Recommended practice to assess and control strand/concrete bonding properties of ASTM A416 prestressing strand

PCI Strand Bond Fast Team

Background

In July 2020, the PCI Technical Activities Council (TAC) approved the first version of the "Recommended Practice to Assess and Control Strand/Concrete Bonding Properties of ASTM A416 Prestressing Strand."[1] That document provided thresholds for bond performance of prestressing strand using the ASTM A1081[2] test and suggests new equations for transfer and development length. This recommended practice and ASTM A1081 focus strictly on the bond of untensioned strand in a standard mortar; they do not address the bond of tensioned strand in combination with a given producer's concrete mixture.

The Transportation Activities Council (TrAC) noted that there were questions in the bridge marketplace on implementing strand bond recommended practice and assessing bond for a given combination of tensioned strand and concrete. TAC allowed a task force to be created with the understanding that the effort did not change the selected thresholds for prequalifying pretensioning strand for the two classes of strand material using ASTM 1081.[3] These values were also discussed in a companion article published in *Aspire*.[4]

A fast team was assembled to update the recommended practice based on input from both the building and bridge communities. The members of the fast team were: Troy Jenkins, TrAC chair; Steve Seguirant, TrAC vice chair and TAC TrAC liaison; Mary Ann Griggas-Smith, TAC member; Oguzhan Bayrak, University of Texas; Clay Naito, Lehigh University; Kris Langer, Pennsylvania Department of Transportation and a member of the American Association of State Highway and Transportation Officials (AASHTO) Concrete Committee; and William Nickas, PCI staff. Jared Brewe of the PCI staff and Richard Miller, TAC chair, worked to resolve all TAC comments in this second edition of the recommended practice. These changes include valuable frequently asked questions and include resolution testing and sample computations that go beyond the ASTM 1081 testing of strand in a surrogate material.

This recommended practice includes extensive commentary, which is presented in italic type following the sections to which it applies.

Section 1—General requirements

1.1 Purpose

The purpose of this recommended practice is to define methods of strand bond testing and a design methodology that can be consistently applied by precast concrete producers, strand manufacturers, structural designers, owners, and their representatives. Precast concrete producers can thereby manufacture pretensioned products with an expectation of satisfactory product behavior consistent with associated structural designs. Repeatability, simplicity, and consistency of tests are important attributes of PCI's recommended practice. Quality control (QC) testing and quality assurance (QA) procedures recommended by or based on the methodologies referred to herein are expected to provide consistent results.

C1.1 This document presents the state-of-the-art and practice on strand bond and updates the first published recommended practice on strand bond.[1] The recommendations presented herein are applicable to seven-wire strands cast in typical commercially available concrete, including self-consolidating concrete. These provisions are also applicable to emerging new materials such as ultra-high-performance concrete (UHPC), albeit conservatively.

The intent of the document is to uniformly inform structural designers, strand manufacturers, precast concrete producers, and owners. In this way, strand bond–related processes from design to production of a product with due consideration given to QC and QA can be performed consistently. Further, this document describes processes and testing methods that can be used for fitness-for-service analysis.

With the aforementioned objectives, this document is organized as follows: Section 2 focuses on QC testing for strands used in pretensioned products. Section 3 presents the recommended transfer and development length expressions intended for use in design and analysis. These expressions differ from the legacy methods used in jurisdictional codes and specifications. They account for change in the strain state between service and strength load cases. Section 4 focuses on procurement. Testing methods for QC or QA at a precast concrete plant are covered in section 5. Section 6 focuses on recommendations for resolution evaluation in the event that QC testing and QA procedures produce conflicting results. Recommendations for fitness-for-service analysis are also included in section 6. Section 7 lists the key references.

Within the context of PCI's recommended practice, QC refers to the testing conducted by product manufacturers (strand manufacturers and precast concrete manufacturers) and QA refers to the testing conducted by owners or their third-party testing agencies to ensure the quality of the product they are purchasing. QC testing for strands is to be conducted by strand producers, and QA testing for strands can be performed by precast concrete producers as well as owners purchasing precast concrete products. QC testing for precast concrete products is to be performed by precast concrete producers. The owners purchasing those products can perform QA testing in their laboratories, or they can contract with third-party testing agencies to conduct QA testing on their behalf.

1.2 Standards

1.2.1 American Association of State and Highway Transportation Officials (AASHTO) AASHTO LRFDBDS-9, *AASHTO LRFD Bridge Design Specifications* ninth edition[5]

1.2.2 ASTM International ASTM A416, *Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete*[6]

ASTM A1081, *Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand*[1]

ASTM C39, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*[7]

1.2.3 American Concrete Institute (ACI) ACI 318-19, *Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19)*[8]

1.2.3 Precast/Prestressed Concrete Institute (PCI) PCI MNL 116-21, *Manual for Quality Control for Plants and Production of Structural Precast Concrete Products*[9]

Section 2—Qualifying strand for pretensioned products

This section contains guidance on QC testing and QA procedures for qualifying strands to be used in pretensioned products.

C2 *For the purposes of this recommended practice, QC refers to physical testing performed on the applicable combination of strand and cementitious materials, whereas QA refers to the collection and evaluation of the relevant test results to ensure compliance with the applicable requirements.*

2.1 Test method

ASTM A1081[2] is a QC test method for determining the bond capability of seven-wire prestressing strand conforming to ASTM A416.[6] Each test consists of six pullout test specimens for which an average test result is reported.

C2.1 *It is important to recognize that the ASTM A1081 test method underwent ruggedness testing within the PCI research program and due diligence study. Variability was noted. The surrogate material used in strand bond testing in accordance with ASTM A1081 is intended to focus attention on the bond capability that is inherent to a given strand type that has been manufactured in compliance with a given manufacturing* *technique. This ASTM A1081 test is not intended to replicate or be representative of a specific concrete that is used by a pretensioned product manufacturer.*

The use of surrogate material for the purpose of qualifying strand is defined by ASTM A1081 and accepted by the strand manufacturers. Further, such testing is intended to minimize scatter that could be associated with different concrete mixture types. However, changes in cement brands or sand sources in the surrogate material have resulted in variable results. While an individual buyer of ASTM A416 strand can specify a higher bond value from an ASTM A1081 test than specified in this document, the strand manufacturer may or may not be able to supply product that is responsive to those needs. While higher bond values obtained in a typical ASTM A1081 test may signal better performance in structural behavioral modes such as strand anchorage and shear strength, higher bond values may also result in an increased level of end-region cracking during the production of precast concrete elements. The end cracking at prestress transfer may be mitigated by strand debonding or additional transverse reinforcement in some applications.

