TRANSFER AND DEVELOPMENT OF 0.7 INCH STRAND IN PRECAST/PRESTRESSED BRIDGE GIRDERS

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ABSTRACT

As the demand for longer girder span, wider girder spacing, and shallower girder depth increase, so does the need for higher concrete strength and larger strand diameter. Large 0.7 inch diameter, Grade 270, low-relaxation prestressing strands have been first used in the construction of the Pacific Street Bridge, Omaha, NE. This successful application has demonstrated the advantages of using 0.7 inch strand and the need for additional research to evaluate the impact of such large strand diameter on girder design.

This paper presents the research in progress at the University of Nebraska-Lincoln to investigate the transfer and development of 0.7 inch diameter strand. According to the 2007 AASHTO LRFD Bridge Design Specifications, transfer length and development length provisions are applicable to 0.5 and 0.6 inch diameter strand only. Experimental work has been carried out to investigate the effect of level of prestressing, and level of confinement on the transfer and development length of 0.7 inch strand. This involved the fabrication of forty-five test specimens, with varying length and level of confinement, for 8 ksi concrete and one 0.7 inch diameter strand in both a prestressed and unstressed state. Results of surface strain measurements indicated that level of confinement does not significantly affect the transfer length. Results of pullout tests indicated that both initial strand stress and level of confinement have significant effect of the development length. Additional testing is in progress to investigate the effects of other parameters, such as concrete strength and strand spacing. The paper will present the test setup, testing results, data analysis, and research conclusions.

Keywords: 0.7 inch strand, Transfer length, Development length, Pullout test

INTRODUCTION

The Narrows Bridge over the Swan River in Perth, Western Australia, opened to traffic in November 1959, was the first bridge in the world that uses 19 - 0.7 in. (17.8 mm) diameter strands for external prestressing cables[1]. Since then, several bridges were built around the world using 0.7 in. (17.8 mm) diameter strand for unbounded/external post-tensioning. Also, two manufacturers in the United States have been making 0.7 in. (17.8 mm) diameter strand for several years to use in mining applications. The American Standards for Testing Materials (ASTM) A 416 – 06 was the first standard that introduced 0.7 in. (17.78 mm) diameter, Grade 270, low-relaxation strand for prestressed concrete applications. Later the American Association of State Highway and Transportation Officials (AASHTO) produced an equivalent standard, M203-07 which covers the mechanical properties of 0.7 in. (17.8 mm) diameter strand, such as breaking strength, yield strength, and elongation[2]. The 0.7 in. (17.8 mm) diameter strand has a cross section area of 0.294 $in.^2$ (189.7 mm^2), which results in a unit weight of 1 lb/ft (1.487 kg/m). The force required for jacking 0.7 in. (17.8 mm) diameter strand up to 75 percent the ultimate strength is 59.5 kip (265 kN), which is 35 percent higher than that of 0.6 in. (15.2 mm) diameter strand and 92 percent higher than that of 0.5 in. (12.7 mm) diameter strand.

Figure 1 shows the percentage of increase in prestressing forces when 0.7 in. (17.8 mm) diameter strands are used in pre-tensioned concrete girders at different horizontal and vertical spacing compared to that of 0.6 in. (15.2 mm) and 0.5 in. (12.7 mm) diameter strands at 2 in. (51 mm) x 2 in. (51 mm) spacing. This figure indicates the significant increase in the flexural capacity of the girder for the same number of strands, which allows for longer spans and/or larger girder spacing. Also, for the same amount of prestressing force, using 0.7 in. (17.8 mm) strands results in fewer number of strands to jack and release, fewer chucks, and higher flexural capacity due to lowering the center of gravity of the strands.

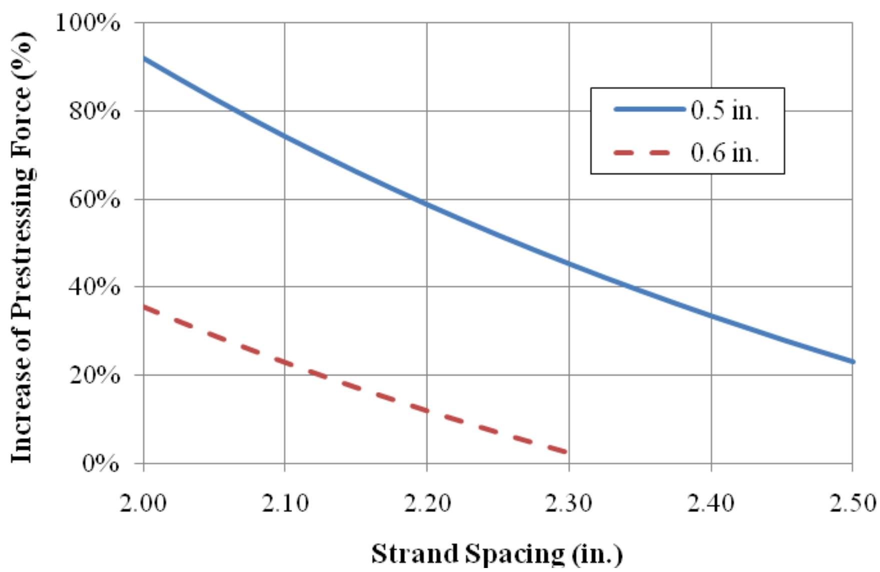


Fig. 1 Increased Prestressing Force due to using 0.7 inch (17.8 mm) Diameter Strands

