Development of Un-Tensioned Pullout Tests to Determine the Bond Quality of Prestressing Reinforcements Used in Pretensioned Concrete Railroad Ties

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Abstract

An experimental program was conducted at Kansas State University (KSU) to evaluate the bond characteristics of prestressing wires and strands used in the manufacture of pretensioned concrete railroad ties. Un-tensioned pullout tests were conducted using both concrete and mortar mediums. The effect of prestressing steel surface condition on bond was evaluated by testing the bond in both the as-received and cleaned condition. A pullout test was developed (and subsequently adopted as ASTM A1096) that can be used to determine the bond quality of prestressing wires that are are in pretensioned concrete members. The pullout test specimens consist of a 4 in. outer-diameter tube with a total length of 8 in. and a steel plate welded to the tube bottom. An un-tensioned wire is held concentrically in the tube while a sand-cement mortar mixture is placed and allowed to cure. Specimens are tested when compressive strength of the mortar is between 4500 and 5000 psi. Pullout test results had excellent correlation with transfer lengths of similar wires when used to manufacture pretensioned concrete railroad ties.

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U.S. Department of Transportation
Federal Railroad Administration

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

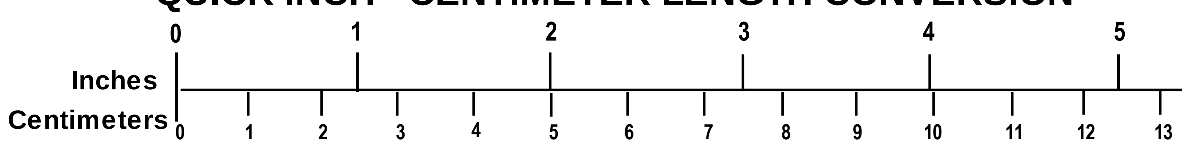
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact andor other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

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Executive Summary

This report summarizes work that is part of a larger project funded by the FRA titled "Quantifying the Effect of Prestressing Steel and Concrete Variables on the Transfer Length in Pretensioned Concrete Crossties." The project has the following Major Research Tasks:

Laboratory Phase

1) Pre-tensioned Concrete Prism Tests
2) Un-Tensioned Pullout Tests with Mortar
3) Tensioned Pullout Tests with Concrete
4) Precise Measurements of the Reinforcement and Indent Geometry
5) Performing Load Tests On The Pre-Tensioned Concrete Prisms

Plant Phase

6) Automated Device for Transfer Length Measurement
7) Measuring Transfer Lengths of Concrete Crossties at the Plant
8) Un-Tensioned Pullout Tests with Concrete

Joint Research Activities

9) Evaluation of Ties Installed in Track

The work presented herein specifically covers the following major research tasks:

Task 2) Un-Tensioned Pullout Tests with Mortar

Task 8) Un-Tensioned Pullout Tests with Concrete

Un-tensioned pullout specimen tests were conducted using both concrete and mortar mediums. The objectives of these tests were to identify the effect of reinforcement surface condition on bond, and to determine if a simple pullout test could be used to predict the transfer length in pretensioned concrete railroad ties. The effect of prestressing steel surface condition on bond was evaluated by conducting pullout tests with wires and strands in both the As-received and Cleaned condition. These tests revealed that the surface condition can have a significant effect on the bond quality of strands and smooth or very lightly-indented wires, but only a minimal effect on the bond of most indented wires used in the manufacture of prestressed concrete railroad ties in North America. The likely reason for this is that, for most indent wires, the indent geometry is the major component influencing the bond.

A standard pullout test was developed for 5.32-mm-diameter wires that can be used to ensure that adequately-bonding prestressing reinforcements are specified and supplied for use in concrete railroad ties. These pullout specimens consist of a 4 in. (100 mm) outer-diameter tube with a total length of 8 in. (200 mm) and a steel plate welded to the bottom of the tube. An un-tensioned 5.32-mm diameter wire was centered in the tube, and the sand-cement mortar was placed and allowed to cure. Specimens were tested when compressive strength of the mortar was between 4500 and 5000 psi (31.0 MPa and 34.5 MPa). Wire end-slip measurements in the

pullout tests had excellent correlation with transfer lengths of similar wires placed in concrete railroad ties.

The pullout test developed in this research program, and presented in Appendix I of this report, had excellent correlation with transfer lengths in pretensioned concrete railroad ties manufactured with the same reinforcements. This test method was adopted by ASTM with minimal changes in 2015 as Test Standard ASTM A1096 "Test Method for Evaluating the Bond Quality of Steel Wire for Concrete Reinforcement."

In addition to un-tensioned pullout tests in mortar, the researchers also conducted un-tensioned pullout tests in concrete during the Plant Phase of the study. These pullout tests with concrete also had good correlation with the transfer lengths in pretensioned concrete railroad ties manufactured with the same wire and concrete mix. However, the pullout test results with concrete were not as consistent as the pullout test results with mortar (larger coefficients of variation). Additionally, the pullout test results with concrete had a lower coefficient of determination, R^2, than the mortar pullout test results when compared directly with transfer length results.

1. Introduction

Prestressed concrete railroad ties are becoming increasingly popular in the United States, and are an essential component for higher speed railway lines. These concrete ties are intended to be more durable, environmentally friendly, and longer lasting than wooden railroad ties. However, many concrete ties crack and fail prematurely before their design life is achieved. In some cases, cracking has been linked to the bond performance of wires and strands used to reinforce concrete ties.

1.1 Background

In order for these prestressed concrete ties to have their maximum load-carrying capacity, the prestressing force must be fully introduced into the railroad tie at a location before the rail load is applied, as illustrated in the figure below. The length required to transfer the prestress force into the concrete member is referred to as the "Transfer Length", and is illustrated in Figure 1.

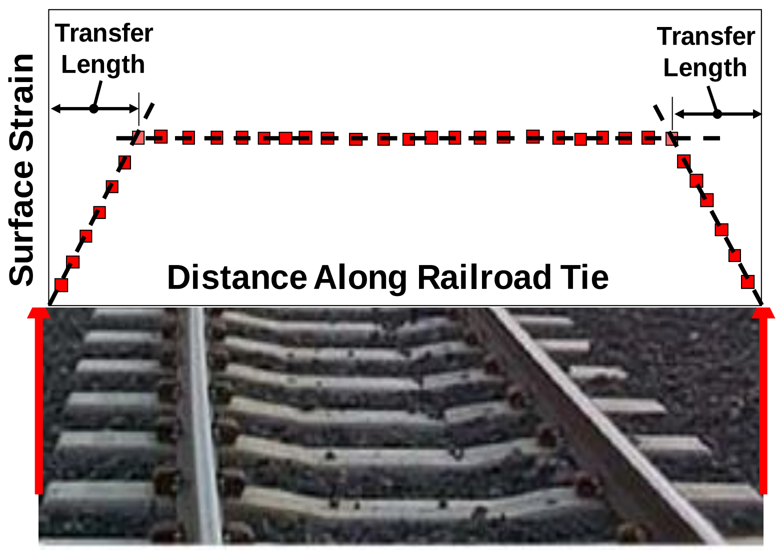


Figure 1. Illustration of the transfer length

Since the prestressed concrete ties are relatively short, and have extremely large impact loads applied near the member ends, most of the prestressed concrete railroad tie producers utilize indented prestressing wires or indented prestressing strands rather than traditional 7-wire smooth prestressing strands. It is generally understood that these indentations serve to improve the bond between the steel and the concrete and therefore reduce the transfer length.

However, because the broad application of these indented reinforcing steels has been so limited, current design codes in the United States do not yet address indented prestressing wire or indented strands in terms of recommended design assumptions for transfer and development length.

Moreover, there is currently not even a standardized indentation pattern (shape, size, depth of indent, etc.) that is utilized by all indented-wire manufacturers. Thus, the corresponding bond behavior of these different wires when placed in various concrete mixtures, in terms of average transfer lengths and typical variations, is essentially unknown.

Thus, there exists the need to determine and quantify the prestressing steel and concrete variables that affect the transfer length in prestressed concrete crossties, so that the proper performance of the ties can be ensured throughout their entire service life. These variables include the type of reinforcing (indented wires vs. indented strands), indent geometry, concrete composition and consistency, and the strength of the concrete at the time of de-tensioning.

In order for prestressed concrete ties to maintain full design capacity throughout their expected service life, prestressing force from steel must be fully introduced into the concrete before the rail load is applied at the rail seat. In general, the rail seat is located 21 inches from the end of the typical crosstie, meaning that the Transfer Length, or length required to transfer prestressing force into the concrete member, must be less than 21 inches. If the transfer length is larger than 21 inches, the concrete railroad tie will not have full design capacity for load application and may be susceptible to cracking (material failure). To ensure that prestressing force is fully transferred to the concrete, a consistent quality contact surface ("good bond") between the prestressing reinforcement and surrounding concrete is essential.

At the time of this study, indented 5.32-mm-diameter, low-relaxation prestressing steel wires are the standard reinforcement type used in most concrete railroad ties produced in the United States. However, some concrete tie manufacturers also utilize 3/8-in.-diameter, low-relaxation steel strands and still other manufacturers are investigating 5/16-in.-diameter low-relaxation steel strands. These smaller diameter strands (less than 0.5 in. diameter) can also be indented similarly to 5.32-mm-diameter wires.

In general, reinforcement indentations improve bonding between steel and concrete, but no standardized indentation pattern (shape, size, depth of indent, etc.) is currently utilized by all wire and strand manufacturers. Therefore, average transfer lengths and typical variations of bond caused by different concrete mixtures and indented reinforcements are essentially absent from the literature.

The railroad ties industry seeks to more fully understand bond performance. This knowledge can be gained by developing a reliable, repeatable, and reproducible quality control bond test to determine bond characteristics between various prestressing wires and strands. A quality control bond test would allow the industry 1) to become informed regarding the bonding performance of reinforcements with various indentation patterns, and 2) to specify the required bond performance of a reinforcement at the time of purchase. Furthermore, a quality control bond test would allow potentially poor-bonding reinforcements to be identified in the lab before they are used in concrete tie manufacturing plants. .

Currently, a pullout test exists to evaluate the bond of 0.5-in.-diameter and 0.6-in.-diameter strands (Ramirez and Russell, 2008), but no standard tests exist to quantify bond performance of smaller-diameter prestressing reinforcements that are used in the manufacture of concrete railroad ties. Therefore, a standardized test is needed to accurately quantify the bond of these smaller-diameter reinforcements.

This report presents results of an experimental testing program performed at Kansas State University (KSU) to develop a bond test for prestressing wires and small diameter strands. The work reported herein is part of a larger project titled "Quantifying the Effect of Prestressing Steel and Concrete Variables on the Transfer Length in Pretensioned Concrete Crossties" that was funded by the Federal Railroad Administration, LB Foster/CXT Concrete Ties, and the KSU University Transportation Center.

The developed test was verified by correlating the pullout data to transfer lengths measured on pretensioned concrete prisms that were fabricated using the same reinforcements. In addition, the pullout test data were compared with transfer length measurements obtained at the LB Foster/CXT Concrete Tie plant in Tucson, AZ to determine if the test could be used to predict the bond performance of the small-diameter prestressing steel reinforcements when used in concrete railroad ties.

1.2 Objectives and Testing Matrices

The objective of this testing program was to develop an un-tensioned pullout test method that could be used to predict the bond performance of small-diameter prestressing reinforcements when used to fabricate pretensioned concrete railroad ties. At the outset of the test program, it was determined that the ideal test should be have the following characteristics.

- Be able to differentiate between reinforcements with varying bond qualities
- Be repeatable within the same laboratory
- Be reproducible at different test sites
- Be relatively simple and inexpensive to conduct

In addition to investigating the bond performance of reinforcements with different indentation geometries, the test program also investigated the influence of reinforcement surface condition on bond. This was done by testing the reinforcements in both their As-received and Cleaned conditions.

The As-received specimens were used to evaluate the overall bond performance of the different reinforcements, which each contained some amount of surface contaminants due to the manufacturing process and possibly some weathering contaminants (rust) and/or other foreign materials that may have been introduced after manufacturing process. The Cleaned specimen tests were performed on the same reinforcements after removing all rust, oils, and surface lubricants with an acidic solution. These tests allowed the researchers to determine the bond performance that could be attributed directly to indent geometry.

1.2.1 Lab Phase: Wire and Strand Pullout Testing in Mortar

The test matrix for the wire and strand pullout tests performed in the lab is shown in Table 1**Error! Reference source not found.**. Each reinforcement type was tested six times and the results were averaged to determine the representative bond performance. The As-received and Cleaned pullout test results were then compared to the measured transfer lengths of accompanying pretensioned prisms using the same reinforcement types.

The pullout specimen geometry, including the specimen diameter and corresponding bond length, was determined through an iterative process that is included in Chapter 5. In the wire pullout test, bond performance models generated by the As-received and Cleaned pullout tests and accompanying pretensioned prisms were based on twelve different wires (labeled WA through WM) and the models were then scrutinized using a 13th wire (WM) from a different steel manufacturer. Although not directly included in the test development phase, this additional wire was used to verify the testing procedure and its accuracy for predicting bond performance. In Table 1 and through this report, both the prestressing steel manufacturer and reinforcement are given an anonymous letter designation.

The specimen geometry and bond length for the strand pullout test was also a prime concern in this test program, as the diameter of the strands used in concrete railroad ties is typically 3/8-in. or less. As previously noted, an un-tensioned pullout test already exists for 0.5-in. and 0.6-in. strands and is referred to as the Standard Test for Strand Bond (Ramirez and Russell, 2008). However, the Standard Test for Strand Bond test uses a 16-in. bond length, and it was not certain if the smaller-diameter wires could also use a similar bond length and still result in a pullout failure.

Note, the goal of a pullout test is to pull the reinforcement through the surrounding medium and therefore cause a bond failure. However, if a 16-in. bond length was used, then the small diameter strands might possibly reach their ultimate tensile strength prior to pulling through the surrounding medium. Thus, initial testing with strands was also conducted to establish the required bond length in the pullout specimens.

Table 1. Testing matrix of lab phase

				Number of test specimens		
	Reinforcement Manufacturer	Reinforcement Identification	Indentation Type	Transfer lengths (# of ends)	As-received un-tensioned pullouts	Cleaned un-tensioned pullouts
Wires	A	[WA]	Smooth	6	6	6
	A	[WB]	Chevron	6	6	
	A	[WC]	Spiral	6	6	
	B	[WD]	Chevron	6	6	
	B	[WE]	Spiral	6	6	6
	B	[WF]	Diamond	6	6	6
	C	[WG]	Chevron	6	6	6
	D	[WH]	Chevron	6	6	6
	E	[WI]	Chevron	6	6	
	E	[WJ]	Chevron	6	6	
	F	[WK]	4-Dot	6	6	
	F	[WL]	2-Dot	6	6	6
	G	[WM]	Chevron	6	6	6
	Wires Total:			**78**	**78**	**42**
Strands	A	[SA]	3/8" 7-Wire, Smooth	6	12	6
	A	[SB]	3/8" 7-Wire, Indented	6	12	6
	A	[SC]	5/16" 3-Wire, Smooth	6	12	6
	B	[SD]	3/8" 7-Wire, Indented	6	12	6
	C	[SE]	3/8" 7-Wire, Indented	6	12	6
	D	[SF]	3/8" 3-Wire, Indented	6	12	6
	Strands Total:			**36**	**72**	**36**

1.2.2 Plant Phase: Wire and Strand Pullout Testing in Concrete

Wire and strand pullout tests, performed in concrete, included un-tensioned pullout tests conducted at a manufacturing plant. A research team from Kansas State University (KSU) visited the LB Foster/ CXT Concrete Tie (CXT) plant in Tucson, AZ to measure transfer lengths in actual, non-prismatic concrete railroad ties. Pullout specimens were cast in addition to railroad ties from which transfer lengths were measured. Fifteen (15) different reinforcements, identical to the ones used for pullout and transfer length tests at KSU, were also for the plant phase. These reinforcements were taken from the exact same coil as the ones that were used in the KSU laboratory testing. Approximately 50 transfer length measurements and six pullout specimens were obtained for each reinforcement type.

The goal of this plant phase work pullout work was to determine if plant-cast pullout specimens in concrete would correlate to the transfer length measurements on concrete ties cast using the same concrete and reinforcement combination. The testing matrix for pullout tests performed in the plant is shown in Table 2.

Table 2. Testing matrix of plant phase

				Number of test specimens	
	Reinforcement Manufacturer	Reinforcement Identification	Indentation Type	Transfer lengths (# of ends)	As-received un-tensioned pullouts
Wires	A	[WA]	Smooth	49	4
	A	[WB]	Chevron	50	5
	A	[WC]	Spiral	47	4
	B	[WD]	Chevron	49	6
	B	[WE]	Spiral	48	6
	B	[WF]	Diamond	49	6
	C	[WG]	Chevron	49	6
	D	[WH]	Chevron	50	6
	E	[WI]	Chevron	50	6
	E	[WJ]	Chevron	47	6
	F	[WK]	4-Dot		
	F	[WL]	2-Dot	47	6
	G	[WM]	Chevron	49	6
	Wires Total:			**584**	**67**
Strands	A	[SA]	3/8" 7-Wire, Smooth	45	6
	A	[SB]	3/8" 7-Wire, Indented	50	6
	A	[SC]	5/16" 3-Wire, Smooth	48	4
	Strands Total:			**143**	**16**

1.3 Organization of the Report

Chapter 2 reviews informative, beneficial research in order to develop quality control pullout tests for steel prestressing wires and smaller diameter steel prestressing strands.

Chapter 3 details the preliminary setup for pullout testing at KSU, including reinforcements, reinforcement storage, cleaning procedure, and necessary machinery.

Chapter 4 discusses development, testing, results, and analysis of wire pullout tests performed at KSU.

Chapter 5 discusses testing, results, and analysis of strand pullout tests performed at KSU.

Chapter 6 reviews experimental pullout testing in concrete performed at the LB Foster/CXT Concrete Tie plant in Tucson, AZ, including testing, results, and test analyses.

Chapter 7 compares results of pullout tests performed in the lab (Chapters 4 and 5) to pullout tests performed in the plant (Chapter 6).

Chapter 8 summarizes conclusions and offers recommendations from this research project.

2. Literature Review

This chapter discusses relevant research concerning the development of quality control pullout tests for steel prestressing wires and smaller diameter steel prestressing strands. The first section presents research used to develop a pullout test for 0.5-in.-diameter strands, and the second major section reviews research on modeling and testing of 5.32-mm-diameter wires and smaller diameter strands.

2.1 0.5-in.-Diameter and Larger Strand Bond Testing

2.1.1 Introduction

Original transfer length equations listed in the American Concrete Institute (ACI) and the American Association of State Highway Transportation Officials (AASHTO) design requirements were established in the late 1950s and early 1960s using Grade 250 stress-relieved strand (Ramirez and Russell, 2008). Since then, Grade 270 low-relaxation strand has become the most commonly used strand for prestressing applications. A study performed by Cousins, Johnston, and Zia (1990) in the mid-1980s demonstrated that a large percentage of measured transfer lengths were larger those predicted from code equations (Ramirez and Russell, 2008).

Consequently, numerous research projects have investigated prestressing strand surface characteristics in order to quantify the inherent factors affecting a strand's transfer length. This work has led to the development of standardized tests that categorize the strand based on one parameter: "bond-ability." "Bond-ability" describes how well or how poorly a prestressing strand bonds to concrete or the mortar in which it is encased. Three standardized tests have been developed:

1. The Moustafa Test, or Large Block Pullout Test, was first introduced in 1992. This test pulls un-tensioned strands from large concrete specimens having a 24-in. x 24-in. cross-section (Logan, 1997; Ross and Russell, 1997; Ramirez and Russell, 2008).

2. The Post-Tensioning Institute (PTI) Bond Test, developed primarily for 0.6-in. strand in 1994 (Ramirez and Russell, 2008), was the basis the original NASP Bond Test. The PTI Bond Test pulls un-tensioned strands from a neat cement mortar, or mortar comprised of only cement and water but with no sand (Ramirez and Russell, 2008).

3. The current North American Strand Producers (NASP) Bond Test, known as the Standard Test Method for the Bond of Prestressing Strand, pulls un-tensioned strands from a sand-cement mortar (Russell, 2006; Ramirez and Russell, 2008). A refined version of this test subsequently became adopted as an ASTM standard (ASTM A1081) in 2012.

The goal of these three pullout tests is to provide an acceptance criterion that quantifies the "bond-ability" of various strands from strand manufacturers. Russell and Paulsgrove (1999b), in a study conducted for the North American Strand Producers (NASP), co1ncluded that "the NASP Bond Test has proven to be the most reliable test of the three" (Ramirez and Russell, 2008). Research that led to the development of the reliable strand bond pullout test is presented in the following sections.

2.1.2 History of Strand Bond Testing Since the Mid-1990s

2.1.2.1 Abrishami and Mitchell (1996)

Abrishami and Mitchell (1996) developed analytical expressions based on responses obtained from experimental results of bond stress vs. strand end-slip measurements. The researchers investigated "pullout" and "push-in" testing with the primary goal of developing analytical equations that would predict bond performance of a pullout specimen. They used finite elements to determine a governing differential equation to quantify bond stress as a function of the slip which, in turn, is a function of distance along the reinforcement.

For a pullout specimen, a tensile force was applied at the bottom of the reinforcement specimen. Boundary conditions were known since the strain in the concrete and steel must be equal to zero at the top face of the specimen. Similarly, the strain of the concrete and steel at the bottom face were known based on the principles of axial deformation. From the specimen geometry and governing differential equation relating bond stress, slip, and axial distance, the constants of integration were found and the top slip and bottom slip were quantified as a function of known parameters (length, Young's moduli, cross-sectional areas, and applied pullout force).

The average slip, taken as the average of the top and bottom strand movements, was then used to predict the pullout force required to produce that slip. Identical analysis was performed for a push-in specimen using appropriate boundary conditions, and the derived expressions were identical, as expected. This methodology was used a third time (again changing boundary conditions to appropriate values) for a combination pullout/push-in specimen. For the linear range, the derived expression was identical to the pullout and push-in cases.

Eight specimens were tested by pullout testing or combined pullout/push-in specimens in order to compare to analytical predictions. Specimens varied from 150 mm to 300 mm long. Half of the specimens were tested using a technique developed by Abrishami and Mitchell (1992) in which a "strain control" loading rate was used. The remaining specimens were tested as "standard pullout specimens." The short specimens indicated a uniform bond stress, while the long specimens showed high stress concentrations at the loaded end(s). The authors also concluded that specimens which failed in splitting showed nearly uniform bond stress distribution after the crack formed. The combined (pushing and pulling) loading resulted in an approximately uniform bond stress, with the maximum-to-average bond stress ratio at approximately 1.10. Specimens that failed in pullout had a ratio of 1.37, and specimens that failed in splitting had a ratio of 1.26. The authors did not discuss derived equation accuracy for predicting pullout force required for a given end slip based on experimental results.

2.1.2.2 Logan (1997)

Logan (1997) investigated the Moustafa pullout test method and its ability to accurately predict the transfer length of a pretensioned concrete member. The strand bond tests Logan performed were conducted using 0.5-in.-diameter strand from six North American strand producers. Logan's tests were a direct response to research conducted in the 1980s and early 1990s that indicated large differences exist in strand bond quality among various strand producers. Due to lack of ASTM standards concerning bond performance, Logan implemented a test program that included pullout tests, end-slip measurements at prestress release and 21 days, and development length tests. Pullout tests were based on the Moustafa method and consisted of six 34-in. saw-cut strand specimens from six manufacturers. The 36-strand specimens (six groups of six specimens) were cast vertically into the concrete with an 18-in. bond length and a 2-in. bond breaker adjacent to the concrete surface. Pullout test blocks and transfer length beams (described in following sections) were cast the same day with identical mix design. All concrete specimens were heat-cured overnight to an average compressive strength of 4350 psi for pullout specimens and 4254 psi for beams.

Pullout tests occurred the morning after casting, and were conducted using a single-strand jack that loaded at a rate of 20 kips per minute and the load was increased until the strands were completely pulled out or the loading rate could no longer be maintained. Four of the six strand groups averaged a maximum pullout force above 36 kips. The remaining two groups averaged less than 12 kips of maximum pullout force and withdrew substantially before reaching these forces. Beam specimens used for end-slip measurements and development length testing had a 6.5-in. x 12-in. rectangular cross-section. Each beam had a single pretensioned, 0.5-in.-diameter, low-relaxation Grade 270 strand located 2-in. from the bottom face of the beam. The formwork was built so that the beams were poured side-by-side, with each of the six tested strands housed in a different form cavity. The beams were poured continuously in 90-ft sections and then saw-cut into five 18-ft beams. End-slip measurements were taken directly after de-tensioning, which occurred by flame-cutting the extreme ends and saw-cutting between beams.

End-slip measurements were used to calculate transfer length and the mean values compared to the predicted ACI transfer length value of 29 in. Four strand types averaged 15 in. as an initial transfer length. The two poor bonding strands averaged transfer lengths of 24 in. and 34 in., respectively. The 21-day end-slip measurements indicated that the transfer length of Group 5 significantly increased by 16 in. (to 40 in.) and the transfer length of Group 6 increased by 14 in. (to 48 in.). Logan concluded that the Moustafa pullout test was a reasonably good predictor of transfer length and bond characteristics for 0.5-in. strand. He concluded that a higher pullout force correlates directly to a shorter transfer length and that end-slip measurements taken immediately after de-tensioning may not accurately detect poor bond characteristics of prestressing strand.

2.1.2.3 Rose and Russell (1997)

Rose and Russell (1997) performed un-tensioned and tensioned pullout tests in order to correlate results to measured transfer lengths of prestressed concrete beams. The authors theorized that strand surface condition significantly impacts the strand's "bond-ability" and that the strand can become contaminated by rust or surface lubricants.

Tests were performed on three 0.5-in., low-relaxation, Grade 270 strand samples from three strand manufacturers, A, B, and C. Strands A, B, and C were tested in their As-received conditions (A). Additionally, strand C was tested three times by modifying its surface condition by: cleaning (C) the strand using muriatic acid, washing with water, and letting dry; cleaning and then lubricating the strand with a silane (S) spray; and cleaning the strand and then placing in a damp environment for three days to promote weathering (W) of the strand. In total, this resulted in six casting and testing cycles. Each cycle consisted of three pretensioned beams, a large pullout block containing 12 un-tensioned pullout specimens, and two tensioned pullout tests. All specimens for each cycle were cast from the same batch of concrete to ensure minimal variation.

Un-tensioned pullout tests consisted of 6-ft. strands cast vertically into the large concrete pullout block with an embedded length of 18 in., and bond breakers placed around the strand samples at both the dead and live ends of the block. The target release strength was set at 4000 psi. All parameters imitated work done by Moustafa and Logan using large-block pullout tests. The applied force, dead-end-slip, and live-end-slip were measured for each pullout strand during testing. Beams used to collect transfer length data were each 17-ft.-long and had a 6-in. x 12-in. rectangular cross-section. Beams containing silane-treated strands were fabricated at 24 ft. instead of 17 ft. to accommodate longer anticipated transfer lengths. Two prestressing strands were cast 2-in. from the bottom face of the beam, and each beam cured for 48 hours in the formwork and under plastic to retain heat and moisture. A DEMEC mechanical strain gage was used to measure surface strain on both sides of the beam at the depth of the strands. Surface strain was measured before and after de-tensioning, and strand end-slip measurements were obtained using calipers.

Results of un-tensioned pullout specimens followed a logical trend. As expected, rust on the weathered strand C (CW) increased the force required to pull the strand from the concrete. Similarly, strand C samples with silane lubricant (CS) required less force to be pulled from the concrete. Both of these measurements were compared to the As-received strand C (CA) specimens. In general, results from un-tensioned pullout specimens were consistent for each of the 6 strand types. Furthermore, transfer-length measurements and strand end-slip measurements were consistent with the trend of pullout results, with ends adjacent to flame-cutting indicating longer transfer lengths than other locations.

However, based on results of silane-lubricated specimens and flame-cut ends, the authors concluded that the un-tensioned pullout test was not a good indicator of pretensioned bond. Second, the authors concluded that, even when silane specimens are omitted, no “clear or useful relationships between pullout strength and transfer length” are evident. Third, researchers found that surface condition affects strand bond performance. A rough surface positively affects bond and a lubricated surface negatively affects bond. Finally, researchers concluded that the un-tensioned pullout test must include a standardized load rate, geometry, and concrete mix in order for test results to beneficially determine pretensioned bond.

2.1.2.4 Russell and Paulsgrove (1999a)

Russell and Paulsgrove (1999a) compared three pullout tests proposed as quality control tests for strand bond: the Moustafa pullout test in concrete, the PTI pullout test in grout, and the friction bond pullout test with a mechanical butt splice and two lengths of strand. The goal of the testing program was to accept one of the test methods as a repeatable test, or to develop a more accurate, reproducible test than any current bond performance tests. Nine new strands, obtained from various manufacturers, were tested in their as-received condition. Two additional strands were tested as control strands because their bond performance was known from Logan (1997).

Four testing sites were used, including one research laboratory, one materials testing laboratory, and two testing sites at strand manufacturers. The eleven strand samples were each 0.5-in.-diameter, Grade 270 low-relaxation strands, and the sources were kept confidential so that testing was conducted as a “blind study” to everyone except the P.I. (Dr. Bruce Russell). Each set of tests consisted of six strand samples. Since the Moustafa test utilized two testing sites, compressive strength of the concrete varied. At the strand manufacturer’s site, the concrete’s compressive strength was unknown for the first set of tests and 3700 psi for the second set of tests. The concrete’s compressive strength was 5000 psi at the materials testing laboratory, and the compressive strength of the grout for the PTI pullout test ranged between 3700-4000 psi for the six batches.

The Moustafa test procedure is documented by Logan (1997). The test procedure for the PTI pullout test was developed by the Post-Tensioning Institute (PTI) for 0.6-in. strand using a neat cement paste. The test allows specimens to be tested in a strength range of 3500-4000 psi, with strength determined using 2-in. cubes. The load is applied by a mechanical jack at a rate of 0.10 in./minute. The specimen passes the test if at least 8000 lbf of force is required to cause a dead end-slip of 0.01 in; the dead end-slip is measured using an LVDT. The friction bond pullout test procedure consists of two identical strands connected with a crimped butt splice, and maximum strand tension force is recorded as the connection fails. An actuator pulls the strand from the top using standard 0.5-in. strand chucks to grip the specimens.

Results of the Moustafa pullout tests reveal that the general trend of strand bond performance accurately ranks the relative bond capacity of each strand at each testing location. However, the Moustafa test showed inconsistencies at the various testing locations. At the materials testing laboratory, the set of results was nearly 15% larger than the results reported by the strand manufacturer. This “unstable variation” led the authors to conclude that the test is inconclusive as a repeatable quality control test because the Moustafa test would “inconsistently reject and accept strands depending on test site.”

The authors further concluded that testing variables must be minimized for an effective bond quality control test. The Moustafa and PTI pullout tests ranked relative strand bond performance, but the friction pullout test inadequately distinguished strand bond performance. The author’s overall recommendation was to refine current Moustafa and PTI pullout tests by eliminating inconsistencies in testing variables. This recommendation became the basis for the “NASP Round Two” set of tests conducted after completion of the described testing regiment.

2.1.2.5 Russell and Paulsgrove (1999b)

Russell and Paulsgrove (1999b) investigated the repeatability and reproducibility of Moustafa, PTI, and NASP pullout tests, which follow procedures documented in Logan (1997) and Russell and Paulsgrove (1999a). The NASP pullout test, developed by the author of this paper, is primarily based on the PTI pullout test with two major modifications. First, a sand-cement mortar is used as the pullout medium instead of the neat cement paste used in the PTI pullout test. Second, the pullout force is recorded at a free end-slip of 0.01 in, 0.10 in., and its maximum value. In the PTI test, the pullout force is reported only at the 0.01-in. value for end slip at the free end of the specimen. The loading rate (0.10 in./minute), steel can diameter (5 in.), bonded embedment length (16 in.), and bond breaker length (2 in.) used for the NASP test were identical to the PTI test. PTI and NASP pullout tests were performed at two locations: Florida Wire and Cable (FWC) strand producer, and the University of Oklahoma (OU). The Moustafa pullout test was also performed at Stresscon Corp. (SC). For the NASP test, FWC and OU performed two rounds of testing for each set of strand specimens. Only one round of Moustafa and PTI tests were performed at each location. For consistency, six specimens represented one round of testing per strand type for each testing procedure.

The nine strand types used in this study were 0.5-in.-diameter, Grade 270, low-relaxation strand, and they were tested in their As-received condition. The Moustafa pullout tests were conducted when the concrete reached a compressive strength of 4000 psi. With the PTI and NASP tests, Series One began when the mortar reached a compressive strength of 3500 psi based on 2-in. mortar cube strengths. Series Two tests for OU and FWC did not begin until mortar strength was higher at both testing sites. For FWC, Series Two tests occurred for mortar cube strengths between 3560-4760 psi, and for OU, Series Two tests occurred for mortar cube strengths between 4470-5610 psi. A concrete mix containing Type III cement and admixtures was used for all Moustafa tests, and a neat cement paste mix containing Type I cement was used for all PTI test specimens. A sand-cement mortar mix containing Type III cement was used for all NASP specimens, except for FWC Series One NASP tests.

Moustafa test results from all three testing sites yielded similar results as NASP Round One Moustafa test results: the Moustafa test was unable to be consistently reproduced at various testing facilities. However, Moustafa test results consistently indicated relative strand performance among tested strands at each testing facility. Comparison of results between OU and Stresscon were somewhat consistent, but FWC results were consistently lower than the other two locations. When values for the nine strand groups were averaged, FWC results were 8000 lbf lower than OU and Stresscon results; therefore, these large testing variations made all other discussion irrelevant. The researchers concluded that "statistical comparisons are moot until the causes of large differences between the test sites are [sic] resolved."

PTI test results had good correlation between testing sites for maximum pullout force and pullout forces measured at 0.10 in. The coefficient of determination, R^2, for the maximum, 0.10-in., and 0.01-in. end-slip measurements were 0.87, 0.90, and 0.73, respectively, thus indicating that the 0.01-in. measurements had the lowest correlation between sites. Since the PTI pullout test is based on the pullout force at a displacement of 0.01 in., the researchers concluded this indicated "significantly weaker ability to reproduce results between test sites."

The NASP test results at different test sites correlated well for the maximum, 0.10- in., and 0.01-in. end-slip pullout values. This led the researchers to make the following two important conclusions. First, the NASP test showed excellent repeatability at each testing site from Series One to Series Two. Second, the NASP test demonstrated excellent reproducibility between the two testing sites because maximum force and pullout force at 0.10-in. end slip showed an R^2 = 0.97 or higher between FWC and OU results and between Series One and Series Two. Pullout force at 0.01-in. end slip matched reasonably well, but not to the same degree. The best correlation of NASP test results between test sites (repeatability) was the pullout force measured at 0.10-in. end slip. Comparison of these test results had a coefficient of determination, R^2, of 0.97.

Study conclusions were that the NASP pullout test was the most reliable of the pullout tests in terms of repeatability and reproducibility. Furthermore, the NASP test had the least variation between test sites for the pullout force measured at the maximum end-slip value or at an end-slip value of 0.10 in. The highest variation was the pullout force measured at 0.01-in. end slip. The authors recommended the NASP pullout test be further developed as a quality control bond test because test results indicate it was more consistent than both the Moustafa and PTI pullout tests.

2.1.2.6 Russell and Brown (2004)

Russell and Brown (2004) used the same test methodology as NASP Round Two testing (Russell and Paulsgrove, 1999b) to further develop the NASP [Strand] Bond Test. This test program included rectangular beams and transfer-length measurements to evaluate bond quality of ten

0.5-in.-diameter, Grade 270 low-relaxation prestressing strands. In addition to rectangular beam tests, this testing program also included three pullout test types: the Moustafa Test, the PTI Bond Test, and the NASP Bond Test. Moustafa and rectangular beam specimens were tested at Coreslab Structures Inc. (CS), and PTI and NASP pullout tests were performed at OU and FWC.

All mixes used for beams and pullout specimens were designed to achieve a minimum 3500 psi and a maximum 4000 psi compressive strength at the time of testing (18 to 24 hours after casting). The Moustafa test used a concrete mix, the PTI test used a neat cement paste, and the NASP test used a sand-cement mortar mix. Mix design was held constant for tests performed at multiple locations. Cement used for all tests was Type III cement, and sand was from Oklahoma, supplied by the Dolese Bros. Co. PTI and NASP specimens were cast as previously documented in NASP Round One and Two testing protocols (Russell and Paulsgrove, 1999a, 1999b).

Testing procedures and specimen setups for the NASP and PTI tests were the same as those documented in NASP Round Two (Russell and Paulsgrove, 1999b). Specimens were cured in a temperature- and humidity-controlled chamber between 70-74^{o}F and 48-52% relative humidity. Moustafa pullout blocks were cast according to Logan (1997). The rectangular beams were each 18-ft. long with a cross section of 6.5 in. x 12 in. Two beam designs, one containing minimal shear reinforcement and one 0.5-in. longitudinal prestressed strand and one with more shear reinforcement (#3 bars spaced at 6 in. on-center) and two 0.5-in. longitudinal prestressed strands, were utilized. Each set of tests consisted of six specimens per strand source for all forms of testing, including the three pullout test methods and rectangular beam testing.

Results of the testing program indicated that the Moustafa Test provided the lowest correlation between specimens cast at various testing sites. This low correlation between testing sites prevented the authors from recommending an acceptable pullout value to ensure bond criteria. However, the Moustafa Test did predict relative strand bond performance for strands tested at the same location and using the same mix.

The PTI pullout test indicated similarly low correlation between test sites but with less severity than the Moustafa Test. Results from PTI tests conducted by FWC showed a high standard deviation, in contrast to tests performed at OU. The authors concluded that the PTI test is a poor quality control test, despite its ability to more accurately predict bonds than the Moustafa test.

The researchers concluded that the best bond test was the NASP [Strand] Bond Test because it demonstrated the strongest correlation between testing sites. The 0.10-in. end-slip value provided the best correlation between test sites, as indicated from NASP Round Two testing. The correlation was lower in Round Three (R^2 = 0.78) than Round Two (R^2 = 0.98), but transfer length correlation was relatively strong in the current testing procedure. The overall research conclusion was that the NASP [Strand] Bond Test was the most reproducible and repeatable bond test currently developed. The authors also found good, direct correlation between NASP pullout values and transfer lengths of the rectangular beams. The authors recommended further research to develop the test into a more robust strand bond acceptance test.

2.1.2.7 Russell (2006)

Russell (2006) documented research done in the NASP Round Four testing and refined the NASP pullout test to determine whether it is an acceptable quality control test for assessing strand bond-ability to concrete. Research performed in this study consisted of refining test protocol and conducting a set of blind round-robin tests at Oklahoma State University (OSU), Purdue University (PU), and the University of Arkansas (UA). NASP pullout testing protocol was introduced in the NASP Round Two testing (Russell and Paulsgrove, 1999b) and implemented in the NASP Round Three testing (Russell and Brown, 2004). This protocol was refined in Round Three testing and used in NASP Round Four testing (Russell, 2006). The Standard NASP [Strand] Bond Test originated from findings of Round Four research.

OSU tested ten, 0.5-in. and two, 0.6-in. Grade 270 low-relaxation strand sources, PU tested four 0.5-in. and one 0.6-in. strand sources, and UA tested six 0.5-in. strand sources. Testing protocol and batching specifications were identical to those listed previously (Russell and Brown, 2004) except specification of the mortar flow value and tightening of the mortar strength window. Mortar used in testing must meet a flow range of 100 to 125, and mortar strength must meet a range of 4500-5000 psi. The NASP [Strand] Bond Test also specifies that specimens be tested 22 to 26 hours after casting.

Sand used to develop the NASP [Strand] Bond Test was obtained from the Dolese Bros. Co. in Stillwater, Okla. Type III cement from Lafarge North America was used to develop the NASP [Strand] Bond Test. Steel holders affixed to the 18-in.-long steel can held the steel strand specimens in the center of the 5-in.-diameter steel cans. In order to test mortar strength, NASP specimens and mortar cubes were made of mortar consolidated with a mechanical vibrator. Mortar for the cube specimens was consolidated using a rubber tamper, thus conforming to ASTM C109.

Mortar strengths at the time of testing were varied to determine the effect on NASP pullout strength. This was facilitated by using different w/c ratios of 0.40, 0.45, and 0.50 in the mortar mix. The researchers noted that mortar mixed with “a w/c of 0.45 was selected as the ‘best chance’ to produce mortar strengths at mid-range of the allowable strengths” Russell (2006). The researchers determined that higher-strength mortar directly correlates to higher pullout strengths based on mortar cube strengths that ranged from 4000-6000 psi. This effect was most evident for higher-bonding strands.

The effect of load control vs. displacement control was also tested. Load control was tested at 5000 lbf/min, and displacement control was tested at 0.10 in./min. The researchers determined that load control does not result in a “softening” or declining portion of the force vs. end-slip curve that is evident for some strands when tested in displacement control. Therefore, the author recommended using a displacement control with a rate of 0.10 in./min to run the NASP [Strand] Bond Test.

Mortar flow value was tested and found that, as water content increases, mortar flow also increases. A mortar flow value of 100 to 125 was recommended based on a w/c ratio of 0.45. An out-of-range flow could indicate a possible problem with mixing procedure or the cement or sand used in that batch. In addition, mortar flow must be noted directly after batching because results showed that flow decreases significantly over time.

Blind round-robin testing was performed at OSU, PU, and UA. Based on availability, various sands and cements were used at each site, but the sand had to conform to ASTM C33 and the cement had to conform to ASTM C150. Based on test results at each location, the NASP [Strand] Bond Test was determined to be repeatable. Overall test criteria and specifications established by the researchers, as well as the NASP Round Two testing and NASP Round Three testing, were determined to provide a good indication of strand bond performance for 0.5-in. and 0.6-in. strands.

Strand acceptance limits were set at 10,500 lbf at a slip of 0.10 in. for the average of six 0.5-in.-diameter strand specimens, which comprise a single test. An additional criteria was specified that no specimen within the group of six have a pullout force less than 9000 lbf. The author recommended the strand bond test be adopted by the Oklahoma Department of Transportation (ODOT) and the AASHTO LRFD bridge design manual. The author also recommended each strand producer in the United States have its strand certified using the NASP [Strand] Bond Test to prove the product conforms to specified quality control standards.

2.1.2.8 Ramirez and Russell (2008)

Ramirez and Russell (2008) extensively investigated the transfer, development, and splice length of 0.5-in.-diameter and 0.6-in.-diameter prestressing strands. The research was divided into four phases: refinement of the NASP [Strand] Bond Test, transfer length measurements, development length tests, and lap-splice testing using mild steel reinforcement. However, the latter three phases are not relevant to the research scope of this chapter, so only the first phase (refinement of the NASP [Strand] Bond Test) was reviewed.

Blind, round-robin pullout testing was performed at OSU and PU, and five 0.5-in.-diameter and two 0.6-in.-diameter strand sources were used for these tests. Results proved to be very repeatable. When a linear regression of pullout results between the two sites was conducted, an $R^2 = 0.92$ was found relative to the “perfect fit” line, indicating strong reproducibility among testing sites. The authors attributed this reproducibility to refined test protocol and systematic specimen preparation.

The authors recommended the standard test for strand bond be adopted by AASHTO into the *LRFD Bridge Design Specifications*, based on demonstrated repeatability and reproducibility. The authors also encouraged AASHTO to require that strand producers certify strand “bond-ability” using the Standard Test for Strand Bond. A strand is acceptable for the Standard Test for Strand Bond if the average of six 0.5-in.-diameter strands is at least 10,500 lbf and no specimen is below 9000 lbf. These values were determined from transfer and development length tests. For 0.6-in.-diameter strands, a strand is acceptable if the average of six strands is at least 12,600 lbf and no specimen is below 10,800 lbf.

2.1.2.9 Peterman (2009)

Research conducted by Peterman (2009) presents the need for a simple strand bond test that can be used as a quality assurance (QA) measure rather than for quality control (QC) purposes. This test would verify the bond of prestressing steel when using SCC mixes, a need recognized by the Precast/Prestressed Concrete Institute (PCI), but that the QA test is also valid for conventional concrete mixes. The goal of the test was to be simple to conduct, but provide accurate results that would effectively indicate bond performance. Test specimens had an 8-in.-wide by 6-in.-tall rectangular cross-section with one 0.5-in.-diameter, Grade 270 prestressing strand cast at a depth, d, of 4.5 in. No shear reinforcement was placed in the beams.

Beam shallowness allowed the required loads to remain light enough to be lifted by a forklift. Beam width relative to beam depth allowed for a stable section during applied loads with no concern of lateral-torsional buckling. The width also gave a large compression zone relative to the depth of reinforcing strand which served to increase the strain of the prestressing steel at nominal capacity. Total beam spans were 11.5 ft. with a constant moment region of 2 ft. at mid-span. This length was purposefully chosen so that the embedment length at each end would be about 80% of the calculated development length of the member, thus allowing for expected bond failure and reducing the chance of flexural failure.

For test loading, suspended concrete blocks were hung from nylon straps, forming the boundary for the constant moment region (2-ft. at mid-span). For various specimens, maximum nominal capacity ranged from approximately 5000-6000 lbf, depending on concrete compressive strength and strand diameter. Bearing conditions consisted of one 0.5-in. neoprene bearing pad at one end and one 0.5-in. Teflon-coated neoprene bearing pad on top of a 1/8-in. steel plate to reduce horizontal restraints. These pads were located with their outer faces a distance of 2-in. from beam ends, making the total clear span 11 ft.-2 in. Beam design capacities were determined using ACI 318 Building Code and AASHTO LRFD Bridge Design Specifications for prestressed beams. Specimen testing consisted of casting the beams using "standard batching, placement, consolidation, curing, and detensioning methods" Peterman (2009). The strands were then ground flush with the end of the beam.

The beams were gradually loaded to 85% of maximum nominal moment capacity of the section, using nylon straps and concrete blocks. Visual end-slip measurements were taken from the end of the beam, documenting any initial cracks. This dead load was sustained for a minimum of 24 hours to observe additional end slip, cracking, or other beam distresses. The beam was finally loaded to full nominal moment capacity for 10 minutes; the beam passed if it did not collapse. The only specified loading rate for the 85% nominal moment was gradual.

Peterman recommended at least two beams be cast simultaneously, since other research from the same research project indicated there was a significant reduction in bond detected when some beams were tested after the first three weeks from the date of casting. One or both beams should be tested when the beam is at least 28 days old.

An alternative trapezoidal section was also allowed and dimensioned in the paper. After 25 rectangular sections and 13 trapezoidal sections were tested, the author observed that there were no consistent differences in the ultimate load-carrying capacity of the two sections. This test served as a quality assurance test for the final product of pretensioned concrete beams. Other ASTM tests – pullout tests, material gradation tests, cement content tests, or strand material tests – are quality control tests that assure material entering the final product meets minimum requirements. However, prior to the above study, no test existed that assured bond quality of the final, prestressed product.

2.2 Smaller Diameter Strand and 5.32-mm Wire Pullout Tests

2.2.1 Introduction

Minimal research has been conducted on the bond of 5.32-mm-diameter steel prestressing wires; therefore, background information presented in the following papers contained smaller diameter steel fibers (0.6 mm and 1.0 mm wires) and larger diameter steel bars (10 mm and 16 mm) to supplement the 5.32-mm research. A literature review of the bond of small diameter, three-wire strand was also conducted.

The primary objective of research performed to date has been to accurately model the surface between prestressing wires and concrete. However, previous research failed to develop a reliable quality control test or propose an acceptable criterion for "bond-ability" of wires. Despite the limitation of available literature, valuable information and conclusions for experimental laboratory researchers were extracted. These findings included insight into indentation depth related to bond performance, the role of indentations (and their geometries) on bond compared to a smooth surface, and the need for of a simple, accurate, and repeatable pullout bond test.

2.2.2 Wire Bond Research

2.2.2.1 Galvez et al. (2011)

Galvez et al. (2010) coupled two models in the analysis of the bond between concrete and indented prestressing steel: a non-associative, plasticity bond model, and a cohesive fracture model for concrete. Experimental testing was performed to compare results to the analytical model. The model was developed for prestressing wires with chevron indents, but it can be expanded to include three- and seven-wire strands.

The ABAQUS model accounted for the cohesive crack model that addressed concrete splitting due to radial pressure of the wire, and the bond model accounted for the bond interface between concrete and prestressing steel. The cohesive crack model used a bilinear approximation of the material-softening function which relates the stress acting across the crack faces to the corresponding crack opening. The bond model was idealized with two simplifications. First, stress distribution was assumed to be uniform along the wire length instead of concentrated at each indent. Second, concrete deformation in the bond zone was idealized based on concrete fracturing at each ridge.

The experimental portion of this research included a series of push-in tests to compare results of the numerical analysis. The push-in-type test was used because it includes radial expansion of the wire relating to bond performance. Tested specimens were rectangles 60 mm wide with three thicknesses (14 mm, 22 mm, or 30 mm). Two embedment lengths, 400 mm for long specimens and 64 mm for short specimens, were chosen to study differences in non-uniform bond stresses for the different-length specimens. The wires were 4 mm, nominal diameter with three indent depths (shallow = 0.015 mm, medium = 0.050 mm, and deep = 0.105 mm). The wires in each specimen were tensioned to 17 kN of force using an actuator. After curing the prestressing force was transferred to the concrete by moving the actuator at a rate of 0.3 mm/min. Longitudinal prism shortening, wire end-slip measurements, crack widths, and release load were recorded during the transfer of prestress.

The ABAQUS model accurately predicted experimental testing results for the long and short embedment-length specimens. The model used mechanical properties of the steel and concrete, depth and geometry of the wire indentation, and parameters of the bond interface to predict concrete response. Test specimens and the model showed that deeper indents result in better bond, but findings also indicated that highest bond stresses result in a higher propensity to split the concrete. The authors were pleased with model accuracy and the success of predicting the bond of wires to concrete. However, the authors recommended that additional research be conducted to extend the findings to “full-scale structural elements” and applications with prestressing strand. Further work also is required to verify if different indent geometries (varying indent side angles, indent orientation, etc.) will also be accurately represented by model.

2.2.2.2 Chanvillard (1999)

Chanvillard (1999) developed a model that attempted to account for the effect of non-straight wires on pullout results and the effect of steel deformation during a pullout test. Wires were tested as straight sections and non-straight combinations of wire segments in which a straight, semicircular, and straight-section of wire were tested. The mathematical model was developed using general static equilibrium principles acting on a curved fiber element.

Approximations were made to the model to account for components of normal and tangential forces on the curved surface using small-angle theory. Steel deformations during testing (slippage of the fiber) were considered, using energy mechanics to provide an accurate model. Work done by external forces was balanced by the internal dissipation of energy through deformations. This slippage (deformation) caused a change in curvature because the dead end remained anchored, or it had not yet slipped at that exact time, and the live end began to travel around a curved surface. Fiber deformation was approximated and used to calculate the strain tensor matrix. This strain tensor, coupled with knowledge of the stress tensor, allowed the researcher to calculate deformation energy in the fiber during pullout testing. The inclusion of cohesion knowledge, friction, and integration of the entire model along the fiber length, allowed the researcher to predict theoretical pullout load-displacement curves.

Wires used to verify model validity were 0.6 mm and 1.0 mm in diameter with varying bonded lengths. Straight pullout tests were performed to observe how closely the model matched results from previous research. Then, non-straight pullout tests were performed to verify the curvature component of the new model. Three tests for each wire diameter, bond length, and configuration were performed, averaged, and compared to the theoretical model predictions. Testing was done in a sand-cement mortar mixture using w/c ratios of 0.4, 0.5, and 0.6. Testing results determined that cohesion, friction, and modeling slope are intrinsic parameters of fiber behavior. The researchers concluded that fiber surface geometry is the main parameter for reinforcement efficiency that it offers in cracked concrete.

2.2.2.3 de Almeida Filho, El Debs, and El Debs (2008)

de Almeida Filho, El Debs, and El Debs (2008) performed two types of pullout tests in concrete using 10-mm- and 16-mm-diameter bars (not strand) to examine various bond-slip properties for different concrete mixes. The bars used were 500 MPa (72.5 ksi) yield stress. Each test configuration was performed three times and averaged to obtain bond strength vs. slip results.

The first type of pullout test loaded bars in unconfined, cylindrical specimens at the bottom of the specimen and measured the end slip at the opposite end (top) using an LVDT. Specimens were clamped into the machine and loaded in displacement control at a rate of 0.01 mm/s for the 10-mm bars and 0.016 mm/s for the 16-mm bars. The LVDT was affixed to the steel bar and measured slip relative to the top surface of the concrete. The 10-mm bars were cast into a 100-mm-diameter tube with a 50-mm bond length, and the 16-mm bars were cast into a 160-mm-diameter tube with an 80-mm bond length. Both specimens had a total length of approximately twice their bond length, i.e., 100 mm and 160 mm total length, respectively, but the exact length was not listed. A bond breaker may have been used, which would account for the apparent discrepancy between bond length and total specimen length.

The second type of pullout test consisted of two concrete prisms with a steel bar cast near the tension (bottom) surface. This bar acted as the only structural piece joining the two prisms. Bond breakers were placed at the ends of both specimens so that a bonded length of 10 bar diameters was achieved. A hinge was placed at the top, and the setup was loaded near mid-span using a short spreader beam. This setup allowed for bond-slip failure as the exposed bar at mid-span pulled out before the concrete near crushing. Specimens containing 10-mm bars were approximately 650 mm in total length with a cross section of 180 mm by 180 mm. Specimens containing 16-mm bars were approximately 1100 mm in total length with a cross section of 240 mm by 240 mm. Beams were instrumented with an LVDT at each outside concrete edge. The LVDTs were attached to the steel bars and measured the slip relative to the concrete surface.

Researchers analyzed the bond stress data at 0.01-, 0.1- and 1.0-mm end slip and also at the ultimate bond stress for the bars. All specimens slipped, but some of the steel specimens ruptured prior to full pullout failure. Bond-stress vs. end-slip results were generally consistent between cylindrical and prism specimens for each test setup. The smaller-diameter bars exhibited slightly higher bond stresses than the larger bars. (Note: This trend was also exhibited between similar bonding strands and wires; bond stress increased as total diameter decreased.) In general, beam specimens had less slip and bond stress than cylindrical specimens. However, the authors attributed this difference to the testing method (prisms were tested in flexure, whereas cylinders were tested with pure axial force). The authors determined that the two pullout methods were both acceptable predictors with low variability in the results, therefore qualifying them as reliable tests. The authors recommended the cylindrical test be used instead of the beam test because of the simpler setup and acceptable accuracy. The beam test was deemed more difficult to set up and to control key variables, particularly the concrete cover and bonded length.

2.2.2.4 Gustavson (2004)

Gustavson (2004) investigated which parameters affect the bond of three-wire prestressing strands. The 6.5-mm (.255 in.) three-wire strands were tested in pullout and push-in tests, and cohesion, friction, and other mechanical properties were documented. The pullout tests were un-tensioned tests, whereas the push-in tests were pretensioned to 28 kN force. Researchers carefully documented strand behavior at pullout loads beyond the initial pretensioned force to determine the bond-slip relationship. The research also modified the strand surface using Teflon spray, plastic film, oil lubricant, and sandblasting to test the effect of surface condition on bond.

Three-wire strands had indents according to the FIB (European) bond report. European code specifies indentation depth and indentation spacing. The authors also modified the three-wire strands by changing the indent spacing (indentations per unit length decreased by approximately half). All strands were cast into 50-mm-diameter steel and plastic tubes with a total height of 75 mm and a wall thickness of 1 mm. A 25-mm aluminum bond break was placed at the bottom of the tested strand length, leaving a bonded strand length of 50 mm. Specimens were consolidated using a vibrating table and covered with plastic lids on the top and bottom surfaces. No specifications were included as to how the plastic caps were fastened at the bottom of the specimen to prevent bleed water or concrete seepage. Nine specimens were cast for each pullout and push-in test.

Pullout test specimens were loaded by applying a tensile force to the strand at the bottom of the specimen and the strand end slip was measured at the opposite (top) end. Displacement control was used for these tests with a load rate of 2.2 mm/min. All specimens were tested after 24 hours curing time. Compressive cylinders were used to determine concrete strength, determined to be 55 MPa at the time of testing. Rotation was permitted by a thrust bearing on the load frame. Rotation amount was recorded by a wire displacement transducer attached to the tube. The length of wire wound at the end of the test, in addition to specimen radius, was used to calculate the angle of rotation. Rotation was found to begin shortly before maximum load was reached. Once begun, rotation rate was also constant.

Push-in test specimens were loaded by applying a compressive force to the strand at the top of the specimen and displacement measurements were taken with a displacement transducer at the top. Again, specimen rotation was allowed. Prestress force was released from 28 kN to 0 kN at a rate of approximately 1 mm/min at the time of testing (24 hours after casting) by manually rotating two wrenches. Concrete strength at the time of testing was between 21 and 35 MPa. Load vs. end-slip curves were built using the difference between displacement measured on the strand and displacement of the top surface of the concrete as prestressing force was released.

The author found that concrete strength did not affect bond capacity of the three-wire strands tested. This finding differs from previous research suggesting that concrete strength does affect bond capacity of indented, deformed bars. The author hypothesized that various failure mechanisms govern deformed bars and coiled strands and the conclusion was made that adhesion between the steel and concrete is not affected by indentations, nor does adhesion affect the overall required pullout force because it is broken prior to reaching the peak load. The second main conclusion was that friction (surface condition) between concrete and steel is substantial in bond performance. However, the author stated that mechanical action of strand indents was the biggest factor affecting bond capacity. This bond capacity can be increased by properly spacing indents, thus aiding in mechanical interlock, or decreased because of too many indents per unit length, thus causing a high propensity for cracking and reduced bond capacity.

2.3 Conclusion

The NASP [Strand] Bond Test was revised several times to increase the repeatability and reproducibility of the strand pullout test. The first draft, dated August 2001, was used only to assess 0.5-in.-diameter, seven-wire strands. This test protocol was used for NASP Round III research (Russell and Brown, 2004). The second version, dated May 2004, included provisions for 0.6-in. seven-wire strands. This procedure was used in NASP Round IV testing (Russell, 2006). After minor protocol changes, the current version of the test, called the Standard Test Method for the Bond of Prestressing Strand (Russell, 2006; Ramirez and Russell, 2008), is a result of NASP and NCHRP funding and is only specified for 0.5-in. and 0.6-in. diameter strands.

Currently, prestressed concrete railroad ties are manufactured primarily with 5.32- mm wire and with smaller diameter (less than 0.5 in.) strand. However, no standard bond tests exist to quantify the performance of these small diameter reinforcement types used by the concrete railroad tie industry. Therefore, research presented in this report is focused on two main goals:

1. Developing a standard test method to assess the bond of 5.32-mm-diameter wire.
2. Evaluating the Standard Test for Strand Bond (STSB) as a possible test for use with smaller-diameter strands, or to propose additional modifications to the STSB if the current version is found to be unacceptable for use with smaller-diameter strands.

3. Reinforcement, Storage, and Cleaning Procedure

3.1 Reinforcement

Nineteen reinforcements were used in research program conducted at Kansas State University (KSU). Thirteen prestressing wires and six prestressing strands from seven steel manufacturers were used in un-tensioned pullout tests described in Chapters 4 and 5. Upon receipt of the reinforcement, the 13 wires were generically labeled [WA] through [WM] and the six strands were generically labeled [SA] through [SF]. Internal nomenclature for pullout testing was developed to easily identify key information. A typical specimen employed in the naming system is shown in Figure 2.

All 13 wires were 5.32-mm-diameter, low-relaxation prestressing wires with various indent geometries. One wire contained no indents (smooth), and the remaining 12 wires were indented in general conformance to ASTM A881. All strands were three-wire or seven-wire, low-relaxation strands with 5/16-in.-diameter or 3/8-in.-diameter. All wires are shown in Figure 3 and all strands are presented in Figure 4. A close-up view of each wire is shown in Figure 5 and a close-up view of each strand is shown in Figure 6. Each reinforcement's ultimate tensile force, ultimate strength, cross-sectional area, and modulus of elasticity as provided by the manufacturer are provided in Table 3.

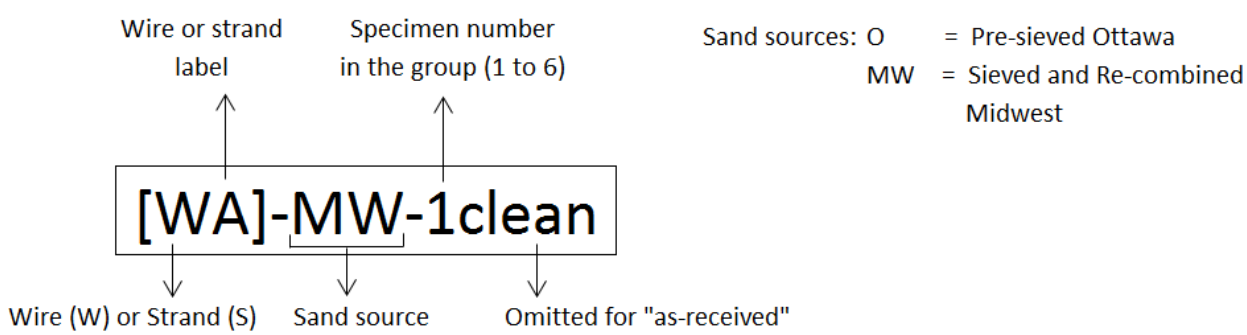


Figure 2. Pullout specimen nomenclature

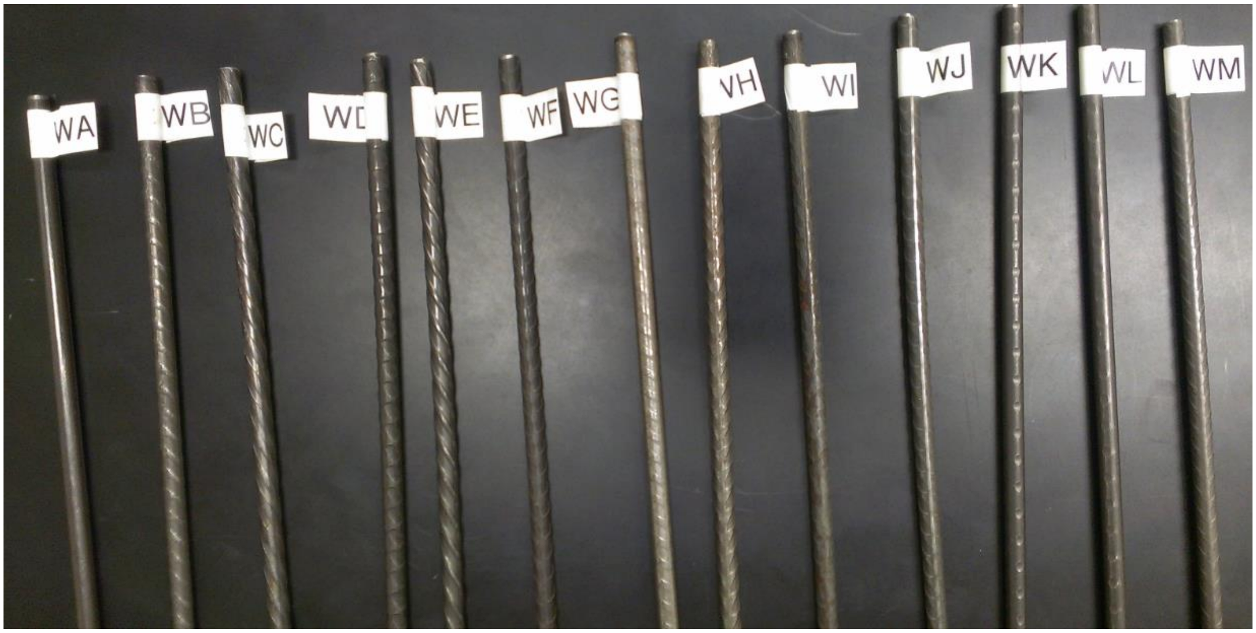


Figure 3. Samples of 13 wires with various indentation geometries

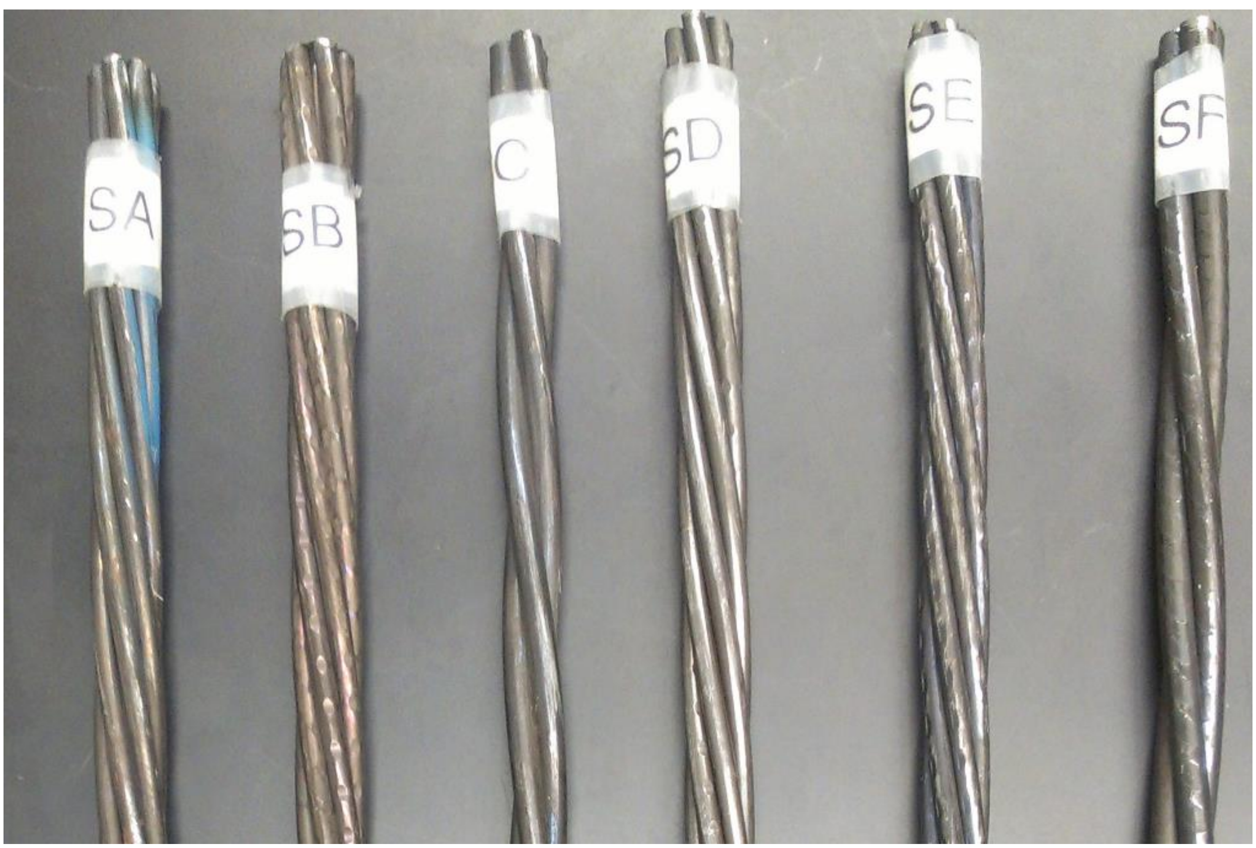


Figure 4. Samples of six strands with various indent geometries and diameters

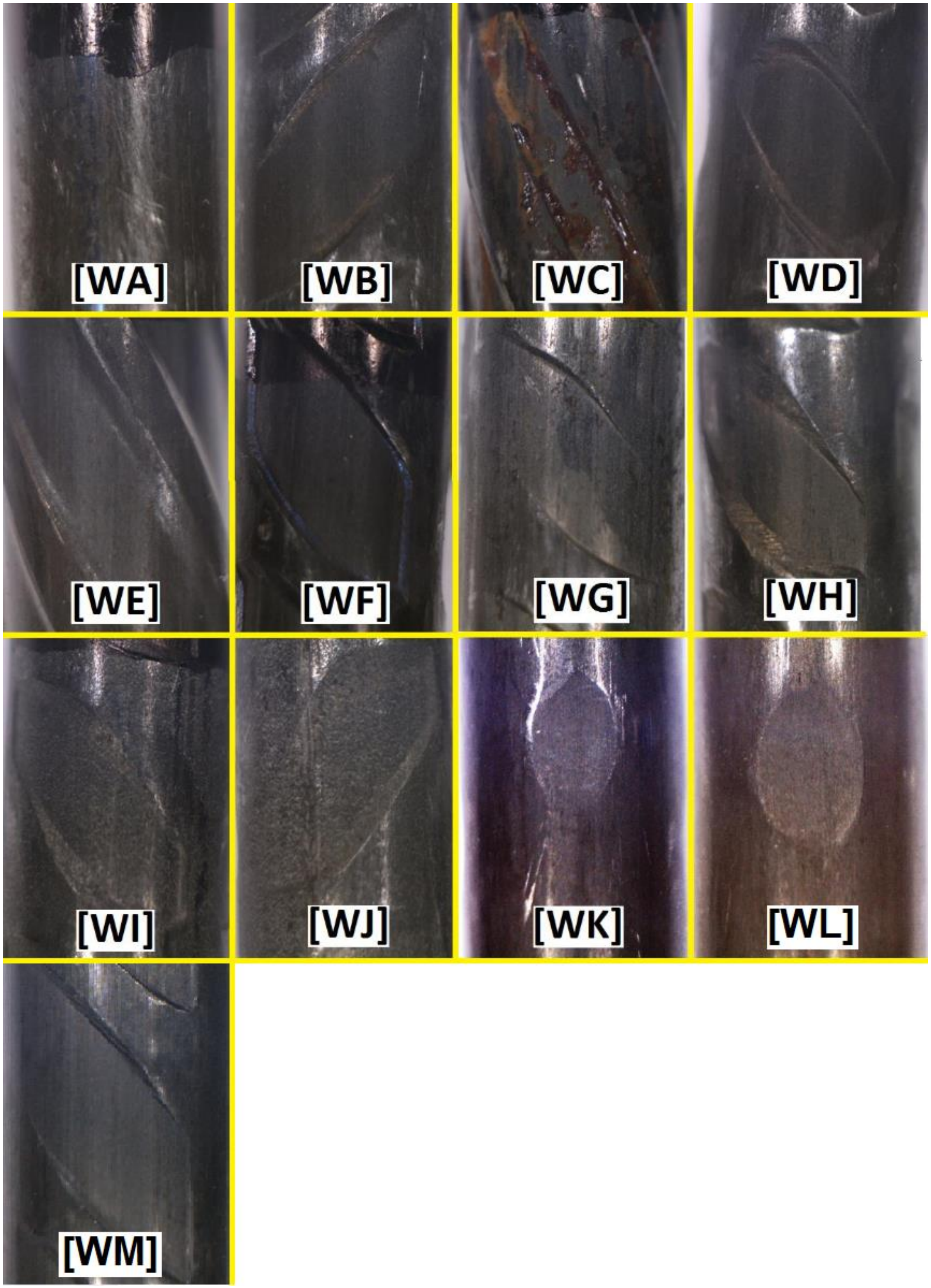


Figure 5. Close-up view of wire specimens

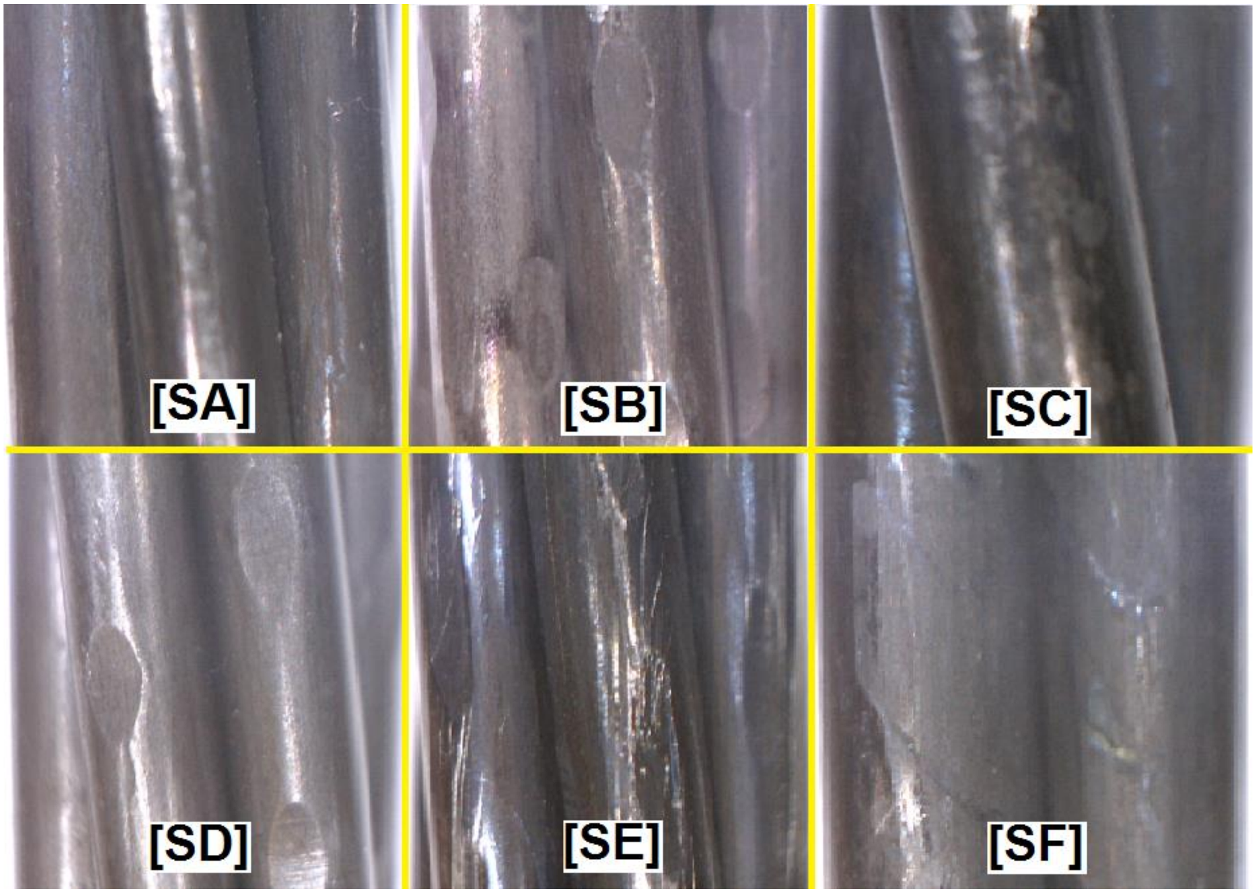


Figure 6. Close-up view of strand specimens

Table 3. Ultimate tensile force/strength, cross-sectional area, and modulus of elasticity of each reinforcement

Reinforcement		Indentation Type	Ultimate Tensile Force (lbf)	Ultimate Tensile Strength (ksi)	Cross-Sectional Area (in^2)	Modulus of Elasticity, E (ksi)
Wire	[WA]	Smooth	10184	293.5	0.0347	29700
	[WB]	Chevron	9712	281.7	0.0345	30510
	[WC]	Spiral	9892	290.3	0.0341	28400
	[WD]	Chevron	9696	275.5	0.0352	30120
	[WE]	Spiral	9258	268.6	0.0345	28570
	[WF]	Diamond	9280	269.2	0.0345	29000
	[WG]	Chevron	9376	271.0	0.0346	30300
	[WH]	Chevron	9438	271.2	0.0348	29870
	[WI]	Chevron	9389	279.5	0.0336	29000
	[WJ]	Chevron	9702	276.9	0.0350	28600
	[WK]	4-Dot	9839	284.6	0.0346	29430
	[WL]	2-Dot	9711	280.9	0.0346	29480
Strand	[SA]	3/8" 7-Wire, Smooth	23661	278.4	0.0850	29000
	[SB]	3/8" 7-wire, Indented	23793	279.9	0.0850	29000
	[SC]	5/16" 3-wire, Smooth	15871	272.7	0.0582	29000
	[SD]	3/8" 7-wire, Indented	24630	288.1	0.0855	29090
	[SE]	3/8" 7-wire, Indented	23069	272.4	0.0847	28100
	[SF]	3/8" 3-wire, Indented	18550	285.4	0.0650	28560

3.2 Reinforcement Storage

The reinforcements used in the laboratory portion of this study were cut from longer reinforcement coils that were first delivered to the CXT Concrete Tie plant in Tucson, AZ. Upon receipt in Tucson, 1000-ft lengths of the reinforcements were cut from the larger coils and sent to KSU. The larger coils were then stored in a shipping container that also contained many large desiccant packs which were used to maintain a very low humidity environment, as these same coils would later be used for the Plant Phase of this research project.

After delivery to KSU, all 19 reinforcement types were cut to 25-ft lengths and were stored in separate polyvinyl chloride (PVC) tubes. Wires were stored in 3-in. diameter PVC tubes and strands were stored in 4-in. diameter PVC tubes. Silica-based desiccant packets were also placed in the PVC tubes to prevent rusting and preserve the reinforcements' As-received surface condition for testing. These 25-foot pieces were then further cut into shorter lengths for testing. If a delay between cutting and testing was expected, specimens were stored in smaller (shorter) PVC tubing until testing. PVC/reinforcement storage racks are shown in Figure 7.

Figure 7. Reinforcement storage rack

3.3 As-received vs. Cleaned Reinforcement

The investigation of how much reinforcement bond performance is attributed to indent geometry and how is attributed to surface condition is essential in understanding the role of indent geometry on bond. In order to assess this, the different reinforcements were tested both in their As-received and Cleaned conditions. The As-received specimens provided a baseline reading for expected bond performance of each reinforcement as they were received from their respective suppliers. The Cleaned specimen tests were performed on bare steel by removing rust, oils, and surface lubricants with an acidic solution. This process allowed researchers to more accurately distinguish between the bond attributed to surface condition and the bond attributed to indent geometry.

All thirteen wires and all six strands were tested in an As-received condition. In order to preserve the As-received surface condition, reinforcements were placed in PVC tubes with silica-based desiccant packets to prevent additional weathering. All As-received specimens were prepared and tested within 24 hours after being removed from the PVC tubes. For more information on the storage procedure, refer to Section 3.2.

Seven wires (WA, WE, WF, WG, WH, WL, and WM) and all six strands were additionally tested in the Cleaned condition. To test in the Cleaned condition, each reinforcement type was removed from the PVC tubes and cleaned using a hydroxyacetic and citric acid, Deoxidine 7310, obtained from the Henkel Corporation, as shown in Figure 8. The acid solution was then diluted with water using a 10:1 water to acid ratio. Each time that the reinforcements were cleaned for pullout testing, approximately 24 fl. oz. of solution was mixed in a plastic spray bottle. Another volume of solution was mixed for each day reinforcement samples were cleaned. All chemicals and steel specimens were handled with nitrile gloves to avoid skin contact. Each reinforcement specimen was cleaned using the following procedure:

1. Rinse with water from a hose with a spray nozzle.
2. Spray with prepared 10:1 solution of Deoxidine 7310 and water and scrub steel surface by (gloved) hand.
3. Rinse with water from a hose with a spray nozzle.
4. Spray with Deoxidine 7310 and water solution. Let sit for approximately 15 seconds.
5. Scrub steel surface with a brass brush for approximately 30 seconds.
6. Rinse with water from a hose with a spray nozzle.
7. Dry steel specimen with clean cloth.
8. Stand specimen on end to allow excess moisture to drain from the specimen.

This cleaning process was performed approximately 45 minutes before the steel was tied into the cans and approximately 90 minutes before mortar was poured, thus allowing sufficient time for the solution to drain and dry but not allow the steel surface to rust or become contaminated.

The visual effect of the cleaning process can be seen in Figure 9 to Figure 21 for the seven wires and six strands.

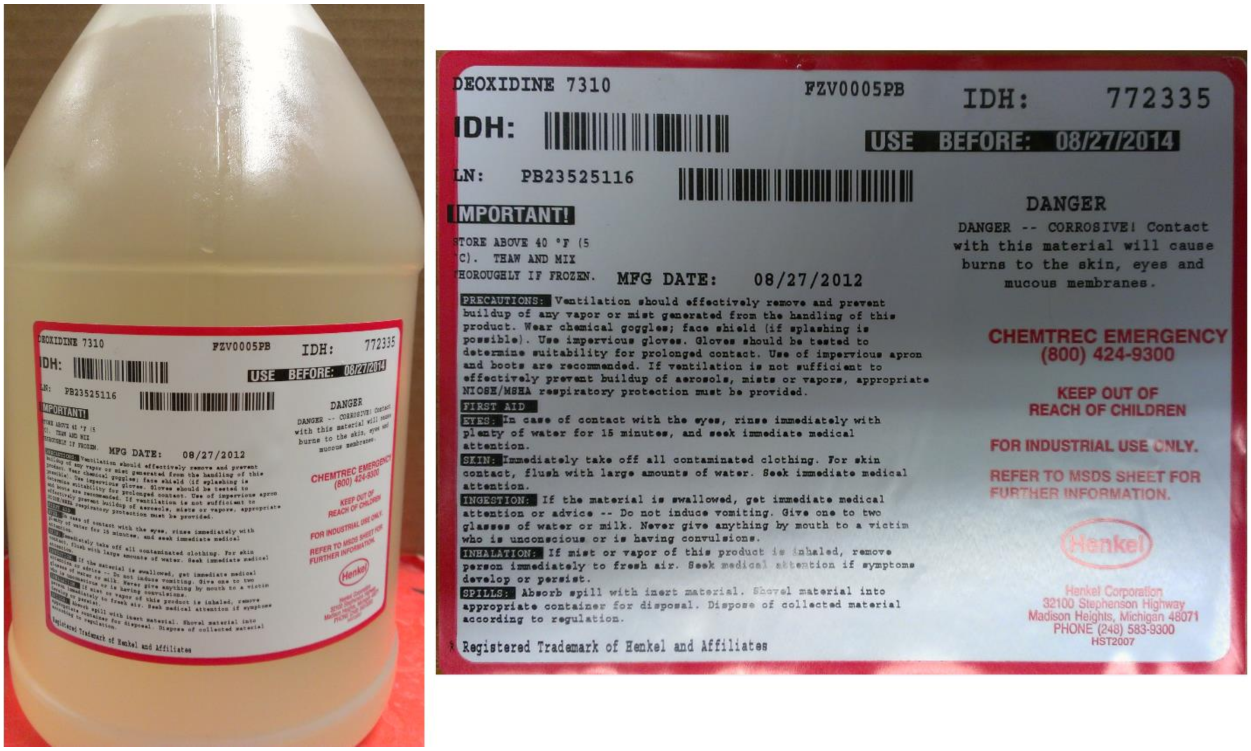


Figure 8. Chemical used in reinforcement cleaning process (Deoxidine 7310)

Figure 9. [WA] As-received vs. cleaned comparison

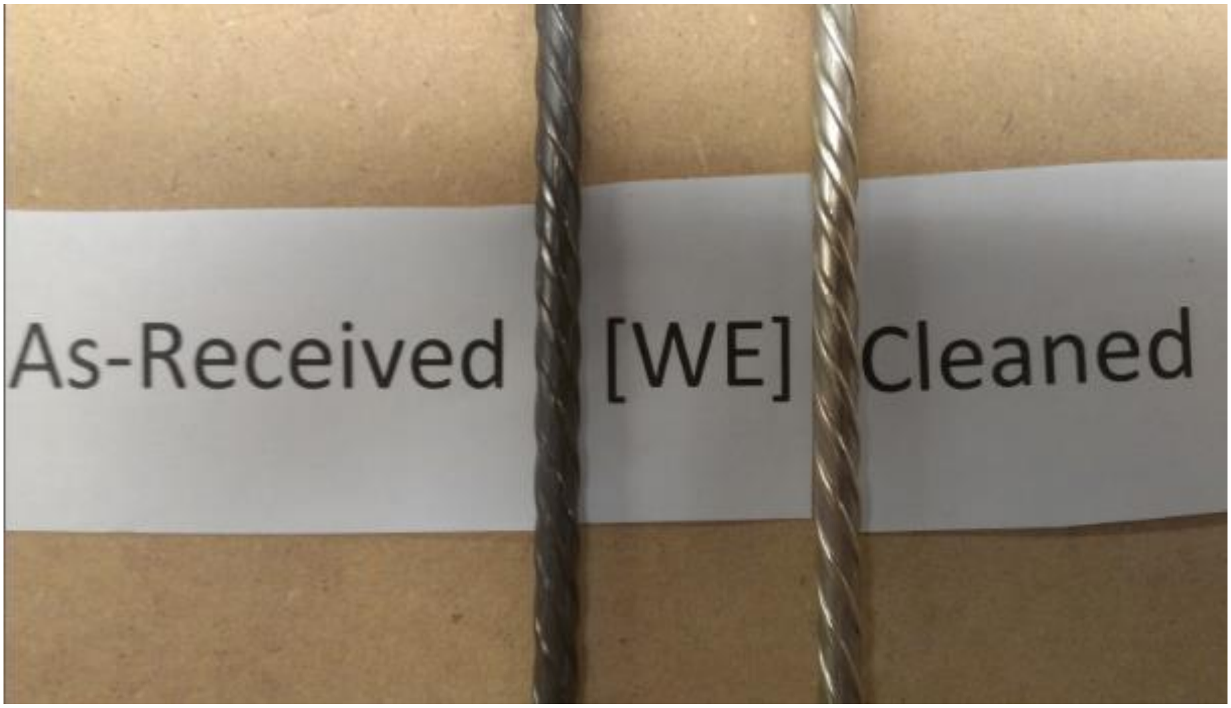


Figure 10. [WE] As-received vs. cleaned comparison

Figure 11. [WF] As-received vs. cleaned comparison

Figure 12. [WG] As-received vs. cleaned comparison

Figure 13. [WH] As-received vs. cleaned comparison

Figure 14. [WK] As-received vs. cleaned comparison

Figure 15. [WM] As-received vs. cleaned comparison

Figure 16. [SA] As-received vs. cleaned comparison

Figure 17. [SB] As-received vs. cleaned comparison

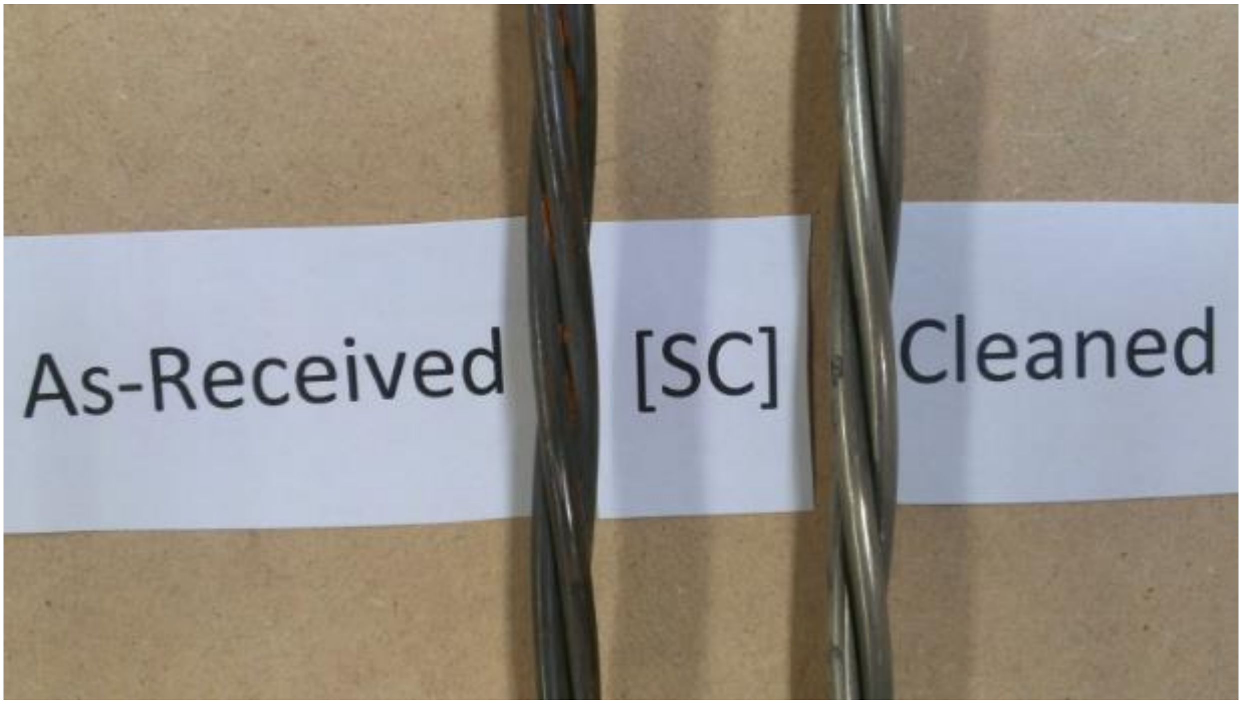


Figure 18. [SC] As-received vs. cleaned comparison

Figure 19. [SD] As-received vs. cleaned comparison

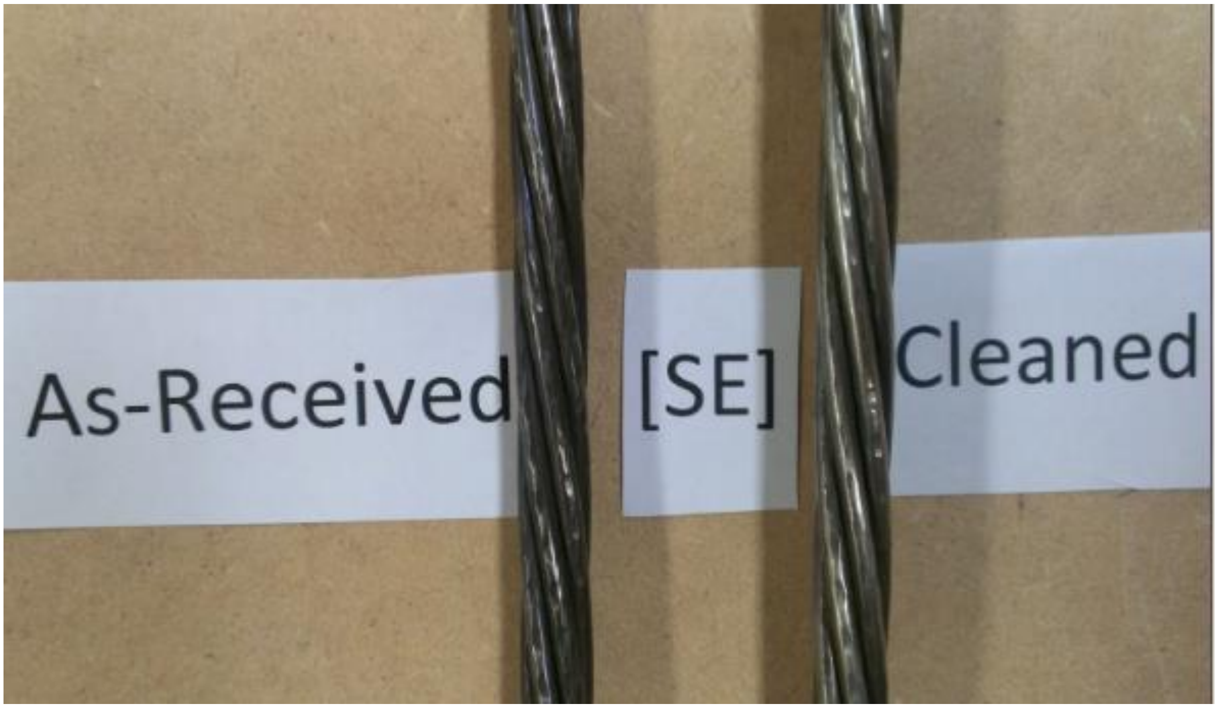


Figure 20. [SE] As-received vs. cleaned comparison

Figure 21. [SF] As-received vs. cleaned comparison

4. Lab Phase: Wire Pullout Testing (Un-tensioned in Mortar)

Chapter 4 discusses test development, experimental program, results, and analysis of the lab portion of wire bond pullout tests. These tests were un-tensioned and performed in mortar.