2.1.1 Qualifying strands for pretensioned applications in accordance with ASTM A1081 should be part of the strand manufacturer's QC process. The results of ASTM A1081 tests should be consistent with values referenced in sections 2.2, 2.3, and 2.4.

2.1.2 In compliance with the PCI-certified plant's quality system manual (QSM), the precast concrete producer should obtain and archive the ASTM A1081 test results furnished by strand manufacturers.

2.2 Standard bond ASTM A1081 value for typical applications

The minimum ASTM A1081 value for qualifying strand to be used by a precast concrete producer in a pretensioned application should be a demonstrated bond strength equivalent to ½ in. diameter, 270 ksi strand exhibiting a six-quarter running average value of 14,000 lb, with no quarterly test average less than 12,000 lb. This type of strand is used in typical precast, prestressed concrete applications.

2.3 High bond ASTM A1081 value

The high bond ASTM A1081 value for strand to be used in pretensioned applications should be a demonstrated bond strength equivalent to ½ in. diameter, 270 ksi strand exhibiting a six-quarter running average value of 18,000 lb, with no quarterly test average less than 16,000 lb. This type of strand should be used in special applications where limited internal redundancy is achieved. Cases may include locations where fewer than three strands are located in a section, web, or stem.

2.4 Demonstrated bond strength

Demonstrated bond strength as noted in sections 2.2 and 2.3 should also apply to prestressing strand with a diameter other than ½ in. A standard bond strength test should be conducted on 0.6 in. diameter strand in accordance with ASTM A1081. A nonstandard bond strength test should be conducted for other diameter strands following ASTM A1081 procedures. Equivalency is determined in accordance with Eq. (2.4).

$$\text{bond strength equivalent} = (\text{specified ½ in. diameter value}) \times 2 \times d_b \tag{2.4}$$

where

d_b = strand diameter, in.

C2.4 *ASTM A1081-21 specifies the test specimen as nominal strand diameters of 0.500. or 0.600 in. The application to other strand diameters is used as a nonstandard test following the same specimen preparation and test protocols.*

Demonstrated bond strength is dependent on the surface area of the strand in the test. Eq. (2.4) is based on a ratio of the strand surface area to the nominal ½ in. diameter strand used in establishing the values in sections 2.2 and 2.3. The values listed in ***Table C2.4*** *are calculated from Eq. (2.4) and are intended for qualifying and purchasing of strands for use in pretensioned concrete applications.*

ASTM A1081 testing involves the use of a surrogate material.

Table C2.4. Demonstrated bond strength equivalents

Strand designation		⅜	7⁄16	½	½ special	9⁄16	0.6	0.62	0.70
Nominal strand diameter, in.		0.375	0.438	0.500	0.520	0.563	0.600	0.620	0.700
Standard bond (2.2)	Six-quarter running average, lb	10,500	12,300	14,000	14,600	15,800	16,800	17,400	19,600
	Minimum quarterly test average, lb	9000	10,500	12,000	12,500	13,500	14,400	14,900	16,800
High bond (2.3)	Six-quarter running average, lb	13,500	15,800	18,000	18,700	20,300	21,600	22,300	25,200
	Minimum quarterly test average, lb	12,000	14,000	16,000	16,600	18,000	19,200	19,800	22,400

The testing is intended to demonstrate to the precast concrete producer that the QC practices of the strand manufacturer are consistent and repeatable.

Section 3—Design

3.1 Development length

The estimated shortest strand development length should be determined in accordance with Eq. (3.1) for elements with concrete release strengths not less than 3500 psi and strand meeting at least the requirements of section 2.2.

$$\ell_d = \left(\frac{3800}{\sqrt{f'_{ci}}} + \frac{7100}{\sqrt{f'_c}}\right) d_b \geq 100 d_b \quad (3.1)$$

where

ℓ_d = development length, in.

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

f'_c = design concrete strength, psi

d_b = strand diameter, in.

C3.1 *The development length from Eq. (3.1) is based on National Cooperative Highway Research Project (NCHRP) report 603,* Transfer, Development, and Splice Length for Strand/Reinforcement in High-Strength Concrete.[10] *The development length equations in the 1995 edition of the* AASHTO LRFD Bridge Design Specifications[11] *and ACI 318-19*[8] *are based on the change in strain between service and strength load cases. The 2009 AASHTO LRFD specifications*[12] *includes multipliers from 1.0 to 1.6, depending on member type and depth. These design specifications and code will generally govern above this value and may be used.*

3.2 Transfer length

The estimated long-term transfer length should be determined in accordance with Eq. (3.2) for products with release strengths not less than 3500 psi.

$$\ell_{tr} = K\left(\frac{3800}{\sqrt{f'_{ci}}}\right) d_b \geq 40 d_b \quad (3.2)$$

where

ℓ_{tr} = transfer length, in.

K = 1.6 for strand meeting the requirements of section 2.2
= 1.0 for strand meeting the requirements of section 2.3

K is permitted to be linearly interpolated for strand between the requirements of sections 2.2 and 2.3 for evaluation purposes.

C3.2 *The transfer length from Eq. (3.1) is based on NCHRP report 603.*[10] *The 2009 AASHTO LRFD specifications*[12] *has used simplified computations for transfer length based on* 60d_b *for both the service and strength load cases. They have not included a* K *value as shown. This simplification may be used by the designer with the understanding that use may yield early-age concrete stresses that could exceed the cracking strength in the top flange in the end zones of beams and girders. Mild steel will control the size of the cracks but will not lower the stresses in the concrete.*

3.3 Transfer length at prestress transfer

For stress calculations at prestress transfer and for shipping and handling, the transfer length in Eq. (3.2) should be used with $K = 0.8$.

Section 4—Purchasing

Purchase orders for prestressing strand intended for use in pretensioned products should require evidence of quarterly testing. Plants should validate reported values though QA testing of prestressing strand on an annual basis.