In 1988, the U.S. strand manufactures proposed increasing the size of prestressing strands used in pre-tensioned concrete bridge girders from 0.5 in. (12.7 mm) diameter to 0.6 in. (15.2 mm) diameter while maintaining the minimum spacing between strands at 2.0 in. (51 mm). The objective of that proposal was to increase the total prestressing force transferred to the concrete by 42%, which significantly improves the structural capacity and durability of bridge girders. At that time, the development length equation stated the minimum spacing between strands required to ensure adequate bond between strands and concrete must be equal to four times the strand diameter. This means that 0.6 in. (15.2 mm) diameter strands cannot be used at a spacing less than 2.4 in. (61 mm). This large spacing eliminates the advantage of having larger strands diameter as it results in a prestressing force per unit inch of concrete less than that of 0.5 in. (12.7 mm) diameter strands at 2.0 (51 mm) spacing. In addition, most manufacturers refused to accommodate the new spacing requirements because of the high expenses associated with retooling their prestressing beds and equipment.

Therefore, the Federal Highway Administration (FHWA) issued a memorandum that forbade the use of 0.6 in. (15.2 mm) diameter strands at 2.0 in. (51 mm) spacing on public structures until further studies were carried out to ensure their safety. After several years of research at the Virginia Military Institute on this issue, the FHWA announced in 1996 that the minimum spacing for 0.6 in. (15.2 mm) diameter strands is 2.0 in. (51 mm), and the minimum spacing for 0.5 in. (12.7 mm) diameter strands is 1.75 in. (45 mm). Shortly after AASHTO adopted the FHWA new spacing requirements in its bridge design specifications[3].

A detailed study on optimized sections for high-strength concrete bridge girders was carried out in 1996 by Russell, et al.[4]. In this study, the effect of strand size and spacing on the capacity and cost of different concrete bridge girders were evaluated at various concrete strengths. Despite the unavailability of 0.7 in. (17.8 mm) diameter strand in the US market at the time of the study, its cost-effectiveness compared to other strand sizes was evaluated. This comparison has indicated that using 0.7 in. (17.8 mm) diameter strands at 2.0 in. (51 mm) in a 10,000 psi (69 MPa) BT-72 girder results in the longest span length and most cost-effective structure compared to 0.5 in. (12.7 mm) and 0.6 in. (15.2 mm) diameter strands[5].

The Pacific Street Bridge over I-680 in Omaha, Nebraska is the first bridge in the United States to use 0.7 in. (17.8 mm) diameter prestressing strand in the precast pre-tensioned concrete girders. The bridge was built in August 2008 as a replacement to an existing bridge due to the deteriorating condition and substandard width of its superstructure. The old bridge was 74 ft (22.6 m) wide and had four spans that are 44 ft 6 in. (13.6 m), 73 ft (22.3 m), 73 ft 6 in. (22.4 m), and 30 ft (9.2 m) long. Each span consisted of 11 steel I-girders at 7 ft (2.1 m) spacing. The new bridge consists of two identical spans, 98 ft (29.9 m) long each with 17 degree skew angle. The bridge has six traffic lanes with a total width of 105 ft 8 in. (32.2 m). The bridge superstructure consisted of twenty NU900 I-girders (ten for each span) that are 35.4 in. (900 mm) deep and spaced at 10 ft 8 in. (3.3 m). Each girder was pre-tensioned using 30-0.7 in. (17.8 mm) diameter strands that are spaced at 2.0 in. (51 mm) horizontal spacing and 2.5 in. (64 mm) vertical spacing.

The main challenge in this project was to design a precast/prestressed concrete alternative that replaces four span steel girders with two span girders while maintaining the same vertical clearance. This challenge necessitated the use of high strength materials, such as 10,000 psi (69 MPa) concrete and large diameter strand. This combination of 0.7 in (17.8 mm) diameter strands with high strength concrete resulted in an efficient and optimized use of the two materials. The biggest challenge in the production of the precast/prestressed girders was those associated with the use of 0.7 in. (17.8 mm) strand. The availability of this large size of strand was not a problem, however, several challenges were associated with the size and stiffness of the strand itself, such as getting the strand out of the coils, retooling the opening in the bulkheads, flexibility issues when feeding the strand through the bulkheads, and acquiring larger chucks and hold down devices for depressing strands. The producer addressed all these issues in a very safe and efficient manner and did not experience any problems.

In spite of this successful application of 0.7 inch (17.8 mm) diameter strand, additional research is needed to evaluate the impact of such large strand diameter on girder design. This article presents the ongoing research project to experimentally evaluate the transfer and development length of 0.7 in. (17.8 mm) diameter strand. Several parameters have been identified to impact the transfer and development length of prestressing strand, such as concrete strength, strand spacing, strand stress, and level of confinement. Although current AASHTO LRFD provisions do not account for the effect of confinement on transfer and development length, earlier studies have indicated the importance of this parameter in addition to the concrete strength, strand stress, and strand spacing[7,8].

This paper is organized as follows. The second section presents the experimental work to evaluate the transfer length of 0.7 in (17.8 mm) diameter strand. Testing setup, procedures, and results are also presented. The third section presents the pullout tests performed to evaluate the development length of 0.7 in. (17.8 mm) strand at varying specimen length, level of confinement, and tensioning force. The last section presents research conclusions and highlights the issues that need to be addressed in future research.

