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Background for the new PCI recommended practice on strand bond

- The new PCI "Recommended Practice to Assess and Control Strand/Concrete Bonding Properties of ASTM A416 Prestressing Strand" specifies two new threshold limits for pullout tests conforming to ASTM A416 and new equations for the transfer and development length of prestressing strand.
- This article provides a summary of more than 30 years of research and knowledge advancement on the bond between concrete and prestressing strand related to the development of the new recommended practice.
- Discussions regarding the adoption and incorporation of the new recommended practice into structural design, strand production, and precast concrete fabrication and quality control practices are ongoing.

PCI Journal (ISSN 0887-9672) V. 65, No. 6, November–December 2020.

PCI Journal is published bimonthly by the Precast/Prestressed Concrete Institute, 8770 W. Bryn Mawr Ave., Suite 1150, Chicago, IL 60631.

In July 2020, the Technical Activities Council and Research and Development Council of PCI approved the new "Recommended Practice to Assess and Control Strand/Concrete Bonding Properties of ASTM A416 Prestressing Strand" (pages 33 to 34). This article provides a brief background on the topic of strand bond and summarizes many years of research that led to the published recommended practice. A more comprehensive review of the bond of prestressing strand to concrete, with additional references and supporting information, will be presented in a future issue of the *PCI Journal*.

History of strand bond issue

In 1988, the Federal Highway Administration (FHWA) issued a memorandum specifying a 1.6 multiplier on the American Association of State Highway and Transportation Officials (AASHTO) development length equation for fully bonded strands and banning the use of 0.6 in. (15 mm) diameter strand.[1] This memorandum was based on the results of transfer-length studies conducted on uncoated strands, accompanying a broader project on epoxy-coated strands, which exhibited very long transfer lengths. Several research projects regarding the behavior of strand bond, in particular for slip-critical applications, were subsequently conducted. In the early 1990s, PCI also established the Task Force on Bonding of Prestressed Concrete Strand in Concrete consisting of task force chair Don Pellow, Roger Becker, Ned Burns, Phil Iverson, Tony Kobayashi, Sue Lane, Don Logan, Sadd Moustafa, Bob Olson, Cliff Sabo, Gus Sason, Kim Seeber, Mario Suarez, and Mike Urbancic to review available data and develop tests to evaluate strand bond.

PCI issued an alert dated September 6, 1995, to all producer members about premature bond failures of strand used as lifting loops. These failures, and other reported premature bond failures, were believed to be due to changes in strand production procedures that may have created a residue on the strand surface, inadvertently affecting the strand bond capacity. At that time, PCI recommended that each producer member determine how best to assure themselves that the strand they used would meet the strand transfer and development length equations in the design specifications.

PCI issued a second alert in August 1996 confirming the concerns expressed in the first alert and describing a test termed the Moustafa pullout test as recommended by Don Logan. PCI recommended that each producer conduct the Moustafa pullout test with a minimum capacity of 36 kip (160 kN) for 0.5 in. (13 mm) diameter strand and also request certification from the strand suppliers that their strand was capable of meeting specified design equations.

In 1998, FHWA's Turner-Fairbank Highway Research Center issued the report "A New Development Length Equation for Pretensioned Strands in Bridge Beams and Piles" (FHWA-RD-98-116) by Sue Lane on an extensive testing program.[2] In addition, state highway agencies, including the Florida Department of Transportation, also were studying the strand bond issue.

In addition to the work being done by PCI, FHWA, and state highway agencies, the North American Strand Producers (NASP) commissioned a study of strand bond in a pretensioned applications for the development of an alternative test method to the Moustafa pullout test.[3] This research, led by Bruce Russell at Oklahoma State University, eventually resulted in the standardization of ASTM A1081, *Standard Test Method for Evaluating Bond of Seven-Wire Prestressing Strand*, in 2012.[4]

In the 2000s, parallel to some of the NASP work, the National Cooperative Highway Research Program (NCHRP) also sponsored research related to strand bond. One project, NCHRP 603, recommended revisions to the transfer, development, and splice length equations for members with concrete strengths greater than 10 ksi (69 MPa).[5] NCHRP 603 recommended an ASTM A1081 minimum average pullout test value of 10,500 lb (46,700 N) for 0.5 in. (13 mm) diameter strand, with a minimum single-test value of 9000 lb (40,000 N), and recommended a modified development length equation based on both the concrete strength at transfer of pretensioning and the design concrete strength.