C4 *This QC reporting by the strand producers should be validated in a quality assurance process that employs independent testing from a qualified laboratory.*

4.1 Evidence of quarterly testing

Evidence of quarterly ASTM A1081 testing by the strand manufacturer should be provided for all strand diameters and shall correspond to the plant where the strand was produced prior to strand shipment. Test values should meet or exceed the requirements of sections 2.2 through 2.4, as specified on the purchase order.

C4.1 *Evidence of demonstrated bond strength is required for all strand sizes by section 2.4. For strand sizes other than 0.500 and 0.600 in., ASTM A1081 testing is used as a non-standard test.*

4.2 Validation testing

Annual validation testing of reported ASTM A1081 values should be performed for QA. Test values should meet or exceed the values of sections 2.2 through 2.4 and are not required to meet the manufacturer's reported values.

Section 5—Quality control testing at the precast concrete plant

The PCI-certified plant's QSM will establish a schedule for QC testing using one of the methods specified in section 5.1 of this recommended practice. For each concrete mixture in use, the testing should not exceed annually or when concrete mixture changes, whichever is shorter. For each strand type in use, the testing shall be conducted when strand supplier changes.

C5 The precast concrete producer should conduct a task hazard analysis consistent with plant operations and develop adequate safety precautions to run the test procedures presented herein.

5.1 Quality control testing methods

In compliance with the PCI-certified plant's QSM, precast concrete producers are required to run one of the QC tests described in this section to assess the strand bond quality in pretensioned products that are being manufactured at a given plant. The pretensioned strand block pullout test and the strand draw-in test are deemed permissible QC tests. The test specimens are fabricated using standard procedures of the precast concrete producer. These standard procedures include the tensioning and detensioning methods, concrete mixture design, concrete consolidation techniques, curing condition, and curing duration.

C5.1 *Compliance of the strand manufacturer's ASTM A1081 test results with the values referenced in sections 2.2 to 2.4 is necessary but not sufficient for acceptance of pretensioned products. Since the surrogate material used in ASTM A1081 testing is not intended to replicate the concrete that is used in a precast concrete plant, additional QC testing is necessary. QC testing at a precast concrete plant is needed to verify the bond quality between the strand and surrounding concrete. The concrete mixture designs used at a precast concrete plant have been demonstrated to influence the bond behavior of the strands in precast concrete products.*[13]

5.1.1 The pretensioned strand block pullout test consists of a tension pullout of the strand from a concrete block. The pullout force and end slip are measured to quantify the bond capacity as detailed in section 5.2.1.

C5.1.1 *The test procedure is based on the Pennsylvania Department of Transportation's Test Method 630,*[14] *which was developed and is summarized by Naito, Cetisli, and Tate.*[15]

5.1.2 The strand draw-in test consists of the measurement of strand slip from the cut face of a pretensioned block or component. The bond capacity is computed from the measured amount of draw-in, as detailed in section 5.2.2.

C5.1.2 *The draw-in test approach is based on the concepts developed by Anderson and Anderson.*[16]

5.1.3 Any test that provides quantitative measurement of bond strength is permitted, provided it is accepted as part of the PCI-certified plant's QSM.

C5.1.3 *As new methods of testing become available, this section is intended to permit the use of additional test methods that will provide quantitative measurements of bond strength of strand in plant conditions similar to the tests described in sections 5.1.1 and 5.1.2. For example, for plants that routinely produce pretensioned products that are sawn to length after casting, draw-in measurements on such products can be used in lieu of the specimens described in section 5.2.2.*

5.2 Quality control testing of strand using plant-supplied materials

The strand bond quality in the precast concrete product is evaluated with the tests recommended in this section. The test procedures are given in sections 5.2.1 and 5.2.2.

C5.2 *These test methods are intended to be used to assess the adequacy of bond between concrete and prestressing strand using production concrete mixtures and as-delivered strand under plant fabrication conditions. The test methods provide a quantitative measure of bond strength and allow for identification of potential bond problems due to changes in strand surface conditions, concrete mixture proportions, concrete consolidation, or changes in production methods.*

5.2.1 The pretensioned strand block pullout test procedure quantifies the bond quality of strand used in pretensioned concrete applications by means of a destructive pullout test of a strand from a concrete prism. The average of three pullout tests is used to determine performance.

5.2.1.1 The molds for the test specimen should measure 6.5 in. wide × 12 in. deep (**Fig. 5.2.1.1**). A 10% tolerance on dimensions is allowed. The specimen length is equal to the bonded length L_b plus an additional 2 in. of unbonded length.

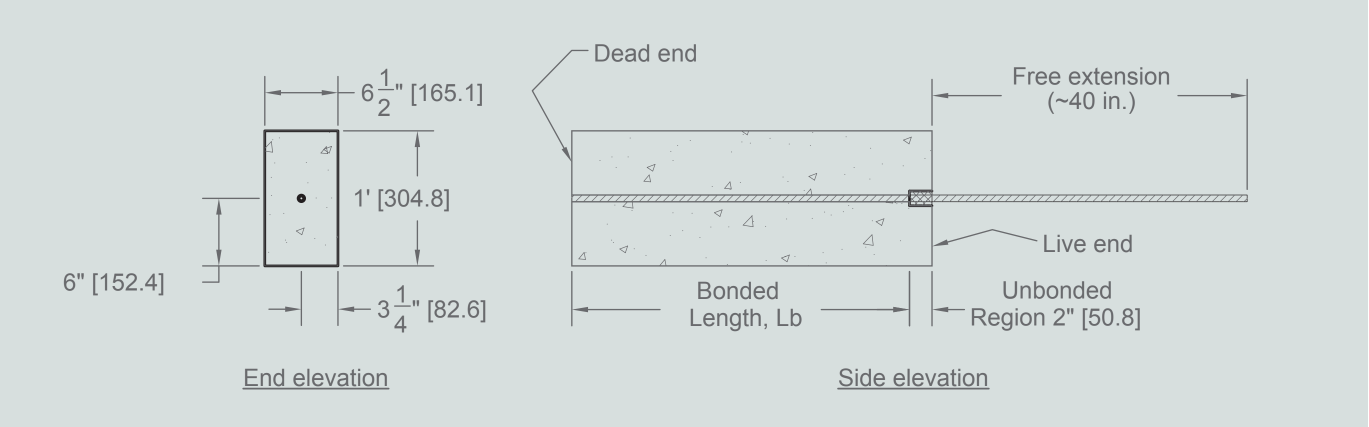

Figure 5.2.1.1. Strand block pullout test specimen.