TRANSFER LENGTH

Transfer length is the length of the strand measured from the end of the prestressed member over which the effective prestress is transferred to the concrete. The transferred force along the transfer length is assumed to increase linearly from zero at the end of the member to the effective prestress at the end of the transfer length as shown in Figure 2. According to the 2007 AASHTO LRFD Bridge Design Specifications with 2008 interim revisions Section 5.11.4.1, transfer length (l_t in.) for fully bonded prestressing strands is equal to $60d_p$, where d_p is the nominal diameter of strand in inches.

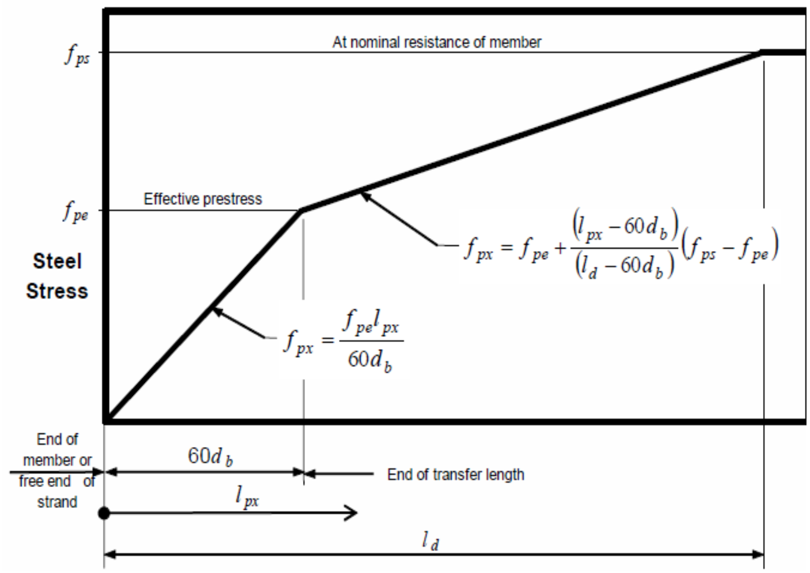


Fig. 2 Idealized Relationship between Stress in Strands and Distance from the Free End of Bonded Prestressing Strands (AASHTO 2007)

Transfer length is important for the shear design and calculations of release stresses at the girder ends. An over-estimated transfer length may result in conservative shear design and higher release stresses at girder ends than predicted. An under-estimated transfer length may result in inadequate shear design and lower release stresses at girder ends than predicted.

To experimentally evaluate the transfer length of prestressing strands, four 8 ft (2.44 m) long specimen were made as shown in Figure 3. Each specimen had a 7 in. (178 mm) x 7 in. (178 m) cross section and only one 0.7 in. (17.8 mm) diameter, Grade 270, low-relaxation strand at the center. Confinement loops of 3/8 in. (9.5 mm) diameter, Grade 60 steel were used at different spacing in each specimen to apply different levels of confinement. These loops are 5 in. (127 mm) x 5 in. (127 mm) in size and spaced as follows: 3 in. (76 mm), 6 in. (152 mm), 9 in. (228 mm), and 12 in. (305 mm).

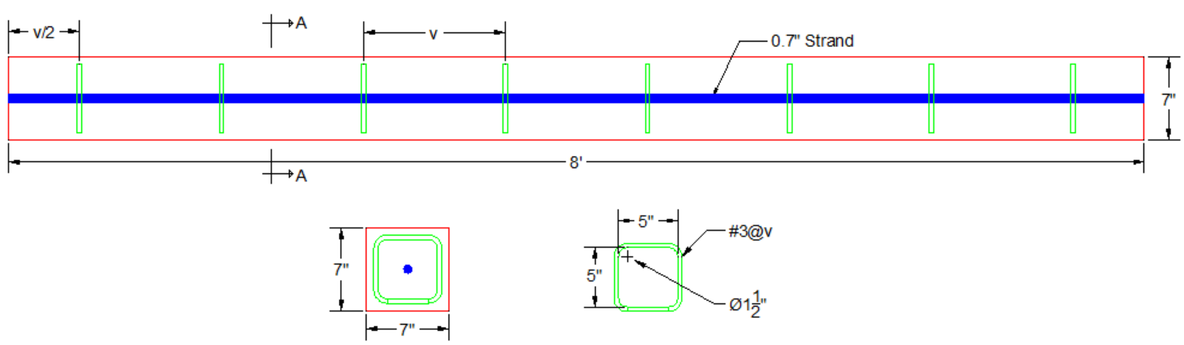
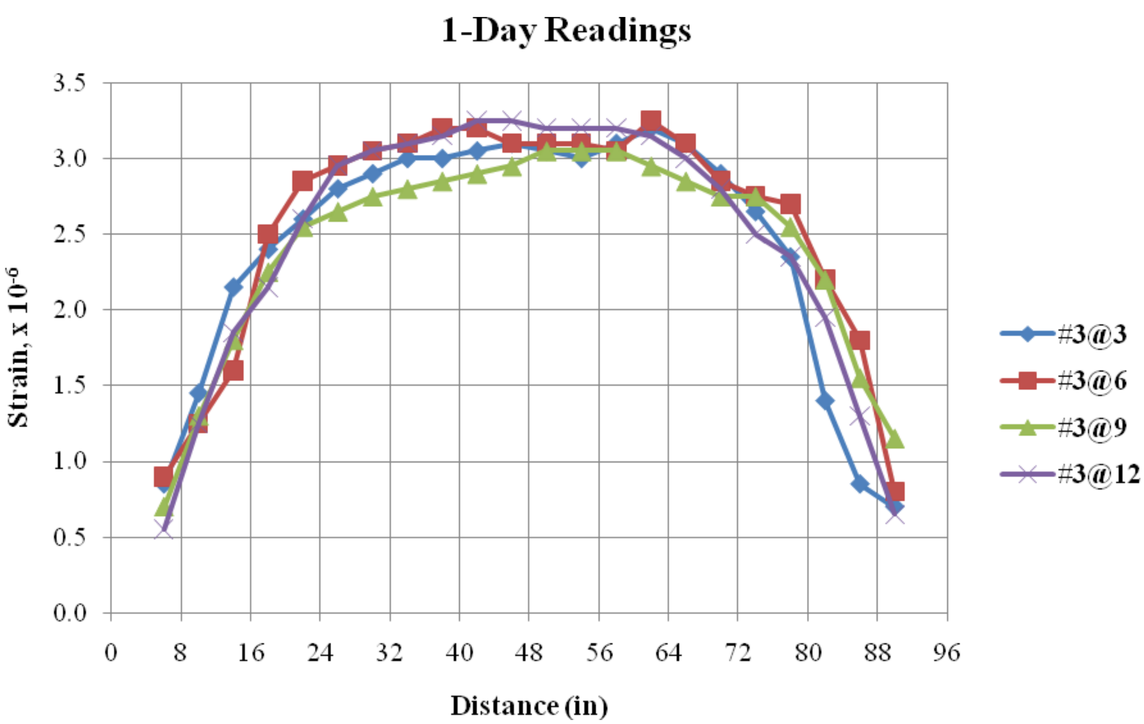


