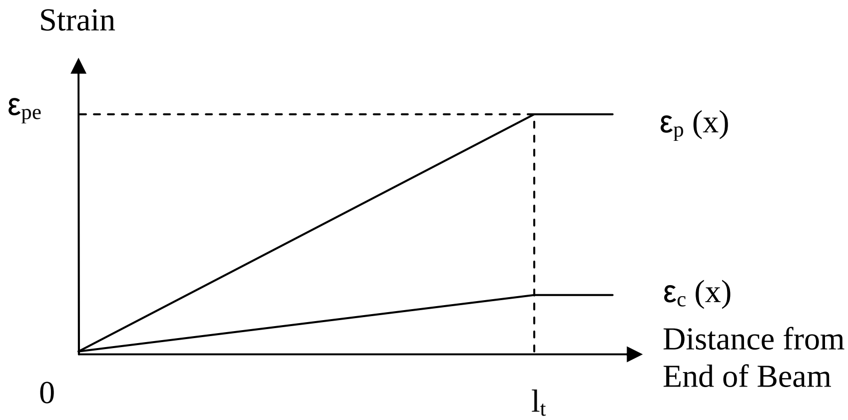


Fig. 10 Idealized Strain Plot

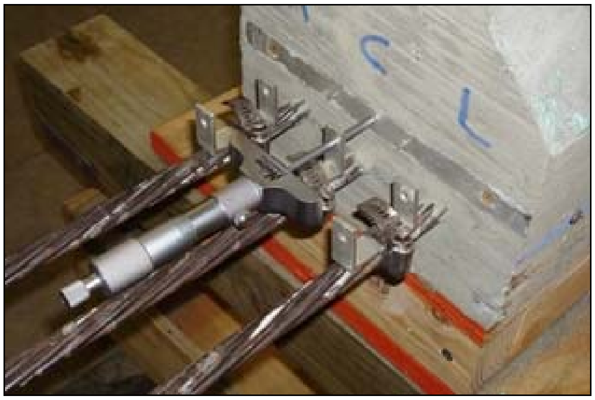
$$l_t = \frac{2E_{ps}}{f_{se}} L_{es} \qquad \text{Eq. 5}$$

where,
l_t = transfer length (in.)
E_{ps} = modulus of elasticity of prestressing steel (ksi)
f_{se} = stress in prestressing strands immediately prior to transfer (ksi)
L_{es} = end slip (in.)

$$l_t = \frac{2E_{ps}}{f_{se} + E_{ps}\varepsilon_{ci}} L_{es} \qquad \text{Eq. 6}$$

where,
l_t = transfer length (in.)
E_{ps} = modulus of elasticity of prestressing steel (ksi)
f_{se} = stress in prestressing strands immediately following transfer (ksi)
ε_{ci} = magnitude of concrete strain plateau immediately after transfer (in./in.)
L_{es} = end slip (in.)

End slip measurements were taken using a depth micrometer. In order to obtain accurate results, it is imperative that solid reference points be established before measurements are taken. A small U-bracket was placed on each strand with a hose clamp providing a stationary reference point for initial and final measurements. A small aluminum flat bar was also embedded in the concrete during casting to provide a flat smooth surface to measure against. Figure 11(a) shows the setup for end slip measurements. As with DEMEC points, three initial measurements were taken prior to transfer and averaged to ensure an accurate reference point. Following transfer measurements were again taken. The difference between the initial and final measurements is the end slip. It should be noted that it was only possible to obtain end slip measurements at the dead end of the beams. When using a torch cut release, the strand tends to fray, as shown in Figure 11(b), at the live end causing the U-brackets to bend or come loose. This negates any measurements at the live end.




(a) (b)

Fig. 11 End Slip Measurements Setup

DEVELOPMENT LENGTH

The development length tests were designed to determine a range of maximum and minimum development lengths for each of the five strand types used throughout the project. A single point bending test was performed on each end of the 24 ft long test specimens with a center-to-center span of 16 ft, allowing for two tests per beam. Figure 12 shows the test setup for one of the single point bending tests. The initial location of the point load, the embedment length, was based upon the calculated development length. A schematic diagram of the test setup is shown in Figure 13.

