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Bond of prestressing strand to concrete

- PCI published a new recommended practice in November 2020 that establishes minimum test pullout values that can be used to define transfer and development lengths for prestressing strand in concrete.

- This article summarizes the research of various sources dating from the 1950s on prestressing strand bonding to concrete in support of the publication of "Recommended Practice to Assess and Control Strand/Concrete Bonding Properties of ASTM A416 Prestressing Strand."

The transfer of prestressing force from prestressed strand to concrete over a predictable length is essential for the reliable performance of prestressed concrete.

In the early days of precast, prestressed concrete construction in the United States, no problems with strand bond were reported. In the past 35 years or so, however, several documented problems have occurred, indicating the need for the quality control and quality assurance program recommended in this article.

Over the past two decades, a direct pullout test method that reasonably predicts the bonding properties of the strand used in precast concrete products has been developed.

In July 2020, the PCI Technical Activities Council and Research and Development Council approved a new "Recommended Practice to Assess and Control Strand/Concrete Bonding Properties of ASTM A416 Prestressing Strand,"[1] which was subsequently published in November 2020 in the *PCI Journal*. It establishes minimum test pullout values that can be used to define transfer and development lengths for prestressing strand in concrete.

The test method was developed to qualify the strand as having bond properties consistent with design expectations. Certain concrete formulations may affect bond quality, and these should be evaluated separately on a case-by-case basis.

This article summarizes background information on strand bond and documents the many years of research that led to the final published recommended practice.

Prestressing strand description

Prestressing steel used in precast concrete in the United States is predominately seven-wire strand. Of the seven wires, six outer wires are wound helically around a center straight wire called the king wire. The king wire is typically 3% to 5% larger in diameter than the surrounding six wires. This configuration ensures that when the strand is tensioned, the outer wires will grip the king wire. The pitch of the wound wires is typically about 8 in. (203 mm). Virtually all seven-wire strand used in the United States is intended to conform to ASTM A416, *Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete*.[2] According to ASTM A416, strand is available in two grades: 250 and 270 ksi (1724 and 1860 MPa). These grade values—250 and 270—refer to the guaranteed minimum ultimate tensile strength (GUTS) of the strand in kip per square inch. Strand is further designated as normal relaxation or low relaxation. The vast majority of strand now sold in the United States is 270 ksi, low-relaxation strand. Strands are available in several diameters. Diameters of 270 ksi strand listed in ASTM A416 are 0.375 (3/8), 0.438 (7/16), 0.500 (½), 0.520 (½ special), 0.563 (9/16), 0.600, and 0.700 in. (9.53, 11.1, 12.7, 13.2, 14.3, 15.2, and 17.8 mm). Diameters are measured across the outermost radius of the wires.

Most prestressing strand used in the United States for bridge products has a diameter of 0.500 or 0.600 in. (12.7 or 15.2 mm); these strand types are designated by ASTM A416 as no. 13 and 15, respectively. Beyond the strand types cited by current ASTM standards, at least one North American strand producer is offering 300 ksi (2070 MPa) GUTS strand in several sizes, and even higher strengths are available overseas.

Strand production

The production of prestressing strand as observed at one manufacturing facility includes the following basic components (**Fig. 1**):

- Coils of nominal ½ in. (12.7 mm) AISI C1080 steel rod stock are cleaned and pretreated. This process can be achieved using a variety of methods. For example, the raw steel coils may be cleaned by pickling (dipping in acid, then rinsing with water) and then treating with phosphate (submerging in a zinc phosphate solution, then rinsing with water and drying).

- Rods from several coils are butt welded end to end and then fed into the wire-drawing machine.

- A series of eight successively smaller dies in the wire-drawing machine draws down the rod stock to wire with a diameter of about one-third the strand diameter. For ½ in. (12.7 mm) diameter strand, the king wire has a diameter of 0.174 in. (4.42 mm), approximately 5% greater than that of the six outer wires. A box containing wire-drawing lubricant, which the wire passes through before entering the die, is integral to the process. This arrangement allows for different lubricants to be used with different dies, and it is not uncommon to use a different lubricant for the first (ripper) die than for subsequent dies. Both the die and the capstan (also called a drawing block, which pulls the wire through the die) are water cooled because the performance of the lubricant and properties of the wire are very sensitive to temperature. At the end of the machine, the individual wire is spooled.

- The seven spools of wire are installed in a stranding machine, sometimes called a skip strander. In this machine, the six outer wires are helically wound around the king wire to form the seven-wire strand, which is temporarily spooled.

- The strand is drawn under tension through an induction furnace. This stage imparts the stress-relieving and low-relaxation properties to the strand.

- A venting hood situated between the furnace and the final cooling bath draws off any vapors created by treatment in the induction furnace.

- The strand is cooled in a spray chamber with recirculated water. This process may remove some additional wire-drawing lubricants if they are sufficiently water soluble.

- The strand is spooled, packaged, warehoused, and shipped to customers.

Occasionally, a wire will break during the drawing process. If this occurs, the production line is stopped and the wire ends are butt welded together. Care must be taken to regularly clean the final spray chamber. Osborn et al.[3] and Hawkins and Ramirez[4] have provided detailed information about strand production processes.

The nature of the bond between prestressing steel and concrete

In precast, prestressed concrete production, prestressing steel is initially tensioned, concrete is cast around it, the concrete hardens, and the strand is released. After release, the strand attempts to return to its original length, but this tendency is resisted by the surrounding concrete through bond. As described by Osborn et al.,[3] Russell and Ramirez,[5] and others, the bond of prestressing strand in concrete is a complex subject. Bonding occurs on a microscopic scale, and there is no way to directly observe or measure it. Thus, bond properties of prestressing steel strands in concrete have to be interpreted from tests. Another barrier to our understanding of bond

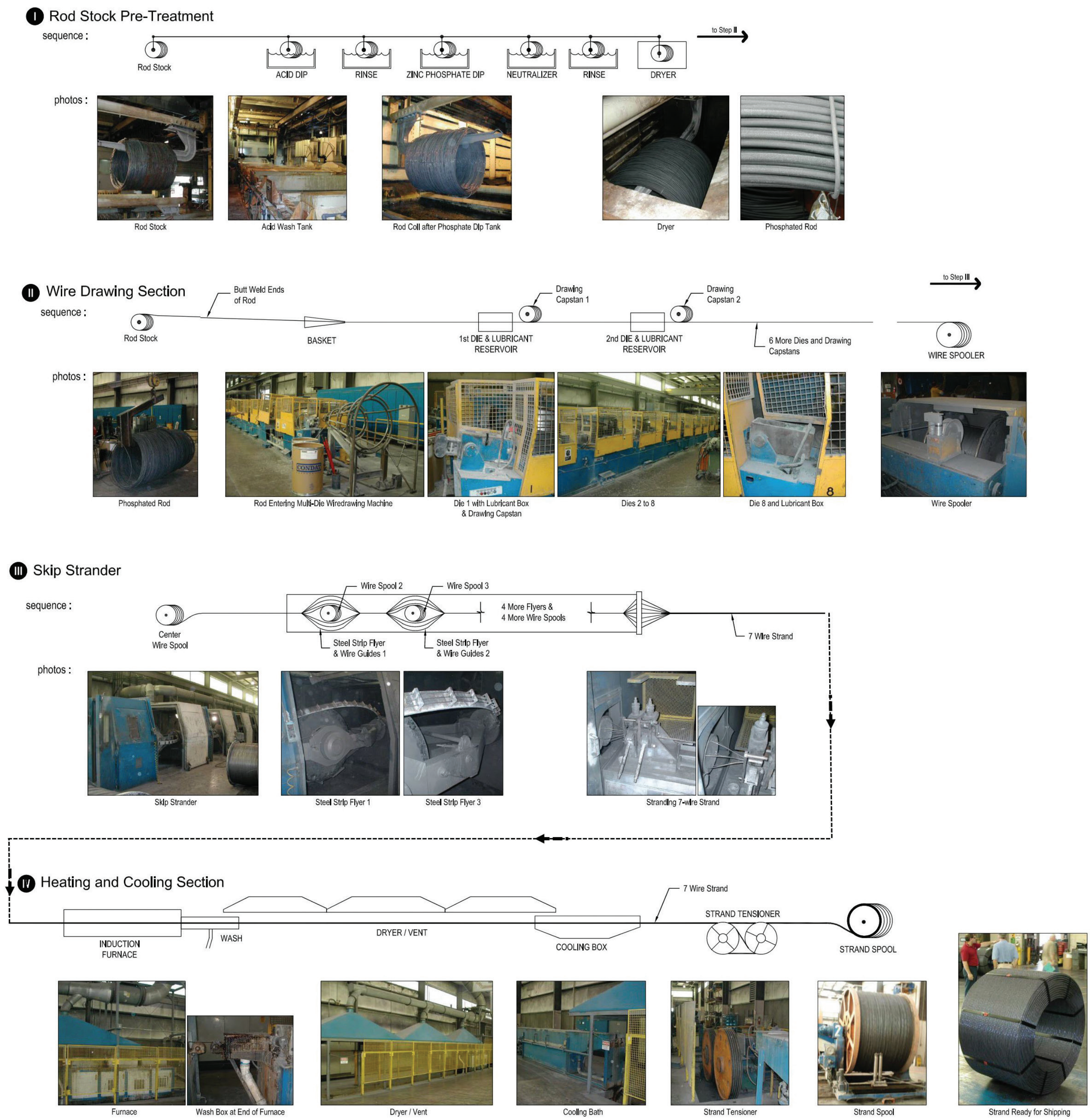


Figure 1. Schematic of strand manufacturing process.

properties is that some of the variables that seem to influence the bond are interdependent. For instance, some researchers cite concrete strength as an important variable; however, two concrete mixtures, one with high strength and one with low strength, are also likely to have different shrinkage properties, which will also affect the results of bond tests.