Fig. 3 Transfer Length Test Specimen

To measure the transfer length, a series of Detachable Mechanical gauges (DEMEC gauges) were placed along the two sides of each specimen at 4 in. (11 mm) spacing, starting 2 in. (6mm) from the end of the concrete specimen, at the same elevation of the prestressing strand before prestress release. These gauges were manufactured by Hayes Manufacturing Company in the United Kingdom. DEMEC readings were taken at release (1-day) and at 7, 14, 21, and 28 days using a W.H. Mayes & Son caliper gauge. The change in the measured distance between DEMEC gauges was used to calculate the strain in the concrete at different ages. Figure 4 plots the 1-day and 28-day strains averaged from the readings of the two sides of each specimen. The predicted transfer length for the 0.7 inch (17.8 mm) diameter strand is 42 in. (1.07 m) according to the AASHTO LRFD[6]. The measured transfer length was calculated using the 95 percent average maximum strain (AMS) method, which was found to be approximately 31 in. (788 mm). This is close to the transfer length estimated based on the measurements taken from a full-scale NU900 girder prestressed using 30-0.7 in. (17.8 mm) diameter strands[9]. This indicates that transfer length of 0.7 in. (17.8 mm) diameter strand can be better predicted using the American Concrete Institute (ACI) 318-08 expression $50d_p$ [10], 35 in. (889 mm), than the 2007 AASHTO LRFD expression $60d_p$ [6], 42 in. (1.07 m), which is significantly conservative.



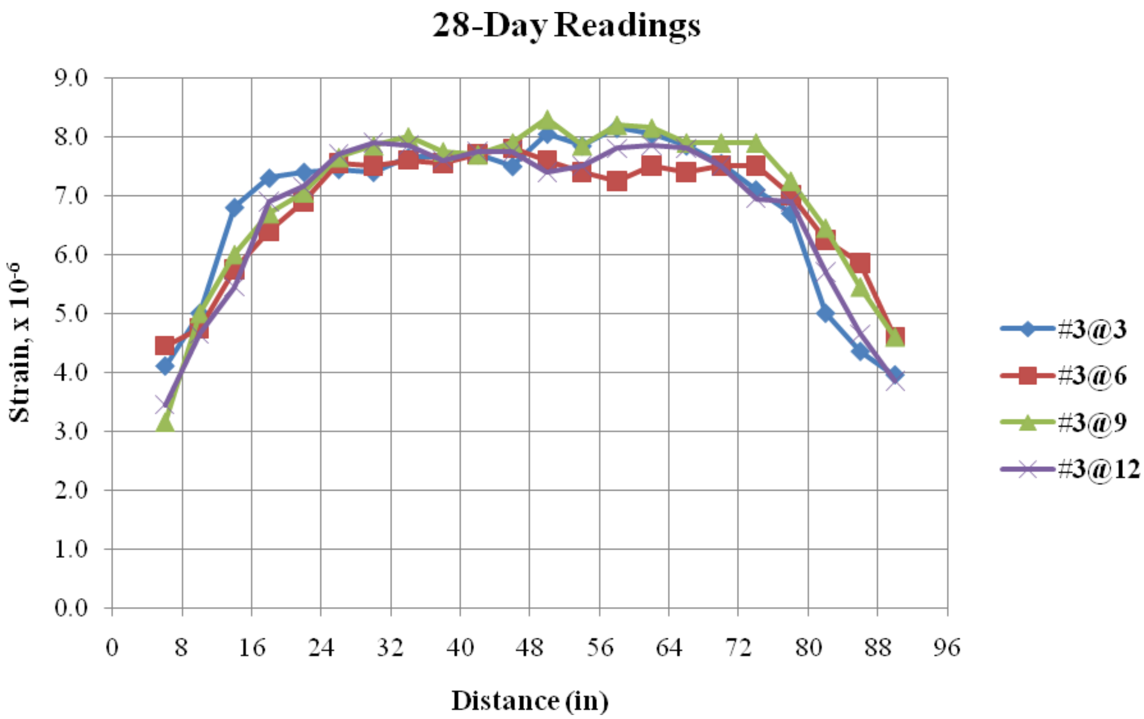


Fig. 4 1-day and 28-day Transfer Length Measurements at Different Levels of Confinement