4.1 Development of the Pullout Test

Development of a standardized 5.32-mm-diameter wire pullout test was undertaken with two main research variables in mind: indent geometry and surface condition. A preliminary test series was also conducted using both force- and displacement-control tests to determine which control type would be best for the wire pullout test. Three specimen sizes and two sand sources were used in the preliminary investigation until an appropriate combination of test parameters was identified that provided repeatable results. Finally, evaluation of additional method parameters was performed and documented. All these topics are discussed in the following section.

4.1.1 Preliminary Specimen Size

The first specimen dimensions tested are shown in Figure 22. A 5-in.-outer-diameter tube with a 1/8-in. wall thickness was used for preliminary testing based on the dimensions of the existing test for 0.5-in. and 0.6-in.diameter seven-wire strands (Ramirez and Russell, 2008). Total tube length was 12 in. total bond length was 9 in. based on prior testing conducted by the primary investigator. Wires WA, WB, and WI were chosen in preliminary trials to develop the wire pullout test because their widely varying indentation depths were expected to produce bounding limits of bond performance for other tested wires.

WA is a smooth wire and, therefore, was expected to have the lowest bond performance. WI has deep chevron indents and, therefore, was expected to be a higher bonding wire. WB, with a shallower chevron indent, was expected to bond somewhere in-between. Preliminary trials were conducted using concrete sand produced by Midwest Concrete Materials ("Midwest Sand") originating from sand pits near Manhattan, Kansas. These preliminary trials produced consistent variation in bond performances of the three wires.

Based on the pullout values from the 3 wire sources, a preliminary embedment length of 9 inches was selected as shown in Figure 22. This length resulted in maximum pullout force values for wire source WI that were close to the yield strength of the wire, but yet still resulted in pullout (bond) failures.

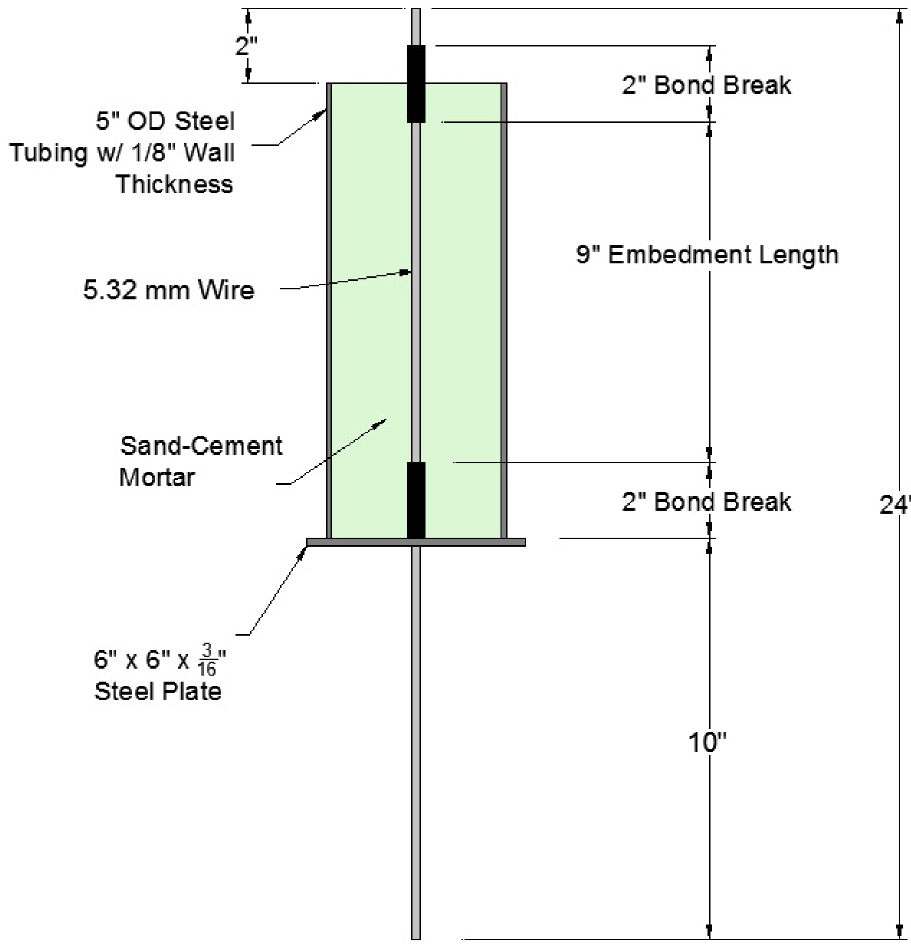
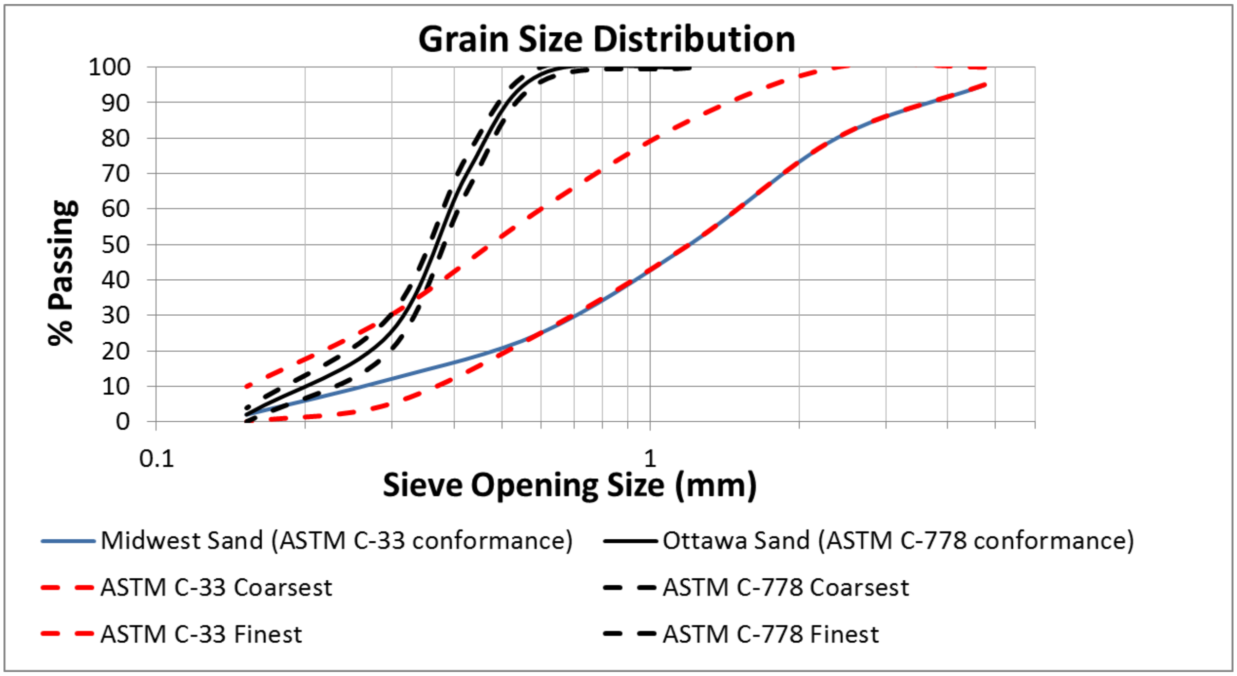


Figure 22. Preliminary wire pullout specimen dimensions

4.1.2 Sand Source (Ottawa Sand vs. Midwest Sand)

Two sand sources were used to develop test specimens. The first source was the "Midwest Sand" conforming to ASTM C33 and described in the previous section. The second source was sieved sand from Ottawa, Illinois which conformed to ASTM C778. The sand from Ottawa, Illinois was supplied by Humboldt Manufacturing Co. in 50-pound containers and will be referred to as "Ottawa Sand" in this report. Since dried and sieved "Ottawa Sand" is readily available for purchasing, this would allow labs located anywhere in the country to readily use the same sand source. The grain-size distributions of both sand sources are shown in Figure 23.



GSD for Midwest Sand

Sieve #	Opening (mm)	% Passing	ASTM C-33 (% Pass)	
			Min	Max
4	4.75	95	95	100
8	2.38	80	80	100
16	1.2	50	50	85
30	0.599	25	25	60
50	0.297	12	5	30
100	0.152	2	0	10

GSD for Ottawa Sand

Sieve #	Opening (mm)	% Passing	ASTM C-778 (% Pass)	
			Min	Max
16	1.20	100	100	100
30	0.599	98	96	100
40	0.425	70	65	75
50	0.297	25	20	30
100	0.152	2	0	4

Figure 23. Sand gradations used for wire pullout specimens

4.1.3 Force Control vs. Displacement Control Test

Before final mix proportions, specimen dimensions, and sand source were established, the researchers investigated the effect of conducting the pullout test in both force-control and displacement-control. In pullout test research conducted by Ramirez and Russell for seven-wire strands (2008), a displacement-controlled test was recommended. However, the researchers wanted to investigate a force-controlled test because required equipment would be less expensive than for a displacement-controlled test, thus allowing invested parties (wire manufacturers, tie manufacturers, and railroad owners) to readily perform the test. Preliminary pullout testing was conducted in displacement control at a rate of at 0.10-in./minute and the loading rate was observed to be approximately 2000 pounds per minute through the linear portion of the load-vs.-strand slip curves.

Using the "Midwest Sand" and WI wire, a pullout test series of 12 specimens was conducted, six in force control and six in displacement control. All 12 specimens were batched at the same time using the same mortar mix, and pullout tests were conducted in a systematic alternating manner (force-control, displacement-control, etc.). Force control tests used a loading rate of 2000 lbs/minute and displacement control tests used a loading rate of 0.1 inch/minute. Both tests loaded the specimen at the bottom, while the applied load and free-end-slip at the opposite (top) end were continuously monitored and recorded using a linear variable differential transformer (LVDT).

Individual results of the force vs. end-slip graphs for the force and displacement control tests are shown in Figure 24. Average results are depicted in Figure 25, and average results excluding the highest and lowest bonding specimens (steepest and shallowest force-vs.-end-slip response) are shown in Figure 26. From Figure 26, both loading methods provide nearly identical data, especially in the ascending region. Therefore, considering test equipment cost and accessibility, the author decided to use a force-controlled setup for the wire pullout test. Any subsequent wire test discussed in this paper was conducted in force control at a loading rate of 2000 lbs/minute. Full specifications of pullout load frame capabilities (as well as additional machinery used for pullout testing) can be found in Section 4.2.5.

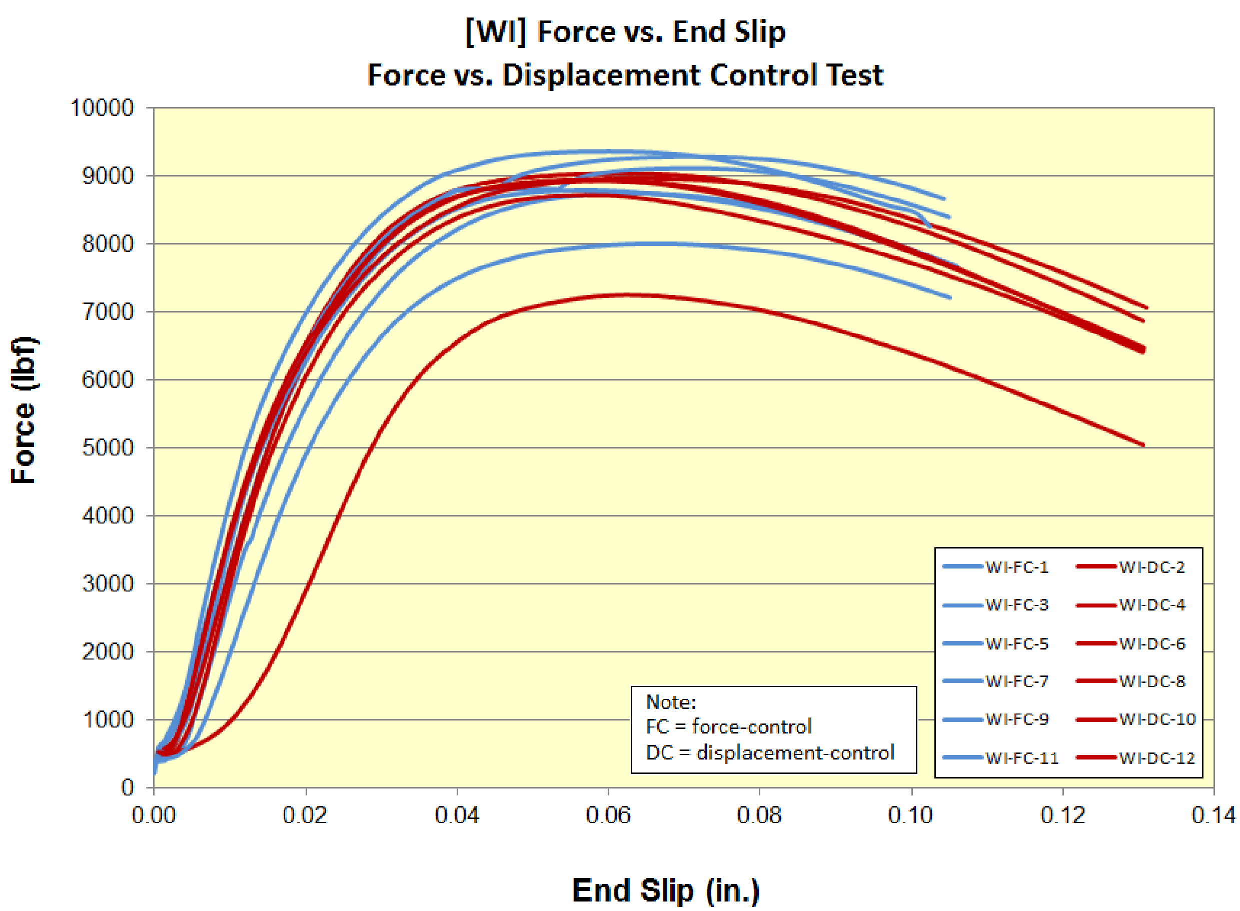


Figure 24. Individual results of force vs. displacement control test

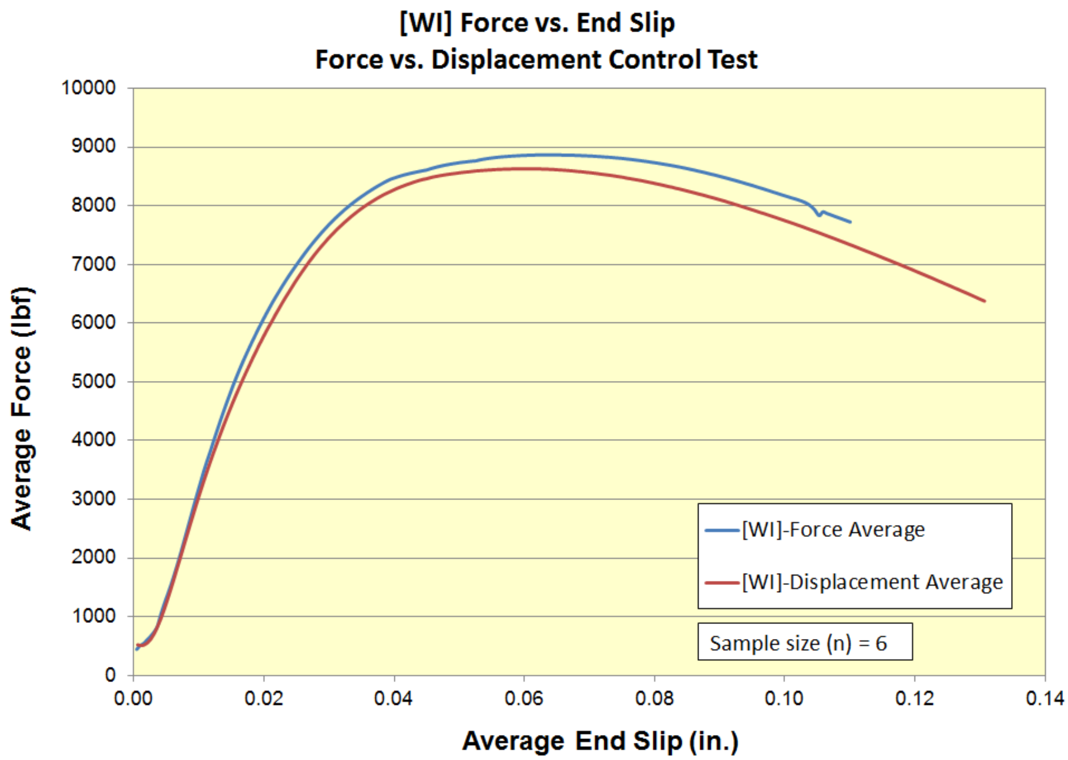


Figure 25. Average results of force vs. displacement control test

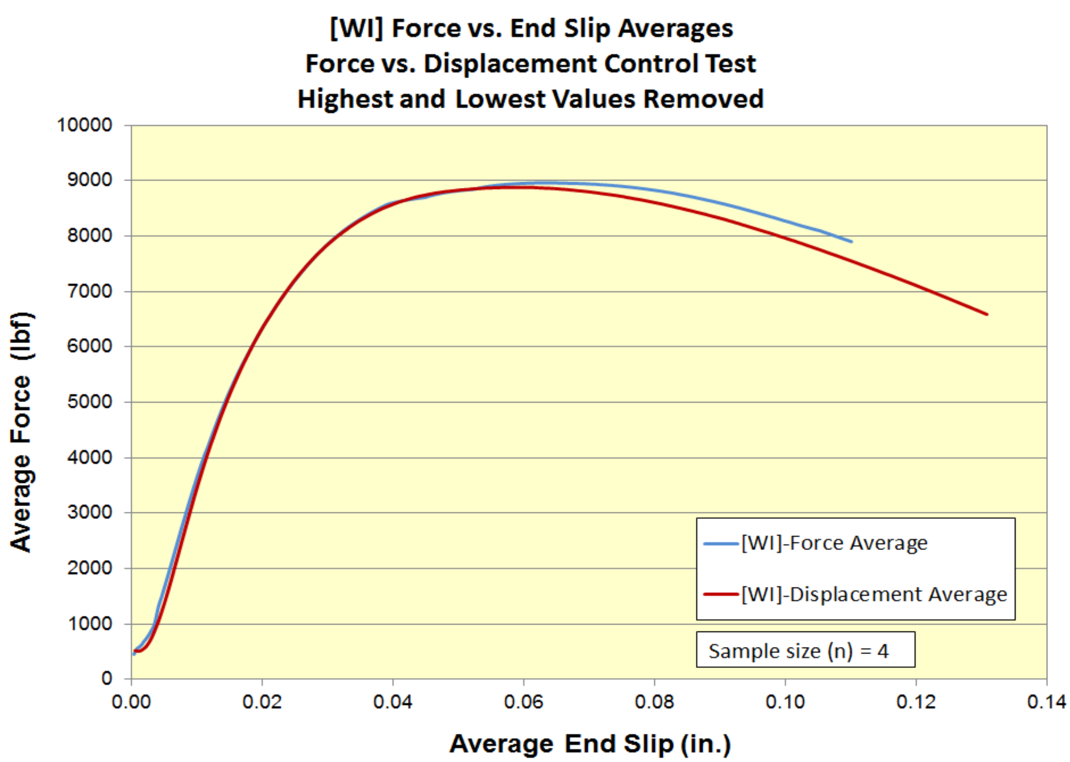


Figure 26. Average results of force vs. displacement control test (min and max excluded)

4.1.4 Rotation Allowed vs. Rotation Restrained Test

The Standard Test for Strand Bond (STSB) prescribes that the stiff test frame used for pullout testing must be "without torsional restraint" (Ramirez and Russell, 2008). This is often accomplished by adding a thrust bearing when connecting the pullout frame to the machine. The frame at Kansas State University has this setup, allowing for specimen rotation during testing (refer to Figure 42).

To determine whether or not this thrust bearing impacted results for wire pullout tests, a special pullout series was conducted in which half the specimens were tested without torsional restraint (with the thrust bearing) and the other half of the specimens were tested with torsional restraint (by removing the thrust bearing). Two wires, WC and WE, were used in this pullout series because they had a spiral indent pattern which is similar to the spiral nature exhibited by multiple-wire strands. Six WC specimens and six WE specimens – three allowed to rotate and three prevented from rotating – were tested on the same day using the same batch of mortar.

The testing order followed a specific process. The three WC specimens allowed to rotate were tested first and then the thrust bearing was removed from the pullout frame. Next, the three WC specimens prevented from rotating were tested, followed by the three WE specimens prevented from rotating. Finally, the thrust bearing was reinstalled on the pullout frame and the final three WE specimens allowed to rotate were tested. Un-sieved Midwest sand was used for these tests.

The hypothesis was made that companion specimens that were not allowed to rotate might exhibit a slightly higher force at a given strand end slip because torsional forces would be present. Averaged results from this test are presented in Figure 27 and Figure 28 for wires WC and WE, respectively.

From Figure 27, the WC specimens with rotation prevented had slightly higher force-vs.-slip response then when rotation was allowed. For the WE specimens, the response was almost identical for the rotation-allowed and rotation-prevented cases. Since test results were not significantly different for the two different restraint conditions, the researchers decided to conduct all additional tests with the thrust bearing present (rotation allowed). This was done so that testing facilities would be able to interchangeably conduct the existing STSB and proposed wire pullout tests without altering the test setup.

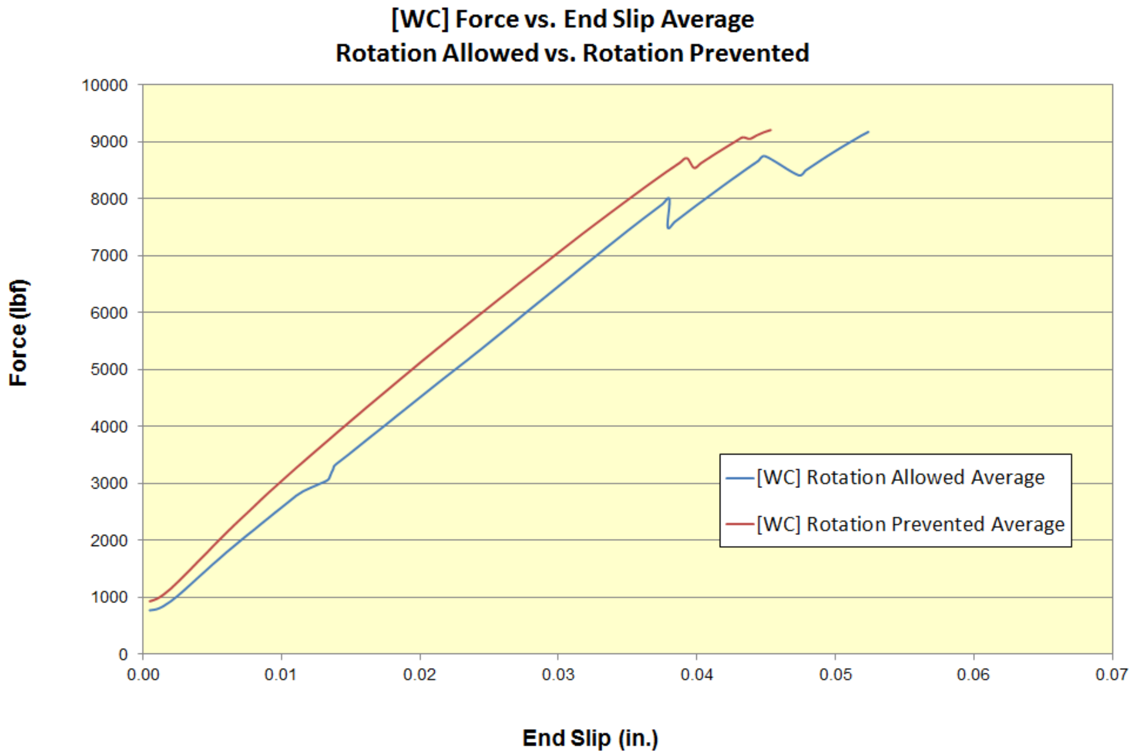


Figure 27. Rotational test results of specimen WC

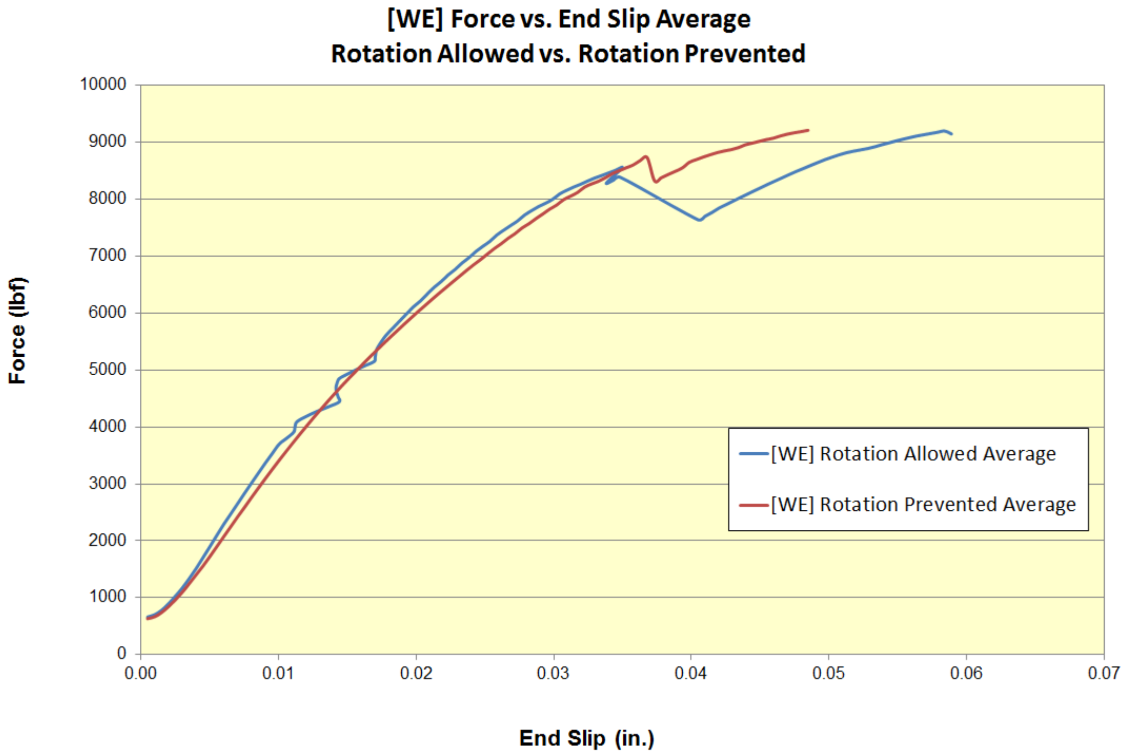


Figure 28. Rotational test results of specimen WE

4.1.5 Finalization of Sand Source and Specimen Size

Specimen size described in Section 4.1.1 was used for all 12 wires (WA through WL) to develop the pullout test. The following parameters were used:

1. Force control with a loading rate of 2000 pounds/min.

2. Rotation allowed through thrust bearing on the load frame

3. Both sand sources were used to test six specimens of all 12 wires to determine which sand gave the most consistent results

When all 12 wires were tested using Midwest and Ottawa sands, the discovery was made that a few of the wire sources were higher-bonding than source WI that was used to set the embedment length at 9 inches (refer to Section 4.1.1). This meant that the highest bonding wire sources would fail by wire material rupture prior to pullout bond failure (desired failure mode). Average pullout force-vs.-end-slip results for preliminary wire specimens using Midwest sand and Ottawa sand are shown in Figure 29 and Figure 30, respectively. Individual force-vs.-end-slip graphs for each wire using each sand source are provided in Appendix B.

The test was stopped automatically using an MTS force limit of 9200 pounds to prevent ruptured wires and damage to the LVDT. This force was selected because it is below the ultimate load for all wires (see Table 3). Any test prematurely terminated resulted in a truncated data set, visually causing the average pullout force vs. end-slip graph to exhibit jagged inconsistencies. Each “dip” in the graphs of Figures 28 and 29 represents sudden termination of one or more of the six specimens (as the pullout force of that specimen reached 9200 pounds). When this occurred, the average data of remaining specimens (at larger end-slip values) is suddenly reduced.

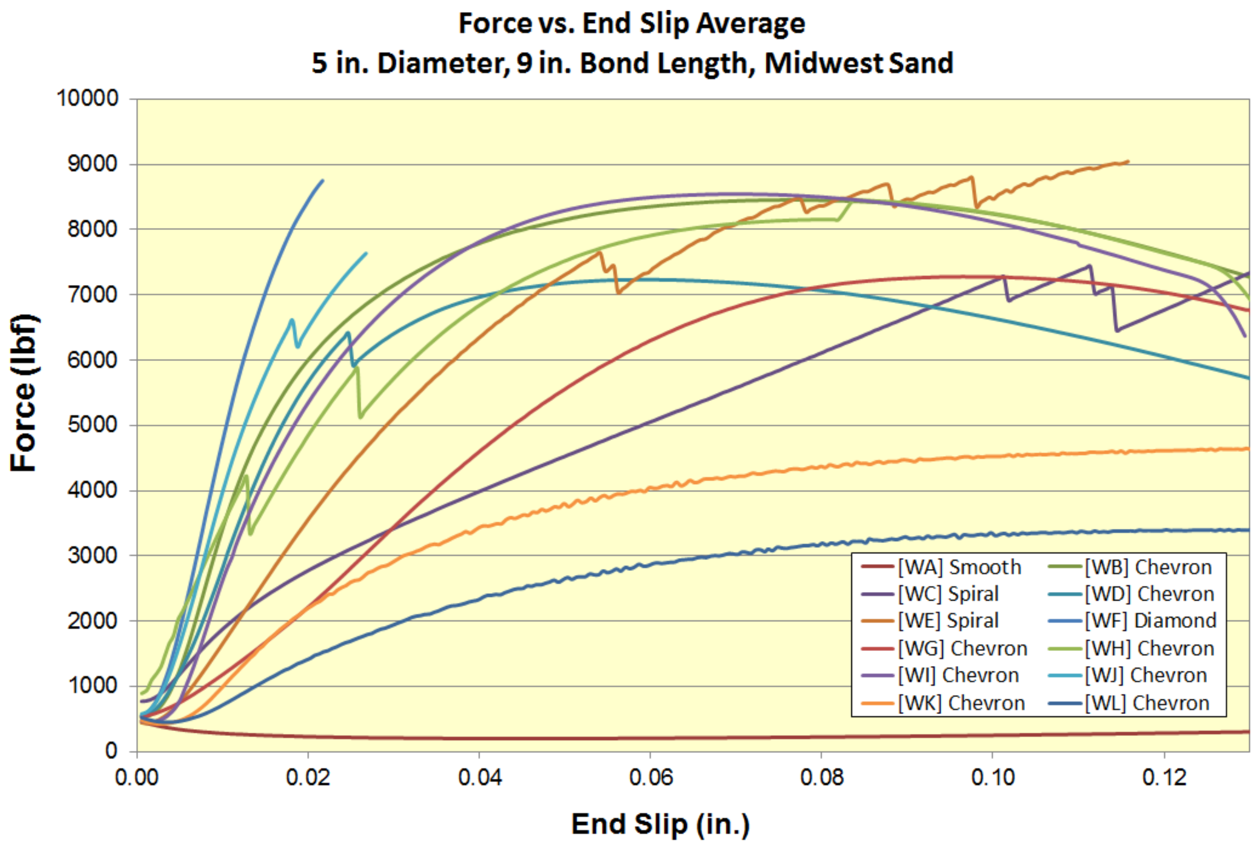


Figure 29. Average force vs. end slip (test development using Midwest sand)

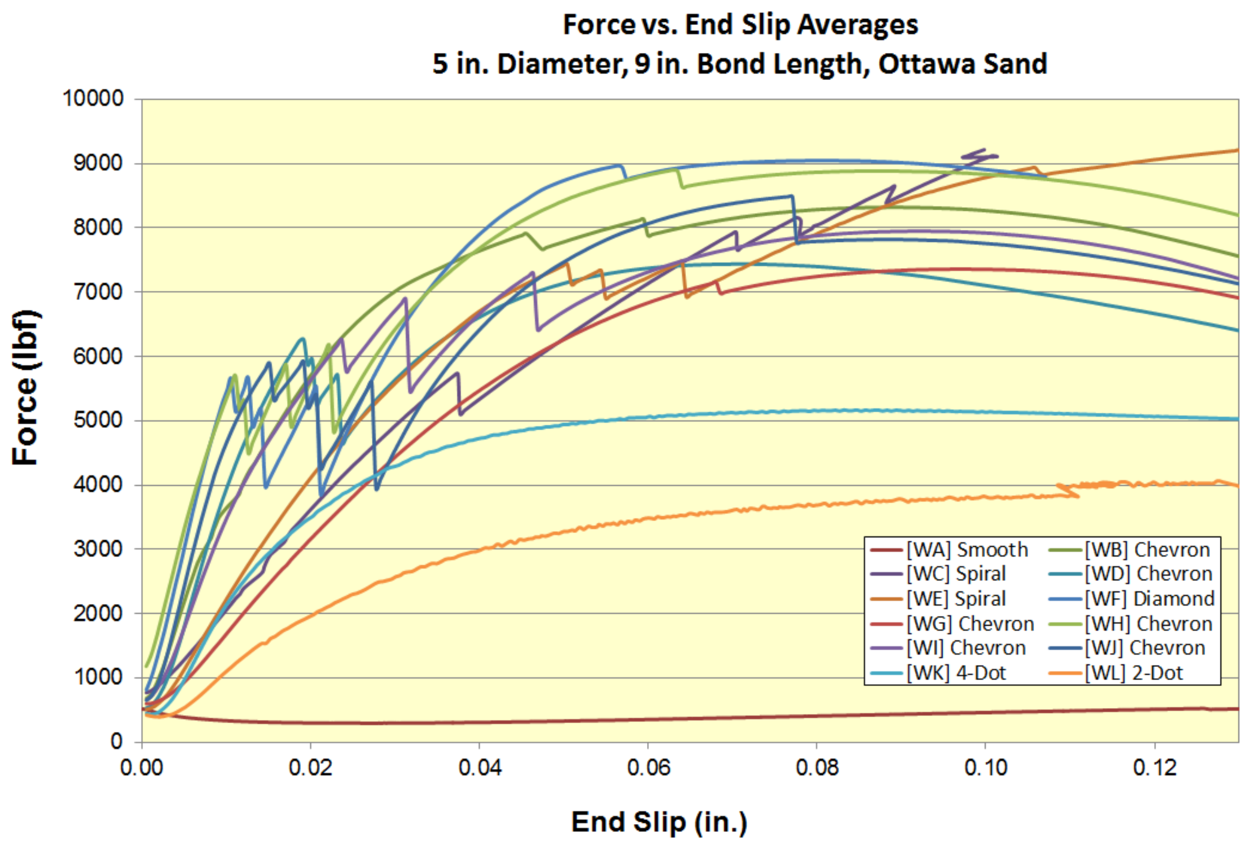


Figure 30. Average force vs. end slip (test development using Ottawa sand)

Results of Figure 29 and Figure 30 clearly indicate that bonded length of the wires (embedment length) should be reduced to ensure a pullout failure for all wire types in the study. To determine the appropriate embedment length, three additional tasks were performed.

1. Determine which sand source provided the most repeatable results as was the original intent of the first round of testing.

2. Vary bond length using the highest bonding wire to determine appropriate bond length.

3. If possible, reduce overall specimen size to reduce materials due to the cost of pre-sieved Ottawa sand.

The first task was completed using a regression analysis that evaluated the performance of the wires in the un-tensioned pullout tests with transfer length measurements from pretensioned prisms manufactured with the same wire types (Bodapati et al., 2013). The summary of Midwest sand and Ottawa sand regression analyses is provided in Figure 31, and full results from both sets of this regression analysis are located in Appendix C. Figure 31 indicates that average results from pullout specimens with Ottawa sand had better correlation with measured transfer lengths from pretensioned prisms, so the Ottawa sand was selected for use in further development of the wire bond test.

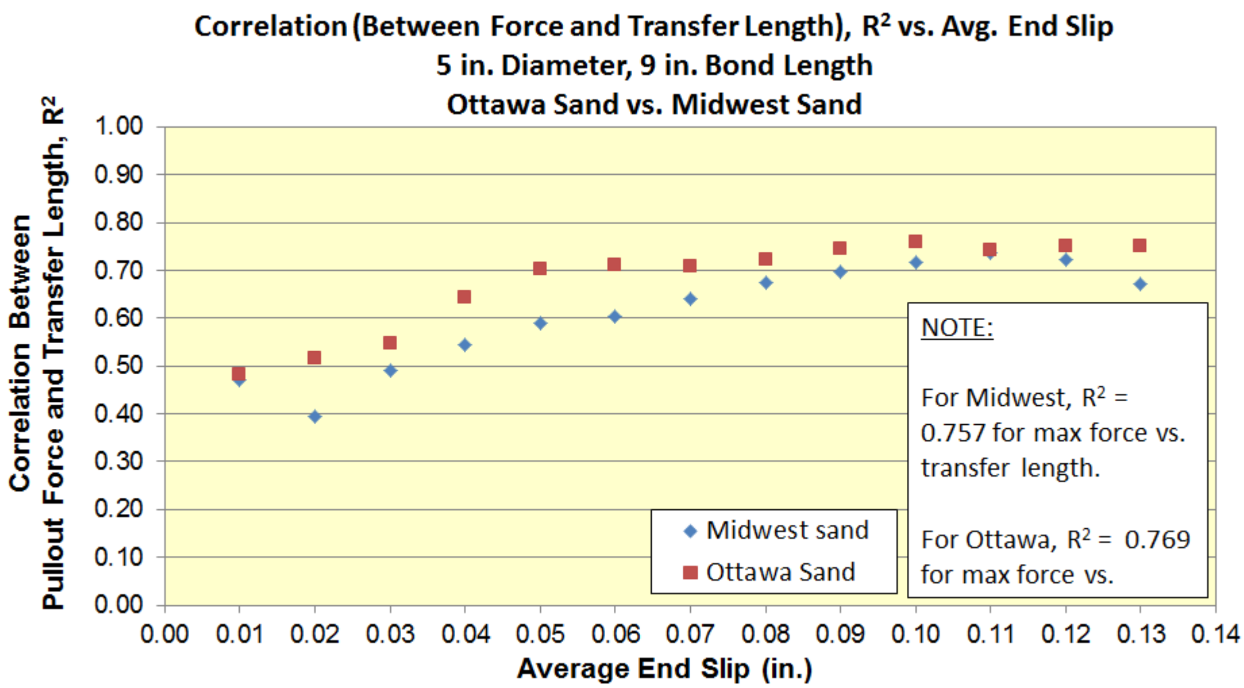


Figure 31. Ottawa vs. Midwest sand specimens' pullout force correlation to transfer lengths

To complete the second task, WF wire source was selected because it exhibited the highest bond in pullout specimens with both Midwest and Ottawa sand. Three different bond lengths were evaluated (5-in., 7-in., and 9-in.). The 9-in. bond length was identical to the previously-used length and was included to verity repeatability of the test. All of the varying bond-length tests were performed in 12-in. tall cylinders, different bond length achieved by changing the length of the bond break material. A total of 12 specimens, 4 with each bond length, were fabricated with the same mortar batch using Ottawa sand. Pullout tests were conducted the following day in a systematic manner by alternating between specimens with different bond lengths.

Results of this test are shown in Figure 32. The 5-in. bond was the only specimen length that demonstrated pullout failures and with no need to terminate the test due to pullout exceeding 9200 pounds. However, maximum pullout force for WF using a 5-in. bond length was only approximately 7300 pounds. Since WF had presented the upper limit of bonding among wires in this pullout testing program, the researchers surmised that a 6-in. bond length would also likely result in a pullout failure below 9200 pounds and may provide the differentiation between pullout test results. Therefore, a 6-in. embedment length was selected for the test.

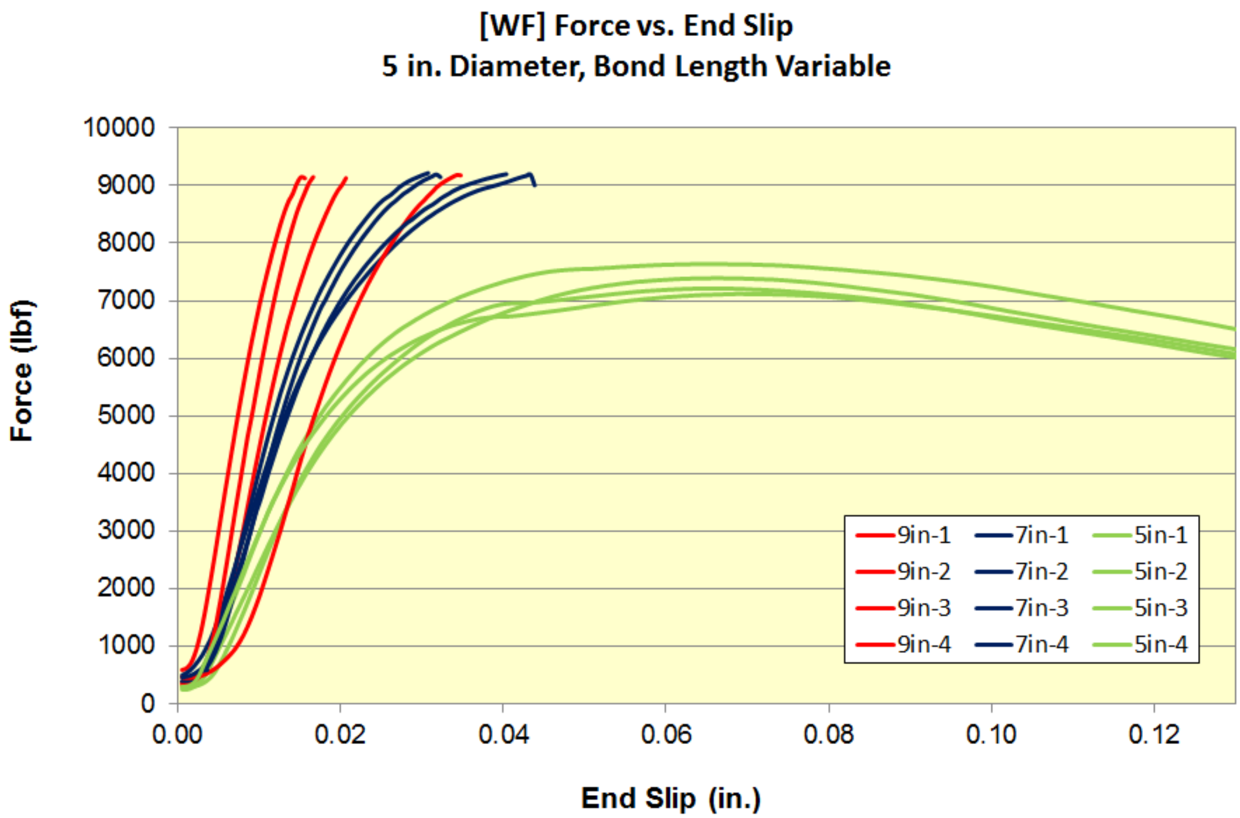


Figure 32. Force vs. end slip for specimen WF with variable bond length

The third task of reducing overall specimen size was accomplished by switching to a 4-in.-diameter tube with a total length of 8-in. Within the 8-in. steel tube, a 6-in. embedment (bond) length was present with a 1-in.-long duct tape bond breaker at the bottom of the tube and a 1-in.-long duct tape bond breaker at the top of the tube (Figure 33). The top bond breaker extended past the top mortar surface by approximately 1 inch to ensure the exact bond length desired in case of settlement. The wire extended past the top mortar surface by approximately 2 inches.

By reducing total specimen length from 12 in. to 8 in. and by switching from a 5-in.-diameter specimen to a 4-in.-diameter specimen, overall material costs would be significantly reduced, since the Ottawa sand is relatively expensive compared to locally-available sands due to drying, sieving and shipping costs. Additionally, a 4"x8" cylindrical specimen size is common in concrete and mortar testing because it is often used for compression strength cylinders. Six individual test results for wire type WF using the test geometry in Figure 33 with Ottawa sand are shown in Figure 34.

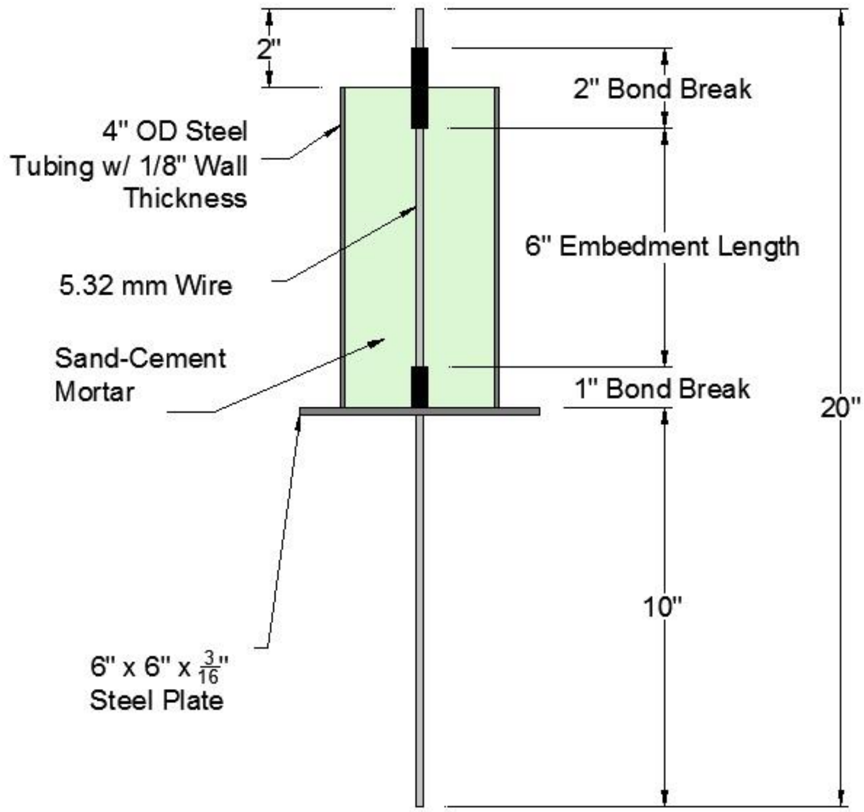


Figure 33. Final dimensions of wire pullout test specimen

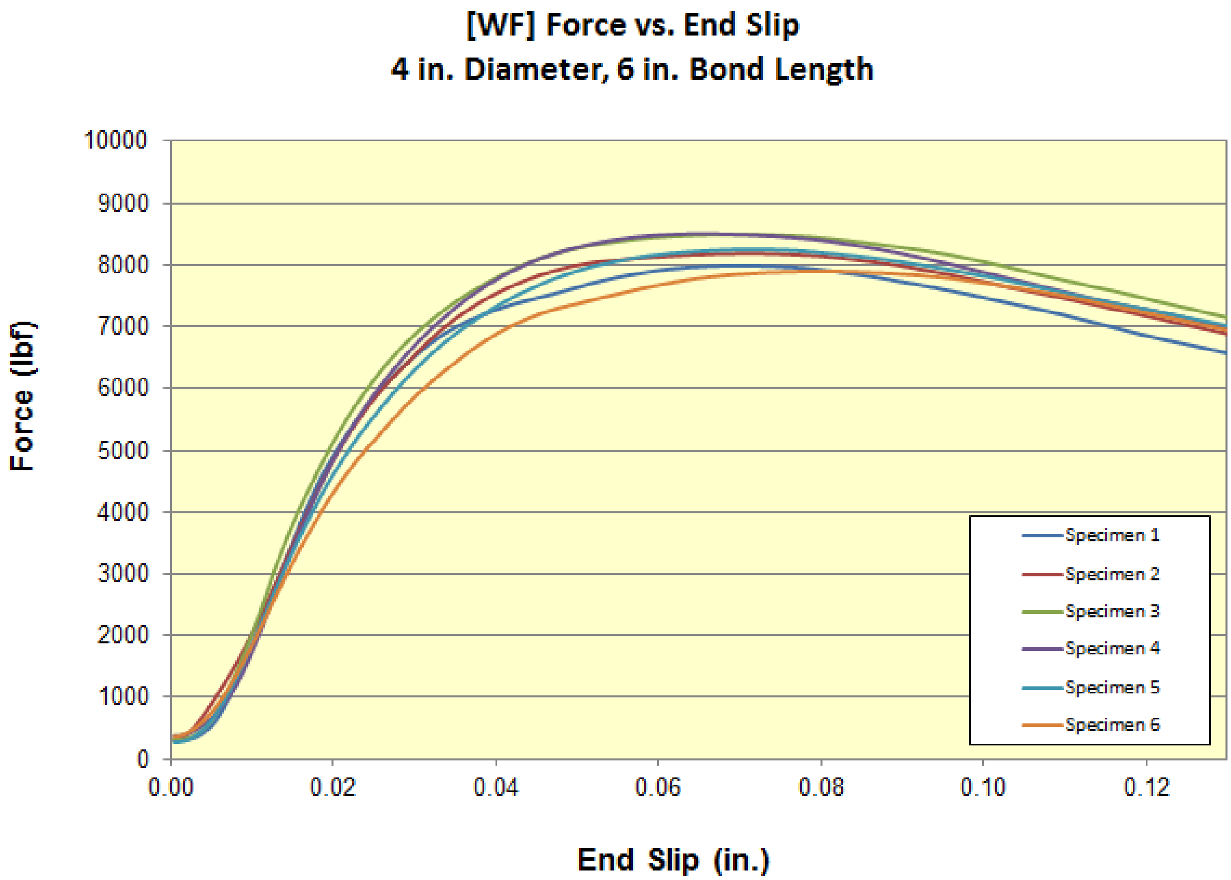


Figure 34. Force vs. end slip for WF in 4-in.-diameter specimen development, 6-in. bond length

4.2 Experimental Program

This section contains information regarding development and verification of a standard pullout bond test for 5.32-mm-diameter steel prestressing wires, including research variables; specimen dimensions; mix proportions, material sources, and batch sizes; specimen casting and storage procedures; and testing procedures to develop the un-tensioned pullout test.

4.2.1 Research Variables

Two primary research variables for the wire testing portion of the lab phase are indent geometry and surface condition. Twelve wires with various indentation patterns and presumably different surface conditions from six steel manufacturers were used to develop the un-tensioned pullout test described in Section 4.1. All wires used were 5.32-mm-diameter, low-relaxation wires that generally conformed to ASTM A881.

The testing matrix for wire pullout tests is shown in Table 4. Each wire was tested six times and the results were averaged to provide the expected bond performance of each wire. The As-received and Cleaned wire pullout test results were compared to transfer lengths from accompanying pretensioned prisms that were fabricated in this same research program using the identical wire sources (Bodapati et al., 2013).

Initially, 12 wire sources WA through WL were used to develop the un-tensioned pullout test and to determine the correlation between pullout test results and transfer length of identical wires in pre-tensioned concrete prisms. Later, a 13th wire (WM) was used to verity the correlation of pullout test results to performance in pre-tensioned applications. Pullout specimens for WM (both As-received and Cleaned) were batched at a later date than the original tests.

Table 4. Matrix of wire pullout testing program (lab phase)

	Wire Manufacturer	Wire Identification	Indentation Type	Number of test specimens: Transfer lengths (# of ends)	Number of test specimens: As-received un-tensioned pullouts	Number of test specimens: Cleaned un-tensioned pullouts
Wires	A	[WA]	Smooth	6	6	6
	A	[WB]	Chevron	6	6	
	A	[WC]	Spiral	6	6	
	B	[WD]	Chevron	6	6	
	B	[WE]	Spiral	6	6	6
	B	[WF]	Diamond	6	6	6
	C	[WG]	Chevron	6	6	6
	D	[WH]	Chevron	6	6	6
	E	[WI]	Chevron	6	6	
	E	[WJ]	Chevron	6	6	
	F	[WK]	4-Dot	6	6	
	F	[WL]	2-Dot	6	6	6
	G	[WM]	Chevron	6	6	6
	Total:			**78**	**78**	**42**

Note: (WM) was used to verity the pullout tests correlation results

4.2.2 Specimen Dimensions

The wire pullout specimens utilized a 4-in.-outer-diameter steel tube, 1/8-in. wall thickness, and a total length of 8-in. A 6-in. by 6-in. steel plate (3/16-in. thick) was tack-welded to the bottom of the tube. The remaining contact surface between the tube and bottom plate was caulked to prevent any leakage. The bottom plate had a 1/4-in.-diameter hole drilled in the center for which to allow the steel wire to pass.

A 6-in. embedment (bond) length with a 1-in.-long duct tape bond breaker was located at the bottom of the 8-in. steel tube and a 1-in.-long duct tape bond breaker was located at the top. The top bond breaker extended past the top mortar surface by approximately 1 inch to ensure exact bond length in case of wire movement during casting. The wire extended past the top mortar surface by approximately 2 inches. A schematic of the wire pullout specimen was presented in Figure 33. The wires were centered in the tube using an additional fixture and secured to the fixture with rebar ties (Figure 35). The 4-in.-diameter steel tubes were re-used by cutting the tack welds, removing the bottom plate, and pushing out the mortar (with a hydraulic actuator and specially-made frame).

Figure 35. Additional fixture used to center reinforcement during casting

4.2.3 Mix Proportions, Material Sources, and Batch Size

A sand-cement mortar mixture was used for all pullout tests. The final mix proportions were a water-to-cement ratio (w/c) of 0.427 and a sand-to-cement (s/c) ratio of 2.0. The cement used was Type III cement from the Monarch Cement Company which conformed to ASTM C150. The mill certification sheet for this cement is shown in Appendix P. Ottawa sand conforming to ASTM C778 was used for all pullout specimens. The sand was pre-sieved and was shipped in 50-pound bags inside of boxes. Figure 36 shows a close-up view of the Ottawa sand used for wire pullout tests.

Figure 36. Ottawa sand used for wire pullout specimens

The As-received specimens were fabricated and tested in groups of 12, with one specimens of each wire type (WA-WL) in each group. Approximately 1.0 ft^3 (139.0 pounds) of mortar was batched for each group of pullout specimens, which was enough to fill all 12 steel specimen tubes plus 12 brass mortar-cube molds and still leave approximately 15 pounds of mortar remaining.

The Cleaned specimens (wire types WA, WE, WF, WG, WH, WL) were fabricated in two groups of 18, with 3 of each wire type included in each batch. For the Cleaned specimens, 196.0 pounds of mortar was batched and each batch was sufficient to fill all 18 steel specimen tubes plus 12 brass mortar-cube molds with approximately 15 pounds of remaining mortar. The mortar batch used for wire WM was identical to the one typically used for As-received specimens (139.0 pounds) since 12 specimens were cast for wire WM (six As-received and six Cleaned).

Total batch weights for the As-received and Cleaned wire pullout tests are shown in Table 5. The As-received and Cleaned mortar batches had identical mix proportions (water-to-cement ratio and sand-to-cement ratio). The only difference between the batches was the total volume needed to accommodate 12 or 18 specimens. The mixer used for all pullout tests was a 1.75 ft^3-capacity pan mixer manufactured by Lancaster Products (Figure 37).

Table 5. Batch weights used for wire pullout specimens

Material	As-Received Batch Weights (lbf)	Cleaned Batch Weights (lbf)
Ottawa Sand	81.1	114.4
Monarch Type III Cement	40.6	57.2
Water	17.3	24.4
Total	**139.0**	**196.0**

Figure 37. Pan mixer used for wire pullout tests

4.2.4 Specimen Casting and Curing Procedures

Each wire was tested six times and the results were averaged. Six mortar batches were made with each batch containing 12 pullout specimens, one with each wire type. The specimens were cast in six different batches so any variations due to slight differences in mortar mixtures would be equally distributed.

Mortar for the wire pullout specimens used the following mixing procedure:

1. Place all sand and cement into the pan mixer and mix for one minute to combine.

2. Start timer while slowly adding all the water.

3. Mix for three minutes.

4. Turn off mixer. Scrape the mixer for two minutes using trowels, giving special attention to any area that collects dry material.

5. Mix for two additional minutes.

Each set of 12 pullout specimens was cast at approximately the same time each day, and the temperature in the curing location was maintained at 73.5 ± 3.5 ^{o}F in accordance with ASTM C109. Mortar temperature, room temperature, relative humidity, and mortar flow were recorded immediately after the mortar was discharged from the mixer.

The consistency of the mortar was determined using a flow table conforming to ASTM C230, and flow value was measured using the method ASTM C1437. The flow measurement process is depicted in Figure 38. Two-inch mortar cubes were made, stored, and tested according to ASTC C109. Pullout specimens were filled in two approximately equal lifts and consolidated using a wand-type vibrator between each lift.

After the specimens and mortar cubes were cast, the top surface of each pullout specimen was smoothed using a small trowel and covered for storage (curing). Pullout test specimens and 2-in. mortar cubes were cured by placing a moist cloth over the top surface of the molds and then covering with plastic. This ensured that the relative humidity of the exposed top surface of the pullout specimens and mortar-cube molds was greater than or equal to 90%. The specimens and cubes were then stored in a temperature- and humidity-controlled, in which the room maintained at a temperature of 73.5 ± 3.5 ^{o}F and a relative humidity above 50%. Figure 39 shows the moist cloth/plastic covering method used for curing the cubes, and Figure 40 shows the curing method used for curing the specimens.

Figure 38. Mortar flow measurement

Figure 39. 2-in. mortar cubes uncovered and covered

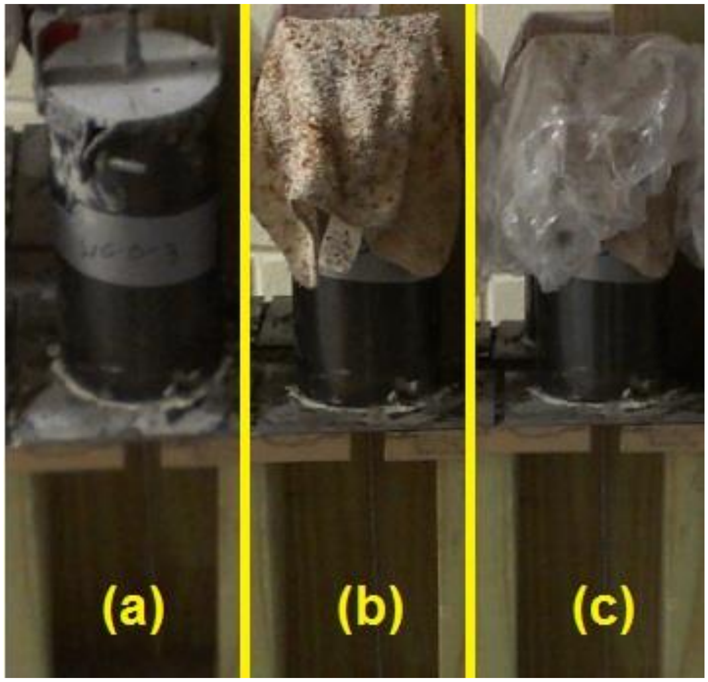


Figure 40. Specimen curing process used at KSU. Specimen is shown (a) after being finished with a trowel, (b) with the moist cloth on top, and (c) with the plastic cover to maintain the moist environment.

Average mortar compressive strength at the time of wire pullout testing (determined from mortar cubes) and mortar flow value are shown in Table 6 for As-received wire specimens and Table 7 for Cleaned wire specimens. Individual mortar cube strengths, flow, and temperature data are located in Appendix D.

Table 6. As-received wire pullout batch summaries

Mortar Batch Name	Avg. Specimen Cure Time (hrs)	Avg. Cube Strength at Time of Test (psi)	Flow Value
Wire Batch #1	20.5	4544	124
Wire Batch #2	19.25	4638	124
Wire Batch #3	20.25	4541	122
Wire Batch #4	25.75	4544	125
Wire Batch #5	20.75	4542	121
Wire Batch #6	20.75	4640	119
Average of Six	**21.25**	**4575**	**122.5**
Wire Batch [WM]	21.5	4560	121

Table 7. Cleaned wire pullout batch summaries

Mortar Batch Name	Avg. Specimen Cure Time (hrs)	Avg. Cube Strength at Time of Test (psi)	Flow Value
Clean Wire Batch #1	17.5	4551	121
Clean Wire Batch #2	18.75	4605	123
Average of Two	**18.25**	**4578**	**122**
Wire Batch [WM]	21.5	4560	121

4.2.5 Testing Procedure and Equipment

Pullout tests were conducted immediately after mortar cube compressive strength reached 4500 psi and ended before cube strength reached 5000 psi. During testing, wires were pulled at a rate of 2000 lbs/minute at the bottom of the specimen, while the applied load and free-end-slip at the opposite (top) end were continuously monitored and recorded. The loading rate of 2000 lbs/min resulted in an average test length of approximately four to five minutes. This test length is similar to other ASTM test standards for concrete members and allowed 18 pullout specimens to be tested within the prescribed 4500-5000 psi compressive strength window. The load was measured by a load cell, while the strand slip was measured using an LVDT. The test setup is shown in Figure 41.

A wire prestressing chuck was used to transfer the load from the lower steel assembly (attached directly to the actuator) to the 5.32-mm wire. The upper steel frame supported the specimen and was suspended from a 100,000-pound-capacity load cell. Note, although a 100,000-pound-capacity load cell was used in the test setup, the load cell was specifically calibrated to a much smaller 10,000 pound range for use in wire testing and a 40,000 pound range for use in strand testing.

A schematic of the pullout load frame used at KSU for pullout testing is shown in Figure 42. This frame is nearly identical to the frame used to develop the Standard Test for Strand Bond (Ramirez and Russell, 2008). A thrust bearing was used between the top plate of the upper frame and the nut securing this frame to the stud that was connected to the load cell (Figure 42). This thrust bearing allowed the top frame to rotate and prevented torsional restraint of the specimens upon loading.

Note, the same testing setup that was used to test the 5.32-mm-diameter wires in this study is also used to test larger-diameter strands using the STSB procedure. Therefore, the pass-through slots in the existing pullout frame were 0.75-in. wide to accommodate large-diameter strands. Since the bearing surface of the wire chucks was smaller than 0.75 in., a steel washer (approximately 1.5-in.-outer diameter and 0.5-in. thick) was fabricated to allow consistent force transfer between the prestressing chuck and lower steel assembly as shown in Figure 43.

An MTS FlexTest GT controller was used to provide closed-loop control of the hydraulic actuator used for the pullout tests. An MTS SilentFlo hydraulic power unit with a 30-gallon-per-minute (gpm) capacity, supplied hydraulic oil at approximately 3000 psi. Data (time, force, and end slip) were collected at every 0.0005-in. of wire free-end-slip. The tip of the LVDT was positioned on the center of the free-end wire and the supporting bracket mounted to the steel can using two magnetic blocks. A close-up view of the LVDT setup and top view of the wire specimen are shown in Figure 44 and Figure 45.

A 250,000-pound capacity Forney testing machine was used to establish the strength of mortar cubes, as shown in Figure 46. A rolling cart was built for the transportation and casting of pullout specimens and mortar cube molds. This cart is presented in Figure 47.

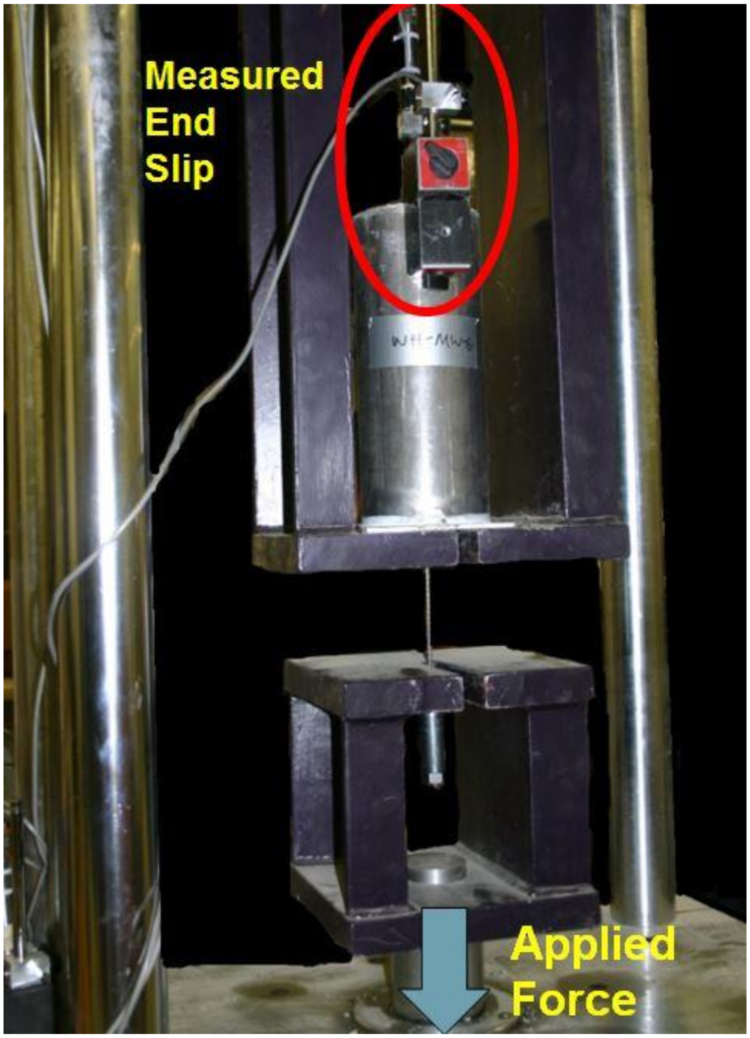


Figure 41. Pullout testing frame with specimen

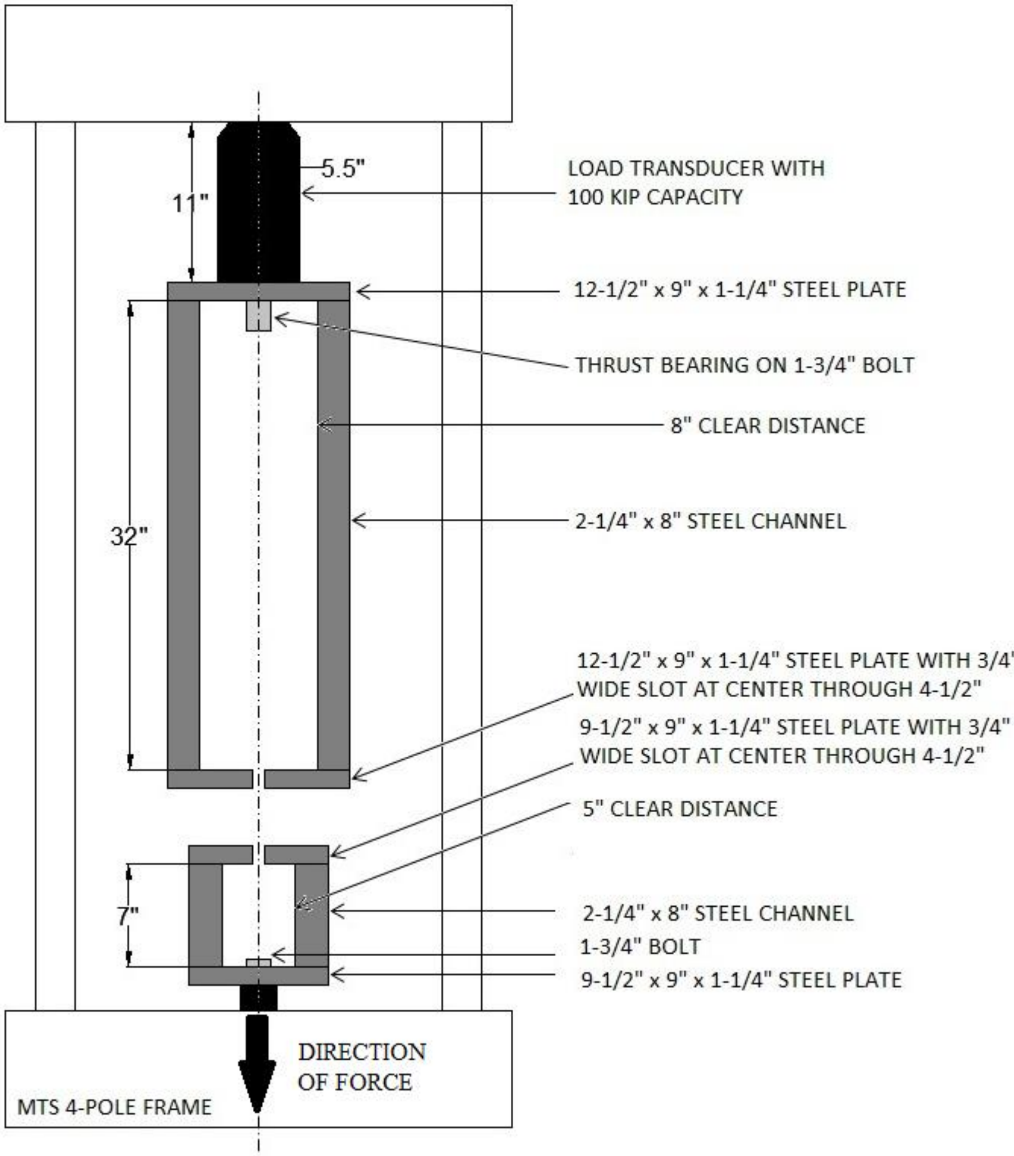


Figure 42. Schematic of pullout load frame at Kansas State University

Figure 43. Washer used to transfer load between wire chuck and lower steel assembly

Figure 44. LVDT and magnetic base setup

Figure 45. Top view of wire specimen

Figure 46. Forney testing machine used for testing mortar cube strength

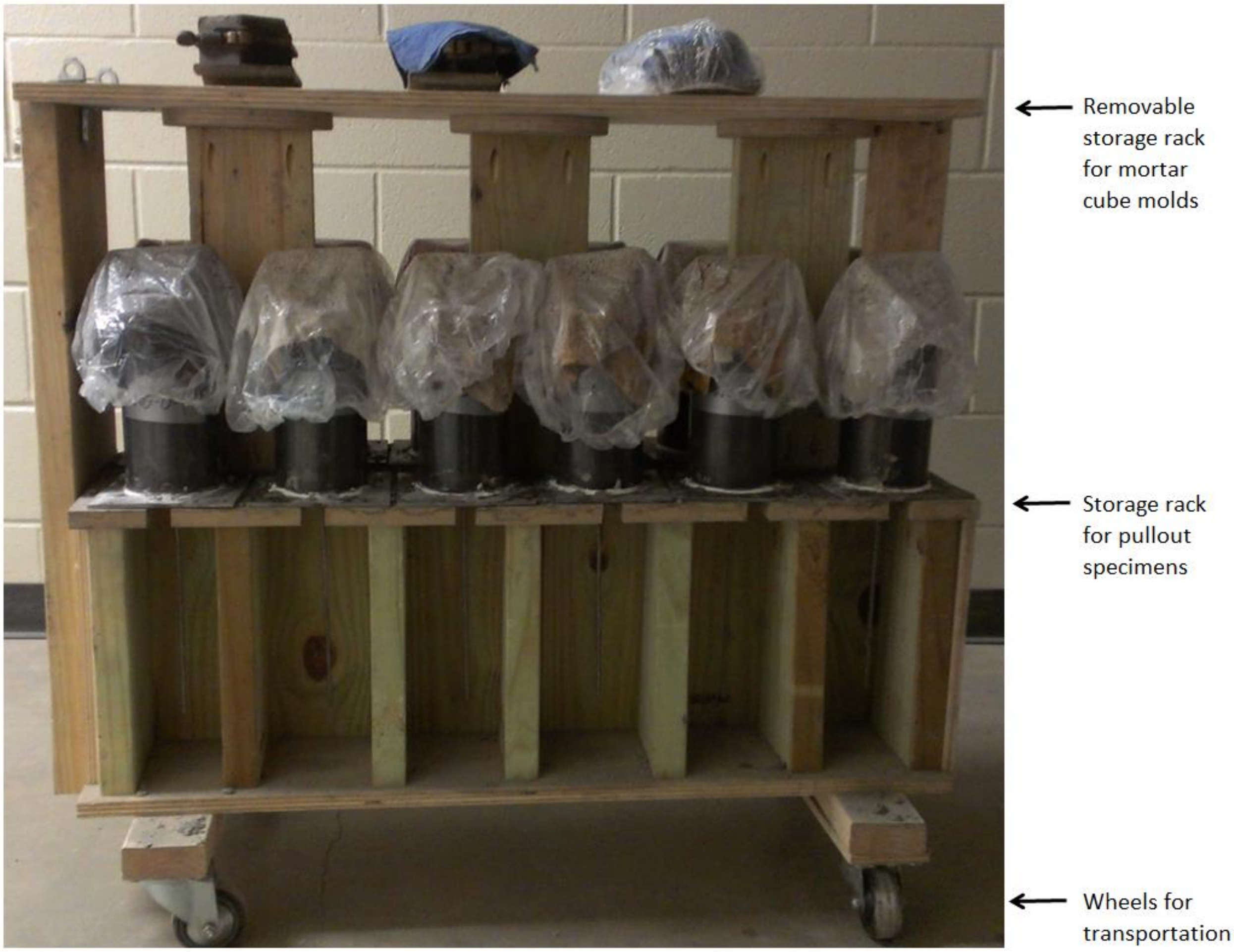


Figure 47. Specimen transportation cart

4.3 Wire Pullout Results and Analysis

Results from the laboratory wire pullout tests are presented in this section. First, results of As-received and Cleaned pullout specimens are presented in succession. The third sub-section presents transfer length measurements obtained from pretensioned concrete prisms using the same wire types. Next, the best method of correlation between pullout tests and transfer lengths is established. The fifth and sixth sub-sections verify the predictive nature of both models (As-received and Cleaned) using the additional wire WM. Finally, results between the As-received data set and Cleaned data set are compared to distinguish between bond attributed to surface condition and bond attributed to indent geometry.

4.3.1 As-received Results

Average As-received force-vs.-end-slip results from each wire source are presented in Figure 48. The average force at each increment of end slip (0.0005 in.) was obtained by adding force results from each of the six specimens and then dividing the sum of force by six.

Each line on the graph represents the average of six individual specimens from the same wire source. Each specimen was cast in a different batch of mortar with identical mix design with the exception of WM. All six WM specimens were cast in the same batch of mortar at a later date (since they were not available during the initial testing). WM specimens were used to verify the As-received-wire correlation model. Force-vs.-end-slip graphs showing individual results of the six specimens for each wire source are included in Appendix E.

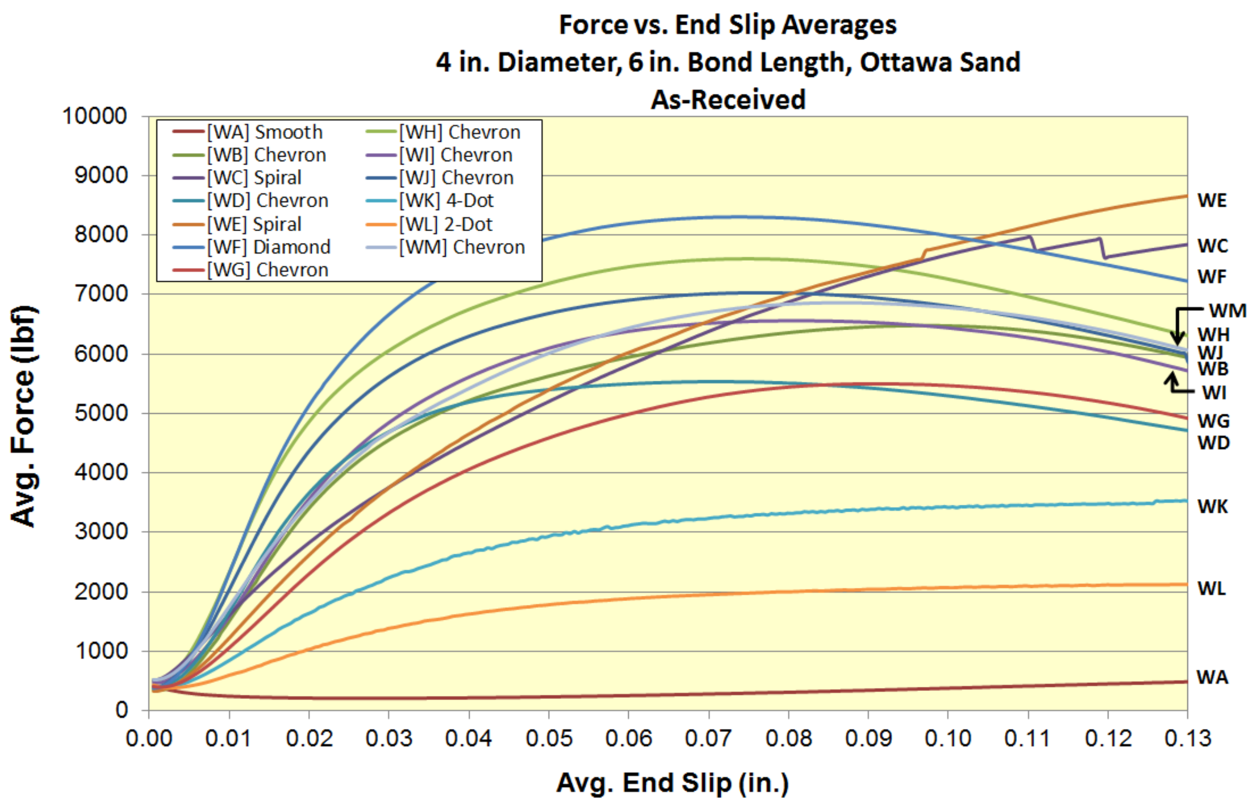


Figure 48. As-received wires, force vs. end-slip averages

4.3.2 Cleaned Results

The averaged cleaned results from each wire source are presented in Figure 49. The average force at each increment of end slip (0.0005 in.) was obtained by adding force results from each of the six specimens and then dividing the sum of force by six.

Each line on the graph represents the average of six specimens from the same wire source. Two batches of mortar with identical mix design were made for the cleaned results. Each batch of mortar contained three specimens of each wire source, except for WM. All six WM specimens were cast in the same batch of mortar at a later date to verify the Cleaned-wire correlation model. Graphs showing individual results of the six specimens for each wire source are included in Appendix E. The wires were cleaned according to the procedure described in Section 3.3.

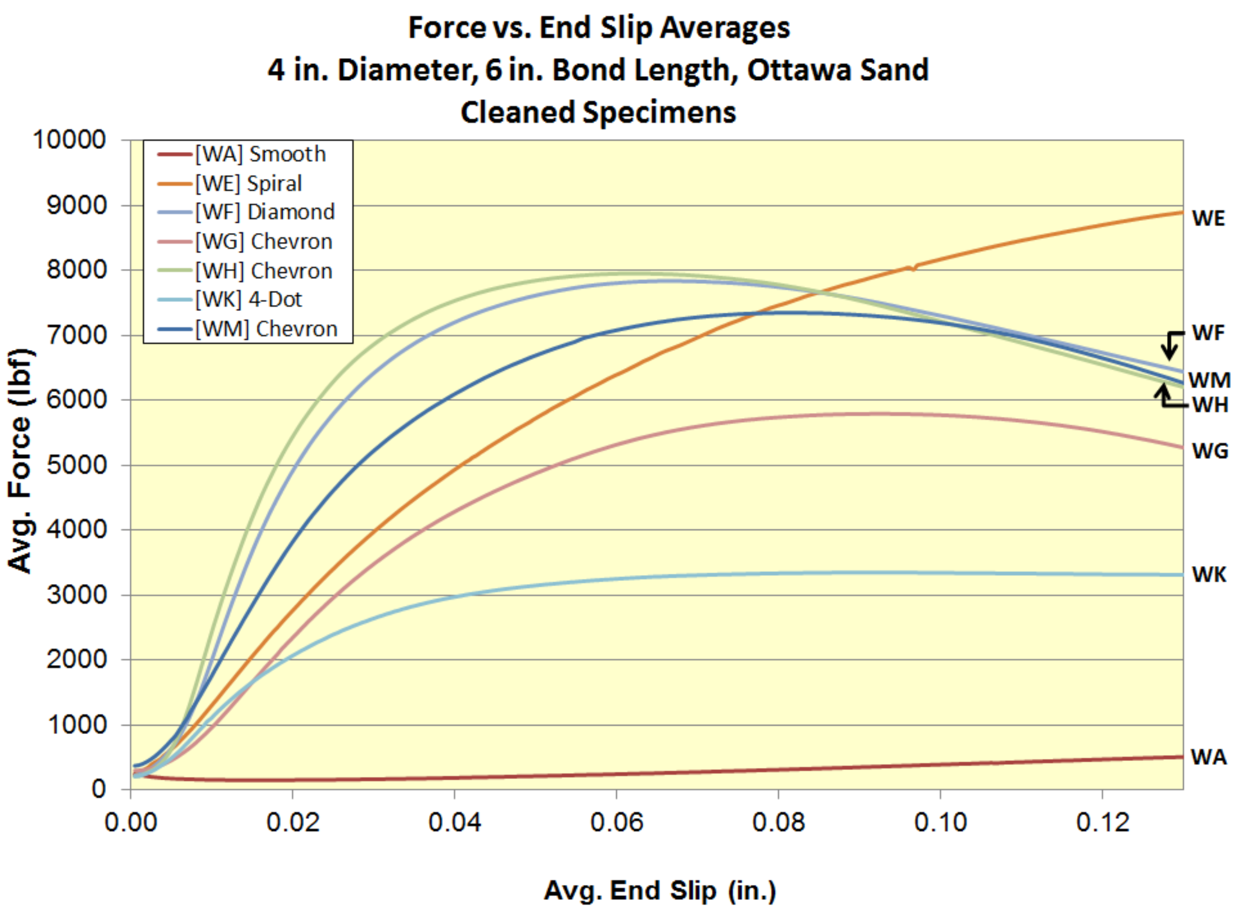


Figure 49. Cleaned wires, force vs. end-slip averages

4.3.3 Transfer Length Data

Data presented in Table 8 shows average wire transfer length measurements, obtained by the KSU research team, determined from measured surface strain data from accompanying pretensioned concrete prisms that were fabricated using the same wire types (WA through WM) as those used in the pullout tests. The transfer-length values are the average of 6 measurements on 3 pretensioned concrete prisms (2 per prism, one at each end). Surface strain data was obtained for the entire length of the prisms. A bilinear strain profile was assumed in calculating the transfer lengths (Bodapati et al., 2013).

Prisms were cast with four wires in a square pattern meant to accurately represent concrete railroad ties. The concrete-to-steel-wire area of each prism was similar to that in typical concrete railroad ties produced in the United States. Additionally, the prisms were cast using a concrete mixture similar to the one used by the LB Foster/CXT Concrete Tie manufacturing facility in Tucson, AZ. The prisms were de-tensioned at approximately 4500 psi ± 200 psi. Actual concrete strength at the time of de-tensioning for each batch is listed in Table 8. Batching and testing procedures used to obtain transfer lengths from these pretensioned prisms are presented in Bodapati's 2013 paper, but are not discussed here.

Table 8. Wire transfer length data

Wire Identification	Avg. Transfer Length (in.)	Concrete Strength at De-tensioning (psi)
[WA]	16.3	4664
[WB]	11.6	4453
[WC]	8.8	4701
[WD]	11.1	4400
[WE]	7.4	4650
[WF]	8.5	4466
[WG]	11.8	4697
[WH]	7.5	4695
[WI]	10.1	4547
[WJ]	9.0	4521
[WK]	14.0	4572
[WL]	18.7	4476
[WM]	9.8	4506

Note: Sample size = 6

4.3.4 Selecting the Method of Analysis

All methods of analysis in this section compare results from Section 4.3.1 (As-received wire pullout data) to results from Section 4.3.3 (wire transfer length data).

Data from wire pullout specimens were analyzed using four methods:

1. Average pullout force at certain free-end-slips

2. Free-end-slip at certain average pullout forces

3. Slope between certain free-end-slip values (0.01 to 0.03 in.)

4. Slope between a certain force values (1000 to 4000 lbf)

4.3.4.1 Average Pullout Force Corresponding to Specific End-Slip Value

The first method of analysis consisted of determining the pullout force required to cause a specific amount of end slip. The standard test for strand bond, ASTM A1081, states the test result should be reported as the pullout force at 0.10-in. of end slip. From NASP Round 2 testing (Russell and Paulsgrove, 1999b), the most reproducible results between multiple testing sites were found at a force occurring at 0.10-in. of end slip.

Researchers in this experimental program sought to determine if the pullout force at 0.10-in. of free-end-slip would provide the best correlation with measured transfer lengths or if better correlation could be achieved using the average pullout force corresponding to some other amount of end slip. Therefore, average pullout force at different end-slip values was compared to average transfer lengths of similar wire types. The pullout force corresponding to end-slip values ranging from 0.01-in. to 0.13-in., in increments of 0.01-in. of end slip, was extracted from the data for all 12 wires types and compared to the transfer length data.

Additionally, maximum force occurring at an end slip less than or equal to 0.10-in. was also compared to transfer length data. This limit of 0.10-in. was used because tests were conducted in force-control and because several wire types had maximum force values that occurred when end-slip values were less than 0.10-in. (i.e. an end slip of 0.10-in. was on the descending portion of the force-vs.-end-slip graph).