Although experts in this area of investigation are in general agreement about the three components of bonding (adhesion, mechanical interlock, and friction), they do not agree about the relative importance of each component. Of the three factors that affect the bond, friction is perhaps the most important for structural performance. Defined as the shearing resistance to interfacial movement, friction is related to transverse or radial pressure of the hardened concrete acting on the strand. The higher the radial pressure is, the higher the resistance to linear movement due to friction will be.

For strand that is pretensioned, cast into concrete, and then released, the radial pressure arises out of the Hoyer effect and shrinkage of the surrounding concrete. When strand is tensioned, its diameter decreases in proportion to the tension based on Poisson's ratio. When it is released, the strand tries to return to its original diameter. Because the expanding strand is constrained by the surrounding concrete, a confining pressure is created. The effect is named the Hoyer effect.[6]

The magnitude of the radial pressure is related to the original strand tension, the concrete shrinkage strain, the concrete modulus of elasticity, restraint provided by surrounding reinforcement, and external lateral pressures. Eventually, this radial pressure lessens because of concrete creep, but strand tension losses over time tend to increase the Hoyer effect.

Thermal contraction and shrinkage of the concrete also add to the radial strain and pressure. The thermal contraction of the concrete occurs early in the life of the prestressed product as the concrete cools after curing. The shrinkage effect initially is small; however, after a few months, the shrinkage strain will be comparable in magnitude to the Hoyer effect strain.

Concretes containing relatively soft limestone coarse aggregates tend to crack less because they have less shrinkage strain, a lower modulus of elasticity, and greater creep. These factors may explain why pullout test forces in concretes containing soft limestones are lower than test forces in similar concretes with harder aggregate.[3]

Early strand bond research

The early U.S. research concerning strand bond was performed by Janney in 1954,[7] Hanson and Kaar in 1959,[8] and Kaar et al. in 1963.[9] These researchers developed equations for transfer and development length that are still in use today. Transfer length is defined as the distance over which the effective prestressing force is transferred to the concrete element. In other words, this is the distance from the end of the strand where no stress is applied to the concrete to the point where all the tension in the strand has been transferred into the concrete. The development length is the sum of the transfer length and the additional distance over which the stress in the strand is developed, from the effective prestress to the stress in the strand at the ultimate flexural strength of the member.

The early research found that transfer and development lengths are directly influenced by the effectiveness of the bond between the strand and the concrete, which is determined by the following three mechanisms:

- adhesion: the chemical bond between the strand and concrete
- the Hoyer effect
- mechanical interlocking: the resistance to movement produced by the deformations cast into the concrete resulting from the pitch of the strand wires and the surface roughness of the wires

The original research in strand bond was based on 250 ksi (1724 MPa) stress-relieved strand, and the conclusions were subsequently verified for the 270 ksi (1860 MPa) low-relaxation strand that is currently in common use. This early work developed transfer- and development-length equations based on the average of measured data instead of the 5% or 10% fractile that is typically used today. Nevertheless, the empirical relations for development and transfer length currently provided in the American Concrete Institute's (ACI's) *Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI-318R-19)*[10] and the American Association of State Highway Transportation Officials' (AASHTO's) *Standard Specifications for Highway Bridges*[11] are based on this work. The transfer length assumed in these codes is given as 50 to 60 times the diameter of the strand.

The early tests had some interesting findings regarding approximate bond stress at initial slip of the strand. It was typically reported that bond stresses in the transfer length ranged between 200 and 600 psi (1379 and 4137 kPa). This is similar to the range measured in pullout tests of untensioned strand. Usually, in pullout tests in concrete, transfer lengths that exceed the values calculated by the ACI 318 equation are generally associated with bond stress less than 400 psi (2758 kPa) at 0.1 in. (2.54 mm) of slip.

The transfer length of strand is typically determined by measuring the longitudinal strain of a prestressed concrete prism after the prestress on the strand is released shortly after casting, when the specified concrete release strength is attained. A strain gradient is present within the transfer length at the two ends of the prestressed prism, but in the center of the element (between the two transfer-length regions) the prestress has been transferred and axial stress and strain are both constant. When strand transfer length is to be determined, it has been believed that the most appropriate specimen configuration is a single-strand specimen of sufficiently small cross section that the stress produced by the strand causes an easily measurable strain deformation. Whittemore or demountable mechanical strain (DEMEC) gauges are typically used to determine strain on the concrete surface.

This measurement approach is less effective for multistrand specimens. This is because with the Whittemore or DEMEC gauge–based measurements, transfer-length data are only a reflection of the average transfer length of all the strands and no information is gained about individual bond variability among the multiple strands. The most accurate method to measure bond variability in multistrand specimens is to individually measure the strand end slip at release on each separate strand. The correlation between strand end slip and transfer length has been shown to be strong.[12,13] The traditional method of measuring transfer length using the typical 4.5 in. × 4.5 in. × 8 ft (114.3 mm × 114.3 in. × 2.4 m) prisms is now in doubt as a result of research by Peterman that was published in 2007.[14] In Peterman's tests, pretensioned strands were placed at various distances from the tops of precast concrete members made with self-consolidating concrete (SCC). The overall depths of the members were also varied. Peterman found that the closer a strand is to the top as-cast surface of the SCC member, the longer and more variable the transfer length will be. This research helps explain why transfer lengths measured from rectangular prisms, as described, are so variable.

Concerns regarding the bond of prestressing strand emerged from research by Cousins et al.,[15] who found that uncoated strands exhibit very long transfer lengths compared with epoxy- and grit-coated strands. This finding led the Federal Highway Administration (FHWA) to issue a memorandum in 1988 dictating that a 1.6 factor be applied to the calculated transfer length.[16] Many strand bond research projects were launched in the early 1990s as a result of this action.

ACI code and AASHTO specifications

ACI 318-19 section 25.4.8 concerning development of pretensioned seven-wire strand in tension is based primarily on the work of Hanson and Kaar,[8] who were Portland Cement Association (PCA) researchers in the late 1950s. They tested normalweight concrete members stressed with Grade 250 (1724 MPa) strand that had actual tensile strengths up to 275 ksi (1896 MPa). The steel stresses immediately after transfer were between 155 and 160 ksi (1069 and 1103 MPa) for their 0.5 in. (12.7 mm) diameter strands in concretes with concrete release strength f_c' values of 3330 or 4170 psi (23 and 29 MPa). The specimens had a minimum cover to the center of the strand of 2 in. (50.8 mm). ACI 318 Eq. (25.4.8.1) for the development length ℓ_d is composed of two terms. The first term, $(f_{se}/3000)d_b$, represents the transfer length ℓ_{tr} for the strand. The second term, $[(f_{ps}-f_{se})/1000]d_b$, represents the additional length over which the strand needs to be bonded so that the stress fps in the prestressing steel at the nominal flexural strength of the member can develop. The ACI 318 expression is essentially identical to the original PCA expression:

$$\ell_d=\left(\frac{f_{se}}{3000}\right)d_b+\left(\frac{f_{ps}-f_{se}}{1000}\right)d_b \quad \text{(ACI 318-19 25.4.8.1)}$$

where

f_{se} = stress in prestressing steel after allowance for all prestress losses

d_b = nominal diameter of prestressing strand

In ACI 318-19, the strength reduction factor ϕ for sections where strand is not fully developed is 0.75 when the distance from the end of the member to the section under consideration is less than the transfer length ℓ_{tr} and varies linearly from 0.75 to 0.9 for distances between the transfer length ℓ_{tr} and development length ℓ_d.

In the AASHTO standard specifications, the transfer length is specified as 60 strand diameters, and the required development length is the same as that of ACI 318 Eq. (25.4.8.1). The FHWA memorandum[16] mandated a 1.6 factor on ACI 318 Eq. (25.4.8.1) for precast concrete slabs and piles. The 2001 update to the AASHTO standard specifications[17] noted that the 1.6 factor was conservative but accurately reflected the worst-case characteristics of strands shipped prior to 1997; however, the authority having jurisdiction could use a value less than 1.6 if that value were based on research or prior successful use.

North American Strand Producers and National Cooperative Highway Research Program research

In 1992, a strand lifting loop pulled out of a precast concrete beam member during handling, and because the project used a previously successful lifting loop design, the incident raised concerns about the bond properties of the strand. Strand from several manufacturers was subsequently acquired and tested.[18] The test method, which was developed in 1974 by Moustafa,[19] involves embedding ½ in. (12.7 mm) diameter strand 18 in. (457.2 mm) into a block of concrete and then slowly pulling the strand out after a 1-day cure. In Moustafa's test, if the maximum pullout force is greater than 36 kip (160 kN), adequate strand bond performance is indicated. In the 1992 tests, only three of seven strand sources demonstrated pullout force exceeding 36 kip.

Between 1974 and 1992, some strand manufacturing processes were altered for economic reasons. Those changes did not affect the GUTS achieved for the strand and therefore may not have seemed concerning to strand manufacturers, which typically sell less than half their output to precast, prestressed concrete producers. However, the 1992 incident involving the precast concrete beam member and the subsequent strand performance test results highlighted to precast concrete producers the need for bond testing of the strand used in their products.

As the precast, prestressed concrete industry became increasingly aware of the possibility of reduced-bonding strand, efforts were initiated to develop test methods to identify how well a given strand can bond. In particular, the North American Strand Producers (NASP) and the National Cooperative Highway Research Program (NCHRP) have made extensive efforts toward this end. Those efforts have shown that the properly executed NASP test method,[20–23] in its 2006 version, can reliably differentiate between strands that provide what can be characterized as poor, adequate, and good bond. In 2012, the NASP test method became codified as ASTM A1081, *Standard Test Method for Evaluating Bond of Seven-Wire Prestressing Strand*.[24]

The ASTM A1081 test method was developed primarily by Bruce Russell, who worked initially with the support of NASP. His work is documented in four reports from 1999 to 2006.[20–23] Briefly, the test consists of a cylindrical specimen of mortar encased in a 5 in. (127 mm) diameter ⅛ in. (3.2 mm) wall thickness steel tube. The test strand is embedded for a length of 16 in. (406 mm). The mortar strength at time of test is 4500 psi (31 MPa) ± 500 psi. The test is conducted at 24 ± 2 hours after casting. The specimen is restrained in a test machine, and load is applied to the strand using displacement control at a rate of 0.1 in. (2.54 mm) per minute measured at the machine head. Load, machine head displacement, and free end slip are measured continuously. The ASTM A1081 test value is the test load corresponding to 0.1 in. end slip.