With each test arose the possibility of two main failure types, flexural or bond, and in some cases a combination thereof. A flexural failure is defined by either crushing of the concrete or rupture of the strand, which can be easily determined. A bond failure is defined by the amount of slip occurring between the end of the strand and the end of the beam, with a limit of 0.01 in. End slip was measured with linear variable differential transformers (LVDTs), with an accuracy of 0.001 in. Figure 14 shows the instrumentation configuration for recording end slips.

Fig. 12 Single Point Bending Test Setup

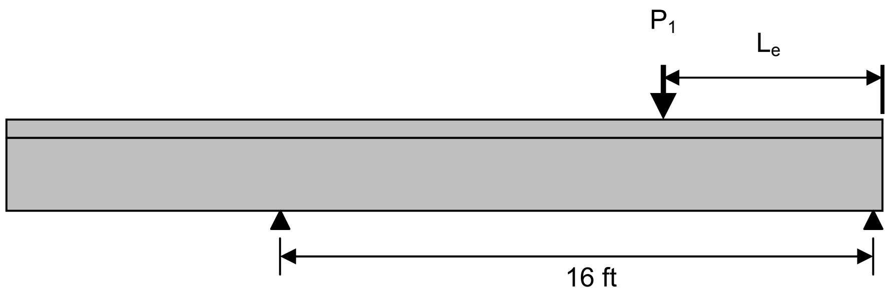


Fig. 13 Single Point Bending Test Schematic

Fig. 14 End Slip Instrumentation

The flexural tests were controlled with applied load steps beginning in 2 kip increments until cracking then 5 kip increments until failure. A flexural failure would indicate that the selected embedment length was longer than the actual development length, in which case the succeeding test of a new specimen would then incorporate a smaller embedment length. A test resulting in a bond failure, a slip of 0.01 in. or greater, would indicate that the selected embedment length was shorter than the actual development length, in which case the succeeding test of a new specimen would incorporate a larger embedment length. This process was repeated for each strand type with the purpose of developing an envelope for the development lengths.

RESULTS

TRANSFER LENGTH

Based upon the concrete surface strains recorded using the DEMEC gauge, a strain profile similar to Figure 15 was created for each transfer zone. The 95% AMS method was used to estimate initial and final transfer lengths. This generally accepted method was used by Barnes et al.[2] and recommended by Buckner[11]. The point at which the strain plateau began (apex) was visually identified and the average maximum strain (AMS) was determined based on those points beyond the apex of the ascending branch. The AMS was then reduced by five percent and a horizontal line plotted. Using the apex point, a linear trend line was fit to the data located between the end of the beam and the apex. Using the equation produced by the trend line, the intersection of the 95% AMS line and the best fit ascending line was determined, which corresponds to the transfer length. Equation 7 shows this calculation.

$$m \cdot l_t + b = 95\% AMS \qquad \text{Eq. 7}$$

where,

m = slope of the ascending branch of strain profile (in./in.^{2})
l_t = transfer length (in.)
b = y-intercept (in./in.)
95% AMS = 95% Average Maximum Strain (in./in)