The coefficient of determination (R^2) between pullout force and transfer length was calculated for each data set described in the previous paragraph. A limited selection of these results are shown in the main body of this report. Results of force at 0.10-in. of end slip compared to transfer length are shown in Table 9 and Figure 50. Results of maximum force less than or equal to 0.10-in. of end slip compared to transfer length are provided in

Table 10 and Figure 51. All results of pullout force at end slips ranging from 0.01-in. to 0.13-in., in increments of 0.01-in. of end slip, are included in Appendix F. The x-coordinate (abscissa) of each point in these graphs represents the average of six transfer length readings; the y-coordinate (ordinate) of each point in these graphs represents the average of six pullout forces required to cause indicated end slips. The R^2 is the correlation between these two averaged data sets.

In addition, the data was re-analyzed for the data set including only wires with non-continuous indentations because pullout tests on smooth and spiral wires (WA, WC, and WE) result in a noticeably-different force-vs.-end-slip behavior than individually-indented wires and researchers wanted to determine if better correlation could be achieved for wires with non-continuous indentations. Therefore, the total number of wires (data points) was decreased to nine for all data sets discussed. Results of the "force at 0.10-in. end slip" are presented in Table 9 and Figure 52. Results of the "max force less than or equal to 0.10-in. end slip" are shown in

Table 10 and Figure 53. The entire set of results of pullout force at end slips ranging from 0.01-in. to 0.13-in., in increments of 0.01-in. of end slip and excluding smooth and spiral wires, is included in Appendix F.

Results of regression analysis for all 12 wires and nine wires (wires with non-continuous indents only) are summarized in Table 11 and Figure 54. The correlation between average pullout force and average transfer length (R^2) is plotted at each increment of end slip. As shown, the R^2 value consistently trends upward and then consistently decreases. This trend occurs for 12-wire and nine-wire data sets, thus indicating reliable results.

For the 12-wire data set (Table 11), average pullout force corresponding to 0.10-in. of end slip provide the highest correlation with measured transfer lengths ($R^2 = 0.872$). However, slightly higher correlation is achieved when maximum pullout force less than or equal to an end slip of 0.10-in. is used ($R^2 = 0.882$). For the nine-wire data set, the pullout force at 0.06-in. end slip, 0.07-in. end slip, and maximum pullout force (ES ≤ 0.10-in.) had nearly identical R^2 values of 0.920, 0.920, and 0.916, respectively.

Thus, for both data sets, the maximum pullout force occurring at an end slip that is less than or equal to 0.10-in. provides essentially the best correlation to measured transfer length data. For the data set including all 12 wires the coefficient of determination, R^2, with this method is 0.882. For the 9-wire data set that excludes smooth and spiral wires the coefficient of determination, R^2, with this method is 0.916.

Table 9. As-received wires, pullout force at 0.10-in. end slip

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Pullout Force at 0.10 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	378	32	8.5	16.3
[WB]	6473	563	8.7	11.6
[WC]	7663	969	12.6	8.8
[WD]	5302	300	5.7	11.1
[WE]	7817	487	6.2	7.4
[WF]	7993	441	5.5	8.5
[WG]	5469	388	7.1	11.8
[WH]	7270	462	6.4	7.5
[WI]	6439	498	7.7	10.1
[WJ]	6814	591	8.7	9.0
[WK]	3434	347	10.1	14.0
[WL]	2067	323	15.6	18.7

Note: Sample Size = 6, WE = 5

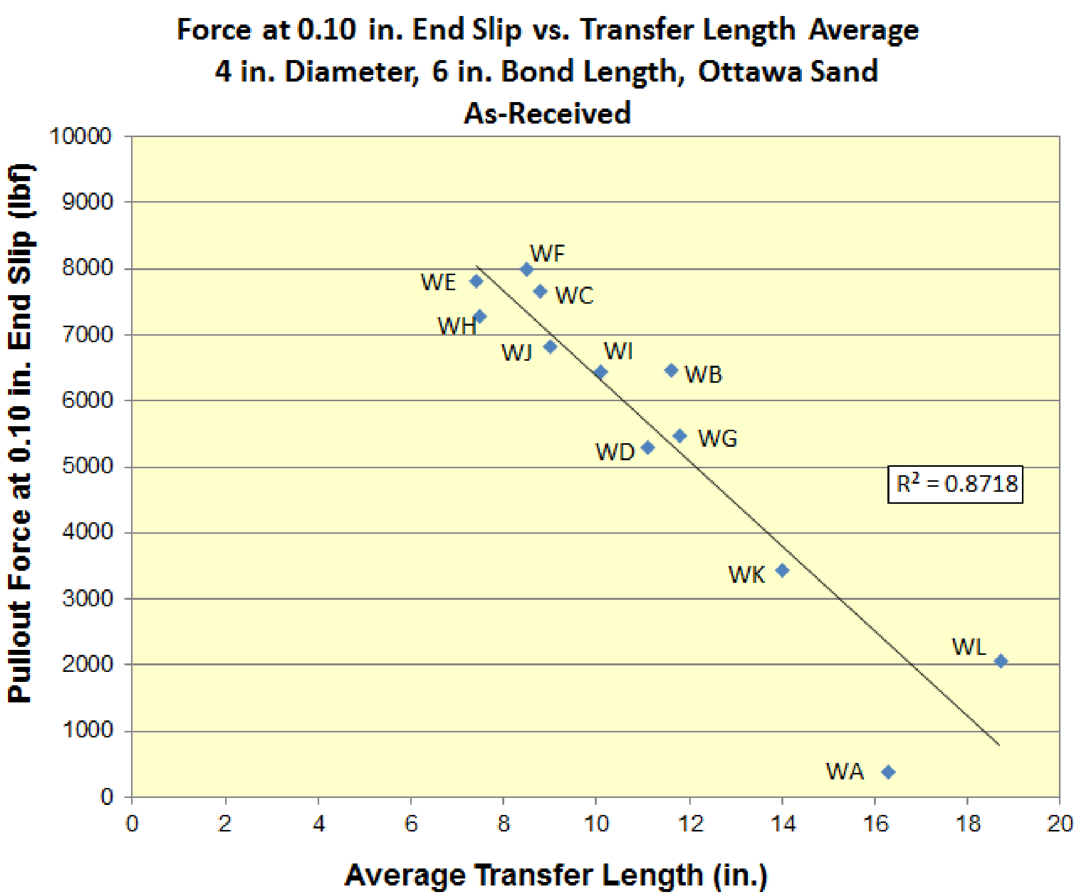


Figure 50. As-received wires, pullout force at 0.10-in. end slip

Table 10. As-received wires, maximum pullout force for end slip ≤ 0.10-in.

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Maximum Pullout Force				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	487	42	8.7	16.3
[WB]	6481	570	8.8	11.6
[WC]	7646	967	12.6	8.8
[WD]	5555	357	6.4	11.1
[WE]	7674	526	6.9	7.4
[WF]	8312	459	5.5	8.5
[WG]	5505	385	7.0	11.8
[WH]	7605	497	6.5	7.5
[WI]	6567	522	8.0	10.1
[WJ]	7034	635	9.0	9.0
[WK]	3447	354	10.3	14.0
[WL]	2068	322	15.6	18.7

Note: Sample Size = 6

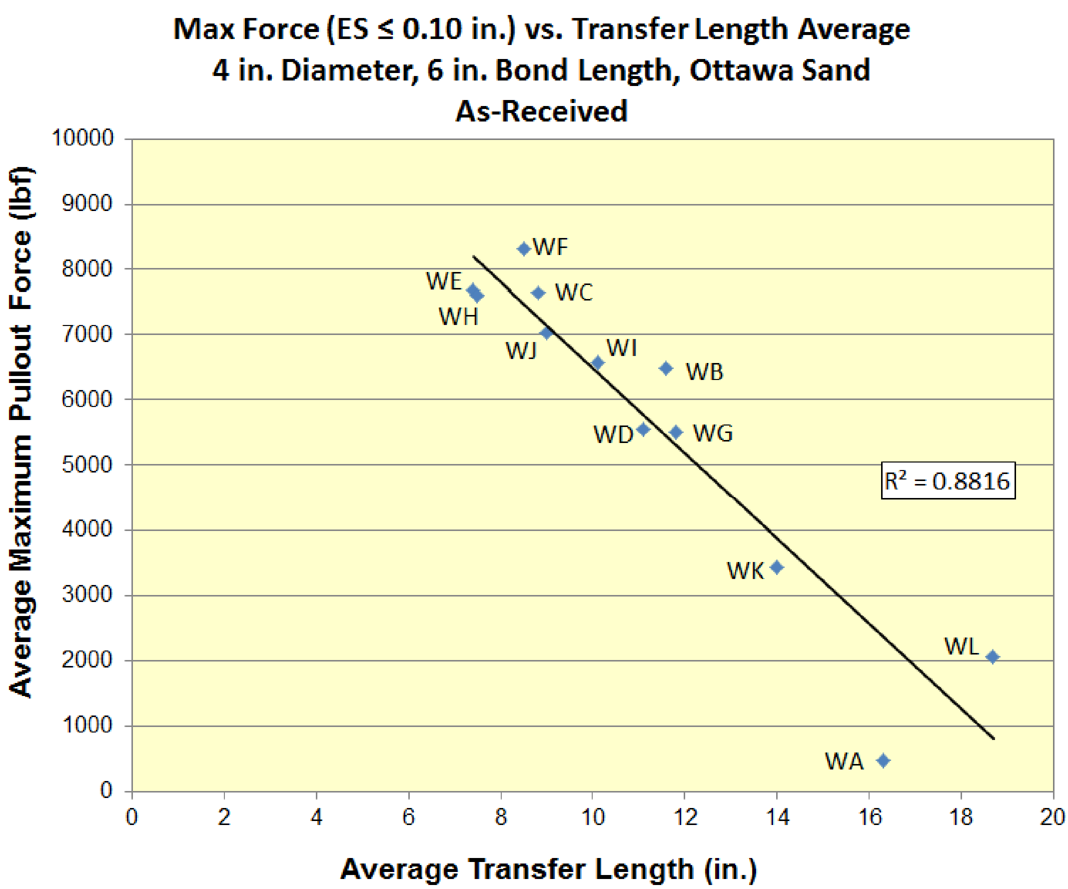


Figure 51. As-received wires, maximum pullout force for end slip ≤ 0.10-in.

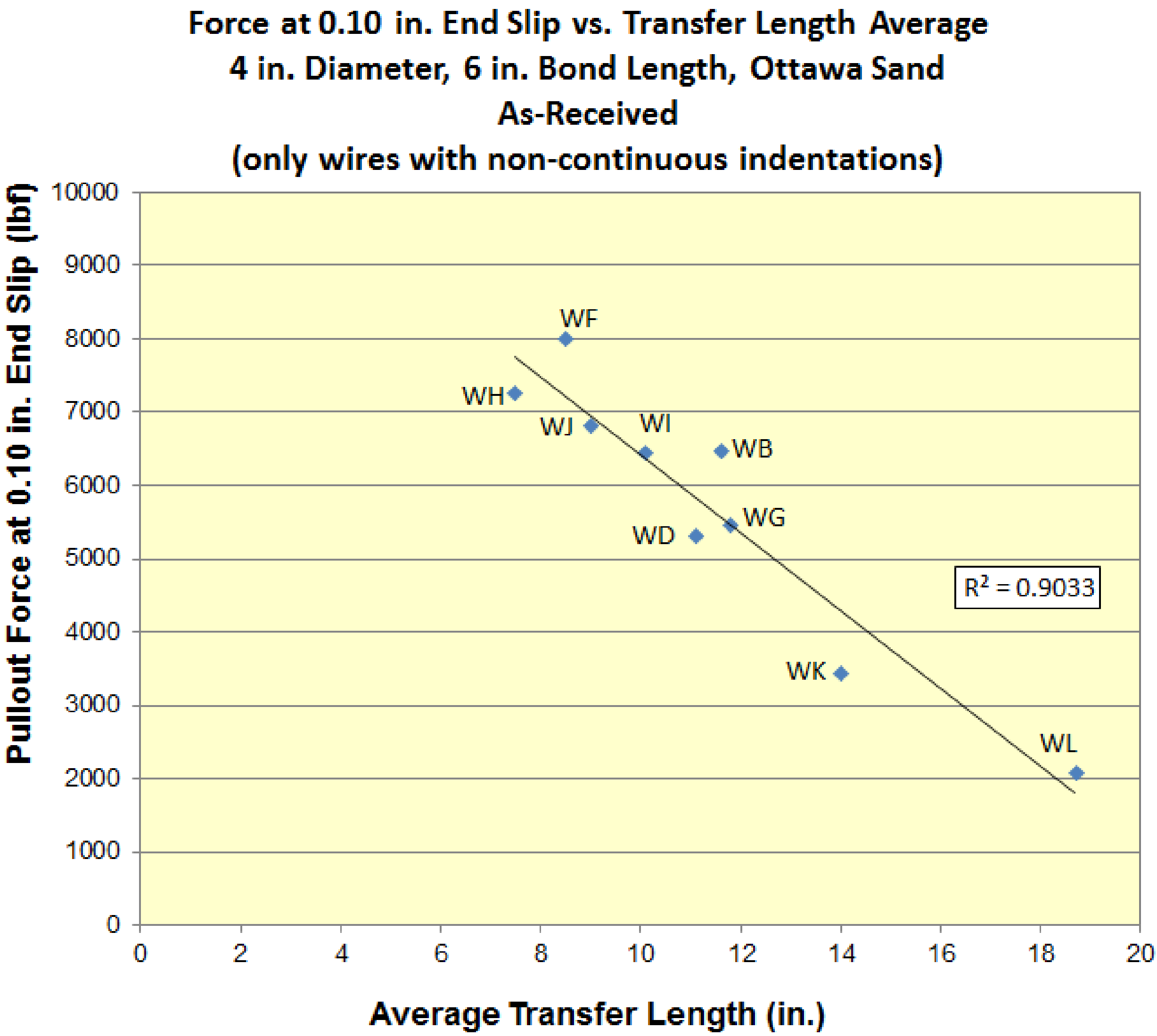


Figure 52. As-received wires, pullout force at 0.10-in. end slip (individual-indents only)

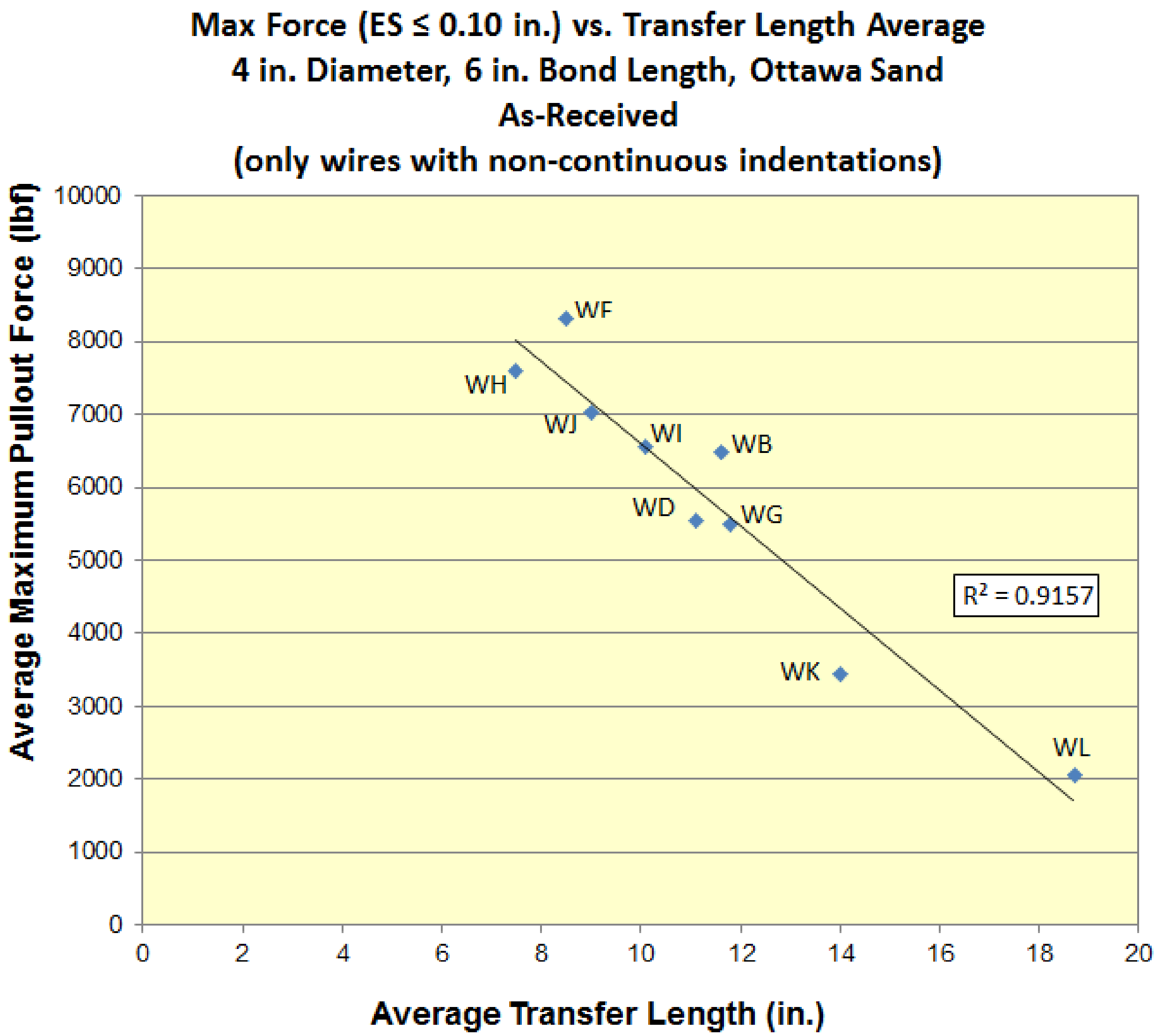


Figure 53. As-received wires, maximum pullout force (individual-indents only)

Table 11. As-received wire regression summary, force at an end slip

End Slip (in.)	R^2	
	All 12 wires	9 wires (individual-indents only)
0.01	0.668	0.834
0.02	0.653	0.864
0.03	0.686	0.888
0.04	0.732	0.904
0.05	0.776	0.915
0.06	0.812	0.920
0.07	0.839	0.920
0.08	0.858	0.917
0.09	0.868	0.910
0.10	0.872	0.903
0.11	0.862	0.893
0.12	0.853	0.884
0.13	0.828	0.878
Max Force ≤ 0.10	0.882	0.916
Highest R^2 of set	**0.882**	**0.920**

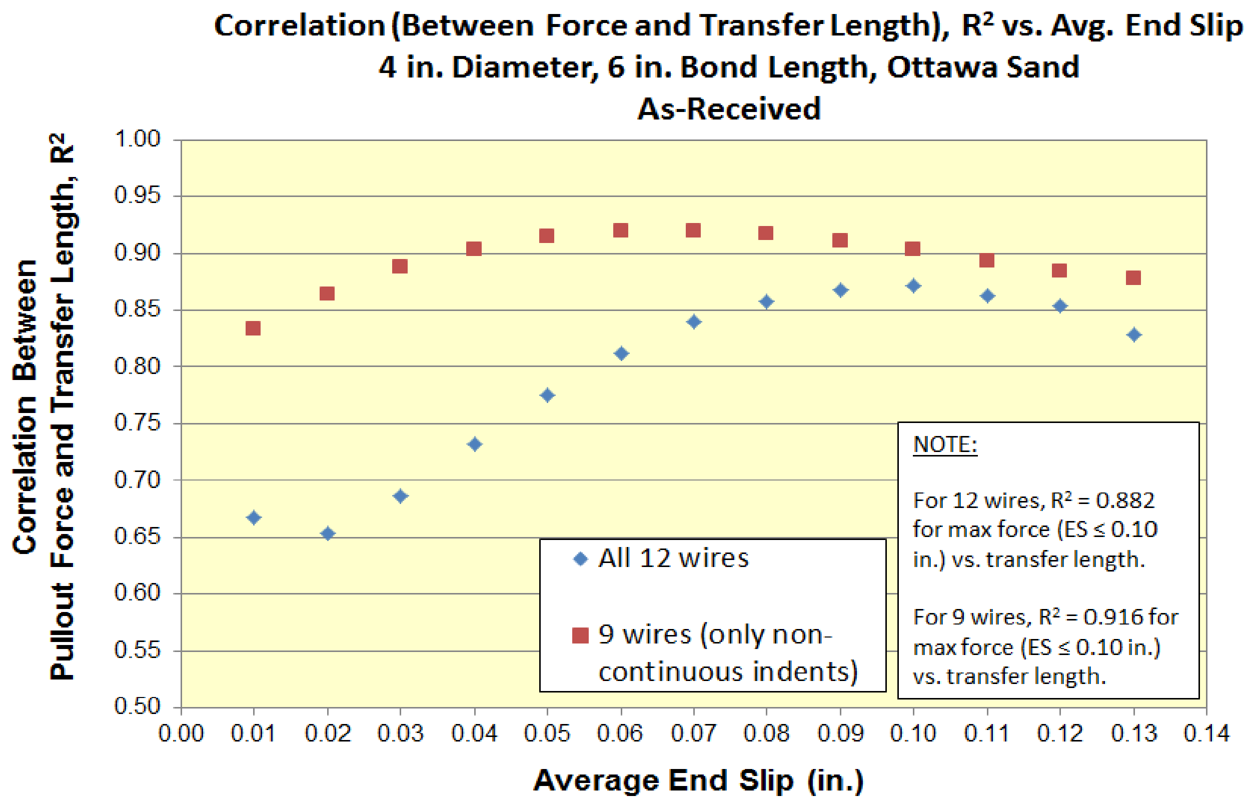


Figure 54. As-received wire regression summary, force at an end slip

4.3.4.2 Average End Slip Corresponding to Specific Pullout Force Value

In this method of analysis, the average end slip at a specific pullout force was compared to average transfer lengths. For all 12 wire types, average end-slip value was determined at pullout forces ranging from 1000 pounds to 6000 pounds in increments of 500 pounds. Using this analysis method, some wire types did not reach the targeted force value due to their lower bond performance. For example, wire WA is not included in any data sets because it never reached the 1000-pound target value. Any wire type that did not reaching the desired force level was omitted from that particular data set. Omitted wires are indicated in Table 12 and Table 13 by an absence of data in the end slip, standard deviation, and coefficient of variance (C.V.) columns. A similar analysis procedure was used for a 9-wire data set that included only wires with non-continuous indentations.

The coefficient of determination (R^2) value between end slip and transfer length was calculated for each data set previously described. A limited selection of these results is included in the main body of this report. Results of the end slip at 1000 pounds of force compared to transfer length are shown in Table 12 and Figure 55. Similar results corresponding to a pullout force of 3500 pounds are presented in Table 13 and Figure 56. The entire set of results of end-slip values corresponding to pullout forces from 1000 to 6000 pounds, in increments of 500 pounds, are listed in Appendix G.

Figure 57 and Figure 58 are for the data set including only wires with non-continuous indents. The x-coordinate (abscissa) of each point in these graphs represents the average of six transfer length readings; the y-coordinate (ordinate) of each point in these graphs represents the average of six end slips caused by the indicated applied force. The R^2 is the correlation between these two averaged data sets.

Results of regression analysis for all applicable wires and all applicable individually-indented wires are summarized in Table 14 and Figure 59. The correlation between average end slip and average transfer length (R^2) is plotted at each increment of force. The R^2 value shows no consistent trend for any location of the graph, in contrast to the case for “force at an end slip” analysis, thus indicating that this method of analysis is not consistent and may be subject to large biases despite the high correlation at a select few locations.

For both data sets, the end-slip values corresponding to a pullout force of 1000 pounds of applied force provide the highest correlation to transfer lengths data for this method of analysis (end slip at a force). For the data set including all 12 wires, an $R^2 = 0.844$ was achieved, and for the 9-wire data set, an $R^2 = 0.943$ was found. However, this high degree of correlation may not be reliable due to the inconsistent trend in the correlation data shown in Figure 59.

Table 12. As-received wires, end slip at 1000-lbf force

As-Received Wire Bond Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand End Slip at 1000 lbf of Force				
Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0075	0.00190	25.3	11.6
[WC]	0.0056	0.00114	20.2	8.8
[WD]	0.0067	0.00161	23.9	11.1
[WE]	0.0082	0.00133	16.1	7.4
[WF]	0.0055	0.00066	12.2	8.5
[WG]	0.0095	0.00231	24.3	11.8
[WH]	0.0050	0.00142	28.6	7.5
[WI]	0.0066	0.00106	16.1	10.1
[WJ]	0.0060	0.00148	24.8	9.0
[WK]	0.0117	0.00273	23.4	14.0
[WL]	0.0200	0.00495	24.8	18.7

Note 1: Sample Size = 6

Note 2: A blank entry means the wire didn't reach that force

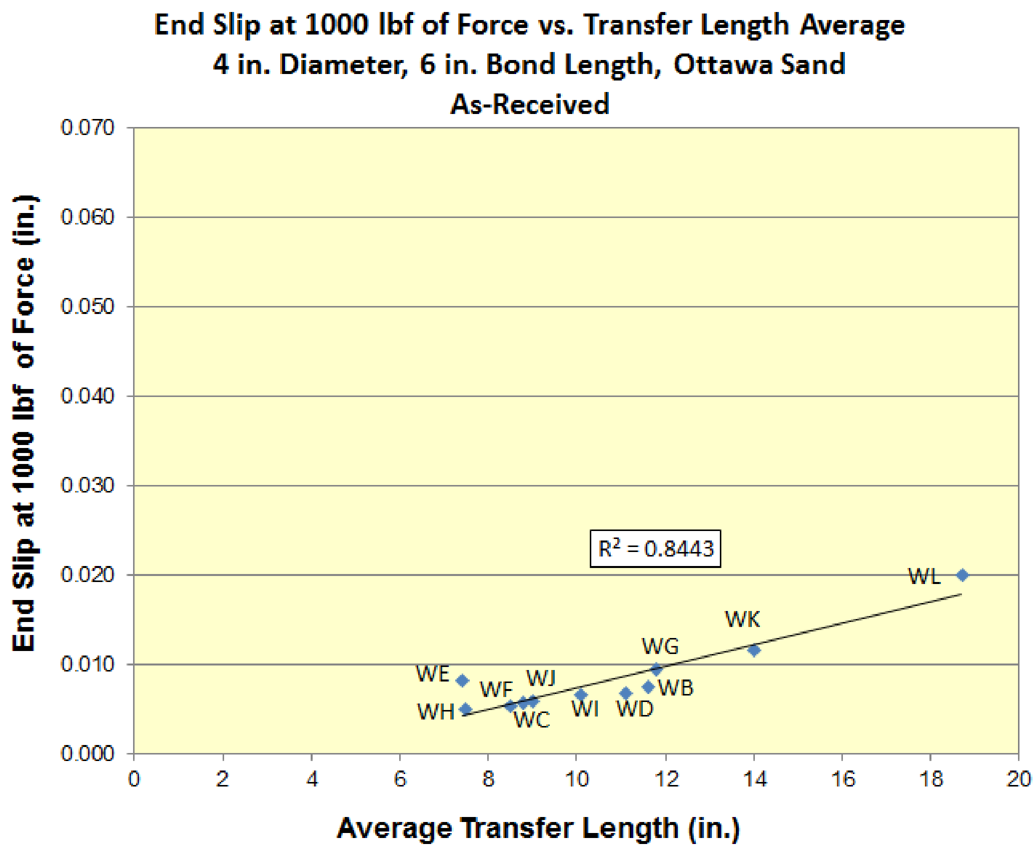


Figure 55. As-received wires, end slip at 1000-lbf force

Table 13. As-received wires, end slip at 3500-lbf force

As-Received Wire Bond Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand End Slip at 3500 lbf of Force				
Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0207	0.00372	17.9	11.6
[WC]	0.0273	0.00459	16.8	8.8
[WD]	0.0189	0.00294	15.5	11.1
[WE]	0.0276	0.00315	11.4	7.4
[WF]	0.0134	0.00135	10.0	8.5
[WG]	0.0322	0.00525	16.3	11.8
[WH]	0.0136	0.00140	10.2	7.5
[WI]	0.0196	0.00238	12.1	10.1
[WJ]	0.0158	0.00296	18.7	9.0
[WK]	0.0611	0.00449	7.3	14.0
[WL]				18.7

Note 1: Sample Size = 6, K = 2

Note 2: A blank entry means the wire didn't reach that force

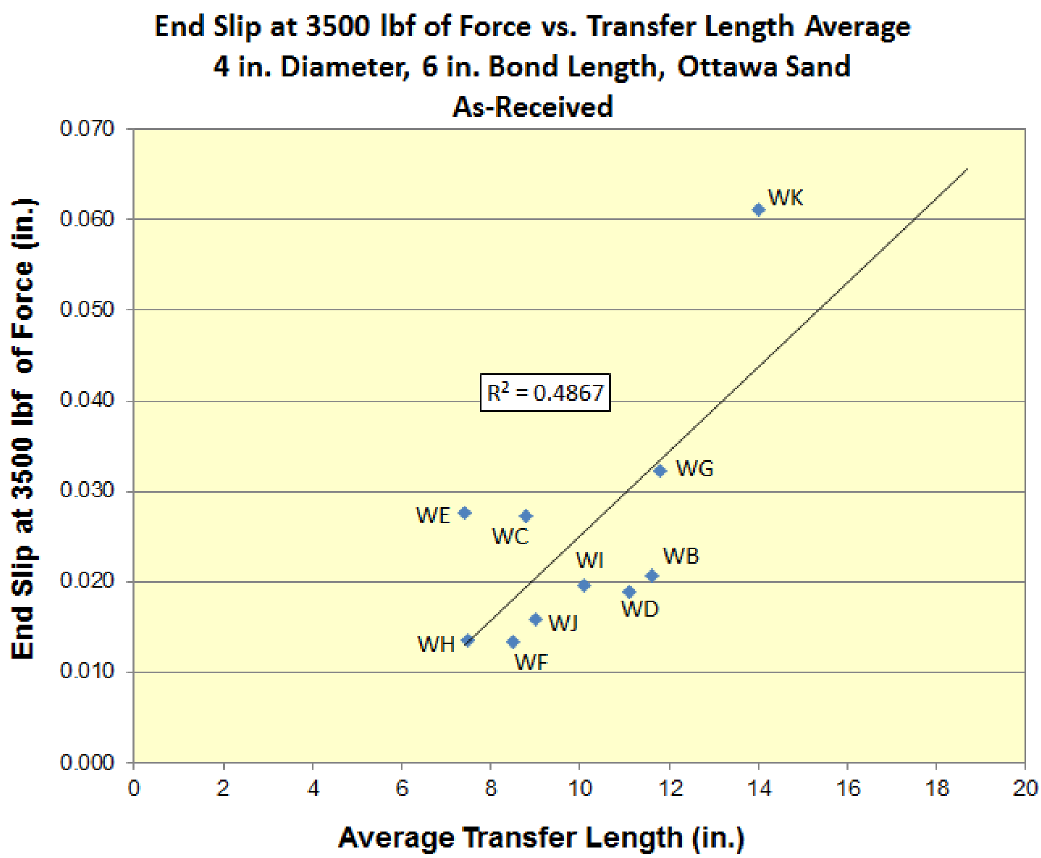


Figure 56. As-received wires, end slip at 3500-lbf force

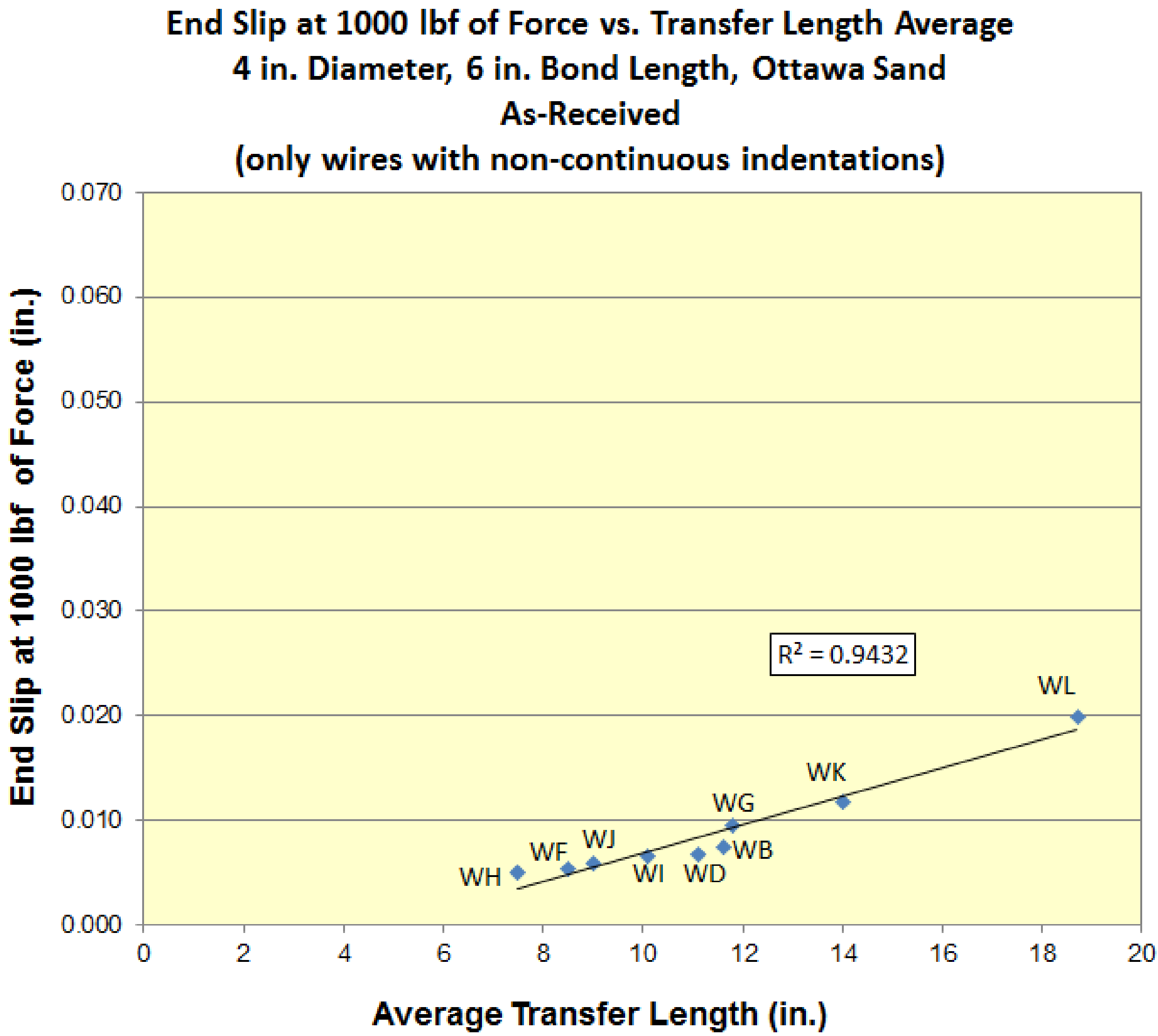


Figure 57. As-received wires, end slip at 1000-lbf force (individual-indents only)

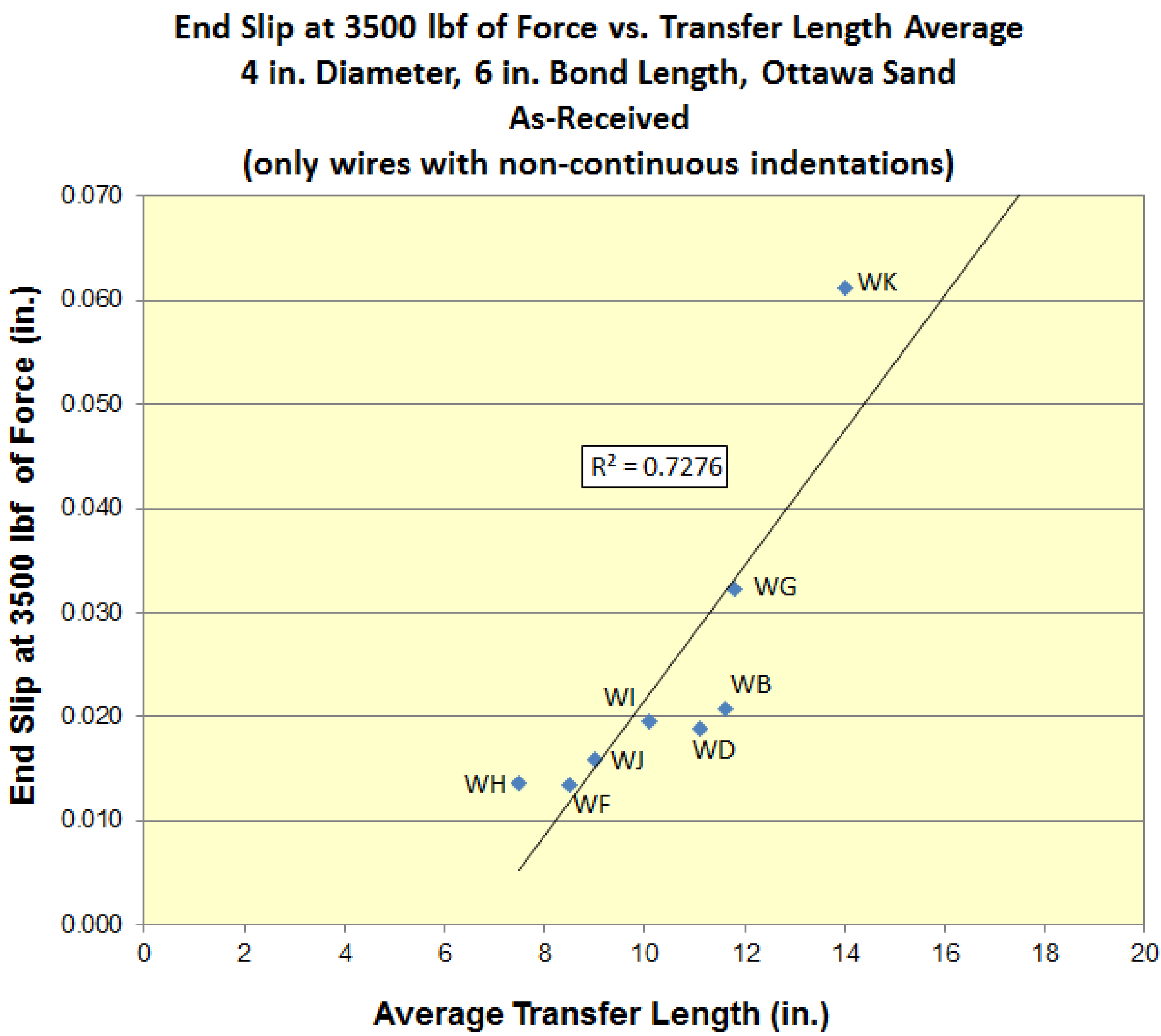


Figure 58. As-received wires, end slip at 3500-lbf force (individual-indents only)

Table 14. As-received wire regression summary, end slip at a force

Pullout Force (lbf)	R^2	
	All applicable wires	All applicable (individual-indented) wires
1000	0.844	0.943
1500	0.809	0.891
2000	0.792	0.870
2500	0.500	0.743
3000	0.494	0.682
3500	0.487	0.728
4000	0.108	0.657
4500	0.145	0.682
5000	0.212	0.690
5500	0.349	0.912
6000	0.281	0.607
Highest R^2 of set	**0.844**	**0.943**

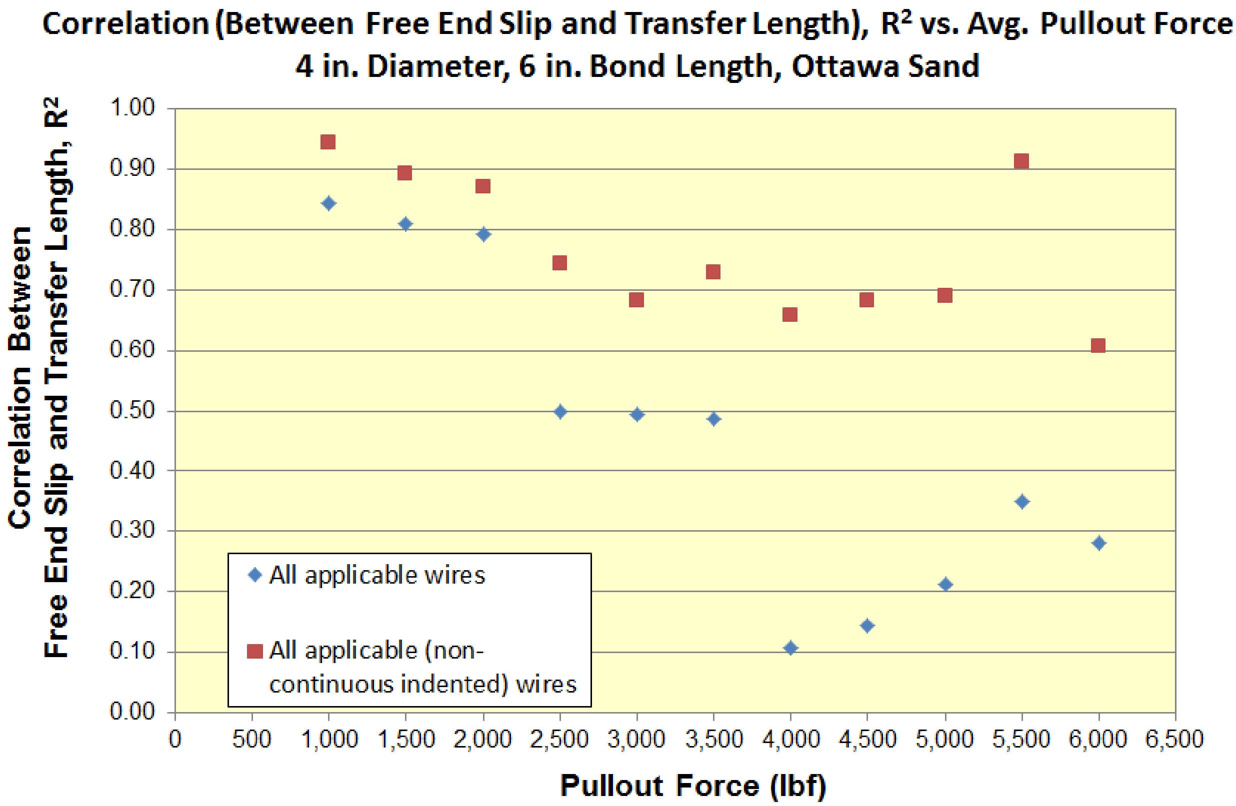


Figure 59. As-received wire regression summary, end slip at a force

4.3.4.3 Slope between Two End-slip Values

The third method of analysis compared the average force-vs-end-slip slope occurring between two end-slip values to average transfer lengths. For this analysis, slope was taken to mean the rise divided by the run of force (rise) vs. end-slip (run) graphs. Note, the slopes were approximated to be linear between 0.01-in. and 0.03-in. of end slip, despite minor changes in actual slopes of the graphs, thus allowing the slope to be calculated as the difference between pullout forces at 0.03-in. and 0.01-in. of end slip, divided by the difference between 0.03-in. and 0.01 in. of end slip. This concept is represented in tabular form in Table 15 and graphically in Figure 60.

Forces causing 0.01-in. and 0.03-in. end slip were extracted from the data for each specimen. The six slopes were then averaged and compared to the average measured transfer lengths of each wire. If the data set did not contain data points at 0.01- and 0.03-in. end slip exactly, then each value was calculated by linear interpolation using the next two closest values, or values just below and just above the desired value.

Similar to the previous 2 methods of analysis, correlation was found for 1) all 12 wire types (Figure 61), and 2) for only the 9 wire types with non-continuous indentations (Figure 62). The x-coordinate (abscissa) of each point in these graphs represents the average of six transfer length readings; the y-coordinate (ordinate) of each point in these graphs represents the average of six graph slopes between 0.01-in. and 0.03-in. of end slip. The R^2 is the correlation between these two averaged data sets.

For the data set including all 12 wires, $R^2 = 0.673$ for the slope between 0.01- and 0.03-in. of end slip and transfer length (Figure 61). For the 9-wire data set that excluded the smooth wire and two spiral wires, $R^2 = 0.886$ for the slope between 0.01- and 0.03-in. end slip and transfer length (Figure 62).

Table 15. As-received wires, slope between two end slips

Wire Bond Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Slope between 0.01-0.03 in. End Slip		
Wire	Avg. Slope of Individual Graphs (kip/in.)	Transfer Length (in.)
[WA]	-1.7	16.3
[WB]	152.5	11.6
[WC]	107.2	8.8
[WD]	151.3	11.1
[WE]	126.5	7.4
[WF]	217.9	8.5
[WG]	113.3	11.8
[WH]	186.7	7.5
[WI]	163.1	10.1
[WJ]	179.2	9.0
[WK]	69.7	14.0
[WL]	39.1	18.7

Note 1: Sample size = 6

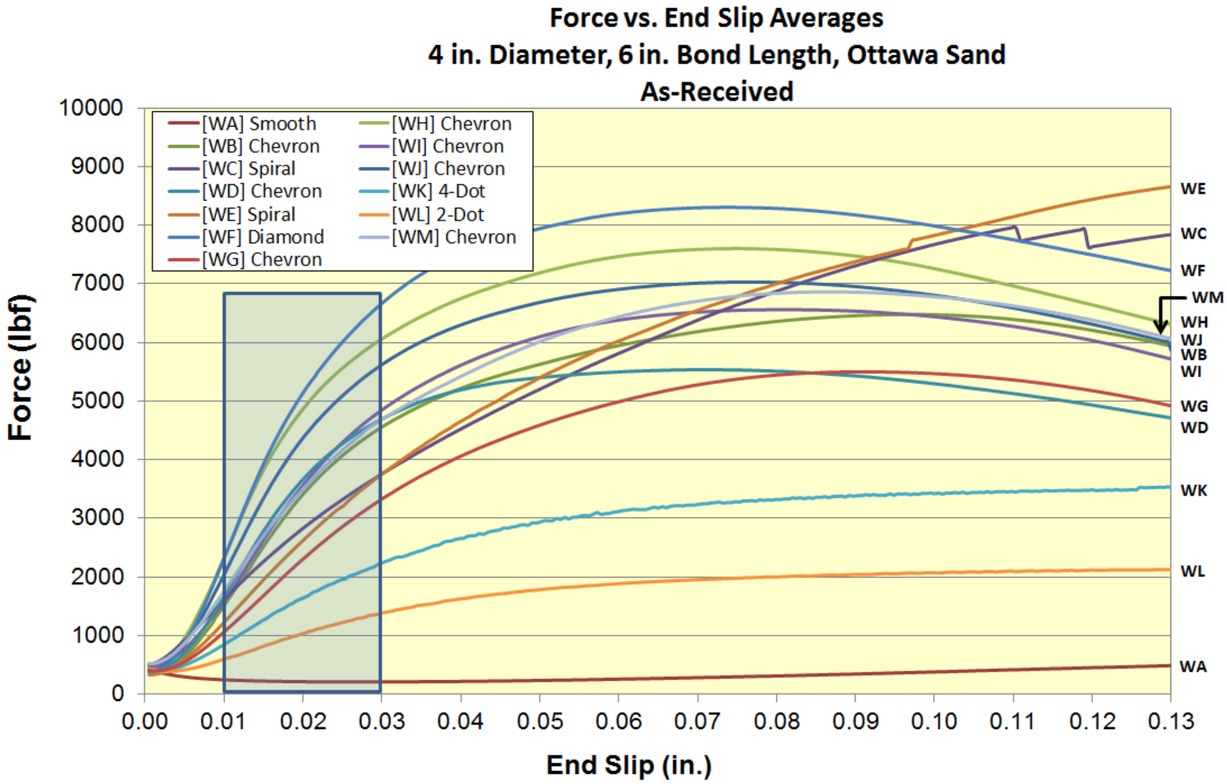


Figure 60. As-received wires, slope between two end slips

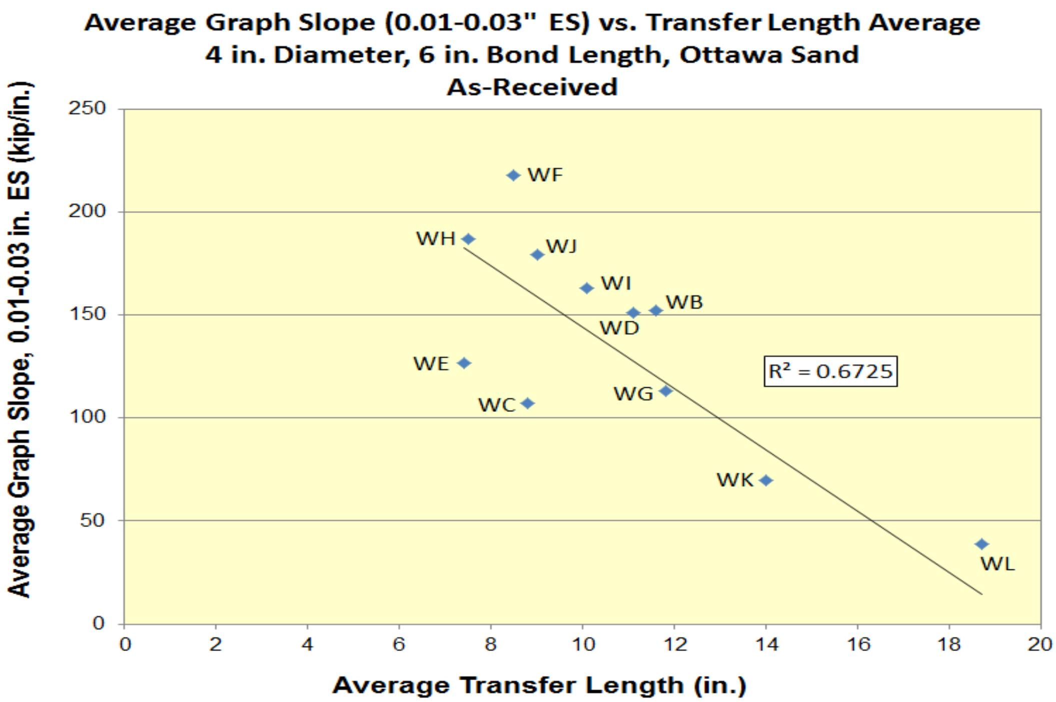


Figure 61. As-received wires, slope between 0.01- and 0.03-in. end slip

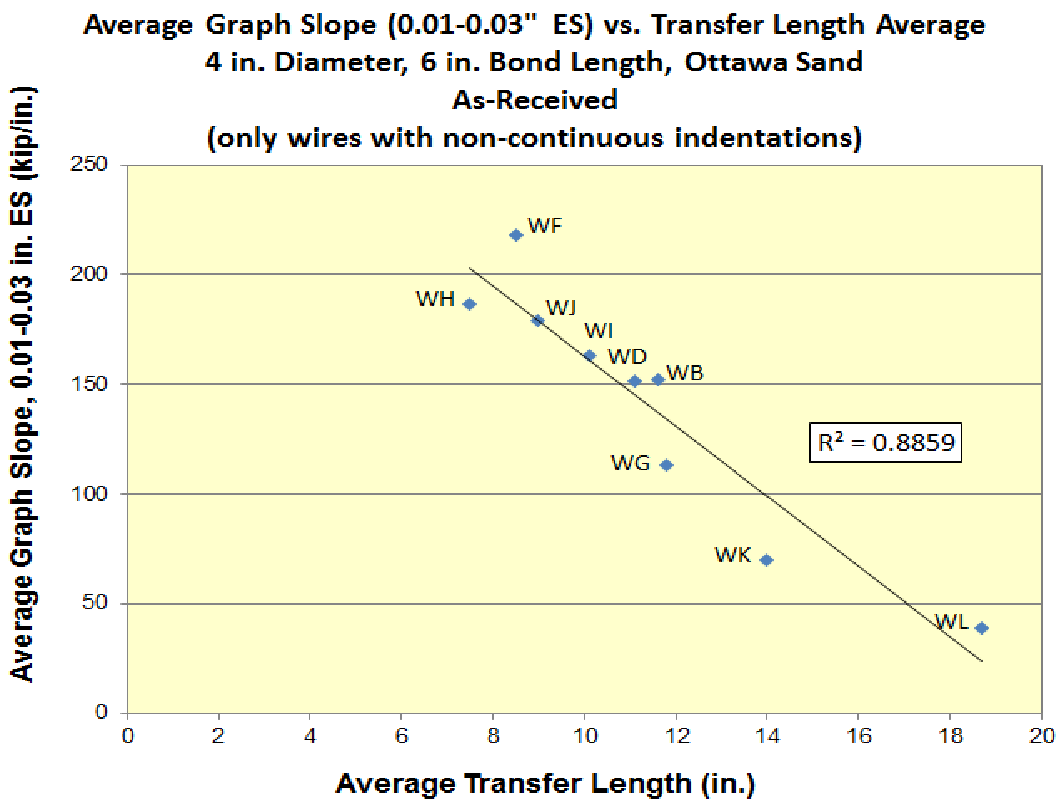


Figure 62. As-received wires, slope between 0.01- and 0.03-in. end slip (individual-indents only)

4.3.4.4 Slope between Two Force Values

The fourth method of analysis compared average force-vs-end-slip slope occurring between two forces to average transfer lengths. For this analysis, slope was defined as the rise divided by the run of force (rise) vs. end-slip (run) graphs. In addition, slopes were approximated to be linear between 1000 and 4000 pounds of force despite minor changes in actual slopes of the graphs, thus allowing the slope to be calculated as the difference between 4000 pounds and 1000 pounds of pullout force, divided by the difference between the end slips at 4000 pounds and 1000 pounds of force. This concept is represented in tabular form in Table 16 and graphically in Figure 63.

The end-slip values corresponding to 1000 and 4000 lbf were extracted from the data for each specimen. The six slopes were then averaged and compared to the average measured transfer length of each wire. If the data set did not contain data points exactly at 1000 and 4000 lbf, then each value was calculated by linear interpolation using the next two closest values, or values just below and just above the desired value.

Specimens from some wire types did not reach 4000 lbf target due to their lower bond performance. Any wire not reaching at least 4000 pounds was omitted from this analysis method. Omitted wires are indicated in Table 16 by an absence of data in the average slope column.

Similar to the previous 3 methods of analysis, correlation was found for 1) all 12 wire types (Figure 61), and 2) for only the 9 wire types with non-continuous indentations (Figure 62).

The x-coordinate (abscissa) of each point in these graphs represents the average of six transfer length readings; the y-coordinate (ordinate) of each point in these graphs represents the average of six graph slopes between 1000 and 4000 pounds of applied force. The R^2 is the correlation between these two averaged data sets.

For the data set including all applicable wires, $R^2 = 0.130$ for the slope between 1000 and 4000 pounds of force and transfer length, as shown in Figure 64. For the data set excluding the smooth wire and two spiral wires, $R^2 = 0.809$ for the slope between 1000 and 4000 pounds of force and transfer length, as shown in Figure 65.

Table 16. As-received wires, slope between two forces

Wire Bond Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Slope between 1000-4000 lbf		
Wire	Avg. Slope of Individual Graphs (kip/in.)	Transfer Length (in.)
[WA]		16.3
[WB]	179.2	11.6
[WC]	111.1	8.8
[WD]	196.5	11.1
[WE]	125.2	7.4
[WF]	314.1	8.5
[WG]	103.0	11.8
[WH]	285.6	7.5
[WI]	188.4	10.1
[WJ]	252.8	9.0
[WK]		14.0
[WL]		18.7

Note 1: Sample size = 6
Note 2: A blank entry means the wire never reached 4000 pounds

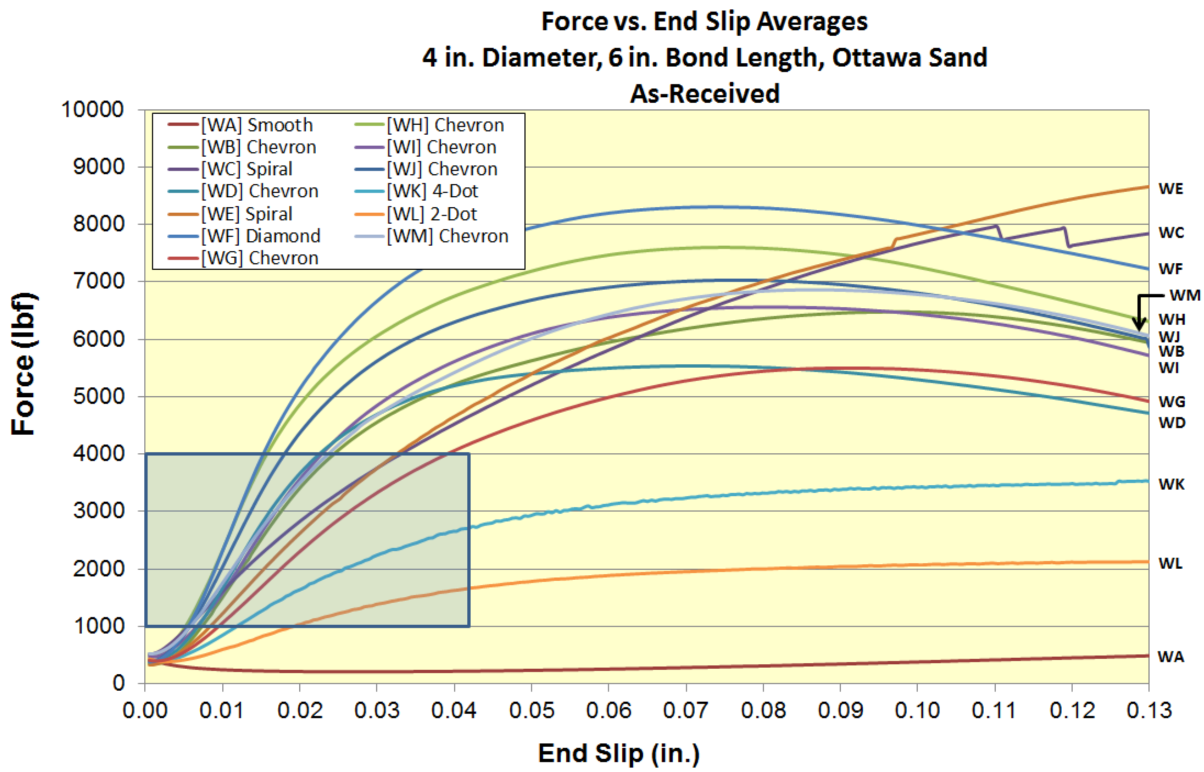


Figure 63. As-received wires, slope between two forces

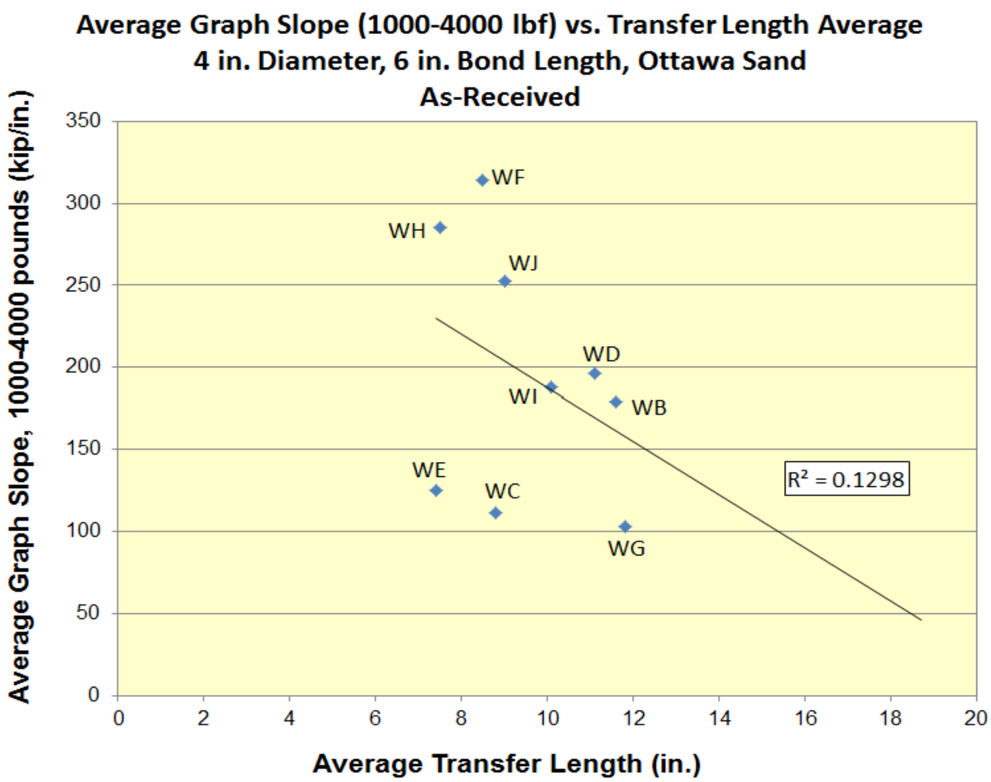


Figure 64. As-received wires, slope between 1000 and 4000 lbf

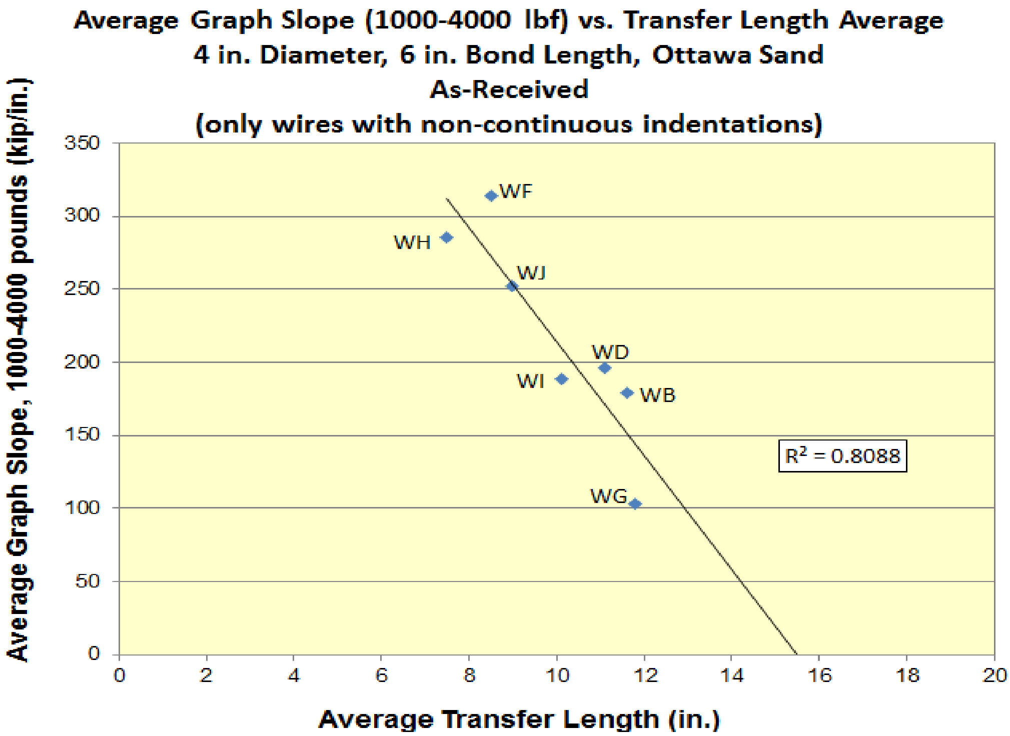


Figure 65. As-received wires, slope between 1000 and 4000 lbf (individual-indents only)

4.3.4.5 Best Analysis Method for Wires

Results of the four methods of analysis are shown in Table 17. When considering these four methods of analysis, one might initially assume best correlation comes from using the end slip at 1000 pounds of applied force (R^2 = 0.943). However, when considering data presented in Figure 59, the inconsistent trend of the data indicates that this method of analysis could be subject to large biases despite the very high correlation at some locations.

When maximum correlation and consistency of the data are used jointly to select the best method of analysis, it can be seen the maximum pullout force at any location less than or equal to 0.10-in. end slip should be selected. This analysis gives a correlation of R^2 = 0.916 when considering only the wires with non-continuous indentations. Furthermore, this method of analysis also provides the highest correlation of R^2 = 0.884 when all 12 wires are considered. These results show that when using the wire pullout test described in Appendix I, this method of analysis should be the most accurate predictor of the wire's transfer length.

From this point forward, the result of the wire bond test should be taken as the maximum load recorded at a free-end-slip less than or equal to 0.10 in.

Table 17. Summary of four methods of wire regression analysis, best correlations

Method of Analysis	Best R^2 achieved for all wires	Best R^2 achieved for individual-indents only	Location where best R^2 occurs	Notes
1) Force at Certain End Slips	0.882	0.916	Max force (ES ≤ 0.10 in.)	9 wires (individual-indent only)
2) End Slip at Certain Forces	0.844	0.943	1000 pounds force	All applicable individual-indent Inconsistent data trend
3) Slope between Two End Slips	0.673	0.886	0.01 in. to 0.03 in. ES	9 wires (individual-indent only)
4) Slope between Two Forces	0.130	0.809	1000 to 4000 pounds force	All applicable individual-indent

4.3.5 Verification of As-received Results

The 13th wire, WM, was used to verify the results of the As-received wire pullout test model. This wire was not used in any development of the wire bond pullout test. Moreover, this wire did not even arrive at the testing facility until after completion of the development program.

The As-received regression analysis using only wires with non-continuous indentations was used to predict the transfer length of WM. The model generated by this data set is shown in Figure 66 and is the same data used to obtain Figure 53 from Section 4.3.4.1 (with the axes switched). Equation 4.1, obtained from the model in Figure 66, gives the equation of the expected transfer length of As-received, indented prestressing wires. Note this equation gives the expected transfer length for 4-in. square prisms in a similar concrete with 4500-psi release strength.

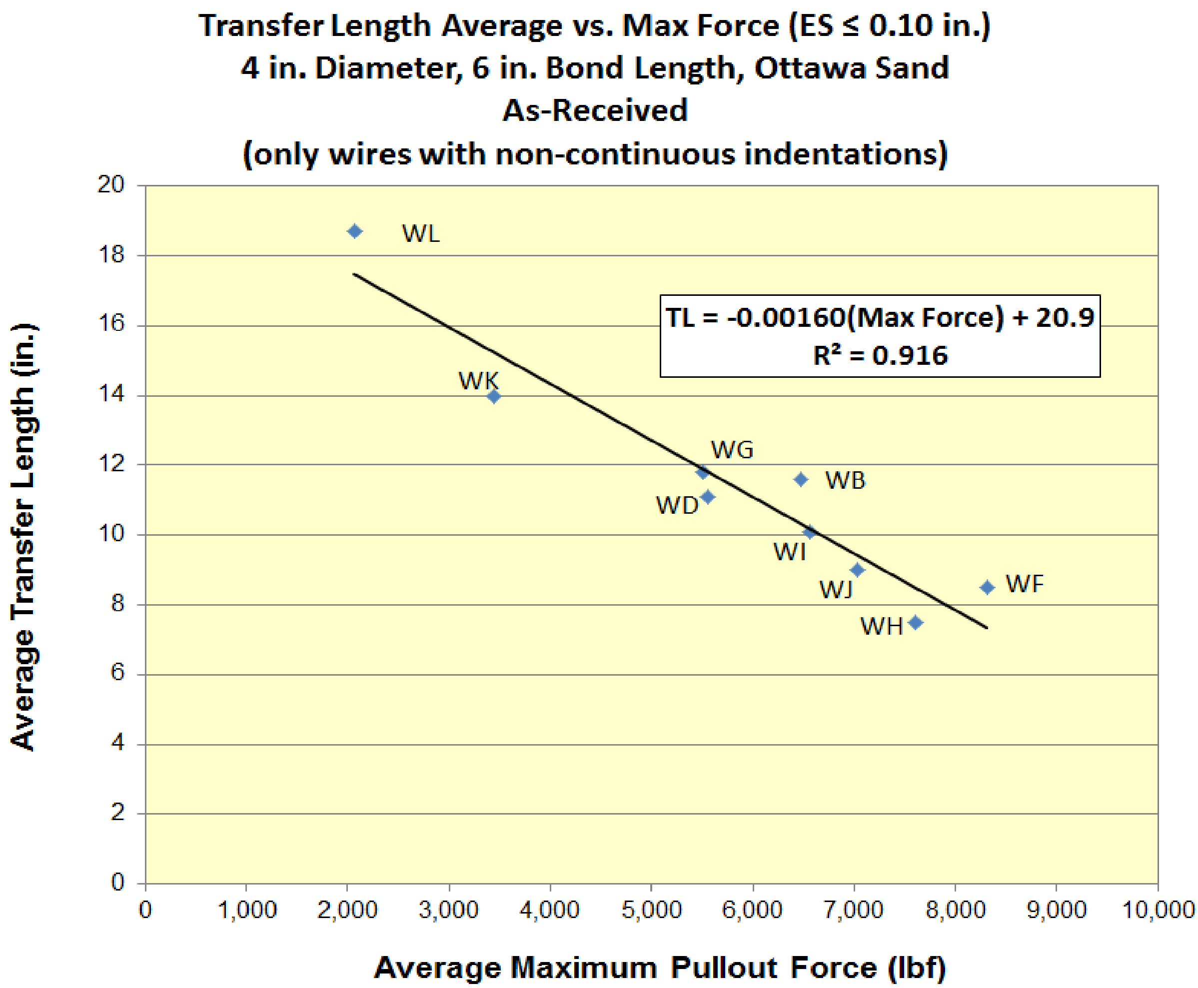


Figure 66. As-received wires, transfer length prediction model

$$TL = 20.9 - (Max\ Force/625) \qquad \text{Equation 4.1}$$

where *TL* = expected As-received transfer length (inches) from prisms

Max Force = maximum force (pounds) for end slip ≤ 0.10 in.

After the model was built, six pullout tests were performed on wire WM in their As-received condition to test whether its transfer length could be predicted. The data was obtained the same way as all of the other wires. Results were compiled and maximum pullout force values (occurring at an end slip less than or equal to 0.l0 in.) for each As-received WM specimen are shown in Table 18. The pullout force vs. end-slip graphs for the six individual As-received WM specimens are shown in Figure 67.

Using the average maximum force of 6879 pounds obtained from Table 18 and Equation 4.1, the predicted transfer length of wire WM using the As-received model is 9.9 inches. The average measured transfer length – using six transfer length measurements – from the pretensioned prisms was found to be 9.8 inches in the lab. The difference between the expected (theoretical) and actual (experimental) transfer lengths is 0.1 in., an error of 1.0%. For the given force (6879 lbf) and using a confidence interval of 95%, the predictive equation (Equation 4.1) gives a predicted range of approximately 8.7 in. to 10.8 in. The results of WM fall within this range.

Figure 68 shows the average maximum force of the six pullout tests using WM in its As-received condition compared to the average of the six measured transfer length measurements. The predictive model (from Figure 66) is also shown in Figure 68 for visual comparison along with the predicted range given by a 95% confidence interval.

This analysis shows the wire pullout test described in Appendix I is an excellent predictor of transfer length for As-received wires with non-continuous indentations. The predicted (theoretical) transfer length of 9.9 in. was almost identical to the actual (experimental) transfer length of 9.8 in. for wire WM in its As-received condition.

Table 18. As-received maximum force values for six WM specimens

As-Received [WM]	
Specimen #	Max Force (lbf)
1	6734
2	7642
3	6063
4	6651
5	6857
6	7325
Average	6879

Std. Dev. (lbf) = 503
Coeff. Of Variation, C.V. (%) = 7.3

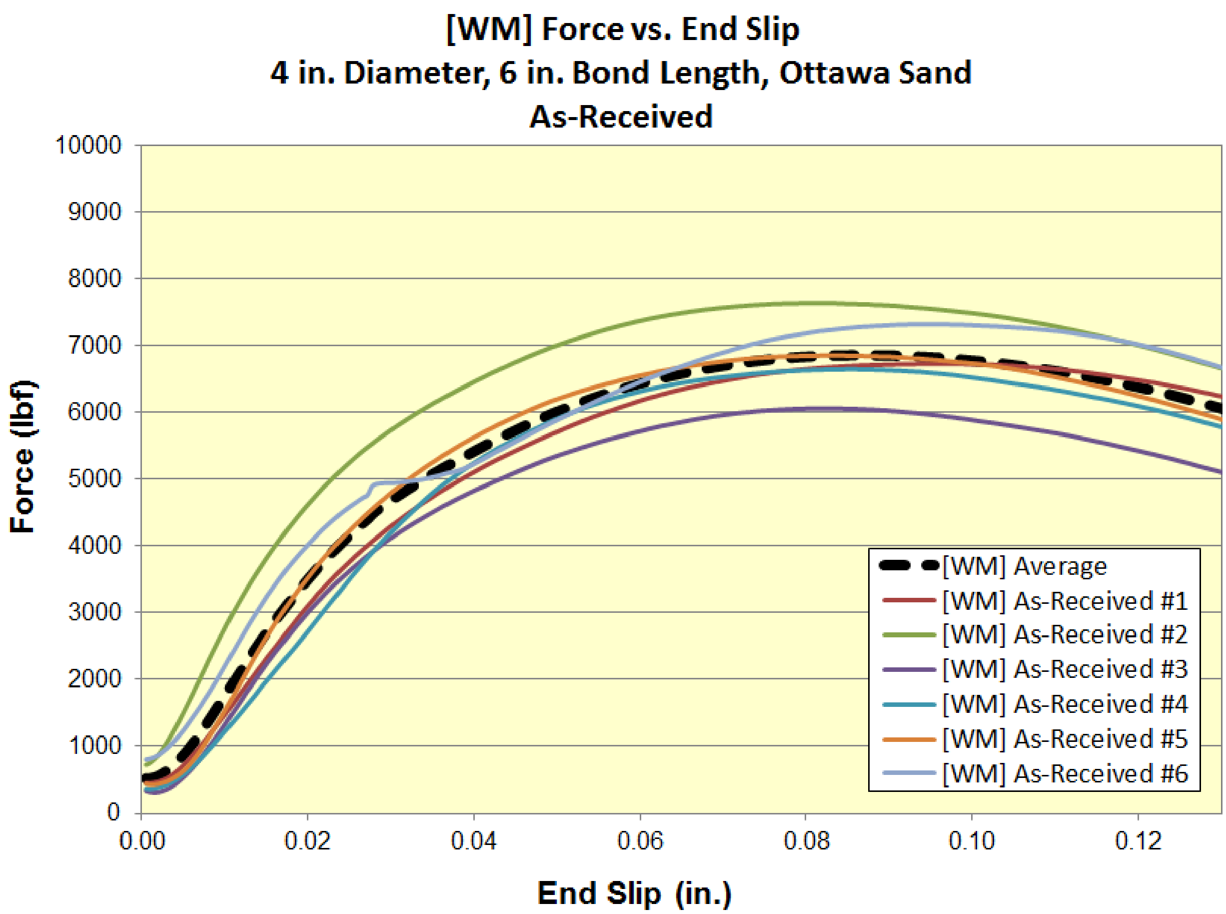


Figure 67. As-received force vs. end-slip graphs (individual and average) for wire WM

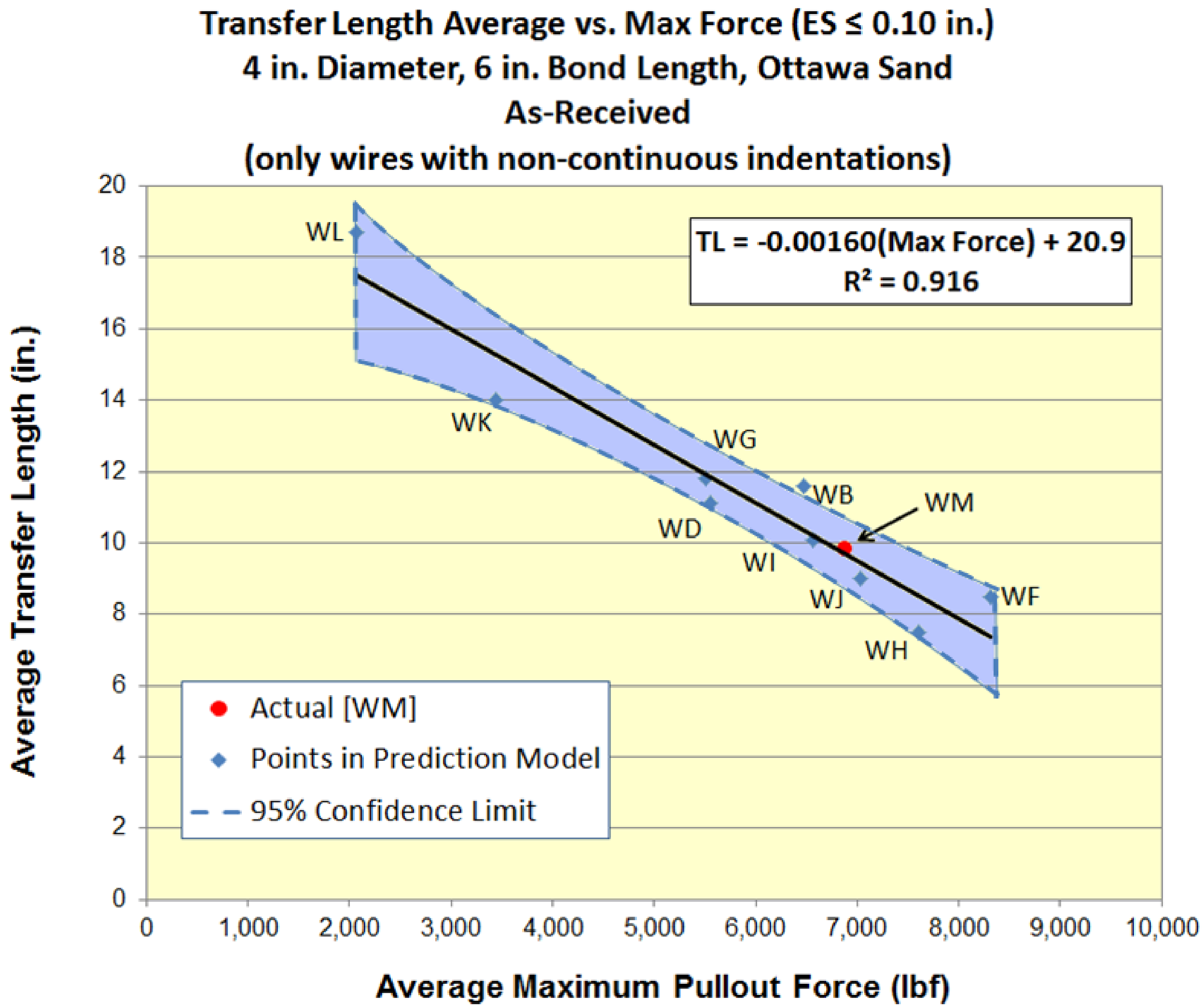


Figure 68. Transfer length vs. average maximum pullout force for As-received wires, including WM, compared with predictive model

4.3.6 Comparison of As-received vs. Cleaned

This section directly compares results of the As-received (Section 4.3.1) and cleaned wire specimens (Section 4.3.2). The analysis focuses on differentiating between bond associated with indent geometry and bond associated with surface condition.

Seven wires (WA, WE, WF, WG, WH, WK, and WM) were tested both in their As-received and cleaned conditions. Of these wires, WG and WM exhibited slight-to-moderate levels of rusting. Wire WK appeared to have a very slight residue coating the surface. The remaining four wires (WA, WE, WF, WH) appeared to have no noticeable signs of either rust or oils. Due to these different surface conditions, it was hypothesized that wires WG and WM may perform slightly worse after being cleaned due to the rust being removed. Slight rusting has been shown to improve bond performance during similar testing done on strands (Gustavson, 2004; Rose and

Russell, 1997; Barnes, Grove, and Burns, 2003). Similarly, it was originally thought wire WK would exhibit better bond after being cleaned due to the oil being removed. It was assumed the remaining four wires would show roughly the same bond performance before and after the cleaning process.

The average pullout force vs. end-slip graph for each wire is shown in Figure 69 through Figure 75. The as-received and Cleaned plots represent averages of the six specimens for those respective tests. Results of the individual pullout tests comparing six As-received specimens to six cleaned specimens can be seen in Appendix H.

From Figure 69 through Figure 75, it can be seen that none of the seven wires performed much differently before or after the cleaning process, especially in the ascending branch. Wires WG and WM actually performed slightly better after cleaning, which was the opposite of the assumed performance. Wire WK also performed slightly better after being cleaned during its initial phases of slip, but after reaching approximately 0.06 in. of end slip, the bond performances were almost identical.

None of the wires exhibited a vast discrepancy in bond performance by the As-received specimens versus the cleaned specimens. Due to this similarity in bond performance, one of two conclusions can be made:

1. All seven of the wires tested for cleaning had roughly the same combination of surface lubricants and/or rusting that affected them all equally.

2. The bond performance of a wire is dominated by the indent geometry and only minimally affected by the surface condition as long as the surface is relatively clean.

Because of the visibly different surface conditions documented by the researchers, coupled with the knowledge that the seven wires selected for cleaning were manufactured by six different companies, the first conclusion is implausible. The latter conclusion makes sense when the overall geometry of the wire is considered. Since the area of the wire indents is large relative to the overall cross-sectional area of the 5.32-mm-diameter wire, it makes sense that the indent geometry would govern the overall bond performance of the wires.