In addition, with NCHRP support,[5] Russell and colleagues studied the correlation between NASP test values and the bond performance of beams with concrete release strengths between 4000 and 9700 psi (28 and 67 MPa) and 56-day concrete strengths from 7000 to 14,500 psi (48 to 100 MPa). The bulk of the efforts covered in the 1999 to 2006 NASP reports was directed at demonstrating bond reliability for transfer conditions; however, Russell also showed in two reports[5,22] that NASP test values probably correlated with the additional development length required beyond the transfer length, though the amount of data was insufficient to be able to demonstrate that result statistically.

The transfer length measurements reported by Russell in 2001[22] suggested that with some beam shapes and prestress levels, transfer lengths can be expected to increase markedly with time. Results published in 2008 in NCHRP report 603[5] confirmed that finding and documented an even greater increase in transfer lengths with time than was documented in the 2001 report, especially for strands that were marginal in their bonding ability. The NCHRP transfer-length test beams were reinforced with mild steel transverse and crack-control reinforcement and were prestressed with either two or four strands.

Figure 2 shows results from the transfer-length tests reported in NCHRP report 603. Those results can be correlated with the NASP test results reported in **Table 1**. Test values toward the left in Fig. 2 were obtained from poorer-than-average NCHRP 603 strand D (similar to NASP quarterly testing strand C in Table 1). Test values to the right in Fig. 2 are for better-than-average NCHRP 603 strands A/B (similar to NASP quarterly testing strand J in Table 1). The NCHRP test values are reported as normalized because they were derived using concrete rather than mortar (as is used in ASTM A1081) and because the concrete release strengths for the NCHRP work ranged from 4 to 9.7 ksi (28 to 67 MPa). Normalization was performed by taking the normalized NASP value as approximately $0.5\sqrt{f_c'}$ times the NASP test value for concrete where concrete design strength f_c' is in kip per square inch. The term *power* in Fig. 2 refers to the use of the nonlinear regression relationships to derive the lines of best fit for the data at release and 240 days and for the recommended design relationship. The lines of best fit give transfer lengths at 240 days that are typically 1.6 times the transfer length at release. Other data in NCHRP report 603 show that about 50% of that increase in transfer length occurred in the first 60 days and that long-term transfer lengths decreased approximately in proportion to $\sqrt{f_c'}$ expressed in kip per square inch.

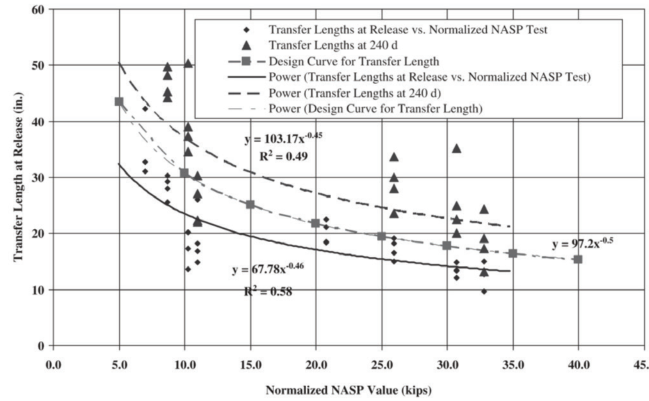


Figure 2. Transfer lengths versus normalized North American Strand Producers bond values for strands D and A/B at release and at 240 days. Source: Hawkins and Ramirez (2010). Note: 1 in. = 25.4 mm; 1 kip = 4.448 kN.

In the development-length tests described in NCHRP report 603, bond failures occurred for beams with NCHRP 603 strand D (ASTM A1081 with a 7400 lb [33 kN] average), but not for beams with NCHRP 603 strands A/B (ASTM A1081 with a 19,725 lb [88 kN] average). In the NCHRP 603 testing, the beams with strands A/B failed in flexure for both 72 and 58 in. (1828.8 and 1473.2 mm) embedment lengths, except for one bond failure at an embedment length of 58 in. The embedment lengths of 72 and 58 in. corresponded to 100% and 80%, respectively, of the ACI code calculated development lengths. Tests were performed at both 100% and 80%

Table 1. Data for control strands for four quarters of North American Strand Producers testing, 2006–2007

Control strand	Number of data points	Strand slip, in.	Mean, lb	Standard deviation, lb	95% confidence interval, ±lb	Coefficient of variation, %
C	45	0.01	8687	806	240	9.3
C	45	0.1	8568	1268	378	14.8
A	46	0.01	11,556	1504	44	13.0
A	46	0.1	17,389	1726	509	9.9
J	41	0.01	18,629	2107	658	11.3
J	41	0.1	22,394	2348	733	10.5

Source: Data from private communication, Russell, 2007, North American Strand Producers quarterly test program. Note: 1 in. = 25.4 mm; 1 lb = 4.448 N.

of the required transfer length so that strand bond at ultimate could be evaluated in the transfer-length region. The one beam that experienced bonding failure attained approximately 90% of its nominal flexural capacity. The results of the development-length and NASP round III tests reported in 2001[22] correlated well with those in NCHRP report 603. The tests included an NASP round III strand HH with an NASP test value of 10,700 lb (48 kN). It was also observed that bond development- and transfer-length values tended to decrease with increases in concrete strength and that decreases in average values for transfer and development length were approximately proportional to $\sqrt{f_c'}$ expressed in kip per square inch.

In the conclusion to NCHRP report 603, the authors recommended that the minimum NASP test value for adequately bonding strand should be taken as 10,500 lb (47 kN) and that the minimum single test value should be no lower than 9000 lb (40 kN).

The recommended expression for the transfer length ℓ_{tr} is shown in NCHRP report 603 Eq. (3.6).

$$\ell_{tr} = \left(\frac{120 d_b}{\sqrt{f'_{ci}}} \right) \geq 40 d_b \qquad \text{(NCHRP 3.6)}$$

The recommended expression for development length ℓ_d is shown in NCHRP report 603 Eq. (3.8).

$$\ell_d = \left(\frac{\ell_{tr} + 225}{\sqrt{f'_c}} \right) \geq 100 d_b \qquad \text{(NCHRP 3.8)}$$

Both of these equations were incorporated into the PCI recommended practice. The equations do not indicate any relationship between NASP pullout force and transfer length.

In contrast to ACI 318 Eq. (25.4.8.1), NCHRP Eq. (3.6) and (3.8) do not contain terms relating to the steel stresses; also, they contain terms from both concrete release and design strength, terms not present in ACI 318 Eq. (25.4.8.1). Concrete release strengths for the data used to develop NCHRP report 603 Eq. (3.6) and (3.8) ranged from 4.0 to 9.7 ksi (28 to 67 MPa), with the corresponding 56-day strengths ranging from 7.0 to 14.5 ksi (48 to 100 MPa). The concrete release and 56-day strengths associated with the NCHRP 603 work were significantly higher than those associated with the PCI-sponsored Kansas State University (KSU) work, discussed later, which had targets of 3800 psi (26 MPa) at release and 6300 psi (43 MPa) at time of test (21 days).

The principal basis for the minimum NASP test values recommended in NCHRP report 603 is the data shown in Fig. 2. Several observations are appropriate. First, the data showing transfer lengths less than 20 in. (508 mm) at NASP test values of 10 to 11 kip (44.48 to 49 kN) may be skewed by the method of translation of results from concrete to mortar as the test medium. Those results have the effect of lowering the NASP test strength required for low transfer-length values at release. Second, there are few data for NASP test values between 11 and 21 kip (48.9 to 93.4 kN), and yet that is the region of particular concern for determining the minimum NASP test strength for adequate bonding strand. Third, NASP test values greater than 30 kip (133.4 kN) are unrealistic (currently not found in industry practice).

Another observation important for correlation with the subsequent KSU research is apparent from Table 1, in which for a given strand, the pullout force at strand slips of both 0.01 and 0.1 in. (0.254 and 2.54 mm) are shown. For the unacceptable NASP quarterly testing strand C, the strength at a slip of 0.01 in. is 1.4% greater than that of the NASP value at 0.1 in. slip. In contrast, for the two acceptable NASP quarterly testing strands, A and J, the NASP values at 0.1 in. slip are 50.4% and 20.2% higher, respectively, than strengths at 0.01 in. slip.

PCI due diligence report

In their 2010 due diligence report to PCI[4] on the work performed to develop the NASP test (ASTM A1081), Hawkins and Ramirez concluded that the number of development-length test results reported in NASP round III[22] and NCHRP report 603[5] were adequate only to establish tentative minimum values for the ASTM A1081 test strengths for good, adequate, and poor bonding strand. Hawkins and Ramirez concluded that establishing statistically defensible ASTM A1081 test value levels for strand with different bond qualities would require additional testing to increase the number of data points.

The due diligence report recommended two changes to the ASTM A1081 test method:

- a definition of an allowable range of stiffness for the testing rig, including a method for calculating that stiffness
- a definition of a method for establishing the acceptable range of angularity for the sand used in the mortar

Other needs identified in the report were demonstrated reproducibility of measured ASTM A1081 test values from at least four, and preferably six, different test sites, and ruggedness testing to meet ASTM's specification approval requirements.