Figure 4 also indicates that there is no clear difference between the strain profiles in the specimens with different confinement reinforcement. This means that there is no significant effect from the level of confinement on the transfer length of 0.7 in. (17.8 mm) diameter strand. This is in agreement with the conclusion of investigation carried out on 0.5 in. (12.7 mm) and 0.6 in. (15.2 mm) strand by Russell and Burns[4]. In this investigation, transfer length was measure experimentally on specimens with 2, 3, and 4 strands, with and without confining reinforcement (#3 @ 4 in.). The conclusion was that confinement reinforcement did not contribute significantly to prestress transfer because the confinement reinforcement remains inactive until concrete cracking occurs, which is usually controlled by end zone reinforcement. Also, transfer length is mainly a function of the stiffness of the uncracked concrete section, which is hardly affected by the amount of confinement reinforcement.
It should be noted that this conclusion was reached by testing a single strand. The number of strands and the spacing among them may have a different effect.

DEVELOPMENT LENGTH

The development length of prestressing strands is defined as the minimum embedment needed to reach the section ultimate capacity without strand slippage. Thus, at the point of strand development, the strand stress could reach a maximum tensile stress without strand-concrete bond failure. The development length is measured from the member end to the point of maximum stress as shown in Figure 2. According to the 2007 AASHTO LRFD Bridge

Design Specifications with 2008 interim revisions Section 5.11.4, development length provision for fully bonded prestressing strands is as follows[6]:

$$l_d \geq k\left[f_{ps} - \frac{2}{3}f_{pe}\right]d_b \tag{5.11.4.2-1}$$

l_d= development length (in)
d_b= nominal strand diameter (in)
f_{ps}= average stress in prestressing steel (ksi)
f_{pe}= effectives stress in prestressing steel (ksi)
k = factor equal to 1.0 for pre-tensioned panels, piling, and other pre-tensioned members with a depth of less than or equal to 24.0 in.; and 1.6 otherwise.

Figure 2 shows the linear relationships between the stress in fully bonded prestressing strand and distance from the end of the girder. These relationships along with the estimated transfer and development length are necessary for identifying the critical sections in flexure and shear and calculating those capacities of the girder. Accurate estimate of the development length is important for the flexure design of girders. While an under-estimated development length might result in a lower girder capacity at the sections within the development length than predicted, an over-estimated development length result in an uneconomical design with unnecessarily excessive reinforcement.

Pullout tests were performed to evaluate the bond between concrete and 0.7 in. (17.8 mm) diameter strand. Three parameters were considered in this testing: embedded length, level of confinement, and stress state of the strand. A total of thirty-nine specimen were poured and tested in the Structural Lab at the Peter Kiewit Institute at the University of Nebraska: twelve 4 ft (1.22 m), fifteen 5 ft (1.52 m), and twelve 6 ft (1.83 m). The specimens had the same cross section as the transfer length specimens shown in Figure 3. Due to the capacity limitations of the prestressing bed, the specimens were fabricated in two phases. Phase I include 21 specimens, which were tested and reported by Akhnoukh in 2008[11]. Phase II include 18 additional specimen that were needed to study the effect of the identified parameters. Figure 5 shows the forms set up in the prestressing bed, Figure 6 shows the placement of the #3 confinement reinforcing around the 0.7 in. (17.8 mm) strand, and Figure 7 shows the test setup. This setup was designed to apply clamping force on the strand while testing to prevent strand slippage and ensure that the ultimate stress is applied. A potentiometer was attached to the strand on the other end of each specimen during testing to monitor the bond failure of the strand, which is defined as any relative movement that is greater than 0.01 inch (0.254mm). This value was determined based on the precision of the used potentiometer.

Fig. 5 Forms of the pullout specimens

Fig. 6 Specimen Strand Confinement

Fig. 7 Pull-out Testing Setup

Table 1 gives the pullout testing results of all thirty-nine specimens. Two types of failure were observed: strand rupture and strand slippage. Specimen that failed above the ultimate strength of 270 ksi (1861 MPa) had strand rupture, while those which failed below 270 ksi (1861 MPa) had strand slippage except those marked with an asterisk. The rupture of those strands at a stress level below the ASTM A416-06 and AASHTO M203-07 specified 270 ksi (1861 MPa) might be attributed to lower strand quality and/or stress concentration due to improper alignment of the inset and chuck. These specimens were still considered in the study as they resulted in stress levels very close to 270 ksi without slippage.