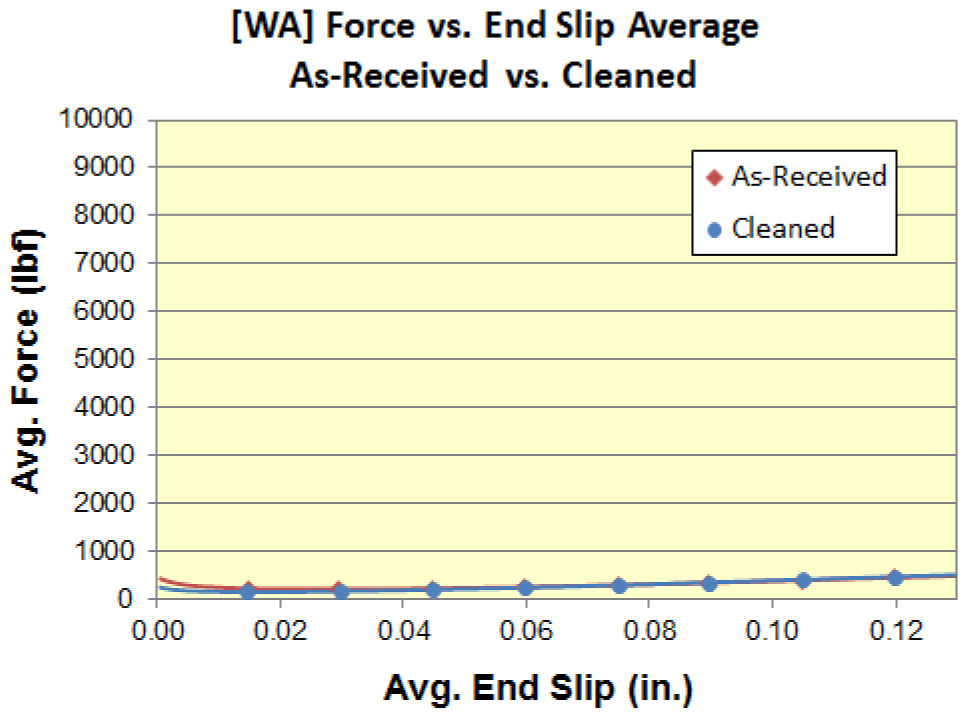


Figure 69. Force vs. end-slip average for wire WA, As-received vs. cleaned

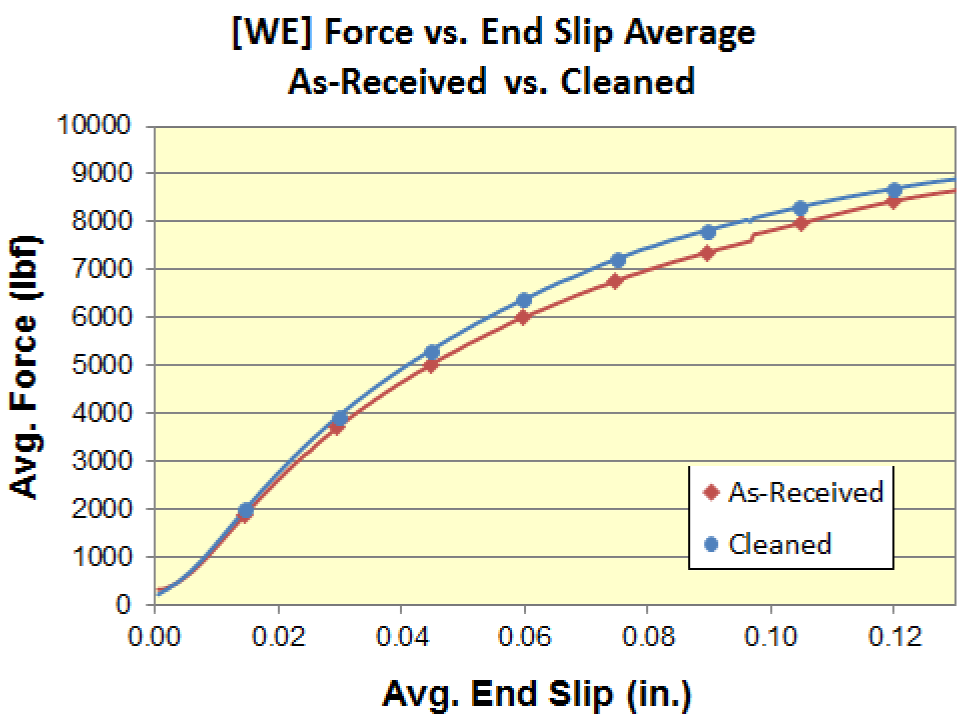


Figure 70. Force vs. end-slip average for wire WE, As-received vs. cleaned

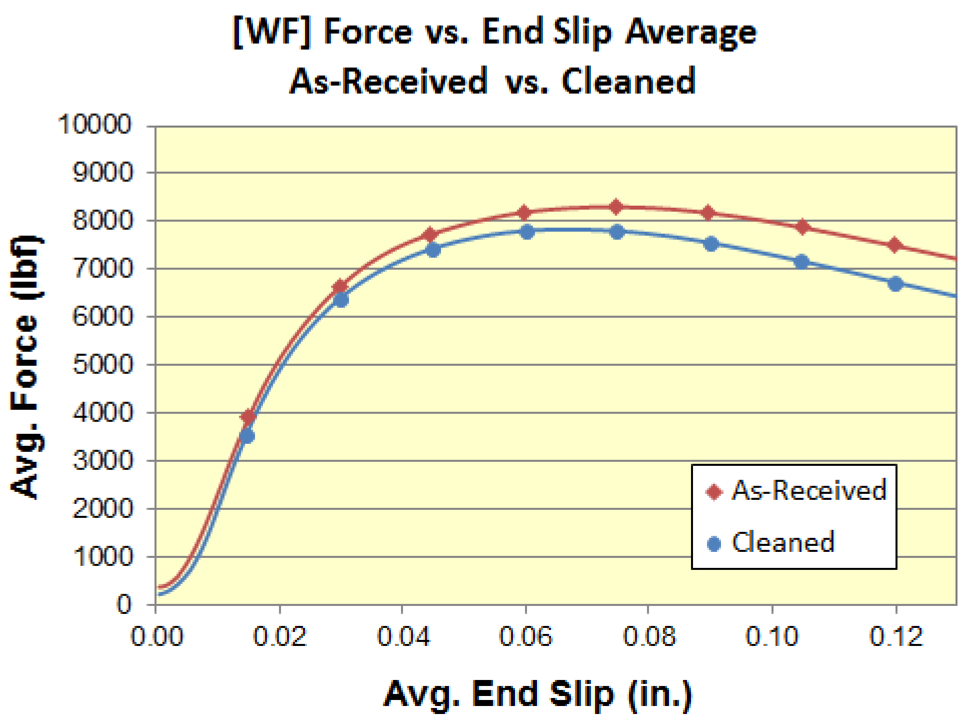


Figure 71. Force vs. end-slip average for wire WF, As-received vs. cleaned

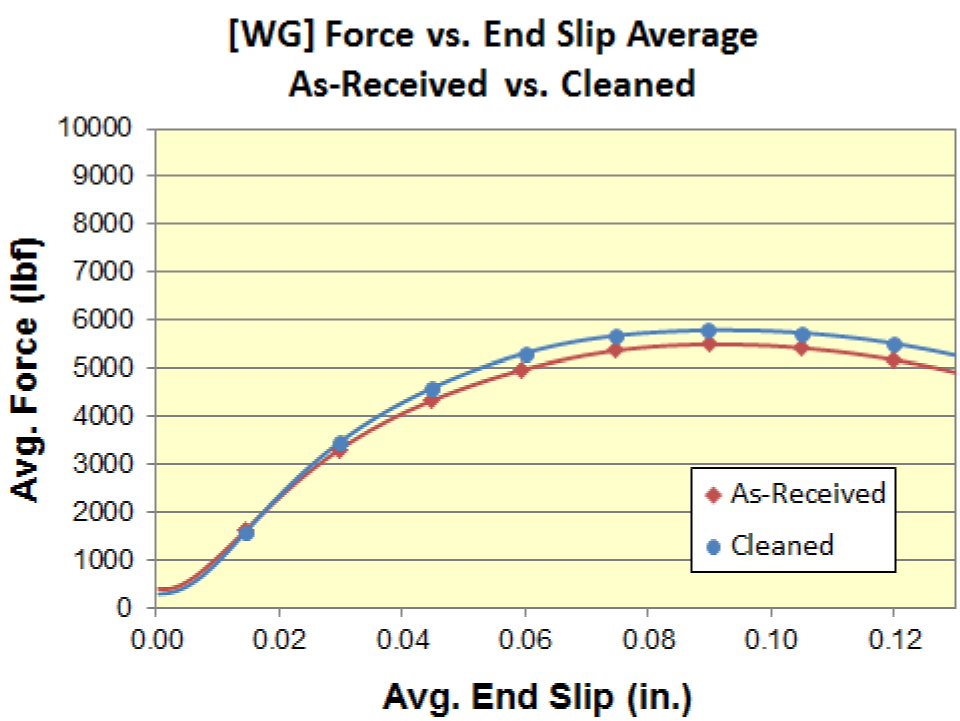


Figure 72. Force vs. end-slip average for wire WG, As-received vs. cleaned

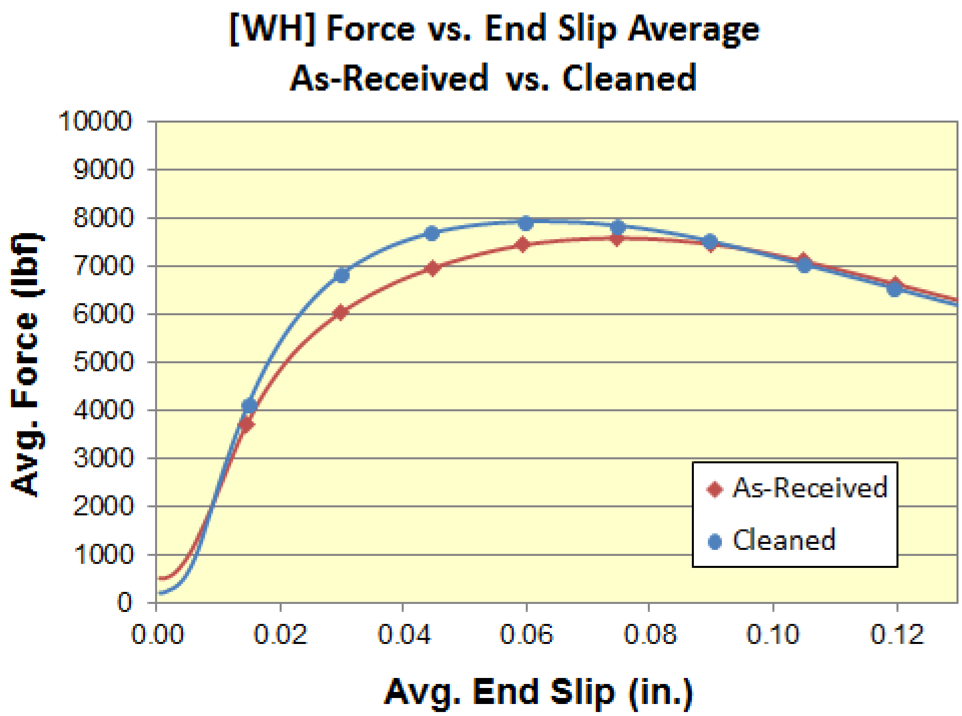


Figure 73. Force vs. end-slip average for wire WH, As-received vs. cleaned

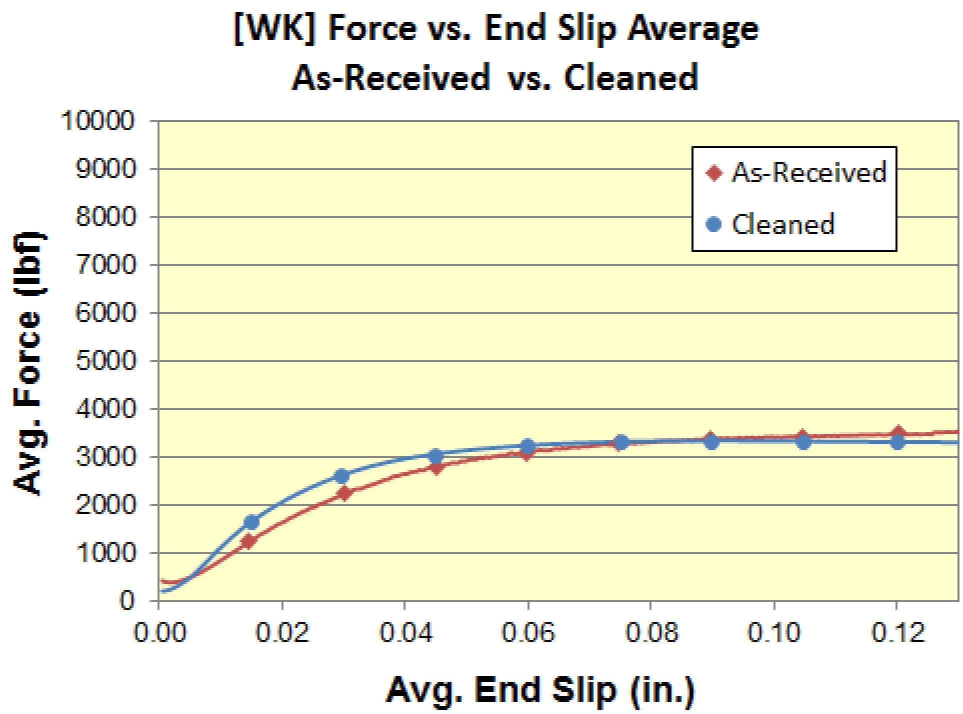


Figure 74. Force vs. end-slip average for wire WK, As-received vs. cleaned

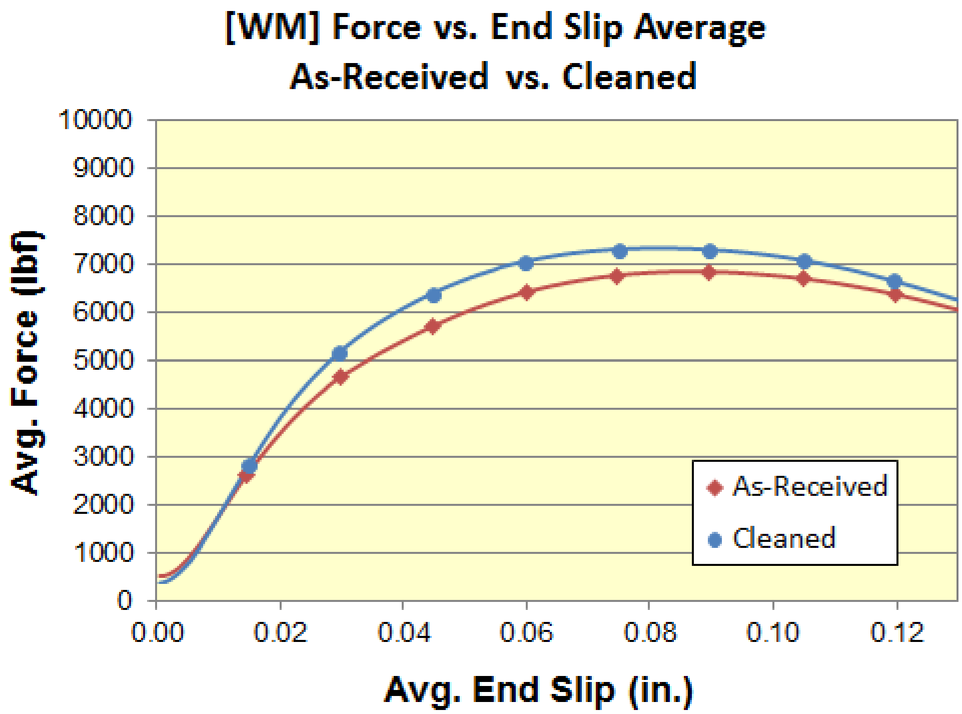


Figure 75. Force vs. end-slip average for wire WM, As-received vs. cleaned

5. Lab Phase; Strand Pullout Testing (Un-tensioned Tests in Mortar)

Chapter 5 discusses the experimental program, results, and analysis of the lab portion of the strand bond pullout tests. These tests are un-tensioned and were performed in mortar.

5.1 Using the Strand Bond Test as a Basis

The Standard Test for Strand Bond was used as a basis for strand bond testing performed in this experimental testing program. The general testing procedure set forth in Ramirez and Russell (2008) was used for the tests presented here. Note that, at the time, no requirement for use of a neoprene rubber pad was in the specifications, and it was not used at Kansas State University.

The primary goal of this lab phase was to provide evidence in favor of expanding the strand bond test to include smaller diameter strands (less than 0.5 in.). This testing program sought first to verify whether or not a 16-in. bond length used for the Standard Test for Strand Bond would be adequate for smaller diameter strands. If the 16-in. bond length was determined to be inadequate (too long), then a modified version of the standard strand bond test would be proposed for smaller diameter strands. Preferably, all parameters except bond length would remain the same as the standard strand bond test.

5.2 Experimental Program

This section contains information used for this experimental testing program regarding the verification of the Standard Test for Strand Bond (Ramirez and Russell, 2008) for seven-wire and three-wire strands with diameters smaller than 0.5 in. This information includes research variables; specimen dimensions; mix proportions, material sources, and batch sizes; specimen casting and storage procedures; and testing procedures used to verify the un-tensioned pullout test for smaller diameter strands.

5.2.1 Research Variables

Three primary research variables for the strand testing portion of the lab phase are strand and indent geometry, surface condition, and bond length. The first two are of great importance because they allow the researchers to better distinguish what portion of a reinforcement's bond performance can be attributed to the surface and indent geometry, and what portion can be attributed to the surface condition. These two effects were investigated by testing the reinforcements in both their As-received and cleaned conditions.

In total, six different strands with different indentation patterns from four different steel manufacturers were used to develop the un-tensioned pullout test described in detail in Chapter 5. All strands were Grade 270, low-relaxation strands. Some strands were 5/16-in. diameter and some were 3/8-in. diameter. Additionally, some were three-wire strands and some were seven-wire strands. The strands were stored in 25-foot lengths in PVC tubes with silica-based desiccant packets to prevent any rusting and preserve the wires' As-received surface condition for testing.

First, the strand and indentation geometry of the steel prestressing strands was investigated by testing the wires with their As-received surface conditions. This allowed for the relative bond performance of the wires to be examined and the establishment of a baseline for expected bond performance.

Second, the surface condition of the strands was tested by cleaning the strands. This occurred by performing further pullout testing on all six of the strands after being subjected to the cleaning process described in depth in Section 3.3. The Cleaned specimen tests were performed on bare steel by removing rust, oils, and surface lubricants with an acidic solution.

Results of these Cleaned specimens were compared to the as-received specimens. This process allowed the researchers to better separate out the bond attributed to surface condition from the bond attributed to surface and indent geometry.

The testing matrix for the strand pullout tests can be seen in Table 19. Each strand was tested six times and the results averaged to give the expected bond performance of each wire. Both the as-received and Cleaned strand pullout results were compared to the measured transfer length of accompanying pretensioned prisms. These prisms were cast using a concrete mixture similar to one used in a major concrete tie manufacturing plant in the United States. The batching and testing procedures used to obtain the transfer lengths from these pretensioned prisms are presented in Bodapati's 2013 paper, but are not discussed here.

Additionally, a third parameter was looked at for strand testing: bond length. This is significant for the smaller diameter strands (less than 0.5 in.), as they are not able to handle as much load before rupturing due to decreased surface and cross-sectional areas compared with larger diameter strands (0.5 in. and larger). This testing program sought first to verify if a 16-in. bond length used for the Standard Test for Strand Bond (Ramirez and Russell, 2008) would be adequate for smaller diameter strands. If the 16-in. bond length was determined to be inadequate (too long), then a modified version of the standard strand bond test would be proposed for smaller diameter strands. Preferably, all parameters except bond length would remain the same as the standard strand bond test.

Table 19. Matrix of strand pullout testing program (lab phase)

Strand Manufacturer	Strand Identification	Indentation Type	Number of test specimens		
			Transfer lengths (no. of ends)	As-received un-tensioned pullouts	Cleaned un-tensioned pullouts
A	[SA]	3/8" 7-Wire, Smooth	6	12	6
A	[SB]	3/8" 7-Wire, Indented	6	12	6
A	[SC]	5/16" 3-Wire, Smooth	6	12	6
B	[SD]	3/8" 7-Wire, Indented	6	12	6
C	[SE]	3/8" 7-Wire, Indented	6	12	6
D	[SF]	3/8" 3-Wire, Indented	6	12	6
Total:			**36**	**72**	**36**

Note: (6) of the "as-received" strand specimens were tested both at a 16 in. bond length and a 9 in. bond length.

5.2.2 Specimen Dimensions

Two specimen sizes were used for the strand bonding portion of the lab phase. The first specimen was the exact same size used for the ASTM A1081 strand bond test and will be referred to as either the "standard length strand specimen" or the "16-in. specimen" for the remainder of this paper. The second specimen was a modified version of the ones used to develop the Strand Bond Test. These modified specimens will be referred to as either the "short-length specimen" or the "9-in. specimen" for the rest of this paper.

The standard length specimens utilized a 5-in.-outer-diameter steel tube, 1/8-in. wall thickness, and a total length of 18 in. A 6-in. by 6-in. steel plate (3/16-in. thick) was tack-welded to the bottom. The remaining contact surface between the tube and bottom plate was caulked to prevent any leakage. Within the 18-in. steel tube, there was a 16-in. embedment (bond) length with a 2-in. long foam-tape bond breaker at the bottom. The strand extended past the top mortar surface by approximately 2 inches. A schematic of the 16-in. pullout specimen is shown in Figure 76. The 5-in.-diameter steel tubes were able to be re-used by cutting the tack welds, removing the bottom plate, and pushing out the mortar (with a hydraulic actuator and specially-made frame).

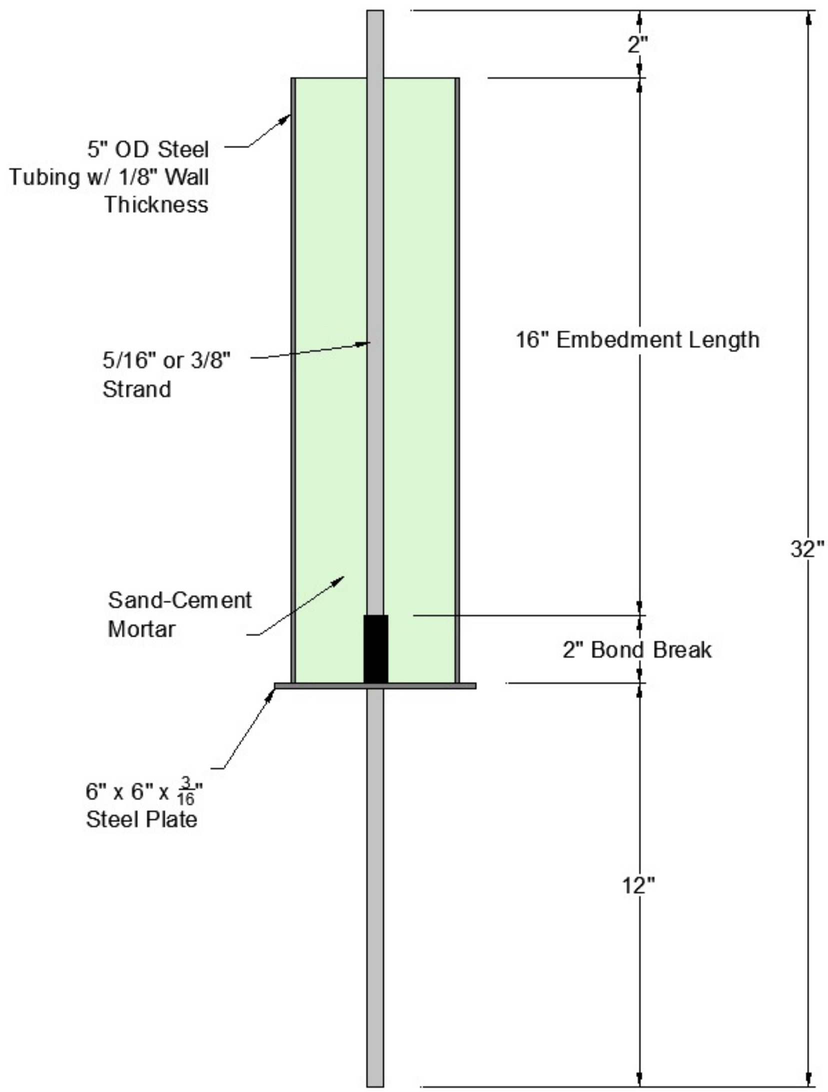


Figure 76. Dimensions of 16-in. strand pullout test specimen

The short-length specimens utilized a 5-in.-outer-diameter steel tube, 1/8-in. wall thickness, and a total length of 12 in. A 6-in. by 6-in. steel plate (3/16-in. thick) was tack-welded to the bottom, and the remaining contact surface was caulked to prevent any leakage. Within the 12-in.-long steel tube, there was a 9-in. embedment (bond) length with a 2-in. long foam-tape bond breaker at the bottom and a 1-in.-long duct tape bond breaker at the top. The top bond breaker extended past the top mortar surface by approximately 1 in. to ensure the exact bond length desired in case of settlement. The strand extended past the top mortar surface by approximately 2 inches. A schematic of the 9-in. pullout specimen is shown in Figure 77. The 5-in.-diameter steel tubes were able to be re-used by cutting the tack welds, removing the bottom plate, and pushing out the mortar (with a hydraulic actuator and specially-made frame).

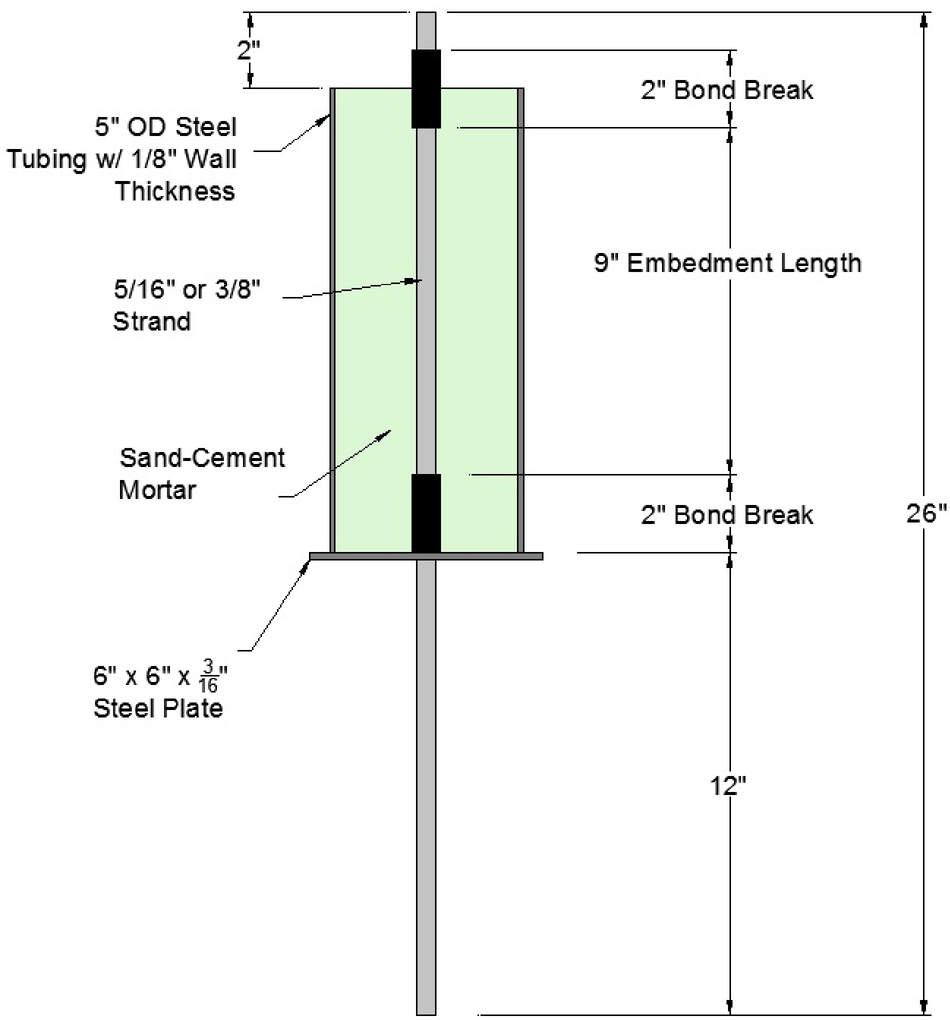


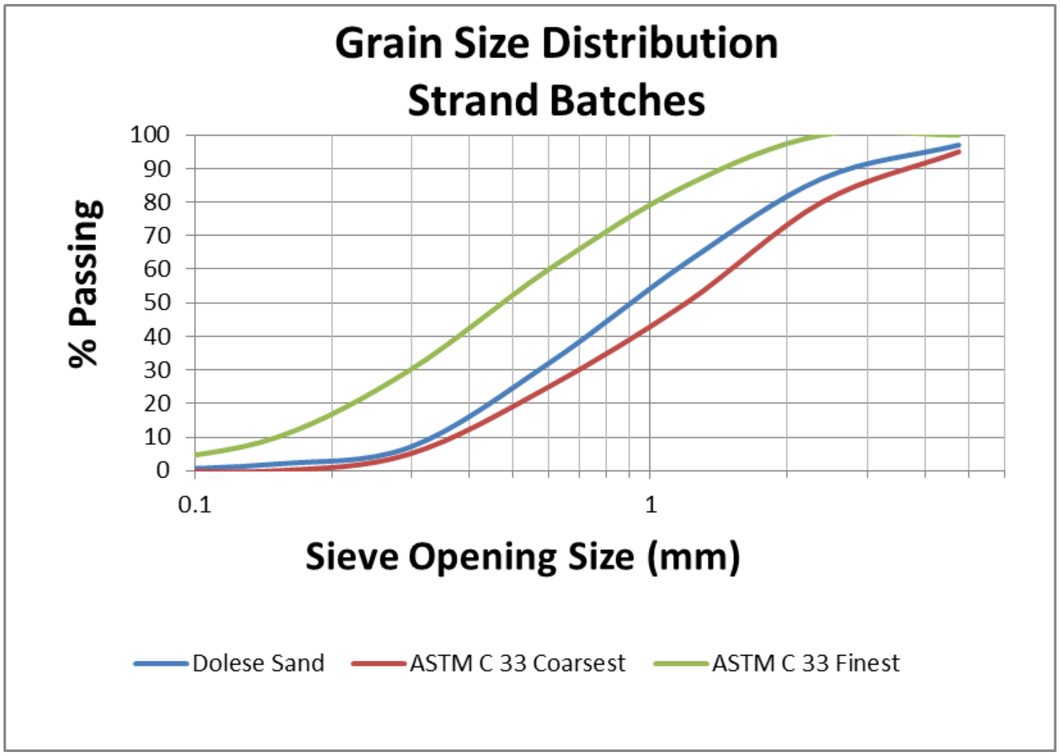
Figure 77. Dimensions of 9-in. strand pullout test specimen

Two different bottom plates were used for the strand specimens. For the 3/8-in.-diameter strands, the bottom plate had a 7/16-in.-diameter hole drilled in the center to allow the steel strand to pass through. For the 5/16-in.-diameter strands, the bottom plate had a 3/8-in.-diameter hole. The strands were held centered in the tube using an additional fixture (shown in Figure 78) and rebar ties.

Figure 78. Additional fixture used to center strands during casting

5.2.3 Mix Proportions, Material Sources, and Batch Size

A sand-cement mortar mixture was used for all tests. The mix proportions were a water-to-cement ratio (w/c) of 0.46 and a sand-to-cement (s/c) ratio of 2.80. The cement used was a Type III cement from the Monarch Cement Company and it conformed to ASTM C150. The mill certification sheet for this cement can be seen in Appendix P. The sand used was supplied by Dolese Bros. Co., Guthrie, Oklahoma. (Note this is the same sand used to develop the Oklahoma State University portion of the NASP and NCHRP Strand Bond Test protocol.) The sand was sieved and then recombined using the grain-size distribution shown in Figure 79 to conform to ASTM C33 and to keep the exact same mortar mix for each batch.



GSD used for strand batches

Sieve #	Opening (mm)	% Passing	ASTM C-33 (% Pass)		% of Total Sand Volume
			Min	Max	
4	4.75	97	95	100	3
8	2.38	87	80	100	10
16	1.2	62	50	85	25
30	0.599	32	25	60	30
50	0.297	7	5	30	25
100	0.152	2	0	10	5
200	0.075	0.0	0	2	2
Σ					100

Figure 79. Sand gradation used for strand pullout specimens

For the standard length strand bond test specimens, 2.75 ft^3 of mortar was batched. Each batch was enough to fill 12 strand specimens and 12 mortar cubes with approximately 25 pounds of mortar leftover. For the short-length strand specimens, 1.85 ft^3 of mortar was batched. Each batch was enough to fill 12 strand specimens and 12 mortar cubes with approximately 25 pounds of mortar leftover.

Total batch weights for strand pullout tests can be seen in Table 20. This same mixture was used for all strand pullout tests for uniformity. The paddle mixer used can be seen in Figure 80.

Table 20. Batch weights used for strand pullout specimens

Material	16 in. Specimens Batch Weights (lbf)	9 in. Specimens Batch Weights (lbf)
Oklahoma (Dolese) Sand	254.2	164.3
Monarch Type III Cement	86.8	58.7
Water	40.0	27.0
Total	**381.0**	**250.0**

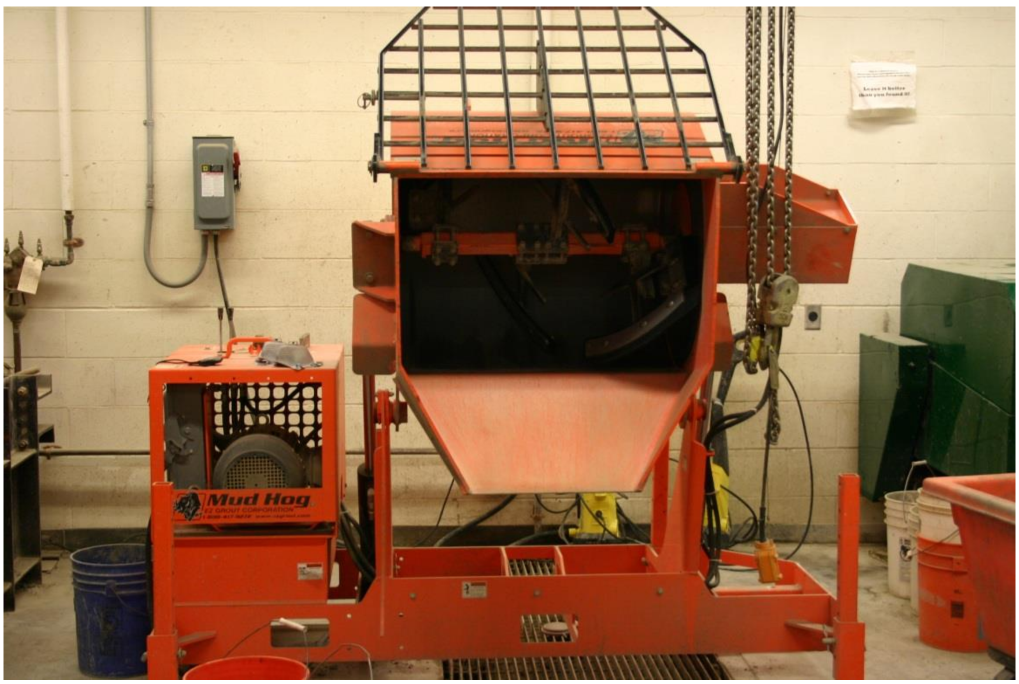


Figure 80. Paddle mixer used for strand pullout tests

5.2.4 Specimen Casting and Curing Procedures

Each strand was tested six times and the results averaged. For the 16-in.-diameter strand specimens, a total of six mortar batches were made. Each batch contained 12 pullout specimens, one As-received and one cleaned specimen for each of the six strands. The specimens were cast in six different batches so that any variations due to slight differences in the mortar mixtures would be equally distributed. For the 9-in.-diameter strand specimens, a total of three mortar batches were made. Each batch contained 12 pullout specimens, two As-received specimens for each of the six strands. The mixer used for strand batches was a paddle mixer with a maximum useable capacity of approximately 7.5 ft^3, as shown in Figure 80.

Mortar for the strand pullout specimens used the following mixing procedure:

1. Place all sieved sand into the paddle mixer and mix for 30 seconds to recombine.

2. Pour approximately 70% of the water into the mixer and mix for 30 seconds.

3. Pour all of cement into the mixer.

4. Start timer while adding remaining water.

5. Mix for three (3) minutes.

6. Turn off mixer. Scrape the mixer for two (2) minutes using trowels, giving special attention to any area that collects dry material.

7. Mix for two (2) minutes.

8. Empty mixer into trough.

Each set of 12 pullout specimens were cast at approximately the same time each day and the temperature in the vicinity of the curing location was maintained at 73.5 ± 3.5 ^{o}F in accordance with ASTM C109. Mortar temperature, room temperature, relative humidity, and mortar flow were recorded directly after the mortar came out of the mixer.

The flow table used for workability testing meets the specifications of ASTM C230, and the flow value is measured using the ASTM C1437 method. A picture of the flow measurement process is shown in Figure 38. Two-in. mortar cubes were made, stored, and tested according to ASTC C109. The pullout specimens were filled in two, approximately equal, lifts and consolidated using a wand-type vibrator between each lift.

After the specimens and mortar cubes were cast, the top surface of each pullout specimen was smoothed using a small trowel and covered for storage (curing). The pullout test specimens and 2-in. mortar cubes were cured by placing a moist cloth over the top surface and covering with plastic. This kept the relative humidity of the specimens and cubes greater than or equal to 90%. The specimens and cubes were then stored in a temperature- and humidity-controlled room, maintained at a temperature of 73.5 ± 3.5 ^{o}F and a relative humidity above 50%. Figure 39 shows a picture of the moist cloth/plastic covering method used for curing the cubes, and Figure 40 shows the curing method used for curing the specimens.

Average mortar strength at the time of strand pullout testing (measured from the mortar cubes) and mortar flow value are shown in

Table 21 for the As-received and cleaned 16-in. strand specimens and Table 22 for the As-received 9-in. strand specimens.

Table 21. As-received and cleaned 16-in. strand pullout batch summaries

Mortar Batch Name	Avg. Specimen Cure Time (hrs)	Avg. Cube Strength at Time of Test (psi)	Flow Value
Strand Batch #1	24	4570	122
Strand Batch #2	24	4598	121
Strand Batch #3	24.25	4607	119
Strand Batch #4	23.75	4598	118
Strand Batch #5	23.75	4601	117
Strand Batch #6	24.25	4639	118
Average of Six	**24**	**4602**	**119.2**

Table 22. As-received 9-in. strand pullout batch summaries

Mortar Batch Name	Avg. Specimen Cure Time (hrs)	Avg. Cube Strength at Time of Test (psi)	Flow Value
Strand Batch #1	23.75	4632	117
Strand Batch #2	23.25	4663	115
Strand Batch #3	23.5	4669	115.5
Average of Three	**23.5**	**4655**	**115.8**

5.2.5 Testing Procedure

The general testing procedure set forth in Ramirez and Russell (2008) was used for the strand tests presented here. At the time of this testing, no requirement on use of a neoprene rubber pad was in the specifications and this was not used at Kansas State University. Other important testing parameters (such as LVDT setup and data acquisition) are given in the following paragraphs.

Pullout tests were performed shortly after the mortar cube strength reached 4500 psi and ended before the cube strength reached 5000 psi. During testing, the strands were pulled with a displacement rate of 0.1 inch/minute at the bottom, while the applied load and free-end-slip at the opposite (top) end were continuously monitored and recorded using an LVDT. This process is shown in Figure 41. Depending on the size of strand, a prestressing chuck with an appropriate size was used for the actuator to bear and apply force to the strand. MTS MultiPurpose TestWare 793 software was used to control the servo-hydraulic actuator and also for data acquisition. A more in-depth breakdown of the testing machinery setup and its specifications can be found in Section 4.2.6. Data (time, force, and end slip) was collected at every 0.0005 in. of free-end-slip using MTS software and hardware.

In the case of 7-wire strands, the LVDT was positioned on the center of the center wire. In the case of the 3-wire strands, the LVDT was positioned on the center of one of the wires. In the case of all three-wire strand test specimens, no wire slipped relative to the other two. If a wire would have slipped relative to the other two, a small piece of metal would have been used to "cap" the strand, and the specimens would have been recast and retested. The LVDT was mounted to the steel tube using two magnetic blocks. A closer view of the LVDT can be seen in the setup shown in Figure 44, and the top view of a typical strand specimen is shown in Figure 81.

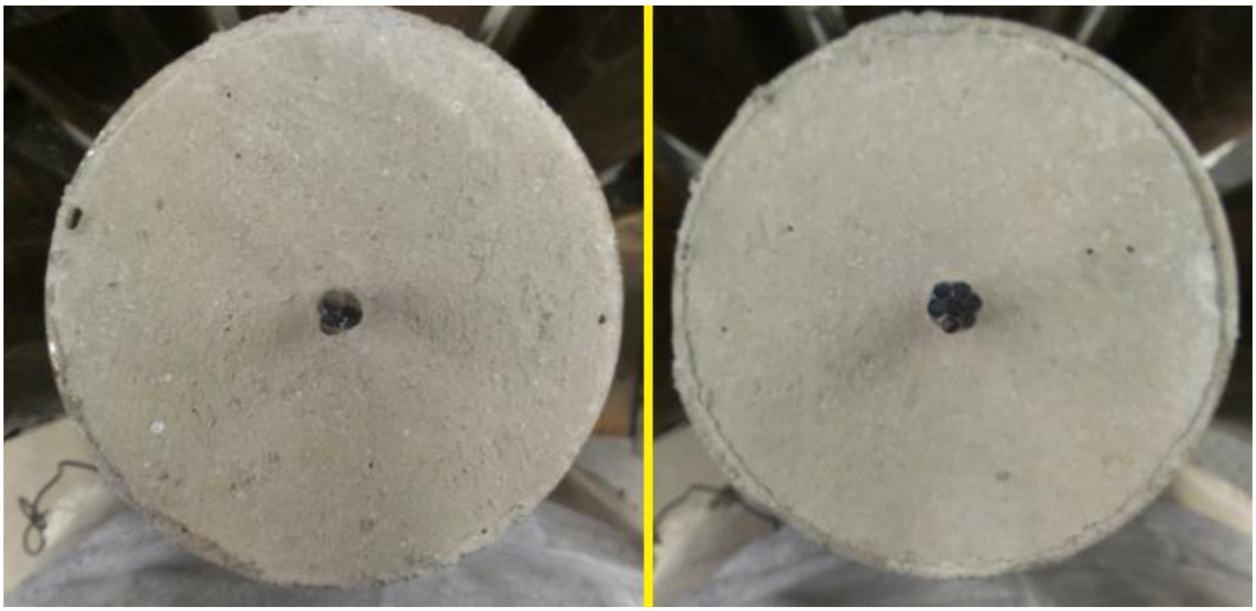


Figure 81. Top view of three-wire and seven-wire strand specimens

5.3 Strand Pullout Results and Analysis

Results of the experimental, lab strand testing program are presented in this section. First, results of the as-received and Cleaned pullout specimens are presented in succession. The third section presents transfer length measurements obtained from pretensioned prisms. Next, the method of analysis used for strand bond testing is established. Finally, results between the As-received data set and the cleaned data set are compared to distinguish between bond attributed to surface conditions and bond attributed to indent geometry.

5.3.1 As-received Results

The averaged As-received force vs. end-slip results from each strand source and use of standard length strand specimens (bond length equal to 16 in.) are presented in Figure 82. The average force at each increment of end slip (0.0005 in.) was obtained by arithmetically adding the force results from each of the six individual specimens and then dividing the sum of force by six. The same process was used to average the end-slip measurements for each strand group.

Each plot on the graph represents the average of six individual specimens from the same strand source. Each of the six specimens was cast in a different batch of mortar. The force vs. end-slip graphs, showing individual results of the six specimens for each strand source, can be seen in Appendix K.

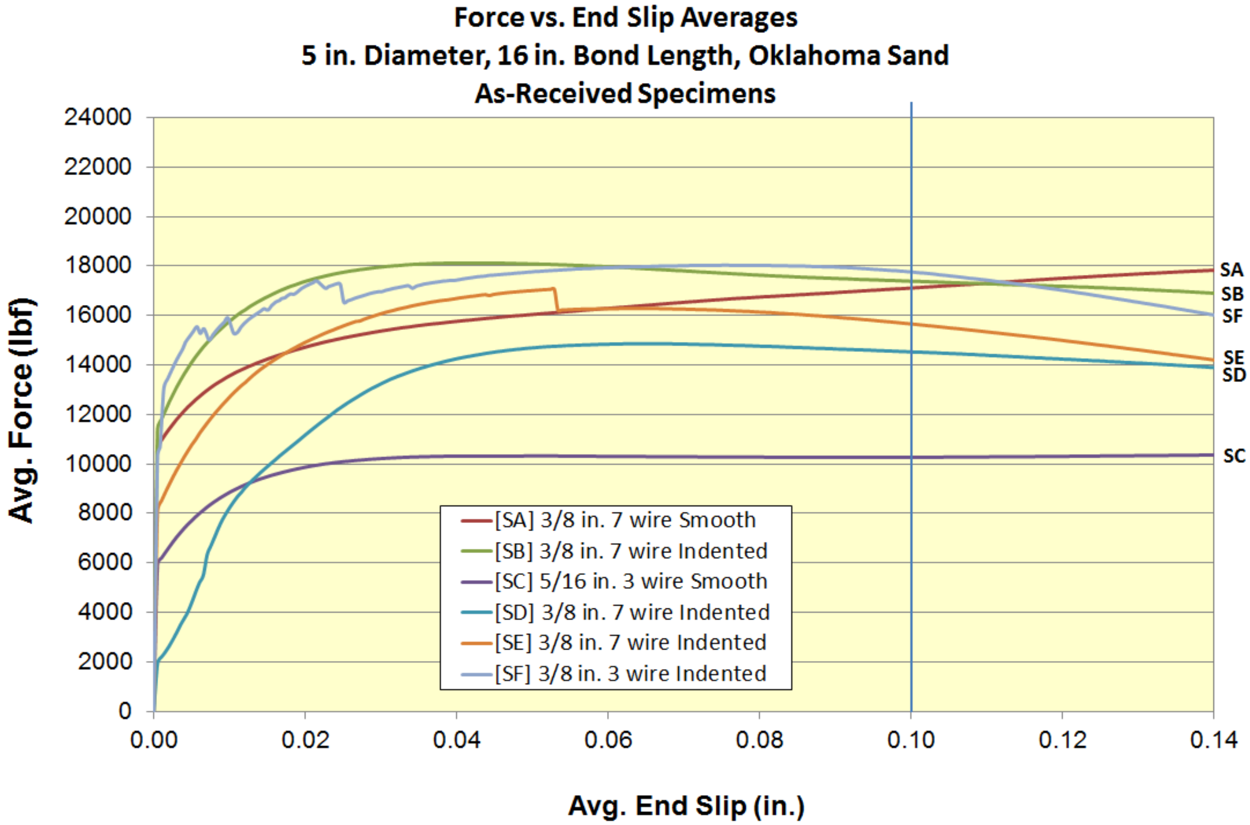


Figure 82. As-received strand force vs. end-slip averages (16-in. bond length)

From Figure 82, it is clear the 16-in. bond length is too long for the higher bonding strands. With this long of a bond length, specimens containing strands SE and SF had to be stopped early during testing for fear of steel rupture failure prior to bond pullout failure. This is represented graphically by the sudden jumps in the graph as one of the high bonding specimens drops out of the data set. The specimens needed to be shortened to accommodate these higher bonding strands. With this goal in mind, a modified specimen size utilizing a 9-in. bond length was proposed for smaller diameter (less than or equal to 0.5 in.) strands by the researchers. No other parameters to the specimen size or testing protocol were changed from the standard strand bond test (Ramirez and Russell, 2008).

Figure 83 shows the average As-received force vs. end-slip results of the shortened length strand specimens (bond length equal to 9 in.). Each plot on the graph represents the average of six individual specimens from the same strand source. Each of the six specimens was cast in a different batch of mortar. The force vs. end-slip graphs, showing the individual results of the six specimens for each strand source, can be seen in Appendix K.

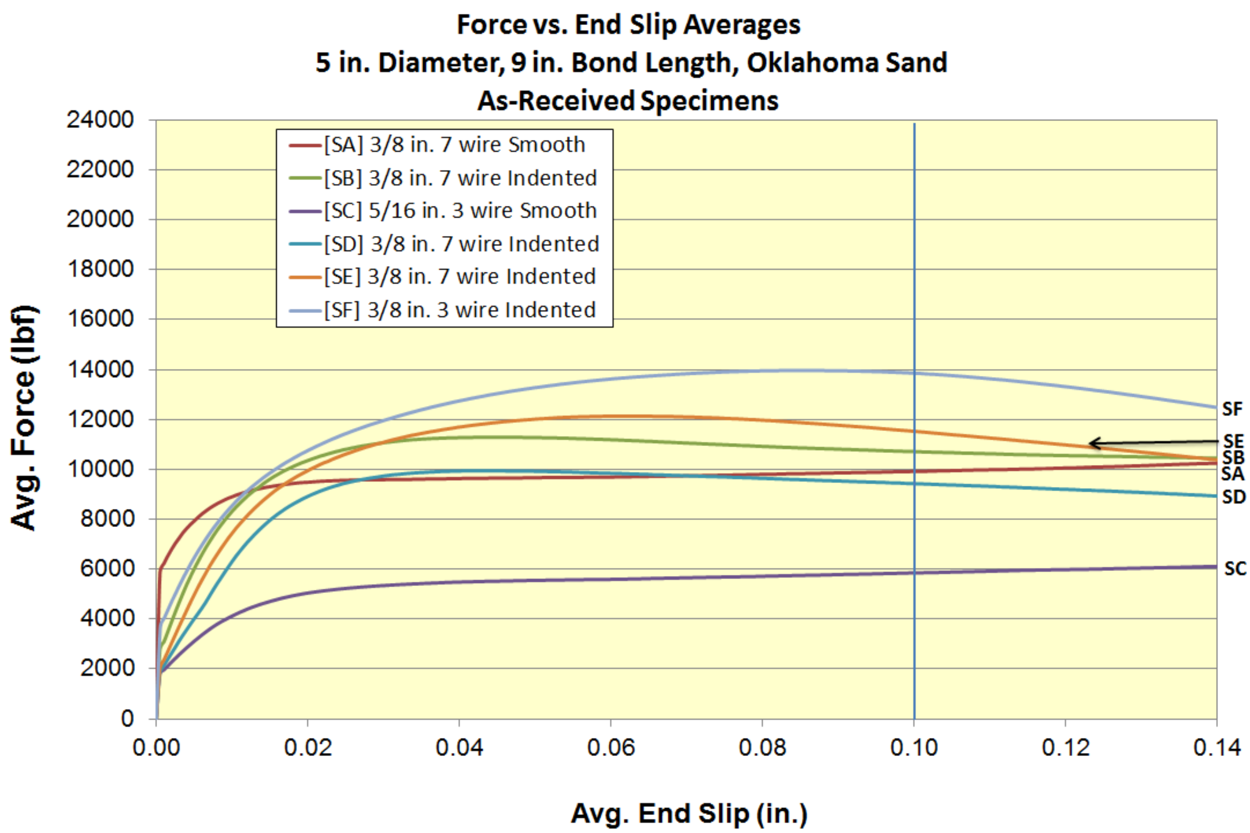


Figure 83. As-received strand force vs. end-slip averages (9-in. bond length)

5.3.2 Cleaned Results

The averaged cleaned force vs. end-slip results from each strand source using standard length strand specimens (bond length equal to 16 in.) is presented in Figure 84. The average force at each increment of end slip (0.0005 in.) was obtained by arithmetically adding the force results from each of the six individual specimens and then dividing the sum of force by six. The same process was used to average the end-slip measurements for each strand group.

Each plot on the graph represents the average of six individual specimens from the same strand source. Each of the six specimens was cast in a different batch of mortar. The force vs. end-slip graphs, showing individual results of the six specimens for each strand source, can be seen in Appendix K.

From Figure 84, it is clear the 16-in. bond length is too long for the higher bonding strands. This was the same trend represented in the As-received strand specimens. With this bond length, specimens containing strands SB, SE, and SF had to be stopped early during testing for fear of steel rupture failure prior to bond pullout failure. This is represented graphically by the sudden jumps in the graph as one of the high-bonding specimens drops out of the data set.

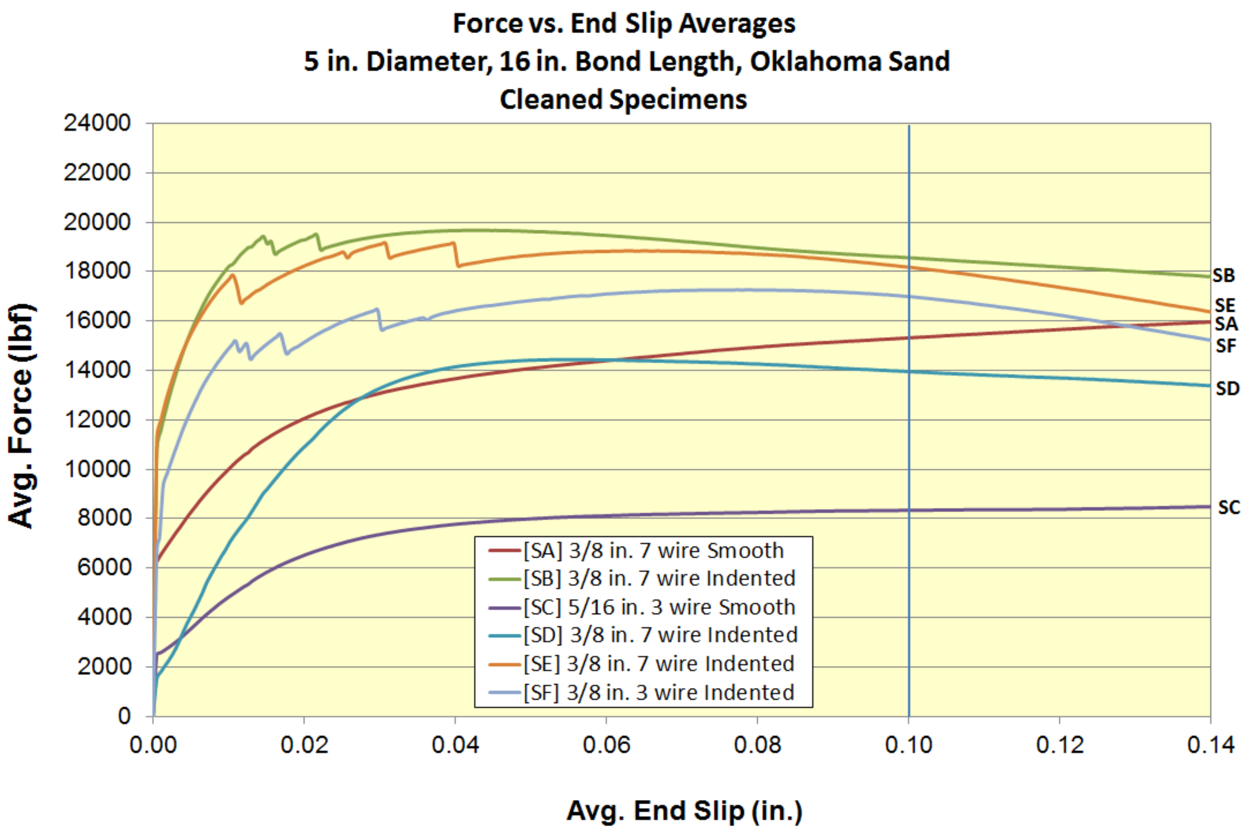


Figure 84. Cleaned strand force vs. end-slip averages (16-in. bond length)

5.3.3 Transfer Length Data

Data presented in Table 23 shows the average strand transfer length measurements determined from the surface strain data obtained by the KSU research team. Transfer lengths were determined from the surface strain data obtained from accompanying pretensioned prisms using the same strands as the pullout tests. Surface strain data was obtained for the entire length of the prisms. A bilinear strain profile was assumed for the software that calculated the transfer lengths.

The strands used for the pretensioned prisms were stored and preserved along with the strands used for the pullout tests. Three pretensioned prisms were cast using each strand. A transfer length was measured from each member end, resulting in a total of six transfer lengths (six data points).

Prisms were cast with four strands in a square pattern and were meant to be as representative as possible of actual concrete railroad ties. The concrete-to-steel-wire area of each prism is approximately the same as that of a typical concrete railroad tie produced in the United States. These prisms were cast using a concrete mixture similar to one used in a major concrete tie manufacturing plant in the United States. This mixture utilized the same coarse aggregate sources, mix proportions, and admixtures as the manufacturing plant. The prisms were de-tensioned at approximately 4500 psi (the same strength of the mortar used for pullout testing). Actual strength of the concrete at the time of de-tensioning for each batch can be seen in Table 23. The batching and testing procedures used to obtain the transfer lengths from these pretensioned prisms are presented in Bodapati's 2013 paper, but are not discussed here.

Table 23. Strand transfer length data

Strand Identification	Avg. Transfer Length (in.)	Concrete Strength at De-tensioning (psi)
[SA]	16.2	4636
[SB]	16.3	4736
[SC]	13.8	4449
[SD]	20.4	4847
[SE]	19.0	4636
[SF]	12.5	4635

Note: Sample size = 6

5.3.4 Analysis

All methods of analysis in this section compared results from Section 5.3.1 (As-received strand pullout data) to results from Section 5.3.3 (strand transfer length data).

This experimental program analyzed the strand pullout data by recording the force at 0.10 in. of free end slip. This method of analysis is laid out in the NASP (Russell, 2006) and NCHRP 603 (Ramirez and Russell, 2008) reports. Due to the large amount of previous research done on prestressing strand bond, no other method of analysis was investigated. The analysis done in this section is provided to give evidence of support or refutation of the modified bond length for strands of smaller diameter (less than 0.5-in. diameter).

The correlation was found for 1) all six wires, and 2) for only the five strands with 3/8-in. diameter. This was done because the transfer lengths obtained from the prisms using 5/16-in.-diameter strands (SC) used different cross-sectional dimensions.

For clarification, the x-coordinate (abscissa) of each point in these graphs represents the average of six transfer length readings; the y-coordinate (ordinate) of each point in these graphs represents the average of six individual pullout forces required to cause 0.10 in. of free end slip. The R^2 is the correlation between these two averaged data sets. Further discussion on strand SC is given below.

For the standard length specimens (16-in. bond length), the pullout force at 0.10 in. of end slip, compared with the average transfer length, can be seen in Table 24 and Figure 85. For the modified-length specimens (9-in. bond length), the pullout force at 0.10 in. of end slip, compared with the average transfer length, can be seen in Table 25 and Figure 86. Both Figure 85 and Figure 86 show the results of the data set including all six strands and the data set including only the 3/8-in.-diameter strands (five strands).

When all six strands are considered, the data sets for both the 16-in. and 9-in. bond length specimens give R^2 values less than 0.005 from Figure 85 and Figure 86. Both of these values show no statistical correlation between the pullout forces and measured transfer lengths. When looking for the source of these results, it became clear strand SC was an outlier. A few ideas as to why the prisms containing strand SC was an outlier have been discussed, but no proof can be given to support any of the claims. Regardless, it is clear something affected the test making SC an outlier.

When the same analysis using only the five 3/8-in.-diameter strands is repeated, the data sets for the 16-in. and 9-in. bond length specimens give R^2 values of 0.852 and 0.573, respectively, from Figure 85 and Figure 86. These values show a decent-to-good correlation between pullout forces and measured transfer lengths of 3/8-in.-diameter strands. If one data point (SC) can change the statistical correlation in such an extreme manner, it is hard to draw conclusions concerning these results. Still it is clear that a 16.-in embedment length is too long for use with higher-bonding strands, and a shorter embedment that that results in pullout of all specimens should be used.

Table 24. As-received strands, pullout force at 0.10-in. end slip (16-in. bond length)

Strand Bond Test Results 5 in. Diameter, 16 in. Bond Length, Oklahoma Sand Pullout Force at 0.10 in. End Slip				
Strand	Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[SA]	17105	1032	6.0	16.2
[SB]	17388	1396	8.0	16.3
[SC]	10267	1958	19.1	13.8
[SD]	14532	782	5.4	20.4
[SE]	15667	987	6.3	19.0
[SF]	17767	0	0.0	12.5

Note: Sample Size = 6, E = 5, F = 1

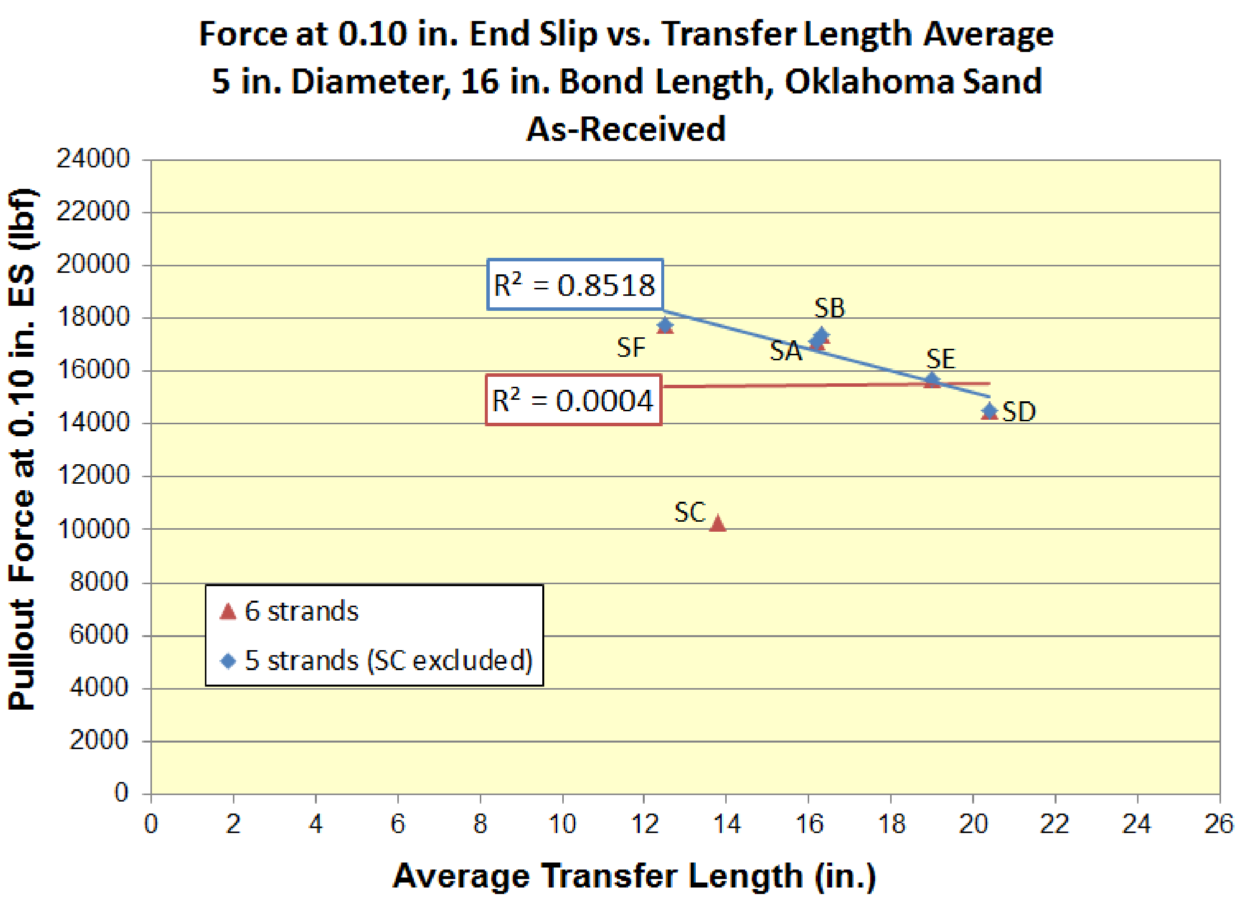


Figure 85. As-received strands, pullout force at 0.10-in. end slip (16-in. bond length)

Table 25. As-received strands, pullout force at 0.10-in. end slip (9-in. bond length)

Strand Bond Test Results 5 in. Diameter, 9 in. Bond Length, Oklahoma Sand Pullout Force at 0.10 in. End Slip				
Strand	Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[SA]	9918	1173	11.8	16.2
[SB]	10718	489	4.6	16.3
[SC]	5852	491	8.4	13.8
[SD]	9433	753	8.0	20.4
[SE]	11537	375	3.2	19.0
[SF]	13862	2005	14.5	12.5

Note: Sample Size = 6

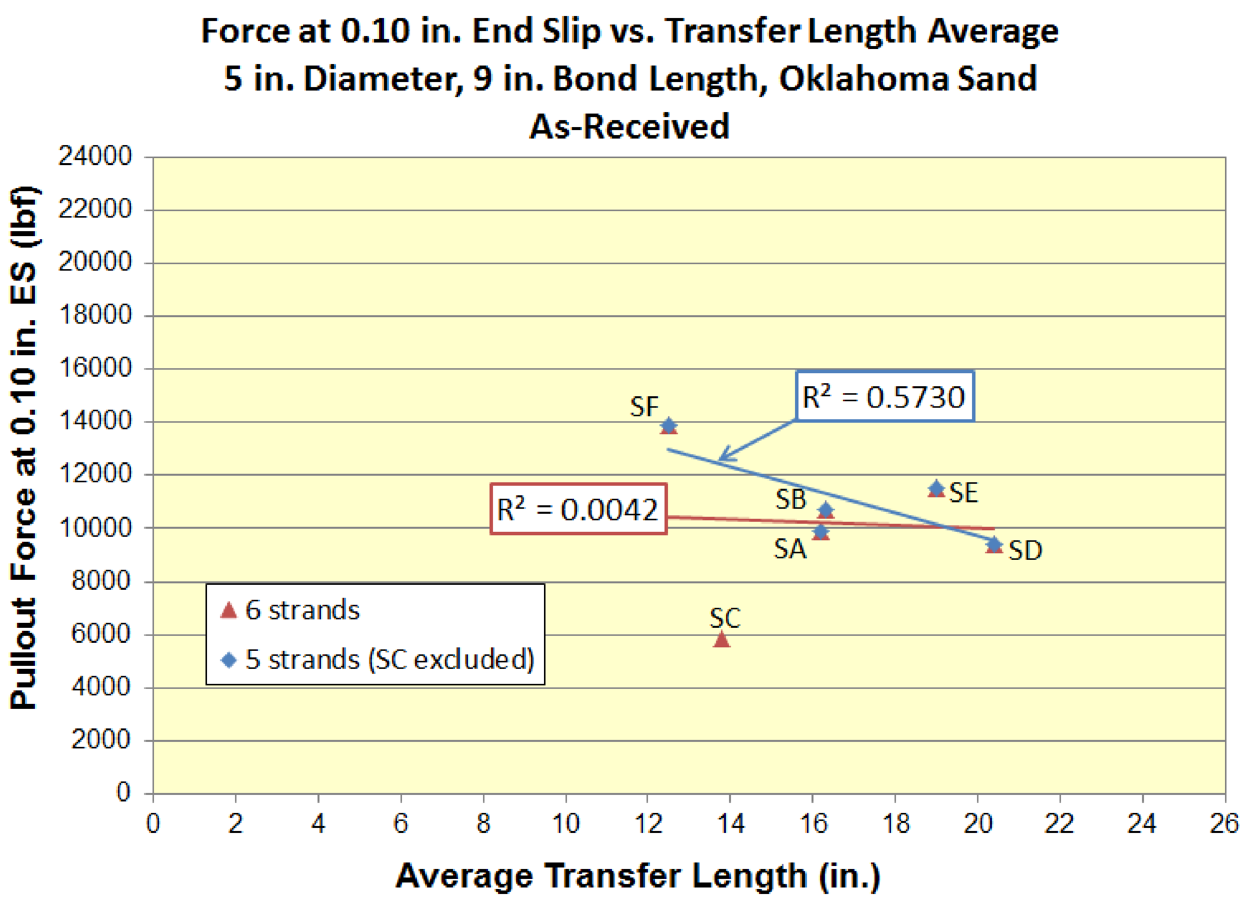


Figure 86. As-received strands, pullout force at 0.10-in. end slip (9-in. bond length)

5.3.5 Comparison of As-received vs. Cleaned

This section directly compares results of As-received (Section 5.3.1) and cleaned strand specimens (Section 5.3.2). This issue focuses on differentiating between bond associated with indent geometry and bond associated with surface condition.

All six strands (SA, SB, SC, SD, SE, and SF) were tested both in their As-received and cleaned conditions using the standard strand bond test (16-in. bond length). Of these strands, SA and SC exhibited slight to moderate levels of rusting. Strand SD appeared to have a slight residue coating the surface, possibly drawing lubricants from manufacturing or some other form of light grease or oil. The remaining three strands (SB, SE, and SF) appeared to have no noticeable signs of either rust or oils. Due to these different surface conditions, it was hypothesized that strands SA and SC would perform slightly worse after being cleaned due to having the rust removed. Slight rusting has been shown to improve bond performance during similar testing done on strands (Gustavson, 2004; Rose and Russell, 1997; Barnes, Grove, and Burns, 2003). Similarly, it was originally thought strand SD would exhibit better bond after being cleaned due to having the oil removed. It was assumed the remaining three strands would show roughly the same bond performance before and after the cleaning process.

Average pullout force vs. end-slip graph for each strand is shown in Figure 87 through Figure 92. Each As-received and Cleaned line on the graphs represents the six averaged specimens for those respective tests. Results of the individual pullout tests comparing six As-received specimens to six cleaned specimens can be seen in Appendix L.

From Figure 87 through Figure 92, it can be seen fairly definitively that four of the six strands (SA, SB, SC, and SE) performed much differently before and after the cleaning process. Strand SA performed worse after the cleaning process, which was anticipated due to the moderate rusting being removed. The bond performance of SB increased considerably after the cleaning process to the point that three of the six tests had to be stopped for fear of the steel strands rupturing instead of pullout bond failure. Similar to SA, the bond performance of SC decreased noticeably after the rust was removed from the surface through the cleaning process. This was expected. Strand SE had a noticeably higher bond capacity after the cleaning process as shown in Figure 91. This point is further illustrated in Appendix L by four of the six cleaned wires having to be stopped prior to pullout failure for fear of material rupture.

The remaining two strands (SD and SF) either performed the same before and after cleaning, as was the case with SD, or gave non-definitive results, as was the case with SF. Strand SD produced nearly the same force vs. end-slip curves in its As-received and cleaned surface conditions. This result can be seen in Figure 90. This was somewhat surprising given the oily nature of the strand’s surface when it arrived at Kansas State University. The results of strand SF were not able to be fully analyzed because five of the six As-received specimens and four of the six cleaned specimens had to be stopped prior to pullout bond failure due to fear of material rupture (reaching the ultimate stress). This result can be seen in Appendix L. Despite stopping the test early, results of SF still appeared to show relatively similar bond performance before and after cleaning, which was the anticipated result. However, further testing would need to be done to confirm this theorem.

While it is not fully known why strands SD and SF exhibited similar bond performance before and after the cleaning process, the general trend for this portion of the strand analysis led to the conclusion that surface condition of prestressing strands does have a noticeable effect on bond performance. This phenomenon was exhibited in four of the six strand sources with all variations represented. Of these smaller diameter strands affected by the surface condition, two were indented, two were not indented, one was three-wire, and three were seven-wire. This conclusion makes sense when the overall geometry of the strand is considered. Since the area of the strand indents is small relative to the overall cross-sectional area of the 5/16-in.-diameter and 3/8-in.-diameter strands, then it makes sense the indent geometry would play a small role in overall bond performance of the strands and surface condition would contribute a much more meaningful portion.

This seems to also explain why strand SA (3/8-in.-diameter seven-wire, smooth) performed better than strand SB (3/8-in.-diameter seven-wire, indented) before the cleaning process, but performed worse than SB after the cleaning process. Strands SA and SB are from the same steel manufacturer. Logic indicates the indented strand, SB, would exhibit higher bond quality than the smooth strand, SA, if the surface conditions were the same. This proved to be true after the cleaning process. Once the rust was removed from SA, it performed noticeably worse than SB after cleaning, which had previously exhibited no rust. Prior to cleaning, SA and SB had nearly identical pullout values at 0.10-in. of end slip for both 16-in. and 9-in. bond lengths as can be seen in Figure 82 and Figure 83.

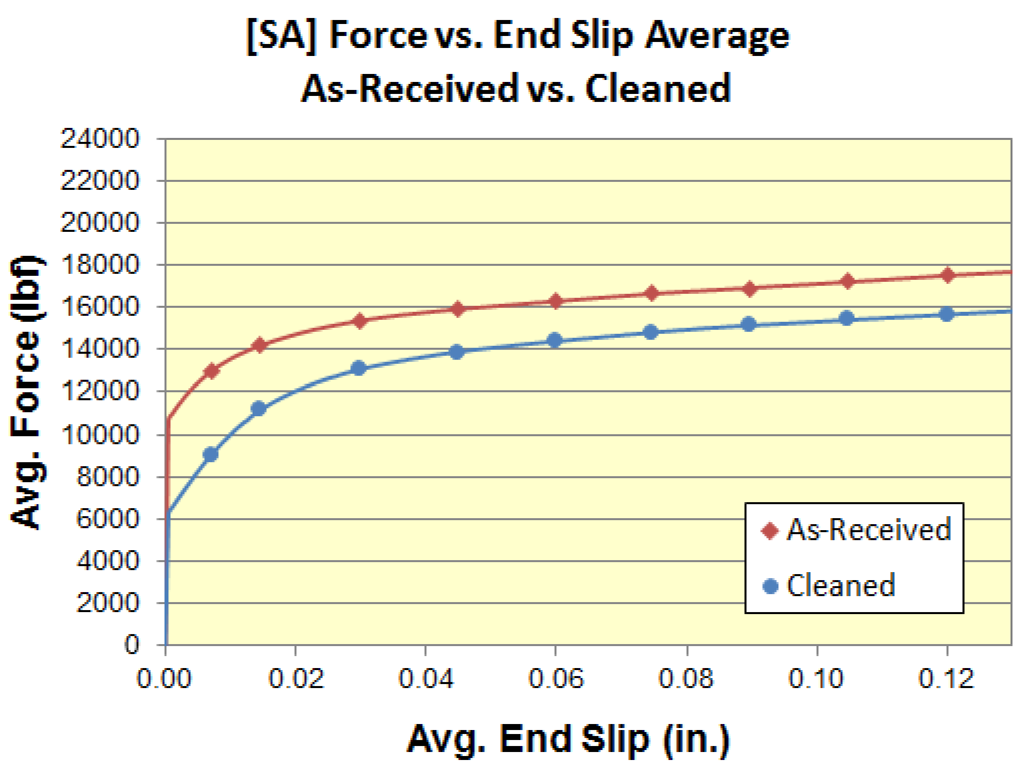


Figure 87. Force vs. end-slip average graphs for strand SA, As-received vs. cleaned

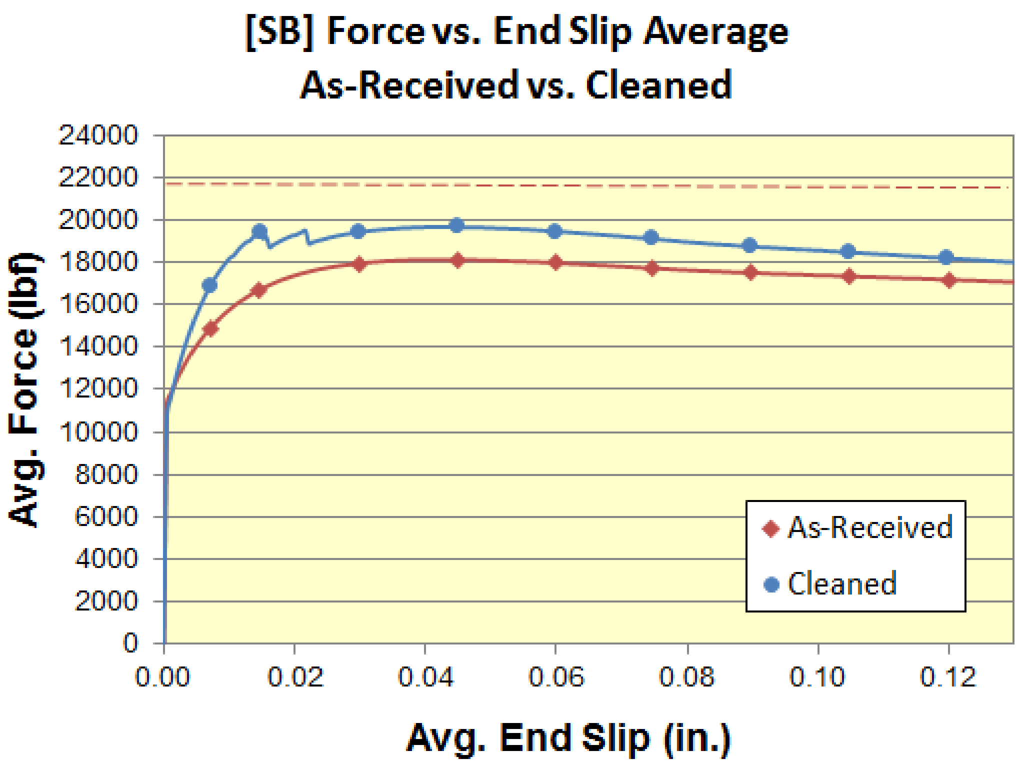


Figure 88. Force vs. end-slip average graphs for strand SB, As-received vs. cleaned

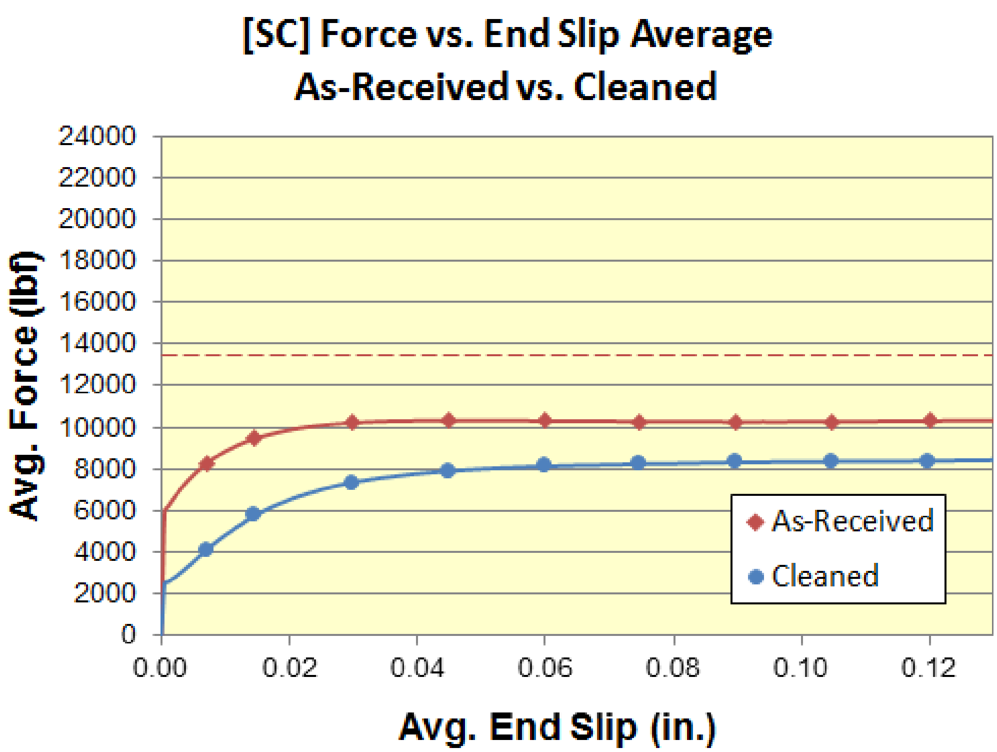


Figure 89. Force vs. end-slip average graphs for strand SC, As-received vs. cleaned

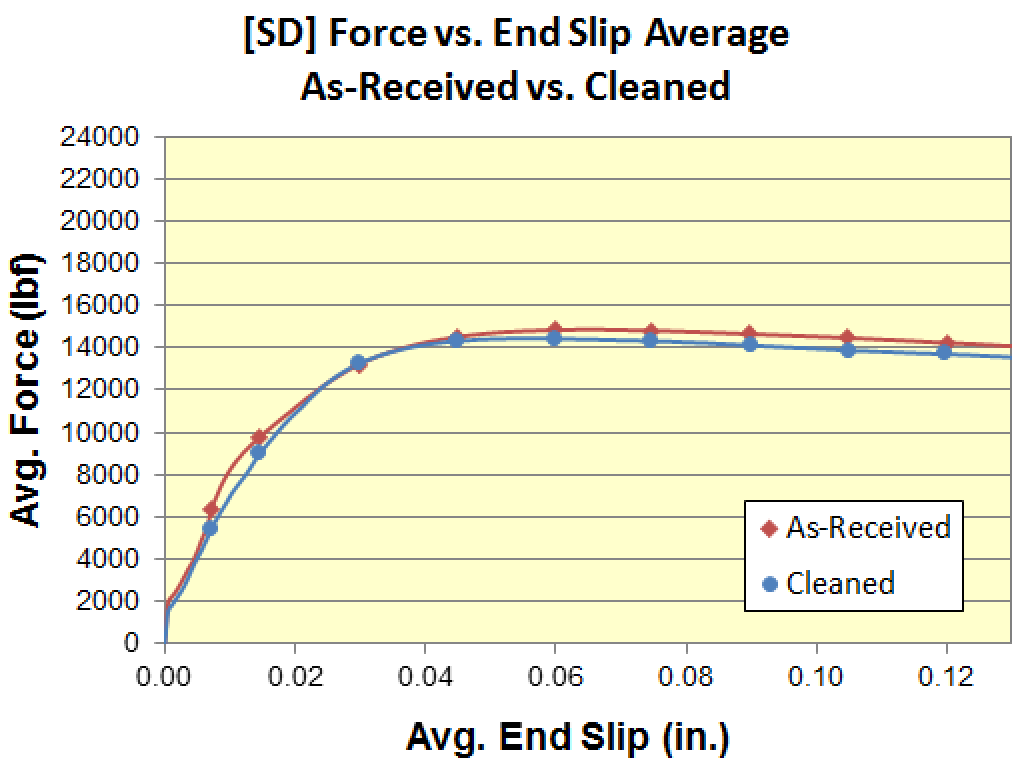


Figure 90. Force vs. end-slip average graphs for strand SD, As-received vs. cleaned

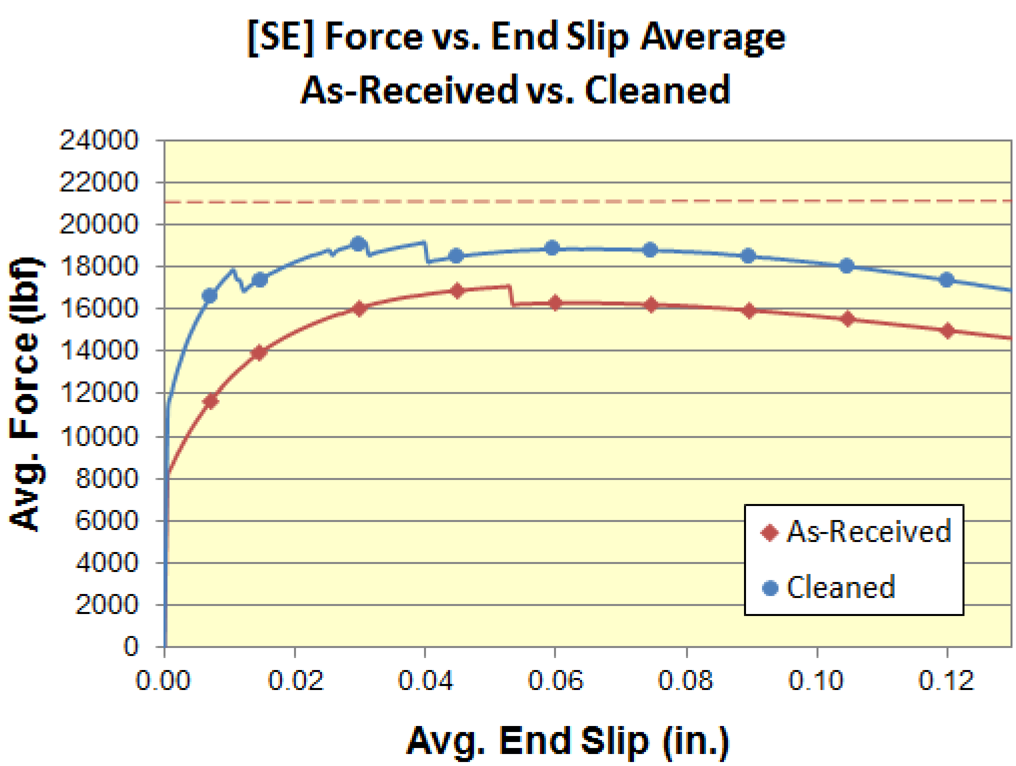


Figure 91. Force vs. end-slip average graphs for strand SE, As-received vs. cleaned

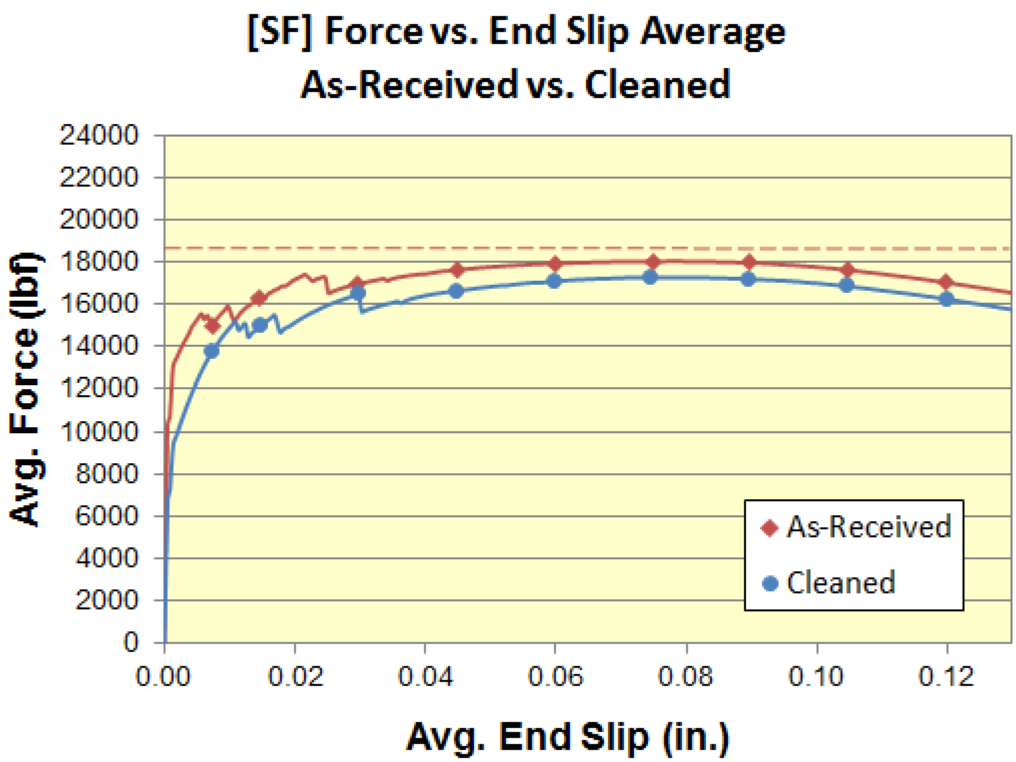


Figure 92. Force vs. end-slip average graphs for strand SF, As-received vs. cleaned

6. Plant Phase; Wire and Strand Pullout Testing (Un-tensioned Tests in Concrete)

Chapter 6 discusses the experimental program, results, and analysis of the plant portion of the wire and strand bond pullout tests. These tests are un-tensioned and were performed in concrete. During the plant phase, the research team from Kansas State University (KSU) measured transfer lengths in actual, non-prismatic concrete railroad ties at the CXT Concrete Ties (CXT) plant in Tucson, Arizona. Pullout specimens were cast in addition to the railroad ties upon which transfer length measurements were taken. Fifteen reinforcements from seven different steel manufacturers, the same as the reinforcements used for pullout and transfer length tests at KSU, were used in the plant phase. Approximately fifty transfer length measurements and six pullout specimens were obtained for each reinforcement type. Table 26 shows the testing matrix of all wires and strands used for the plant testing phase.

Table 26. Testing matrix of plant phase

	Reinforcement Manufacturer	Reinforcement Identification	Indentation Type	Number of test specimens	
				Transfer lengths (no. of ends)	As-received un-tensioned pullouts
Wires	A	[WA]	Smooth	49	4
	A	[WB]	Chevron	50	5
	A	[WC]	Spiral	47	4
	B	[WD]	Chevron	49	6
	B	[WE]	Spiral	48	6
	B	[WF]	Diamond	49	6
	C	[WG]	Chevron	49	6
	D	[WH]	Chevron	50	6
	E	[WI]	Chevron	50	6
	E	[WJ]	Chevron	47	6
	F	[WK]	4-Dot		
	F	[WL]	2-Dot	47	6
	G	[WM]	Chevron	49	6
	Wires Total:			**584**	**67**
Strands	A	[SA]	3/8" 7-Wire, Smooth	45	6
	A	[SB]	3/8" 7-Wire, Indented	50	6
	A	[SC]	5/16" 3-Wire, Smooth	48	4
	Strands Total:			**143**	**16**

6.1 General Testing Protocol

The general testing protocol used for pullout testing at CXT was the same as the methodology developed at KSU. A 4-in.-diameter by 8-in.-long steel cylinder mold was used to cast the specimens. The steel reinforcement was held centered in the molds using an external fixture similar to the ones used at KSU. Minor differences between the two protocols are listed below.

Concrete was used for the CXT pullout tests instead of the sand-cement mortar used at KSU. The concrete used for pullout testing came from the same batches as the concrete used to pour the railroad ties. The CXT pullout specimens were consolidated in two lifts using a vibrating table instead of the wand-type concrete vibrator used to consolidate the mortar at KSU. A slump test using a slump cone was done to measure the workability of the concrete rather than the flow table measurement used for the mortar at KSU. The concrete strength at CXT was measured by casting 12 4-in. x 8-in. cylinders instead of the 2-in. mortar cubes used for testing mortar strength at KSU.

The specimens were stored in a temperature-controlled room at approximately 150 ^{o}F, which allowed the specimens and strength cylinders to heat up similarly to the concrete railroad ties themselves. A force controlled test was run by manually controlling the flow rate of a small hydraulic pump. This pump was not servo-controlled as was the setup at KSU. The force was applied at the bottom, and the end slip was continuously measured and recorded at the top using an LVDT. This is the same process used at KSU.

6.2 Experimental Program

This section contains information used for this experimental testing program regarding pullout bond tests using steel prestressing wires and strands in a plant environment. Information includes specimen dimensions; mix proportions, material sources, and batch sizes; specimen casting and storage procedures; and testing procedures used while performing pullout tests at a concrete railroad tie plant.

6.2.1 Specimen Dimensions

Two specimen sizes were used for the pullout testing portion of the plant phase, one for wire specimens and one for strand specimens. Both specimens were the exact same size except for the bond length used. The wire specimens utilized a 6-in. bond length and the strand specimens utilized a 4-in. bond length. The shorter embedment lengths were used for the pullout specimens with concrete because previous research indicated that pullout tests with a concrete medium may result in higher pullout forces than pullout tests utilizing mortar and having the same embedment length and compressive strength at the time of testing.

The wire specimens utilized a 4-in.-inner-diameter steel splitting cylinder mold, 1/4-in. wall thickness, and a total length of 8 in. A 6-in. by 6-in. steel plate (1/4-in. thick) was held fixed to the bottom using two wing nuts. Within the 8-in.-long steel mold, there was a 6-in. embedment (bond) length with a 2-in.-long duct tape bond breaker at the bottom of the wire specimens. The wire extended past the top concrete surface by approximately two inches. A schematic of the CXT wire pullout specimen is shown in Figure 93. The bottom plate had a 1/4-in.-diameter hole drilled in the center to allow the steel wire to pass through. The wires were held centered in the cylinder mold using an additional fixture (shown in Figure 95).

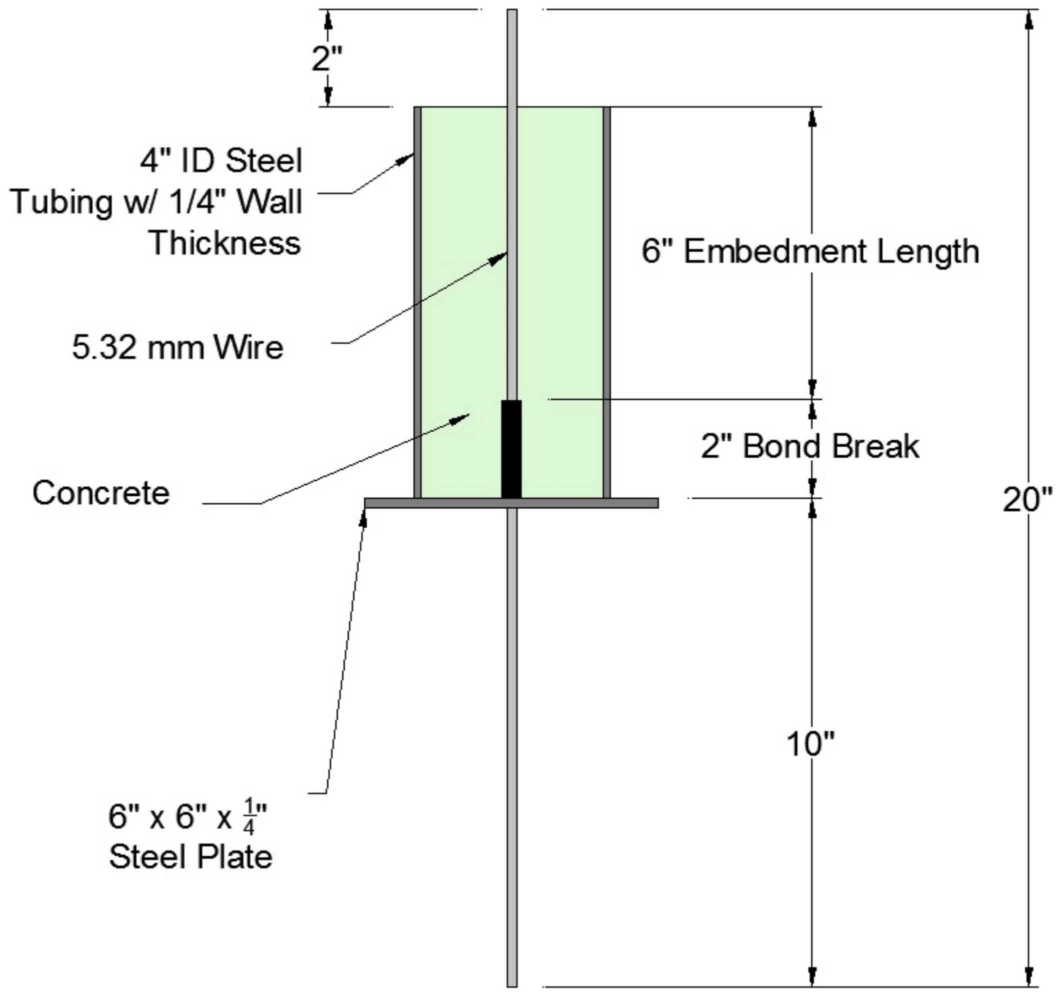


Figure 93. Dimensions of wire pullout test specimen at CXT

The strand specimens utilized a 4-in.-inner-diameter steel splitting cylinder mold, 1/4-in. wall thickness, and a total length of 8 in. A 6-in. by 6-in. steel plate (1/4-in. thick) was held fixed to the bottom using two wing nuts. Within the 8-in.-long steel mold, there was a 4-in. embedment (bond) length with a 4-in.-long duct tape bond breaker at the bottom of the strand specimens. The strand extended past the top concrete surface by approximately two inches. A schematic of the CXT strand pullout specimen is shown in Figure 94. The bottom plate had a 1/4-in.-diameter hole drilled in the center to allow the steel wire to pass through. The strands were held centered in the cylinder mold using an additional fixture (similar to the one shown in Figure 95).