The molds should be made of steel or wood and allow for easy removal after fabrication. The molds should be made watertight after assembly around the prestressed strand. Special care should be taken to seal areas where the strand extends from the mold. The molds should be designed to hold the strand at the center of the cross section.

C5.2.1.1 *The bonded length of the strands is equal to the transfer length of 60 strand diameters, in accordance with the ninth edition of the AASHTO LRFD specifications[5] article 5.9.4.3.1, rounded down to the nearest 0.5 in. The bonded lengths are tabulated relative to different strand diameters in* ***Table C5.2.1.1****. With a bonded length equal to the transfer length, it is assumed that the strand will slip before material failure of the strand occurs. In cases of high-quality concrete and high-quality strand bond condition, it is possible that the strand may fracture first. For these cases, the results will provide a lower-bound estimate of the bond capacity.*

5.2.1.2 The movement of the strand with respect to the concrete should be measured on the rear (dead) end. A dial gauge or displacement transducer with a graduation of 0.001 in. and a minimum stroke of 0.5 in. should be used. The load should be measured with a calibrated load cell in line with the strand being tested. Use of a jack pressure gauge is not recommended unless the gauge has been calibrated with a load cell and provides a resolution of ±20 lb.

5.2.1.3 The testing apparatus should consist of a through-hole hydraulic jack or universal testing machine, a reusable strand chuck, and a bearing plate. The bearing plate should have an adequate bearing area to prevent crushing of the concrete surface. The hydraulic jack should have a controller that allows for a smooth load increase of 20 kip/min. A schematic of a usable testing configuration is shown in **Fig. 5.2.1.3**. The jack should have a minimum stroke of 4 in. to allow for full pullout.

C5.2.1.3 *The loading apparatus should be supported to ensure that there is clearance between the strand and the center hole ram. Alignment of the strand within the ram is essential to perform a successful test.*

5.2.1.4 The test specimens should be cast in a horizontal orientation on the precast concrete plant's prestressing bed around the stressed strand. An initial jacking stress of 75% of the strand ultimate strength is recommended; however, other standard plant jacking stresses are also acceptable. No additional reinforcement should be used in the test specimen. If possible, the specimens should be situated at the end of the strand run, in line with a precast concrete element that is being fabricated. Adequate free strand length should be provided on the unbonded end to allow for jacking. (A length of 40 in. is recommended.)

5.2.1.5 Placement, consolidation, curing, and detensioning methods should conform to standard plant practice as applicable to the type of concrete being used. If a range of jacking stresses are used in the plant, the highest strand stress should be used for the test.

5.2.1.6 PCI MNL 116[9] qualification testing requirements should be met to determine the compressive strength of the concrete at transfer and at the time of testing. The cylinders are prepared and cured so as to be representative of the test

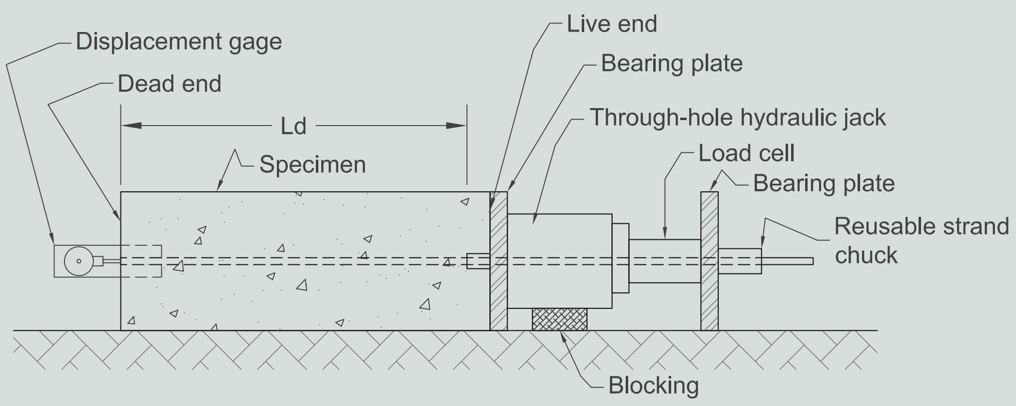

Figure 5.2.1.3. Strand block pullout test setup.

Table C5.2.1.1. Strand block pullout test specimen dimensions

Strand designation	⅜	7⁄16	½	½ special	9⁄16	0.6	0.62	0.70
Nominal strand diameter, in.	0.375	0.438	0.500	0.520	0.563	0.600	0.620	0.700
Bond length L_b, in.	22.5	26.0	30.0	31.0	33.5	36.0	37.0	42.0
Specimen length, in.	24.5	28.0	32.0	33.0	35.5	38.0	39.0	44.0

specimen. In addition, all qualification requirements in PCI MNL 116 should be met.

5.2.1.7 The initial prestress should be transferred in accordance with plant procedures for a given strand size, concrete mixture, and pretensioned product.

C5.2.1.7 *The intention of the test is to examine the performance of the strand bond when used in standard plant operations. It is important to use the same detensioning method in the test procedure that is used in plant production. Consequently, standard plant detensioning procedures should be used. Those procedures may involve flame cutting of strands, gradual detensioning, or other methods. It is expected that faster detensioning will result in greater strand bond damage prior to testing. If multiple methods of detensioning are used by the precast concrete producer, the fastest prestress transfer method should be used for the test.*

5.2.1.8 The release strength of the concrete should conform to the applicable design specifications.

C5.2.1.8 *For producers using different release strengths for different products, use of the minimum release strength in the strand bond test is recommended. Additional tests may be performed to determine product-specific bond strength values.*

5.2.1.9 After release of prestress, the strand should be cut flush with the surface of the specimen at the dead end and a 40 in. length of strand should be left on the live end (debonded side). The cut side should be ground flat with an abrasive wheel to provide a smooth bearing surface for the displacement measurements.

5.2.1.10 Testing of the specimens will take place within 24 hours after release. Pullout tests of the three specimens will be conducted sequentially over a duration of less than 2 hours to ensure consistency in concrete strengths.

5.2.1.11 The specimens are tested in the horizontal position. The displacement gauge is attached to the strand at the dead end of the specimen (Fig.5.2.1.3). At the dead end of the specimen, the displacement gauge is attached to one of the outer strand wires.