In the due diligence report,[4] Hawkins and Ramirez concluded that the strength values specified in the 2006 NASP testing protocol[23] were reasonable for the data available but were not statistically justifiable. Hawkins and Ramirez recommended an acceptance value at least 10% higher than the 10,500 lb (47 kN) NASP and NCHRP report 603 proposed acceptance value (1.1 × 10,500 = 11,550 lb [51.3 kN]). Further, from the associated development-length tests, the acceptance value for a 5% fractile test value would be at least 13,500 lb (60 kN). This recommendation did not consider the additional statistical variation expected to occur when testing strand at multiple sites, nor did it consider the reduced variation one would expect if evaluating multiple strands in a prestressed member simultaneously.

The due diligence report made four primary recommendations:

- PCI should endorse the ASTM A1081 procedure for evaluating strand bond.
- The PCI Plant Certification Program should require PCI-certified precast concrete producers to make bond tests to demonstrate the adequacy of the strands they purchase for the concrete mixtures, product dimensions, and product reinforcements used. Use of the Peterman small beam flexure test[25] was recommended for this purpose.
- Round robin ASTM A1081 testing should be conducted to provide required ASTM repeatability and ruggedness data.
- Multivariable, statistically planned testing should be done to correlate ASTM A1081 test values for three strands with different bonding ability with their transfer- and development-length values.

Members of NASP made available to the due diligence investigators the results of the routine quarterly strand bond testing performed in six consecutive quarters starting in April 2006 for 0.5 in. (12.7 mm) diameter strands for all individual NASP members. These data indicated that most strand manufacturers were providing strands with remarkably consistent bond strengths from quarter to quarter and the coefficients for variation for those bond strengths were better than the same coefficients for the strength testing of plant-produced concretes.

The due diligence report recommended that strand manufacturers be encouraged to provide their PCI producer customers the results of at least eight quarters of ASTM A1081 testing for their products and that customers expect coefficients of variation for the average strengths for the eight quarters not to exceed 0.11. The NASP members also made available the ASTM A1081 values for the three differing-quality control strands that were tested along with the strand manufacturers' samples for the period from September 2006 through August 2007 (**Table 2**). Those control strands corresponded to strands with lower-than-average, middle-of-the road, and better-than-average performance. The strands represented in Table 1 had been used in both the NASP round IV[23] and NCHRP 603[3] testing. Strand D in the NCHRP 603 testing was strand C in NASP round IV and strand FF in NASP round III. Strand B in the NCHRP 603 testing was strand J in NASP round IV. For the 0.1 in. (2.54 mm) strand slip value for the ASTM A1081 test, mean values were 17,389 lb (77.3 kN) for the middle-of-the road strand A and 22,394 lb (99.6 kN) for the better-than-average strand J. The coefficients of variation for both strands A and J were less than 0.11. Strand series used throughout the NASP and NCHRP test programs are identified in **Table 3**.

Table 2. Results of ASTM A1081 testing by strand manufacturers in the North American Strand Producers quarterly test program for six quarters starting in April 2006

Strand type	Average ASTM A1081 value	Number of plants	Typical standard deviation, %
Lower than average	Within 3% of 15,000 lb	2	8
Middle of the road	Within 6% of 17,000 lb	3	8
Better than average	Within 5% of 22,500 lb	4	8

Note: 1 lb = 4.448 N.

NASP participants have continued to conduct strand bond quality tests. **Table 4** presents overall results for 12 quarters through 2009, as provided by an NASP representative to the Strand Bond Task Group.

KSU research

In 2011, PCI awarded a contract to KSU to conduct an investigation to establish acceptance criteria for 0.5 in. (12.7 mm) diameter prestressing strand for pretensioned applications. There were six primary objectives for this project:

1. By using samples from one strand source, establish the robustness of procedures by performing ruggedness

Table 3. Test strand designations in various testing programs

Strand type	NASP quarterly testing, 2006–2007	NASP round III	NASP round IV	NCHRP 603
Lower than average	C	FF	C	D
Middle of the road	A	n/a	n/a	n/a
Better than average	J	n/a	J	B

Note: n/a = not applicable; NASP = North American Strand Producers; NCHRP = National Cooperative Highway Research Program.

Table 4. North American Strand Producers quarterly test program data for ASTM A1081 bond strengths from various strand manufacturers, 2006–2009

Range minimum, lb	Range maximum, lb	Quarterly standard test for strand bond value, lb												Total STSB value, lb
		3Q06	4Q06	1Q07	2Q07	3Q07	4Q07	1Q08	2Q08	3Q08	1Q09	2Q09	3Q09	
		Number of plants												
		10	10	9	9	9	9	9	9	9	8	9	9	
0	4990	0	0	0	0	0	0	0	0	0	0	0	0	0
5000	8490	0	0	1	0	0	0	0	0	0	0	0	0	1
8500	10,490	1	0	0	0	0	0	1	1	1	0	0	0	4
10,500	12,990	0	0	0	0	0	0	0	0	0	0	1	0	1
10,500	12,990	3	0	0	0	0	1	0	0	1	0	1	0	6
13,000	15,490	2	2	2	1	1	0	1	3	0	2	0	0	14
15,500	17,990	1	2	1	2	3	4	1	2	2	2	0	3	23
18,000	20,490	3	2	1	2	2	0	0	0	0	2	2	1	15
20,500	22,990	0	3	0	2	3	1	5	2	4	2	5	4	31
23,000	25,490	0	1	4	2	0	3	1	1	1	0	0	1	14
25,500	28,000	0	0	0	0	0	0	0	0	0	0	0	0	0

Source: Adapted from Lanier and Hawkins (2017).

Note: The average standard test for strand bond (STSB) for all plants was 18,810 lb. n/a = not applicable. 1 lb = 4.448 N.

testing for the ASTM A1081 test method in accordance with ASTM E1169, *Standard Practice for Conducting Ruggedness Tests*.[26]

2. By round robin testing in accordance with ASTM C670-03, *Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials*,[27] and ASTM E691-09, *Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method*,[28] verify the reproducibility of the ASTM A1081 test method for evaluating strand bond.

3. Provide additional test results for Level I and Level II quality control tests as defined in NCHRP report 621.[3]

4. Through design studies, establish the sensitivity of the response of representative prestressed products to variations in strand transfer lengths calculated using ACI 318 Eq. (25.4.8.1). Use this information to establish a recommendation for a statistical basis for the required threshold test values for strand acceptance per ASTM A1081. Demonstrate that the customarily expected margins of safety for design per ACI 318 are not compromised by the recommended threshold test values.

5. Through flexural testing of a statistically significant number of 6.5 × 12 in. (165.1 × 304.8 mm) standard flexural beams, establish recommended threshold test values that will provide assurance of adequate performance in accordance with the information developed in objective 4.

6. Through flexural testing of a significant number of 8 × 6 in. (203.2 × 152.4 mm) flexural beams in accordance with Peterman's small beam flexure test,[25] establish an acceptance value for strands that correlates with ASTM A1081 values and provides adequate performance per objective 4.

Polydorou and colleagues published the results of the KSU research in 2015.[29] The work completed as part of meeting objective 3 is not discussed in this report.

Strand selection

To respond to objectives 1 and 2, the KSU researchers obtained seven different 0.5 in. (12.7 mm) diameter, seven-wire, 270 ksi (1860 MPa) market-condition strands from a selection of North American strand manufacturers plus one non-market-condition strand that was known to have a low bonding value. The bonding ability of the strands was evaluated using the ASTM A1081 procedures. **Figure 3** shows the six specimen results (average of six specimen tests equals one ASTM A1081 test) for the different tests for each strand source. **Figure 4** shows the average load-slip curves for the six specimen test results.

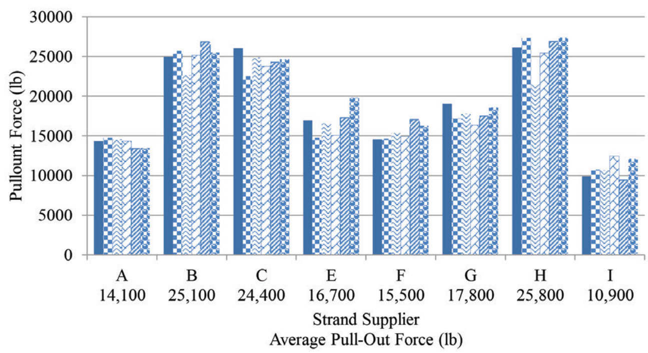


Figure 3. ASTM A1081 test results for the Kansas State University (KSU) strand selection process (January 2012). All tests performed by KSU. Note: 1 lb = 4.448 N.

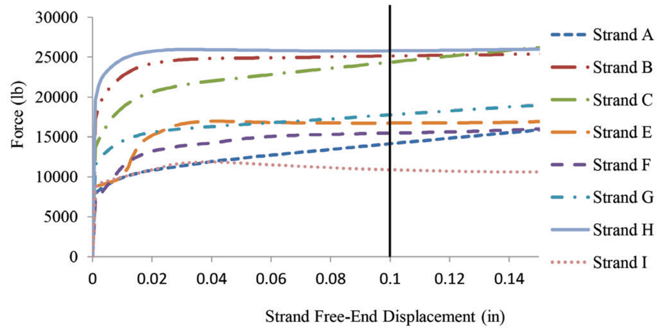


Figure 4. Load-slip curves for the Kansas State University (KSU) strand selection process. All tests performed by KSU. Source: Reprinted with persmission from NCHRP
Note: 1 in. = 25.4 mm; 1 lb = 4.448 N.

These KSU results were used to select the three strand sources—designated A, G, and I—used in the evaluations that followed. KSU strand I, with an average ASTM A1081 test value of 10.9 kip (48.5 kN), represented a non-market-condition strand, even though the average test value for this strand was similar to the minimum average test value requirement proposed in NCHRP report 603. KSU strand A, with an average ASTM A1081 test value of 14.1 kip (62.7 kN), represented a lower-than-average-bonding market strand. KSU strand G, with an average test value of 17.8 kip (79.1 kN), represented a middle-of-the-road market strand. Three market strands showed higher average pullout test values than KSU strand G, and three market strands showed lower average strengths than KSU strand G.