Tab. 1 Results from Pull-out Testing

Specimen No.	**3 # 3 - Pre-tensioned**			**5 # 3 - Pre-tensioned**			**5 # 3 - Non-tensioned**		
	4 ft	**5 ft**	**6 ft**	**4 ft**	**5 ft**	**6 ft**	**4 ft**	**5 ft**	**6 ft**
1	277	269*	278	279	278	295	249	264*	264
2	255	283	285	279	294	273	233	269	270
3	247	283	277	268*	295	286	248	255	241
4	249	280	277	278	269*	299	230	272	273
5		275			268*			269	
Average (ksi)	**257**	**280**	**280**	**278**	**289**	**288**	**240**	**266**	**262**
Std. Dev.	**14.0**	**3.7**	**3.9**	**0.4**	**9.5**	**11.7**	**9.8**	**7.5**	**14.4**

* indicates strand rupture below the ASTM A 416 – 06 & AASHTO M203-07 Standard of 270 ksi (1861 MPa)

EFFECT OF LEVEL OF CONFINEMENT

According to the 1996 AASHTO Standard Specifications for Highway Bridge Design Section 9.22.2, nominal reinforcement is required to enclose prestressing strands for at least distance *d* from the end of the girder, where *d* is the depth of the girder. The specifications did not stipulate a minimum amount of confinement reinforcement. The 2007 AASHTO LRFD Specifications Section 5.10.10.2 stipulates that at least #3 deformed bars with spacing not exceeding 6 in. (152 mm) should be used to enclose prestressing strands. Although this statement acknowledges the need for confinement reinforcement for prestressing strands, it does not provide adequate information to quantify the effect of this reinforcement on the development length, which is not the case in the development of reinforcing bars (refer to 2007 AASHTO LRFD Section 5.11.2.1.3, and ACI 318-08 Section 12.2.3)

To evaluate the effect of level of confinement on the bond between the concrete and 0.7 in. (17.8 mm) diameter strand, thirteen specimens were made using 5#3 (high confinement), Grade 60 confinement loops (i.e. stirrups) and another thirteen specimens were made using 3#3 stirrups (low confinement). Each group consisted of four 4 ft (1.22 m) long specimens, five 5 ft (1.52 m) long specimens, and four 6 ft (1.83 m) long specimens. Stirrups were distributed at equal spacing as shown in Figure 3. All twenty-six specimens were pre-tensioned at 59.5 kip (265 kN), which is 75% the ultimate strand strength. Figure 8 presents the results from the pull-out testing of the two groups of specimens. This figure indicates that the required amount of confinement to develop the 0.7 in. (17.8 mm) strand varies with the embedment length of the strand. Although 5#3 stirrups were needed for the strand to reach an ultimate strength of 270 ksi (1861 MPa) in the 4 ft (1.22 m) long specimens, only 3#3 stirrups were needed for the same strand to reach the stress level in the 5 ft (1.52 m) and 6 ft (1.83 m) long specimens. Therefore, it can be concluded that level of confinement has a significant effect on the development of 0.7 in. (17.8 mm) strand. This effect is more pronounced on strands with a shorter embedment length than in those with a long embedment length. This conclusion will assist researchers and designers in identifying the minimum amount of confinement reinforcement required to develop 0.7 in. (17.8 mm) strand within a specific length.

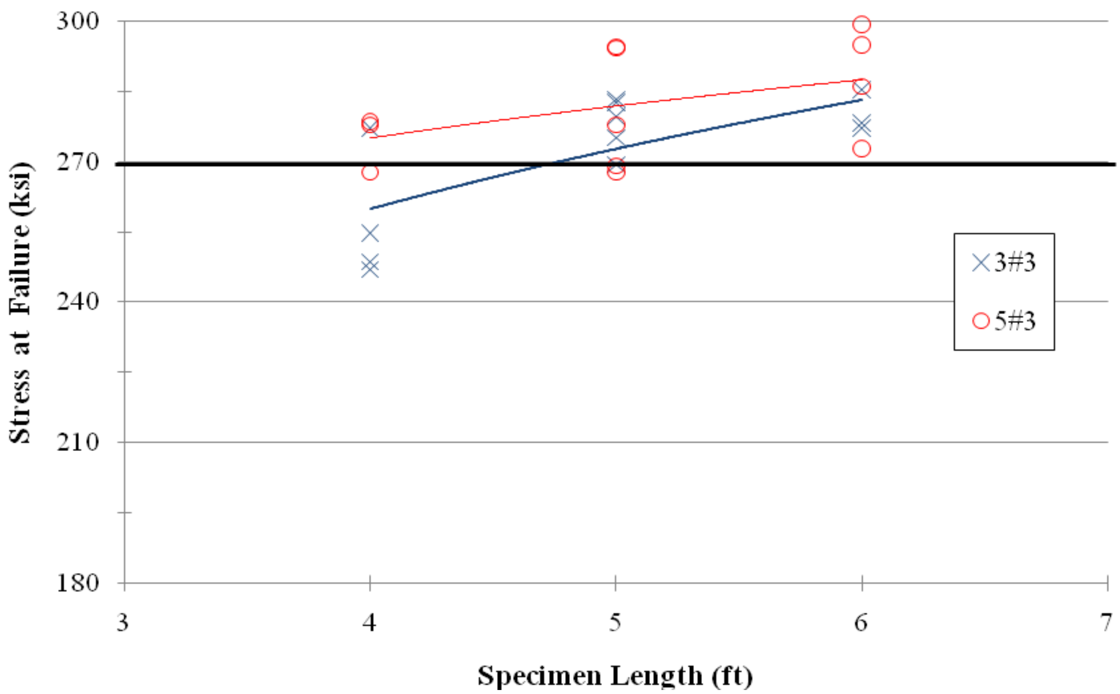


Fig. 8 Effect of Level of Confinement on Pull-out Testing Results

WEDGING EFFECT

Strand wedging “Hoyer” effect is one of the mechanisms that contribute to the transfer of prestressing force from the strand to the surrounding concrete. When the prestressing force is applied, strand elongates and its cross section area shrinks (Poisson’s effect). At release, strand cross section area at the end of the transfer length remains the same due to the applied stress, while its original cross section area at the end of the members is almost restored due to absence of stresses. This gradual change in the cross section area of the strand (wedge-like shape) along the transfer length results in increased bond with concrete. Pullout tests of strand are commonly performed on non-tensioned strands for simplicity, which eliminates the contribution of strand wedging to the bond with concrete.