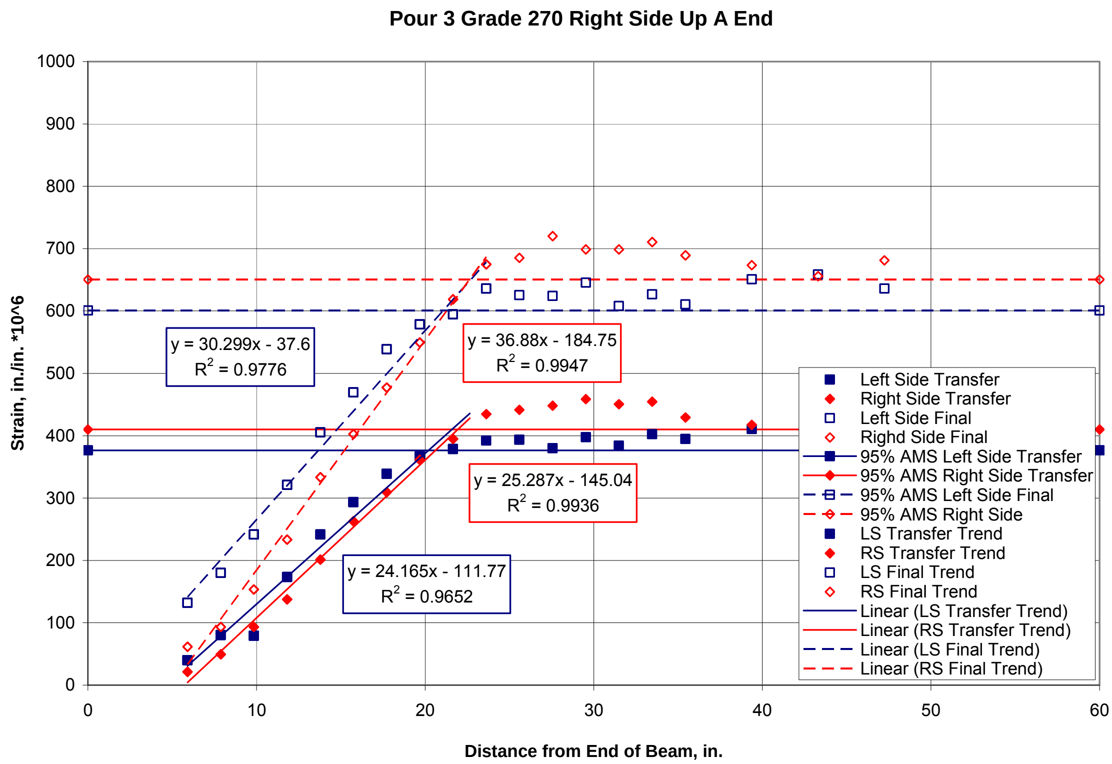


Fig. 15 Transfer Length Strain Profile

The initial and final transfer lengths are shown in Table 3 in terms of strand diameter. The values from Table 3 for the initial measurements are also plotted in Figure 16 and compared with $50d_b$, $60d_b$ and the transfer length portion of Equation 1. It can be seen that beams cast with a normal orientation had shorter transfer lengths than the adjacent inverted beam containing the same strand in all comparisons except for the dead end of beam 6.270.5S. It is also shown that transfer lengths of the live end of six of the eight inverted beams exceeded the ACI value of $50d_b$, three of which exceeded the AASHTO value of $60d_b$. Two of the dead ends also exceeded the ACI limit, while all of the beams with a normal casting orientation fell below the $50d_b$. The first portion of Equation 1 gave a more conservative estimate of actual transfer lengths, but was still exceeded by the transfer lengths of the live end of three inverted beams, two of which contained Grade 300 strand; therefore, the current code provisions may be unconservative for use with the Grade 300 strands.

Table 3 Transfer Lengths

Jacking Stress	Beam	Live (strand dia.)		Dead (strand dia.)		Code Provisions		
		Initial	Final	Initial	Final	$50d_b$	$\frac{f_{se}}{3}d_b$	$60d_b$
$0.67*f_{pu}$	2.270.5N.R	36	39	25	25	50	56	60
	2.270.5N.U	60	60	49	52	50	56	60
	2.300.5N.R	42	43	28	31	50	62	60
	2.300.5N.U	87	88	47	50	50	62	60
	3.270.5S.R	42	44	27	29	50	56	60
	3.270.5S.U	51	56	40	46	50	56	60
	3.300.5S.R	41	42	27	29	50	62	60
	3.300.5S.U	82	86	42	51	50	62	60
$0.75*f_{pu}$	5.270.5S.R	40	43	26	30	50	63	60
	5.270.5S.U	53	56	40	43	50	63	60
	5.300.5S.R	41	44	28	34	50	70	60
	5.300.5S.U	49	51	38	42	50	70	60
	6.270.5S.R	41	42	33	36	50	64	60
	6.270.5S.U	43	43	36	36	50	64	60
	6.270.6N.R	32	32	18	24	50	64	60
	6.270.6N.U	38	40	22	26	50	64	60