After selecting the three strands, the KSU researchers obtained at least 3000 ft (914.4 m) of each strand from the strand manufacturers. Then, in February and March 2012, the investigators tested samples from those strands in accordance with ASTM A1081 to verify that their properties were similar to those obtained in the initial selection process in January 2012. Table 5 summarizes those test results.

Table 5. Average ASTM A1081 strengths for selected Kansas State University strands

Strand	January 2012 tests, kip	February and March 2012 tests, kip	Change, %
I	10.9	9.3	-15
A	14.1	12.7	-10
G	17.8	17.4	-2

Note: All tests were performed by KSU. 1 kip = 4.448 kN.

Several observations are appropriate. The load-slip curve for KSU strand I (Fig. 4) shows that a maximum pullout force was developed at a slip of about 0.03 in. (0.762 mm) and that the pullout force then decreased with increasing slip. That behavior is similar to the behavior for the nonacceptable NASP quarterly test program's strand C (Table 1). For KSU strand I, all six specimen test results showed this behavior. For the other seven KSU strands A through H (there was no strand D), no more than two of the six specimen test results that compose a single ASTM A1081 test showed that behavior. Consequently, the average result for KSU strands A through H was an increase in pullout force with increasing slip. This behavior mirrors that noted for the NASP quarterly test program's strands A and J in Table 1.

Figure 4 also shows that for a given slip, there was little difference between the pullout force for KSU strand A compared to the pullout force for KSU strand I for slips less than about 0.03 to 0.04 in. (0.762 to 1.016 mm); however, for slips greater than 0.04 in., the pullout force for KSU strand A increased with increasing slips, whereas the pullout force for KSU strand I decreased with increasing slips. Consequently, the pullout force at 0.1 in. (2.54 mm) slip was about 30% greater for KSU strand A than KSU strand I.

The difference between the January 2012 results and the February and March 2012 results shown in **Table 5** is interesting. Although the February and March results are lower than the January results for all three strands, the former results are within approximately 1 standard deviation of the latter results; therefore, it can reasonably be said that all results are statistically from the same population.

Ruggedness and reproducibility testing

Next, the KSU team investigated the materials used to prepare the mortar mixture for the ASTM A1081 tests. First, while the researchers were waiting for the delivery of the 3000 ft (914.4 m) of strand for each selected strand type, they performed tests with KSU strand F and two cements different from that used in the January 2012 tests. The average strength obtained for KSU strand F (Fig. 3) for the January 2012 tests was 15.5 kip (68.9 kN). The use of the other two cements resulted in average strengths of 13.7 and 12.1 kip (60.9 and 53.8 kN). These results represented a decrease in strength of up to 22% and were outside the range of the changes shown in Tables 4 and 5. Because other factors were held constant and only the cement source was different, a cement-source-related effect was apparent.

The effects of sand characteristics, Type III cement source, and curing procedures were then systematically studied. A specific sand source was selected, and the sand was graded to a specific gradation. This graded sand was used in all subsequent tests conducted at KSU for ruggedness and reproducibility tests. Cements were obtained from six different sources, and ASTM A1081 test results were used to select a specific cement source for subsequent ruggedness testing. **Figure 5** shows the results of the cement source testing and the results from five laboratories participating in the interlaboratory study.

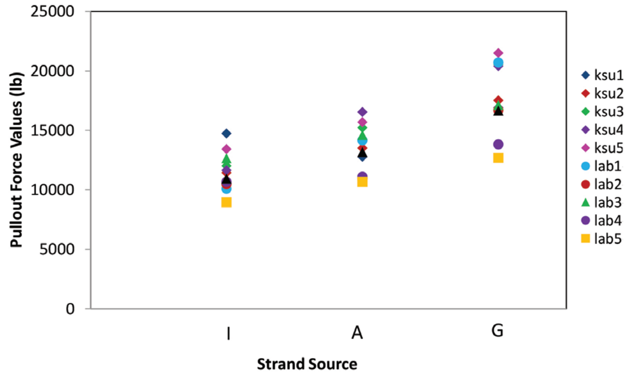


Figure 5. Data spread for ASTM A1081 for mortars made with different cements. Note: 1 lb = 4.448 N.

The KSU researchers preliminarily investigated the composition of the ASTM C150 Type III cements used in the cement selection testing for composition differences related to bond to strand. They concluded that to explore this issue would require significant effort, with supplemental testing beyond that envisioned for the PCI-sponsored KSU project, and that success of such an effort was not assured. Therefore, this issue was not further investigated, but it is thought to be one likely source of the variability in ASTM A1081 results noted in the interlaboratory study discussed in the next section. However, note that the ASTM A1081 tests all ranked the three strands in the same order for a given cement.

The ASTM A1081 method was investigated for ruggedness by systematically varying three parameters specified in the ASTM A1081 test protocol and suspected of influencing results:

- mortar mixture flow (100% to 125%)
- mortar compressive strength of samples at the time of testing (4500 to 5000 psi [31 to 34 MPa])
- test-loading rate (0.08 to 0.12 in./min [2.032 to 3.048 mm/min])

Only the mixture flow factor was determined to be statistically significant, and the researchers initially recommended changing it to 105% to 120% to reduce the variability of the ASTM A1081 method results.

Interlaboratory study

To determine the reproducibility of the ASTM A1081 test method, the KSU investigators completed an interlaboratory study. Most of the independent laboratories were state department of transportation (DOT) laboratories, and KSU demonstrated to the personnel of each DOT laboratory how to conduct ASTM A1081 tests before they began testing.

The study used two variations of the ASTM A1081 test method. Method A was the ASTM A1081 method as specified and using local sands, which were different for each of the participating DOT laboratories, and method B was a modification of method A based on the findings of the ruggedness testing. Method B required that all participating laboratories use a specific sand source with a specific gradation (graded by KSU and shipped to all participating laboratories). Method B also required a 0.45 water-cement ratio and eliminated the prescribed ASTM A1081 time-window constraint for reaching the required mortar strength of method A.

Each DOT laboratory and KSU used ASTM C150 Type III cement from a different source. The KSU 1 through KSU 5 values in **Table 6** are results for ASTM A1081 tests using method A when there were systematic variations made in the cement sources. **Table 7** presents results for method B. The scatter in the results for the three strands tested by the participating laboratories is shown in **Fig. 6** for method A. **Table 8** presents average ASTM A1081 strengths, standard deviations, and coefficients of variation for methods A and B.

The average coefficient of variation for test results for the three strands among the participating laboratories was 14% for method A (the current ASTM A1081 protocol) and 11% for method B. Although the coefficient of variation for method B was lower, it was concluded that method B's additional modifications to ASTM A1081 procedures were not desirable for two reasons:

- The use of a standard graded sand that was graded and shipped from a single source nationwide would raise considerably the cost of ASTM A1081 testing.
- The coefficient of variation of 14% for method A was no greater than that for strength tests of concretes produced nationwide.

Several observations are appropriate. First, every laboratory participating in the interlaboratory study ranked the average performance of the strands in their method A tests as G > A > I (Fig. 6 and Table 6); however, the spread in the six specimen test results for any average value resulted in an overlap in individual results among the three strands. Thus, for ASTM A1081 testing, the focus must be on the average result of six specimen tests and not the individual specimen test results.

Second, the marked variation in average test results for a given strand among the various participating laboratories in-

Table 6. Kansas State University interlaboratory study reproducibility results using method A

Lab ID Strand	Average mortar compressive strength before test, psi	Average mortar compressive strength after test, psi	Average mortar mixture flow, %	Strand A average pullout force, lb	Strand I average pullout force, lb	Strand G average pullout force, lb
KSU 1	4554	4701	122.5	12,803	14,739	16,921
KSU 2	4655	4672	122.4	13,534	11,446	17,534
KSU 3	4589	4736	118	15,250	12,036	20,548
KSU 4	4654	4675	124	16,564	11,652	20,423
KSU 5	4619	4641	122	15,711	13,441	21,503
Lab 1	4630	4785	115	14,163	10,114	20,725
Lab 2	4535	4668	120	10,947	10,515	16,722
Lab 3	4634	4814	117.5	14,634	12,681	17,127
Lab 4	4630	4995	111	11,103	10,682	13,832
Lab 5	4699	4896	120.7	10,687	8966	12,715
Lab 6	4511	4522	123.5	13,201	10,955	16,695

Note: 1 lb = 4.448 N; 1 psi = 6.895 kPa.

Table 7. Kansas State University interlaboratory study reproducibility results using method B

Lab ID	Average mortar compressive strength before test, psi	Average mortar compressive strength after test, psi	Average mortar mixture flow, %	Strand A average pullout force, lb	Strand I average pullout force, lb	Strand G average pullout force, lb
KSU 1	4525	4485	114.5	14,267	11,585	17,060
KSU 2	4525	4443	112	14,890	12,981	17,307
KSU 3	4516	4731	116	13,510	10,373	16,807
KSU 4	4579	4728	112.7	15,343	11,163	17,495
KSU 5	4578	4794	116	13,397	11,027	16,993
Lab 1	4648	4709	116	15,250	9581	19,037
Lab 2	4707	4884	113.5	13,437	10,331	20,570
Lab 3	4551	4799	107.5	19,367	13,876	20,591
Lab 4	4475	4820	115	12,653	12,445	17,338
Lab 5	4359	4475	115.3	11,886	10,582	15,046
Lab 6	4010	4115	114.5	13,813	11,589	17,735

Note: 1 lb = 4.448 N; 1 psi = 6.895 kPa.

dicates that although credence should be given to the absolute value of the average test result for a given strand, considerable variance in that average test value can be anticipated, even among laboratories trained in performing the ASTM A1081 test. Although this variability argues against pass/fail testing for strand bond by laboratories, appropriate third-party testing by a laboratory with experience running ASTM A1081 tests will provide important information to inform PCI-certified producers' quality control and quality assurance efforts.