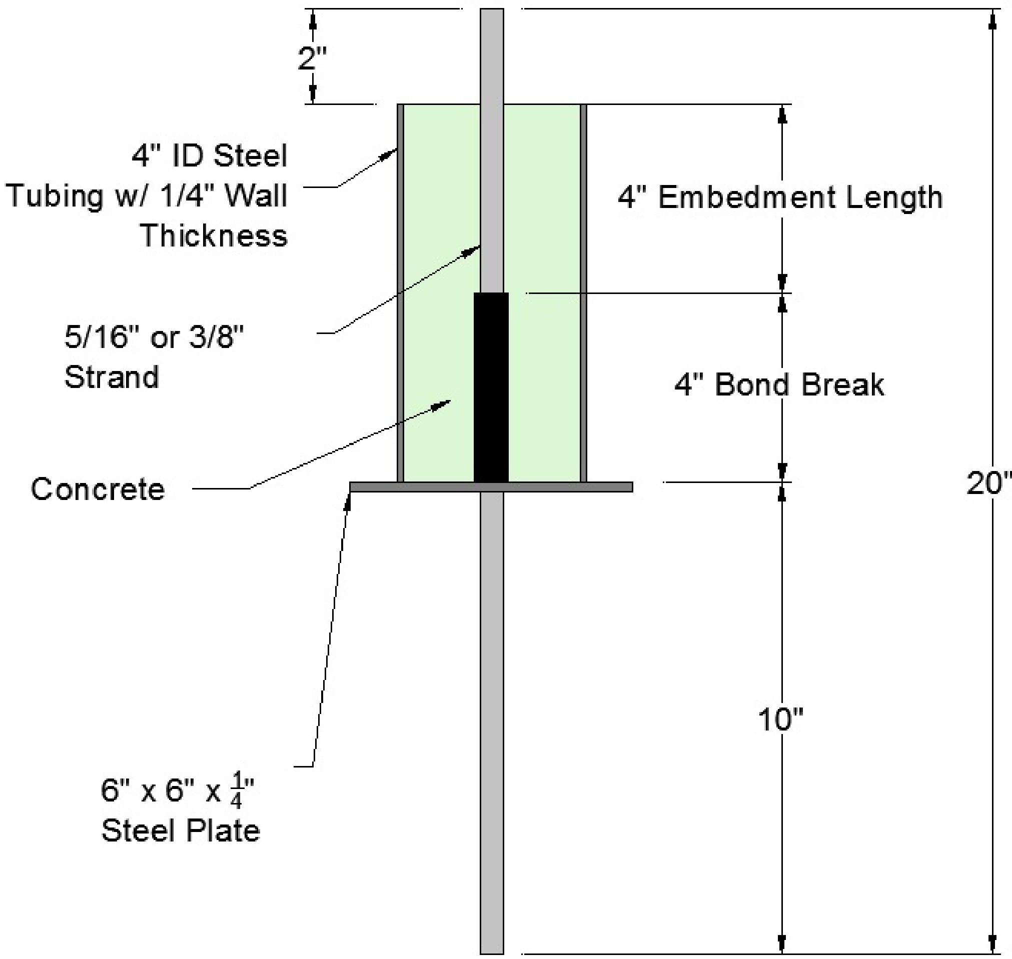


Figure 94. Dimensions of strand pullout test specimen at CXT

Figure 95. Additional fixture used to center reinforcement during casting at CXT

6.2.2 Mix Proportions, Material Sources, and Batch Size

The 15 reinforcements were cast on 10 separate days using 10 separate concrete batches. The batches had water-to-cement (w/c) ratios typical of most concrete railroad tie plants in the United States. The cement used was a Type III cement conforming to ASTM C150. The sand and rock sources were local, Arizona aggregates used in CXT's standard concrete mix. High-range water reducers were also used for workability.

Approximately 2 yd^3 of concrete was batched at a time with approximately 3 ft^3 of that concrete being used for quality control purposes and 1.75 ft^3 used specifically for the pullout tests. Concrete used for pullout testing came from the same batches as the concrete used to pour the railroad ties.

All concrete batching was done by CXT's batch plant. Consistency and quality of this concrete was verified by the batch plant and quality control (QC) employees working for CXT.

6.2.3 Casting and Specimen Curing Procedures

Each reinforcement was tested six times and the results averaged. All reinforcements were tested in their As-received condition during the plant phase. In addition to the pullout specimens, 12 4-

in. x 8-in. cylinders were cast to test the compressive strength of the concrete. The pullout specimens and cylinders used for strength were consolidated in two lifts using a vibrating table. A slump test using a slump cone was done to measure the workability of the concrete.

The vibrating action from the vibrating table, along with the superplasticizer, provided a relatively smooth finish with no further need to smooth the surface. The specimens were covered with plastic to retain moisture during curing. They were then stored in a temperature-controlled closet at approximately 150 ^{o}F. The outside and inside of the storage closet can be seen in Figure 96. This allowed the specimens and cylinders used for strength to heat up similarly to the concrete railroad ties. No humidity-control mechanism was present in the curing closet.

Average concrete strength at the time of pullout testing (measured from the 4-in. x 8-in. cylinders) and average specimen curing time are shown in

Table 27 for the As-received wire and strand pullout specimens tested at CXT.

Different 4-in. x 8-in. cylinders were driven by a SureCure temperature matching system to reveal when de-tensioning could begin and to track strength throughout the duration of the cutting operation. The temperature was driven by a thermal couple embedded in the concrete ties themselves.

Figure 96. Outside and inside of temperature-controlled storage closet at CXT

Table 27. As-received pullout batch summaries at CXT, wire, and strand

Reinforcements Used in This Batch	Avg. Specimen Cure Time (hrs)	Avg. Cylinder Strength at Time of Test (psi)
[WA]	12.5	5884
[WB]	10.75	6585
[WC] / [SC]	14.0	6607
[WD] / [WG]	11.0	5965
[WE] / [SA]	13.0	5924
[WF] / [WH]	12.0	5190
[WI]	8.75	4651
[WJ]	9.75	5532
[WL] / [SB]	13.0	6536
[WM]	10.5	6245
Average	**11.5**	**5912**

6.2.4 Testing Procedures

Specimen testing began at approximately the same time as de-tensioning of the concrete ties. Strength of the concrete was monitored before, during, and after pullout testing.

A force controlled test was run in a Forney testing machine by manually controlling the flow rate of a small hydraulic pump. This pump was not servo-controlled as was the setup at KSU. The overall testing setup at CXT can be seen in Figure 97. The force control rate ranged from approximately 30-35 pounds/sec, which equates to 1800-2100 pounds/min. The force was applied at the bottom, and the end slip was continuously measured and recorded at the top using an LVDT. This is the same process used at KSU. The load was recorded by means of a 10,000-pound-capacity pressure transducer. Time, end slip, and force data were obtained in 0.1-second intervals. A close-up view of the specimen in the testing machine and a close-up of the LVDT mounted on the specimen can be seen in Figure 98.

Figure 97. Manually controlling force loading rate at CXT

Figure 98. a) Specimen in testing machine at CXT and b) LVDT on specimen at CXT

6.3 Results and Analysis

Results of the experimental, plant wire and strand testing program are presented in this section. First, results of the As-received wire pullout specimens are presented. Second, As-received strand pullout results are documented. The third section presents transfer length measurements obtained from actual pretensioned concrete railroad ties. Finally, analysis used for both the wire and strand bond testing is established and the findings presented.

6.3.1 Wire Pullout Results

Average As-received force vs. end-slip results at CXT from each wire source are presented in Figure 99. The average force at each increment of end slip (0.0005 in.) was obtained by arithmetically adding the force results from each of the six individual specimens and then dividing the sum of force by six. The same process was used to average the end-slip measurements for each wire group.

Each curve on the graph represents the average of six individual specimens from the same wire source, except for the following wires: WA and WC are represented by four specimens; WB is represented by five specimens. The reduced numbers of specimens are a result of malfunctions with the LVDT and data acquisition software. All specimens from the same wire source were cast from the same batch of concrete at the same time. Force vs. end-slip graphs showing individual results of the six specimens for each wire source can be seen in Appendix N.

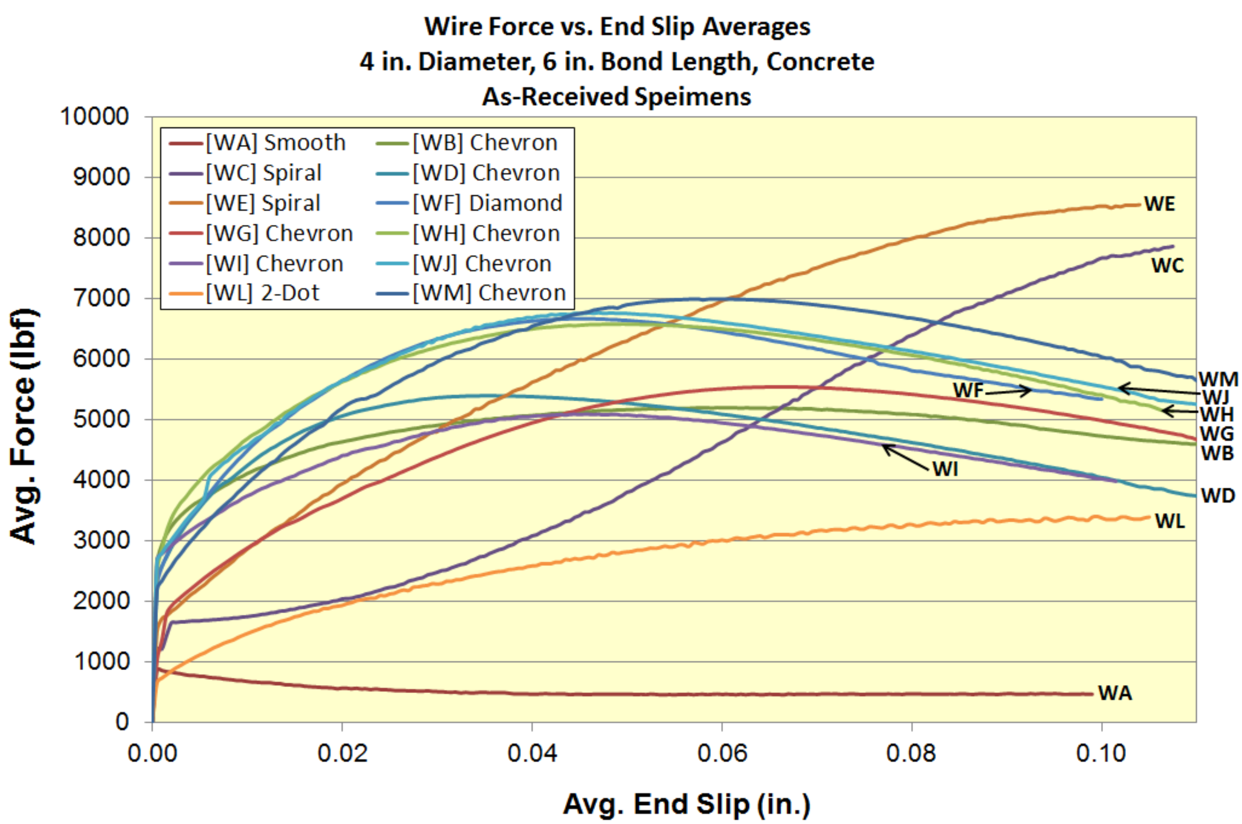


Figure 99. As-received wire force vs. end-slip averages at CXT

6.3.2 Strand Pullout Results

Due to an error that took place in the plant, pullout specimens at CXT containing strand SB were tested using a 6-in. bond length instead of the 4-in. bond length used for strands SA and SC. Because of the different bond lengths of the specimens, the bond stress was used for the CXT results instead of pullout force. Bond stress is defined as the pullout force at any location divided by the total surface area in contact with the concrete. This surface area is mathematically defined as the perimeter of the strand multiplied by the bond length. Table 28 contains the bond area for strands SA, SB, and SC. All of the pullout forces from this point forward will be divided by the respective bond areas.

Average As-received bond stress vs. end-slip results at CXT from each strand source are presented in Figure 100. The average force at each increment of end slip (0.0005 in.) was obtained by arithmetically adding the force results from each of the six individual specimens and then dividing the sum of force by six. The same process was used to average the end-slip measurements for each wire group.

Each curve on the graph represents the average of six individual specimens from the same strand source except for SC, which is represented by four specimens. The reduced number of specimens is a result of malfunctions with the LVDT and data acquisition software. All specimens from the same strand source were cast from the same batch of concrete at the same time. Bond stress vs. end-slip graphs showing individual results of the six specimens for each strand source can be seen in Appendix N.

Table 28. Bond areas of different bonded strand lengths

Strand Identification	[SA]	[SB]	[SC]
Indentation Type	3/8" 7-Wire, Smooth	3/8" 7-wire, Indented	5/16" 3-wire, Smooth
Cross-Sectional Area (in^2)	0.0850	0.0850	0.0582
Perimeter Length (in.)	1.378	1.378	2.138
6 in. Long Bond Area (in^2)	8.268	8.268	12.828
4 in. Long Bond Area (in^2)	5.512	5.512	8.552

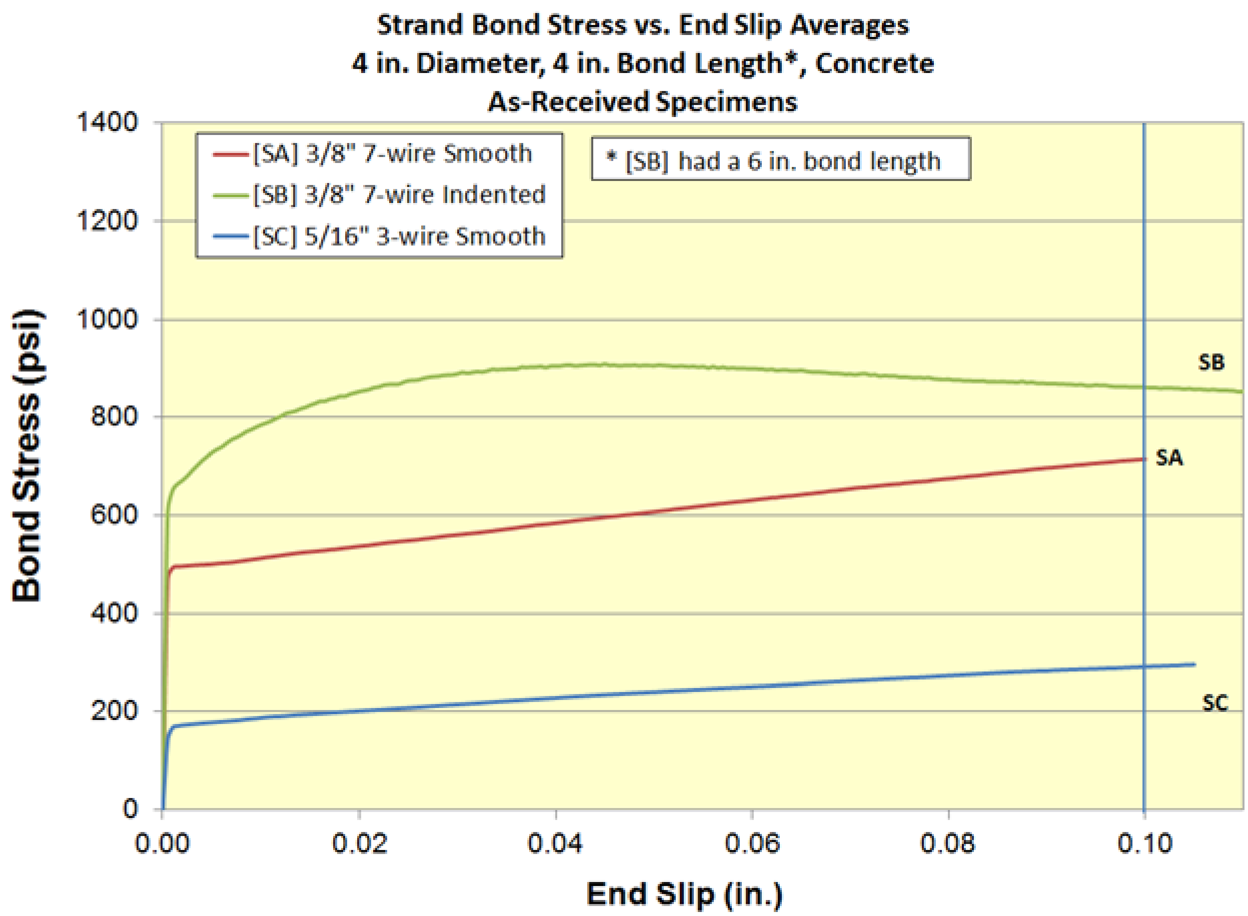


Figure 100. As-received strands, bond stress vs. end-slip averages at CXT

6.3.3 Transfer Length Data

Data presented in Table 29 shows the average wire and strand transfer length measurements determined from the surface strain data obtained by the KSU research team while at CXT. Transfer lengths were determined from the surface strain data obtained from actual accompanying pretensioned concrete railroad ties using the same wires and strands as the pullout tests. Surface strain data was obtained for a distance of 28 inches from the tie end. A bilinear strain profile was assumed for the software that calculated the transfer lengths.

The reinforcements used for the pretensioned concrete railroad ties were stored and preserved along with reinforcements used for the pullout tests. Reinforcements were stored in their coils inside of a sealed shipping freight box. Inside the box were large silica-based desiccant packets to maintain surface conditions as received from the manufacturer/supplier.

Forty-five pretensioned concrete ties were cast using each reinforcement type. A transfer length determination at both ends of 25 ties was attempted at de-tensioning, resulting in a total of approximately 50 transfer length data points per reinforcement. The actual number of transfer lengths obtained for each reinforcement type is shown in Table 26. Railroad ties manufactured with wires each contained twenty individual wires. Railroad ties containing SA and SB used eight strands, and ties containing SC used 12 strands. All of these steel configurations gave an almost identical total steel area due to the differences in the areas of each individual wire compared to the 3/8-in.-diameter strands (SA and SB) and the 5/16-in.-diameter strand (SC).

These concrete railroad ties were cast using the concrete mixture described in Section 6.2.2. Concrete strength at the time of de-tensioning is listed in Table 29. Strength was measured from a SureCure temperature-match curing system. Note, the concrete plant had a minimum release strength requirement of 5000 psi, so all of the compressive strengths listed in Table 29 were above this value. Since the The testing procedure used to obtain the transfer lengths from these pretensioned concrete railroad ties is presented in a separate report.

Table 29. CXT wire and strand transfer length data

Reinforcement Identification	Avg. Transfer Length[1,2] (in.)	Concrete Strength at De-tensioning (psi)
[WA]	14.3	5365
[WB]	10.2	6450
[WC]	11.2	5617
[WD]	9.7	5440
[WE]	8.6	5277
[WF]	7.8	5063
[WG]	10.9	5440
[WH]	8.3	5063
[WI]	10.8	5217
[WJ]	9.4	5447
[WL]	13.3	6600
[WM]	9.2	6650
[SA]	14.4	5277
[SB]	15.6	6600
[SC]	15.9	5617

Note 1: Sample size ≈ 50

Note 2: Bilinear surface strain profile assumed

6.3.4 Analysis

Analysis in this section compared results from Sections 6.3.1 (As-received wire pullout data) and 6.3.2 (As-received strand pullout data) to results from Section 6.3.3 (transfer length data). The wire analysis is given first and the strand analysis second.

6.3.4.1 Wire Pullout Analysis

Analysis of the wires was performed using the method of Section 4.3.4.5. This method uses maximum pullout force at any location with less than or equal to 0.10-in. end slip and was found from the laboratory experimental program to provide the best correlation to measured transfer lengths.

The correlation was found for 1) all 12 wires and 2) for only the wires with non-continuous indentations (nine wires). This was done because the smooth and spiral wires exhibit a different slip pattern than the individually-indented wires, and the researchers wanted to see whether or not a good correlation could be achieved for wires with indents specifically conforming to ASTM C881. The results of the analysis are presented in tabular form in Table 30. Graphical results of the analysis using all 12 wires are shown in Figure 101 and Figure 102, using only the nine-wire data set (wires with non-continuous indentations). The number of pullout tests performed for each wire source is indicated in the notes of Table 30. Average transfer length value is represented by approximately 50 individual transfer length measurements.

This method of analysis also provides a correlation of $R^2 = 0.680$ when all 12 wires are considered. Furthermore, this analysis gives a correlation of $R^2 = 0.825$ when considering only the wires with non-continuous indentations.

Table 30. As-received wires, maximum pullout force at CXT

As-Received Wire Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Concrete Maximum Pullout Force (ES ≤ 0.10 in.)				
Wire	Avg. Pullout Force (lbf)	Std. Dev.[1] (lbf)	C.V.[1] (%)	Avg. Transfer Length[2] (in.)
[WA]	903	128	14.2	14.3
[WB]	5230	261	5.0	10.2
[WC]	7655	1131	14.8	11.2
[WD]	5459	596	10.9	9.7
[WE]	8526	301	3.5	8.6
[WF]	6694	701	10.5	7.8
[WG]	5554	386	6.9	10.9
[WH]	6618	1017	15.4	8.3
[WI]	5175	203	3.9	10.8
[WJ]	6789	343	5.1	9.4
[WL]	3438	325	9.4	13.3
[WM]	7004	726	10.4	9.2

Note 1 : Sample Size = 6, WA = 4, WB = 5, WC = 4

Note 2 : Sample Size ≈ 50, Bilinear surface strain profile assumed

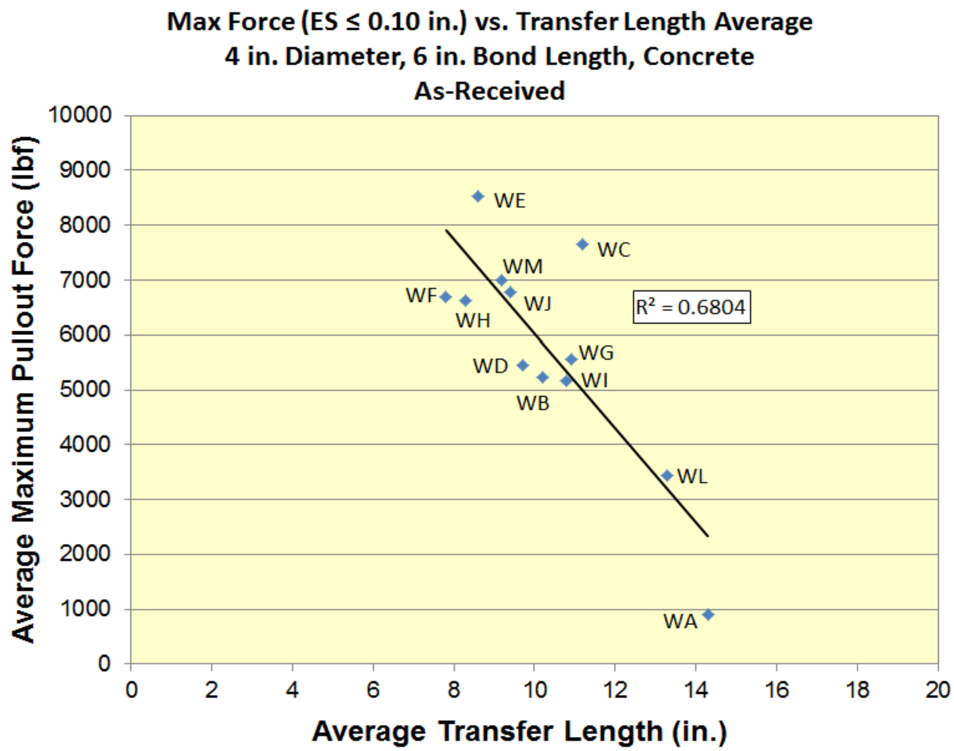


Figure 101. As-received wires, maximum pullout force at CXT

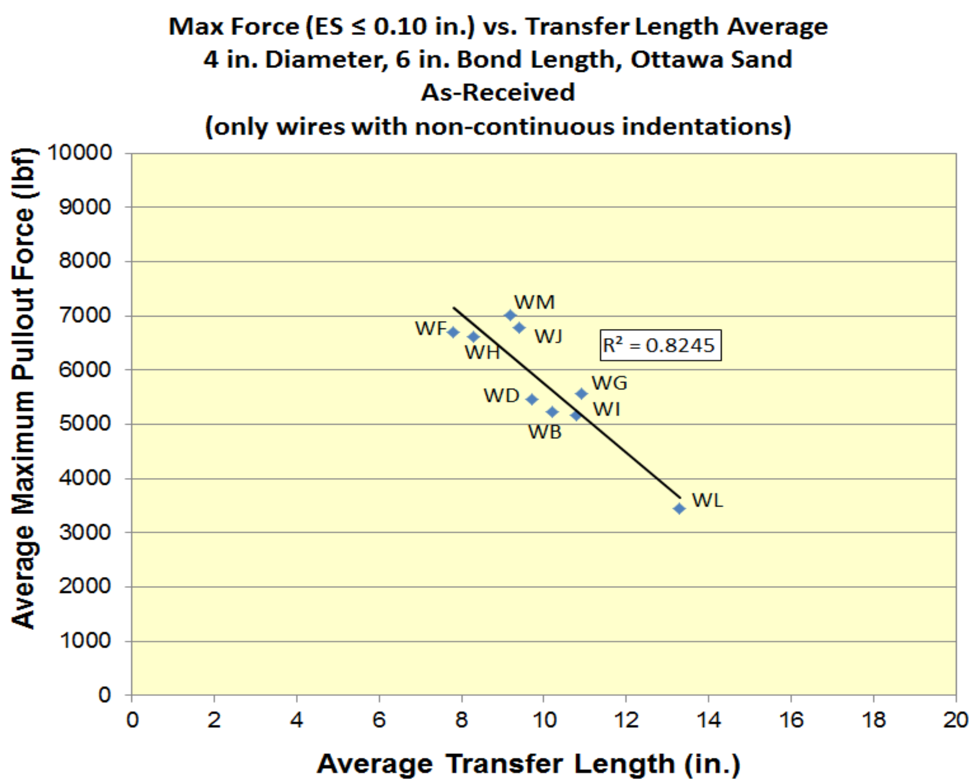


Figure 102. As-received wires, maximum pullout force at CXT (individual-indents only)

This analysis shows that even when using concrete, the wire pullout test described in Appendix I is a good indicator of transfer length for wires with non-continuous indentations. Additionally, this analysis shows the wire pullout test to be a fair indicator of transfer lengths for all wire indent types.

This is an interesting conclusion given the wide variation of concrete strengths (shown in Table 29) during each set of pullout tests for each wire. It is important to clarify that the variable concrete strength during the pullout tests does not allow us to compare relative bond performance between the wire groups. However, since the pullout tests were performed at roughly the same time as the de-tensioning of the concrete railroad ties, these pullout concrete strengths are similar to the actual strength of the concrete used in the railroad ties. By performing the pullout tests at roughly the same time as de-tensioning occurred, the variable of concrete strength was more or less negated as shown by the good correlation between maximum pullout force and measured transfer length. This makes sense because it is assumed that the maximum pullout force increases and the transfer length decreases when the concrete strength increases.

It is hypothesized the wire pullout tests would have had even better correlation with the transfer lengths measured from the concrete railroad ties had the pullout specimens been cured at the same temperature as the ties themselves. This could have been achieved by driving the temperature of the pullout specimens using a temperature-match curing system.

6.3.4.2 Strand Pullout Analysis

Analysis of the strands was performed according to the method laid out in the NASP (Russell, 2006) and NCHRP 603 (Ramirez and Russell, 2008) reports. This standard test for strand bond uses the pullout force at 0.10 in. of free end slip. The analysis here correlates the measured transfer lengths to the bond stress corresponding to this pullout force. Results of the analysis using the three strand sources are given in Table 31 and Figure 103. The number of pullout tests performed for each strand source is indicated in the notes of Table 31. The average transfer length value is represented by approximately 50 individual transfer length measurements.

This analysis gives a correlation of $R^2 = 0.200$ between the bond stress recorded at 0.10 in. of end slip and the measured transfer length. This analysis shows when using concrete and only three strand sources, the strand pullout test described in Section 6.2 is a poor indicator of transfer length for smaller diameter strands.

Table 31. As-received strands, bond stress at 0.10-in. end slip at CXT

As-Received Strand Pullout Test Results 4 in. Diameter, 4 in. Bond Length[2], Concrete Pullout Force at 0.10 in. End Slip				
Strand	Avg. Bond Stress[1] (psi)	Std. Dev. (psi)	C.V. (%)	Avg. Transfer Length[3] (in.)
[SA]	715	100	14.0	14.4
[SB]	862	31	3.6	15.6
[SC]	291	85	29.0	15.9

Note 1: Sample Size = 6, SC = 4

Note 2: Strand [SB] has a 6 in. bond length

Note 3: Sample Size ≈ 50, Bilinear surface strain profile assumed

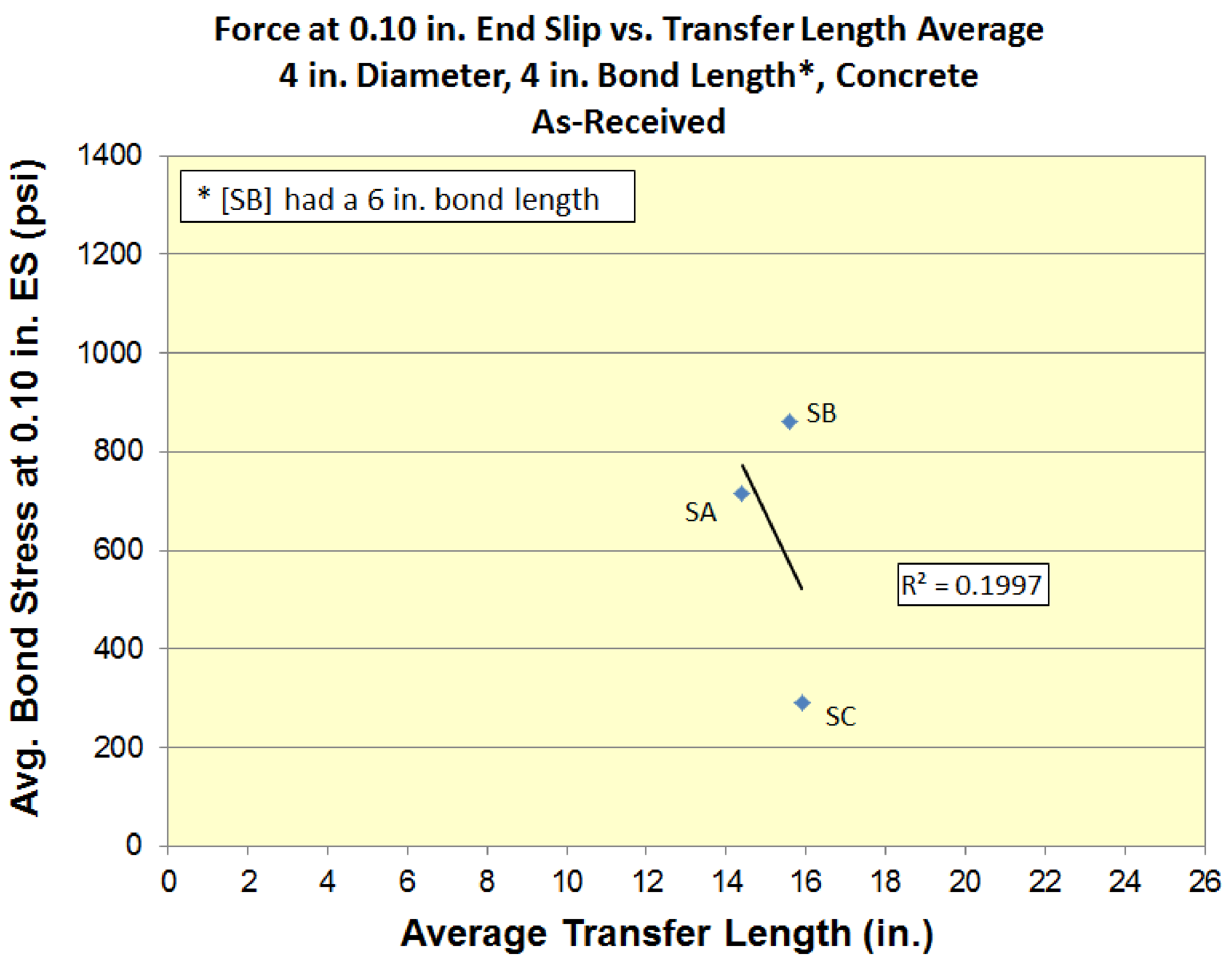


Figure 103. As-received strands, bond stress at 0.10-in. end slip at CXT

7. Comparing Results of Lab and Plant Phases

Chapter 7 compares As-received results of the wire and strand bond pullout tests between the lab and the plant phases. The lab tests are un-tensioned and were performed in mortar, whereas the plant tests are un-tensioned and were performed in concrete.

Any test results obtained in the laboratory will commonly be referred to as Kansas State University (KSU) tests, and any tests performed at the concrete railroad tie plant will commonly be referred to as CXT Concrete Ties (CXT) tests.

7.1 Comparison of Wire Data

7.1.1 Procedural Differences between Lab and Plant Wire Tests

A number of procedural similarities and differences exist between the wire pullout tests performed in the lab at Kansas State University (KSU) and the wire pullout tests performed in the plant at CXT Concrete Ties (CXT).

There are three main similarities between the lab and plant phases. First, both tests were un-tensioned. Second, force was applied at the bottom of the specimen and an LVDT was placed on the top of the specimen to measure the free-end-slip in both testing locations. Third, the specimen sizes at both locations were almost identical. Both wire specimens utilized a 4-in.-diameter steel tube with a total length of 8-in. A 6-in. by 6-in. steel plate was attached at the bottom. Within the 8-in.-long steel tube, there was a 6-in. embedment (bond) length with a 2-in.-long duct tape bond breaker. The wire extended past the top surface by approximately two inches and below the plate by approximately 10 inches, at the end of which the force was applied. The schematic of the specimens used at KSU is presented in Figure 33 and the schematic of the specimens used at CXT can be seen in Figure 93. Again, they have some minor differences but are nearly identical.

The main difference between the lab and plant phases is that mortar was used during the lab pullout tests at KSU and concrete was used during the plant pullout tests at CXT. This was a planned research variable. Another difference – albeit an unplanned, but unavoidable one – was the strength at which each pullout test was performed. Pullout tests at KSU were performed with mortar batches whose strengths were consistently around 4500 psi. Pullout tests at CXT were performed with concrete batches that fluctuated in strength. This variation in strength occurred because the pullout tests at CXT were performed at approximately the same time that the railroad ties were de-tensioned (to be used to take transfer length measurements). Average mortar and concrete strengths for each set of wire pullout tests can be seen in Table 32. Additionally, the force-controlled loading rate was held perfectly constant (steady) at a rate of 2000 pounds/min. during testing at KSU, whereas the force-controlled loading rate ranged from approximately 1800-2100 pounds/min. at CXT. The KSU tests were able to remain at a constant loading rate due to the servo-hydraulic actuator and computer software, which precisely controlled the hydraulic fluid levels. The CXT tests were run in a Forney testing machine in which the small hydraulic pump could only be manually controlled using a screw-type valve. The last major difference between the two testing sites is the curing methodology. The pullout specimens and mortar cubes used to test the compressive strength at KSU were stored for curing in a temperature- and moisture-controlled room. Details of this curing methodology can be found in

Section 4.2.4. The pullout specimens and 4-in. x 8-in. cylinders used to test the compressive strength at CXT were stored in a temperature-controlled closet, but it was not humidity-controlled. Details of this curing methodology can be found in Section 6.2.3.

7.1.2 As-received Wire Results

This section presents results of the As-received wire pullout specimen tests performed at KSU and at CXT. Twelve of the 13 wires used in this study were tested both at KSU and at CXT. WK was not tested at CXT due to timing constraints.

Average pullout force vs. end-slip graph for each wire source is shown in Figure 104 through Figure 115. Each “KSU average” or “CXT average” curve on the graphs represents the average of six individual specimens from the same wire source, except for the following wires: the WA and WC data sets at CXT are represented by four specimens; the WB data set at CXT is represented by five specimens. The reduced numbers of specimens are a result of malfunctions with the LVDT and data acquisition software while at CXT. Results of the individual pullout tests comparing six KSU specimens to six CXT specimens for each wire source can be seen in Appendix O.

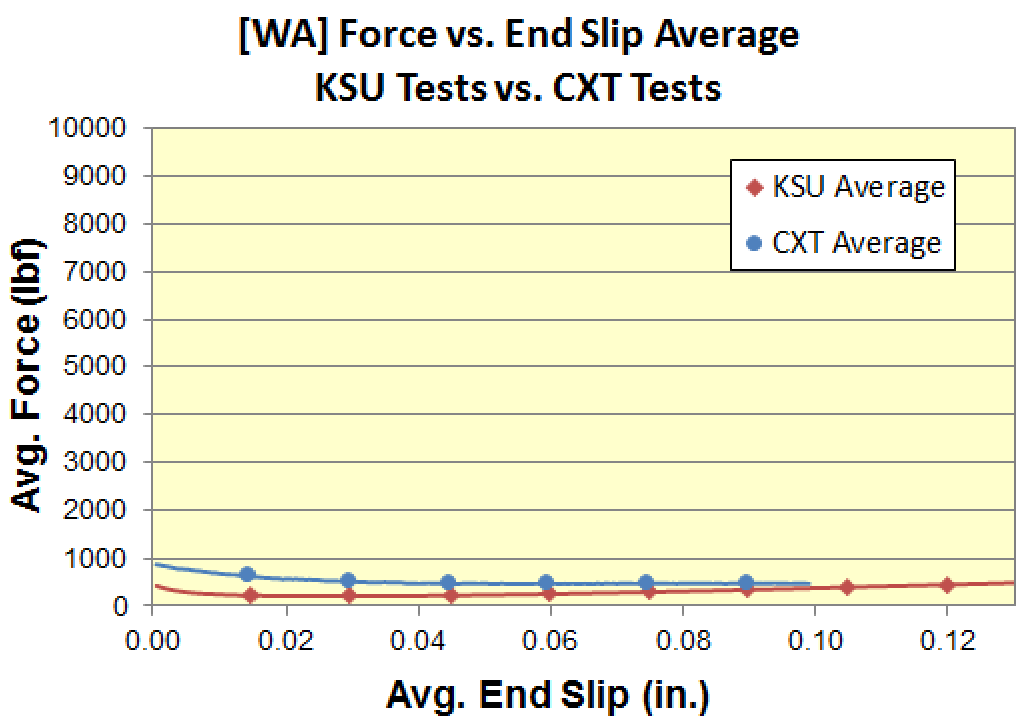


Figure 104. Force vs. end-slip average graphs for wire WA, KSU vs. CXT

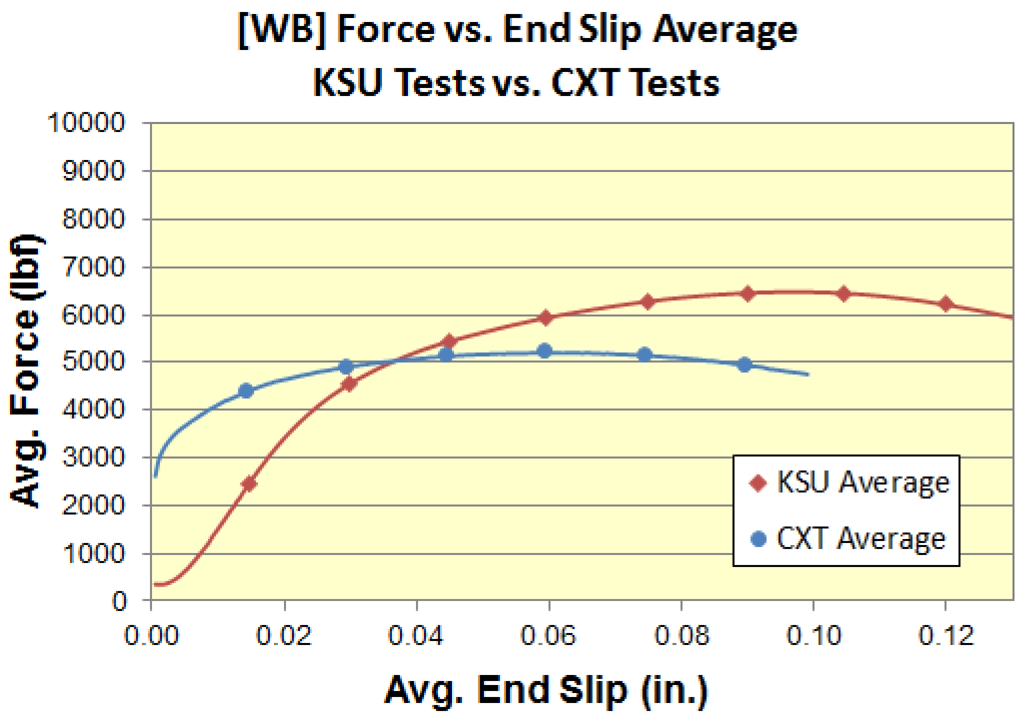


Figure 105. Force vs. end-slip average graphs for wire WB, KSU vs. CXT

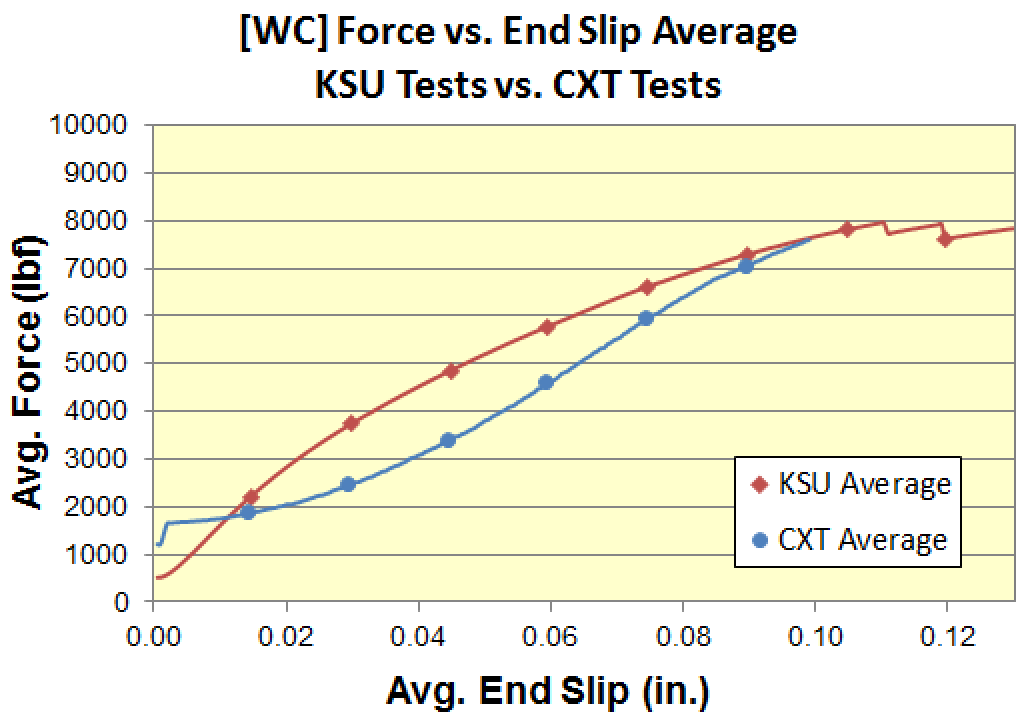


Figure 106. Force vs. end-slip average graphs for wire WC, KSU vs. CXT

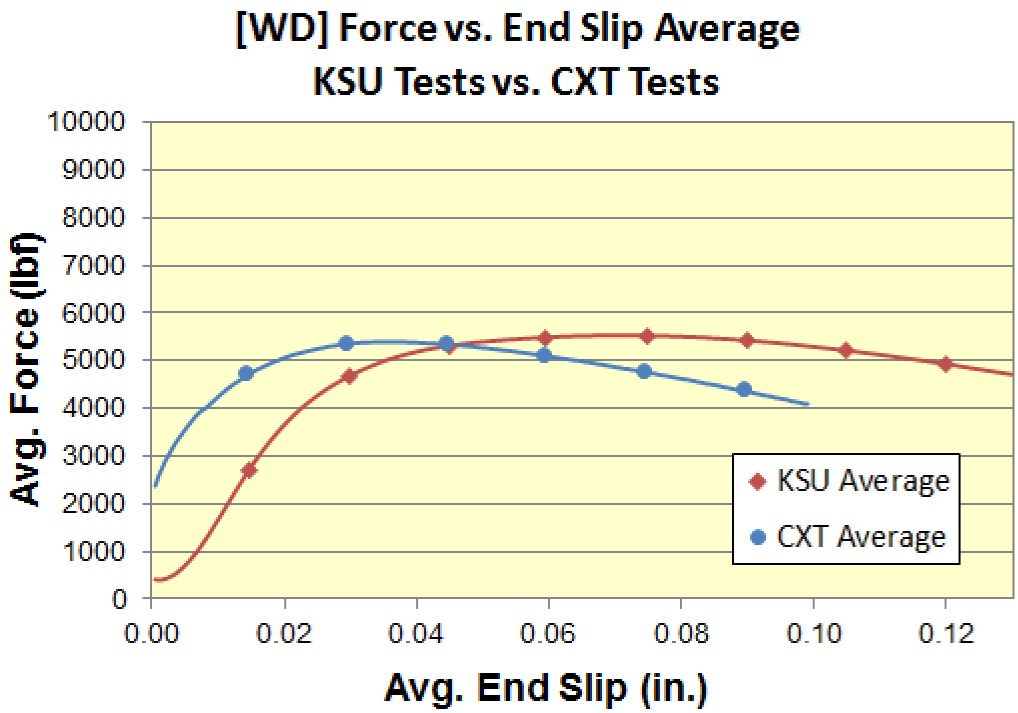


Figure 107. Force vs. end-slip average graphs for wire WD, KSU vs. CXT

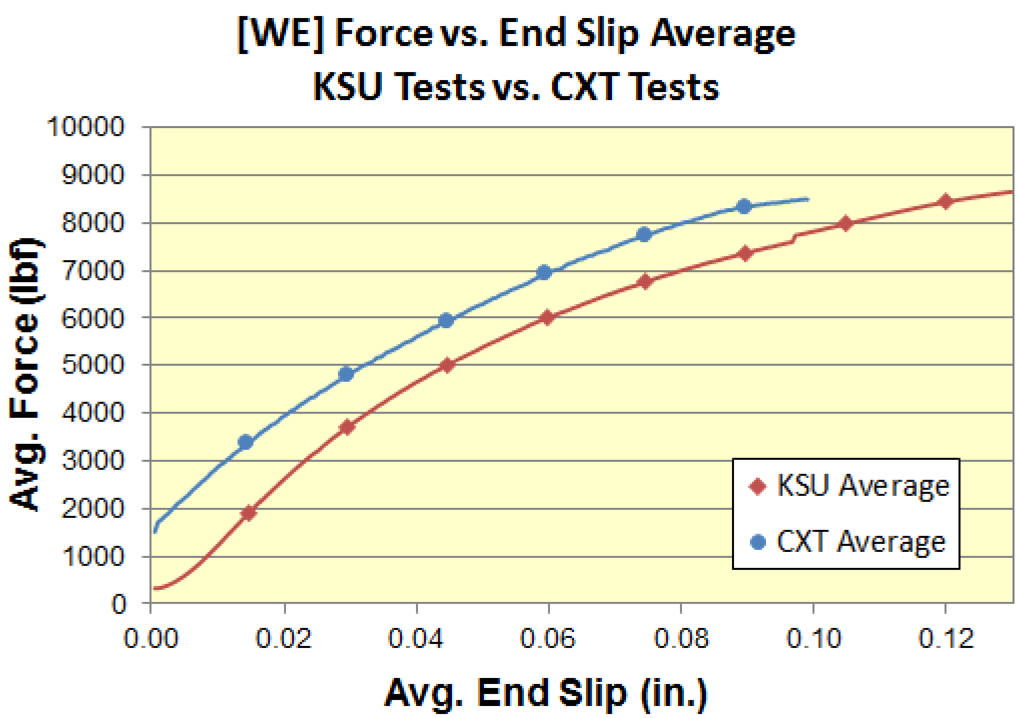


Figure 108. Force vs. end-slip average graphs for wire WE, KSU vs. CXT

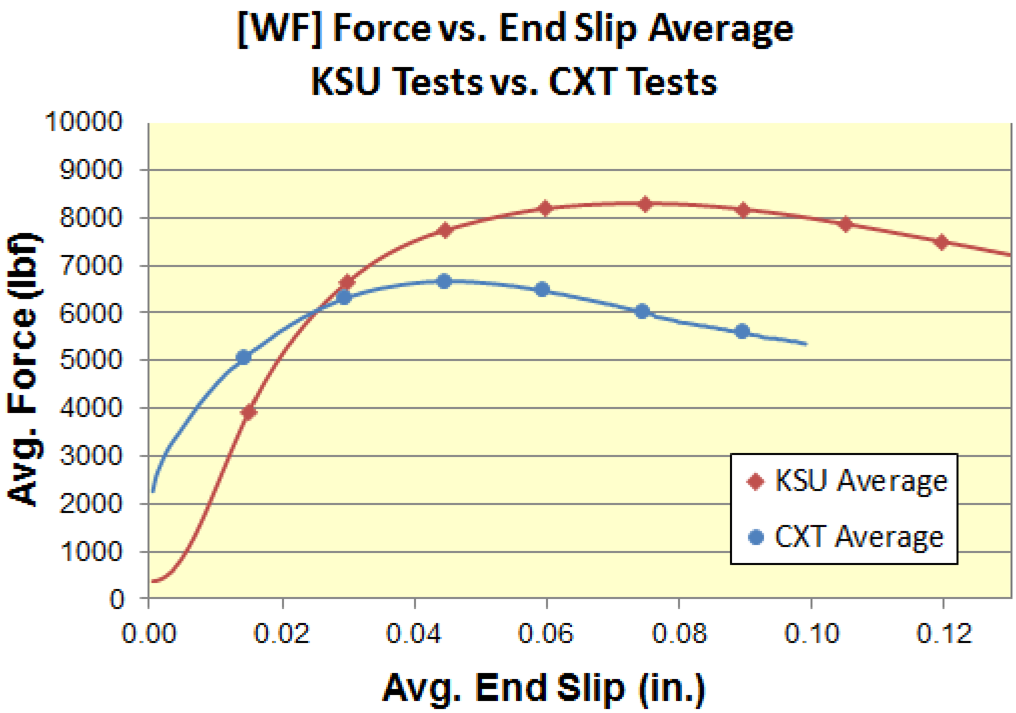


Figure 109. Force vs. end-slip average graphs for wire WF, KSU vs. CXT

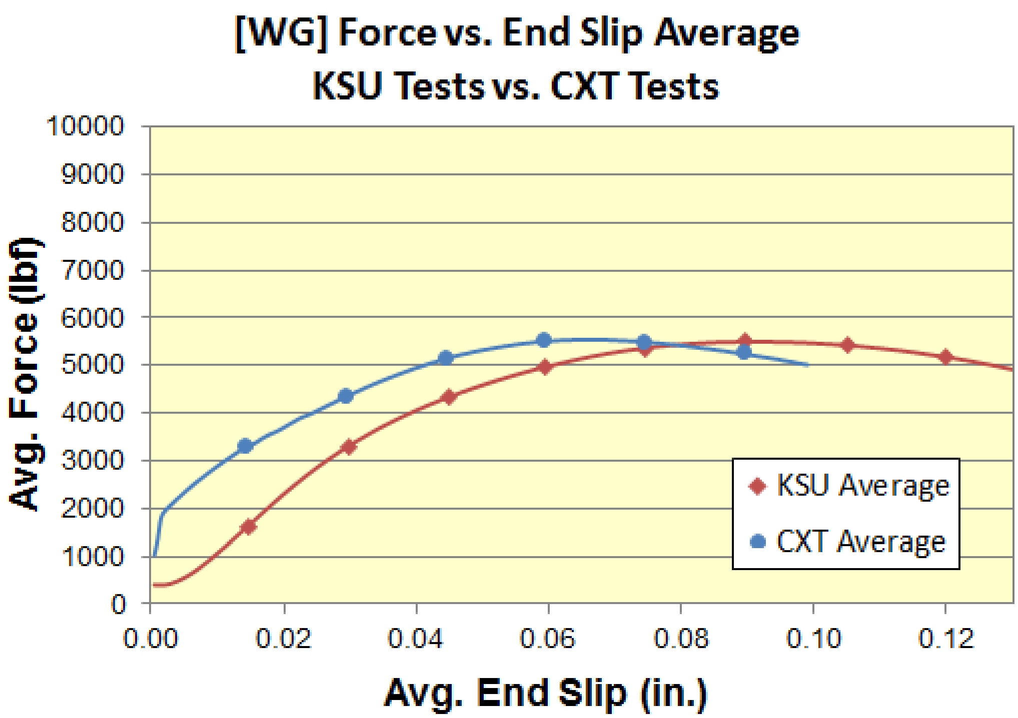


Figure 110. Force vs. end-slip average graphs for wire WG, KSU vs. CXT

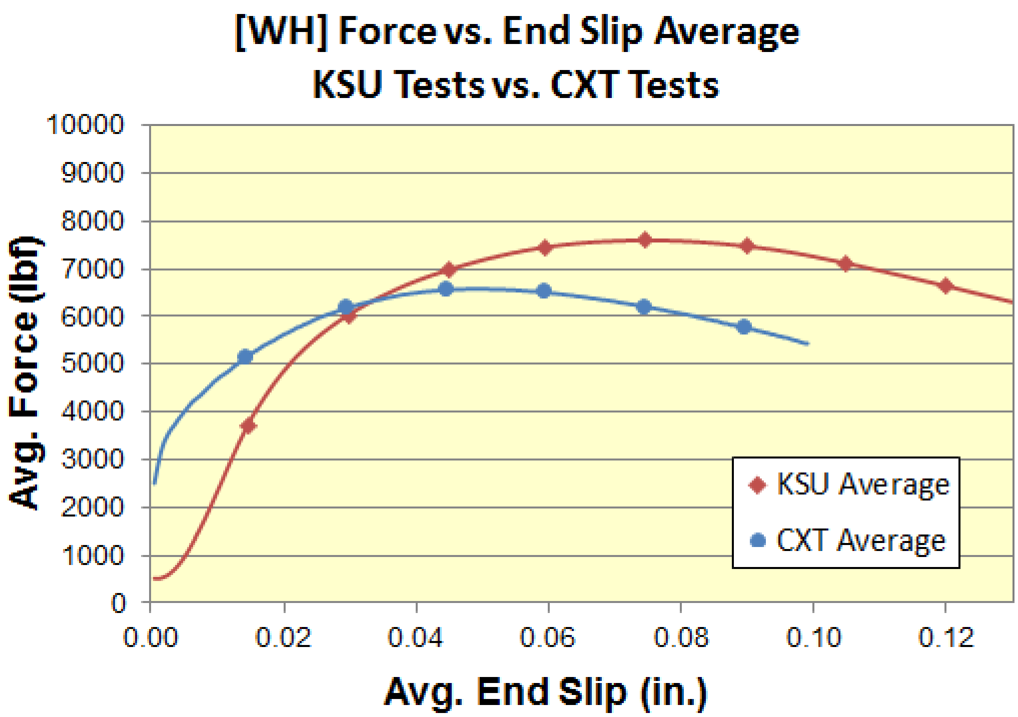


Figure 111. Force vs. end-slip average graphs for wire WH, KSU vs. CXT

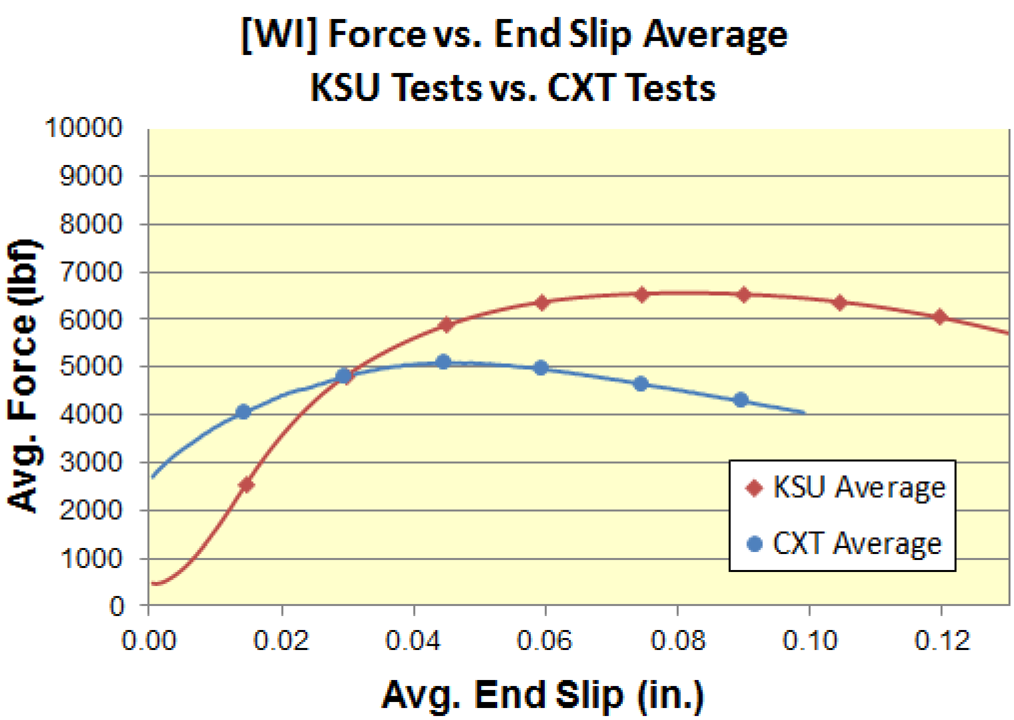


Figure 112. Force vs. end-slip average graphs for wire WI, KSU vs. CXT

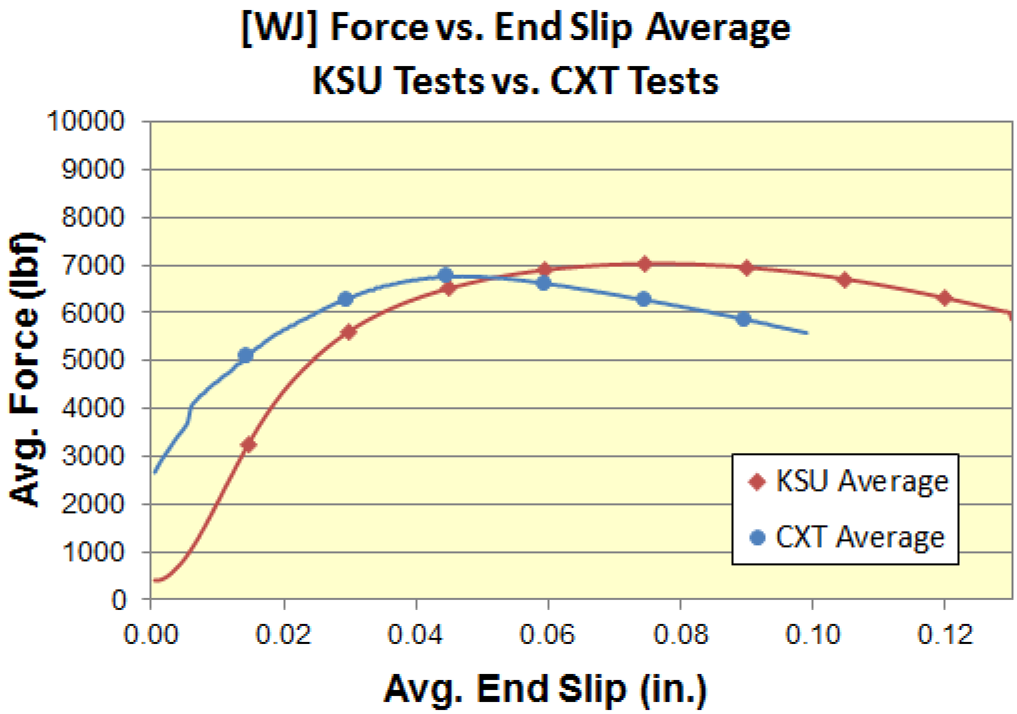


Figure 113. Force vs. end-slip average graphs for wire WJ, KSU vs. CXT

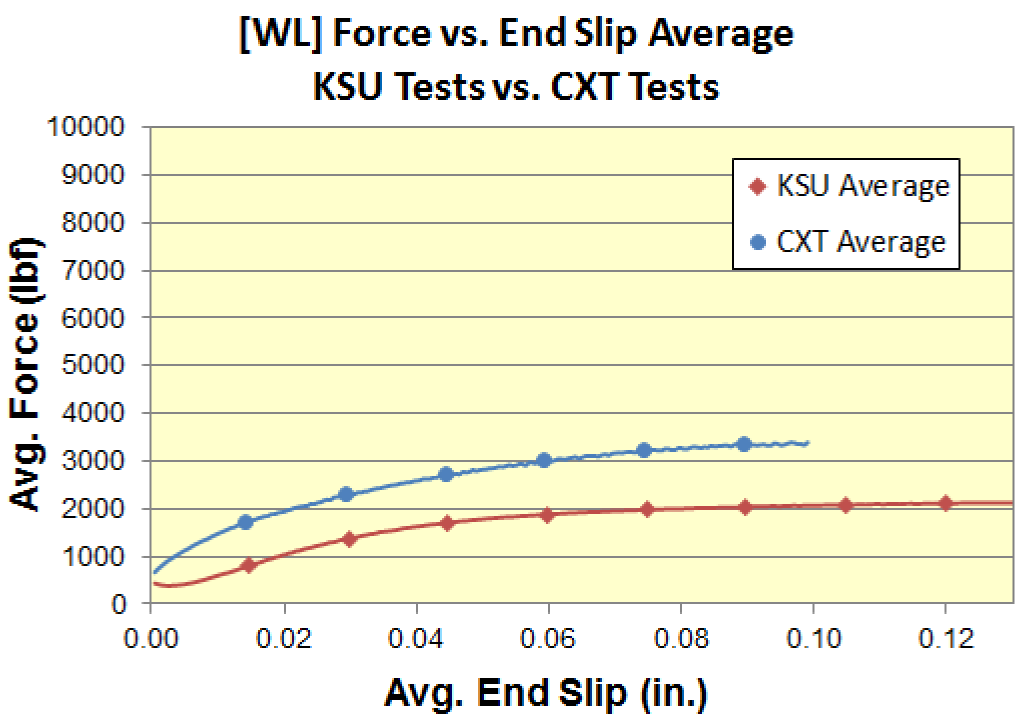


Figure 114. Force vs. end-slip average graphs for wire WL, KSU vs. CXT

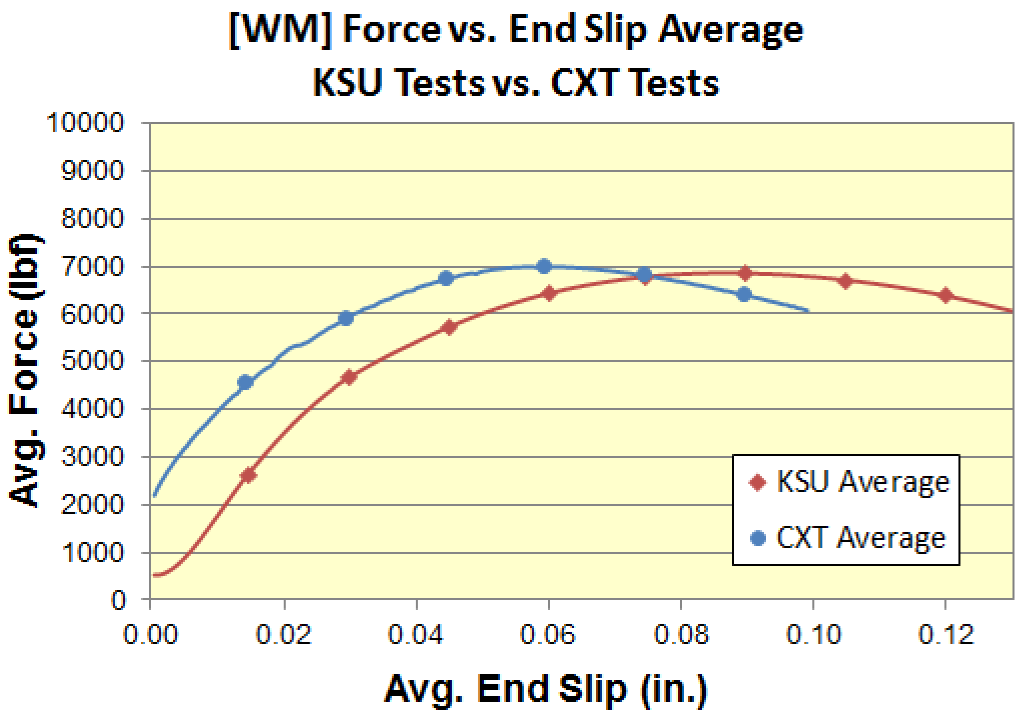


Figure 115. Force vs. end-slip average graphs for wire WM, KSU vs. CXT

7.1.3 Analysis of KSU Pullout Tests vs. CXT Pullout Tests

All methods of analysis in this section compare results from Section 4.3.1 (As-received wire pullout data at KSU) to results from Section 6.3.1 (As-received wire pullout data obtained at CXT). As per Section 4.3.4.5 of this report, wire data obtained at the maximum pullout force occurring at a location with equal to or less than 0.10 in. of end slip was used to compare the KSU and CXT data sets. This was done for all 12 wires and for only the wires with non-continuous indentations (nine wires).

Results of this analysis are presented in Table 32 and include the average maximum pullout forces, standard deviations, coefficient of variations (C.V.), and average mortar/concrete strengths at the time of testing for both KSU and CXT data sets. The data are also represented graphically for all 12 wires in Figure 116 and for only wires with non-continuous indentations in Figure 117. Each value in the table and each point on the graph represents the average of the individual maximum pullout forces measured at end slips less than or equal to 0.10 in. The x-axis (abscissa) shows these forces taken from CXT pullout tests. The y-axis (ordinate) shows these forces obtained from KSU pullout tests. The R^2 is the correlation between these two averaged data sets.

The "Perfect Test" line represents the data of a fictional test in which the maximum pullout force at KSU was identical to the maximum pullout force at CXT for all pullout tests. "The nearness of the data to the 'perfect line' is an indicator of whether the test is repeatable and reproducible between test sites" (Russell and Paulsgrove, 1999b). The tests performed at KSU and CXT are fundamentally different (one being in mortar, the other in concrete), but the "Perfect Test" line still gives some insight into the similarities and differences between the two tests.

From Table 32 it can be seen that the maximum pullout force results from KSU and those from CXT are relatively similar. Pullout forces from both sites showed similar scatter. The average coefficients of variation (C.V.) were 8.5% and 9.2% for values obtained at KSU and CXT, respectively. Neither of the testing sites showed a propensity to produce higher or lower results than the other site. Four of the 12 wire groups (WB, WF, WH, and WI) tested at KSU gave noticeably higher results than the corresponding wire groups at CXT. Similarly, three of the 12 wire groups (WA, WE, and WL) tested at CXT gave noticeably higher results than the corresponding wire groups at KSU. The remaining five wire groups (WC, WD, WG, WJ, and WM) had nearly identical maximum pullout forces at both testing locations. As can be seen in Figure 104 through Figure 115, the maximum forces for the tests performed at KSU generally occurred at a higher end-slip value than the maximum forces for the tests performed at CXT. For example, Figure 110 shows that despite the maximum force *value* being nearly identical for wire WG, *location of this value* occurs at approximately 0.09 in. of end slip at KSU and at approximately 0.06 in. of end slip at CXT.

When all 12 wires are included in the data sets, a correlation of $R^2 = 0.861$ was achieved. With the data sets containing only the chevron-indented wires (nine wires), a correlation of $R^2 = 0.782$ was achieved. Both of these values show very good correlation for the two different testing methodologies, especially since the tests at KSU were performed in mortar and the tests at CXT were performed in concrete (and the concrete had relatively variable strengths). Additionally, orientations of the actual test results to the "Perfect Test" lines indicate the two tests yield similar pullout force results at 0.10 inches of slip.

Another point of interest is the point of first slip. This can be seen in Figure 104 through Figure 115 as the force at which the end begins to slip. Since the LVDT is taking readings at the end opposite to the end of the applied force, it does not record any readings until the cohesion and/or mechanical interlock along the entire length of the wire is broken. In mortar, the point of first slip is assumed to occur after cohesion alone is overcome. For concrete, the point of first slip is assumed to occur after both cohesion and mechanical interlock between the steel and aggregates is overcome. For tests performed at KSU, the point of first slip in the mortar mixture occurred between 331 and 522 pounds, which are within a close range. For the tests performed at CXT, the forces at the point of first slip in the concrete mixture were much more variable with a range from 665 to 2701 pounds.

Table 32. Maximum pullout force and mortar/concrete strength data for As-received wires at KSU vs. CXT

As-Received Wire Pullout Test Results 4 in. Diameter, 6 in. Bond Length Average Maximum Pullout Force (ES ≤ 0.10 in.)								
	KSU Test Data Mortar (sample size = 6)				CXT Test Data Concrete (sample size = 6, WA = 4, WB = 5, WC = 4)			
Wire	Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Avg. Mortar Strength[1] (psi)	Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Avg. Concrete Strength (psi)
[WA]	487	42	8.7	4575	903	128	14.2	5884
[WB]	6481	570	8.8	4575	5230	261	5.0	6585
[WC]	7646	967	12.6	4575	7655	1131	14.8	6607
[WD]	5555	357	6.4	4575	5459	596	10.9	5965
[WE]	7674	526	6.9	4575	8526	301	3.5	5924
[WF]	8312	459	5.5	4575	6694	701	10.5	5190
[WG]	5505	385	7.0	4575	5554	386	6.9	5965
[WH]	7605	497	6.5	4575	6618	1017	15.4	5190
[WI]	6567	522	8.0	4575	5175	203	3.9	4651
[WJ]	7034	635	9.0	4575	6789	343	5.1	5532
[WL]	2068	322	15.6	4575	3438	325	9.5	6536
[WM]	6879	503	7.3	4575	7004	726	10.4	6245

Note 1: Each of the six specimens at KSU were cast in a different batch of mortar and averaged.
The mortar strength of 4575 psi is the average of all six batches.

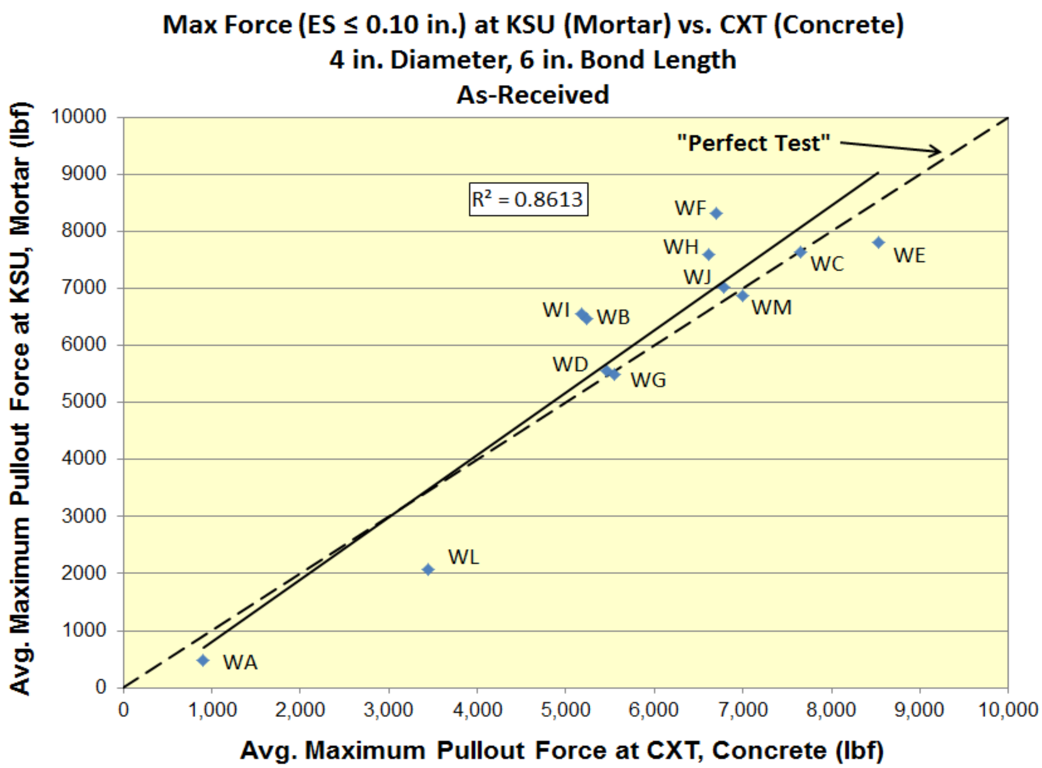


Figure 116. Maximum pullout force data for As-received wires, KSU vs. CXT

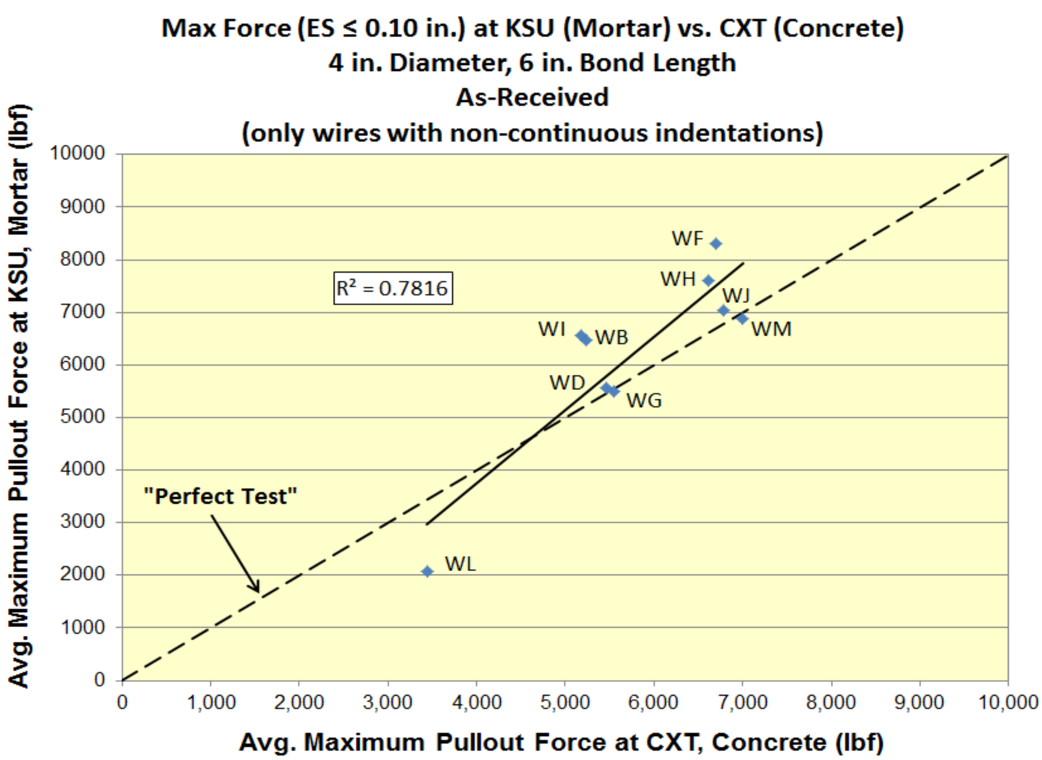


Figure 117. Maximum pullout force data for As-received wires, KSU vs. CXT (individual-indents only)

7.1.4 Analysis of KSU Pullout Tests vs. CXT Transfer Length Measurements

The analysis presented in this section compares results from Section 4.3.1 (As-received wire pullout data at KSU) to results from Section 6.3.3 (As-received transfer length measurements obtained at CXT).

This analysis is the capstone of the wire bond testing program as a quality control test. It focuses on a question regarding bond testing that the railroad industry is interested in: "Can a quality control wire pullout test performed in a lab be used to predict the transfer lengths of concrete ties produced at a plant?" The desire is to be able to test small samples of the wire in a relatively cheap quality control test and to be able to use those test results to predict the bond quality (and transfer length) of actual concrete railroad ties with relative certainty. This section aims to answer that question directly.

A coefficient of determination (R^2) value was calculated by comparing the pullout force measured at KSU to the transfer lengths measured at CXT. As per Section 4.3.4.5 of this report, the maximum pullout forces occurring at a location with equal to or less than 0.10 in. of end slip were obtained from un-tensioned pullout tests in mortar performed at KSU. These pullout tests followed the testing methodology and protocol set forth in Appendix I. The transfer lengths were obtained from actual pretensioned concrete railroad ties cast at CXT Concrete Tie Plant in Tucson, Arizona.

The correlation was found for 1) all 12 wires and 2) only the chevron-indented wires, as has been the case for the majority of the wire testing. Results of the average maximum force compared with the average transfer length can be seen in

Table 33. Figure 118 shows the results for all 12 wires, and Figure 119 shows the results for only the wires containing chevron indents (nine wires). Each pullout force data point in the table and on the graphs represents the average of the six individual maximum pullout forces measured at end slips less than or equal to 0.10 in. at KSU. Each transfer length data point in the table and on the graphs represents the average of the 50 transfer lengths measured at CXT. The R^2 is the correlation between these two averaged data sets.

Table 33. KSU pullout forces vs. CXT transfer lengths for As-received wires

As-Received Wire Bond Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Maximum Pullout Force (ES ≤ 0.10 in.)				
Wire	KSU Avg. Pullout Force (n = 6)[1] (lbf)	Std. Dev. (lbf)	C.V. (%)	CXT Avg. Transfer Length[2] (n ≈ 50)[1] (in.)
[WA]	427	24	5.6	14.3
[WB]	6481	570	8.8	10.2
[WC]	7646	967	12.6	11.2
[WD]	5555	357	6.4	9.7
[WE]	7674	526	6.9	8.6
[WF]	8312	459	5.5	7.8
[WG]	5505	385	7.0	10.9
[WH]	7605	497	6.5	8.3
[WI]	6567	522	8.0	10.8
[WJ]	7034	635	9.0	9.4
[WL]	2068	322	15.6	13.3
[WM]	6879	503	7.3	9.2

Note 1: n = Sample size used to obtain the average value

Note 2: Bilinear surface strain profile assumed

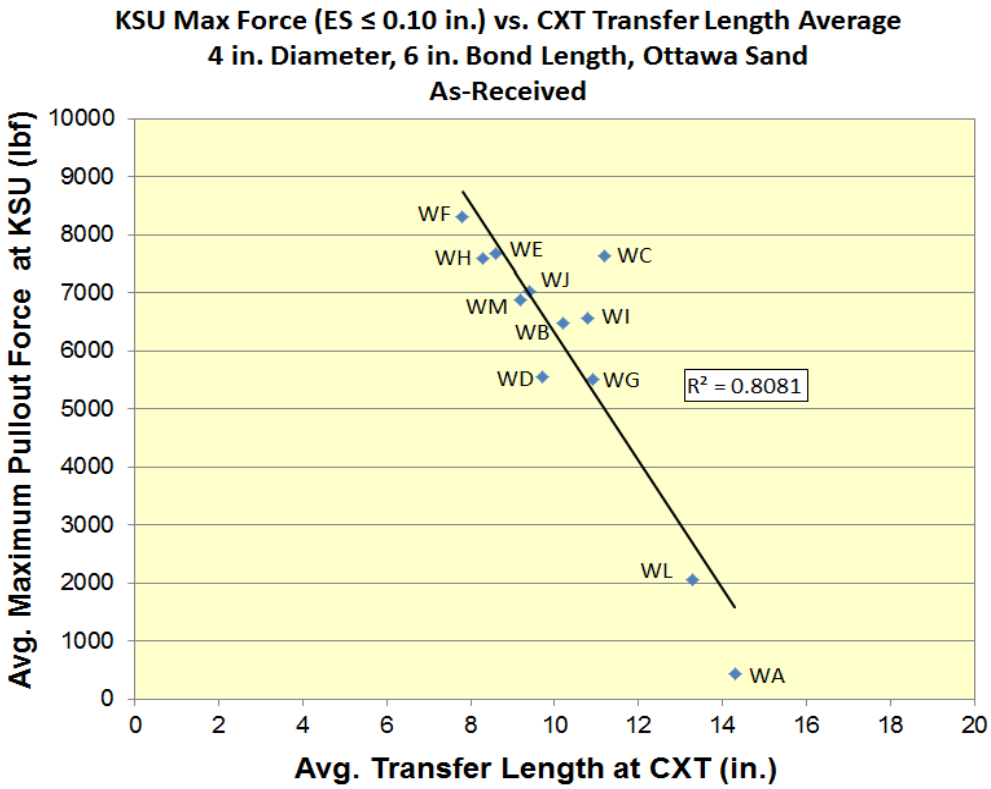


Figure 118. KSU pullout forces vs. CXT transfer lengths for all 12 As-received wires

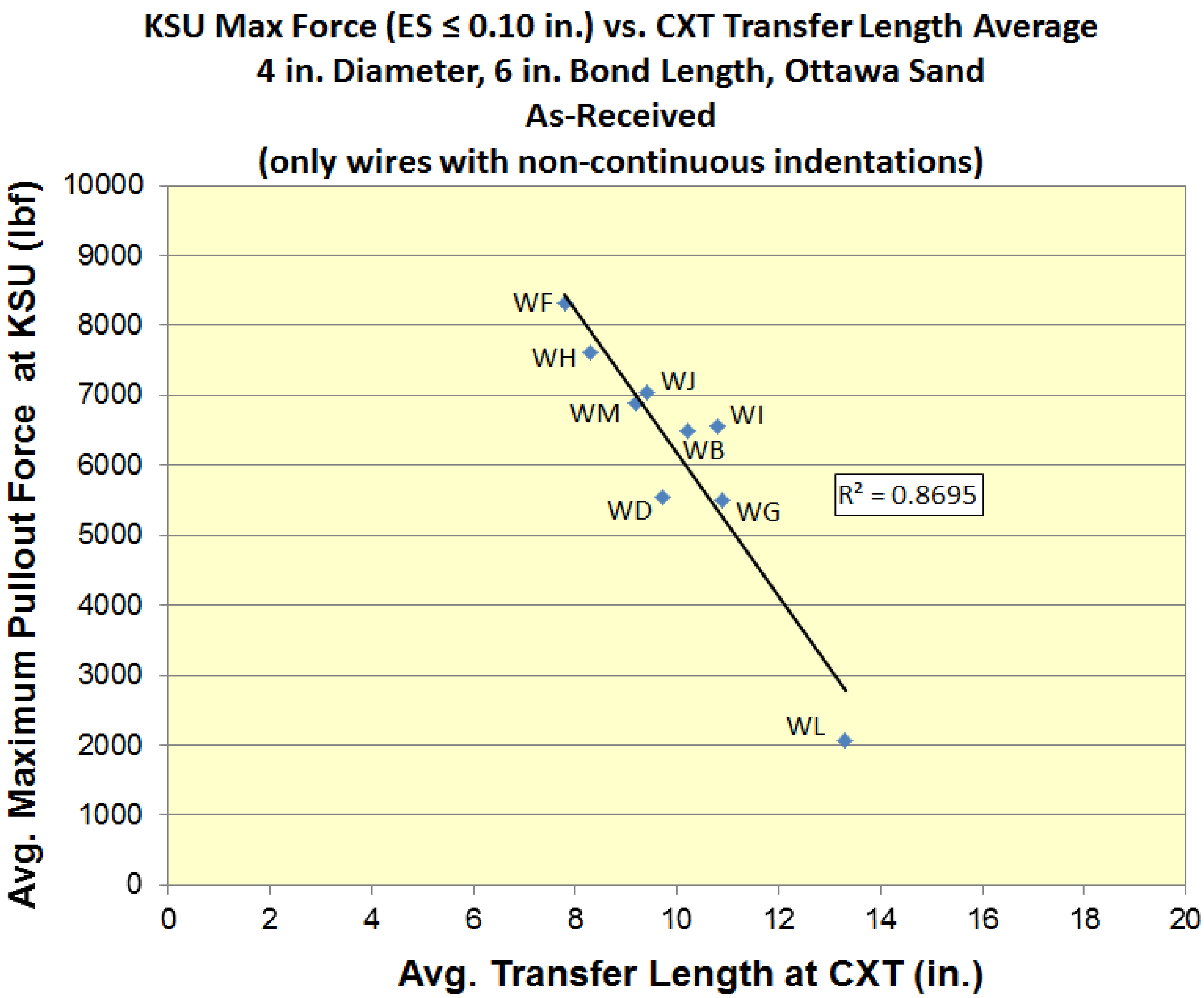


Figure 119. KSU pullout forces vs. CXT transfer lengths for As-received wires with individual-indents only

For the data set including all 12 wires, a correlation of $R^2 = 0.808$ was achieved. For the data sets containing only the chevron-indented wires (nine wires), a correlation of $R^2 = 0.870$ was achieved. Both of these values show extremely good correlation between the pullout tests performed in mortar at the KSU laboratory and the transfer lengths obtained from actual concrete railroad ties produced at CXT.

Based on this analysis, the answer to the question "Can a quality control wire pullout test performed in a lab be used to predict the transfer lengths of concrete ties produced at a plant?" is "Yes." The regression analysis using only wires with non-continuous indentations (nine-wire set) can be used to predict the transfer length of concrete railroad ties using other wire sources conforming to ASTM C881. This set of data was used because at present, the spiral and smooth wires are not permitted to be used in prestressed concrete railroad tie production in the United States. The model generated by this data set is shown in Figure 120 and is the same data used to obtain Figure 119 above. Equation 7.1, obtained from the model in Figure 120, gives the equation of the expected transfer length of As-received, indented prestressing wires when used in concrete railroad ties. The maximum force value input into this equation shall be obtained using the wire pullout test described in Appendix I.