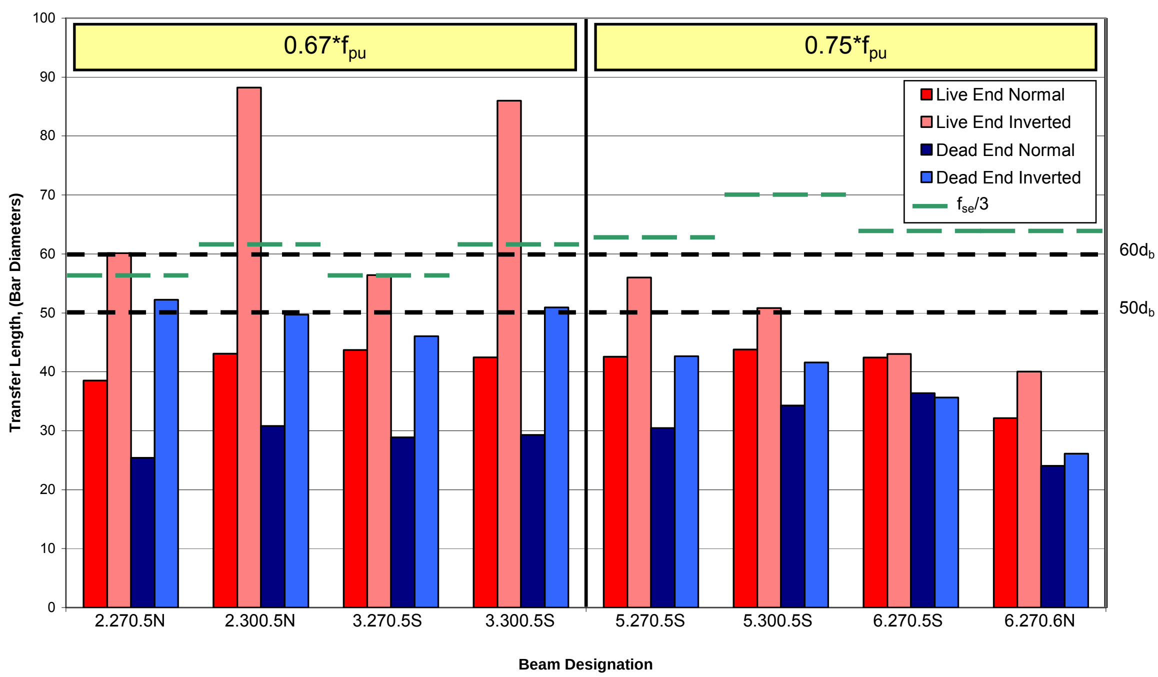


Fig. 16 Transfer Length Comparison of Beam Orientation

In addition to measuring concrete surface strains, end slip measurements were also recorded and used to calculate transfer lengths. As previously discussed, Equation 6 was used to calculate transfer lengths. All prestress losses were calculated up to the point just after transfer, including elastic shortening, relaxation, and any shrinkage that may have taken place, if the time of transfer was after the end of moist curing. The concrete strains used in Equation 6 were taken from the plots similar to Figure 15. Table 5 lists both the transfer lengths calculated based on end slips and transfer lengths based on surface strains. All of the transfer lengths calculated using end slips shown in Table 5 were slightly smaller than those calculated using surface strains. As with transfer lengths calculated from concrete surface strains, end slip values for strands in beams with an inverted orientation were larger than those cast in beams with a normal orientation.

Table 5 End Slip Measurements

Jacking Stress	Beam	Average End Slip (in.)	L_t (End Slip) (in.)	L_t (Strains) (in.)
$0.67*f_{pu}$	2.270.5N.R	0.034	10.5	12.5
	2.270.5N.U	0.057	18.0	26.0
	2.300.5N.R	0.003	1.0*	15.5
	2.300.5N.U	0.089	25.0	25.0
	3.270.5S.R	0.039	12.5	14.5
	3.270.5S.U	0.058	18.0	23.0
	3.300.5S.R	0.046	13.0	14.5
	3.300.5S.U	0.077	22.0	25.5
$0.75*f_{pu}$	5.270.5S.R	0.044	12.5	15.0
	5.270.5S.U	0.063	17.5	21.5
	5.300.5S.R	0.048	12.0	17.0
	5.300.5S.U	0.066	16.5	21.0
	6.270.5S.R	0.051	14.0	18.0
	6.270.5S.U	0.060	17.0	18.0
	6.270.6N.R	0.049	13.5	14.5
	6.270.6N.U	0.056	15.5	15.5