Finally, as Fig. 5 shows, the variable with the greatest effect on variation in the absolute average value for the ASTM A1081 test is related to the as-yet-undefined composition, properties, and condition of the ASTM C150 Type III

Table 8. Summary of Kansas State University interlaboratory study reproducibility results

Parameter	Strand A, method A	Strand A, method B	Strand G, method A	Strand G, method B	Strand I, method A	Strand I, method B
Average pullout force, lb	13,500	14,300	17,700	17,800	11,600	11,400
Standard deviation	1903	1882	2728	1576	1543	1212
Coefficient of variation	0.14	0.13	0.15	0.09	0.13	0.11
Note: 1 lb = 4.448 N.						

cement used for the mortar.

Although the interlaboratory study showed that credence should be given to the absolute value of the average test value for a given strand, it also showed that when assessing the acceptability of a given average or lower-than-average bonding strand, attention should be given to the form of the load-slip curve. The ASTM A1081 test only requires that the capacity at a slip of 0.1 in. (2.54 mm) be recorded; however, in the interlaboratory study, laboratories 4 and 5 (Table 7) recorded complete load-slip curves. **Figure 7** shows laboratory 4's method B results for strands A and I, and **Fig. 8** shows laboratory 5's method A results for the same strands. Both laboratories recorded decreasing pullout forces with increasing slips starting at about 0.03 in. for KSU strand I. The same result is apparent for strand I in Fig. 4.

The steel stress in strand at release is typically about 190 ksi (1310 MPa) for Grade 270 (1860 MPa) strand. For 0.5 in. (12.7 mm) diameter strand, that stress typically results in a slip immediately after release of about 0.03 in. (7.62 mm). The stress of 190 ksi is in the elastic range of behavior for the strand, and the stress in the strand in the ASTM A1081 test is also in its elastic response range. To achieve the design flexural strength of a typical pretensioned, precast concrete beam when testing, the strand will be stressed to 250 ksi (1724 MPa) or more, a value that is well into the yield range for the strand. In the yield range, the diameter of the strand decreases with increasing stress. Maintenance of bond capacities consistent with ASTM A1081 results for the low slips that occur close to the maximum moment location is not likely. Therefore, a strand that shows a decreasing pullout force with increasing slips beyond 0.03 in. (7.62 mm) slip is less likely to have more acceptable bond behavior than a strand that exhibits a similar level of pullout force at a slip of 0.03 in. but for which the pullout force continues to increase significantly with increasing slips beyond 0.03 in.

Although this noted behavior may be too detailed for a strand bond specification, strand manufacturers should strive to provide strand that has increasing ASTM A1081 pullout force with increasing strand slips beyond 0.03 in. (7.62 mm).

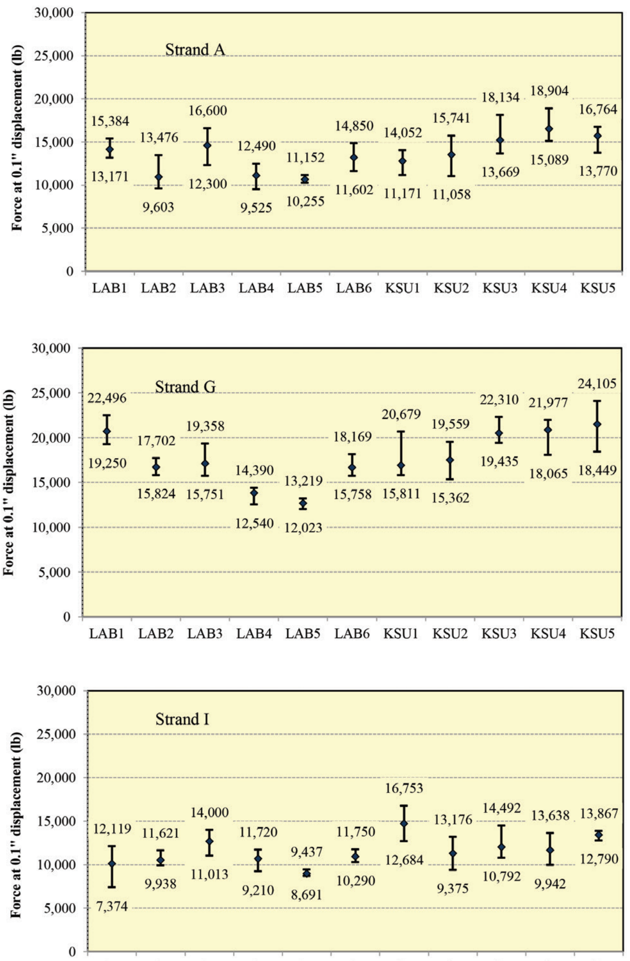
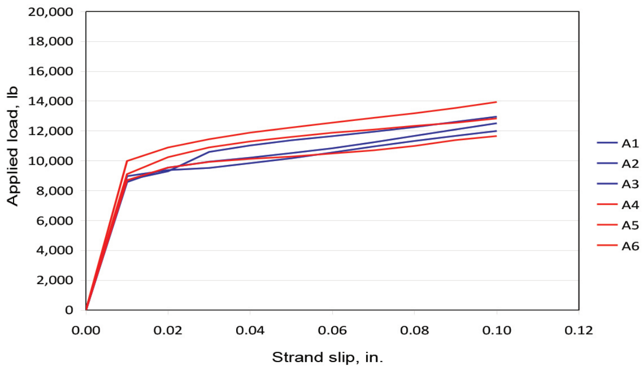


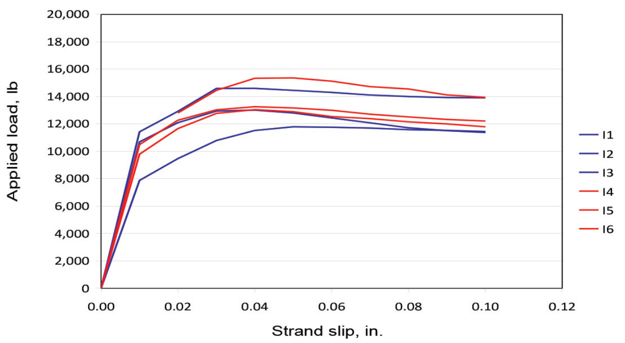
Figure 6. Scatter in Kansas State University interlaboratory study results for method A. Note: 1″ = 1 in. = 25.4 mm; 1 lb = 4.448 N.

Beam testing

To meet objectives 5 and 6 of the PCI contract with KSU, thirty 6.5 wide × 12 in. deep (165.1 × 304.8 mm) beams were fabricated and tested at Stresscon's precast concrete plant in Colorado Springs, Colo. Beams had a single strand placed centrally within the width of the beam and 2 in. (50.8 mm) above the soffit. Ten beams were built for each test strand and tested once at each end for a total of 20 tests for each strand and 60 tests overall. Single-point loading was used, with

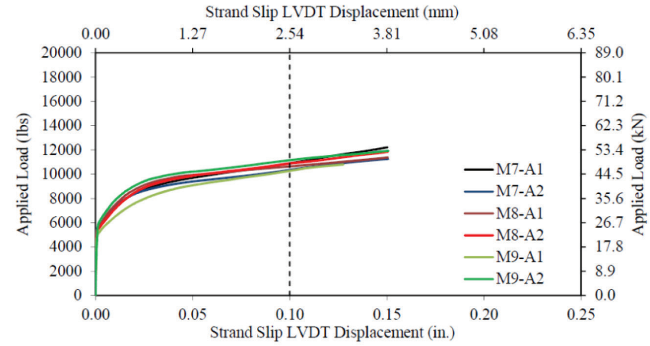


KSU strand A tested at laboratory 4

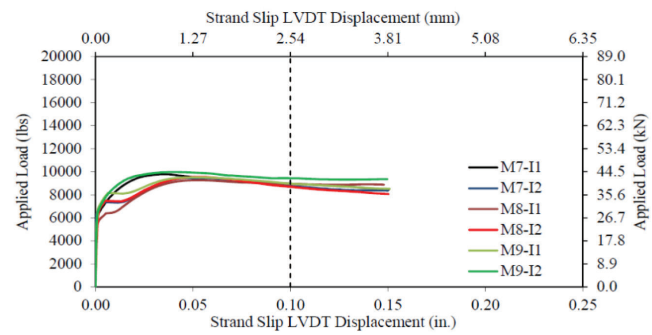


KSU strand I tested at laboratory 4

Figure 7. Load-slip curve results for method B testing at laboratory 4.



KSU strand A tested at laboratory 5



KSU strand I tested at laboratory 5

Figure 8. Load-slip curve results for method B testing at laboratory 5.

the load placed at 60% or 80% of the ACI 318 development length ℓ_d from the end of the beam. Shear reinforcement, which was placed in the central part of the beam, did not extend into the strand embedment length region.

Concrete strengths averaged 3800 psi (26 MPa) at release at 1 day or less and 6300 psi (43 MPa) at 21 days. The strand steel stress after losses at the time of test was calculated to be about 184 ksi (1269 MPa). Beams were cast with five in one line, and the prestress was released by saw cutting that line. Beams were then cured until testing.

Unfortunately, because of bearing problems with the saw, the cutting saw blade wobbled, resulting in a longer-than-planned cutting time and significant beam end abrasion, which prevented accurate initial strand end slip measurements. A noncontact laser speckle device was used to measure concrete surface strains before and after detensioning.

The targets on the beams for laser speckle measurements were unfortunately compromised by the curing. As a result, transfer lengths at the time of testing were taken as the sum of the transfer-length increase implied by strand end slip growth and the initial laser determined transfer length measured at release. Consequently, there is some uncertainty about the accuracy of the reported transfer lengths at time of testing. Average transfer lengths for the 20 ends of beams with each strand type at release and tested at 21 days are reported in **Table 9**.