C5.2.1.11 *Avoid the inner wire for displacement measurement as relative slip may occur between the inner and outer wires of the strand, adversely affecting the accuracy of the measurement.*

5.2.1.12 The jack and bearing plates are supported with blocking prior to loading to ensure that the strand is centered in the test setup. Apply a load at rate of 20 kip/min. A 10% tolerance on the loading rate is permitted.

C5.2.1.12 *Take proper safety precautions against potential flying debris that may be generated during failures.*

5.2.1.13 Record the applied load (in pounds) and displacements regularly such that a minimum of 10 points are recorded prior to a dead end displacement of 0.10 in. Record the load to the nearest pound and the displacement to the nearest 0.001 in. Note the load level F_u when the dead end displacement is 0.10 in. Continue recording until one of the the following is met:

- a 25% decrease in load is measured
- the strand fractures
- a displacement of 0.5 in. is measured on the dead end

C5.2.1.13 *The applied load at dead end slip of 0.10 in. should be measured accurately. The initial slip may occur abruptly, so manual measurements should include a record of the load prior to the initiation of slip. A minimum of 10 points is required. Note that some of the points may consist of a load reading and a zero-slip measurement.*

5.2.1.14 Bond quality is computed relative to estimated development lengths measured for the chosen concrete properties and strand type. The estimated minimum length to fracture the strand L_{ult} should be computed according to Eq. (5.2.1.14).

$$L_{ult} = \frac{f_{pu} \times A_{ps}}{F_u} \times L_b \tag{5.2.1.14}$$

where

L_{ult} = estimated minimum length to fracture the strand, in.

f_{pu} = minimum tensile strength of strand, ksi

A_{ps} = area of strand, in.^{2}

F_u = average measured force corresponding to 0.10 in. slip at dead end of three specimen, kip

L_b = bonded length of strand, in.

C5.2.1.14 *The bonded length of strand in the pretension pullout test is less than the code-specified strand development length. This test is intended to provide estimates of the minimum development length. The length calculated by Eq. (5.2.1.14) can be taken as the best estimate for in situ development length for the particular strands and concrete used to fabricate a precast concrete component. For fitness-for-service evaluations, these estimates should be taken as more-representative values than those obtained using Eq. (3.1). The value computed using Eq. (5.2.1.14) can be compared with the governing code or Eq. (3.1). Resistance values below the governing code equation indicate that the pretensioned fabrication conditions exceed code estimates. Values greater than the governing code equations indicate that code-based development length may not be achieved using the tested strand and concrete. For the latter case, the development lengths should be based on the measured resis-*

tance values computed using Eq. (5.2.1.14).

While this test is intended to assess the bond quality for development of strands, if L_{ult} is less than or equal to that calculated in accordance with Eq. (3.1) or the code development length, it is reasonable to assume that the transfer length will also be acceptable.

5.2.1.15 The value computed using Eq. (5.2.1.14) can be compared with the governing code or Eq. (3.1). Resistance values below the governing code equation indicate that the pretensioned fabrication conditions exceed code estimates. Values greater than the governing code equations indicate that code-based development length may not be achieved using the tested strand and concrete. For the latter case, the development lengths should be based on the measured resistance values computed using Eq. (5.2.1.14).

5.2.2 The strand draw-in test procedure quantifies the bond quality of seven-wire strand used in prestressed concrete applications by means of measuring strand slip from a cut face of a pretensioned component or prism.

***C5.2.2** Pretensioning is made possible by casting concrete around stressed strands. When prestress is transferred to concrete, strands tend to slip, enlarge in diameter, and wedge into surrounding concrete with a mechanism known as the Hoyer effect. By assuming a linear variation of stress in the strand from zero at the cut face to the initial prestress at the calculated transfer length, this test method allows for quantification of the quality of bond.*

5.2.2.1 The test specimens may consist of products being fabricated at the precast concrete plant (for example, hollow-core slabs) for use in a structure. Alternatively, a representative concrete prism should be fabricated. The molds for the prism test specimen measure 6.5 in. wide × 12 in. deep. The specimen length is at least $240d_b$. The molds are designed to hold the strand at the center of the cross section.

5.2.2.2 The movement of the strand with respect to the concrete is measured on a cut face. A depth gauge with an accuracy of at least 0.016 in. is required. An example of a device used to measure strand slip is shown in **Fig. 5.2.2.2**. Measurements are taken only to the outer wires of the strand since the center wire is not in contact with the concrete and is not an indicator of strand bond.

5.2.2.3 The alternative test specimens are cast in a horizontal orientation on a precast concrete plant's prestressing bed around the stressed strand. An initial jacking stress of 75% of the strand ultimate strength is recommended; however, the standard plant jacking stress is also acceptable. No additional reinforcement is used in the test specimen. If possible, the specimens are situated at the end of a strand run, in line with a precast concrete element that is being fabricated.

5.2.2.4 Placement, consolidation, and curing methods should conform to standard plant practice as applicable to the type of concrete being used. If a range of jacking stresses are used in the plant, the highest strand stress should be used for the test.

5.2.2.5 PCI MNL 116[9] qualification testing requirements should be met to determine the compressive strength of the concrete at transfer of prestress. The cylinders are prepared and cured so as to be representative of the test specimen. In addition, all qualification requirements in PCI MNL 116 should be met.

5.2.2.6 The initial prestress should be transferred in accordance with plant procedures for a given strand size, concrete mixture, and pretensioned product.

5.2.2.7 The release strength of the concrete should conform to the design application.

5.2.2.8 The specimens are cut at midspan. The draw-in of the strand is measured from both cut faces to the nearest $\frac{1}{64}$ in. The average draw-in of the outer wires on each face is determined. The average of the two face measurements is the average draw-in value Δ_s. Measurements should be taken within 24 hours of saw cutting.

5.2.2.9 A maximum amount of draw-in should be estimated from the transfer length assumed in design in accordance with Eq. (5.2.2.9).

$$\Delta_{s,max} = \frac{L_{ti} f_{pi}}{2E_{ps}} \qquad (5.2.2.9)$$

where

$\Delta_{s,max}$ = maximum allowable draw-in, in.

L_{ti} = transfer length used in design, in.

f_{pi} = initial stress in strand at transfer, ksi

Figure 5.2.2.2. Strand draw-in measuring device.