After reports of ASTM A1081 test results not meeting the recommended pullout values in 2008 and a due diligence review that recommended changes to the test method and establishing multiple levels for strand with different bond qualities, PCI funded a major research project to evaluate the ruggedness and repeatability of the ASTM A1081 test method. The results of this work, published in the May–June 2016 and July–August 2016 issues of *PCI Journal*, recommended a minimum pullout value of 28,200 lb (125,500 N) to meet current design equations for development length.[6,7] This initial minimum pullout value aimed to reflect the test result variability and the confidence in test procedure repeatability and ruggedness. The value contained a high bias to address the variability in procedure, and many proposed that the age-adjusted aspect of having shorter transfer and development lengths for aged and high-strength concrete needed to be revised. The research project also identified the time-dependent nature of transfer length, finding that transfer length increased over time from initial transfer, and confirmed the influence of concrete strength on strand bond.

Current design provisions

The American Concrete Institute's *Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19)*[8] provisions for the development of pretensioned seven-wire strands in tension are provided in section 25.4.8, more specifically, Eq. (25.4.8.1).

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

where

l_d = development length in tension of pretensioned strand, in.

f_{se} = effective stress in prestressed reinforcement, after allowance for all prestress losses, psi

d_b = nominal diameter of prestressing strand, in.

f_{ps} = stress in the prestressed reinforcement at nominal flexural strength, psi

The total development length given by Eq. (25.4.8.1) consists of a combination of the transfer length, which is the length of embedded pretensioned reinforcement required to transfer the effective prestress to the concrete (the first term in the equation), and the bond length, which is the length of bonded pretensioned reinforcement required to develop the design strength of the reinforcement (the second term in the equation). The same transfer length for flexural members is also defined in ACI 318-19 section 21.2.3 as the first term in Eq. (25.4.8.1). For a typical effective prestress of about 174 ksi (1200 MPa) at transfer, this transfer length corresponds to $58d_b$. Further, ACI 318-19 section 22.5.7.1 specifies a transfer length of $50d_b$ for strand to design for the effect of reduced prestressing force on sectional shear strength.

The ninth edition of the *AASHTO LRFD Bridge Design Specifications*[9] provisions for the development of bonded strand are provided in Article 5.9.4.3.2:

$$l_d \geq \kappa\left(f_{ps} - \frac{2}{3}f_{pe}\right)d_b \qquad \text{(AASHTO 5.9.4.3.2-1)}$$

where

κ = multiplier factor

f_{pe} = effective prestress in the prestressing steel, ksi

Like the ACI equation, the AASHTO LRFD specifications equation consists of a combination of the transfer length and the bond length; however, AASHTO LRFD specifications Article 5.9.4.3.1 states that the transfer length may be taken as $60d_b$. AASHTO LRFD specifications also includes in the development length equation the multiplier factor κ that is 1.0 for pretensioned panels, piling, and other pretensioned members with a depth less than or equal to 24.0 in. (610 mm) and 1.6 for pretensioned members with a depth greater than 24.0 in.

Recommended practice

The approved "Recommended Practice to Assess and Control Strand/Concrete Bonding Properties of ASTM A416 Prestressing Strand" establishes ASTM A1081[10] minimum average pullout values of 14,000 lb (62,000 N) for all 0.5 in. (13 mm) diameter strand and 18,000 lb (80,000 N) for high-bond-strength 0.5 in. diameter strand.