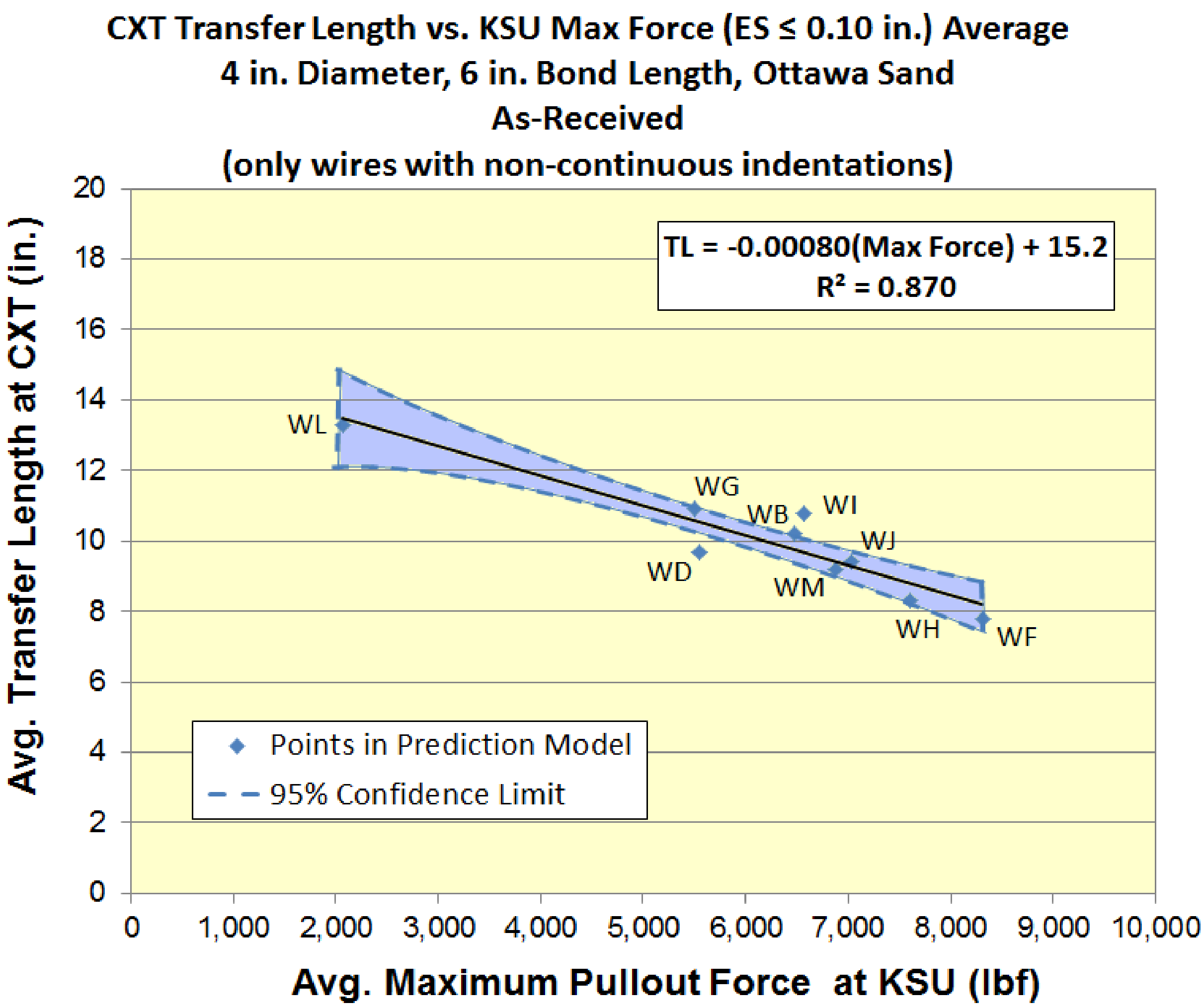


Figure 120. Transfer length prediction model in concrete for As-received wires

$$TL = 15.2 - (\text{Max Force}/1250) \qquad \text{Equation 7.1}$$

where *TL* = expected transfer length (in inches) in concrete railroad ties using pretensioned wires

Max Force = maximum force (in pounds) for end slip ≤ 0.10 in.

7.2 Comparison of Strand Data

7.2.1 Procedural Differences between Lab and Plant Strand Tests

A number of procedural similarities and differences exist between the strand pullout tests performed in the lab at KSU and those performed in the plant at CXT.

There are two main similarities between the lab and plant phases. First, both tests were un-tensioned. Second, a force was applied at the bottom of the specimen and an LVDT was placed on the top of the specimen to measure the free end slip in both testing locations.

Numerous differences exist between the two pullout tests performed on strands. First, mortar was used during the lab pullout tests at KSU and concrete was used during the plant pullout tests at CXT. This was a planned research variable. Second, specimen sizes at both locations were very different. The two specimen sizes at KSU were both 5-in.-outer-diameter. The first standard specimen length was 18 in. in total and 16 in. in bond. The second, modified specimen length was 12 in. in total length and 9 in. in bond. The schematic of the two specimen sizes at KSU can be seen in Figure 76 and Figure 77, respectively. The specimens at CXT utilized a 4-in.-inner-diameter steel tube with a total length of 8 in. Within the 8-in.-long steel tube, there was a 4-in. bond length. The schematic of the specimens used at CXT can be seen in Figure 94. The third difference – albeit an unplanned, but unavoidable one – was the strength at which each pullout test was performed. Pullout tests at KSU were performed with mortar batches whose strengths were consistently around 4500 psi. Pullout tests at CXT were performed with concrete batches that fluctuated in strength. This variation in strength occurred because the pullout tests at CXT were performed at approximately the same time that the railroad ties were de-tensioned (to be used to take transfer length measurements). The average mortar or concrete strengths for KSU and CXT strand pullout tests are referred to in Section 7.2.3. Fourth, the KSU specimens were run in displacement control at a constant rate of 0.1 in./min. Specimens at CXT were force-controlled with a loading rate of approximately 1800-2100 pounds/min. The KSU tests were able to remain at a constant loading rate due to the servo-hydraulic actuator and computer software, which precisely controlled the hydraulic fluid levels. The CXT tests were run in a Forney testing machine in which the small hydraulic pump could only be manually controlled using a screw-type valve. The fifth and last major difference between the two testing sites was the curing methodology. The pullout specimens and mortar cubes used to test the compressive strength at KSU were stored for curing in a temperature- and moisture-controlled room. Details of this curing methodology can be found in Section 5.2.4. The pullout specimens and 4-in. x 8-in. cylinders used to test the compressive strength at CXT were stored in a temperature-controlled closet, but it was not humidity controlled. Details of this curing methodology can be found in Section 6.2.3.

7.2.2 As-received Strand Results

This section presents the results of the As-received strand pullout tests performed at KSU and CXT. Three of the six strands used in this study, SA, SB, and SC, were tested at both KSU and CXT. SA and SB are both 3/8-in.-diameter, seven-wire strands. SC is a 5/16-in.-diameter, three-wire strand. SA and SC are both smooth strands, whereas SB is indented.

Due to an error that took place in the plant, pullout specimens at CXT containing strand SB were tested using a 6-in. bond length instead of the 4-in. bond length used for strands SA and SC. Furthermore, specimens at KSU had two varying bond lengths (16 in. and 9 in.). Because of the different bond lengths of the specimens, bond stress was used for direct comparison of pullout results instead of pullout force. Bond stress is defined as the pullout force divided by the total surface area in contact with the mortar or concrete. This surface area is mathematically defined as the perimeter of the strand multiplied by the bond length. Table 34 contains the bond areas for strands SA, SB, and SC. All pullout forces from this point forward will be divided by the respective bond areas.

Average bond stress vs. end-slip graph for each strand source is shown in Figure 121 through Figure 123. Each "KSU average" or "CXT average" curve on the graphs represents the average of six individual specimens from the same strand source, except for the SC data set at CXT which is represented by four specimens as a result of malfunctions with the LVDT and data acquisition software. Results of the individual pullout tests comparing six KSU specimens to six CXT specimens for each strand source can be seen in Appendix O.

Table 34. Bond areas corresponding to different bond lengths in strands

Strand Identification	[SA]	[SB]	[SC]
Indentation Type	3/8" 7-Wire, Smooth	3/8" 7-wire, Indented	5/16" 3-wire, Smooth
Cross-Sectional Area (in²)	0.0850	0.0850	0.0582
Perimeter Length (in.)	1.378	1.378	2.138
16 in. Long Bond Area (in²)	22.048	22.048	34.208
9 in. Long Bond Area (in²)	12.402	12.402	19.242
6 in. Long Bond Area (in²)	8.268	8.268	12.828
4 in. Long Bond Area (in²)	5.512	5.512	8.552

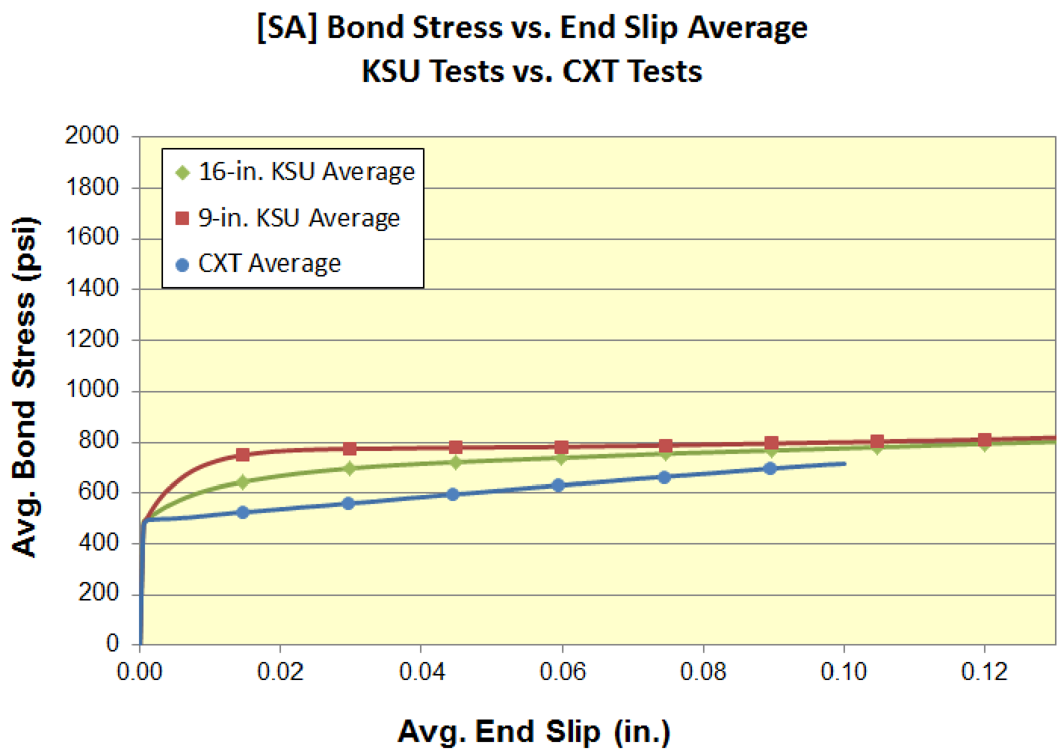


Figure 121. Bond stress vs. end-slip average graphs for strand SA, KSU vs. CXT

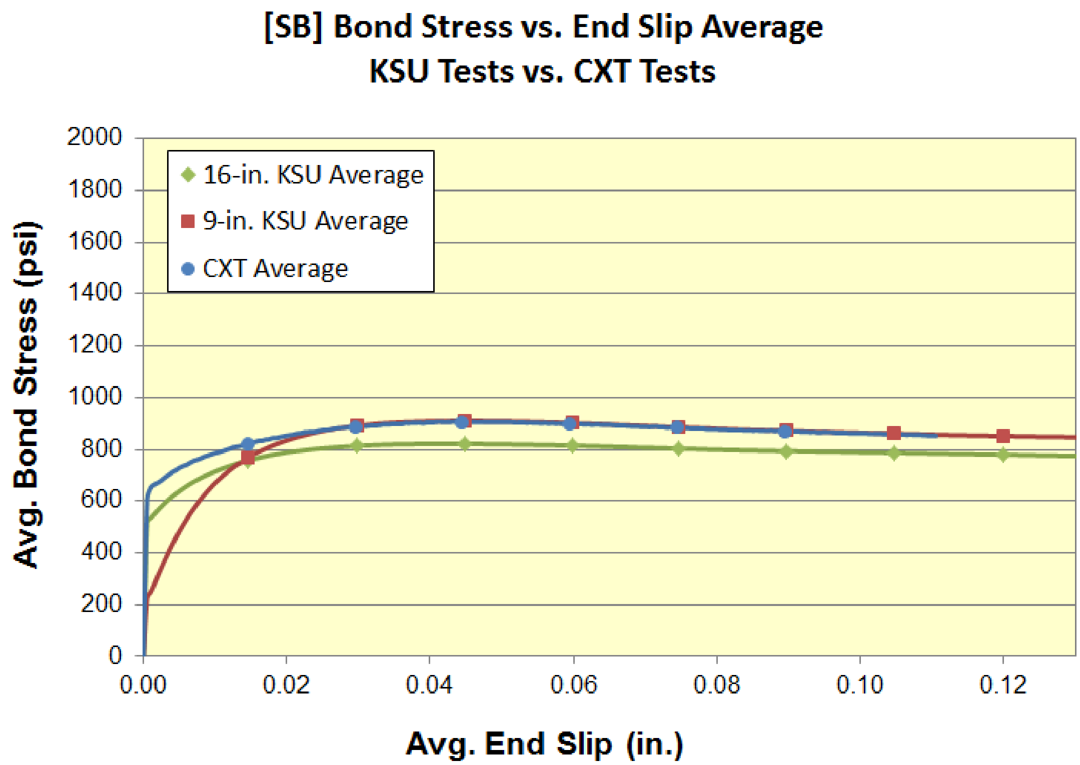


Figure 122. Bond stress vs. end-slip average graphs for strand SB, KSU vs. CXT

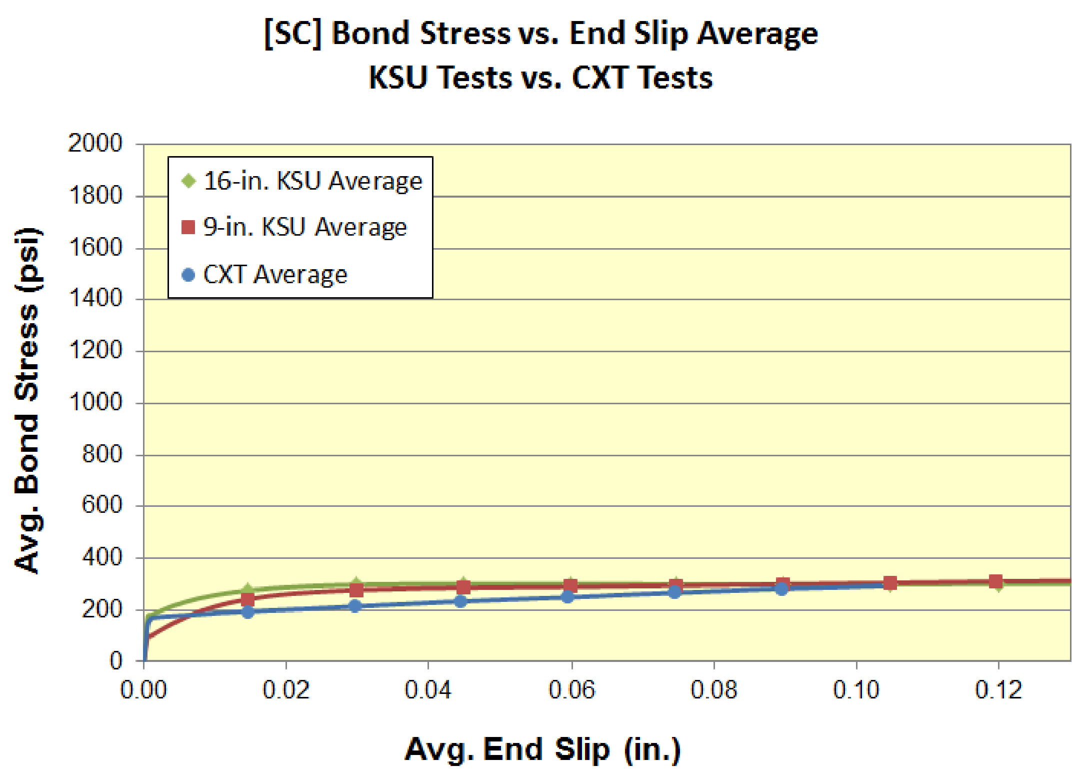


Figure 123. Bond stress vs. end-slip average graphs for strand SC, KSU vs. CXT

7.2.3 Analysis of KSU Pullout Tests vs. CXT Pullout Tests

All methods of analysis in this section compare results from Section 5.3.1 (As-received strand pullout data at KSU) to results from Section 6.3.2 (As-received strand pullout data obtained at CXT). The bond stress derived from the pullout force obtained at 0.10 in. of end slip was used to compare the KSU and CXT data sets. Due to the difference in bond length, the bond stress of each strand source was again used instead of pullout force for the direct comparison of pullout results. CXT results were compared to KSU test results with both 16-in. and 9-in. bond lengths.

Average bond stress, standard deviation, coefficient of variations (C.V.), and average mortar/concrete strength at the time of testing are presented in

Table 35 for both KSU (16-in. bond length) and CXT (4 in. bond length) data sets. The data is also represented graphically in Figure 124. The data for the KSU specimens with a 9-in. bond length and the same CXT data with a 4-in. bond length are presented in Table 36 and Figure 125.

Each data point in the tables and on the graphs represents the average of the individual bond stress values. The bond stress was obtained by dividing the pullout force which caused 0.10 in. of end slip by the bond area (strand perimeter multiplied by the bond length). The x-axis shows the bond stress from the CXT pullout tests. The y-axis shows the bond stress from the KSU pullout tests. The R^2 shows the correlation between these two data sets.

The “Perfect Test” line represents a fictional test in which the bond stress obtained at KSU would be identical to the bond stress obtained at CXT for all pullout tests. “The nearness of the data to the ‘perfect line’ is an indicator of whether the test is repeatable and reproducible between test sites” (Russell and Paulsgrove, 1999b). The tests performed at KSU and CXT are fundamentally different (one being in mortar, the other in concrete), but the “Perfect Test” line still gives some insight into the similarities and differences between the two tests.

From

Table 35 and Table 36, it can be seen that the bond stress results from KSU and CXT are extremely similar and showed similar scatter. The average coefficients of variation (C.V.) were 11.0%, 8.3%, and 15.5%, respectively, for the bond stress results obtained for KSU specimens with 16-in. and 9-in. bond lengths and CXT specimens with a 4-in. bond length.

When the 16-in. bond length specimens from KSU were compared with the CXT specimens, a correlation of $R^2 = 0.949$ was achieved. When the 9-in. bond length specimens from KSU are compared with the CXT specimens, a correlation of $R^2 = 0.798$ was achieved. Both of these values show very good correlation for the two different testing methodologies, especially considering the tests at KSU were performed in mortar and the tests at CXT were performed in concrete (and the concrete had relatively variable strengths). Additionally, the orientations of the actual test results to the “Perfect Test” lines indicate the two tests yield similar results. These regression values must be viewed in context, however. With only three strands in this analysis, it is hard to draw any deeply meaningful conclusions.

Another item of interest is the point of first slip. This point can be seen in Figure 121 through Figure 123 as the force at which end slip begins to occur. Since the LVDT is taking readings at the end opposite to the end of applied force, it does not record any readings until the cohesion and/or mechanical interlock along the entire length of the wire is broken. For concrete, the point of first slip is assumed to occur after both cohesion and mechanical interlock between the steel and aggregates is overcome. For strands SA and SC, however, the points of first slip for all three specimen sizes (two KSU and one CXT) were approximately the same. The SB results were more variable: the 16-in. bond length KSU specimens and the 6-in. bond length CXT specimens slipped at almost identical bond stresses, but the 9-in. bond length KSU specimens started slipping at lower bond stresses. Despite this, this data lends to the idea that the first slip response of strands is similar for both mortar and concrete.

Table 35. Bond stress data at 0.10-in. end slip for As-received strands, KSU (16 in. bond length) vs. CXT

As-Received Strand Pullout Test Results Bond Stress at 0.10 in. End Slip								
	KSU Test Data 16 in. Bond Length, Mortar (sample size = 6)				CXT Test Data 4 in. Bond Length[2], Concrete (sample size = 6, SC = 4)			
Strand	Bond Stress (psi)	Std. Dev. (psi)	C.V. (%)	Avg. Mortar Strength[1] (psi)	Bond Stress (psi)	Std. Dev. (psi)	C.V. (%)	Avg. Concrete Strength (psi)
[SA]	776	47	6.0	4602	715	100	14.0	5924
[SB]	789	63	8.0	4602	862	31	3.6	6536
[SC]	300	57	19.1	4602	291	85	29.0	6607

Note 1: Each of the six specimens at KSU were cast in a different batch of mortar and averaged. The mortar strength of 4602 psi is the average of all six batches.

Note 2: Strand [SB] was accidentally tested with a 6 in. bond length. This was corrected for in the bond stress calculation.

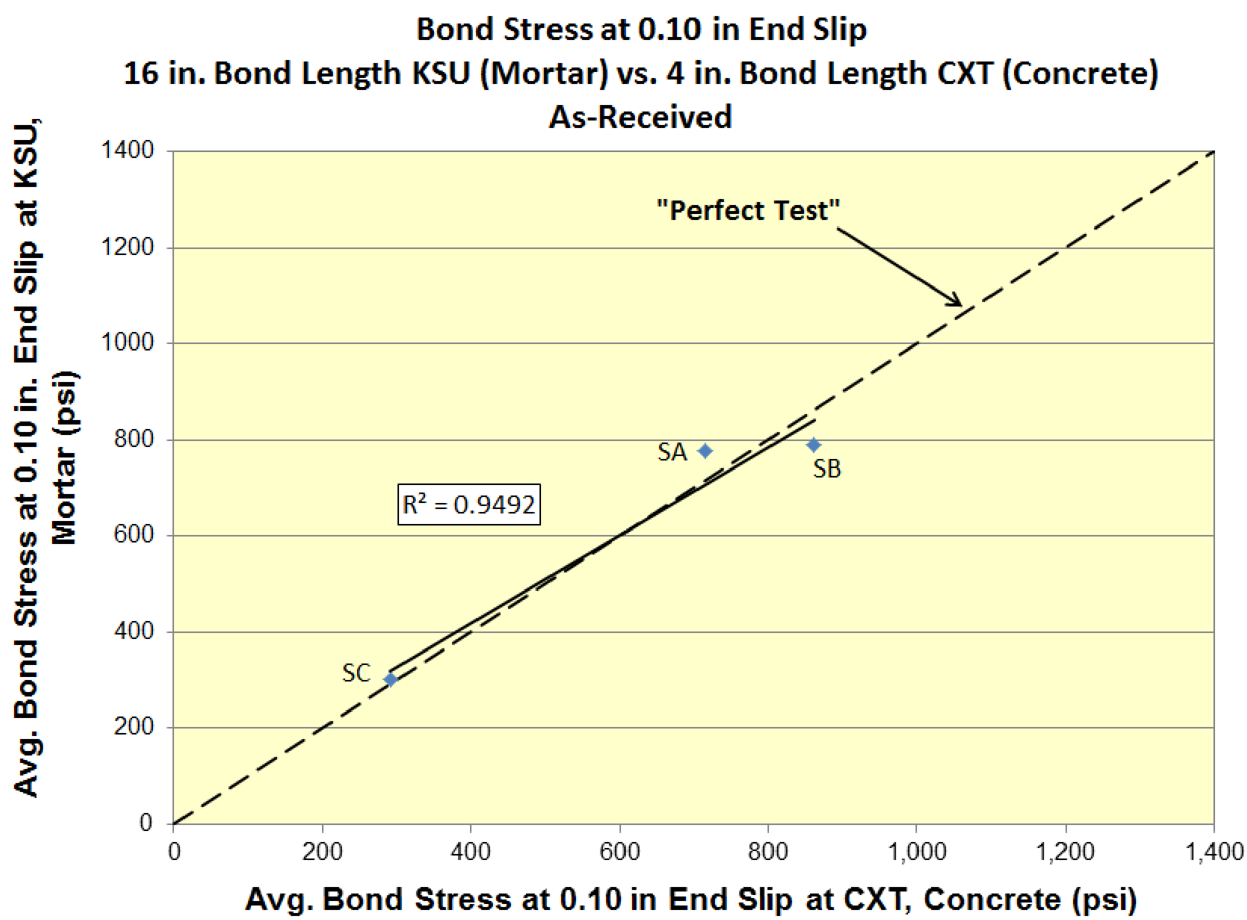


Figure 124. Bond stress data at 0.10-in. end slip for As-received strands, KSU (16-in. bond length) vs. CXT

Table 36. Bond stress data at 0.10-in. end slip for As-received strands, KSU (9-in. bond length) vs. CXT

As-Received Strand Pullout Test Results Bond Stress at 0.10 in. End Slip								
	KSU Test Data 9 in. Bond Length, Mortar (sample size = 6)				CXT Test Data 4 in. Bond Length[2], Concrete (sample size = 6, SC = 4)			
Strand	Bond Stress (psi)	Std. Dev. (psi)	C.V. (%)	Avg. Mortar Strength[1] (psi)	Bond Stress (psi)	Std. Dev. (psi)	C.V. (%)	Avg. Concrete Strength (psi)
[SA]	800	95	11.8	4655	715	100	14.0	5924
[SB]	864	39	4.6	4655	862	31	3.6	6536
[SC]	304	26	8.4	4655	291	85	29.0	6607

Note 1: Each of the six specimens at KSU were cast in a different batch of mortar and averaged. The mortar strength of 4655 psi is the average of all six batches.
Note 2: Strand [SB] was accidentally tested with a 6 in. bond length. This was corrected for in the bond stress calculation.

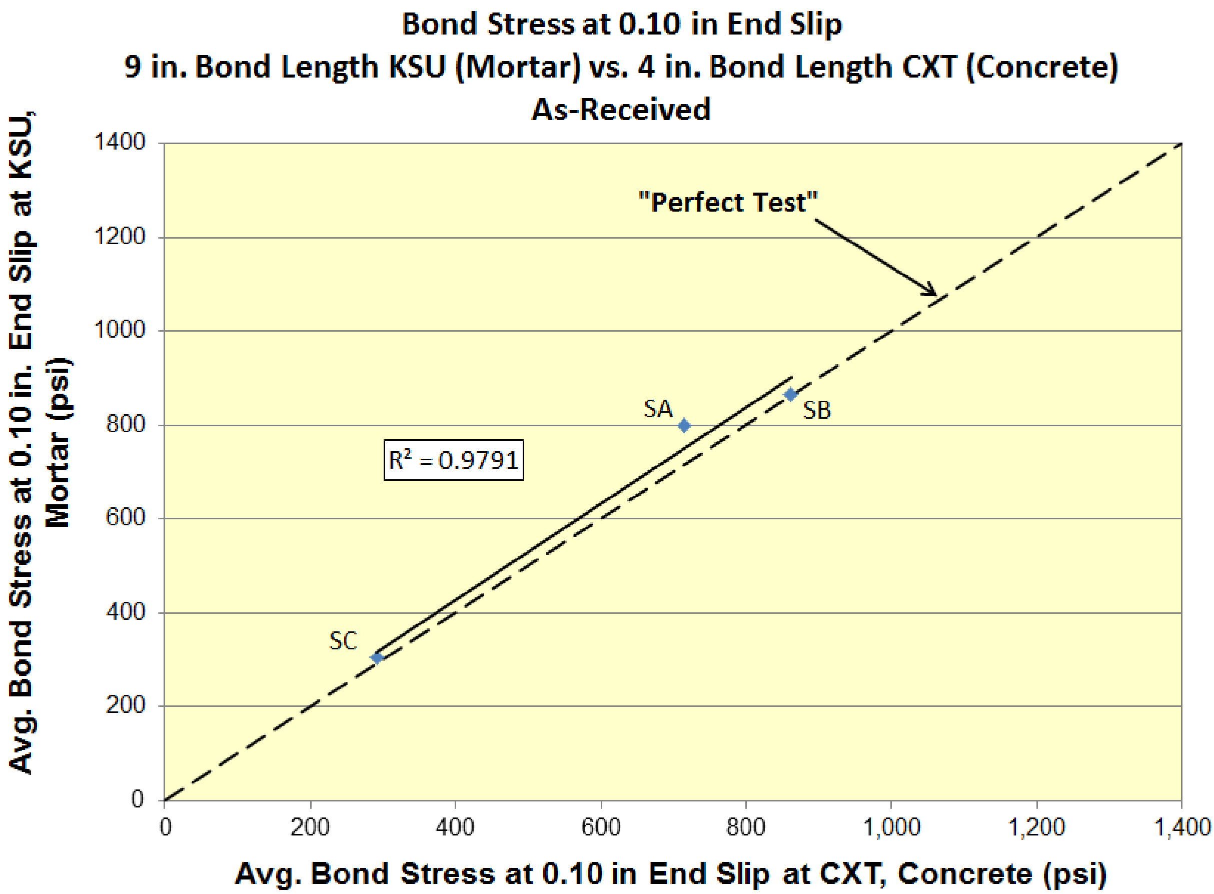


Figure 125. Bond stress data at 0.10-in. end slip for As-received strands, KSU (9-in. bond length) vs. CXT

7.2.4 Analysis of KSU Pullout Tests vs. CXT Transfer Length Measurements

The analysis presented in this section compares the results from Section 5.3.1 (As-received strand pullout data at KSU) to the results from Section 6.3.3 (As-received transfer length measurements obtained at CXT). The CXT results were compared to both the 16-in. and the 9-in. bond length KSU tests.

This analysis is the capstone of the strand bond testing program as a quality control test. With interest from the railroad industry to use small diameter (less than 0.5 in.) strands in concrete railroad ties, this analysis aims to answer an important question for the industry: “Can an un-tensioned quality control strand pullout test performed in a lab be used to predict the transfer lengths of actual concrete ties produced at a plant?” The desire is to be able to test small samples of the strand in a relatively cheap quality control test and be able to use those test results to predict the bond quality (and transfer length) of actual concrete railroad ties with relative certainty. This section aims to answer that question exactly.

A coefficient of determination (R^2) was calculated by comparing the pullout force measured at KSU to the transfer lengths measured at CXT. A pullout force corresponding to 0.10 in. of end slip was used. These pullout forces were obtained from un-tensioned pullout tests in mortar performed at KSU. The pullout tests follow the testing methodology and protocol set forth in Appendix H of NCHRP Repot 603 (Ramirez and Russell, 2008). The transfer lengths were obtained from actual pretensioned concrete railroad ties cast at CXT Concrete Ties in Tucson, Arizona.

The correlation was found for 1) the 16-in. bond length KSU specimens and 2) the 9-in. bond length KSU specimens. Results of the average pullout force at 0.10 in. of end slip compared with the average transfer lengths can be seen in

Table 37 and Figure 126 for the 16-in. bond length KSU specimens. Table 38 and Figure 127 show the 9-in. bond length KSU specimen results. Each pullout force data point in the table and on the graphs represents the average of six individual pullout forces measured at 0.10 in. of end slip at KSU. Each transfer length data point in the table and on the graphs represents the average of the 50 transfer length measurements obtained at CXT. The R^2 is the correlation between these two averaged data sets.

Table 37. KSU pullout forces vs. CXT transfer lengths for As-received strands (16-in. bond length)

As-Received Strand Bond Test Results 5 in. Diameter, 16 in. Bond Length, Oklahoma Sand Pullout Force at 0.10 in. End Slip				
Strand	KSU Avg. Pullout Force (n = 6)[1] (lbf)	Std. Dev. (lbf)	C.V. (%)	CXT Avg. Transfer Length[2] (n ≈ 50)[1] (in.)
[SA]	17105	1032	6.0	14.4
[SB]	17388	1396	8.0	15.6
[SC]	10267	1958	19.1	15.9

Note 1: n = sample size used to obtain the average value

Note 2: Bilinear surface strain profile assumed

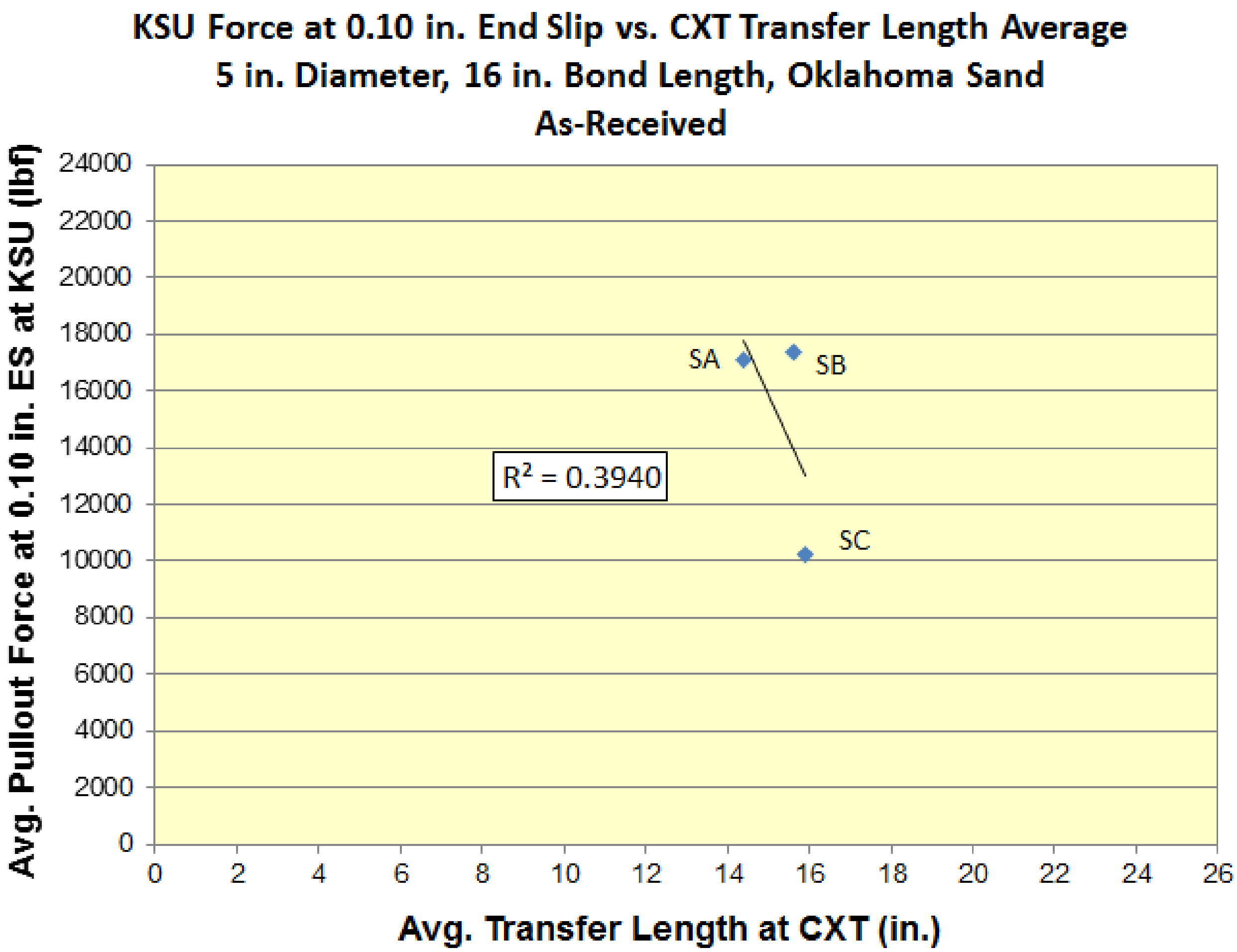


Figure 126. KSU pullout forces vs. CXT transfer lengths for As-received strands (16-in. bond length)

Table 38. KSU pullout forces vs. CXT transfer lengths for As-received strands (9-in. bond length)

As-Received Strand Bond Test Results 5 in. Diameter, 9 in. Bond Length, Oklahoma Sand Pullout Force at 0.10 in. End Slip				
Strand	KSU Avg. Pullout Force (n = 6)[1] (lbf)	Std. Dev. (lbf)	C.V. (%)	CXT Avg. Transfer Length[2] (n ≈ 50)[1] (in.)
[SA]	9918	1173	11.8	14.4
[SB]	10718	489	4.6	15.6
[SC]	5852	491	8.4	15.9

Note 1: n = sample size used to obtain the average value

Note 2: Bilinear surface strain profile assumed

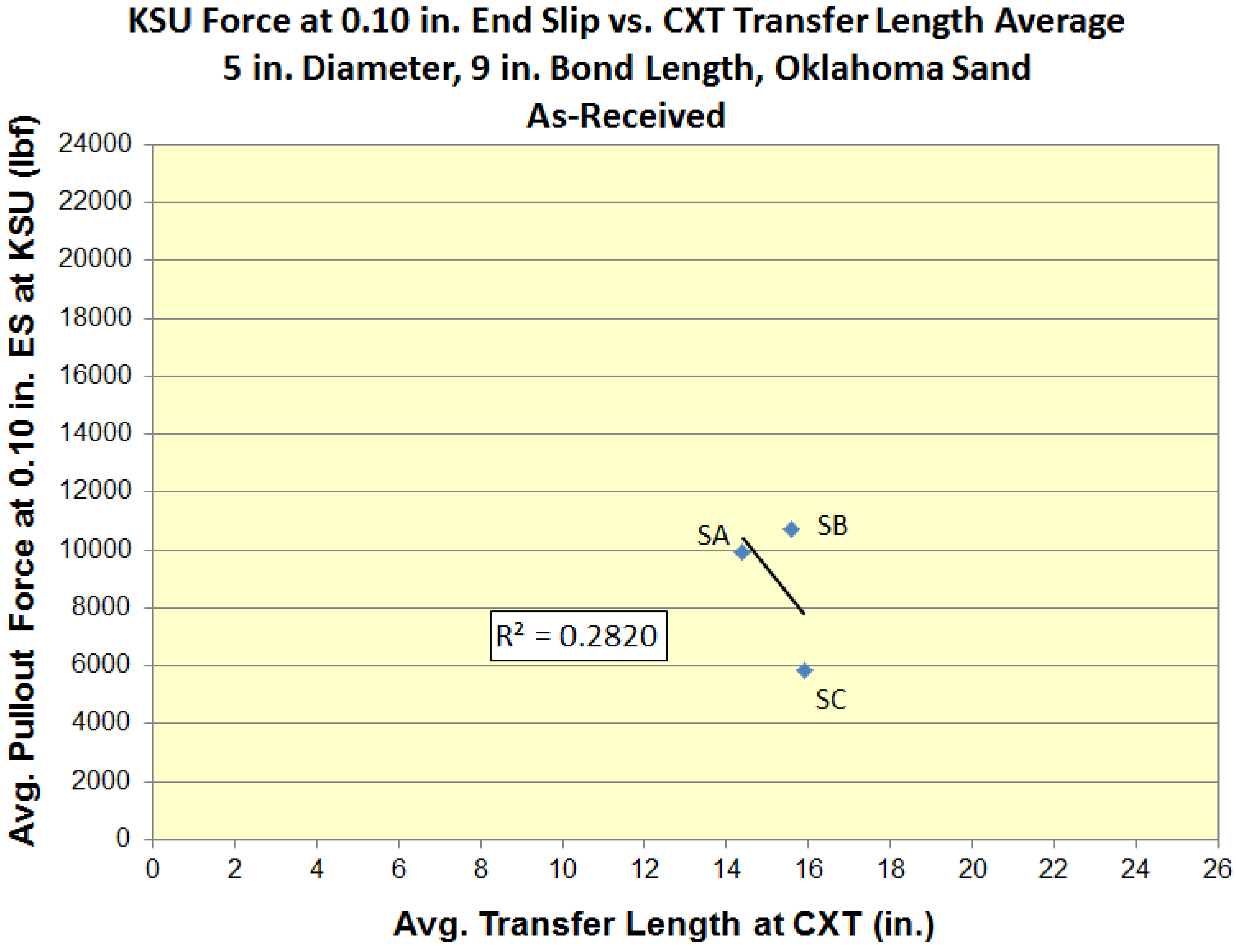


Figure 127. KSU pullout forces vs. CXT transfer lengths for As-received strands (9-in. bond length)

For the 16-in. bond length data set, a correlation of $R^2 = 0.394$ was achieved. For the 9-in. bond length data set, a correlation of $R^2 = 0.282$ was achieved. Both of these values show poor correlation between the pullout tests performed in mortar at the KSU laboratory and the transfer lengths obtained from actual concrete railroad ties produced at CXT.

Based on this limited analysis, the answer to the question “Can an un-tensioned quality control strand pullout test performed in a lab be used to predict the transfer lengths of actual concrete ties produced at a plant?” is “Not at this time.” Again, due to the limited number of strands used to generate these results, these regression values must be viewed in context. With only three strands in this analysis, it is hard to draw any deeply meaningful conclusions.

Recalling the As-received transfer lengths of the strands obtained in the lab from Section 5.3.3, it appears some surface condition factors could also be at work which have not been accounted for. In the lab, strand SB and strand SA performed almost identically despite strand SA having a moderate level of surface rust. This alone was odd since strand SB had indentations and strand SA did not. However, it was determined in Section 5.3.5 that the surface condition of the strand was an important parameter based on the results of the cleaning process.

In both the lab and the plant tests, strand SA (smooth strand) had slightly lower average transfer length values than strand SB (indented strand). This lends to the notion that the surface condition is more important to bond than the very light indentation in Strand SB. The average transfer length from both the lab and plant phases can be seen in Table 39.

Table 39. Transfer length differences between lab and plant

Strand Identification	Average Transfer Length (in.)	
	Lab (KSU) Mortar (n = 6)	Plant (CXT) Concrete (n = 50)
[SA]	16.2	14.4
[SB]	16.3	15.6

Note: n = Sample size

8. Conclusions and Recommendations

8.1 Conclusions

The objectives for conducting the un-tensioned pullout tests were to evaluate the effect of lubricants on the bond of prestressing reinforcements and to explore if a pullout test could be used as a possible quality control test for bond in pretensioned concrete railroad ties. Both of these objectives have been successfully met, with the pullout test developed in this study being successfully adopted as a standard test procedure by ASTM (ASTM A1096). Five conclusions can be drawn on the development of the wire bond test and subsequent results and analysis:

1. The un-tensioned wire pullout test developed at KSU and presented in Chapter 4 was able to distinguish between higher and lower bonding wires. This is supported by results from Section 4.3.1. The testing methodology is summarized in Appendix I.

2. This un-tensioned wire pullout test yielded consistent pullout strength results when six different mortar batches were used. The repeatability of these results is shown by the individual pullout graphs presented in Appendix E.

3. This un-tensioned wire pullout test had excellent correlation with the bond performance of the wires in pretensioned applications. The most accurate correlation with transfer length was achieved by the maximum pullout force occurring at or before 0.10 in. of free-end-slip. This method of analysis yielded a coefficient of determination (R^2) equal to 0.882 when all 12 wires were considered. An $R^2 = 0.916$ was achieved when only the nine wires with non-continuous indentations were considered. These results can be seen in Section 4.3.4.1.

4. The un-tensioned wire pullout test described in Appendix I was able to accurately predict the transfer length of a previously untested wire. A predictive model for the transfer length of a pretensioned wire is given in Section 4.3.5 based on the results of a regression analysis. This model (Equation 4.1) was able to predict the transfer length of a previously untested wire to within 0.1-in. accuracy. The measured (experimental) transfer length was 9.8 in. and the predicted (theoretical) transfer length was 9.9 in.

5. There was not a consistent bond quality for wires having the same general indent pattern (i.e. all wires with "chevron" indents do not bond approximately the same).

Three conclusions were made on the validity of the Standard Test for Strand Bond for smaller diameter strands:

1. The Standard Test for Strand Bond caused some of the smaller diameter strands (less than 0.5-in.-diameter) to fail in material rupture rather than bond failure. This was caused by a bond length that was too long.

2. The Standard Test for Strand Bond can be used in its entirety for smaller diameter strands by shortening the bond length to 9 in. and the overall specimen length to 12 in. With this shorter bond length, none of the specimens failed by material rupture.

3. The Standard Test for Strand bond had decent-to-good correlation with measured transfer lengths when only the five strands with 3/8-in.-diameter were considered. For the 16-in. bond length specimens, an $R^2 = 0.852$ was achieved. For the 9-in. bond length specimens, an $R^2 = 0.573$ was achieved. When all six strands were considered, no statistical correlation was found between the pullout results and measured transfer lengths. These results can be seen in Section 5.3.4.

Two related conclusions concerning surface condition can be drawn from comparing the pullout results using As-received vs. cleaned specimens:

1. The surface condition of prestressing wires is not the dominant bond characteristic. Rather, the indent geometry plays a much larger role. Since the area of the wire indents is large relative to the overall cross-sectional area of the 5.32 mm-diameter wires, the indent geometry governs the overall bond performance of the wires.

2. The surface condition of prestressing strands is a very important bond characteristic. Since the area of the strand indents is smaller relative to the overall cross-sectional area of the 5/16 in.-diameter and 3/8 in.-diameter strands (than the ratio for 5.32-mm-diameter wires), the indent geometry plays a smaller role in the overall bond performance of the strands and the surface condition contributes a much more meaningful portion to the overall bond performance of the strands. This conclusion is also supported by 1) Rose and Russell (1997) and 2) Barnes, Grove, and Burns (2003) for seven-wire, 0.5-in.-diameter strands and by Gustavson (2004) for a three-wire, 6.5-mm-diameter strands.

Six conclusions can be drawn when comparing lab data using mortar to plant data using concrete:

1. Maximum pullout forces from wire tests performed in mortar had very good correlations with transfer lengths measured from actual concrete railroad ties. An $R^2 = 0.808$ was achieved when all 12 wires were considered. An $R^2 = 0.870$ was achieved when only the nine wires with non-continuous indentations were considered. These results can be seen in Section 7.1.4.

2. Based on the excellent correlation between maximum pullout forces from wire tests in mortar and transfer lengths measured from actual concrete railroad ties, Equation 7.1 of Section 7.1.4 is given to predict the transfer length of concrete railroad ties using prestressed wires.

3. For most wire sources, the maximum pullout forces are similar in pullout tests conducted in mortar and concrete. However, the maximum pullout force occurred at a higher end slip in mortar than it did in concrete. This trend can be seen for each wire source in Figure 104 through Figure 115.

4. Maximum pullout forces from strand tests performed in mortar had poor correlations with the transfer lengths measured from actual concrete railroad ties. An $R^2 = 0.394$ was achieved using the standard 16-in. bond length specimens. An $R^2 = 0.282$ was achieved using the modified 9-in. bond length specimens. These results can be seen in Section

7.2.4.

5. The bond stress vs. end-slip curves for strand pullout specimens cast in mortar and in concrete look similar even for three different bond lengths (16 in., 9 in., and 4 in.). This can be seen in Figure 121 through Figure 123.

6. For both wires and strands, the pullout tests performed in mortar and in concrete yielded similar results. These results are shown in Sections 7.1.3 and 7.2.3 for wires and strands, respectively.

8.2 Recommendations

Based on the previous conclusions, five recommendations are made about the future wire bond testing:

1. The testing methodology of Appendix I can be sued as a specification for the bond quality of prestressing wires. The test result of the wire bond test should be taken as the maximum load recorded at a free-end-slip less than or equal to 0.10 in. This quantity proved to have the best correlation with the measured transfer length.

2. While the current research established that the un-tensioned pullout test presented herein is quite repeatable (when using different mortar batches), the authors recommend that the wire pullout test be conducted at other locations to establish the reproducibility of test results. Preferably, this would be done in a round-robin (blind-to-the-tester) style program.

3. Equation 7.1 (shown in Section 7.1.4), along with results of the pullout test described in Appendix I, should be used as a preliminary means for estimating the transfer length of concrete railroad ties using similar mix designs, release strengths, and pre-tensioned non-continuously indented wires.

The authors make two recommendations concerning the strand tests performed on smaller diameter strands:

1. Further testing at other locations using the "modified" Standard Test for Strand Bond should be conducted with smaller diameter strands and a 9-in. bond length. This will help establish the reproducibility of test results. Preferably, this would be done in a round-robin (blind-to-the-tester) style program.

2. Once the reproducibility of the "modified test for strand bond" is established or refuted for smaller diameter strands, then threshold values for acceptance could be recommended and the test be adopted as a quality control standard to provide a minimum bond quality of small diameter prestressing strands used in railroad tie applications.

9. References

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Appendix A.
Lab Phase, Wire; Test Development Batch Summaries

FRA DATA SHEET

Batch Name:	MW #2	Performed By:	Matthew Arnold
Batch Date:	1/19/2012	Wire Type #1:	[WI]
Batch Time:	2:18pm	Wire Type #2:	[WI]

Mix proportions	Can size		
	5"x10"	5"x12"	Actual
MW Sand (lbf)	134.9	155.4	155.4
Type III Cement (lbf)	67.4	77.7	77.7
Water (lbf)	27.7	31.9	31.9
Total (lbf)	230.0	265.0	265.0

		Wt. of Sand	
		D = 4"	D = 5"
Sieve	#4	6.88	7.93
	#8	20.65	23.79
	#16	41.30	47.58
	#30	34.41	39.65
	#50	17.89	20.62
	#100	13.77	15.86
	Σ	134.90	155.43

Flow Table Value : 117

Water Added (± lbf: 0

Temp / Humid: 59 °F / 23 %H

w/c: 0.410

s/c: 2.0

Avg Cube 4765 psi

Test Date: 1/20/2012 Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)
8:32a	18 hr	1.1	17835	4459	10:29a		1.10	19930	4983
8:32a		1.2	18030	4508	10:33a		1.11	20005	5001
9:17a	19 hr	1.3	18220	4555	10:48a	20.5 hr	1.12	19660	4915
9:28a		1.4	18760	4690			1.13		
9:35a		1.5	19390	4848			1.14		
9:48a	19.5 hr	1.6	19390	4848			1.15		
9:52a		1.7	18905	4726			1.16		
10:09a	20 hr	1.8	18995	4749			1.17		
10:20a		1.9	19620	4905			1.18		

Time	Since Batch	Specimen Force Control		Max Load (lbf)	Time	Since Batch	Specimen Displ. Control		Max Load (lbf)
8:54a	18.5 hr	[WI]	F-1	8741	9:07a	19 hr	[WI]	D-1	9032
9:14a	19 hr	[WI]	F-2	9279	9:25a		[WI]	D-2	8717
9:34a		[WI]	F-3	9109	9:43a	19.5 hr	[WI]	D-3	8965
9:52a	19.5 hr	[WI]	F-4	8783	9:59a		[WI]	D-4	7248
10:19a	20 hr	[WI]	F-5	7999	10:06a	20 hr	[WI]	D-5	8937
10:26a		[WI]	F-6	9356	10:32a	20.5 hr	[WI]	D-6	8932

Figure A-1. Force control vs. displacement control batch summary

FRA DATA SHEET

Batch Name: WC / WE Rotation

Performed By: Matthew Arnold

Batch Date: 5/22/2012

Batch Time: 1:16pm

Mix proportions	# of cans	
	12	Actual
UMW Sand (lbf)	155.4	155.4
Type III Cement (lbf)	77.7	77.7
Water (lbf)	31.9	31.9
Total (lbf)	265.0	265.0

Flow Table Value : 124

Water Added (± lbf): -1.0

Concrete Temp: 76.2 °F

Room Temp/Humid: 72.2 °F / 41 %H

w/c: 0.41

s/c: 2.0

Avg Cube 5115 psi

Test Date: 5/23/2012

Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
9:03a	19 hr	1	20200	5050					
10:03a	20 hr	2	20885	5221					
10:32a	20.5 hr	3	20295	5074					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:17a	1	[WC]-UMW-	1 (r)	9223 *	10:26a	10	[WE]-UMW-	1 (r)	9208 *
9:24a	2	[WC]-UMW-	2 (r)	9221 *	10:32a	11	[WE]-UMW-	2 (r)	9203 *
9:30a	3	[WC]-UMW-	3 (r)	9223 *	10:38a	12	[WE]-UMW-	3 (r)	9217 *
9:42a	4	[WC]-UMW-	1 (nr)	9210 *	10:03a	7	[WE]-UMW-	1 (nr)	9218 *
9:49a	5	[WC]-UMW-	2 (nr)	9223 *	10:10a	8	[WE]-UMW-	2 (nr)	9219 *
9:56a	6	[WC]-UMW-	3 (nr)	9222 *	10:15a	9	[WE]-UMW-	3 (nr)	9214 *

Notes: * denotes a specumen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure A-2. Rotation allowed vs. rotation restrained batch summary

FRA DATA SHEET

Batch Name:	8 wires : 1	Performed By:	Matthew Arnold
Batch Date:	1/26/2012		
Batch Time:	2:22pm		

Mix proportions	# of cans		
	8	12	Actual
MW Sand (lbf)	104.4	152.5	104.4
Type III Cement (lbf)	52.2	76.2	52.2
Water (lbf)	21.4	31.3	21.4
Total (lbf)	178.0	260.0	178.0

		Wt. of Sand	
		8 cans	12can
Sieve	#4	5.33	7.78
	#8	15.98	23.34
	#16	31.96	46.68
	#30	26.63	38.90
	#50	13.85	20.23
	#100	10.65	15.56
	Σ	104.40	152.49

Flow Table Value : 120

Water Added (± lbf 0

Temp / Humid: 71 °F / 28 %H

w/c: 0.41

s/c: 2.0

Avg Cub 4807 psi

Test Date:	1/27/2012	Performed By:	Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	ax Load (lb	Cube Str. (psi)
8:26a	18hr	1	17965	4491	10:03a		10	19910	4978
9:02a	18.5hr	2	18310	4578	10:16a	20hr	11	20550	5138
9:06a		3	18480	4620	10:18a		12	20560	5140
9:18a		4	18365	4591					
9:24a	19hr	5	19070	4768					
9:38a		6	19045	4761					
9:42a		7	18625	4656					
9:51a	19.5hr	8	19955	4989					
10:00a		9	19880	4970					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:37a	7	[WA]-MW-	1	538	8:46a	2	[WI]-MW-	1	8714
8:52a	3	[WB]-MW-	1	8514	9:06a	5	[WJ]-MW-	1	9224
8:59a	4	[WC]-MW-	1	9514 *	Notes:				
8:39a	1	[WD]-MW-	1	6663	* denotes a specimen that was stopped early for fear of rupturing.				
9:15a	6	[WE]-MW-	1	9409 **	** denotes a specimen that ruptured				
9:43a	8	[WF]-MW-	1	9400 *					

Figure A-3. As-received wires, eight wires #1 batch summary (Midwest sand)

FRA DATA SHEET

Batch Name: 8 wires : 2 — Performed By: Matthew Arnold

Batch Date: 2/2/2012

Batch Time: 2:18pm

Mix proportions	# of cans		
	8	12	Actual
MW Sand (lbf)	104.4	152.5	104.4
Type III Cement (lbf)	52.2	76.2	52.2
Water (lbf)	21.4	31.3	21.4
Total (lbf)	178.0	260.0	178.0

		Wt. of Sand	
		8 cans	12can
Sieve	#4	5.33	7.78
	#8	15.98	23.34
	#16	31.96	46.68
	#30	26.63	38.90
	#50	13.85	20.23
	#100	10.65	15.56
	Σ	104.40	152.49

Flow Table Value : 120

Water Added (± lbf 0

Temp / Humid: 69 °F / 31 %H

w/c: 0.41

s/c: 2.0

Avg Cub 4619 psi

Test Date: 2/3/2012 — Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	ax Load (lb	Cube Str. (psi)
8:28a	18 hr	1	17815	4454	9:38a	19.5 hr	10	18815	4704
8:31a		2	18115	4529	9:40a		11	19005	4751
8:52a	18.5 hr	3	18465	4616	9:43a		12	18905	4726
9:08a		4	18395	4599					
9:10a	19 hr	5	18095	4524					
9:14a		6	17160	4290					
9:17a		7	18660	4665					
9:24a		8	19125	4781					
9:35a		9	19180	4795					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:03a	5	[WA]-MW-	2	579	9:22a	8	[WI]-MW-	2	8093
9:14a	7	[WB]-MW-	2	8378	8:56a	4	[WJ]-MW-	2	9200 *
8:48a	3	[WC]-MW-	2	9200 *	Notes:				
9:06a	6	[WD]-MW-	2	7390	* denotes a specimen that was stopped early for fear of rupturing.				
8:32a	1	[WE]-MW-	2	9378 *	** denotes a specimen that ruptured				
8:41a	2	[WF]-MW-	2	9200 *					

Figure A-4. As-received wires, eight wires #2 batch summary (Midwest sand)

FRA DATA SHEET

Batch Name:	8 wires : 3	Performed By:	Matthew Arnold
Batch Date:	2/9/2012		
Batch Time:	2:26pm		

Mix proportions	# of cans		
	8	12	Actual
MW Sand (lbf)	104.4	152.5	104.4
Type III Cement (lbf)	52.2	76.2	52.2
Water (lbf)	21.4	31.3	21.4
Total (lbf)	178.0	260.0	178.0

		Wt. of Sand	
		8 cans	12can
Sieve	#4	5.33	7.78
	#8	15.98	23.34
	#16	31.96	46.68
	#30	26.63	38.90
	#50	13.85	20.23
	#100	10.65	15.56
	Σ	104.40	152.49

Flow Table Value : 119

Water Added (± lbf 0

Temp / Humid: 69 °F / 36 %H

w/c: 0.41

s/c: 2.0

Avg Cub 4678 psi

Test Date: 2/10/2012 Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:37a	18 hr	1	17915	4479	9:54a	19.5 hr	10	19125	4781
8:40a		2	18595	4649	9:58a		11	19210	4803
9:02a	18.5hr	3	17840	4460	10:03a		12	19025	4756
9:07a		4	18880	4720					
9:27a	19 hr	5	18780	4695					
9:29a		6	18280	4570					
9:38a		7	18545	4636					
9:46a		8	18840	4710					
9:50a		9	19485	4871					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:20a	6	[WA]-MW-	3	553	8:48a	1	[WI]-MW-	3	8875
8:54a	2	[WB]-MW-	3	8675	9:00a	3	[WJ]-MW-	3	9156 *
9:07a	4	[WC]-MW-	3	9224 *	Notes:				
9:28a	7	[WD]-MW-	3	6398 *	* denotes a specimen that was stopped early for fear of rupturing.				
9:13a	5	[WE]-MW-	3	9222 *	** denotes a specimen that ruptured				
9:36a	8	[WF]-MW-	3	9194 *					

Figure A-5. As-received wires, eight wires #3 batch summary (Midwest sand)

FRA DATA SHEET

Batch Name: 8 wires ; 4 — Performed By: Matthew Arnold

Batch Date: 2/14/2012

Batch Time: 2:25pm

Mix proportions	# of cans		
	8	12	Actual
MW Sand (lbf)	104.4	152.5	104.4
Type III Cement (lbf)	52.2	76.2	52.2
Water (lbf)	21.4	31.3	21.4
Total (lbf)	178.0	260.0	178.0

		Wt. of Sand	
		8 cans	12can
Sieve	#4	5.33	7.78
	#8	15.98	23.34
	#16	31.96	46.68
	#30	26.63	38.90
	#50	13.85	20.23
	#100	10.65	15.56
	Σ	104.40	152.49

Flow Table Value : 118

Water Added (± lbf 0 — w/c: 0.41

Temp / Humid: 69 °F / 31 %H — s/c: 2.0 — Avg Cube 4584 psi

Test Date: 2/15/2012 — Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:24a	18 hr	1	17370	4343	10:06a		10	18590	4648
8:27a		2	17375	4344	10:10a	20 hr	11	18790	4698
8:38a		3	17715	4429	10:12a		12	19080	4770
9:12a	19 hr	4	18080	4520					
9:18a		5	18100	4525					
9:38a		6	18675	4669					
9:42a	19.5 hr	7	18420	4605					
9:50a		8	18815	4704					
9:52a		9	19020	4755					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:30a	5	[WA]-MW-	4	453	9:04a	1	[WI]-MW-	4	7875
9:58a	8	[WB]-MW-	4	8461	9:24a	4	[WJ]-MW-	4	9059
9:16a	3	[WC]-MW-	4	9200 *	Notes:				
9:52a	7	[WD]-MW-	4	8060	* denotes a specimen that was stopped early for fear of rupturing.				
9:38a	6	[WE]-MW-	4	9214 *	** denotes a specimen that ruptured				
9:10a	2	[WF]-MW-	4	9200 *					

Figure A-6. As-received wires, eight wires #4 batch summary (Midwest sand)

FRA DATA SHEET

Batch Name:	8 wires ¡ 5	Performed By:	Matthew Arnold
Batch Date:	2/16/2012		
Batch Time:	2:15 PM		

Mix proportions	# of cans		
	9	12	Actual
MW Sand (lbf)	117.3	152.5	117.3
Type III Cement (lbf)	58.7	76.2	58.7
Water (lbf)	24.0	31.3	24.0
Total (lbf)	200.0	260.0	200.0

		Wt. of Sand	
		9 cans	12can
Sieve	#4	5.98	7.78
	#8	17.95	23.34
	#16	35.91	46.68
	#30	29.92	38.90
	#50	15.56	20.23
	#100	11.97	15.56
	Σ	117.30	152.49

Flow Table Value : 118

Water Added (± lbf 0

Temp / Humid: 69 °F / 38 %H

w/c: 0.41

s/c: 2.0

Avg Cub 4560 psi

Test Date: 2/17/2012 Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:37a	18 hr	1	17910	4478	10:06a	19.5 hr	10	18545	4636
8:39a		2	18025	4506			11	19080	4770
8:41a	18.5 hr	3	18040	4510			12	18255	4564
9:02a		4	18140	4535					
9:04a		5	18200	4550					
9:06a	19 hr	6	17920	4480					
9:12a		7	18270	4568					
9:18a		8	18180	4545					
9:32a		9	18325	4581					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:39a	8	[WA]-MW-	5	455	9:17a	5	[WI]-MW-	5	8874
8:56a	2	[WB]-MW-	5	8313 *	9:10a	4	[WJ]-MW-	5	9224 *
9:25a	6	[WC]-MW-	5	9200 *	Notes:				
8:43a	1	[WD]-MW-	5	7754	* denotes a specimen that was stopped early for fear of rupturing.				
9:31a	7	[WE]-MW-	5	9213 *	** denotes a specimen that ruptured				
9:04a	3	[WF]-MW-	5	9203 *					

Figure A-7. As-received wires, eight wires #5 batch summary (Midwest sand)

FRA DATA SHEET

Batch Name:	8 wires i6	Performed By:	Matthew Arnold
Batch Date:	2/23/2012		
Batch Time:	2:28pm		

Mix proportions	# of cans		
	8	12	Actual
MW Sand (lbf)	176.0	152.5	176.0
Type III Cement (lbf)	88.0	76.2	88.0
Water (lbf)	36.1	31.3	36.1
Total (lbf)	300.0	260.0	300.1

		Wt. of Sand	
		8 cans	12can
Sieve	#4	9.0	7.8
	#8	26.9	23.3
	#16	53.9	46.7
	#30	44.9	38.9
	#50	23.3	20.2
	#100	18.0	15.6
	Σ	176.0	152.49

Flow Table Value : 123

Water Added (± lbf 0

Temp / Humid: 69 °F / 34 %H

w/c: 0.41

s/c: 2.0

Avg Cub 4721 psi

Test Date: 2/24/2012 Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:53a	18.5 hr	1	18925	4731	10:25a	20 hr	10	19690	4923
8:55a		2	17725	4431	10:27a		11	19495	4874
9:06a		3	18620	4655	10:30a		12	18510	4628
9:13a		4	18190	4548					
9:19a		5	18105	4526					
9:32a	19 hr	6	19120	4780					
9:56a		7	19325	4831					
10:06a		8	19595	4899					
10:19a		9	19330	4833					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:38a	6	[WA]-MW-	6	540	9:03a	2	[WI]-MW-	6	8856
9:11a	3	[WB]-MW-	6	8443	9:41a	7	[WJ]-MW-	6	9227 *
9:17a	4	[WC]-MW-	6	9219 *	Notes:				
9:47a	8	[WD]-MW-	6	9214 *	* denotes a specimen that was stopped early for fear of rupturing.				
9:31a	5	[WE]-MW-	6	9220 *	** denotes a specimen that ruptured				
8:56a	1	[WF]-MW-	6	9210 *					

Figure A-8. As-received wires, eight wires #6 batch summary (Midwest sand)

FRA DATA SHEET

Batch Name: 2 wires ; 1 — Performed By: Matthew Arnold

Batch Date: 3/29/2012

Batch Time: 4:10pm

Mix proportions	# of cans		
	8	12	Actual
MW Sand (lbf)	103.8	148.4	148.4
Type III Cement (lbf)	51.9	74.2	74.2
Water (lbf)	21.3	30.4	30.4
Total (lbf)	177.0	253.0	253.0

		Wt. of Sand	
		8 cans	12can
Sieve	#4	5.3	7.6
	#8	15.9	22.7
	#16	31.8	45.4
	#30	26.5	37.9
	#50	13.8	19.7
	#100	10.6	15.1
	Σ	103.8	148.39

Flow Table Value : 123

Water Added (± lbf: 0

Temp / Humid: 72 °F / 56 %H

w/c: 0.41

s/c: 2.0

Avg Cube: 4818 psi

Test Date: 3/30/2012 — Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
9:07a	17 hr	1	19510	4878			9	19515	4879
9:10a		2	17740	4435	11:01a	19 hr	10	19820	4955
9:13a		3	18475	4619			11	19920	4980
9:59a	18 hr	4	18830	4708			12	19385	4846
10:02a		5	19450	4863					
10:24a	18.5 hr	6	19695	4924					
10:28a		7	19400	4850					
10:46a		8	19510	4878					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:43a	2	[WG]-MW-	1	8705	9:35a	1	[WH]-MW-	1	8881
9:55a	4	[WG]-MW-	2	6761	9:49a	3	[WH]-MW-	2	9193 *
10:08a	6	[WG]-MW-	3	6280	10:02a	5	[WH]-MW-	3	8438
10:16a	7	[WG]-MW-	4	7757	10:29a	7	[WH]-MW-	4	7283
10:37a	10	[WG]-MW-	5	7482	10:23a	9	[WH]-MW-	5	8085
10:49a	12	[WG]-MW-	6	6779	10:43a	11	[WH]-MW-	6	9195 *

Notes: * denotes a specumen that was stopped early for fear of yielding
** denotes a specimen that yielded

Figure A-9. As-received wires, [WG] and [WH] batch summary (Midwest sand)

FRA DATA SHEET

Batch Name:	WK & WL 5" MW	Performed By:	Matthew Arnold
Batch Date:	7/10/2012		
Batch Time:	3:08pm		

Mix proportions	# of cans	
	12	Actual
MW Sand (lbf)	148.4	148.4
Type III Cement (lbf)	74.2	74.2
Water (lbf)	30.4	30.4
Total (lbf)	253.0	253.0

	Sieve	Wt. of Sand
Sieve	#4	7.6
	#8	22.7
	#16	45.4
	#30	37.9
	#50	19.7
	#100	15.1
	Σ	148.39

Flow Table Value :	123
Water Added (± lbf	0
Concrete Temp :	73 °F
Room Temp / Humid:	72.2 °F / 55 %H

w/c: 0.41
s/c: 2.0
Avg Cube 4598 psi

Test Date: 7/11/2012 Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:48a	17.5 hr	1	18250	4563	10:06a		9	18320	4580
8:50a		2	18265	4566					
9:22a	18 hr	3	17980	4495					
9:28a		4	18300	4575					
9:42a	18.5 hr	5	19145	4786					
9:50a		6	19125	4781					
10:02a	19 hr	7	17170	4293					
10:04a		8	18975	4744					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:15a	1	[WK]-MW-	1	4234	9:18a	2	[WL]-MW-	1	3119
9:21a	3	[WK]-MW-	2	4631	9:25a	4	[WL]-MW-	2	3015
9:28a	5	[WK]-MW-	3	5128	9:31a	6	[WL]-MW-	3	3795
9:35a	7	[WK]-MW-	4	4714	9:38a	8	[WL]-MW-	4	3760
9:41a	9	[WK]-MW-	5	5134	9:46a	10	[WL]-MW-	5	3768
9:50a	11	[WK]-MW-	6	5232	9:53a	12	[WL]-MW-	6	3997

Notes: * denotes a specumen that was stopped early for fear of yielding
** denotes a specimen that yielded

Figure A-10. As-received wires, [WK] and [WL] batch summary (Midwest sand)

FRA DATA SHEET

Batch Name: Ottawa # 1

Performed By: Matthew Arnold

Batch Date: 3/14/2012

Batch Time: 12:18pm

Mix proportions	# of cans	
	10	Actual
MW Sand (lbf)	121.7	121.7
Type III Cement (lbf)	60.9	60.9
Water (lbf)	27.4	27.4
Total (lbf)	210.0	210.0

Flow Table Value : 127

Water Added (± lbf 0

Temp / Humid: 73 °F / 55 %H

w/c: 0.45

s/c: 2.0

Avg Cub 4816 psi

Test Date: 3/15/2012

Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
10:12a	22 hr	1	18340	4585	11:14a		9	19780	4945
10:14a		2	18490	4623	11:16a		10	19440	4860
10:52a	22.5 hr	3	18880	4720	11:19a		11	19470	4868
10:55a		4	19125	4781	11:21a		12	19750	4938
11:01a		5	19850	4963					
11:04a		6	19420	4855					
11:06a		7	19260	4815					
11:09a	23 hr	8	19370	4843					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
10:18a	1	[WA]-O-	1	519	10:39a	4	[WG]-O-	1	7434
11:11a	9	[WB]-O-	1	See next	11:22a	10	[WH]-O-	1	9198 *
10:51a	6	[WC]-O-	1	9222 *	10:26a	2	[WI]-O-	1	9176 *
10:32a	3	[WD]-O-	1	8632	11:05a	8	[WJ]-O-	1	9218 *
10:45a	5	[WE]-O-	1	9202 *					
10:58a	7	[WF]-O-	1	9207 *					

Notes: * denotes a specumen that was stopped early for fear of yielding
** denotes a specimen that yielded

Figure A-11. As-received wires, 10 wires #1 batch summary (Ottawa sand)

FRA DATA SHEET

Batch Name:	Ottawa # 2	Performed By:	Matthew Arnold
Batch Date:	3/27/2013		
Batch Time:	1:50pm		

Mix proportions	# of cans	
	11	Actual
MW Sand (lbf)	135.7	135.7
Type III Cement (lbf)	67.8	67.8
Water (lbf)	30.5	30.5
Total (lbf)	234.0	234.0

Flow Table Value : 121

Water Added (± lbf: -1.4 | w/c: 0.45

Temp / Humid: 73 °F / 54 %H | s/c: 2.0 | Avg Cube 4970 psi

Test Date: 3/28/2012 | Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
11:45a	22 hr	1	18900	4725					
12:47p	23 hr	2	20720	5180					
1:19p	23.5 hr	3	20015	5004					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
12:37p	3	[WA]-O-	2	733	12:56p	7	[WG]-O-	2	8309
1:21p	11	[WB]-O-	2	8558	12:43p	5	[WH]-O-	2	9205 *
1:02p	8	[WC]-O-	2	9224 *	1:13p	10	[WI]-O-	2	9210 *
1:08p	9	[WD]-O-	2	9192 *	12:28p	2	[WJ]-O-	2	9216 *
12:48p	6	[WE]-O-	2	9221 *	12:18p	1	[WB]-O-	1	8517
12:39p	4	[WF]-O-	2	9229 *					

Notes: * denotes a specumen that was stopped early for fear of yielding
** denotes a specimen that yielded

Figure A-12. As-received wires, 10 wires #2 batch summary (Ottawa sand)

FRA DATA SHEET

Batch Name:	Ottawa # 3	Performed By:	Matthew Arnold
Batch Date:	4/12/2012		
Batch Time:	1:39pm		

Mix proportions	# of cans	
	10	Actual
MW Sand (lbf)	124.6	124.6
Type III Cement (lbf)	62.3	62.3
Water (lbf)	28.0	28.0
Total (lbf)	215.0	214.9

Flow Table Value :	124					
Water Added (± lbf	-0.3	w/c:	0.45			
Temp / Humid:	68 °F / 46 %H	s/c:	2.0	Avg Cub	4678	psi

Test Date:	4/13/2012	Performed By:	Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:41a	19 hr	1	17125	4281	10:36a		9	19165	4791
9:19a	19.5 hr	2	18310	4578					
9:43a	20 hr	3	18810	4703					
9:49a		4	18150	4538					
9:58a		5	18910	4728					
10:14a	20.5 hr	6	18815	4704					
10:30a	21 hr	7	18435	4609					
10:32a		8	19115	4779					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
10:17a	9	[WA]-O-	3	630	9:59a	6	[WG]-O-	3	6409
10:05a	7	[WB]-O-	3	8104	9:32a	2	[WH]-O-	3	9200 *
9:47a	4	[WC]-O-	3	8223 *	9:53a	5	[WI]-O-	3	7562
10:11a	8	[WD]-O-	3	7209	10:20a	10	[WJ]-O-	3	7820
9:39a	3	[WE]-O-	3	9218 *					
9:25a	1	[WF]-O-	3	9048					

Notes: * denotes a specumen that was stopped early for fear of yielding
** denotes a specimen that yielded

Figure A-13. As-received wires, 10 wires #3 batch summary (Ottawa sand)

FRA DATA SHEET

Batch Name:	Ottawa # 4	Performed By:	Matthew Arnold
Batch Date:	4/17/2012		
Batch Time:	1:48p		

Mix proportions	# of cans	
	10	Actual
MW Sand (lbf)	124.8	
Type III Cement (lbf)	62.4	
Water (lbf)	27.8	
Total (lbf)	215.0	0.0

Flow Table Value : 127

Water Added (± lbf 0

Temp / Humid: 72 °F / 44 %H

w/c: 0.445

s/c: 2.0

Avg Cub 4859 psi

Test Date: 4/18/2012 Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:28a	18.5 hr	1	18775	4694	9:31a		9	19580	4895
8:31a		2	19435	4859	9:45a	20 hr	10	20395	5099
8:50a	19 hr	3	18890	4723	9:48a		11	18990	4748
9:01a		4	19700	4925	9:50a		12	20300	5075
9:04a		5	18915	4729					
9:11a		6	19625	4906					
9:15a		7	18630	4658					
9:24a	19.5 hr	8	19990	4998					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:35a	10	[WA]-O-	4	579	8:55a	3	[WG]-O-	4	6253
8:48a	2	[WB]-O-	4	8133	9:00a	4	[WH]-O-	4	8887
9:29a	9	[WC]-O-	4	9223 *	8:42	1	[WI]-O-	4	8353
9:18a	7	[WD]-O-	4	6560	9:23a	8	[WJ]-O-	4	9216 *
9:12a	6	[WE]-O-	4	9217 *					
9:06a	5	[WF]-O-	4	9205 *					

Notes: * denotes a specumen that was stopped early for fear of yielding
** denotes a specimen that yielded

Figure A-14. As-received wires, 10 wires #4 batch summary (Ottawa sand)

FRA DATA SHEET

Batch Name:	Ottawa # 5	Performed By:	Matthew Arnold
Batch Date:	4/26/2012		
Batch Time:	2:19p		

Mix proportions	# of cans	
	10	Actual
MW Sand (lbf)	125.0	125.0
Type III Cement (lbf)	62.5	62.5
Water (lbf)	27.5	27.5
Total (lbf)	215.0	215.0

Flow Table Value : 124

Water Added (± lbf -0.17 w/c: 0.44

Temp / Humid: 73 °F / 46 %H s/c: 2.0 Avg Cub 4616 psi

Test Date: 4/27/2012 Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
9:44a		1	17520	4380	11:08a		9	17770	4443
10:13a		2	19205	4801	11:25a		10	17850	4463
10:15a		3	17350	4338	11:27a		11	18745	4686
10:17a	DEFECT	4			11:29a		12	19390	4848
10:19a		5	17890	4473					
10:41a		6	19075	4769					
10:43a		7	18220	4555					
10:59a		8	19125	4781					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
11:17a	10	[WA]-O-	5	693	11:05a	8	[WG]-O-	5	8735
10:37a	3	[WB]-O-	5	9226 *	10:19a	1	[WH]-O-	5	9190 *
10:46a	5	[WC]-O-	5	9224 *	10:25a	2	[WI]-O-	5	9188 *
11:11a	9	[WD]-O-	5	9197 *	10:58a	7	[WJ]-O-	5	9199 *
10:39a	4	[WE]-O-	5	9222 *					
10:52a	6	[WF]-O-	5	9216 *					

Notes: * denotes a specumen that was stopped early for fear of yielding
** denotes a specimen that yielded

Figure A-15. As-received wires, 10 wires #5 batch summary (Ottawa sand)

FRA DATA SHEET

Batch Name:	Ottawa # 6	Performed By:	Matthew Arnold
Batch Date:	5/3/2012		
Batch Time:	2:03p		

Mix proportions	# of cans	
	10	Actual
MW Sand (lbf)	125.2	125.2
Type III Cement (lbf)	62.6	62.6
Water (lbf)	27.2	27.2
Total (lbf)	215.0	215.0

Flow Table Value :	124				
Water Added (± lbf	0	w/c:	0.435		
Temp / Humid:	74 °F / 66 %H	s/c:	2.0	Avg Cub	4570 psi

Test Date: 5/4/2012 Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:48a	19 hr	1	16440	4110	1:05p	23 hr	9	19000	4750
9:35a	19.5 hr	2	16240	4060					
10:10a	20 hr	3	16680	4170					
11:45a	21.5 hr	4	17960	4490					
12:16p	22 hr	5	18300	4575					
12:33p	22.5 hr	6	18635	4659					
12:46p		7	18145	4536					
1:03p	23 hr	8	17640	4410					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
12:12p	3	[WA]-O-	6	746	12:32p	7	[WG]-O-	6	7997
12:46p	9	[WB]-O-	6	9226 *	12:00p	1	[WH]-O-	6	9215 *
12:49p	10	[WC]-O-	6	9223 *	12:06p	2	[WI]-O-	6	9197 *
12:21p	5	[WD]-O-	6	9188 *	12:15p	4	[WJ]-O-	6	9205 *
12:27p	6	[WE]-O-	6	9213 *					
12:38p	8	[WF]-O-	6	9216 *					

Notes: * denotes a specumen that was stopped early for fear of yielding
** denotes a specimen that yielded

Figure A-16. As-received wires, 10 wires #6 batch summary (Ottawa sand)

FRA DATA SHEET

Batch Name:	WK & WL Ottawa	Performed By:	Matthew Arnold
Batch Date:	5/24/2012		
Batch Time:	3:13pm		

Mix proportions	# of cans	
	15	Actual
MW Sand (lbf)	183.8	183.8
Type III Cement (lbf)	91.9	91.9
Water (lbf)	40.0	40.0
Total (lbf)	315.7	315.7

Flow Table Value :	121				
Water Added (± lbf	-1.25				
Concrete Temp:	75.5 °F	w/c:	0.435		
Room Temp / Humid:	72.7 °F / 56 %H	s/c:	2.0	Avg Cube	4817 psi

Test Date:	5/25/2012	Performed By:	Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:44a	17.5 hr	1	18035	4509	10:20a		9	19765	4941
9:27a	18 hr	2	18990	4748					
9:38a	18.5 hr	3	18615	4654					
9:56a		4	18235	4559					
10:10a	19 hr	5	19450	4863					
10:12a		6	20680	5170					
10:14a		7	20060	5015					
10:17a		8	19580	4895					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:09a	1	[WK]-O-	1	5118	9:13a	2	[WL]-O-	1	3573
9:17a	3	[WK]-O-	2	5449	9:22a	4	[WL]-O-	2	4878
9:27a	5	[WK]-O-	3	5037	9:32a	6	[WL]-O-	3	3581
9:36a	7	[WK]-O-	4	5873	9:41a	8	[WL]-O-	4	4836
9:45a	9	[WK]-O-	5	5168	9:50a	10	[WL]-O-	5	3987
9:53a	11	[WK]-O-	6	4581	9:59a	12	[WL]-O-	6	3128

Notes: * denotes a specumen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure A-17. As-received wires, [WK] and [WL] batch summary (Ottawa sand)