*Invalid measurement

DEVELOPMENT LENGTH

A range of development lengths (maximum and minimum possible) was determined based on the results for the single point bending tests. The maximum and minimum final transfer lengths for each strand type were selected based on the concrete surface strain plot for each transfer zone, previously shown in Figure 15. In addition to the calculation of transfer lengths, the flexural bond length was also calculated for each flexural test. Each flexural bond length was taken as the difference of the embedment length used during a flexural test and the corresponding transfer length. The minimum flexural bond length shown in Table 6 was equal to the maximum calculated flexural bond length that still resulted in a bond failure, while the maximum flexural bond length shown in Table 6 was equal to the minimum calculated flexural bond length that still resulted in a flexural failure.

The ranges for the development lengths include both a maximum and minimum based on the single point bending tests previously discussed. The maximum development length was conservatively taken as the sum of the maximum transfer length and maximum flexural bond length from Table 6 for each strand type. Conversely, the minimum development length was taken as the sum of the minimum transfer length and minimum flexural bond length.[4] This method was used for all strand types excluding the Grade 300 strand used in Pour 5. One test resulting in a bond failure had a significantly longer flexural bond length, thus the maximum and minimum development lengths were calculated providing the most conservative range.

The results in Table 6 also include the coupled and uncoupled values for the development lengths, including and excluding the effect of the inverted beams as well as the calculated development length for each strand type based on ACI and AASHTO provisions. ACI and AASHTO resulted in similar values with the minimum used in the comparison for conservatism. Figure 17 shows a graphical representation of the results listed in Table 6. Ranges for development lengths are shown including and excluding the influence of the inverted beams. The development length ranges of only the normally oriented beams are smaller than the development length ranges including the inverted beams. Ranges for both situations all fall below the calculated values except for the ranges including inverted beams containing Grade 300 strands. This shows that the current development length equations, Equations 1 and 4 may be unconservative for Grade 300 strand. It should also be noted, that those ranges that exceeded the code values were highly influenced by the inverted beams, which had very long transfer lengths, which exceeded all three code provisions.

Table 6 Development Lengths

	Strand	Orientation	Transfer (in.) min	Transfer (in.) max	Flexural Bond (in.) min	Flexural Bond (in.) max	Development Length (in.) Uncoupled min	Uncoupled max	Coupled min	Coupled max	Code
$0.67*f_{pu}$	270.5N	Normal	12.5	19.5	NA	46.5	NA	66.0	48.5	76.5	78.0
		Inverted	26.0	30.0	36.0	NA	62.0	NA			
	300.5N	Normal	15.5	21.5	26.5	44.5	42.0	66.0	42.0	88.5	86.0
		Inverted	25.0	44.0	35.0	NA	60.0	NA			
	270.5S	Normal	14.5	22.0	36.0	*38.0*	50.5	60.0	46.5	77.0	79.0
		Inverted	23.0	28.0	32.0	49.0	55.0	77.0			
	300.5S	Normal	14.5	22.0	39.0	*48.0*	53.5	70.0	31.5	91.0	87.0
		Inverted	25.5	43.0	*17.0*	46.5	42.5	89.5			
$0.75*f_{pu}$	270.5S	Normal	15.0	21.0	39.0	42.0	54.0	63.0	54.0	72.5	73.0
		Inverted	18.0	28.0	50.5	44.5	68.5	72.5			
	300.5S*	Normal	17.0	22.0	55.0	38.0	55.0	77.0	51.5	80.5	84.0
		Inverted	21.0	25.5	34.5	NA	55.5	NA			
	270.6N	Normal	14.5	19.5	46.5	51.5	61.0	71.0	59.0	78.0	88.0
		Inverted	15.5	24.0	44.5	54.0	60.0	78.0			

*The maximum and minimum flexural bond lengths were calculated differently because of one significantly long flexural bond length that resulted in a bond failure.