In addition to the recommended minimum average pullout values, the recommended practice provides the following modified development length equation:

$$l_d = \left(\frac{3800}{\sqrt{f'_{ci}}} + \frac{7100}{\sqrt{f'_c}}\right)d_b \geq 100d_b$$

where

f'_{ci} = concrete strength at transfer, psi

f'_c = design concrete strength, psi

Similar to the ACI 318-19 equation, the first term corresponds to the transfer length and the second term corresponds to the flexural bond length. However, for the calculation of transfer length, the recommended practice specifies a multiplier on the first term based on the strand bonding qualities of 1.6 for minimum-bond-strength strand or 1.0 for high-bond-strength strand. The recommend practice reduces the multiplier to 0.8 for stress calculations at detensioning.

Figure 1 shows differences between the development and transfer lengths in the recommended practice and the design equations in ACI 318-19 and AASHTO LRFD specifications.

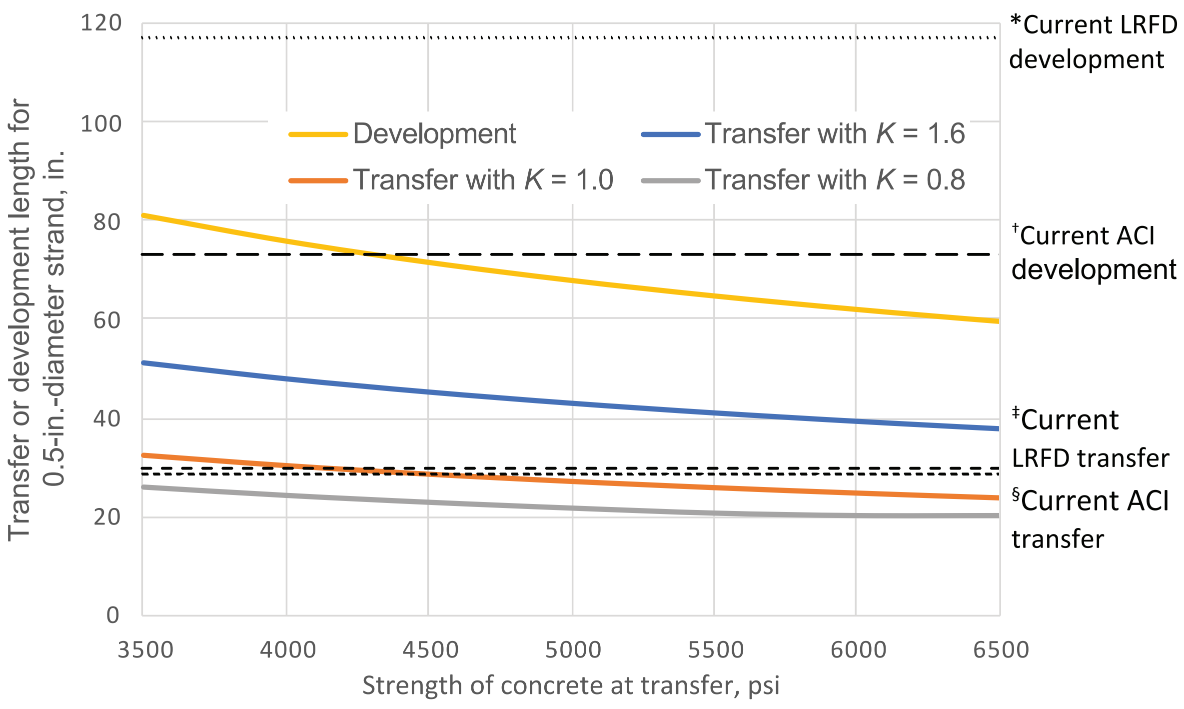

Figure 1. Comparison of transfer and development length calculated using the strand bond recommended practice, AASHTO LRFD specifications, and ACI 318.

Note: Calculations for transfer and development length assume that the design concrete strength f'_c is 1.5 times the concrete strength at transfer f'_{ci}. κ = multiplier factor; LRFD = load- and resistance-factor design. 1 in. = 25.4 mm; 1 psi = 6.895 KPa.