E_{ps} = elastic modulus of strand, ksi

C5.2.2.9 *The maximum draw-in is computed based on the assumption that the stress in the strand at the cut face is zero and the stress linearly increases to the initial prestress. The average differential strain over this length is thus equal to* $f_{pi}/2E_{ps}$.

This test is intended to estimate a maximum draw-in in accordance with Eq. (5.2.2.9). This value can be taken as a best estimate for particular strands and concrete used to fabricate a precast concrete product. For fitness-for-service evaluations, these estimates should be taken as more-representative values than those obtained using code equations.

This test is intended to assess the bond quality for transfer of prestress. However, if the draw-in is less than or equal to that calculated in accordance with Eq. (5.2.2.9), it is reasonable to assume that the development length will also be acceptable.

5.2.2.10 When average draw-in values exceed the maximum calculated in accordance with Eq. (5.2.2.9), further evaluation of strand bond and its impact on the design should be undertaken.

C5.2.2.10 *Such evaluations can include revisiting the ASTM A1081 testing of the specific strand used or evaluation of the impact of increased transfer and development lengths on the specific product design.*

Section 6—Resolution evaluation

6.1 Purpose

Resolution evaluation may be used when results from QC and QA testing contradict each other. Otherwise, resolution evaluation is not necessary. Governing aspects of structural design control the type of resolution evaluation that is required.

6.1.1 If the ASTM A1081 test results reported by the strand manufacturer or the QA testing agency do not meet specified requirements, the precast concrete producer should immediately stop production of precast concrete products using that strand and save some of the strand in question. The precast concrete producer should then cast six specimens per section 5.2.1 or 5.2.2 for evaluation.

C6.1.1 *It is prudent for resolution to occur before shipping and erection commences.*

6.2 Strand bond evaluation

6.2.1 For cases in which the development or transfer lengths (Eq. [3.1] or [3.2]) control the design, and QC and QA testing in accordance with sections 2 and 5 produce conflicting results or conclusions, the results produced by the tests recommended in sections 5.2.1 or 5.2.2 should be taken as the determining value. The actual concrete and strand interaction seen in tests recommended in section 5 are more representative of the structural behavior of the precast concrete product.

6.2.2 In cases where the design calculated development length and transfer length are not controlling the service and strength design at a section, strand bond quality may not have any impact on fitness-for-service. For these cases, the bond strength may not meet the standard ASTM A1081 value of sections 2.2, 2.3, and 2.4, but the results produced by the test methods of section 5 may be acceptable as approved by the owner.

C6.3 *Transfer and development lengths for the specific strand and concrete combinations can be estimated from the test methods of section 5.*

Section 7—References

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Frequently Asked Questions

Q1: Does PCI's recommended practice document address the quality control (QC) guidance that can be used by strand manufacturers?

A1: Yes. Section 2 of this document provides answers for these questions by focusing on QC testing for strands used in pretensioned products.

Q2: Does PCI's recommended practice document provide design guidance for transfer length and development length calculations?

A2: Yes. The recommended transfer and development length expressions are presented in section 3.

Q3: Does PCI's recommended practice document provide guidance for strand procurement?

A3: Yes. Section 4 focuses on procurement.

Q4: Does PCI's recommended practice document include guidance that is sensitive to different types of concrete and different types of designs that call for a spectrum of concrete compressive strengths at prestress transfer?

A4: Yes. The transfer length and the development length expressions included in Section 3 cover all types of concrete resulting in different compressive strengths at prestress transfer and 28 days.

Q5: Does PCI's recommended practice document address development length?

A5: Yes. The development length expression presented in section 3 represents the state-of-the-art design expression developed in a study funded by National Cooperative Highway Research Program. This expression is more versatile than the design expressions included in *AASHTO LRFD Bridge Design Specifications* and ACI 318-19, and for most practical range of variables, it provides comparable development length estimates. These legacy methods used in the jurisdictional codes account for change in strain between service and strength load cases.

Q6: Does PCI's recommended practice document address QC issues at a precast concrete plant?

A6: Yes. Testing methods for QC at a precast concrete plant are covered in section 5.

Q7: Does PCI's recommended practice document address quality assurance (QA) issues for the owners?

A7: Yes. Testing methods for QA at a precast concrete plant are covered in section 5.

Q8: Does PCI's recommended practice document address the conflicts that may arise during QC and QA testing?

A8: Yes. Section 6 focuses on recommendations for resolution evaluation in the event that QC testing and QA procedures produce conflicting results.

Q9: Does PCI's recommended practice document address fitness-for-service analysis?

A9: Yes. Recommendations for fitness-for-service analysis are included in section 6.

Q10: Should strand manufacturers hire a laboratory to independently perform periodic ASTM A1081 tests?

A10: Some strand producers perform ASTM A1081 testing as part of their in-house QC process and occasionally calibrate their system by performing a parallel test at an accredited laboratory. If an owner or precast concrete manufacturer elects to retain a third-party testing facility to perform ASTM A1081 testing, they should not use the same testing laboratory used by the strand producer.

Q11: Should the precast concrete producer hire an independent laboratory to periodically perform ASTM A1081 testing as a QA measure for the information the producer is receiving from their strand supplier?

A11: Some precast concrete producers, as part of their quality systems manual (QSM), may require ASTM A1081 testing to verify information provided by the strand supplier. Other precast concrete producers harvest a strands sample(s) and store it based on delivered strand lot size and product type for future testing in the event that strand bond issues manifest themselves, in compliance with their internal QSM.

Q12: Should the precast concrete producer perform ASTM A1081 testing or testing using the methods (pretensioned strand block pullout test or strand draw-in test) of this PCI recommended practice as part of the producer's daily QC program?

A12: No. Daily QC testing is not the intent of this recommended practice. Instead, this recommended practice requires the testing described herein to occur during the initial qualification program for each concrete mixture. It also includes reconfirmation annually through a process to verify that the plant's concrete mixtures and the strands continue to perform as intended. This periodic verification does not need to occur for every prequalified concrete mixture and every strand supplied to the plant, but it should represent the full spectrum of strands used and all types of concrete mixtures used in pretensioned products produced during the preceding quarter. Once the initial concrete mixture design has been approved with the specific supplier of the strand, random verification testing is intended to reconfirm the original performance is still met, as intended. It has been noted that moving from Type III cements to portland limestone cements has caused changes in bond characteristics.