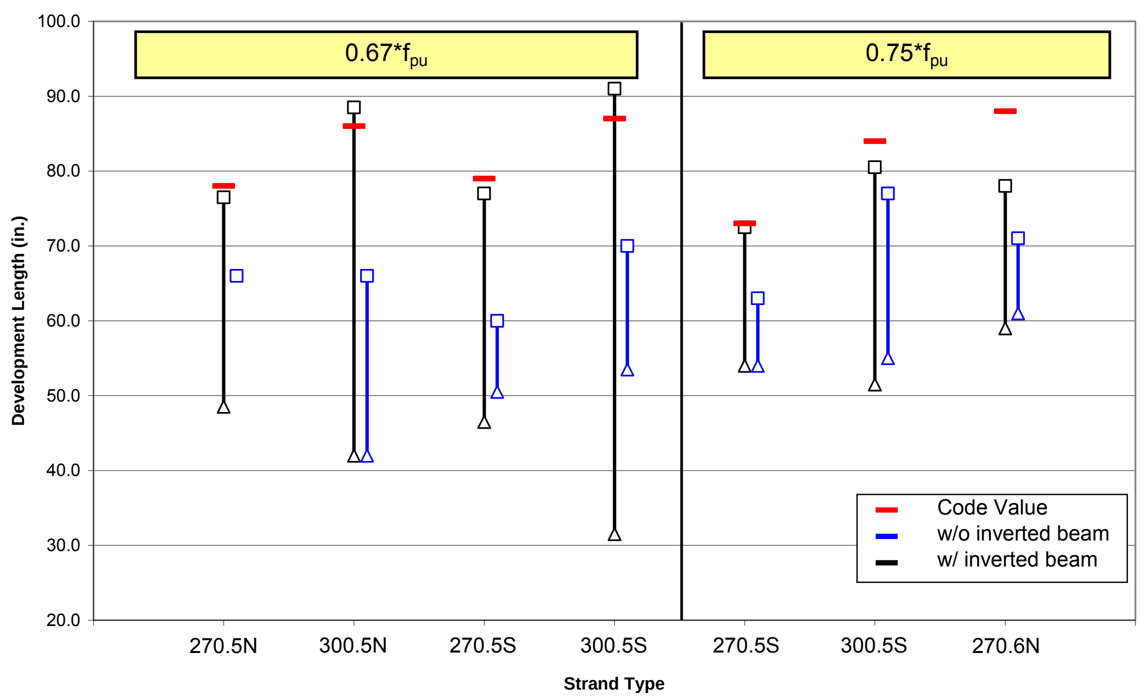


Fig. 17 Development Lengths

STRAND BOND QUALITY

Along with the transfer and development length tests, it is recommended that the strand also pass two specified bond tests. The two tests used to verify the surface conditions of the strands used in this project were the Large Block Pullout Test[12] (LBPT) and the North American Strand Producers (NASP) Test[13]. LBPT and NASP tests were performed on each size and grade of strand used throughout the project. All strand types with the exception of the Grade 270 ½ in. diameter super used in Pour 6 passed both tests. The Grade 270 ½ in. diameter super strand did have a ratio of actual pullout force to required pullout force of 0.92, which is less than 1.0, but this strand showed favorable results in transfer and development length tests.[14]

CONCLUSIONS

The purpose of this investigation was to compare the effects of strand strength and casting position on the transfer and development lengths in pretensioned prestressed concrete girders. Transfer and development lengths were calculated for three sizes and two strengths of strand in beams cast with traditional orientations and beams with inverted orientations. As expected, the beams with inverted orientations did exhibit less favorable bond characteristics than those beams cast with normal orientations.

Transfer lengths for beams cast with inverted orientations showed a significant increase in transfer lengths ranging from a slight increase to two times the transfer length of the adjacent normally oriented beams, many of which exceeded code values. Beams cast with inverted orientations containing Grade 300 strands did show larger increases in transfer lengths in two of the three pours in which they were included than the adjacent beams containing Grade 270 strands. Beams cast with normal orientations containing Grade 300 strands behaved similarly to those containing Grade 270 strands, all of which fell below the code values.