In this study, the effect of wedging on the development of 0.7 in. (17.8 mm) diameter strand was investigated. Thirteen specimens were tested with pre-tensioned strand, while another thirteen specimens were tested without pre-tensioned strand. Each group consisted of four 4 ft (1.22 m) long specimens, five 5 ft (1.52 m) long specimens, and four 6 ft (1.83 m) long specimens that were confined with 5#3, Grade 60 stirrups. Figure 9 presents the pullout test results of the two groups. This figure indicates that pre-tensioning the strand results in a significant increase in the stresses at failure, and more importantly, change in the mode of failure from gradual slippage to strand rupture. This concludes that using non-prestressed strand in pullout testing for evaluating the development length is conservative as it results in lower bond strength and unrealistic failure mode.

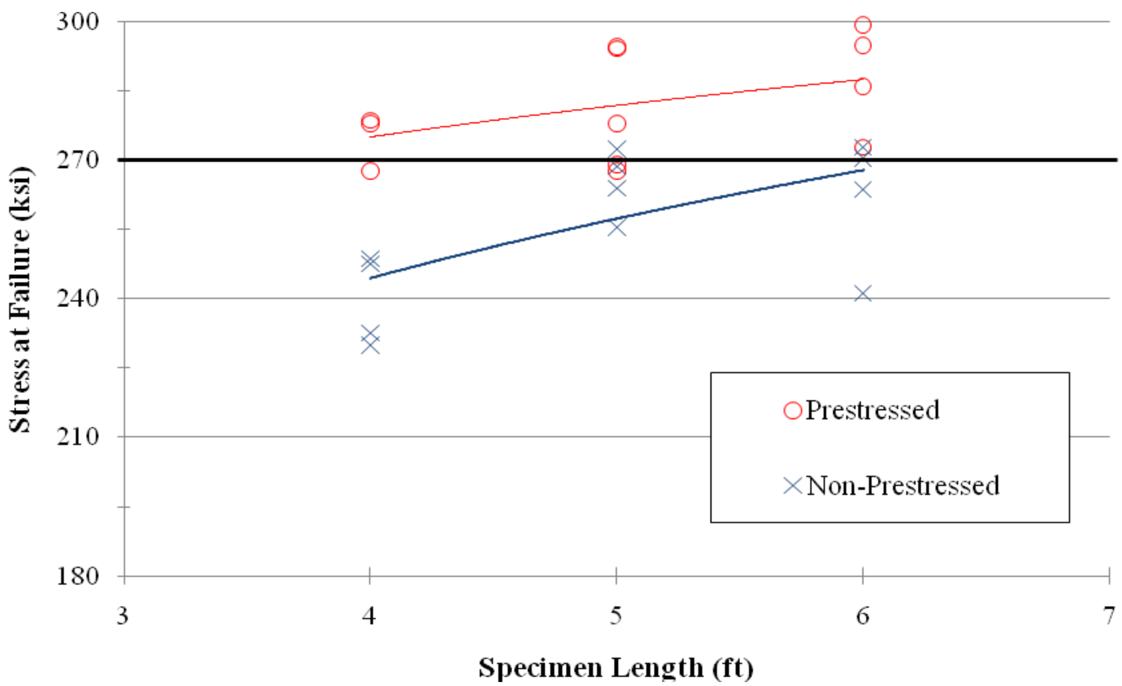


Fig. 9 Results of Prestressed and Non-Prestressed Strand from Pull-out Testing

EFFECT OF EMBEDMENT LENGTH

Figure 10 plots the results of testing all thirty-nine 0.7 in. (17.8 mm) diameter strand specimens grouped into three cases: 1) non-tensioned strands with 5#3 confinement reinforcement; 2) pre-tensioned strands with 3#3 confinement reinforcement; and 3) pre-tensioned strands with 5#3 confinement reinforcement. These three groups were designed to evaluate the effect of embedment length on each case.

Comparing case #1 versus case #3 shows the added bond strength achieved by the strand wedging that takes place at release. For all lengths, the increase is significant but not constant. This is because the embedment length itself has no impact on the wedging effect, but it has a significant impact on developing the strand up to the development length. Comparing case #2 versus case #3 shows the effect of level of confinement on the development of 0.7 in. (17.8 mm) diameter strand. In this comparison, the embedment length has similar effect as the amount of confinement on developing prestressing strand. Much less confinement is required to develop the strand in the 5 ft (1.52 m) and 6 ft (1.83 m) long specimens than that in 4 ft (1.22 m) long specimens. This can be attributed to the increased adhesion and mechanical interlock between the strand and the concrete with the embedment length. Consequently, development length equations should take into account the amount of confinement within that length.