Q13: If a suspect strand has been identified after the pretensioned product has been cast, what tests should or should not be performed?

A13: Because the root cause is unknown, the ASTM A1081 testing on any strand from that same lot and reel can be appropriate. The ASTM A1081 tests will give an indication regarding the purchase compliance by using the surrogate material, not the actual concrete the strand is cast in. Using the stored samples and strand material from the same reels, when/if possible, is the best approach to identify the root cause. However, this approach will require using a sample of strand from the same manufacturer produced in the same lot. The pretensioned strand block pullout test should be performed for development length fit-for-service decisions and can be used for reasonable assurance of transfer length issues. The strand draw-in test provides direct information on transfer length and can be used for reasonable assurance for development-length issues. It is important to note that standard-bond strand and other strand bond testing—such as ASTM A981, *Standard Test Method for Evaluating Bond Strength for 0.600-in. [15.24-mm] Diameter Seven-Wire Steel Strand, Grade 270 [1860], Used in Prestressed Ground Anchors*—and ASTM A1081 tests have reported a drop in bond strength when using portland limestone cement rather than Type III cement. (ASTM A981 does not use sand.) A recently commissioned study by the U.S. Army Corp of Engineers (ACOE) is underway and was expected to be completed in the third quarter of 2023. The early ASTM A981 test results from this effort reinforce the need for strand to be tested in the actual concrete mixture, rather than the surrogate material used in ASTM A1081. The initial results also indicate that the current thresholds set by this PCI recommended practice are valid for concrete mixtures employing Type III cement. Strand manufacturers and pretensioned concrete producers should monitor whether unintended consequences occur when cement types or suppliers change.

Q14: Why do the typical jurisdictional design procedures (*AASHTO LRFD Bridge Design Specifications*, ACI 318, and ACI/PCI 319) specify transfer and development lengths that are commonly longer than the minimum lengths determined by using the relevant expressions from this recommended practice?

A14: The testing for compliance using the pretensioned strand block pullout tests and the strand draw-in tests are based on known interdependencies. The jurisdictional design approaches include values for multipliers such as AASHTO LRFD section 5.9.4.3.2, including Eq. (5.9.4.3.2-1) for K (values of 1, 1.6, and 2.0), are generally based on other structural performance expectations established based on global performance and not the isolated (and complex) strand bond force transfer. These values are based on the strand classified as standard-bond strand.

Q15: When should the design specify high-bond strand instead of standard-bond strand?

A15: High-bond strand is reserved for special applications where a limited number of strands crosses a critical location. Designers, inspectors, and owners will find that the use of high-bond strand has adverse impacts at prestress transfer as it increases the quantity and widths of the cracks in the end regions. The rapidly transferred pretensioning forces in the end regions may require additional debonding to control cracking and additional debonding may challenge the anchorage of the tension tie needed to transfer axial (if any), flexural, and shear forces into the supports. Additional mild reinforcement may be used in cases where anchorage of the tension tie proves to be challenging with debonded strands. In this way, the widths of the tension cracks may be controlled.

Q16: Can the designer use the actual ultimate- and service-limit state demand-to-capacity ratio D/C of the actual pretensioned element to allow the use of strands with measured transfer and development lengths that do not comply with the governing code or the values calculated with expressions included in this recommended practice?

A16: Such practice is not recommended. Initial strand slippage is one aspect of the evaluation. Long-term values for transfer and development lengths have been documented to increase with increasing levels of microcracking and accumulated damage. The values for the PCI recommended practice are the most conservative values for the initial slippage, and they are deemed to provide consistent reliability over the long term.

Q17: Is it possible to predict ASTM A1081 test results by using the results from pretensioned strand block pullout tests or strand draw-in tests?

A17: No. Such an analysis is not possible. ASTM A1081 uses surrogate material in assessing bond quality, whereas the pretensioned strand block pullout tests and the strand draw-in tests employ the actual concrete in the pretensioned product. The values from the latter two tests do not directly translate to ASTM A1081 values.

Q18: When there is a conflict in strand testing results between ASTM A1081 and either the pretensioned strand block pullout tests or the strand draw-in tests, which results govern?

A18: Results from the pretensioned strand block pullout tests will govern for determination of development length, and based on the quality of bond observed in this test, it would be possible to estimate if there can be concerns related to transfer length. The strand draw-in test will govern for determination of transfer length, and based on the quality of bond observed in this test, it would be possible to estimate whether there could be concerns related to development length. With that said, the actual development length cannot be quantified with the strand draw-in test nor can the actual transfer length be quantified with the pretensioned strand block pullout test. Both tests provide direct information on the quality of bond between the strand and the concrete used in a pretensioned product. ASTM A1081 tests employ a surrogate material and do not inform the calculation of the transfer length or development length directly. Example calculations are provided to better inform this discussion.

Q19: Where can I find additional background information on the first edition of this PCI recommended practice?

A19: The necessary background information can be found in the following paper:

Osborn, A., M. Lanier, and N. Hawkins. 2021. "Bond of Prestressing Strand to Concrete." *PCI Journal* 66 (1): 28–48. https://doi.org/10.15554/pcij66.1-04.

Additional foundational work that has led to this current recommended practice can be found in the following publications:

Anderson, A. R., and R. G. Anderson. 1976. "An Assurance Criterion for Flexural Bond in Pretensioned Hollow Core Units." *ACI Journal Proceedings* 73 (8): 457–464. https://doi.org/10.14359/11087

Rose, D. R., and B. W. Russell. 1997. "Investigation of Standardized Tests to Measure the Bond Performance of Prestressing Strand." *PCI Journal* 42 (4): 56–80. https://doi.org/10.15554/pcij.07011997.56.80.

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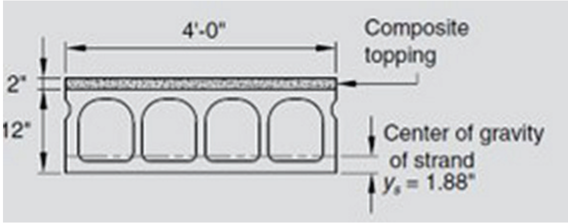
Osborn, A. E. N., J. S. Lawler, and J. D. Connolly. 2008. *Acceptance Tests for Surface Characteristics of Steel Strands in Prestressed Concrete*. NCHRP report 621. Washington, DC: National Academies Press. https://doi.org/10.17226/14206.