Appendix B.
Lab Phase, Wire; Test Development Individual Pullout Graphs

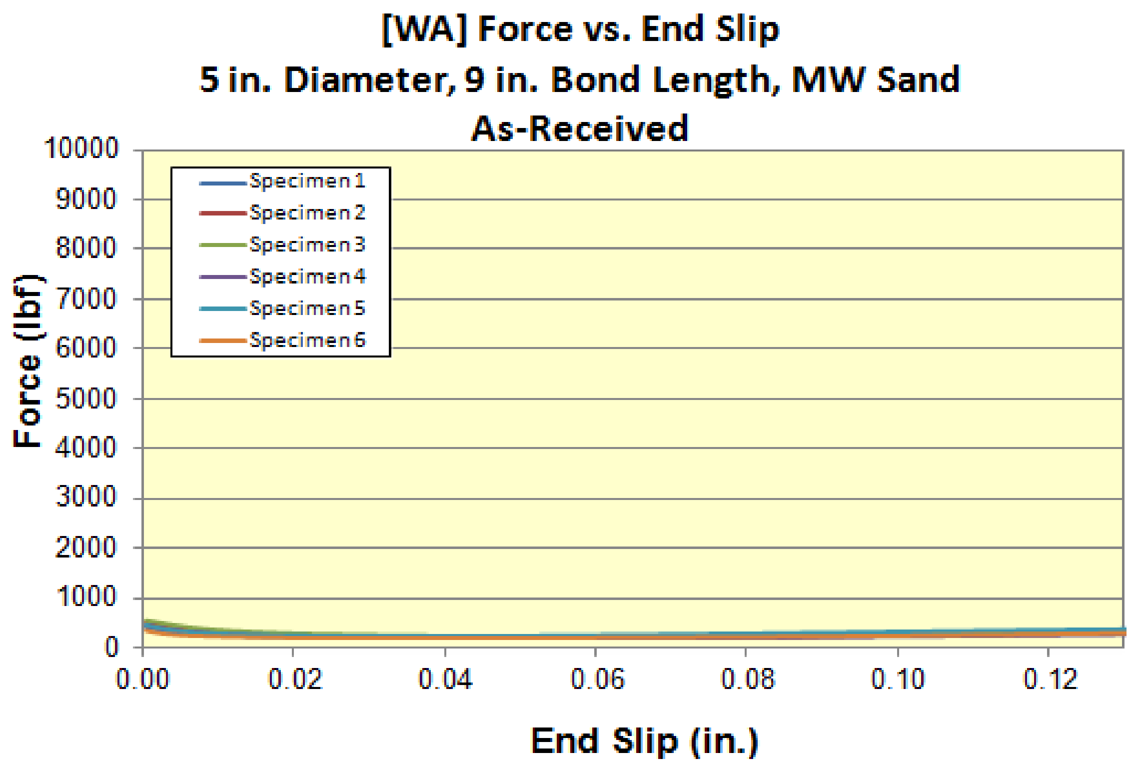

Figure B-1. Midwest sand [WA] force vs. end-slip individual graphs

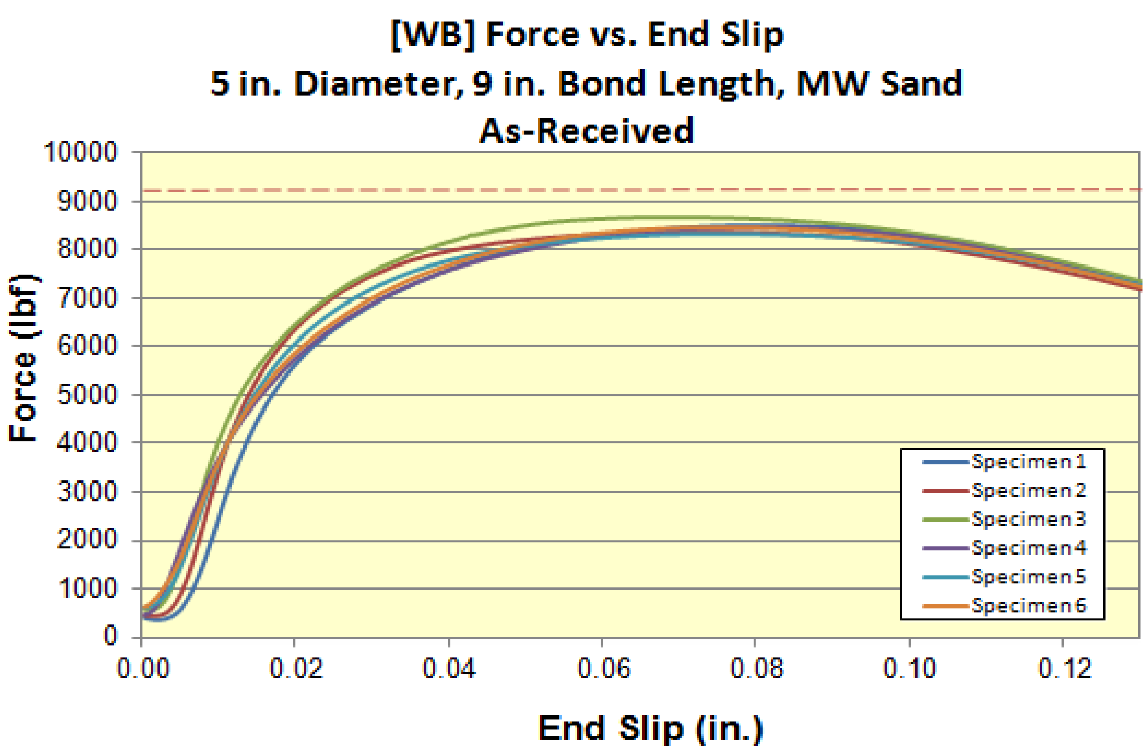

Figure B-2. Midwest sand [WB] force vs. end-slip individual graphs

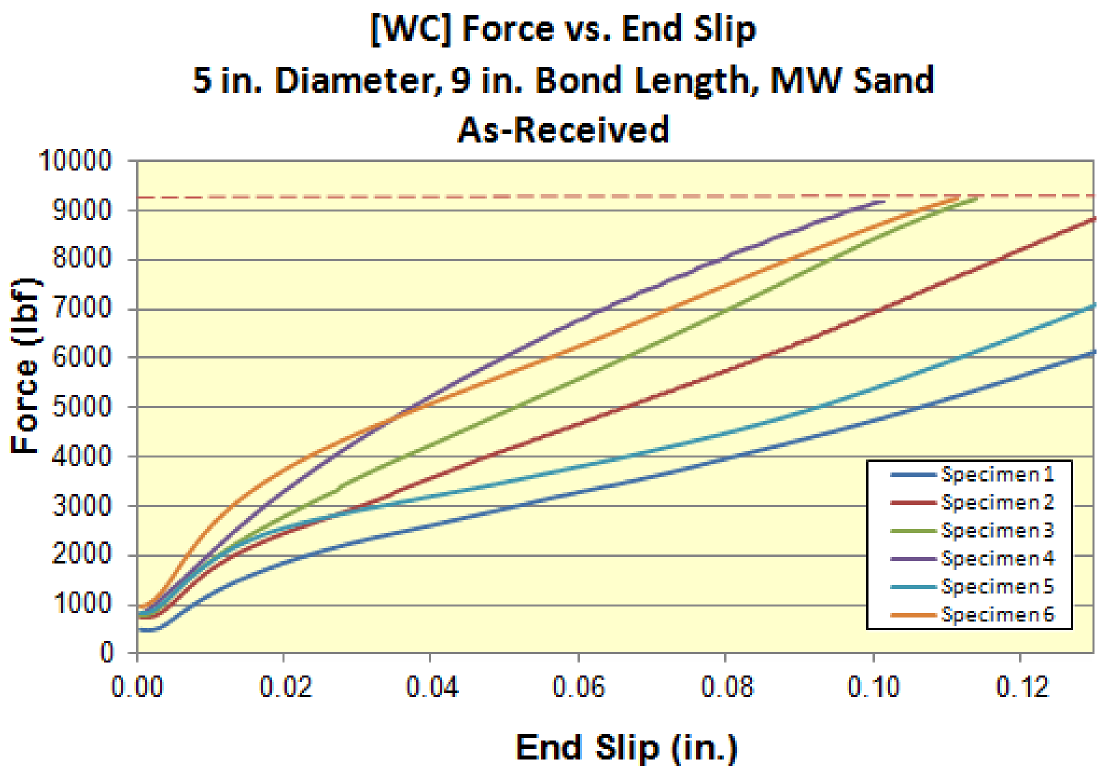

Figure B-3. Midwest sand [WC] force vs. end-slip individual graphs

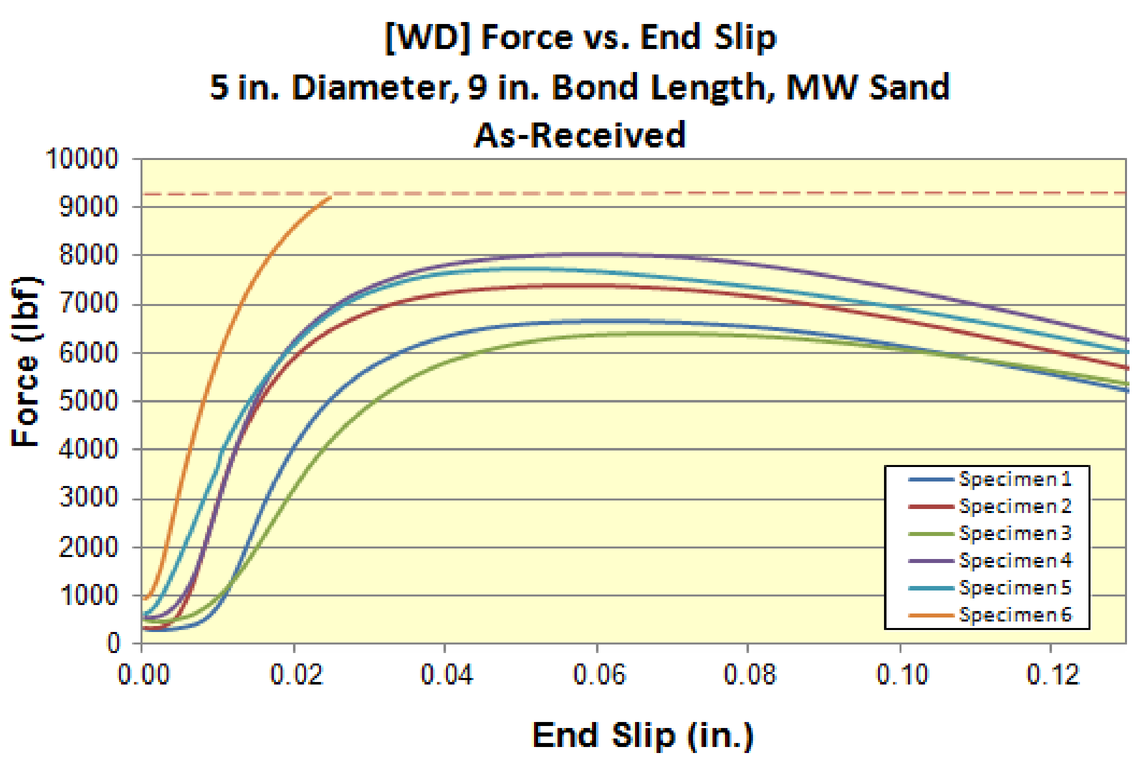

Figure B-4. Midwest sand [WD] force vs. end-slip individual graphs

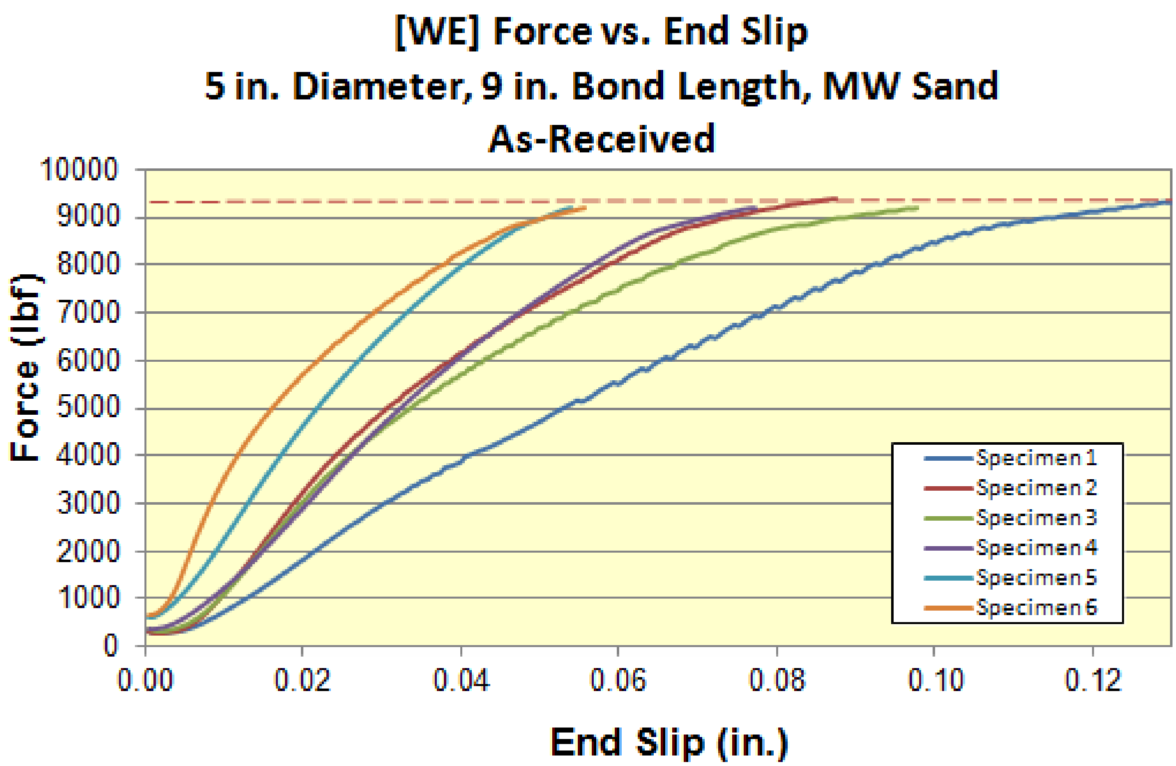

Figure B-5. Midwest sand [WE] force vs. end-slip individual graphs

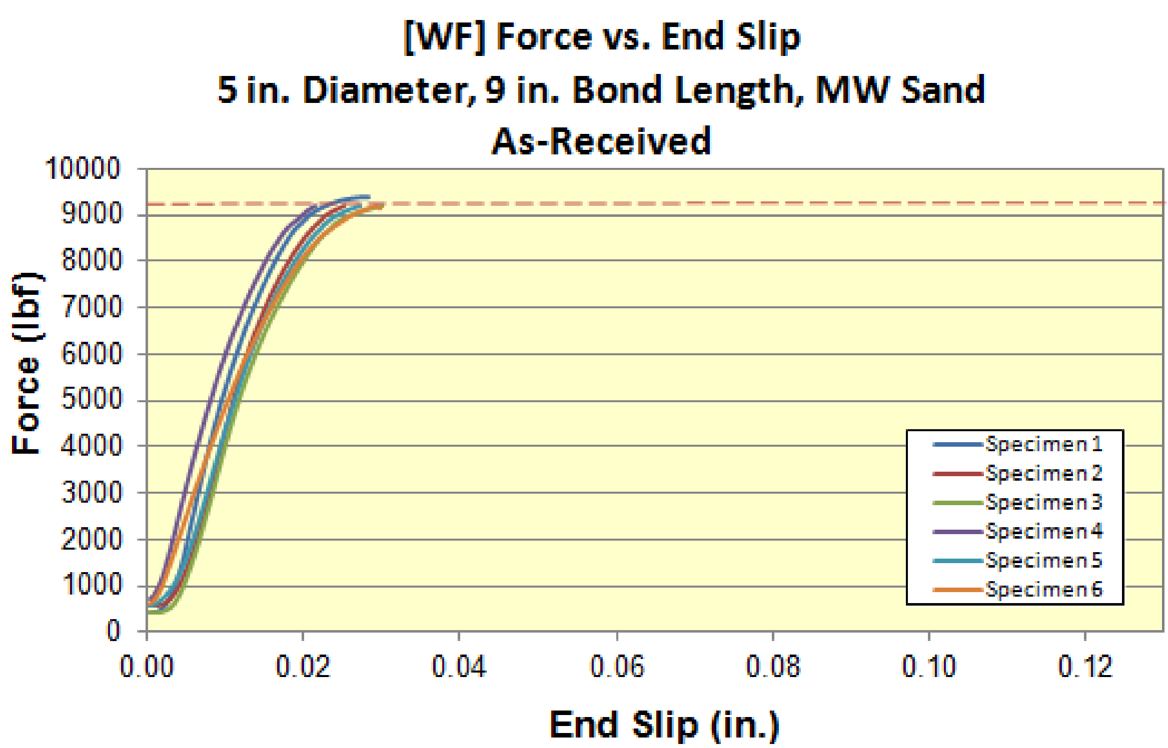

Figure B-6. Midwest sand [WF] force vs. end-slip individual graphs

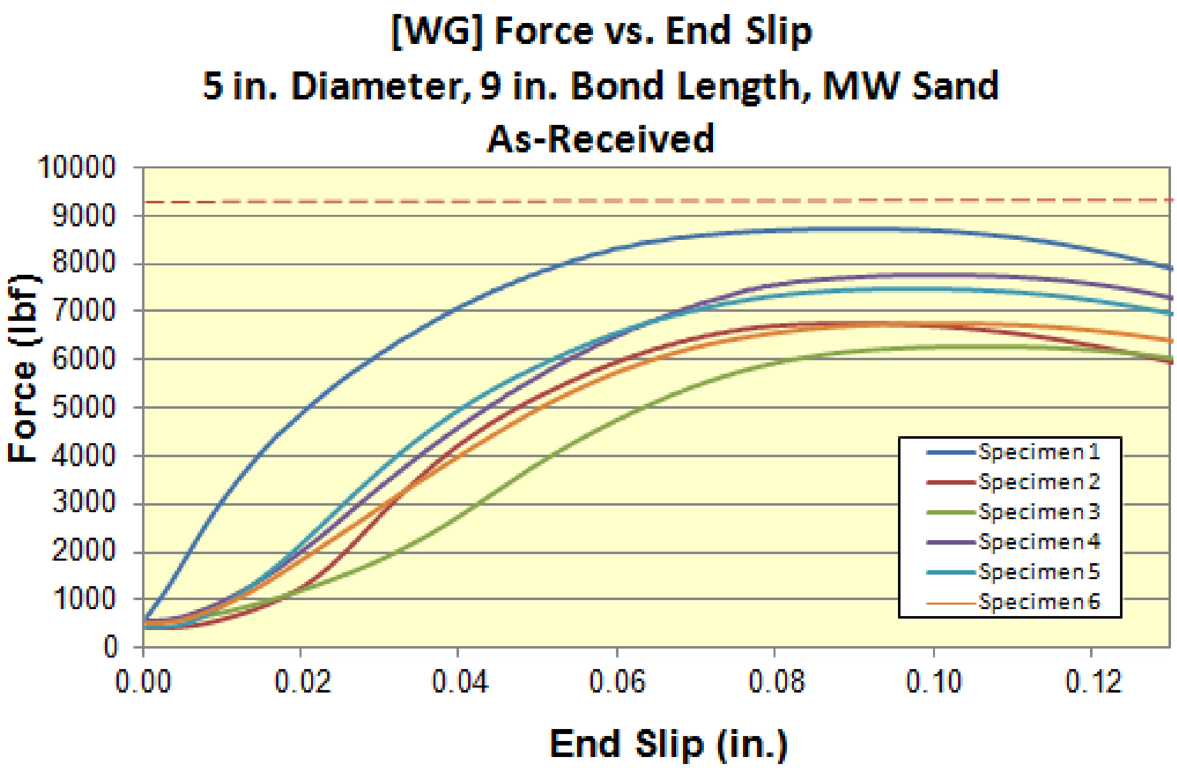

Figure B-7. Midwest sand [WG] force vs. end-slip individual graphs

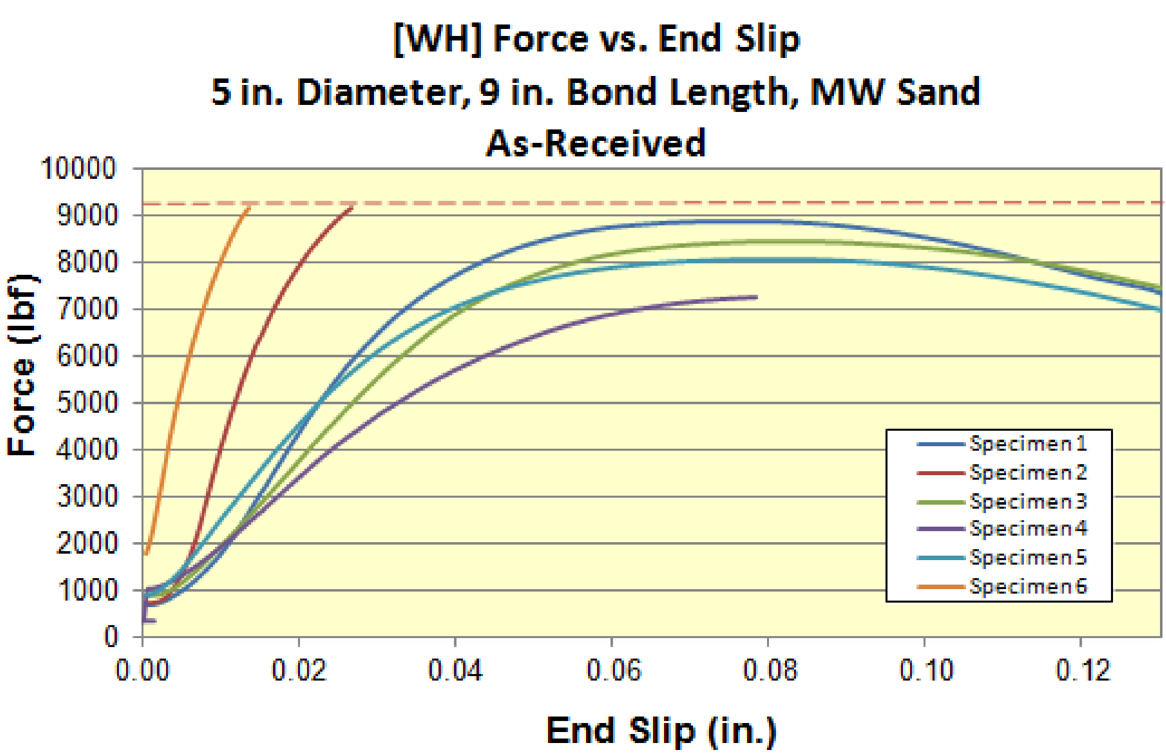

Figure B-8. Midwest sand [WH] force vs. end-slip individual graphs

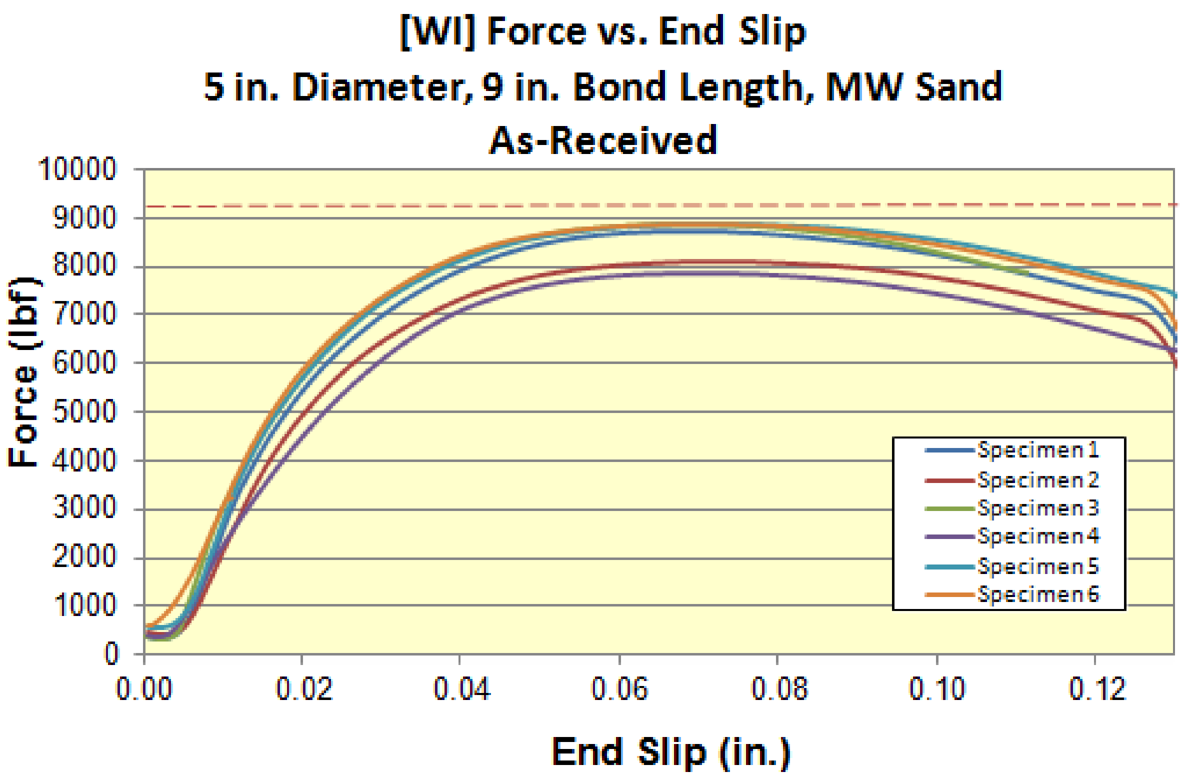

Figure B-9. Midwest sand [WI] force vs. end-slip individual graphs

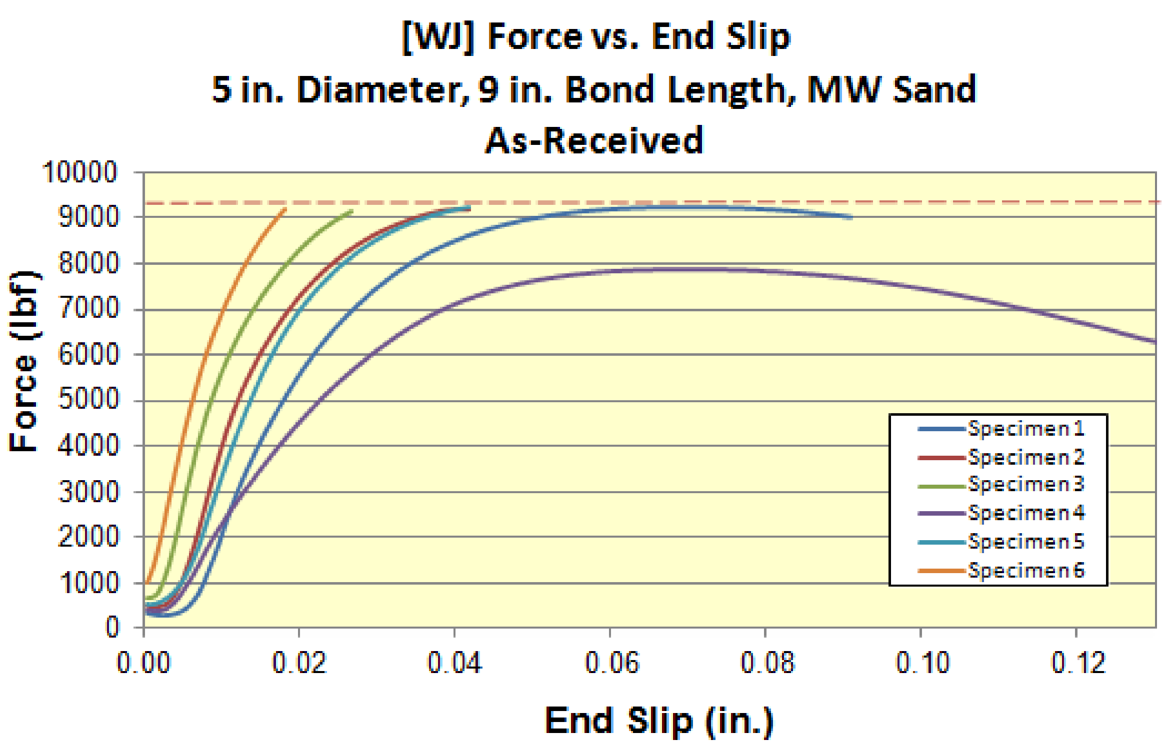

Figure B-10. Midwest sand [WJ] force vs. end-slip individual graphs

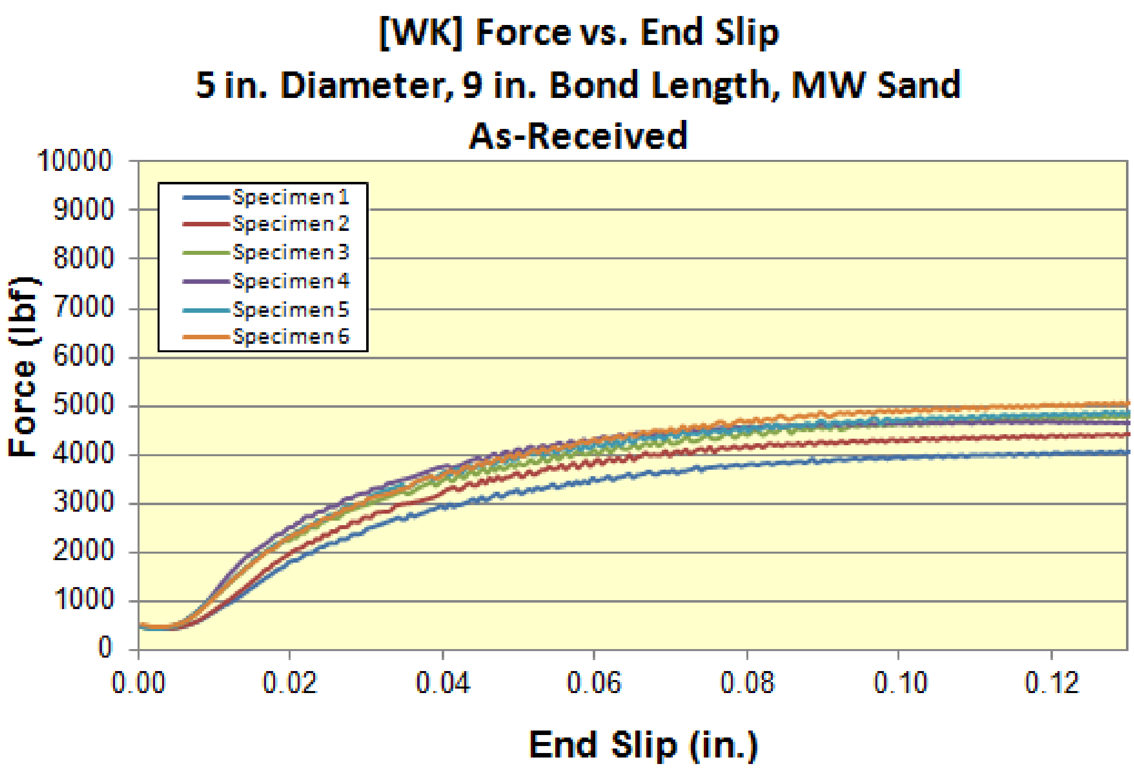

Figure B-11. Midwest sand [WK] force vs. end-slip individual graphs

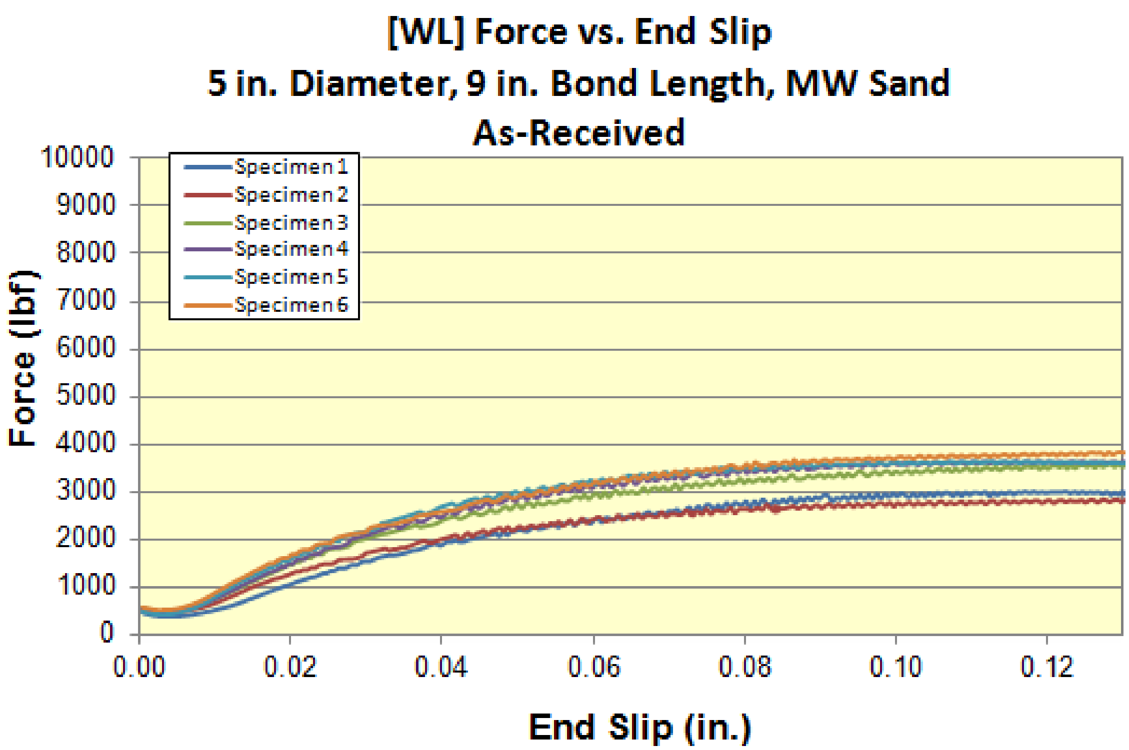

Figure B-12. Midwest sand [WL] force vs. end-slip individual graphs

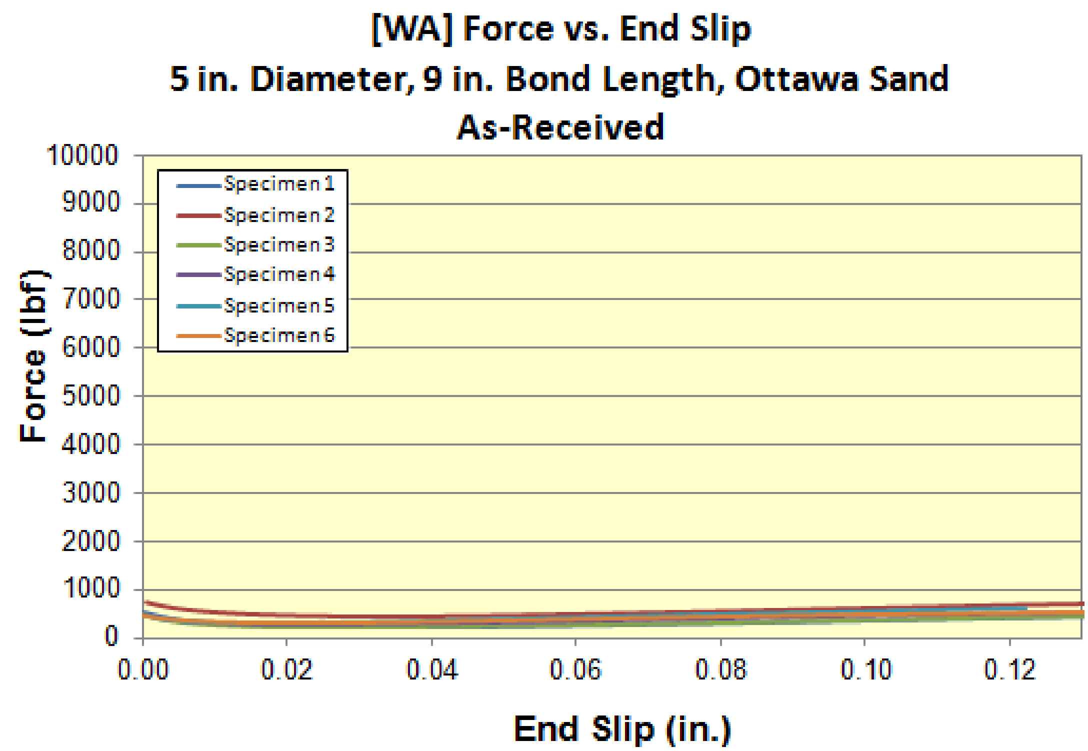

Figure B-13. Ottawa sand [WA] force vs. end-slip individual graphs

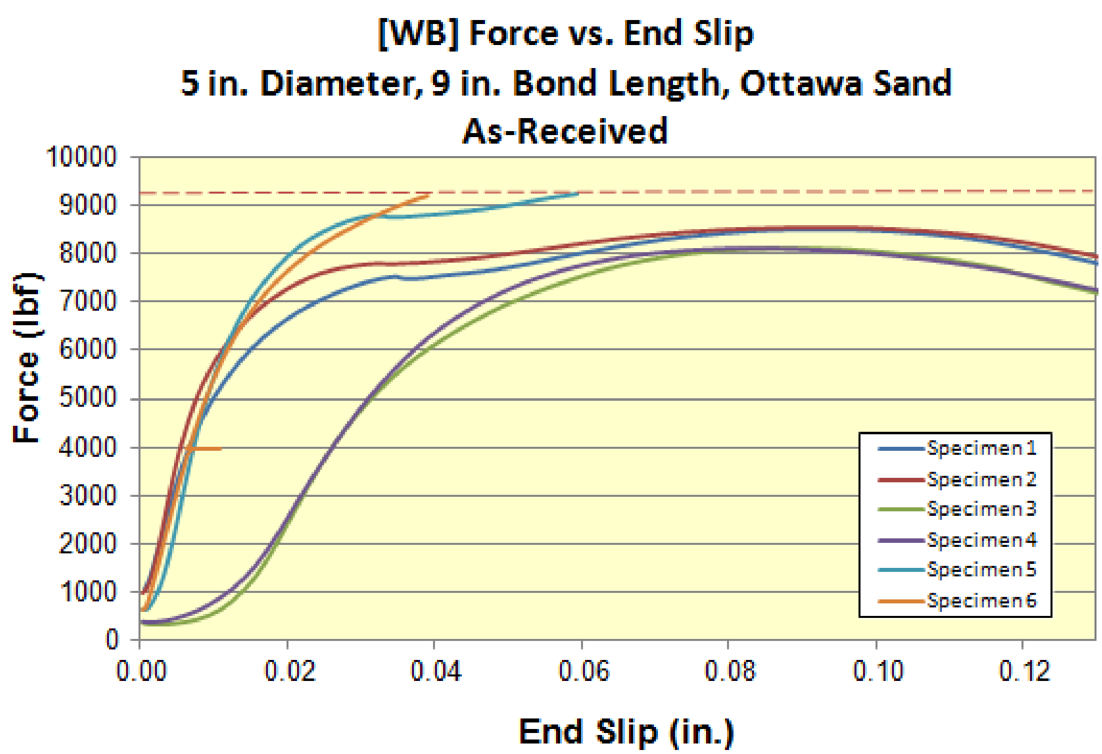

Figure B-14. Ottawa sand [WB] force vs. end-slip individual graphs

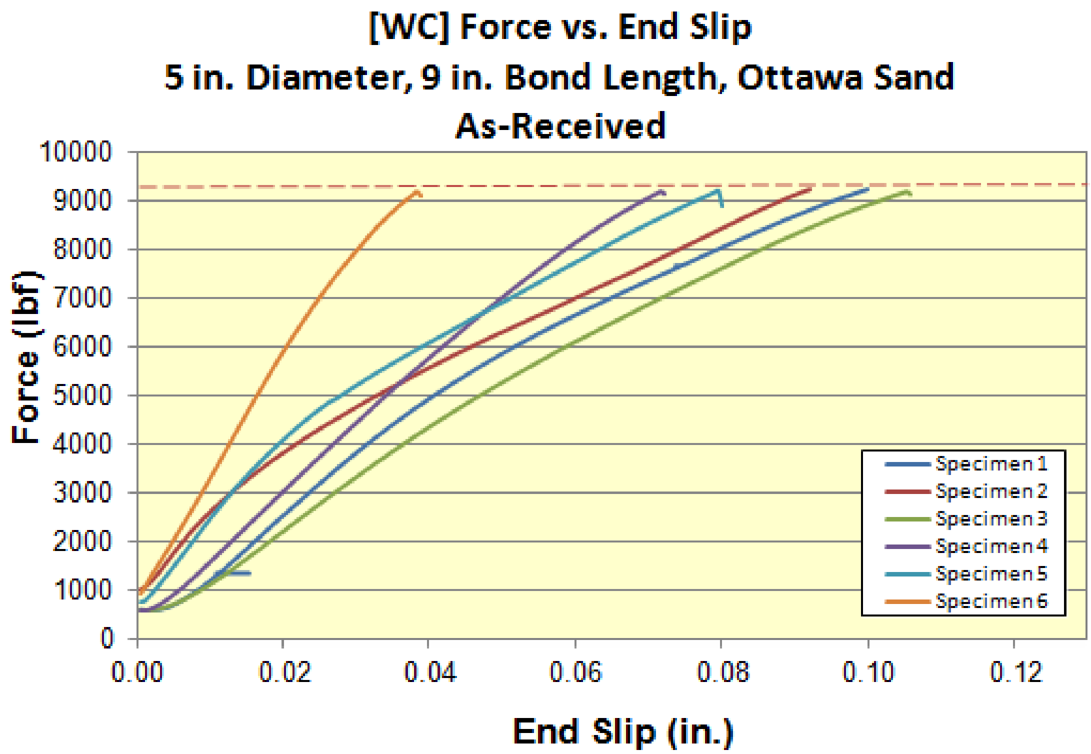

Figure B-15. Ottawa sand [WC] force vs. end-slip individual graphs

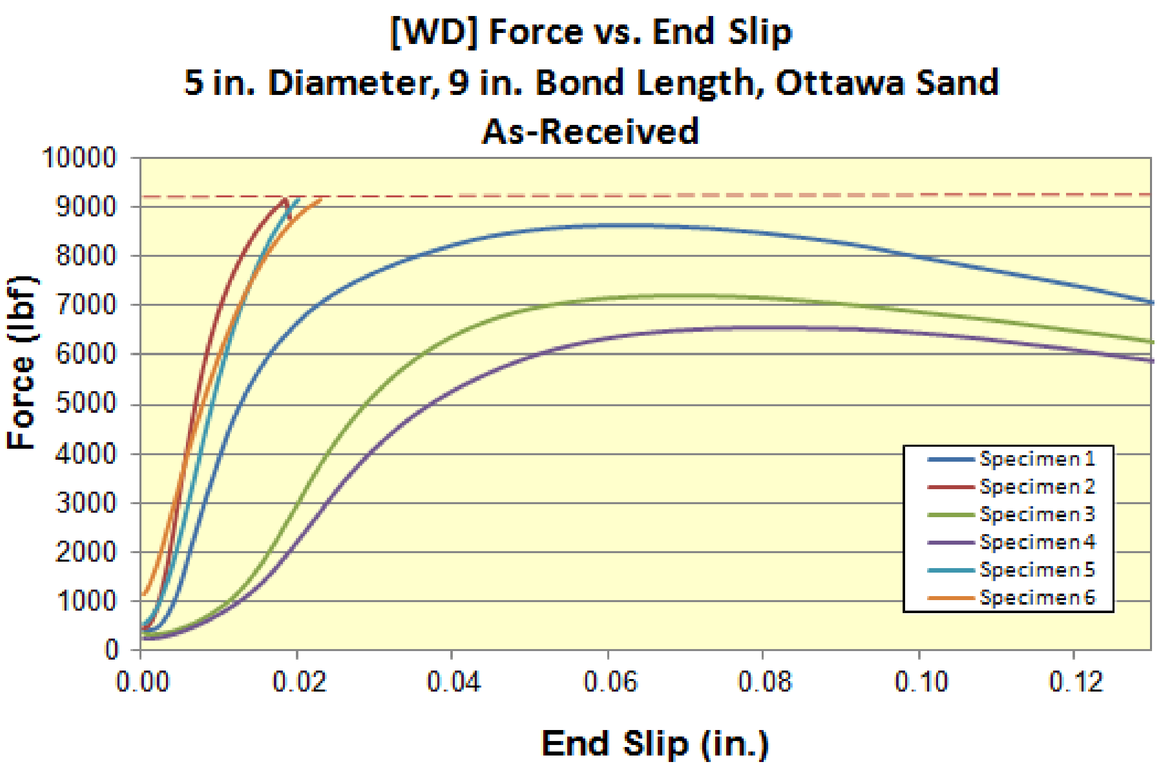

Figure B-16. Ottawa sand [WD] force vs. end-slip individual graphs

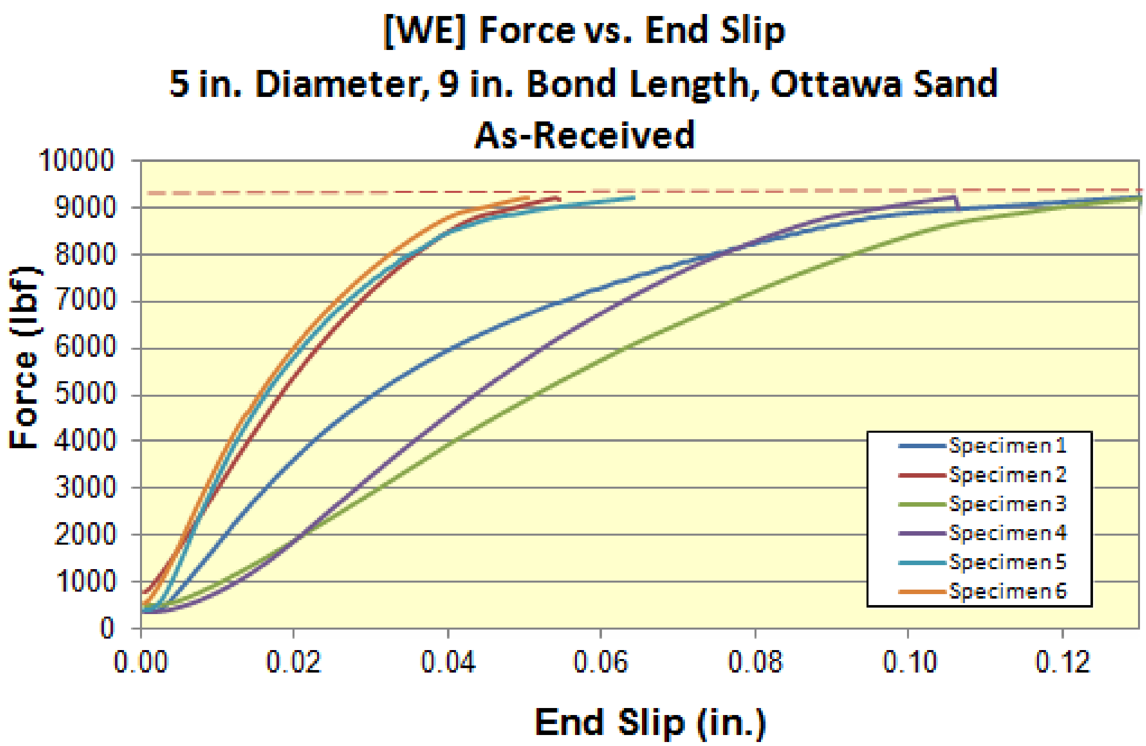

Figure B-17. Ottawa sand [WE] force vs. end-slip individual graphs

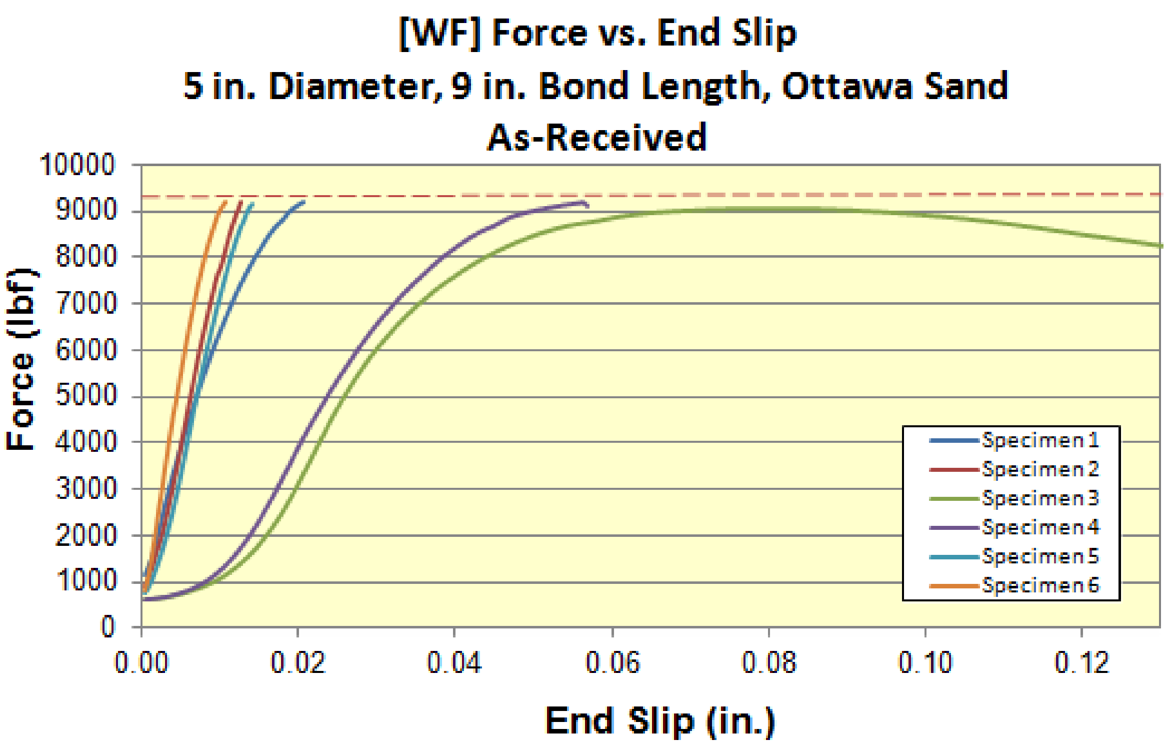

Figure B-18. Ottawa sand [WF] force vs. end-slip individual graphs

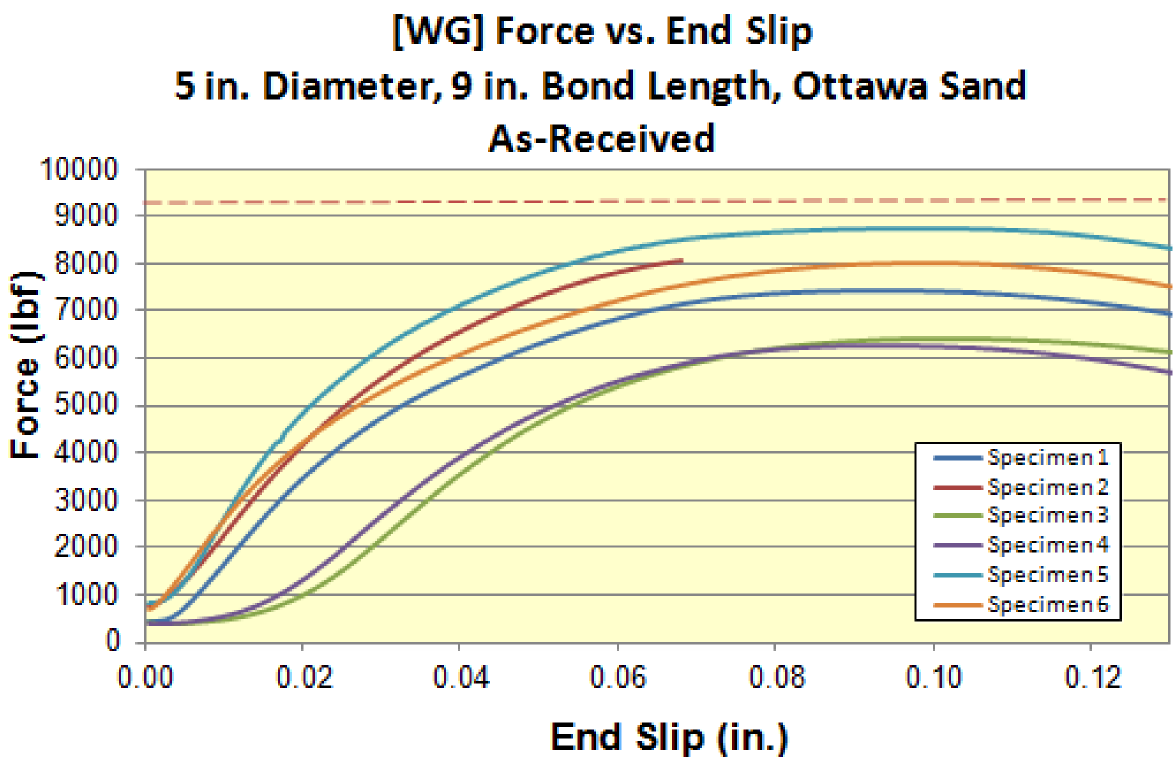

Figure B-19. Ottawa sand [WG] force vs. end-slip individual graphs

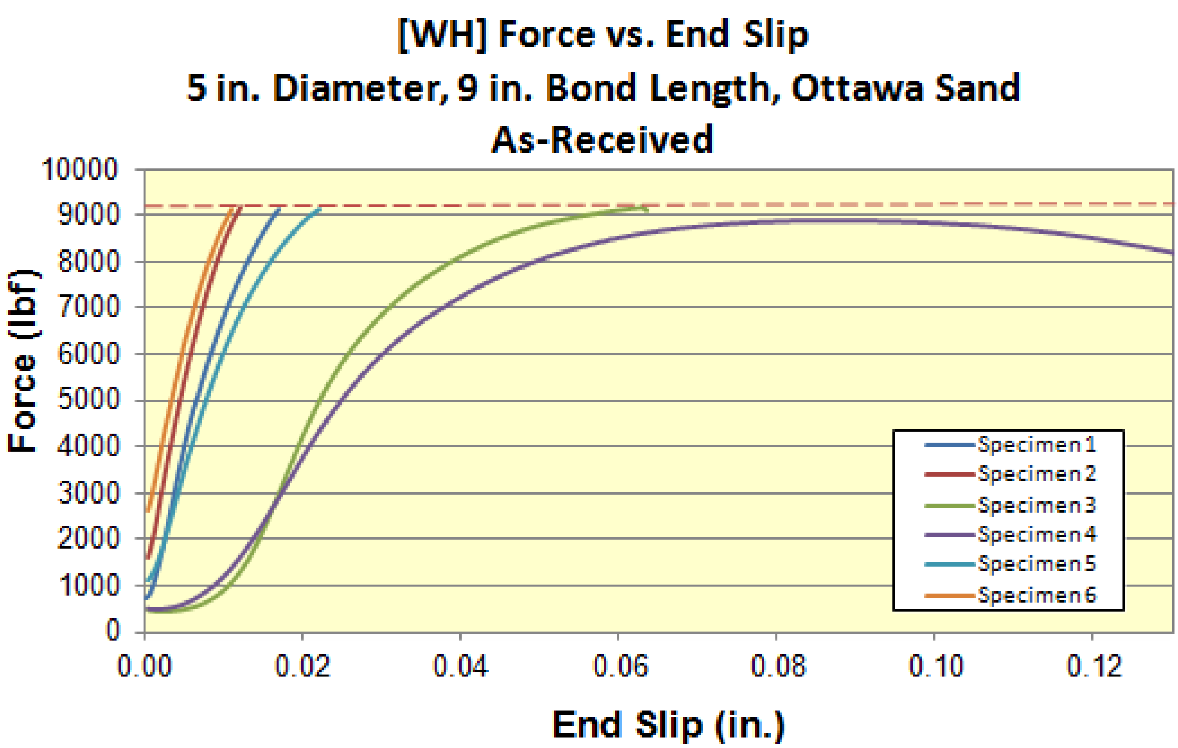

Figure B-20. Ottawa sand [WH] force vs. end-slip individual graphs

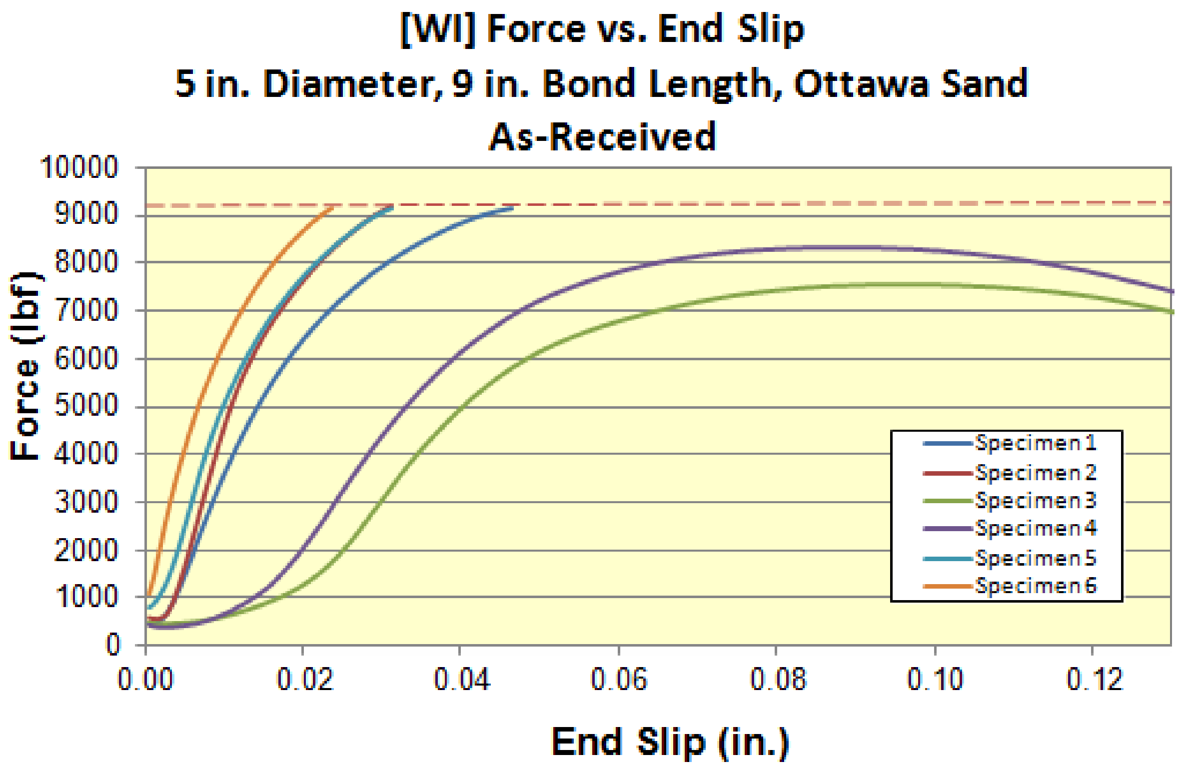

Figure B-21. Ottawa sand [WI] force vs. end-slip individual graphs

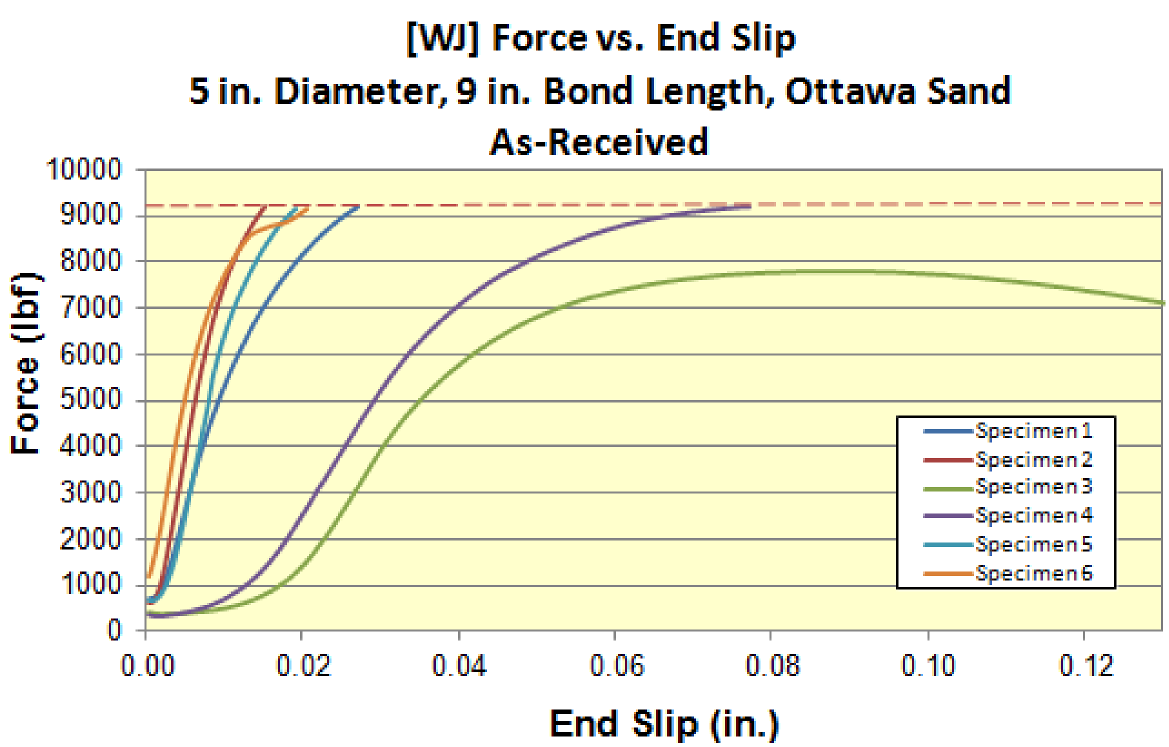

Figure B-22. Ottawa sand [WJ] force vs. end-slip individual graphs

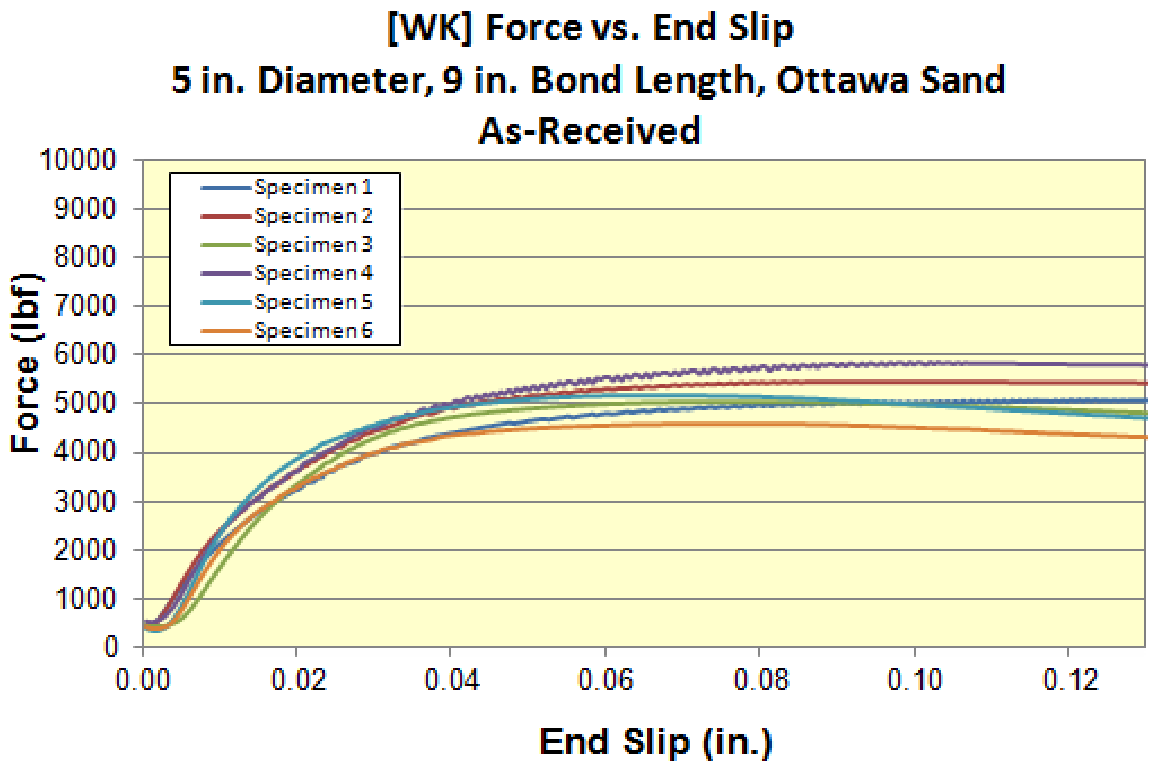

Figure B-23. Ottawa sand [WK] force vs. end-slip individual graphs

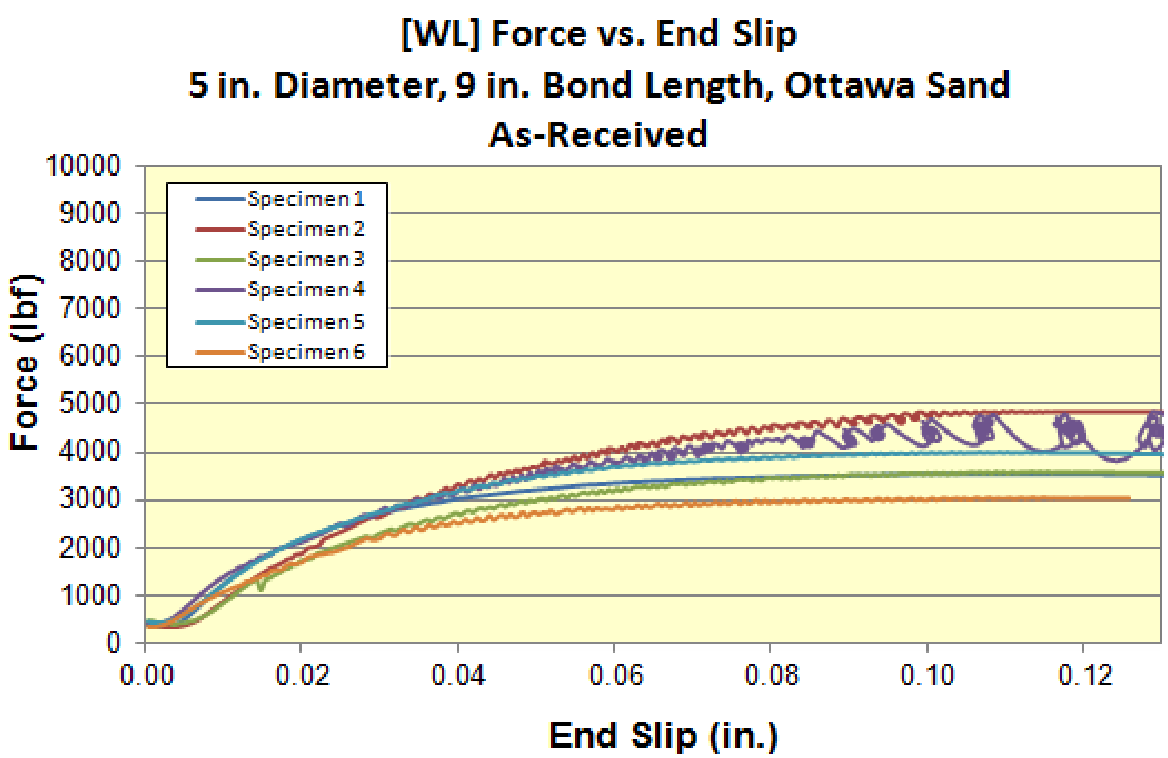

Figure B-24. Ottawa sand [WL] force vs. end-slip individual graphs

Appendix C.
Wire Test Development Force at Certain End-slips Analysis

Table C-1. Test development analysis, pullout force at 0.01-in. end slip (Midwest sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Midwest Sand Pullout Force at 0.01 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	282	43	15.3	16.3
[WB]	3243	510	15.7	11.6
[WC]	1830	402	22.0	8.8
[WD]	2674	1668	62.4	11.1
[WE]	1582	930	58.8	7.4
[WF]	4800	784	16.3	8.5
[WG]	1143	815	71.3	11.8
[WH]	3531	2262	64.1	7.5
[WI]	2480	337	13.6	10.1
[WJ]	3807	1745	45.8	9.0
[WK]	944	138	14.6	14.0
[WL]	688	108	15.6	18.7

Note: Sample Size = 6

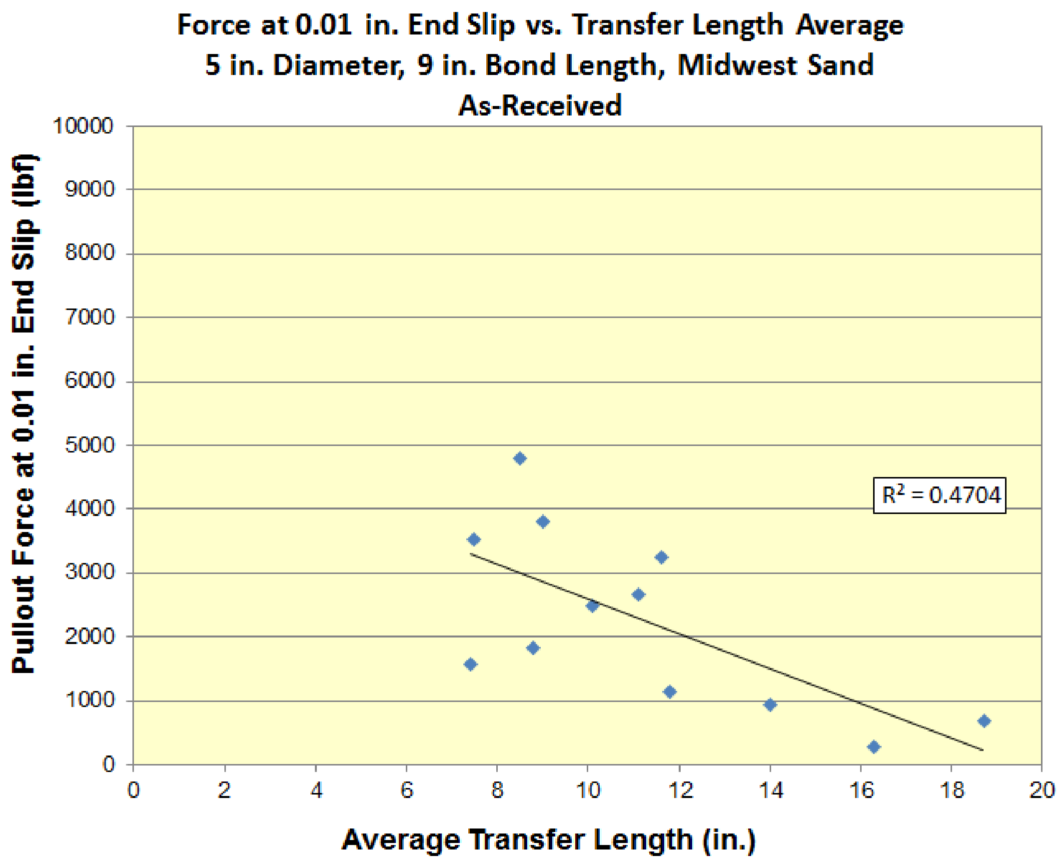

Figure C-1. Test development analysis, pullout force at 0.01-in. end slip (Midwest sand)

Table C-2. Test development analysis, pullout force at 0.02-in. end slip (Midwest sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Midwest Sand Pullout Force at 0.02 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	229	26	11.5	16.3
[WB]	5952	307	5.2	11.6
[WC]	2752	603	21.9	8.8
[WD]	5607	1742	31.1	11.1
[WE]	3504	1256	35.9	7.4
[WF]	8499	438	5.2	8.5
[WG]	2176	1227	56.4	11.8
[WH]	4119	2367	57.5	7.5
[WI]	5253	447	8.5	10.1
[WJ]	6438	1336	20.7	9.0
[WK]	2186	241	11.0	14.0
[WL]	1402	200	14.3	18.7

Note: Sample Size = 6, J = 5

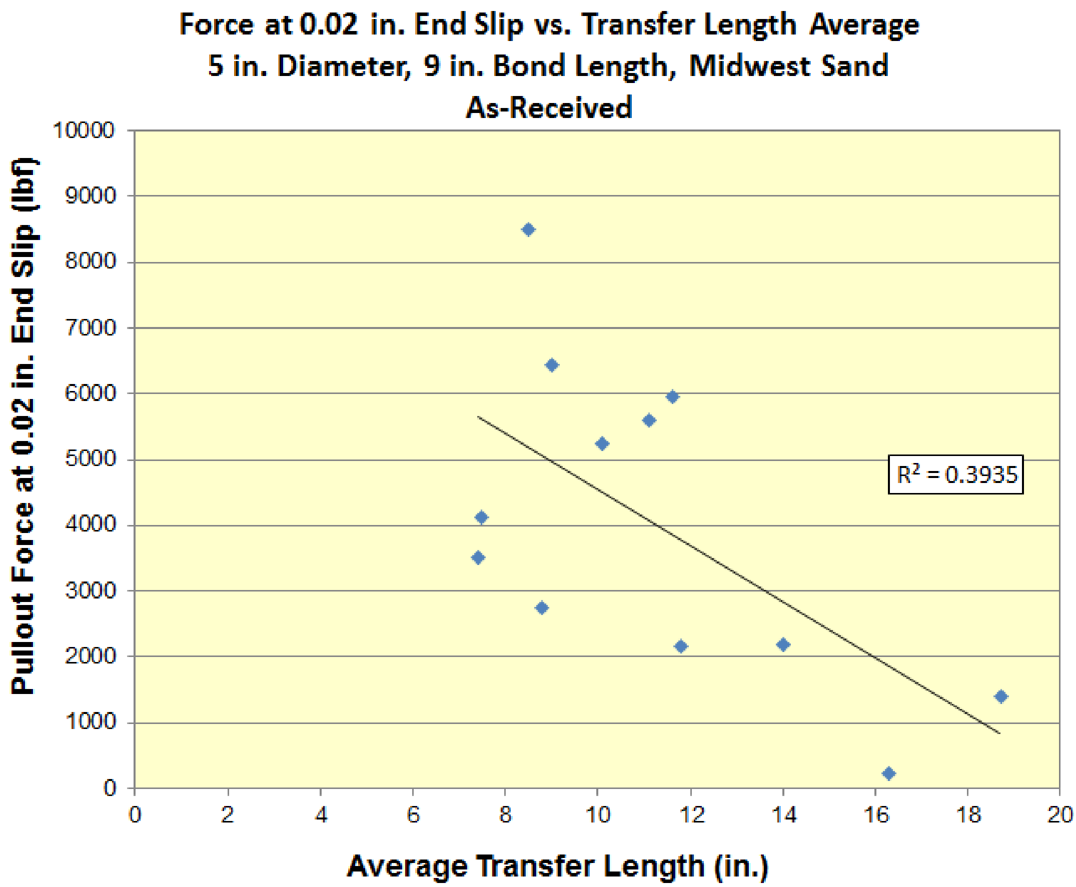

Figure C-2. Test development analysis, pullout force at 0.02-in. end slip (Midwest sand)

Table C-3. Test development analysis, pullout force at 0.03-in. end slip (Midwest sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Midwest Sand Pullout Force at 0.03 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	208	21	10.0	16.3
[WB]	7129	274	3.8	11.6
[WC]	3405	786	23.1	8.8
[WD]	6386	2598	40.7	11.1
[WE]	5091	1361	26.7	7.4
[WF]	9155	15	0.2	8.5
[WG]	3410	1325	38.9	11.8
[WH]	5809	3236	55.7	7.5
[WI]	6853	460	6.7	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	2880	258	9.0	14.0
[WL]	1946	239	12.3	18.7

Note: Sample Size = 6, D = 5, F = 2, H = 4, J = 5

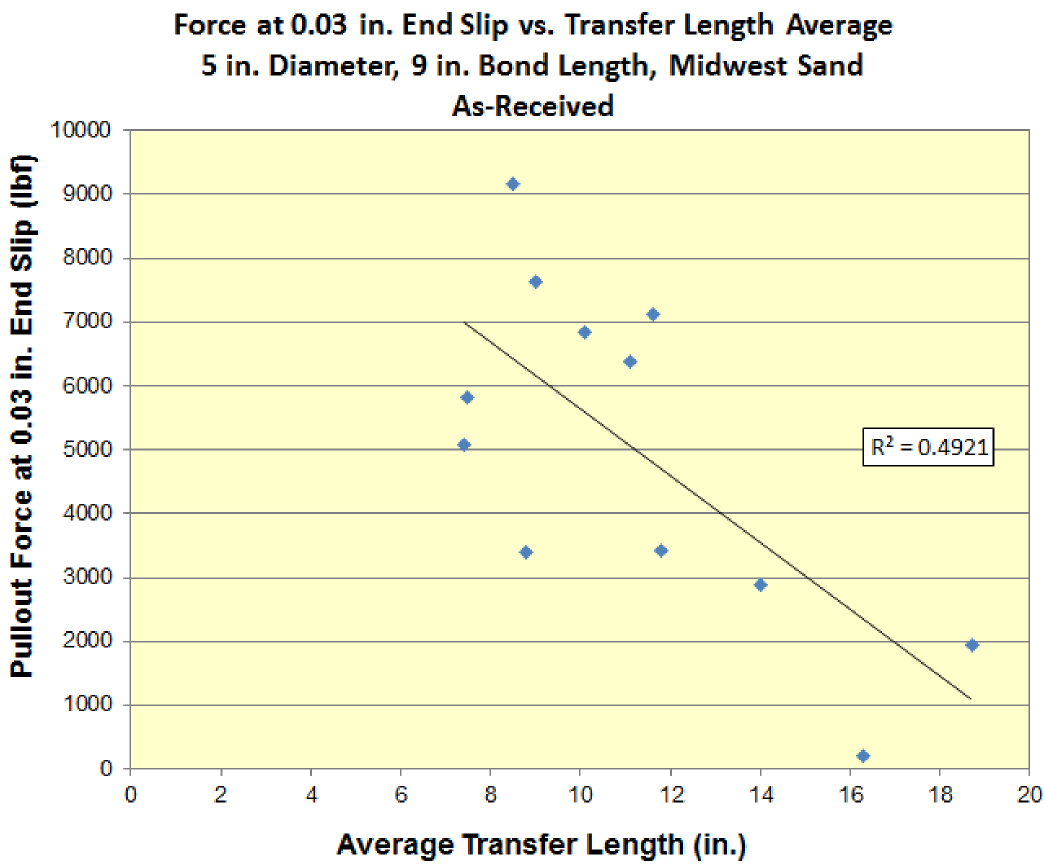

Figure C-3. Test development analysis, pullout force at 0.03-in. end slip (Midwest sand)

Table C-4. Test development analysis, pullout force at 0.04-in. end slip (Midwest sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Midwest Sand Pullout Force at 0.04 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	200	19	9.7	16.3
[WB]	7782	217	2.8	11.6
[WC]	3978	960	24.1	8.8
[WD]	6961	786	11.3	11.1
[WE]	6341	1466	23.1	7.4
[WF]				
[WG]	4578	1305	28.5	11.8
[WH]	6920	728	10.5	7.5
[WI]	7791	429	5.5	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	3436	269	7.8	14.0
[WL]	2324	298	12.8	18.7

Note: Sample Size = 6, D = 5, F = 0, H = 4, J = 5

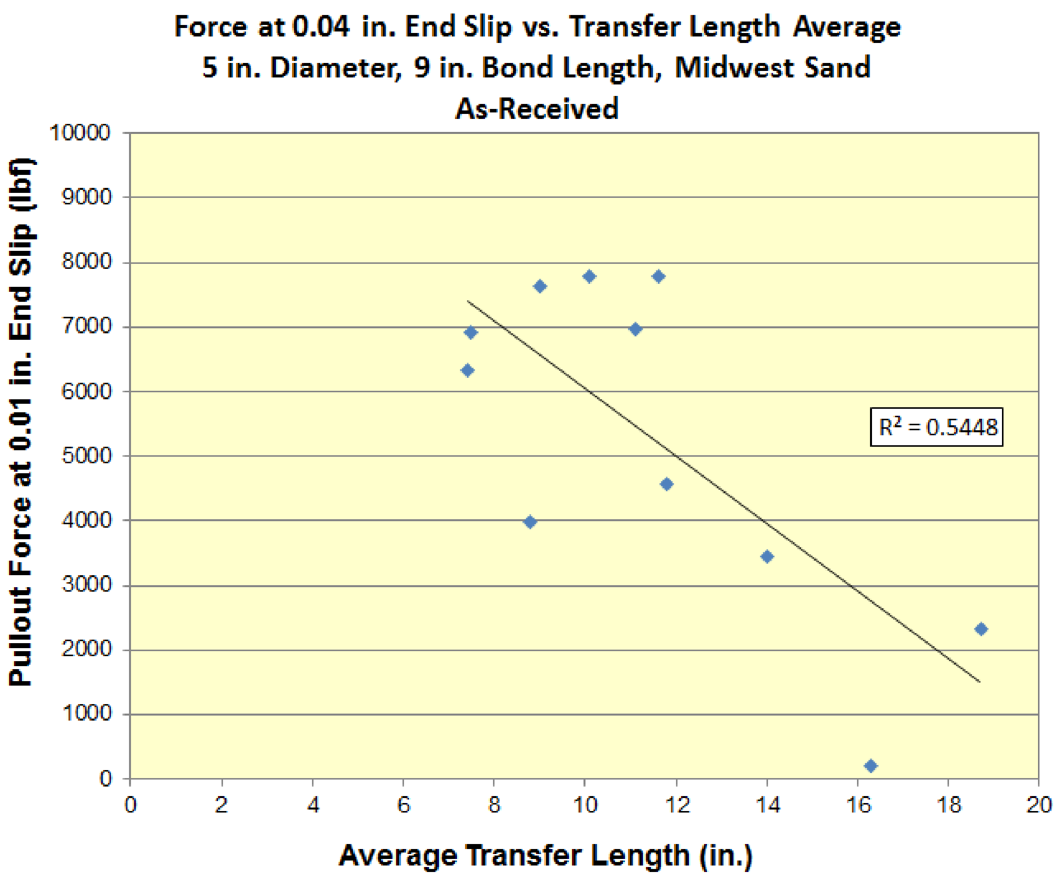

Figure C-4. Test development analysis, pullout force at 0.04-in. end slip (Midwest sand)

Table C-5. Test development analysis, pullout force at 0.05-in. end slip (Midwest sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Midwest Sand Pullout Force at 0.05 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	200	20	9.9	16.3
[WB]	8153	166	2.0	11.6
[WC]	4521	1117	24.7	8.8
[WD]	7182	688	9.6	11.1
[WE]	7274	1448	19.9	7.4
[WF]				
[WG]	5547	1190	21.5	11.8
[WH]	7588	713	9.4	7.5
[WI]	8287	416	5.0	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	3802	279	7.3	14.0
[WL]	2636	326	12.4	18.7

Note: Sample Size = 6, D = 5, F = 0, H = 4, J = 5

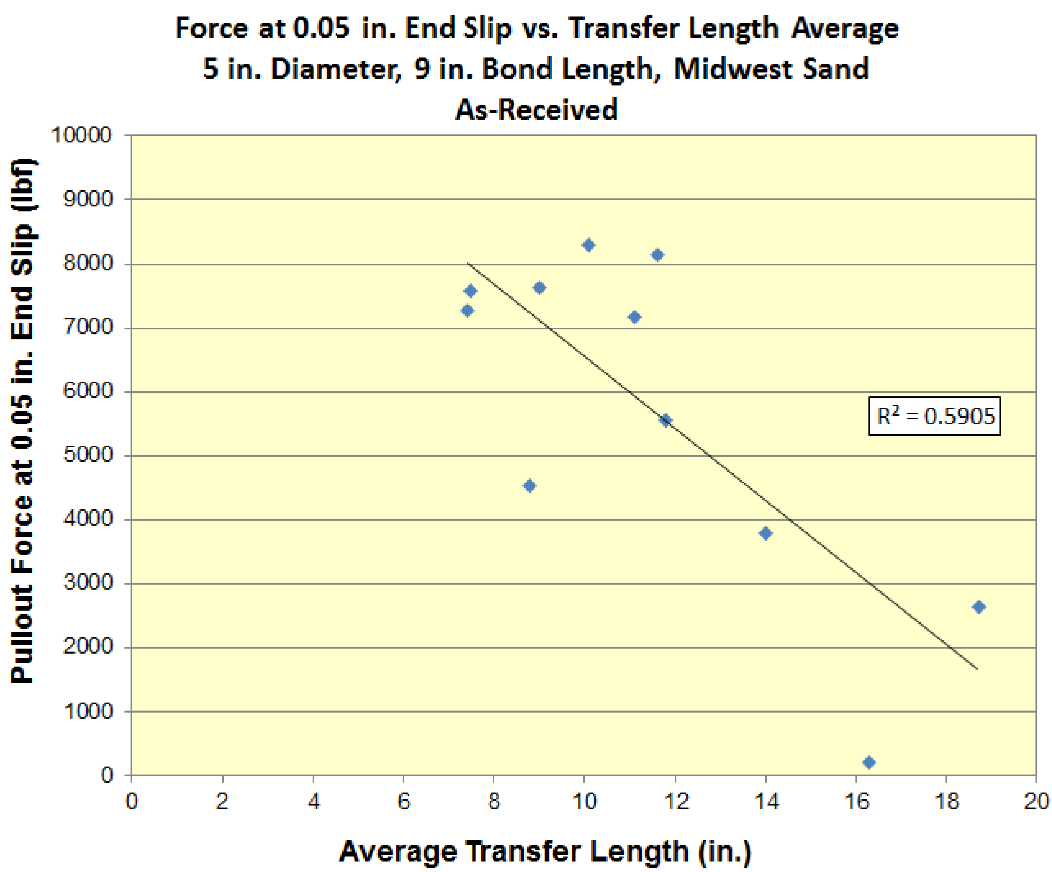

Figure C-5. Test development analysis, pullout force at 0.05-in. end slip (Midwest sand)

Table C-6. Test development analysis, pullout force at 0.06-in. end slip (Midwest sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Midwest Sand Pullout Force at 0.06 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	204	20	10.0	16.3
[WB]	8353	134	1.6	11.6
[WC]	5053	1263	25.0	8.8
[WD]	7234	633	8.8	11.1
[WE]	7342	1096	14.9	7.4
[WF]				
[WG]	6302	1076	17.1	11.8
[WH]	7954	666	8.4	7.5
[WI]	8493	411	4.8	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	4047	282	7.0	14.0
[WL]	2849	360	12.6	18.7

Note: Sample Size = 6, D = 5, E = 4, F = 0, H = 4, J = 5

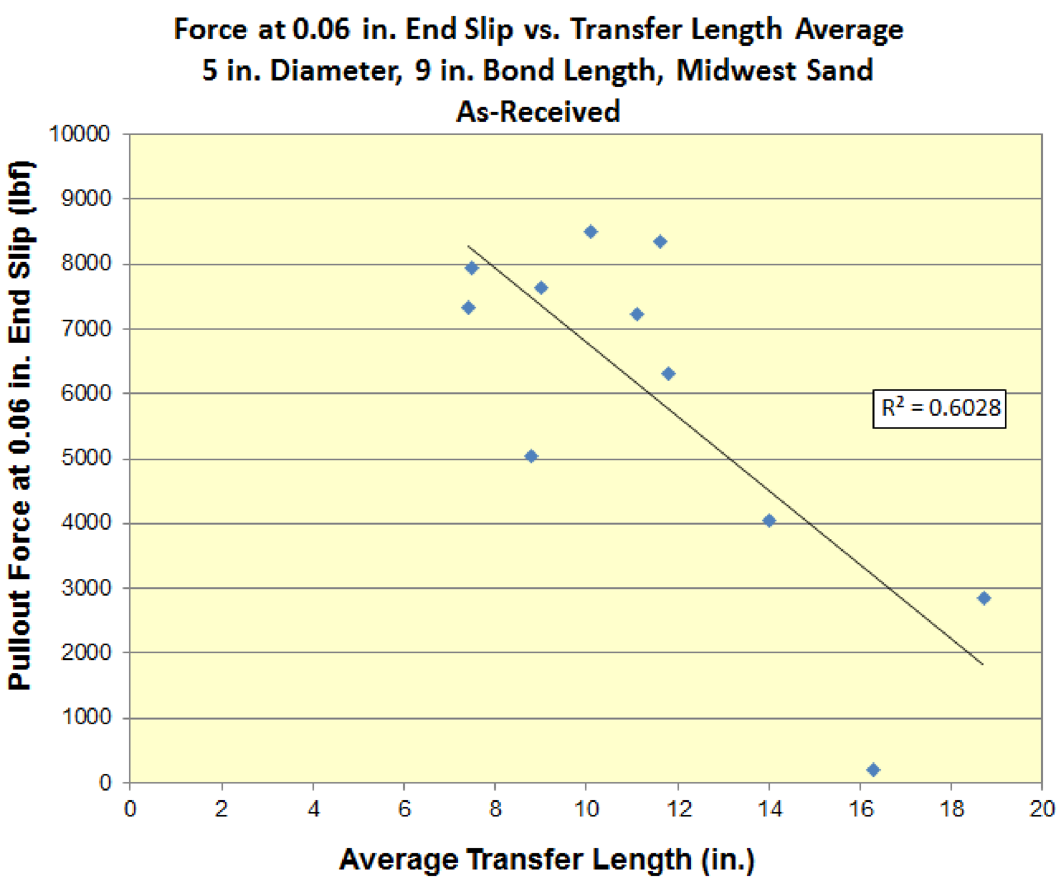

Figure C-6. Test development analysis, pullout force at 0.06-in. end slip (Midwest sand)

Table C-7. Test development analysis, pullout force at 0.07-in. end slip (Midwest sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Midwest Sand Pullout Force at 0.07 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	212	22	10.4	16.3
[WB]	8440	114	1.4	11.6
[WC]	5554	1395	25.1	8.8
[WD]	7189	596	8.3	11.1
[WE]	8079	1039	12.9	7.4
[WF]				
[WG]	6801	955	14.0	11.8
[WH]	8118	620	7.6	7.5
[WI]	8545	407	4.8	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	4209	313	7.4	14.0
[WL]	3031	382	12.6	18.7

Note: Sample Size = 6, D = 5, E = 4, F = 0, H = 4, J = 5

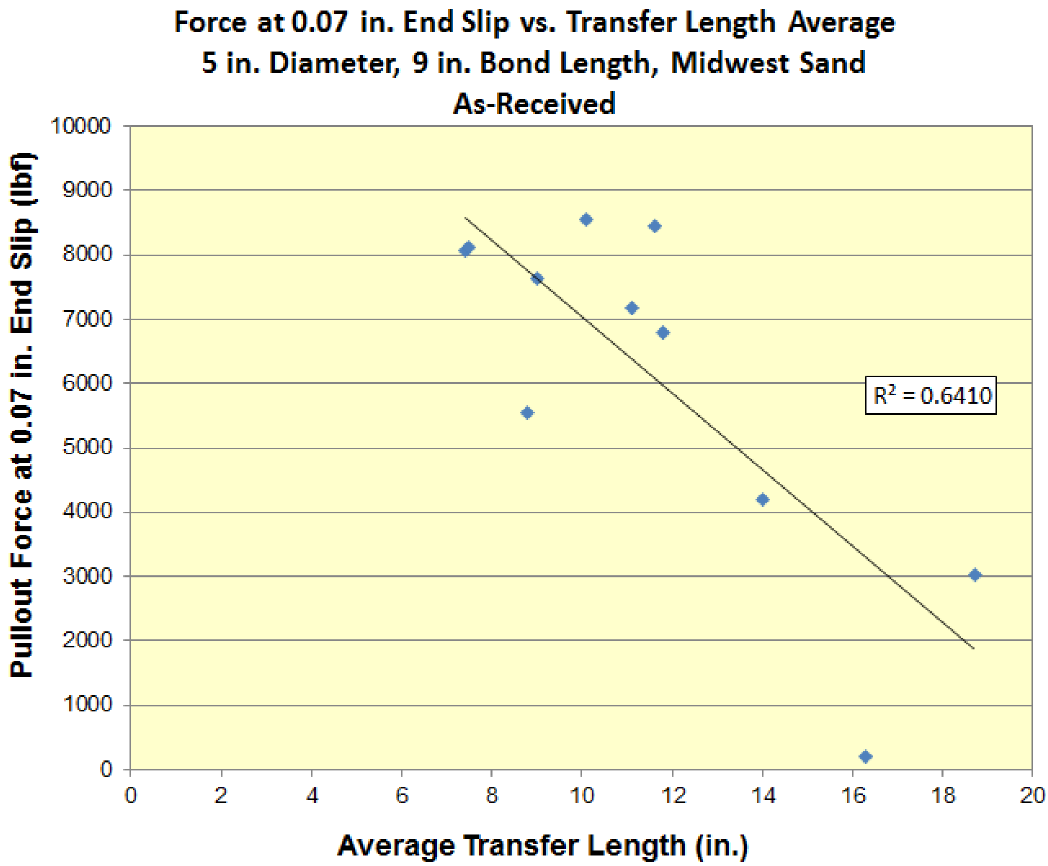

Figure C-7. Test development analysis, pullout force at 0.07-in. end slip (Midwest sand)

Table C-8. Test development analysis, pullout force at 0.08-in. end slip (Midwest sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Midwest Sand Pullout Force at 0.08 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	222	23	10.6	16.3
[WB]	8451	108	1.3	11.6
[WC]	6093	1513	24.8	8.8
[WD]	7070	552	7.8	11.1
[WE]	8365	873	10.4	7.4
[WF]				
[WG]	7122	871	12.2	11.8
[WH]	8464	322	3.8	7.5
[WI]	8501	404	4.7	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	4373	303	6.9	14.0
[WL]	3155	372	11.8	18.7

Note: Sample Size = 6, D = 5, E = 3, F = 0, H = 3, J = 5

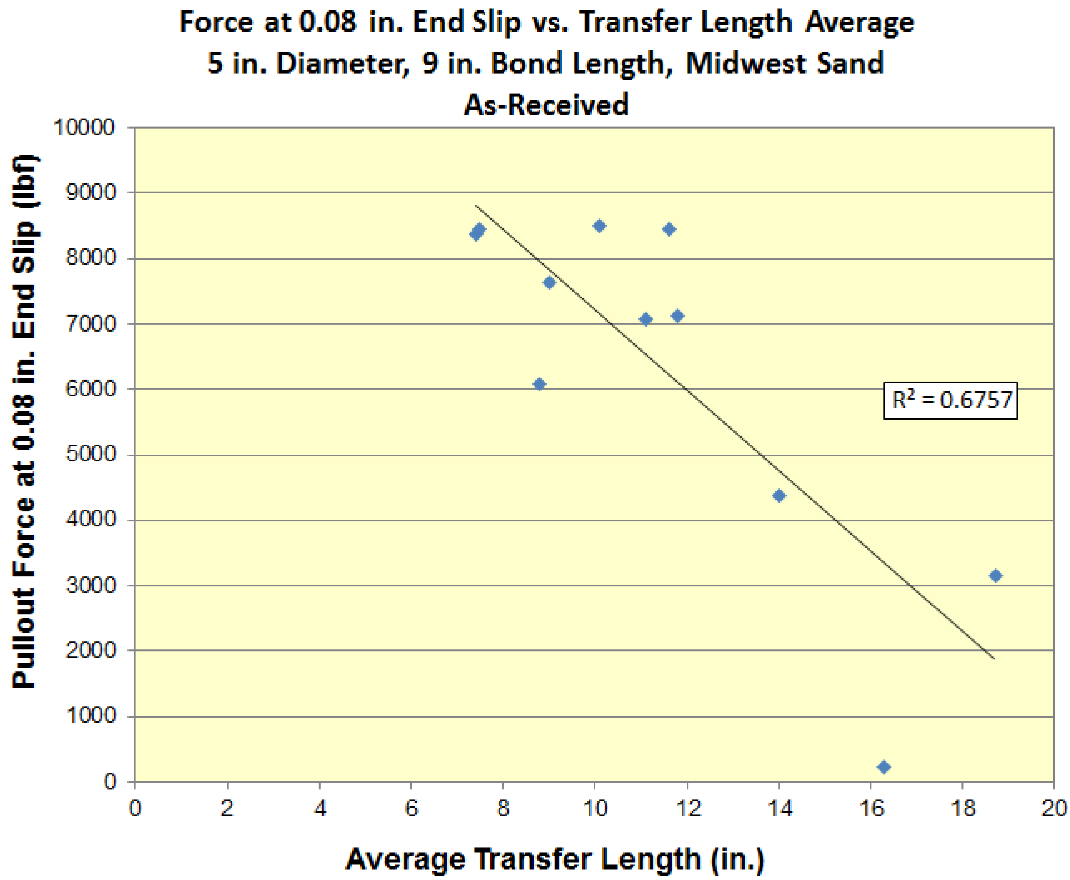

Figure C-8. Test development analysis, pullout force at 0.08-in. end slip (Midwest sand)

Table C-9. Test development analysis, pullout force at 0.09-in. end slip (Midwest sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Midwest Sand Pullout Force at 0.09 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	234	26	10.9	16.3
[WB]	8392	102	1.2	11.6
[WC]	6643	1613	24.3	8.8
[WD]	6889	510	7.4	11.1
[WE]	8468	585	6.9	7.4
[WF]				
[WG]	7254	820	11.3	11.8
[WH]	8414	297	3.5	7.5
[WI]	8370	398	4.8	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	4471	319	7.1	14.0
[WL]	3292	348	10.6	18.7