To ensure initial cracking at the load points, 4 in. (101.6 mm) tall, U-shaped crack initiators covered with cloth tape for debonding were placed at the load point locations for the first 10 beams. However, after release of those beams, higher-than-normal surface strains were observed near these crack initiators. Consequently, crack initiators were omitted for the remaining 20 beams. Instead, saw cutting was used to make a 1 in. (25.4 mm) deep notch directly under the load point. In addition, to introduce additional concrete tensile zone weakening and simulate cracking, additional 1.4 in. (35.56 mm) deep saw cuts were made in some of the beam soffits located outside of the calculated ACI transfer-length region of 30.7 in. (779.8 mm) from the beam ends.

Researchers took care to record, as accurately as possible, first cracking. For the two embedment lengths of 60% and 80% of the ACI 318 development length ℓ_d, the theoretical loads for first cracking differed by less than 5%. For the full 6.5 × 12 in. (165.1 × 304.8 mm) cross section, the average theoretical value for first cracking for those two lengths was 7.71 kip (34.2 kN).

Because of the wide variations in the manner in which cracks were preformed in the beams, first-cracking comparisons could be made for only six beam end tests for each strand (ends for beams 8, 9, and 10). For the six ends, the average observed loads for first cracking were 8.44, 7.80, and 7.22 kip (37.5, 34.7, and 32.1 kN) for KSU strands G, A, and I, respectively.

Table 9. Measured Kansas State University strand transfer lengths

Strand	ASTM 1081 value, lb	Number of data points	Transfer length			
			Average at release, in.	Average at 21 days, in.	Range at 21 days, in.	Average increase at 21 days 12 hours, %
A	14,100	20	35.8	48.5	34.6–69.5	35
G	17,800	20	28.1	37.7	29.1–49.1	34
I	10,900	20	42.2.	54.7	32.1–83.0	30

Note: 1 in. = 25.4 mm; 1 lb = 4.448 N.

Table 10. Summary of Kansas State University beam flexure test results

Beam group	Development length l_d, %	Average measured transfer length l_{tr}, in.	Average M_{exp}/M_n	Number of $M_{exp}/M_n < 1.0$	Average end slip in test, in.	Number of end slips > 0.05, in.
A	60	50.4	1.29	0	0.183	1
A	80	46.6	1.15	1	0.046	1
G	60	36.9	1.32	0	0.220	1
G	80	38.4	1.21	0	0.033	0
I	60	53.5	1.21	2	>0.668	7
I	80	56.0	1.09	3	0.227	6

Note: M_{exp} = experimental moment; M_n = calculated nominal moment capacity. 1 in. = 25.4 mm.

Table 10 summarizes the beam test results. There were six experimental moment M_{exp} results for each beam group. The transfer length at the time of the test in Table 9 is shown separately for the two different embedment lengths in Table 10 (average measured transfer length ℓ_{tr}). The calculated nominal moment capacity M_n values were calculated based on the bilinear relationship specified for the development of prestressing stresses with increasing embedment in ACI 318. The results show that KSU strand I was consistently incapable of meeting ACI 318 development-length requirements; KSU strand G performed better than ACI 318 requirements, and KSU strand A marginally met ACI 318 requirements.

The results for number of end slips > 0.05 in. (1.27 mm) in Table 10 are of particular interest for evaluation of strand performance and for documenting the marginal performance of KSU strand A and the unacceptable performance of KSU strand I. End slips in excess of 0.05 in. result in reduced beam-shear capacity and increased deflections. The increase in deflections for strand end slips greater than 0.05 in. was clearly visible for the test beams in the KSU research. As discussed in the PCI due diligence report,[4] the reduction in beam-shear capacity with such strand slips was also clearly identified in the beam test results of NASP round III.[23]

A review of typical production precast, pretensioned concrete products shows that almost all pretensioned, precast concrete structural members will contain at least six strands. The performance of the member will be determined by the average bond characteristics for those six strands. The fact that 2 out of 20 results for KSU strand A and 1 out of 20 results for KSU strand G were unacceptable means that in practice, the performance of KSU strands A and G will likely be acceptable; however, any strand with worse bonding characteristics than strand A would not be desirable. For KSU strand I, there were 13 excessive end slips out of a total of 20 tests. The performance of KSU strand I is clearly unacceptable.

Determining ASTM A1081 threshold values

To determine the ASTM A1081 threshold values necessary to satisfy code development-length requirements, the KSU researchers used a simple statistical analysis of the average beam performance correlated with the average ASTM A1081 test value for each strand source as measured in the interlaboratory study. A polynomial analysis was used to give a best fit to the test data (**Fig. 9**).

In Fig. 9, the vertical axis is the M_{exp}/M_n, as discussed for Table 10, and the symbols are the result for a given strand source. Further, because the beam test work was all done on single strands and the minimum number of strands in the customary precast, prestressed concrete beam is six, an averaging proce-

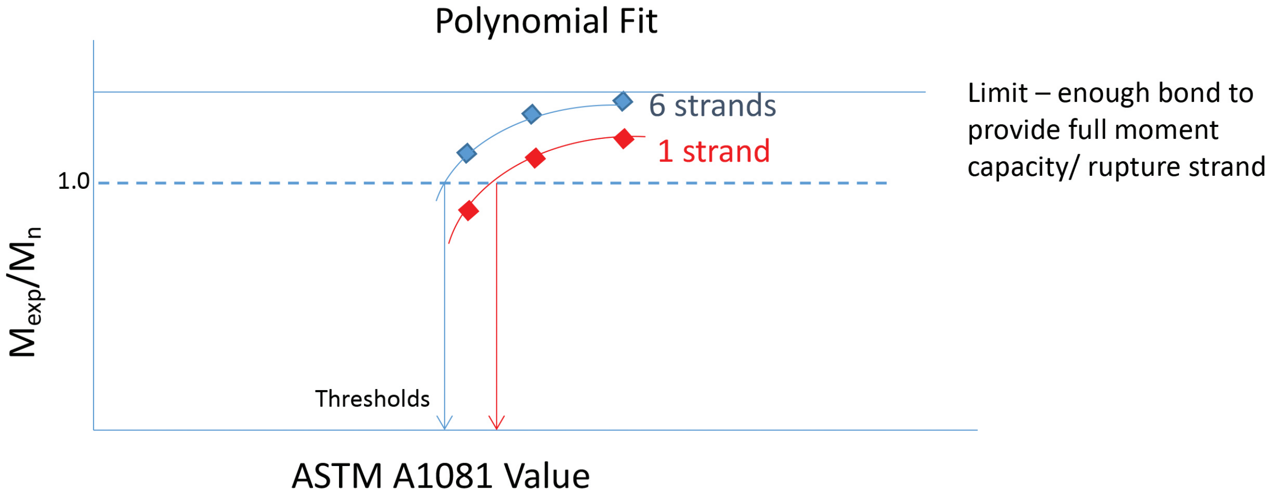


Figure 9. Representation of the Kansas State University procedure for ASTM A1081 threshold determination. Note: M_{exp} = experimental moment; M_n = calculated nominal moment capacity.

dure was used to derive appropriate ASTM A1081 values for that condition. **Table 11** presents the resultant recommended ASTM A1081 values for single-strand and six-strand beams.

The pullout force for a 90% confidence interval on a 10% fractile (an above-average probability) and six strands corresponds to a value about 2 standard deviations above the average test result. Therefore, the required ASTM A1081 value recommended by the KSU researchers was effectively 14 kip (62.2 kN). Note that the corresponding average force for six strands is 10.9 kip (48.4 kN), which is about the same value recommended by Russell and Ramirez in NCHRP report 603[5] based on the testing of beams with multiple strands.

Peterman beam testing

Following completion of the KSU flexural beam testing, three beams for each strand with dimensions meeting Peterman beam test requirements were fabricated using the same concrete mixture as that used for the flexural beam tests. Those beams were tested under the Peterman protocol published in 2009.[25] All of the beams with KSU strand I experienced large strand slip and deflection growth during the 24-hour load-hold period at 85% of M_n and failed prior to reaching 100% M_n. All of the beams with KSU strands A and G passed the test.

The initial ASTM A1081 testing for the selection of the strand to be used for the KSU research was done in January 2012. Because the flexural beam testing was not completed until August 2014, questions were raised as to the validity of the January 2012 tests for characterizing the strands used in the flexural beam testing more than two years later. During that same period, Peterman was conducting additional bond-related research at KSU, which indicated that the adopted procedure of storing the strands in a protected condition would likely preserve the initial condition for an extended period.

Development of recommended practice

Based on the research and findings discussed in this article, a joint task group composed of representatives of NASP and PCI tried, without success, to develop a consensus document on procedures to assess and control the bond of ASTM A416 prestressing strand.[31] The NASP representatives wanted any recommended practice to be market based, with minimum required ASTM A1081 values no greater than those recommended by Russell and coauthors.[5,20–23] The NASP representatives did, however, agree to commit to ongoing quarterly testing of their strands to demonstrate the reliability and consistency over time of the bonding properties and to provide results of that testing on request to purchasers of their strands. PCI representatives desired a commitment to guaranteed ASTM A1081 values that would be higher than those recommended by Russell and coauthors and more consistent with the findings from the KSU research. When NASP and PCI did not achieve consensus, PCI decided to independently publish its recommended practice.

The recommended practice recognizes the desirability of having strands with two differing guaranteed ASTM A1081 values. Strand meeting the lower pullout criteria is referred to as normal bond strand. Strand meeting the higher pullout criteria is referred to as high bond strand. This concept is also consistent with the documented ongoing results of quarterly testing by various strand manufacturers.