Q20: It appears that there is a long history on the use of the draw-in test for hollow-core components. Have there been tests using this approach for wet-cast products as well?

A20: In addition to the original work by Anderson and Anderson (1976), Rose and Russell showed a linear correlation between strand draw-in and transfer length through their work and that of other researchers on wet-cast components.

PCI recommended practice on strand bond example 1

A precast concrete producer is fabricating hollow-core sections (4HC12+2) that are reinforced with five ½ in. diameter, Grade 270 seven-wire strands meeting ASTM A416. The section is not bond critical and requires standard bond strand. The precast concrete section consists of the following:



Precast concrete (normalweight):

f'_c = 6000 psi

f'_{ci} = 4000 psi

E_c = 4700 ksi

Topping concrete (normalweight):

f'_c = 4000 psi

E_c = 3800 ksi

Prestressing steel:

f_{pu} = 270 ksi

f_{pi} = 202.5 ksi

f_{se} = 166.0 ksi

f_{ps} = 265.2 ksi

Quality control testing using plant-supplied materials is conducted to assess the adequacy of the bond between the concrete and the prestressing strand. Testing in accordance with section 5.2.1 of the recommended practice is conducted.

The pretensioned strand block pullout test is conducted. Three 6.5 in. wide and 12 in. deep block molds were fabricated at the end of the stand run and were subject to the same stressing, detensioning, and curing conditions as the hollow-core components. The bonded lengths of the specimens are 30 in. The following measured forces at 0.10 in. slip are recorded:

	Test 1	Test 2	Test 3	Average
F_u, kip	31.50	32.50	34.75	32.92

Determine whether the bond quality is adequate.

Solution

The estimated minimum length to fracture the strand can be computed in accordance with Eq. (5.2.1.14).

$$L_{ult} = \frac{f_{pu} \times A_{ps}}{F_u} \times L_b = \frac{250 \text{ ksi} \times 0.153 \text{ in.}^2}{32.92 \text{ kip}} \times 30 \text{ in.} = 37.6 \text{ in.}$$

In accordance with Eq. (3.1), the section has a required development length of:

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

$$= \max\left(\left(\frac{3800}{\sqrt{4000}} + \frac{7100}{\sqrt{6000}}\right)\times 0.5 \text{ in.},\ 100\cdot 0.5 \text{ in.}\right) = 75.9 \text{ in.}$$

The estimated minimum length to fracture the strand is less than the recommended development length. The bond quality of the strand in the application meets code requirements. As noted in commentary section C5.2.1.14, it is reasonable to assume that the transfer length will also be acceptable.

Prevailing code solution

The section was designed in accordance with ACI 318-19. Do the strand bond test results meet code requirements?

In accordance with ACI 318-19 Eq. (25.4.8.1):

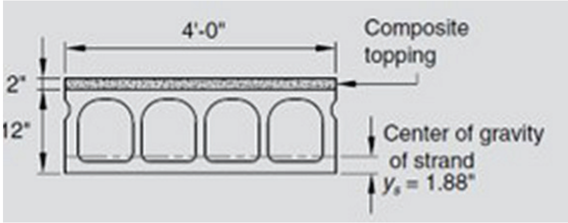
$$\ell_d = \left(\frac{f_{se}}{3000}\right)d_b + \left(\frac{f_{ps} - f_{se}}{1000}\right)d_b$$

$$= \left(\frac{166{,}000}{3000}\right)0.5 + \left(\frac{256{,}000 - 166{,}000}{1000}\right)0.5 = 77.3 \text{ in.}$$

The estimated minimum length to fracture the strand is less than the code-recommended development length.

PCI recommended practice on strand bond example 2

A precast concrete producer is fabricating hollow-core sections (4HC12+2) that are reinforced with ½ in. diameter, Grade 270 seven-wire strands meeting ASTM A416. The section is not bond critical and requires standard bond strand. The precast concrete section consists of the following:



Precast concrete (normalweight):

f'_c = 6000 psi

f'_{ci} = 4000 psi

E_c = 4700 ksi

Topping concrete (normalweight):

f'_c = 4000 psi

E_c = 3800 ksi

Prestressing steel:

f_{pu} = 270 ksi

f_{pi} = 202.5 ksi

f_{se} = 166.0 ksi

f_{ps} = 265.2 ksi

E_{ps} = 28,500 ksi

Quality control testing using plant-supplied materials is conducted to assess the adequacy of the bond between the concrete and the prestressing strand. Testing in accordance with section 5.2.2 of the recommended practice is conducted.

The strand draw-in test is conducted on cut sections of the hollow-core component. The following measurements are taken at 23 hours after cutting.

Draw-in, in.	Wire 1	Wire 2	Wire 3	Wire 4	Wire 5	Wire 6	Average
Left cut	5/64	4/64	3/64	4/64	8/64	7/64	0.081
Right cut	6/64	7/64	9/64	4/64	5/64	6/64	0.096

Determine whether the bond quality is adequate.

Solution

The estimated minimum transfer length from the pullout can be computed in accordance with Eq. (5.2.1.14).

$$L_{ti1} = \frac{f_{pi} \times A_{ps}}{F_i} \times L_b = \frac{202.5 \text{ ksi} \times 0.153 \text{ in.}^2}{32.50 \text{ kip}} \times 30 \text{ in.} = 28.6 \text{ in.}$$

The estimated maximum amount of draw-in can be computed in accordance with Eq. (5.2.2.9).

$$\Delta_{s,max} = \frac{L_{ti} f_{pi}}{2E_{ps}} = \frac{28.6 \text{ in.} \times 202.5 \text{ ksi}}{2 \times 28{,}500 \text{ ksi}} = 0.102 \text{ in.}$$

In accordance with section 5.2.2.8, the average of the two face measurements is:

$$\Delta_s = \frac{0.081 + 0.096}{2} = 0.089 \text{ in.}$$

The measured amount of draw-in is less than the maximum measured amount of draw-in allowed. The bond quality of the strand in the application meets code requirements for transfer length. As noted in commentary section C5.2.2.9, it is reasonable to assume that the development length will also be acceptable.

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Reader comments

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