*Current LRFD development length is based on the ninth edition of the AASHTO LRFD specifications Eq. (5.9.4.3.2-1), including a 1.6 multiplier for member depths greater than 24 in.

†Current ACI development length is based on ACI 318-19 Eq. (25.4.8.1) and assumes that stress in prestressed reinforcement at nominal strength f_{ps} equals 260 ksi (1800 MPa).

‡Current LRFD transfer length of $60d_b$ is based on AASHTO LRFD specifications, ninth edition, section 5.9.4.3.1.

§Current ACI transfer length is based on ACI 318-19 Eq. (25.4.8.1) and assumes effective stress in prestressed reinforcement after losses f_{se} equals 170 ksi (1200 MPa).

Incorporating the recommendations into practice

PCI has started the process of working with its industry partners and ACI and AASHTO committees to incorporate this recommended practice into the governing design standards.

From the engineer's perspective, the new recommended practice will affect calculations for the fiber stresses at transfer and may control the end-region tension tie for the shear strength of the section. The end-region tension tie has more impact on the design in accordance with AASHTO LRFD specifications because of the use of the modified compression field theory. In the bridge community, many engineers recognize the critical nature of the tension tie in the end zones of girders and have expressed support to specify minimum-bond strand for typical beam products, whereas some engineers and producers have expressed support to specify high-bond strand for single-row shallow panels and products. The engineering community continues to evaluate the special cases that may require high-bond strand.

From the strand producer's perspective, the new recommended practice will require additional quality control testing for each plant to provide the ASTM A1081 pullout value for their specific strand. For strand producers, the challenge is that they often have strand that has been shipped to a producer that may not have the ASTM A1081 test results. If strand producers routinely produce and provide strand that meets the high-bond strand criteria but then find one test result that falls below the acceptance criteria, the strand may have been already used in a bond-critical product.

From the plant quality control perspective, the new recommended practice will require plants looking to maintain records in accordance with the PCI Plant Certification Program to acquire and retain the ASTM A1081 test results from their strand supplier and the specific plant. As published in the May–June 2020 *PCI Journal*[11] and effective July 1, 2020, the PCI Plant Certification Program approved addenda to the *Manual for Quality Control for Plants and Production of Structural Precast Concrete Products* (MNL-116)[12] and *Manual for Quality Control for Plants and Production of Architectural Precast Concrete Products* (MNL-117)[13] requiring at least annual ASTM A1081 test results for all strand sizes in use at the plant. The implementation of the recommended practice and the threshold limits into the PCI Plant Certification Program is ongoing.

Acknowledgments

The development of the recommended practice results from the efforts of many people within the precast concrete industry, in particular, the PCI Strand Bond Advisory Group consisting of chair Mike LaNeir, consultant Neil Hawkins, Ken Baur, Roger Becker, Jon Cornelius, Harry Gleich, John Lawler, Don Logan, Frank Nadeau, Andy Osborn, and Bruce Russell. Special acknowledgment is given to Roger Becker, former PCI vice president of technical services, who served on the initial task force in the early 1990s and championed many years of research and development into the recommended practice until his recent retirement. Becker often said he could not retire until the industry resolved strand bond, and we wish him well in his retirement.

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Abstract

The new PCI "Recommended Practice to Assess and Control Strand/Concrete Bonding Properties of ASTM A416 Prestressing Strand" specifies two new threshold limits for pullout tests conforming to ASTM A416 and new equations for the transfer and development length of prestressing strand. This article provides a summary of more than 30 years of research and knowledge advancement on the bond between concrete and prestressing strand related to the development of the new recommended practice. Discussions regarding the adoption and incorporation of the new recommended practice into structural design, strand production, and precast concrete fabrication and quality control practices are ongoing.

Keywords

ASTM A416, bond, development length, prestressing, pullout test, strand, strand production, structural design, transfer length.

Reader comments

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