For normal bond strand, one ½ in. (12.7 mm) diameter strand needs to demonstrate a minimum six-quarter running average ASTM A1081 value of 14 kip (62.2 kN) with no quarterly test average less than 12 kip (53.3 kN). Based on the KSU investigations and prior research, this strand would provide better than 90% confidence interval of the 10% fractile, exceeding ACI 318–specified transfer and development provisions for prestressing strand regardless of who conducts

Table 11. ASTM A1081 threshold values needed to meet ACI 318 development length requirements

Type of analysis	Pullout force, lb*		
	Average	90% confidence interval on 10% fractile	90% confidence interval on 5% fractile
1 strand, 20 beam ends	14,400	18,800	19,800
1 strand, 10 beam ends tested at 60% ACI development length l_d	13,400	17,400	18,400
1 strand, 10 beam ends tested at 80% ACI development length l_d	14,800	19,300	20,500
6 strands, 20 beam ends	10,900	13,900	14,600
6 strands, 10 beam ends tested at 60% ACI development length l_d	10,100	12,700	13,400
6 strands, 10 beam ends tested at 80% ACI development length l_d	11,400	14,500	15,300

Note: ACI = American Concrete Institute. 1 in. = 25.4 mm; 1 lb = 4.448 N.

*Corresponding to achieving the ACI 318 calculated nominal moment capacity in 6.5 × 12 in. single-strand beams for the ASTM A1081 interlaboratory study.

the ASTM A1081 test and what cement is used. Strands with these ASTM A1081 bonding properties are suitable for use where the performance of the precast, pretensioned concrete element does not rely primarily on the prestress enhancement of shear capacity in the end (support) regions. Such elements typically contain mild steel transverse and crack-control reinforcement in the end region and can accommodate some strand slip without compromising the serviceability of the element.

For high-bond strand, one ½ in. (12.7 mm) diameter strand needs to demonstrate a minimum six-quarter running average ASTM A1081 value of 18 kip (80 kN) with no quarterly test average less than 16 kip (71.2 kN). Use of this type of strand is desirable for pretensioned, precast concrete elements that are subjected to large concentrated loads within the transfer length and elements, such as hollow-core members, that are designed without transverse reinforcement and rely on the prestress within the end region to provide necessary shear capacity and serviceability for the element.

The draft of the unpublished NACP-PCI consensus document[31] recommended that ASTM A1081 testing for quality control purposes be performed only by laboratories experienced in such testing, as defined by the following four conditions:

- The laboratory has equipment that has been shown to provide reliable and repeatable ASTM A1081 results. The laboratory personnel performing the ASTM A1081 testing must be experienced in such testing and aware of the sensitivity of ASTM A1081 test results to variations in test procedures and in materials used.

- The laboratory has the ability to procure, store, and maintain in an unaffected condition a consistent type of cement and other materials used for ASTM A1081 testing.

- The laboratory has demonstrated over at least three quarters of testing of the same strand that it is able to do what is reasonable to eliminate inappropriately low or high ASTM A1081 results caused by material or testing procedure variations.

- The laboratory has a demonstrated method of maintaining confidentiality of test results.

Conclusion

The following conclusions can be drawn:

- The use of the ASTM A1081 test procedure can provide definitive information on the relative bond strength of prestressing strands from differing sources; however, ASTM A1081 strength values were found in the KSU research to be sensitive to, among other things, the composition, properties, and condition of the cement used in the ASTM A1081 test. For a given strand, average ASTM A1081 test values measured by different test laboratories can vary markedly, even when those laboratories all use the same graded sand, if they use ASTM C150 Type III portland cement from different cement producers.

- Characterizing the adequacy of the bond performance of a given strand requires knowledge of the effect of that performance on more than end slips and flexural strength. The bond performance's effect on loads for cracking, crack widths, deflections, and shear strength must also be considered.

- For current typical strand prestress levels, both transfer and development lengths change approximately in proportion to $\sqrt{f_c'}$ in ksi, where f_c' is the concrete strength at release for transfer lengths and the concrete strength at the start of service-level loading for development length.

- In the ASTM A1081 test, if the pullout load of a given strand at a slip of about 0.03 to 0.04 in. (0.762 to 1.016 mm) or less exceeds that of the pullout load of the same strand at a slip of 0.1 in. (2.54 mm) for three or more of the six individual-specimen test results making up the ASTM A1081 test, the bond performance of that strand in a strand-bond-sensitive pretensioned, precast concrete element likely will be inadequate unless the ASTM A1081 pullout load at 0.1 in. is well above 14,000 lb (62.2 kN). Thus, laboratories experienced in ASTM A1081 testing for strand manufacturers should determine the bond acceptability of a given average to lower-than-average bonding strand based not only on the average pullout load of a given strand at a slip of 0.1 in. but also on the form of the complete load-slip curve up to a slip of 0.1 in. Strand-bond-sensitive pretensioned, precast concrete elements are defined as those elements that may be subjected to concentrated loads close to their ends within the transfer length for the strand and elements that are shear critical by reliance on the effects of the prestress in the end regions to provide the necessary shear capacity for the element. Thin products and products with the minimum required clear cover to the strand can have increased transfer and development lengths, particularly where there is thin top cover in their as-cast position.[7–9]

- The average ASTM A1081 test values recorded for a given strand can vary markedly from laboratory to laboratory, even when those laboratories are trained in performing the ASTM A1081 test. This may be partly due to operator differences but is likely also due to the cement used in the test. Thus, laboratories performing the ASTM A1081 test should meet the requirements of an ASTM A1081 experienced test laboratory as defined by researchers at KSU[31] and in the draft of the unpublished NACP-PCI consensus document.[31] These laboratories have the appropriate equipment, procedures, and personnel awareness of sensitivity of test results to variation in test procedures such that the laboratory has been shown to provide reliable and repeatable ASTM A1081 test results.

- With a strand-bond-optimum ASTM C150 Type III cement source, strands having ASTM A1081 values of 14 kip (62.2 kN) or greater and a pullout load that increases with increasing slips beyond 0.03 in. (0.762 mm) have an above-average probability (90% confidence interval on the 10% fractile) of providing development lengths that equal or are less than ACI 318 specified development lengths. For the same ASTM A1081 test value, strand average transfer-length test values exceed ACI 318 specified transfer lengths and a multiplier on the calculated transfer-length value is needed to provide an above-average value for the transfer length.

- With a strand-bond-optimum ASTM C150 Type III cement source, ASTM A1081 benchmark values of 18 kip (80 kN) or more (in other words, high-bond strand) are required for an above-average probability that a strand will have average transfer lengths at release that satisfy ACI 318–specified transfer lengths.

- Transfer lengths as calculated by NCHRP report 603 Eq. (3.6) increase with time, with the length at 240 days being typically 1.6 times that at release and the length at 60 days being 1.3 or more times that at release. Those factors tend to decrease as release strength is increased, as the number of strands in the section increases, and as the transverse reinforcement in the beam end increases.

- The findings from statistical analyses considering interlaboratory variability, cement source variability, source variability, and variability associated with using mortar-based test specimens to predict performance in concrete led to the choice of ASTM A1081 test acceptance criteria that are comfortably conservative. If we were to consider single-strand members, an ASTM A1081 pullout force criteria of 18 kip (80 kN) would result for normal-bond strand. However, considering that actual precast concrete members are typically made with more than six strands, a pullout force criteria of 14 kip (62.2 kN) with no individual tests less than 12 kip (53.3 kN) is considered reasonable. It should be noted that the ASTM A1081 test itself uses an average of six specimens instead of a value based on the 5% or 10% fractal, which somewhat reduces the conservatism implied by the test criteria. It should also be noted that through judicious choice of cement used in test specimens, an enhanced pullout force can be achieved, further reducing the conservatism of the test method.

- Beam tests indicate that a strand meeting the ASTM A1081 pullout capacity of 14 kip (62.2 kN) will have a transfer length approximately 60% greater than predicted by the ACI equations. This finding is consistent with the AASHTO multiplier. Hence, the recommended practice indicates that ½ in. (12.7 mm) strand meeting the ASTM A1081 14 kip (62.2 kN) pullout capacity with no single value less than 12 kip (53.3 kN) should have a transfer length reliably less than about 80 strand diameters (40 in. [1016 mm]). The beam tests also indicate that ½ in. strand meeting the ASTM A1081 18 kip (80 kN) pullout capacity with no single value less than 16 kip (71.2 kN) should have a transfer length reliably less than about 50 strand diameters (25 in. [635 mm]). Interpolation between these values is permitted.

- Strands with diameters other than ½ in. (12.7 mm) and GUTS other than 270 ksi (1860 MPa) should have pullout criteria values multiplied by $2 \times d_b \times f_{pu}/270$, with d_b measured in inches and f_{pu} in ksi.

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Notation

d_b = nominal diameter of prestressing strand

f'_c = concrete design strength

f'_{ci} = concrete release strength

f_{ps} = stress in prestressing steel at nominal flexural strength

f_{pu} = stress in prestressing steel at ultimate flexural strength

f_{se} = stress in prestressing steel after allowance for all prestress losses

ℓ_d = development length

ℓ_{tr} = transfer length

M_{exp} = experimental moment

M_n = calculated nominal moment capacity

ϕ = strength reduction factor

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Abstract

The transfer of prestressing force from prestressed strand to concrete over a predictable length is essential for the reliable performance of prestressed concrete. Although no problems with strand bond were reported in the early days of precast, prestressed concrete construction in the United States, several documented problems have occurred in the past 35 years or so, indicating the need for the quality control and quality assurance program recommended in this article.

Over the past two decades, a direct pullout test method that reasonably predicts the bonding properties of the strand used in precast concrete products has been developed. This test method was developed to qualify the strand as having bond properties consistent with design expectations. Certain concrete formulations may affect bond quality, and these should be evaluated separately on a case-by-case basis.

In July 2020, the PCI Technical Activities Council and Research and Development Council approved a new "Recommended Practice to Assess and Control Strand/Concrete Bonding Properties of ASTM A416 Prestressing Strand," which was subsequently published in November 2020. It establishes minimum test pullout values that can be used to define transfer and development lengths for prestressing strand in concrete. This article summarizes background information on strand bond and documents the many years of research that led to the final published recommended practice.

Keywords

ASTM A1081, ASTM A416, bond, development length, transfer length.

Reader comments

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