Development length ranges were developed for each size and grade strand, including and excluding the effects of the inverted beams. Excluding the data from the inverted beams, for both Grade 270 and Grade 300 strands, the maximum end of the development length range fell below the code value. With the inclusion of the inverted beam data, the maximum end of the development length ranges for two of the three pours containing Grade 300 strands exceeded the code value. This is attributed to the extremely large transfer lengths for the inverted beams containing Grade 300 strands.

Based on the results of this investigation, the authors recommend the following:

1. For strands cast with more than 12 in. of fresh concrete beneath them, the transfer length should be increased from $50d_b$ and $60d_b$ in ACI and AASHTO, to $70d_b$ for Grade 270 strands and $100d_b$ for Grade 300 strands. Both the $70d_b$ and $100d_b$ also anticipate a 12 percent increase in initial prestress as the tests resulting in the longest transfer lengths had an initial prestress of $0.67*f_{pu}$.

2. For strands cast with more than 12 in. of fresh concrete beneath them, the modification factors of 1.3 and 1.4 used for nonprestressed reinforcement should be applied to the ACI and AASHTO development length equations, respectively.
3. The aforementioned values recommended for transfer lengths need additional research for verification. Additional research should be completed on the top strand effect for both Grade 270 and Grade 300 strand. This research should include the effects of casting position, both the amount of concrete above and below the strand coupled with various water to cement ratios, as the true rationale behind the extreme increases has yet to be determined.

REFERENCES

1. American Concrete Institute (ACI). (2005). *Building Code Requirements for Structural Concrete and Commentary*, Farmington Hills, Michigan.
2. Barnes, R. W., Grove, J. W., and Burns, N. H., "Experimental Assessment of Factors Affecting Transfer Length," *ACI Structural Journal*, V. 100, No. 6, November-December 2003, pp. 740-748.
3. Petrou, Michael F., Wan, Baolin, Joiner, Walter S., Trezos, Constantin G., and Harries, Kent A., "Excessive Strand End Slip in Prestressed Piles," *ACI Structural Journal*, V. 97, No. 5, September-October 2000, pp. 774-782.
4. Hodges, H. T. (2006). "Top Strand Effect and Evaluation of Effective Prestress in Prestressed Concrete Beams," M.S. Thesis, Virginia Tech, Blacksburg, VA.
5. American Association of State Highway and Transportation Officials (AASHTO). (2006). *AASHTO LRFD Bridge Design Specification*, Washington, D.C.
6. Nassar, A. J. (2002). "Investigation of Transfer Length, Development Length, Flexural Strength, and Prestress Loss Trend in Fully Bonded High Strength Lightweight Prestressed Girders," M.S. Thesis, Virginia Tech, Blacksburg, VA.
7. Jeanty, P. R., Mitchell, D., and Mirza, M. S., "Investigation of "Top Bar" Effects in Beams," *ACI Structural Journal*, V. 85, No. 3, May-June 1988, pp. 251-257.
8. Peterman, R. J., "The Effects of As-Cast Depth and Concrete Fluidity on Strand Bond," *PCI Journal*, V. 52, No. 3, May-June 2007, pp. 72-101.
9. Larson, K. H., Peterman, R. J., and Esmaeily, A., "Bond Characteristics of Self-consolidating Concrete for Prestressed Bridge Girders," *PCI Journal*, V. 52, No. 4, July-August 2007, pp. 44-57.
10. Guyon, Y. (1960). Prestressed Concrete, John Wiley & Sons, New York.
11. Buckner, C. D. (1994). "An Analysis of Transfer and Development Lengths for Pretensioned Concrete Structures." *Report No. FHWA-RD-94-049*, Federal Highway Admistration, Washington, D.C.
12. Logan, D. R., "Acceptance Criteria for Bond Quality of Strand for Pretensioned Prestressed Concrete Applications," *PCI Journal*, V. 42, No. 2, March-April 1997, pp. 52-90.
13. Mote, J. (2001). "Bond Mechanics of Steel Prestressing Strand," M.S. Thesis, University of Oklahoma, Norman, OK.

14. Loflin, B. J. (2008). "Bond and Material Properties of Grade 270 and Grade 300 Prestressing Strand," M.S. Thesis, Virginia Tech, Blacksburg, VA.