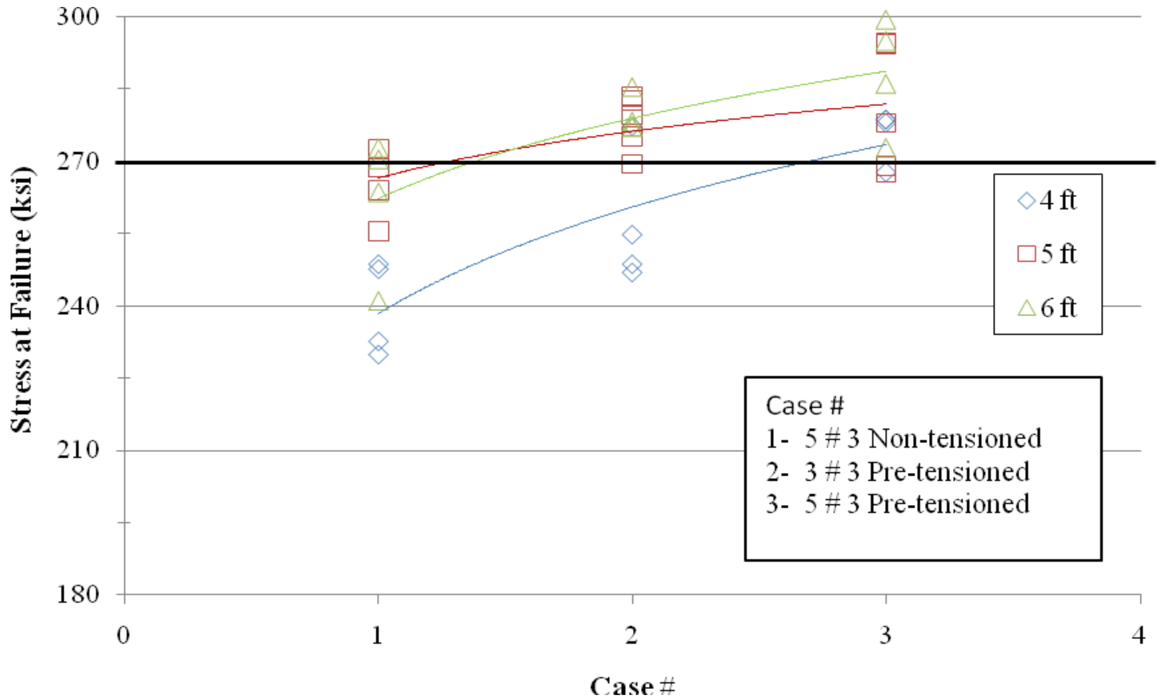


Fig. 10 Overall Results for Confinement, Prestressing Strand, and Length from Pull-out Testing

SUMMARY AND CONCLUSIONS

This study examined the transfer and development length of 0.7 in. (17.8 mm) diameter, Grade 270, low-relaxation strand for prestressed concrete applications. Forty-three specimens were produced at varying lengths with a 7 in. (178 mm) x 7 in. (178 m) cross section and only one 0.7 in. (17.8 mm) diameter prestressing strand at the center. Confinement loops of 3/8 in. (9.5 mm) diameter, Grade 60 steel were used at different spacing in each specimen to apply different levels of confinement. These loops are 5 in. (127 mm) x 5 in. (127 mm) in size and equally spaced.

Transfer length was determined by a series of Detachable Mechanical strain gauges (DEMEC gauges) placed before release along the two sides of four 8 ft (2.44 m) specimen at 4 in. (11 mm) spacing and at the same elevation of the prestressing strand. DEMEC readings were taken at release (1-day) and at 7, 14, 21, and 28 days using a caliper gauge and the change in the measured distance between DEMEC gauges was used to calculate the strain in the concrete at different ages.

Development length was determined using twelve 4 ft (1.22 m), fifteen 5 ft (1.52 m), and twelve 6 ft (1.83 m) long specimens. Three variables were taken into account: embedment length, level of confinement, and the stress state of the strand. Pullout testing of the thirty-nine specimens was performed while strand slippage, strand stress, and mode of failure were monitored.

Following are conclusions drawn from this study:

1) The transfer length of 0.7 in. (17.8 mm) diameter strand is approximately 31 in. (788 mm), which is closer to the transfer length predicted using the American Concrete Institute (ACI) 318-08 expression of $50d_p$, than the one predicted using the 2007 AASHTO LRFD expression of $60d_p$.

2) The level of confinement does not have significant effect on the transfer length of 0.7 in. (17.8 mm) diameter strand because confinement reinforcement remains inactive until concrete cracks, which does not usually occur at transfer.

3)The level of confinement has significant effect on the development length of 0.7 in. (17.8 mm) diameter strand. The higher the level of confinement, the shorter the development length.

4) The required amount of confinement to develop the 0.7 in. (17.8 mm) strand decreases with a longer embedment length of the strand in concrete.

5) Due to a wedging effect of the strand at the time of release, pre-tensioning the strands in pullout test specimens is required in order to accurately measure the development length of 0.7 in. (17.8 mm) diameter strand.

Future research at the University of Nebraska will include testing specimen with multiple 0.7 in. (17.8 mm) diameter strands to investigate the effect of concrete strength and strand spacing on the bond between the strand and concrete, which will provide accurate prediction of the transfer length and development length of 0.7 in. (17.8 mm) diameter strand.

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