Note: Sample Size = 6, D = 5, E = 1, F = 0, H = 3, J = 5

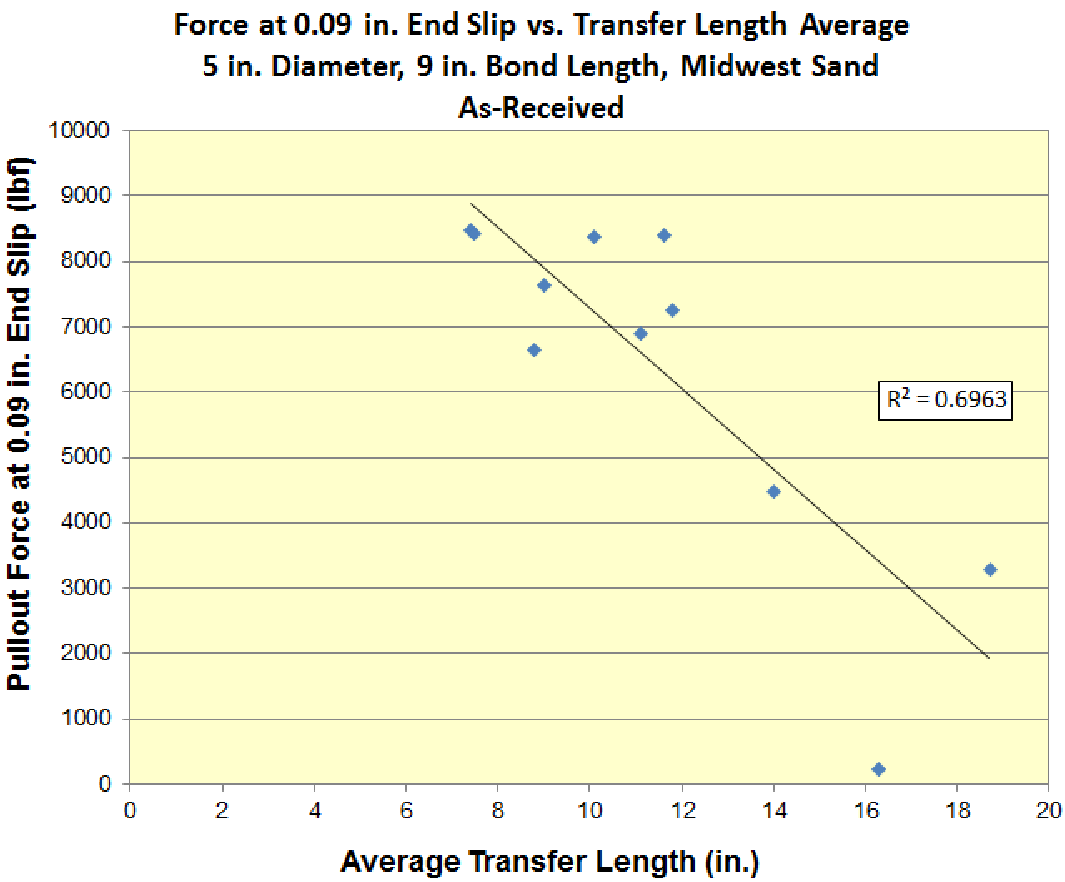

Figure C-9. Test development analysis, pullout force at 0.09-in. end slip (Midwest sand)

Table C-10. Test development analysis, pullout force at 0.10-in. end slip (Midwest sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Midwest Sand Pullout Force at 0.10 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	248	27	10.8	16.3
[WB]	8242	95	1.1	11.6
[WC]	7197	1679	23.3	8.8
[WD]	6652	473	7.1	11.1
[WE]	8497	0	0.0	7.4
[WF]				
[WG]	7276	797	10.9	11.8
[WH]	8252	254	3.1	7.5
[WI]	8122	393	4.8	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	4524	310	6.8	14.0
[WL]	3354	351	10.5	18.7

Note: Sample Size = 6, D = 5, E = 1, F = 0, H = 3, J = 5

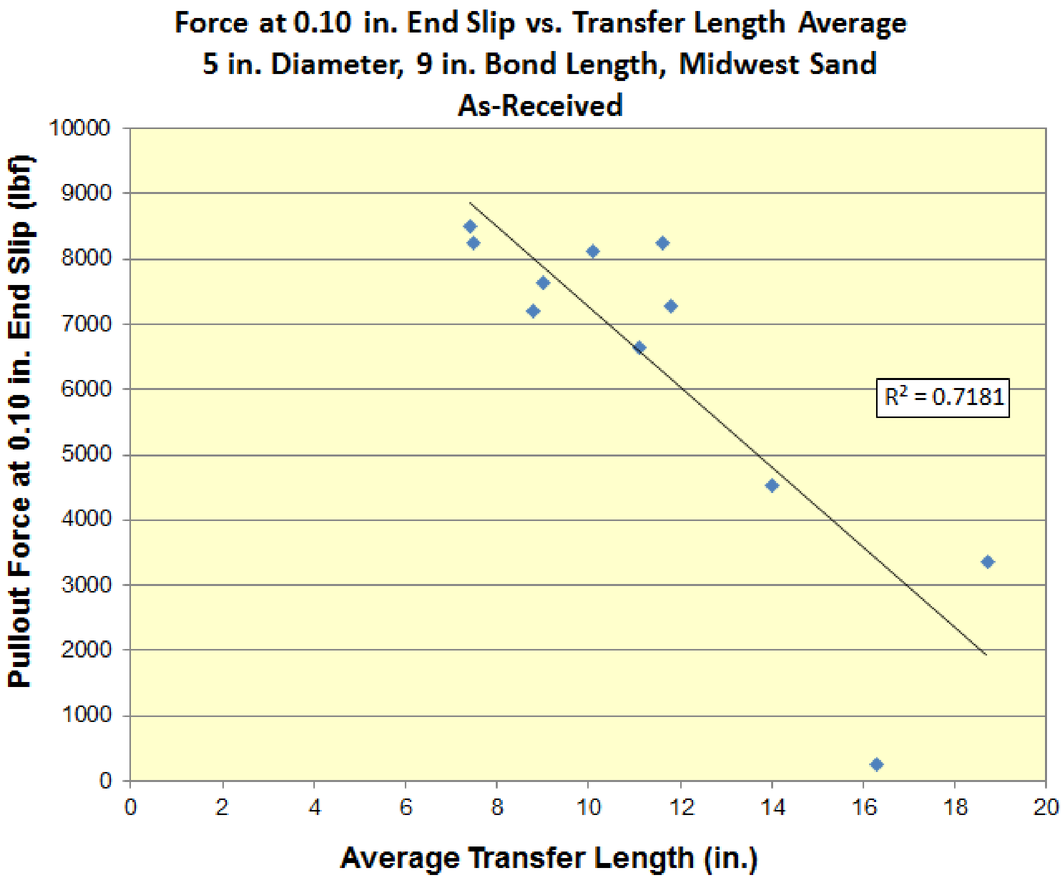

Figure C-10. Test development analysis, pullout force at 0.10-in. end slip (Midwest sand)

Table C-11. Test development analysis, pullout force at 0.11-in. end slip (Midwest sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Midwest Sand Pullout Force at 0.11 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	265	28	10.6	16.3
[WB]	7995	88	1.1	11.6
[WC]	7361	1610	21.9	8.8
[WD]	6369	437	6.9	11.1
[WE]	8898	0	0.0	7.4
[WG]	7208	770	10.7	11.8
[WH]	7996	212	2.6	7.5
[WI]	7798	389	5.0	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	4565	306	6.7	14.0
[WL]	3352	352	10.5	18.7

Note: Sample Size = 6, C = 5, D = 5, E = 1, F = 0, H = 3, J = 5

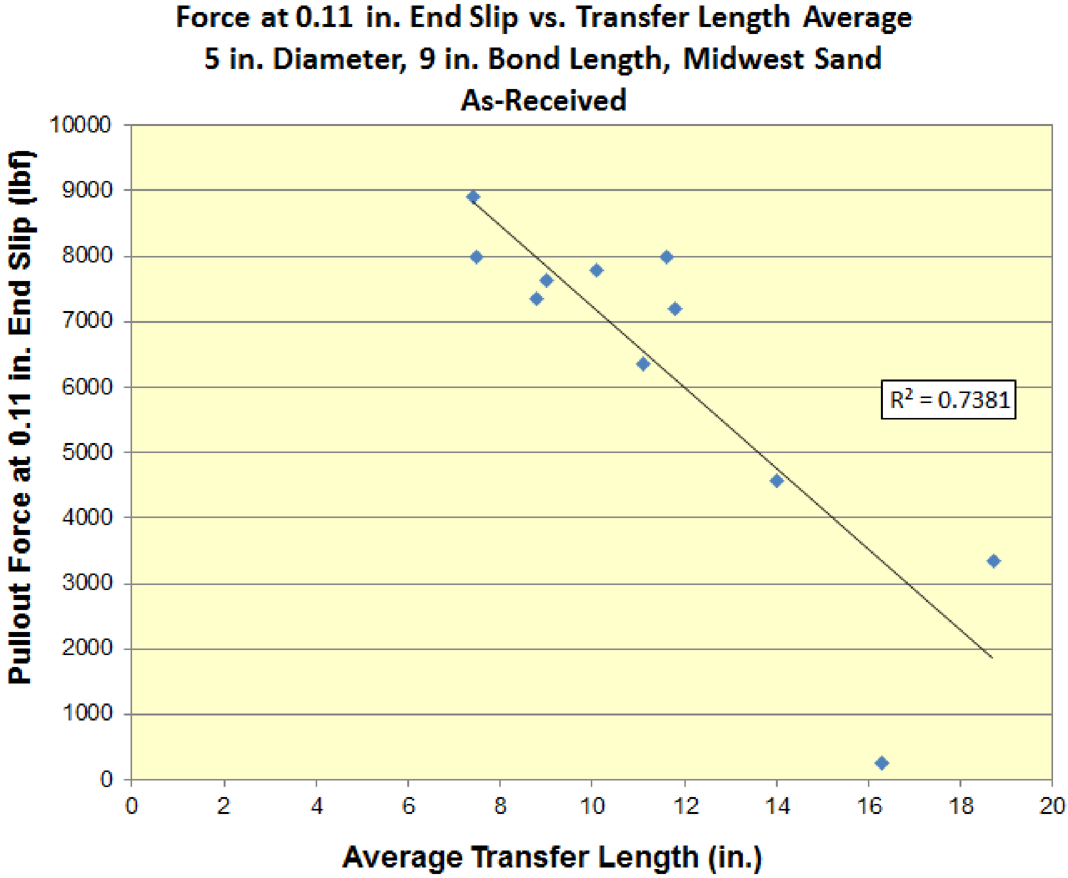

Figure C-11. Test development analysis, pullout force at 0.11-in. end slip (Midwest sand)

Table C-12. Test development analysis, pullout force at 0.12-in. end slip (Midwest sand)

As-Received Pullout Test Results

5 in. Diameter, 9 in. Bond Length, Midwest Sand Pullout Force at 0.12 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	283	29	10.1	16.3
[WB]	7676	69	0.9	11.6
[WC]	6767	1073	15.9	8.8
[WD]	6065	401	6.6	11.1
[WE]	9046	0	0.0	7.4
[WF]				
[WG]	7046	735	10.4	11.8
[WH]	7666	179	2.3	7.5
[WI]	7393	434	5.9	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	4614	316	6.8	14.0
[WL]	3386	356	10.5	18.7

Note: Sample Size = 6, C = 3, D = 5, E = 1, F = 0, H = 3, I = 5, J = 5

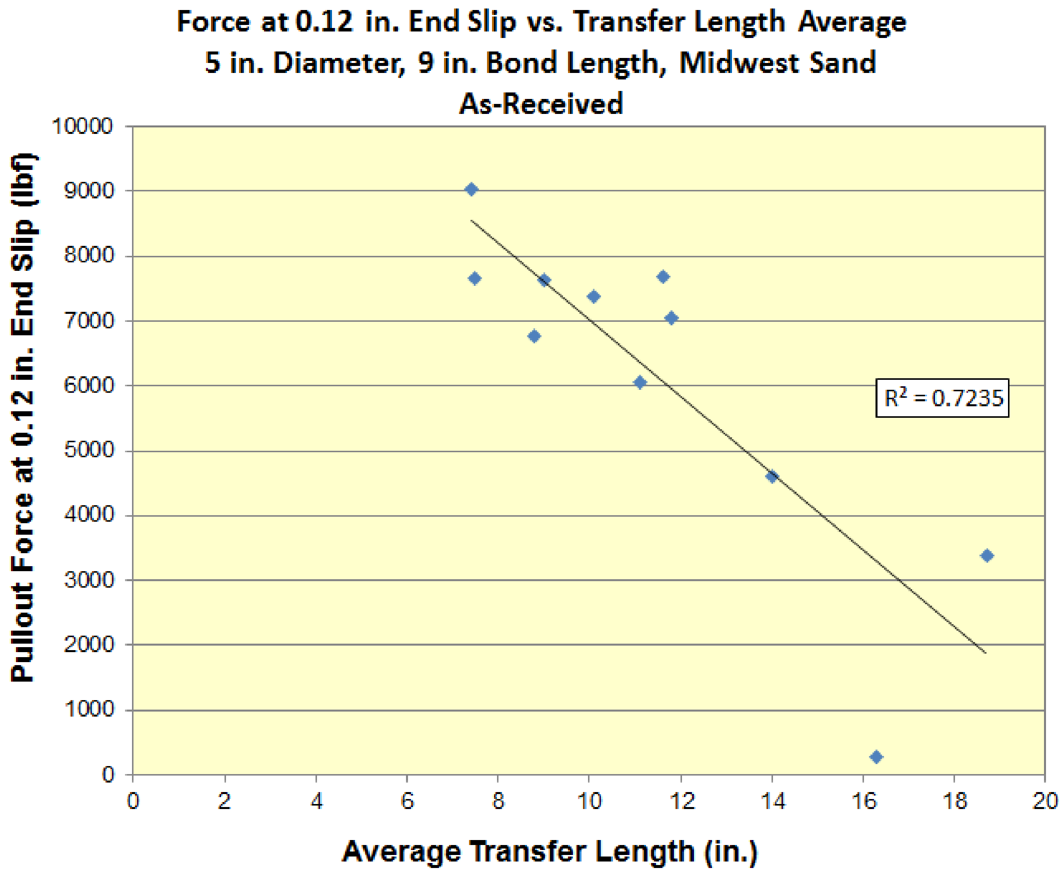

Figure C-12. Test development analysis, pullout force at 0.12-in. end slip (Midwest sand)

Table C-13. Test development analysis, pullout force at 0.13-in. end slip (Midwest sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Midwest Sand

Pullout Force at 0.13 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	301	29	9.5	16.3
[WB]	7278	52	0.7	11.6
[WC]	7313	1126	15.4	8.8
[WD]	5735	358	6.2	11.1
[WE]				
[WF]				
[WG]	6771	689	10.2	11.8
[WH]	6960	621	8.9	7.5
[WI]	6371	1130	17.7	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	4648	321	6.9	14.0
[WL]	3392	370	10.9	18.7

Note: Sample Size = 6, C = 3, D = 5, E = 0, F = 0, H = 3, I = 5, J = 5

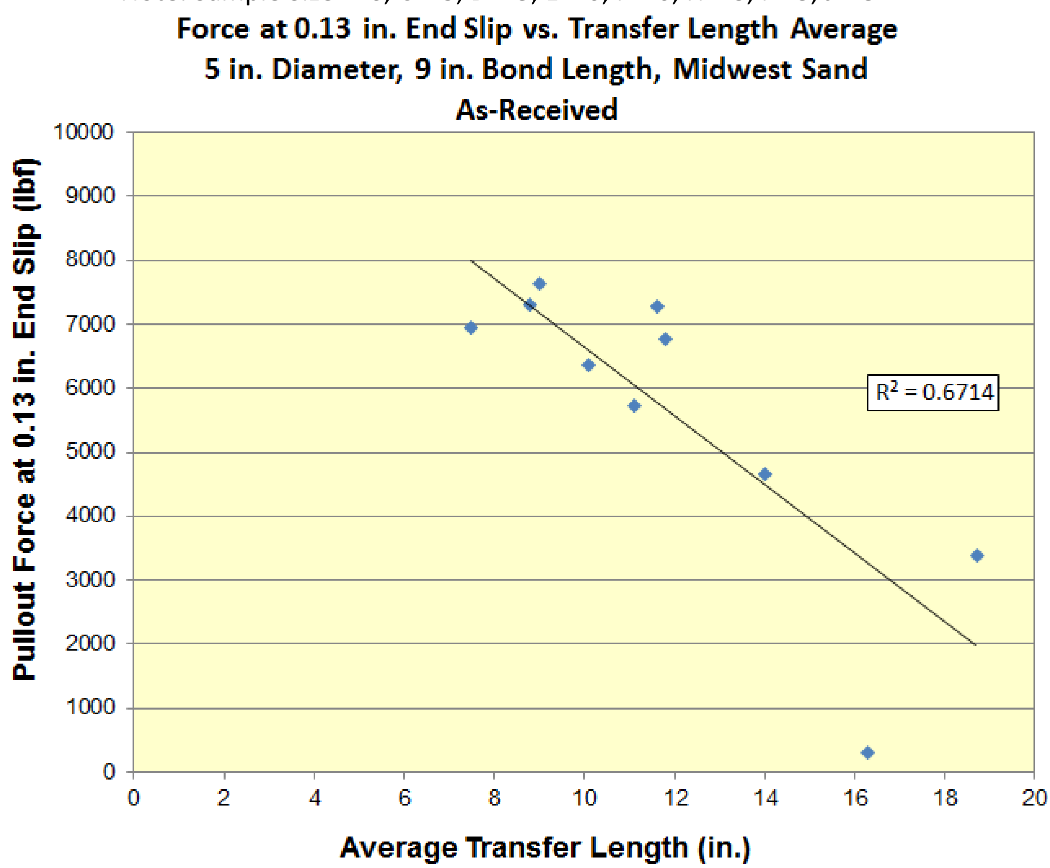

Figure C-13. Test development analysis, pullout force at 0.13-in. end slip (Midwest sand)

Table C-14. Test development analysis, maximum pullout force (Midwest sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Midwest Sand Maximum Pullout Force

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	452	65	14.3	16.3
[WB]	8463	114	1.3	11.6
[WC]	7172	1675	23.4	8.8
[WD]	7573	922	12.2	11.1
[WE]	9115	284	3.1	7.4
[WF]	9228	78	0.8	8.5
[WG]	7289	801	11.0	11.8
[WH]	8496	678	8.0	7.5
[WI]	8547	407	4.8	10.1
[WJ]	8973	492	5.5	9.0
[WK]	4557	316	6.9	14.0
[WL]	3362	355	10.6	18.7

Note: Sample Size = 6

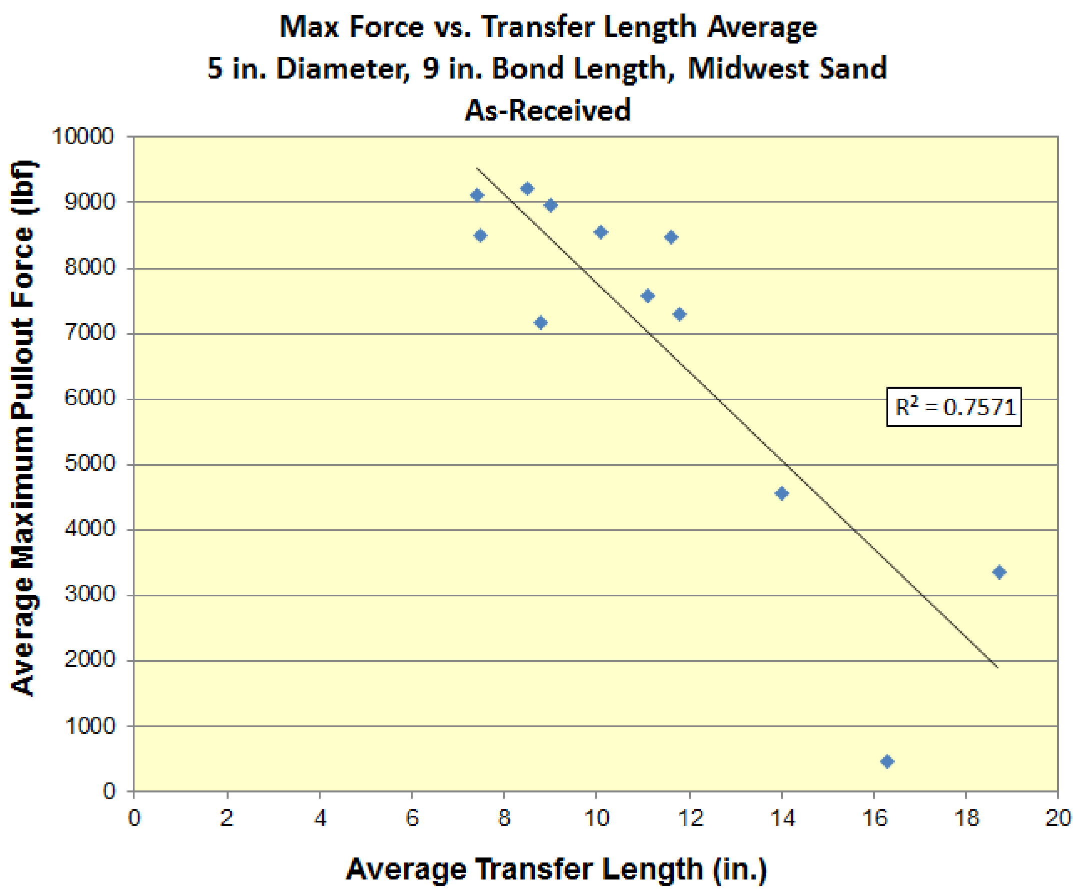

Figure C-14. Test development analysis, maximum pullout force (Midwest sand)

Table C-15. Test development analysis, pullout force at 0.01-in. end slip (Ottawa sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Ottawa Sand

Pullout Force at 0.01 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	334	83	24.7	16.3
[WB]	3592	2124	59.1	11.6
[WC]	1991	787	39.5	8.8
[WD]	3788	2332	61.6	11.1
[WE]	2135	1040	48.7	7.4
[WF]	5301	3087	58.2	8.5
[WG]	1619	850	52.5	11.8
[WH]	5199	3121	60.0	7.5
[WI]	3353	2096	62.5	10.1
[WJ]	4522	2917	64.5	9.0
[WK]	2058	271	13.1	14.0
[WL]	1064	185	17.4	18.7

Note: Sample Size = 6

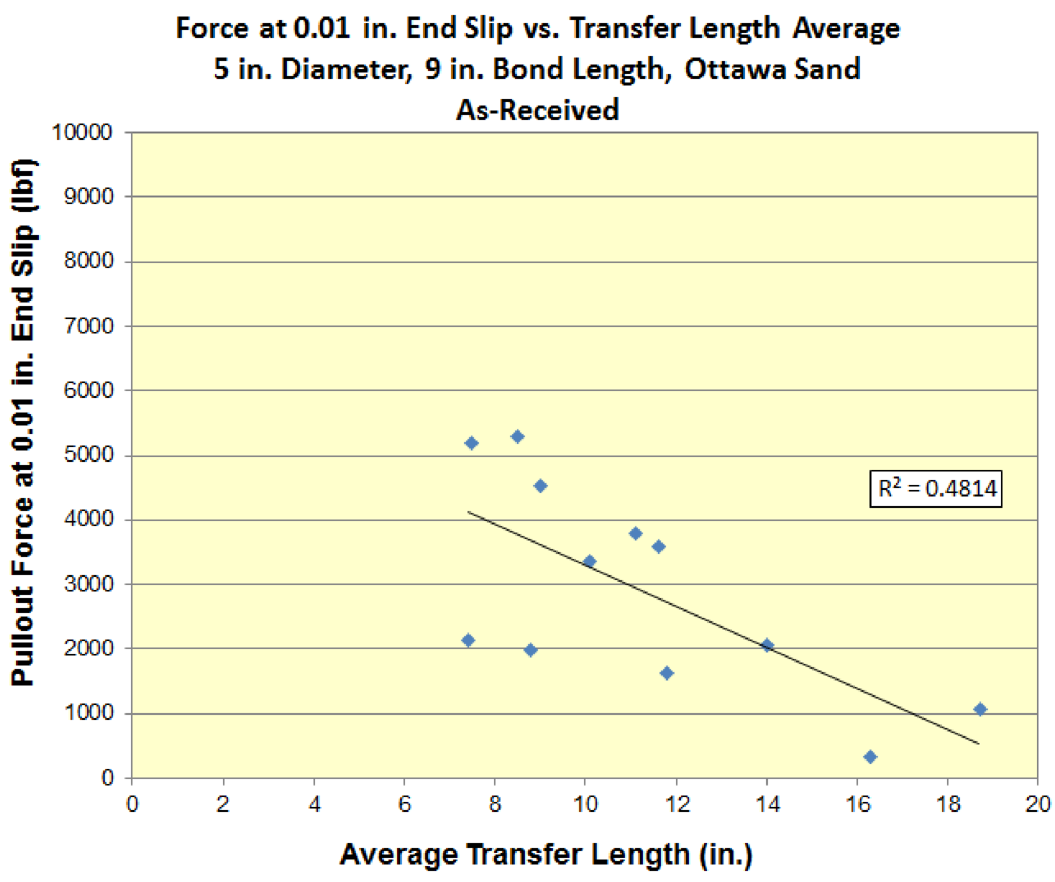

Figure C-15. Test development analysis, pullout force at 0.01-in. end slip (Ottawa sand)

Table C-16. Test development analysis, pullout force at 0.02-in. end slip (Ottawa sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Ottawa Sand

Pullout Force at 0.02 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	299	71	23.8	16.3
[WB]	5688	2139	37.6	11.6
[WC]	3595	1471	40.9	8.8
[WD]	5865	4032	68.8	11.1
[WE]	4056	1732	42.7	7.4
[WF]	5276	5315	100.7	8.5
[WG]	3119	1469	47.1	11.8
[WH]	5518	2322	42.1	7.5
[WI]	5573	2887	51.8	10.1
[WJ]	5206	3379	64.9	9.0
[WK]	3474	229	6.6	14.0
[WL]	1937	216	11.2	18.7

Note: Sample Size = 6, D = 5, F = 3, H = 3, J = 4

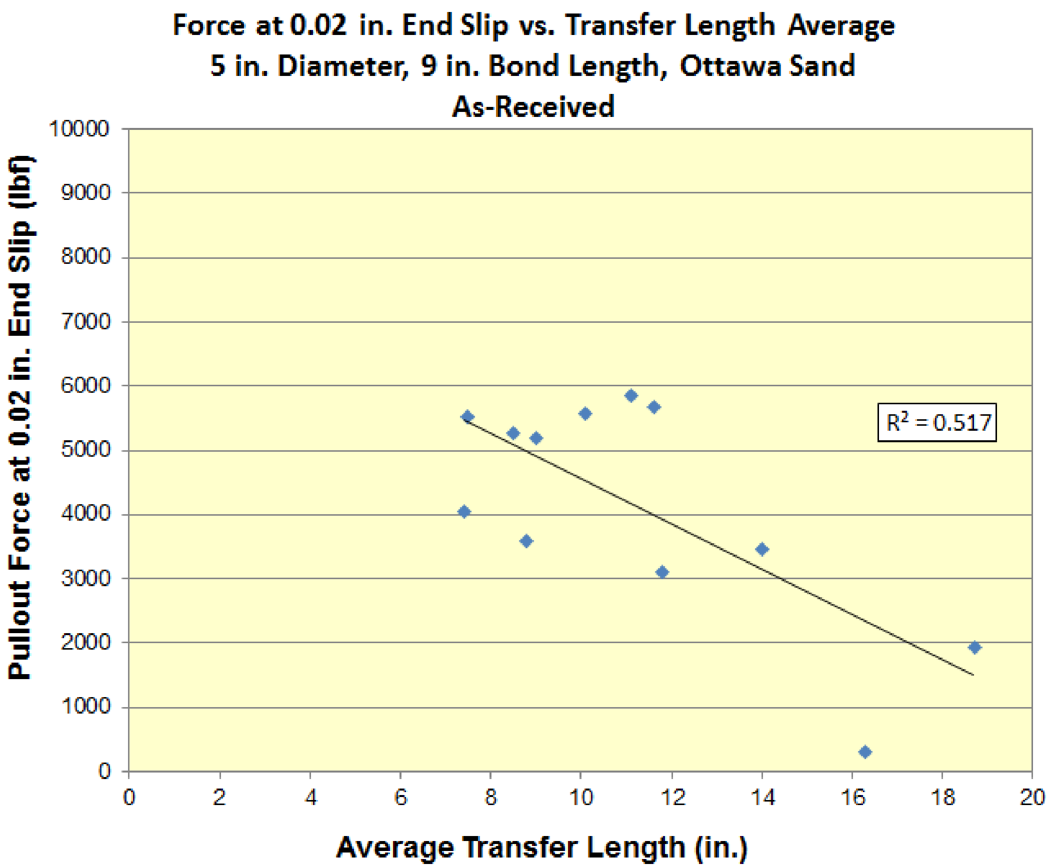

Figure C-16. Test development analysis, pullout force at 0.02-in. end slip (Ottawa sand)

Table C-17. Test development analysis, pullout force at 0.03-in. end slip (Ottawa sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Ottawa Sand

Pullout Force at 0.03 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	296	67	22.6	16.3
[WB]	7012	1481	21.1	11.6
[WC]	4910	1681	34.2	8.8
[WD]	5603	4342	77.5	11.1
[WE]	5550	1968	35.5	7.4
[WF]	6218	267	4.3	8.5
[WG]	4407	1498	34.0	11.8
[WH]	6384	441	6.9	7.5
[WI]	6679	2525	37.8	10.1
[WJ]	4484	648	14.5	9.0
[WK]	4290	231	5.4	14.0
[WL]	2546	230	9.0	18.7

Note: Sample Size = 6, D = 3, F = 2, H = 2, I = 5, J = 2

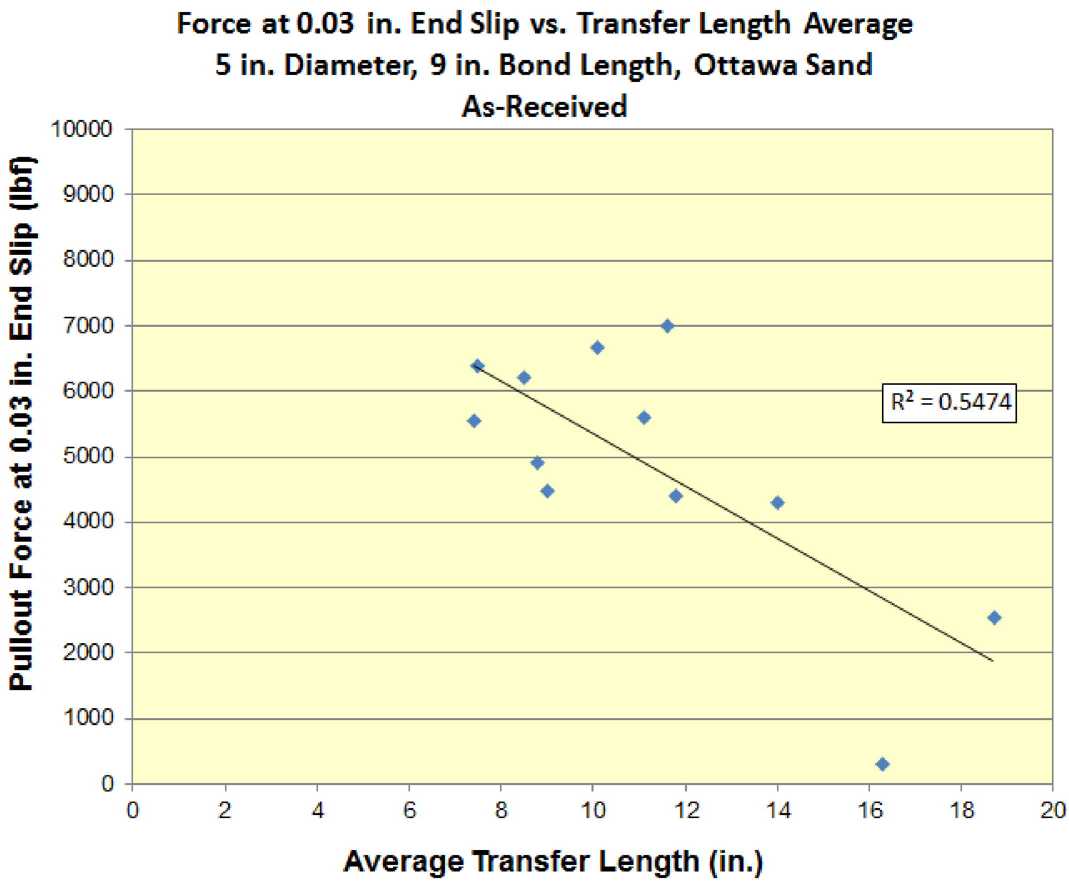

Figure C-17. Test development analysis, pullout force at 0.03-in. end slip (Ottawa sand)

Table C-18. Test development analysis, pullout force at 0.04-in. end slip (Ottawa sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Ottawa Sand

	Pullout Force at 0.04 in. End Slip			
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	307	69	22.5	16.3
[WB]	7621	1039	13.6	11.6
[WC]	5307	806	15.2	8.8
[WD]	6599	1226	18.6	11.1
[WE]	6688	1975	29.5	7.4
[WF]	7876	308	3.9	8.5
[WG]	5457	1323	24.2	11.8
[WH]	7667	449	5.9	7.5
[WI]	6641	1633	24.6	10.1
[WJ]	6392	650	10.2	9.0
[WK]	4717	264	5.6	14.0
[WL]	2983	255	8.5	18.7

Note: Sample Size = 6, C = 5, D = 3, F = 2, H = 2, I = 3, J = 2

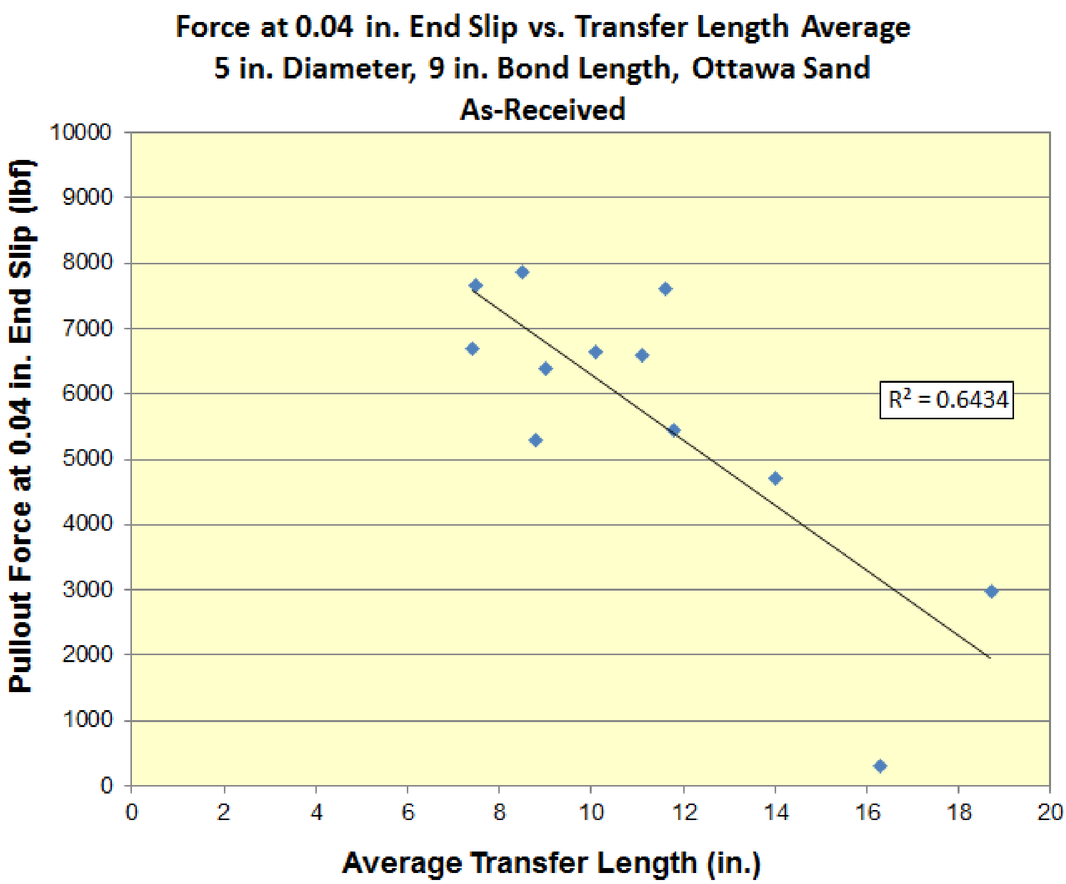

Figure C-18. Test development analysis, pullout force at 0.04-in. end slip (Ottawa sand)

Table C-19. Test development analysis, pullout force at 0.05-in. end slip (Ottawa sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Ottawa Sand

Pullout Force at 0.05 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	327	73	22.3	16.3
[WB]	7779	704	9.0	11.6
[WC]	6259	805	12.9	8.8
[WD]	7134	1059	14.8	11.1
[WE]	7411	1726	23.3	7.4
[WF]	8732	280	3.2	8.5
[WG]	6259	1177	18.8	11.8
[WH]	8419	390	4.6	7.5
[WI]	6692	544	8.1	10.1
[WJ]	7463	652	8.7	9.0
[WK]	4944	304	6.1	14.0
[WL]	3270	328	10.0	18.7

Note: Sample Size = 6, B = 5, C = 5, D = 3, F = 2, H = 2, I = 2, J = 2

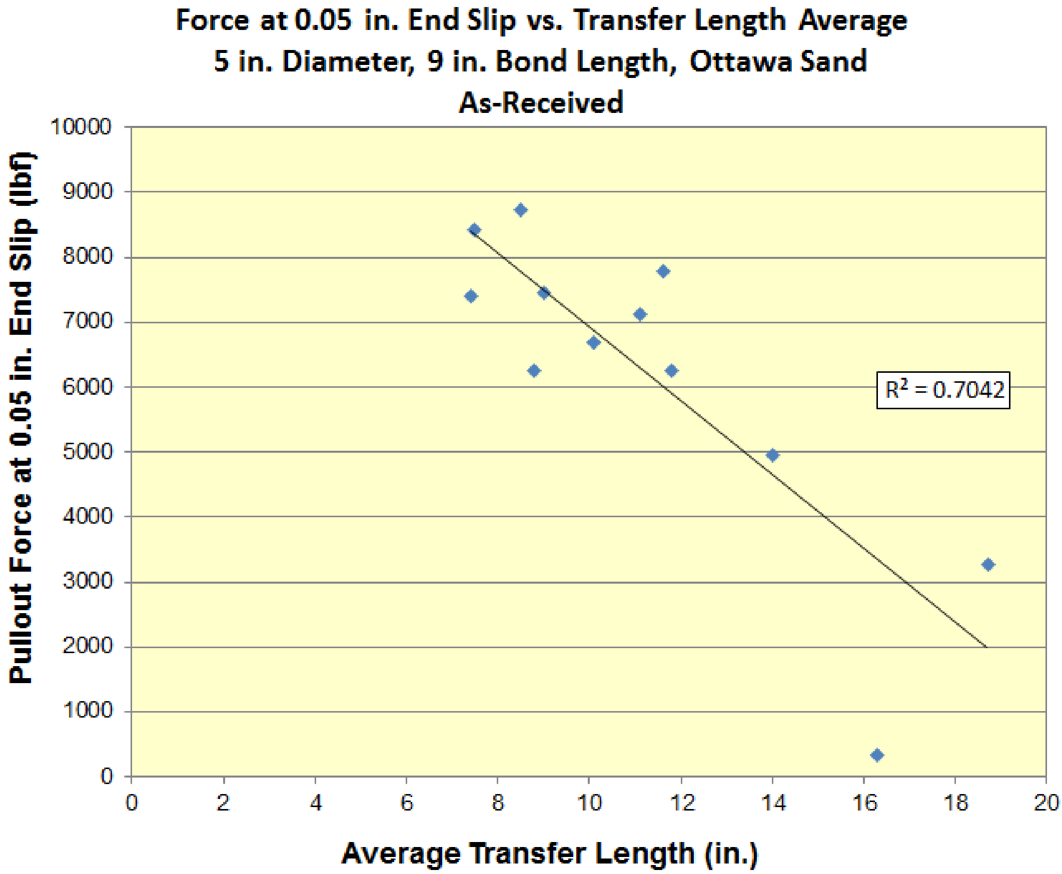

Figure C-19. Test development analysis, pullout force at 0.05-in. end slip (Ottawa sand)

Table C-20. Test development analysis, pullout force at 0.06-in. end slip (Ottawa sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Ottawa Sand Pullout Force at 0.06 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	352	77	21.9	16.3
[WB]	7882	265	3.4	11.6
[WC]	7127	860	12.1	8.8
[WD]	7373	947	12.8	11.1
[WE]	7231	1230	17.0	7.4
[WF]	8842	0	0.0	8.5
[WG]	6837	1080	15.8	11.8
[WH]	8824	314	3.6	7.5
[WI]	7316	524	7.2	10.1
[WJ]	8067	690	8.6	9.0
[WK]	5049	314	6.2	14.0
[WL]	3491	431	12.3	18.7

Note: Sample Size = 6, B = 4, C = 5, D = 3, E = 4, F = 1, H = 2, I = 2, J = 2

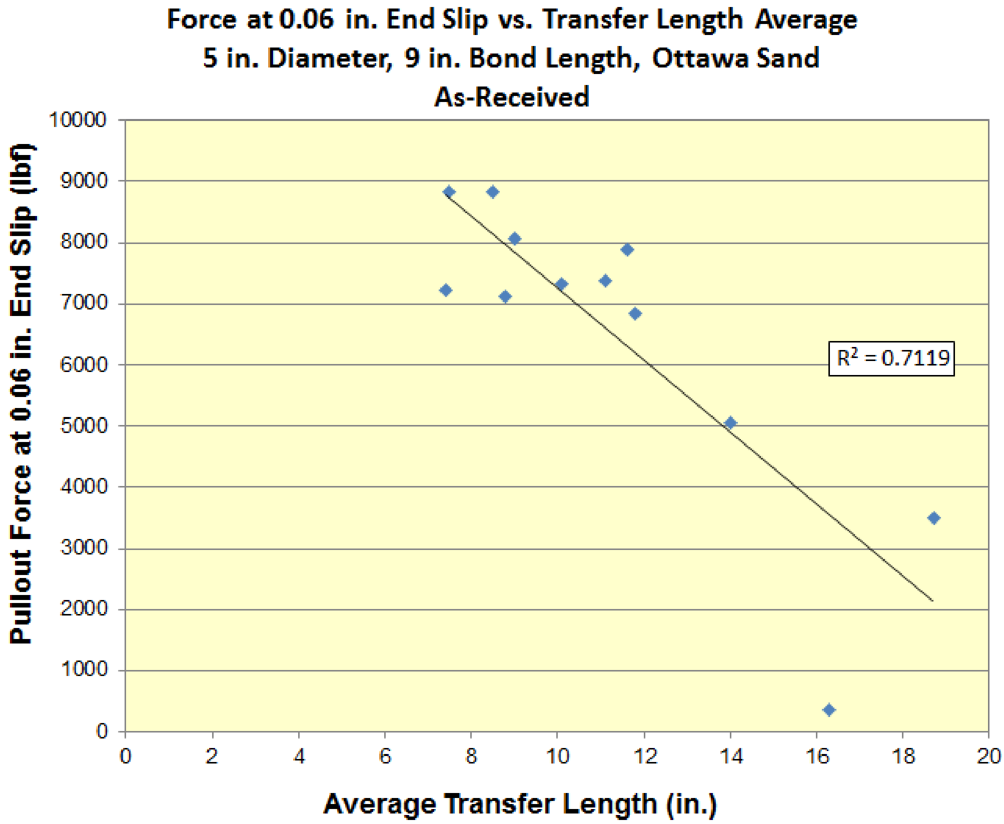

Figure C-20. Test development analysis, pullout force at 0.06-in. end slip (Ottawa sand)

Table C-21. Test development analysis, pullout force at 0.07-in. end slip (Ottawa sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Ottawa Sand Pullout Force at 0.07 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	380	81	21.4	16.3
[WB]	8139	203	2.5	11.6
[WC]	7909	898	11.4	8.8
[WD]	7437	871	11.7	11.1
[WE]	7273	556	7.6	7.4
[WF]	9008	0	0.0	8.5
[WG]	7016	1010	14.4	11.8
[WH]	8750	0	0.0	7.5
[WI]	7671	490	6.4	10.1
[WJ]	8372	716	8.5	9.0
[WK]	5130	354	6.9	14.0
[WL]	3657	486	13.3	18.7

Note: Sample Size = 6, B = 4, C = 5, D = 3, E = 3, F = 1, G = 5, H = 1, I = 2, J = 2

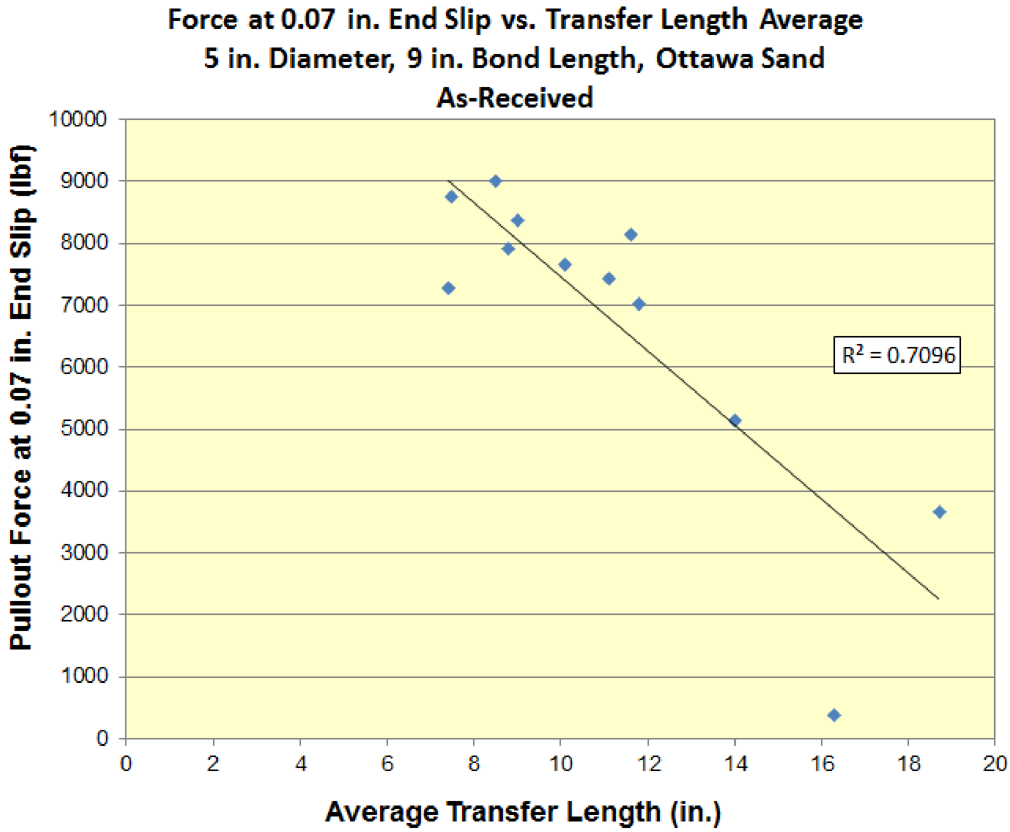

Figure C-21. Test development analysis, pullout force at 0.07-in. end slip (Ottawa sand)

Table C-22. Test development analysis, pullout force at 0.08-in. end slip (Ottawa sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Ottawa Sand Pullout Force at 0.08 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	406	84	20.8	16.3
[WB]	8282	195	2.4	11.6
[WC]	8026	412	5.1	8.8
[WD]	7402	803	10.8	11.1
[WE]	7885	485	6.2	7.4
[WF]	9046	0	0.0	8.5
[WG]	7240	958	13.2	11.8
[WH]	8865	0	0.0	7.5
[WI]	7875	443	5.6	10.1
[WJ]	7789	0	0.0	9.0
[WK]	5162	375	7.3	14.0
[WL]	3755	524	13.9	18.7

Note: Sample Size = 6, B = 4, C = 3, D = 3, E = 3, F = 1, G = 5, H = 1, I = 2, J = 1

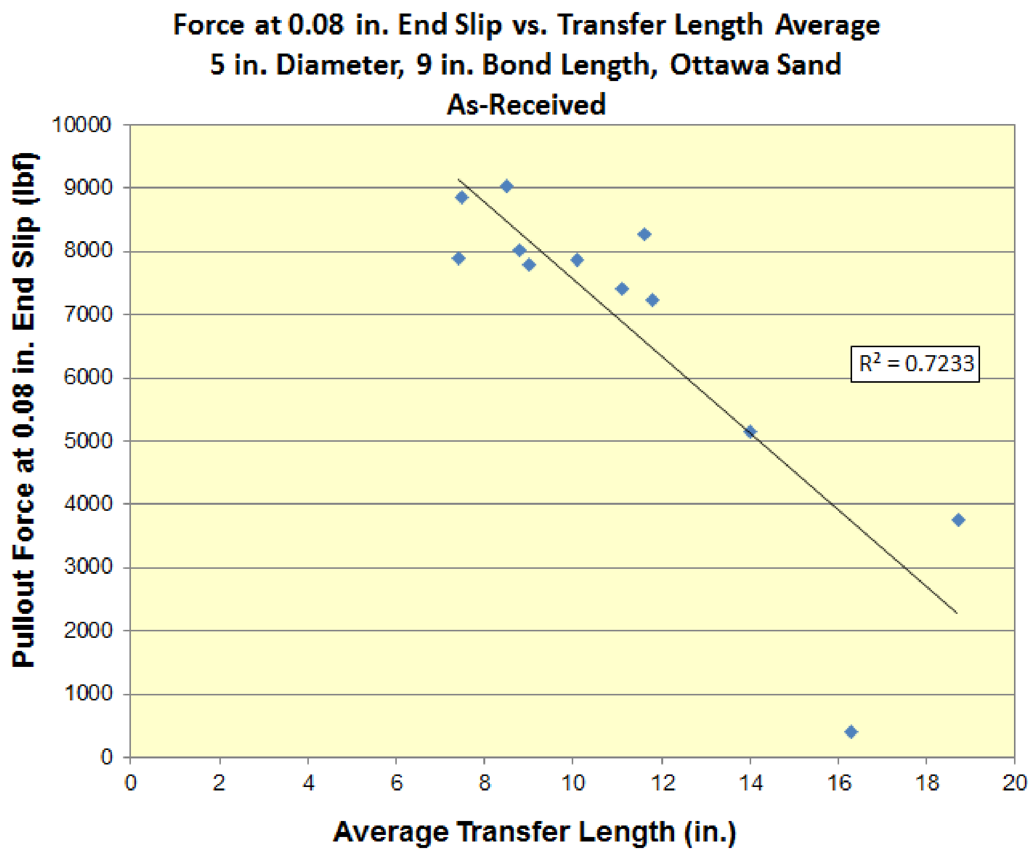

Figure C-22. Test development analysis, pullout force at 0.08-in. end slip (Ottawa sand)

Table C-23. Test development analysis, pullout force at 0.09-in. end slip (Ottawa sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Ottawa Sand

Pullout Force at 0.09 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	434	87	20.0	16.3
[WB]	8320	213	2.6	11.6
[WC]	8489	112	1.3	8.8
[WD]	7287	731	10.0	11.1
[WE]	8413	411	4.9	7.4
[WF]	9018	0	0.0	8.5
[WG]	7339	943	12.9	11.8
[WH]	8883	0	0.0	7.5
[WI]	7947	404	5.1	10.1
[WJ]	7819	0	0.0	9.0
[WK]	5163	394	7.6	14.0
[WL]	3843	555	14.4	18.7

Note: Sample Size = 6, B = 4, C = 2, D = 3, E = 3, F = 1, G = 5, H = 1, I = 2, J = 1

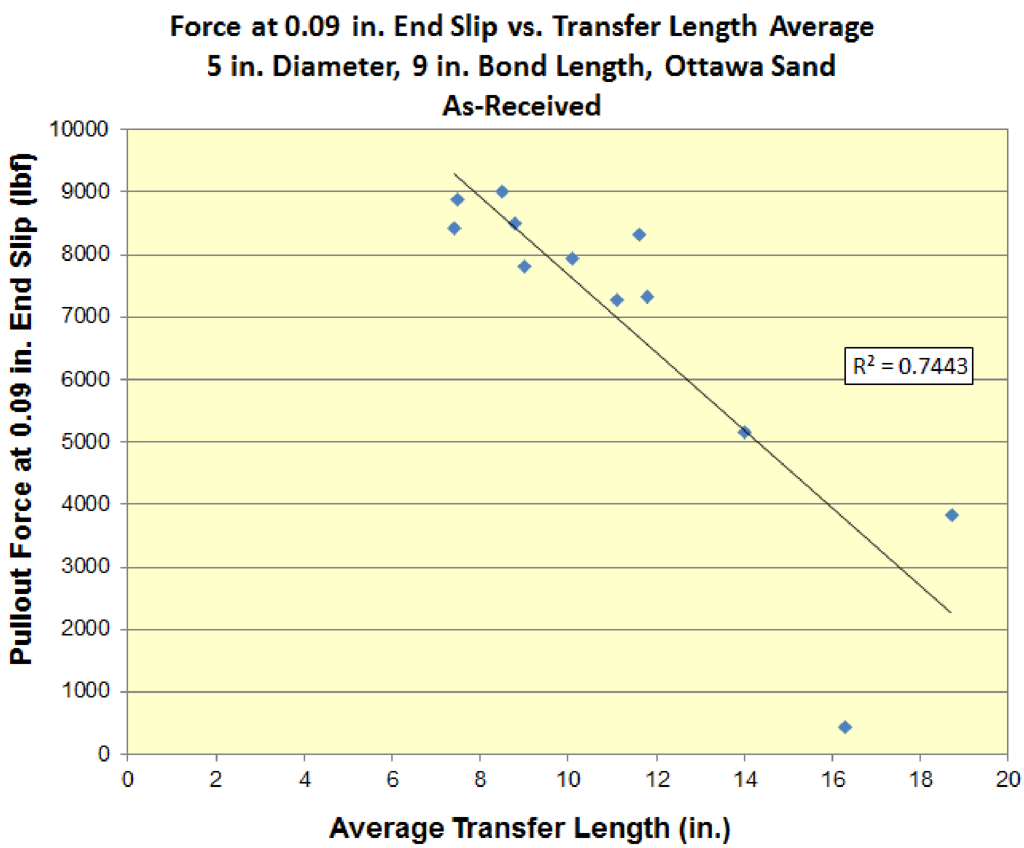

Figure C-23. Test development analysis, pullout force at 0.09-in. end slip (Ottawa sand)

Table C-24. Test development analysis, pullout force at 0.10-in. end slip (Ottawa sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Ottawa Sand

Pullout Force at 0.10 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	461	89	19.3	16.3
[WB]	8272	243	2.9	11.6
[WC]	9218	0	0.0	8.8
[WD]	7112	650	9.1	11.1
[WE]	8778	280	3.2	7.4
[WF]	8909	0	0.0	8.5
[WG]	7356	945	12.8	11.8
[WH]	8836	0	0.0	7.5
[WI]	7923	368	4.6	10.1
[WJ]	7760	0	0.0	9.0
[WK]	5145	424	8.2	14.0
[WL]	3840	573	14.9	18.7

Note: Sample Size = 6, B = 4, C = 1, D = 3, E = 3, F = 1, G = 5, H = 1, I = 2, J = 1

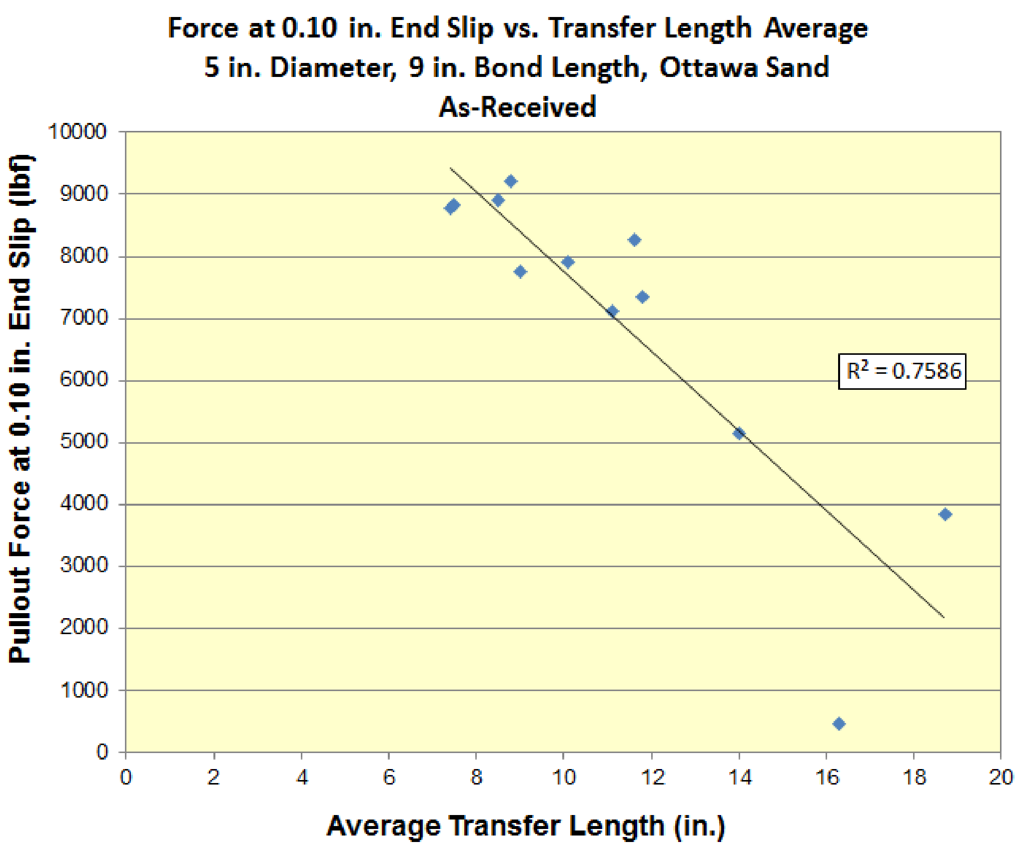

Figure C-24. Test development analysis, pullout force at 0.10-in. end slip (Ottawa sand)

Table C-25. Test development analysis, pullout force at 0.11-in. end slip (Ottawa sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Ottawa Sand

Pullout Force at 0.11 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	486	91	18.6	16.3
[WB]	8130	281	3.5	11.6
[WC]				
[WD]	6909	584	8.5	11.1
[WE]	8887	96	1.1	7.4
[WF]	8793	0	0.0	8.5
[WG]	7299	949	13.0	11.8
[WH]	8715	0	0.0	7.5
[WI]	7798	318	4.1	10.1
[WJ]	7624	0	0.0	9.0
[WK]	5111	437	8.5	14.0
[WL]	3937	626	15.9	18.7

Note: Sample Size = 6, B = 4, C = 0, D = 3, E = 2, F = 1, G = 5, H = 1, I = 2, J = 1

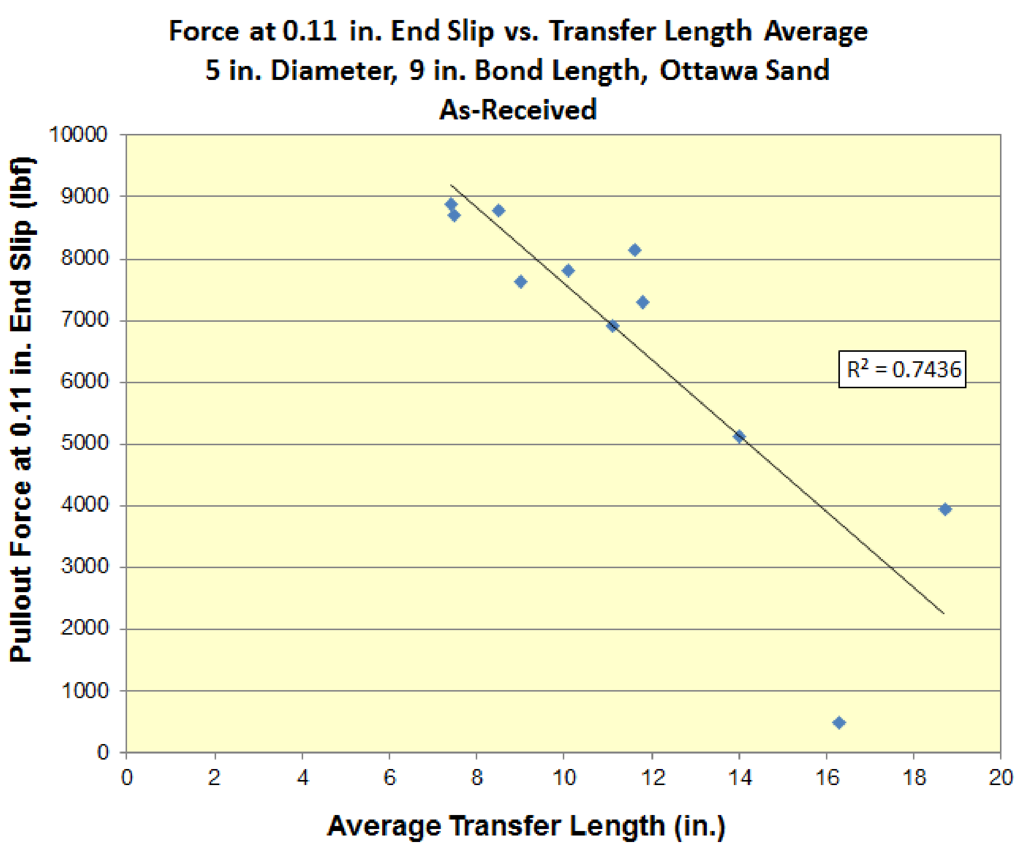

Figure C-25. Test development analysis, pullout force at 0.11-in. end slip (Ottawa sand)

Table C-26. Test development analysis, pullout force at 0.12-in. end slip (Ottawa sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Ottawa Sand

Pullout Force at 0.12 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	510	93	18.1	16.3
[WB]	7890	318	4.0	11.6
[WC]				
[WD]	6677	530	7.9	11.1
[WE]	9062	36	0.4	7.4
[WF]	8793	0	0.0	8.5
[WG]	7161	949	13.3	11.8
[WH]	8510	0	0.0	7.5
[WI]	7574	261	3.4	10.1
[WJ]	7403	0	0.0	9.0
[WK]	5065	463	9.1	14.0
[WL]	3893	589	15.1	18.7

Note: Sample Size = 6, B = 4, C = 0, D = 3, E = 2, F = 1, G = 5, H = 1, I = 2, J = 1

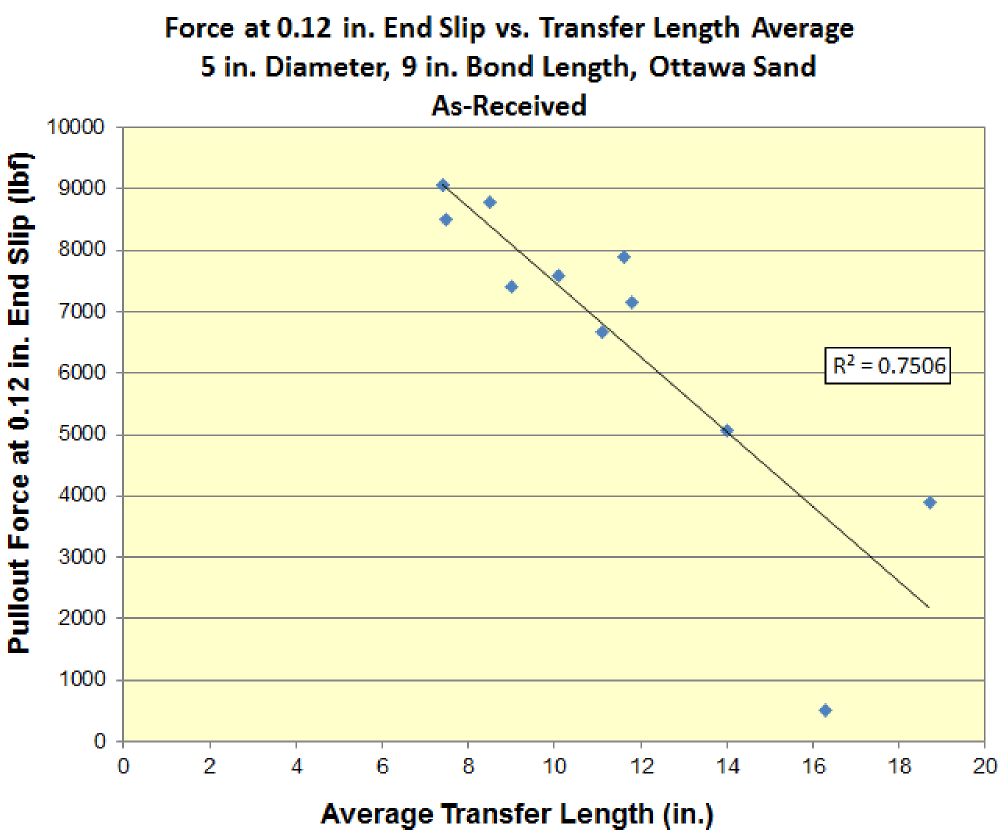

Figure C-26. Test development analysis, pullout force at 0.12-in. end slip (Ottawa sand)

Table C-27. Test development analysis, pullout force at 0.13-in. end slip (Ottawa sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Ottawa Sand

Pullout Force at 0.13 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	517	95	18.4	16.3
[WB]	7578	343	4.5	11.6
[WC]				
[WD]	6409	464	7.2	11.1
[WE]	9201	3	0.0	7.4
[WF]	8793	0	0.0	8.5
[WG]	6912	941	13.6	11.8
[WH]	8206	0	0.0	7.5
[WI]	7217	209	2.9	10.1
[WJ]	7133	0	0.0	9.0
[WK]	5031	488	9.7	14.0
[WL]	3851	566	14.7	18.7

Note: Sample Size = 6, A = 5, B = 4, C = 0, D = 3, E = 2, F = 1, G = 5, H = 1, I = 2, J = 1

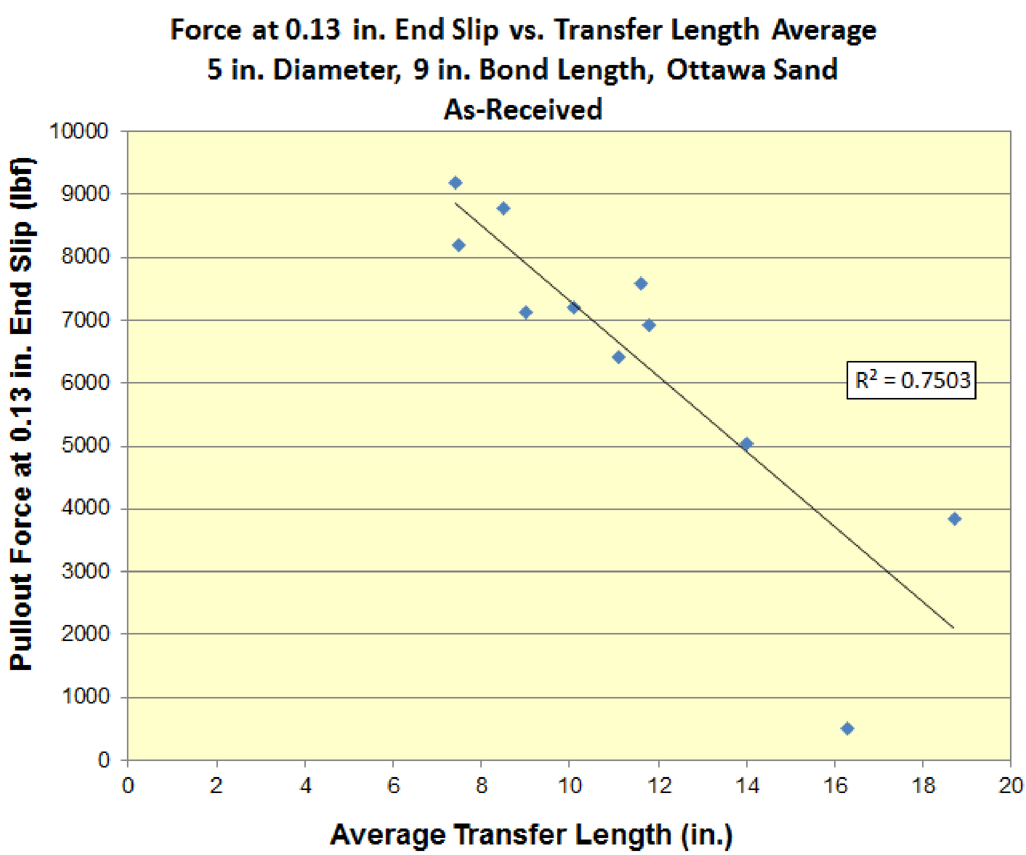

Figure C-27. Test development analysis, pullout force at 0.13-in. end slip (Ottawa sand)

Table C-28. Test development analysis, maximum pullout force (Ottawa sand)

As-Received Pullout Test Results

5 in. Diameter, 9 in. Bond Length, Ottawa Sand Maximum Pullout Force				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	516	99	19.1	16.3
[WB]	8624	453	5.3	11.6
[WC]	9063	198	2.2	8.8
[WD]	8314	1045	12.6	11.1
[WE]	8987	301	3.4	7.4
[WF]	9168	56	0.6	8.5
[WG]	7482	900	12.0	11.8
[WH]	9119	105	1.2	7.5
[WI]	8770	618	7.1	10.1
[WJ]	8949	506	5.6	9.0
[WK]	5195	396	7.6	14.0
[WL]	3799	480	12.6	18.7

Note: Sample Size = 6

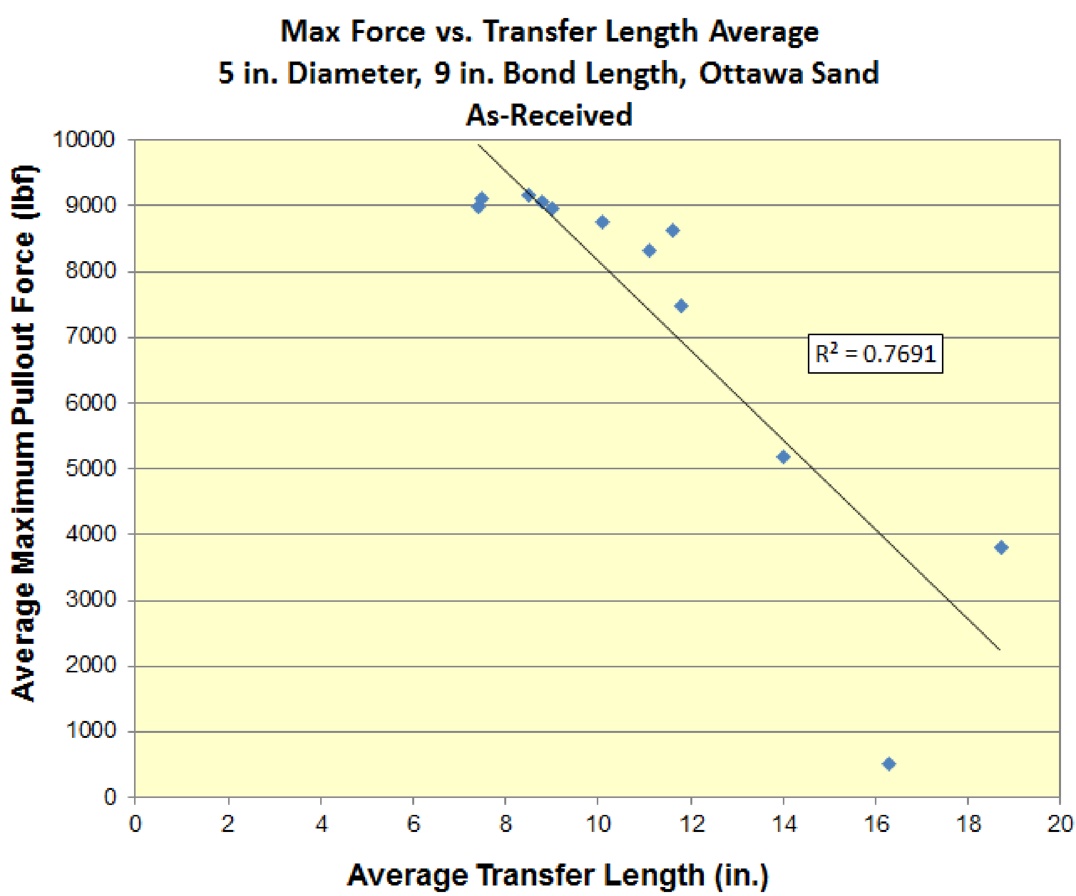

Figure C-28. Test development analysis, maximum pullout force (Ottawa sand)

Appendix D.
Lab Phase, Wire; As-received and Cleaned Batch Summaries

FRA DATA SHEET

Batch Name:	Wire Batch # 1	Performed By:	Matthew Arnold
Batch Date:	6/14/2012		
Batch Time:	3:25pm		

Mix proportions	# of cans	
	12	Actual
Ottawa Sand (lbf)	81.2	81.2
Monarch Type III Cement (lbf)	40.6	40.6
Water (lbf)	17.2	17.2
Total (lbf)	139.0	139.0

Flow Table Value :	124			
Water Added (± lbf	0	Avg Cube Strength	4544	psi
Concrete Temp:	74.9 °F	w/c:	0.425	
Room Temp / Humid:	74.0 °F / 63 %H	s/c:	2.0	

Test Date:	6/15/2012	Performed By:	Matthew Arnold

Time	Since Batch (hr)	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:51a	17.5 hr	1	14630	3658	12:30p	21.25 hr	9	18195	4549
8:54a		2	13345	3336	12:33p		10	18305	4576
10:00a	18.5 hr	3	15295	3824					
11:03a	19.5 hr	4	18145	4536					
11:05a		5	17880	4470					
11:58a		6	18240	4560					
12:04p	20.75 hr	7	18025	4506					
12:22p	21 hr	8	18430	4608					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
11:30a	4	[WA]	1	1304	12:15p	11	[WG]	1	5861
12:19p	12	[WB]	1	6826	11:59a	8	[WH]	1	7435
11:23a	3	[WC]	1	8809	11:51a	6	[WI]	1	6032
12:05p	9	[WD]	1	5612	12:10p	10	[WJ]	1	6290
11:43a	5	[WE]	1	9210 *	11:17a	2	[WK]	1	3407
11:09a	1	[WF]	1	7883	11:57a	7	[WL]	1	2305

Notes: * denotes a specumen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure D-1. As-received wires, batch summary #1 (Ottawa sand)

FRA DATA SHEET

Batch Name:	Wire Batch # 2	Performed By:	Matthew Arnold
Batch Date:	6/19/2012		
Batch Time:	3:13pm		

Mix proportions	# of cans	
	12	Actual
Ottawa Sand (lbf)	81.2	81.2
Monarch Type III Cement (lbf)	40.6	40.6
Water (lbf)	17.2	17.2
Total (lbf)	139.0	139.0

Flow Table Value :	124			
Water Added (± lbf	0.3	Avg Cube Strength	4638	psi
Concrete Temp:	75.1 °F	w/c:	0.425	
Room Temp / Humid:	74.9 °F / 63 %H	s/c:	2.0	

Test Date: 6/20/2012 Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:55a	17.75 hr	1	17570	4393	10:34a	20.25 hr	9	19405	4851
8:57a		2	17800	4450	10:40a		10	18780	4695
9:24a	18.25 hr	3	17890	4473	10:42a		11	19155	4789
9:26a		4	18200	4550	11:56a	21.5 hr	12	19870	4968
9:42a	18.5 hr	5	18580	4645					
9:56a		6	17905	4476					
10:15a	20 hr	7	18435	4609					
10:31a		8	18635	4659					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
10:01a	7	[WA]	2	1542	10:03a	8	[WG]	2	5155
9:33a	1	[WB]	2	5472	9:49a	5	[WH]	2	7864
10:17a	11	[WC]	2	8489	10:13a	10	[WI]	2	6450
9:41a	3	[WD]	2	5600	9:45a	4	[WJ]	2	6706
10:07a	9	[WE]	2	9210 *	9:37a	2	[WK]	2	3427
9:55a	6	[WF]	2	8364	10:22a	12	[WL]	2	2029

Notes: * denotes a specumen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure D-2. As-received wires, batch summary #2 (Ottawa sand)

FRA DATA SHEET

Batch Name: Wire Batch # 3 | Performed By: Matthew Arnold

Batch Date: 6/21/2012

Batch Time: 2:13pm

Mix proportions	# of cans	
	12	Actual
Ottawa Sand (lbf)	81.1	81.1
Monarch Type III Cement (lbf)	40.6	40.6
Water (lbf)	17.3	17.3
Total (lbf)	139.0	139.0

Flow Table Value : 122

Water Added (± lbf): 0

Concrete Temp: 74.8 °F

Room Temp / Humid: 72.4 °F / 60 %H

Avg Cube Strength 4541 psi

w/c: 0.427

s/c: 2.0

Test Date: 6/22/2012 | Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:33a	18.25 hr	1	17430	4358	10:59a		9	18145	4536
8:35a	DEFECT	2	15810	3953					
8:37a		3	16910	4228					
9:12a	19 hr	4	17025	4256					
9:50a	19.5 hr	5	18125	4531					
10:11a	20 hr	6	18485	4621					
10:34a	20.25 hr	7	17825	4456					
10:57a	20.75 hr	8	18230	4558					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:55a	1	[WA]	3	644	9:58a	2	[WG]	3	5229
10:12a	5	[WB]	3	6672	10:17a	6	[WH]	3	7140
10:02a	3	[WC]	3	8363	10:07a	4	[WI]	3	6750
10:41a	11	[WD]	3	5484	10:28a	8	[WJ]	3	7688
10:22a	7	[WE]	3	9218 *	10:45a	12	[WK]	3	4174
10:33a	9	[WF]	3	8552	10:38a	10	[WL]	3	2660

Notes: * denotes a specumen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure D-3. As-received wires, batch summary #3 (Ottawa sand)

FRA DATA SHEET

Batch Name:	Wire Batch # 4	Performed By:	Matthew Arnold
Batch Date:	6/26/2012		
Batch Time:	1:06p		

Mix proportions	# of cans	
	12	Actual
Ottawa Sand (lbf	81.1	81.1
Monarch Type III Cement (lbf)	40.6	40.6
Water (lbf)	17.3	17.3
Total (lbf)	139.0	139.0

Flow Table Value :	125			
Water Added (± lbf	0	Avg Cube Strength	4544	psi
Concrete Temp:	75.6 °F	w/c:	0.427	
Room Temp / Humid:	72.7 °F / 57 %H	s/c:	2.0	

Test Date:	6/27/2012	Performed By:	Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:42a	19.5 hr	1	14630	3658	2:26p	25.25 hr	9	17725	4431
8:48a		2	15095	3774	3:03p	26 hr	10	18230	4558
10:55a	21.75 hr	3	16975	4244	3:08p		11	18125	4531
11:17a		4	15815	3954	3:11p		12	18040	4510
12:03p	23 hr	5	16070	4018					
12:06p		6	17030	4258					
1:08p	24 hr	7	17805	4451					
2:01p	25 hr	8	18750	4688					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
2:00p	1	[WA]	4	803	2:29p	7	[WG]	4	5002
2:43p	11	[WB]	4	6174	2:24p	6	[WH]	4	6872
2:18p	5	[WC]	4	8892	2:35p	9	[WI]	4	5821
2:39p	10	[WD]	4	4970	2:13p	4	[WJ]	4	6425
2:07p	3	[WE]	4	9062	2:03p	2	[WK]	4	3253
2:47p	12	[WF]	4	7562	2:32p	8	[WL]	4	2496

Notes: * denotes a specumen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure D-4. As-received wires, batch summary #4 (Ottawa sand)

FRA DATA SHEET

Batch Name:	Wire Batch # 5	Performed By:	Matthew Arnold
Batch Date:	6/28/2012		
Batch Time:	1:43p		

Mix proportions	# of cans	
	12	Actual
Ottawa Sand (lb	81.1	81.1
Monarch Type III Cement (lbf)	40.6	40.6
Water (lbf)	17.3	17.3
Total (lbf)	139.0	139.0

Flow Table Value :	121			
Water Added (± lbf	0	Avg Cube Strength	4542	psi
Concrete Temp:	75.2 °F	w/c:	0.427	
Room Temp / Humid:	73.1 °F / 59 %H	s/c:	2.0	

Test Date:	6/29/2012	Performed By:	Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:51a	19 hr	1	17300	4325	10:51a	21 hr	9	18945	4736
8:53a		2	17095	4274	10:53a		10	17940	4485
9:47a	20 hr	3	18595	4649	10:55a		11	18185	4546
9:49a		4	18010	4503	10:57a		12	17815	4454
10:08a	20.5 hr	5	17705	4426					
10:10a		6	18105	4526					
10:24a	DEFECT	7							
10:30a	20.75 hr	8	18210	4553					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
10:15a	5	[WA]	5	860	10:24a	7	[WG]	5	5955
10:44a	12	[WB]	5	6445	9:58a	1	[WH]	5	8079
10:17a	6	[WC]	5	9225 *	10:29a	9	[WI]	5	7202
10:34a	10	[WD]	5	6191	10:03a	2	[WJ]	5	7091
10:07a	3	[WE]	5	9226 *	10:13a	4	[WK]	5	3377
10:38a	11	[WF]	5	8597	10:27a	8	[WL]	5	2118

Notes: * denotes a specumen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure D-5. As-received wires, batch summary #5 (Ottawa sand)

FRA DATA SHEET

Batch Name:	Wire Batch # 6	Performed By:	Matthew Arnold
Batch Date:	7/5/2012		
Batch Time:	1:15pm		

Mix proportions	# of cans	
	12	Actual
Ottawa Sand (lb	81.1	81.1
Monarch Type III Cement (lbf)	40.6	40.6
Water (lbf)	17.3	17.3
Total (lbf)	139.0	139.0

Flow Table Value :	119			
Water Added (± lbf	0	Avg Cube Strength	4640	psi
Concrete Temp:	76.0 °F	w/c:	0.427	
Room Temp / Humid:	72.5 °F / 60 %H	s/c:	2.0	

Test Date:	7/6/2012	Performed By:	Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
9:03a	19.75 hr	1	17920	4480	10:36a		9	18525	4631
9:05a		2	18275	4569					
9:36a		3	17965	4491					
9:55a	20.75 hr	4	19185	4796					
10:08a	21 hr	5	18600	4650					
10:10a		6	18900	4725					
10:32a	21.25 hr	7	19015	4754					
10:34a		8	18660	4665					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:50a	4	[WA]	6	-	10:03a	7	[WG]	6	5835
10:07a	8	[WB]	6	7304	10:23a	12	[WH]	6	8246
9:33a	1	[WC]	6	9225 *	9:45a	3	[WI]	6	7153
10:16a	10	[WD]	6	5477	9:51a	5	[WJ]	6	8013
9:57a	6	[WE]	6	9212 *	10:13a	9	[WK]	6	4262
9:39a	2	[WF]	6	8924	10:20a	11	[WL]	6	2820

Notes: * denotes a specumen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure D-6. As-received wires, batch summary #6 (Ottawa sand)

FRA DATA SHEET

Batch Name: Phase 2 Wires WA / WE / WK — Performed By: Matthew Arnold

Batch Date: 9/24/2012

Batch Time: 4:32pm

Mix proportions	# of cans	
	18	Actual
Ottawa Sand (lbf)	114.4	114.4
Monarch Type III Cement (lbf)	57.2	57.2
Water (lbf)	24.4	24.4
Total (lbf)	196.0	196.0

Time	Test Order	Specimen		Max Load (lbf)
9:32a	3	[WA]	1	673
9:37a	5	[WA]	2	568
9:48a	8	[WA]	3	658
9:58a	11	[WA]	4	595
10:11a	14	[WA]	5	736
10:20a	17	[WA]	6	662

Flow Table Value: 121

Water Added (± lbf): 0

Concrete Temp: 77.1 °F

Room Temp / Humid: 72.7 °F / 53 %H

Avg Cube Strength: 4551 psi

w/c: 0.427

s/c: 2.0

Test Date: 9/25/2012 — Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:58a	16.5 hr	1	16820	4205	10:32a	18 hr	9	17990	4498
9:01a		2	17280	4320					
9:28a	17 hr	3	18385	4596					
9:48a	17.25 hr	4	18165	4541					
10:06a	17.5 hr	5	17860	4465					
10:08a		6	18140	4535					
10:18a	17.75 hr	7	18380	4595					
10:30a	18 hr	8	18495	4624					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:20a	1	[WE]	1	9218 *	9:33a	4	[WK]	1	2973
9:27a	2	[WE]	2	9210 *	9:38a	6	[WK]	2	3098
9:42a	7	[WE]	3	9184 *	9:49a	9	[WK]	3	3418
9:52a	10	[WE]	4	9043	10:00a	12	[WK]	4	4030
10:05a	13	[WE]	5	9218 *	10:11a	15	[WK]	5	3420
10:16a	16	[WE]	6	9216 *	10:21a	18	[WK]	6	3311

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure D-7. Cleaned wires, batch summary #1 (Ottawa sand)

FRA DATA SHEET

Batch Name: Phase 2 Wires WF / WG / WH Performed By: Matthew Arnold
Batch Date: 10/1/2012
Batch Time: 3:32pm

Mix proportions	# of cans	
	18	Actual
Ottawa Sand (lb	114.4	114.4
Monarch Type III Cement (lbf)	57.2	57.2
Water (lbf)	24.4	24.4
Total (lbf)	196.0	196.0

Flow Table Value : 123
Water Added (± lbf 0
Concrete Temp: 77.6 °F
Room Temp / Humid: 73.4 °F / 51 %H

Time	Test Order	Specimen		Max Load (lbf)
9:34a	1	[WF]	1	7768
10:02a	4	[WF]	2	7070
10:18a	7	[WF]	3	8780
10:33a	10	[WF]	4	8493
10:49a	13	[WF]	5	7194
11:03a	16	[WF]	6	7723

Avg Cube Strength 4605 psi
w/c: 0.427
s/c: 2.0

Test Date: 10/2/2012 Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:31a	17 hr	1	17490	4373	10:51a	19.25 hr	9	18200	4550
8:35a		2	16845	4211	11:05a	19.5 hr	10	18685	4671
8:38a		3	17120	4280	11:20a	19.75 hr	11	19020	4755
9:10a	17.5 hr	4	18205	4551	11:22a		12	18335	4584
9:16a	17.75 hr	5	17785	4446					
9:32a	18 hr	6	18260	4565					
10:12a	18.75 hr	7	18585	4646					
10:35a	19 hr	8	18695	4674					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:45a	3	[WG]	1	5311	9:40a	2	[WH]	1	7450
10:08a	5	[WG]	2	5614	10:12a	6	[WH]	2	7763
10:24a	8	[WG]	3	5901	10:28a	9	[WH]	3	8486
10:39a	11	[WG]	4	6132	10:43a	12	[WH]	4	8319
10:54a	14	[WG]	5	6132	10:58a	15	[WH]	5	8413
11:08a	17	[WG]	6	5737	11:13a	18	[WH]	6	7366

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure D-8. Cleaned wires, batch summary #2 (Ottawa sand)

FRA DATA SHEET

Batch Name:	Wire Batch WM	Performed By:	Matthew Arnold
Batch Date:	3/5/2013		
Batch Time:	3:42pm		

Mix proportions	# of cans	
	12	Actual
Ottawa Sand (lbf	81.12	81.12
Monarch Type III Cement (lbf)	40.56	40.56
Water (lbf)	17.32	17.32
Total (lbf)	139.00	139.00

Flow Table Value :	121			
Water Added (± lbf	0	Avg Cube Strength	4560	psi
Concrete Temp:	72.4 °F	w/c:	0.427	
Room Temp / Humid:	68.6 °F / 31 %H	s/c:	2.0	

Test Date:	3/6/2013	Performed By:	Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
9:03a	17.25	1	16385	4096	12:54p	21.25	9	18015	4504
9:12a	17.5	2	16145	4036	1:04p	21.5	10	18070	4518
10:17a	18.5	3	17190	4298	1:13p	21.5	11	18540	4635
11:43a	20	4	17680	4420	1:22p	21.75	12	18275	4569
11:47a	20	5	17465	4366	1:34p	22	13	18155	4539
11:51a	20.25	6	17845	4461	1:51p	22	14	18695	4674
12:35p	20.75	7	18020	4505	1:54p	22.25	15	17995	4499
12:38p	21	8	18395	4599					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
12:41p	1	[WM]	1	6734	12:47p	2	[WM]	1clean	7399
12:52p	3	[WM]	2		12:58p	4	[WM]	2clean	7277
1:02p	5	[WM]	3	6064	1:07p	6	[WM]	3clean	6642
1:12p	7	[WM]	4	6652	1:17p	8	[WM]	4clean	7014
1:21p	9	[WM]	5	6858	1:27p	10	[WM]	5clean	7956
1:32p	11	[WM]	6	7326	1:37p	12	[WM]	6clean	7860

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure D-9. As-received and cleaned wires, batch summary for wire [WM] (Ottawa sand)

Appendix E.
Lab Phase, Wire; As-received and Cleaned Individual Pullout Graphs

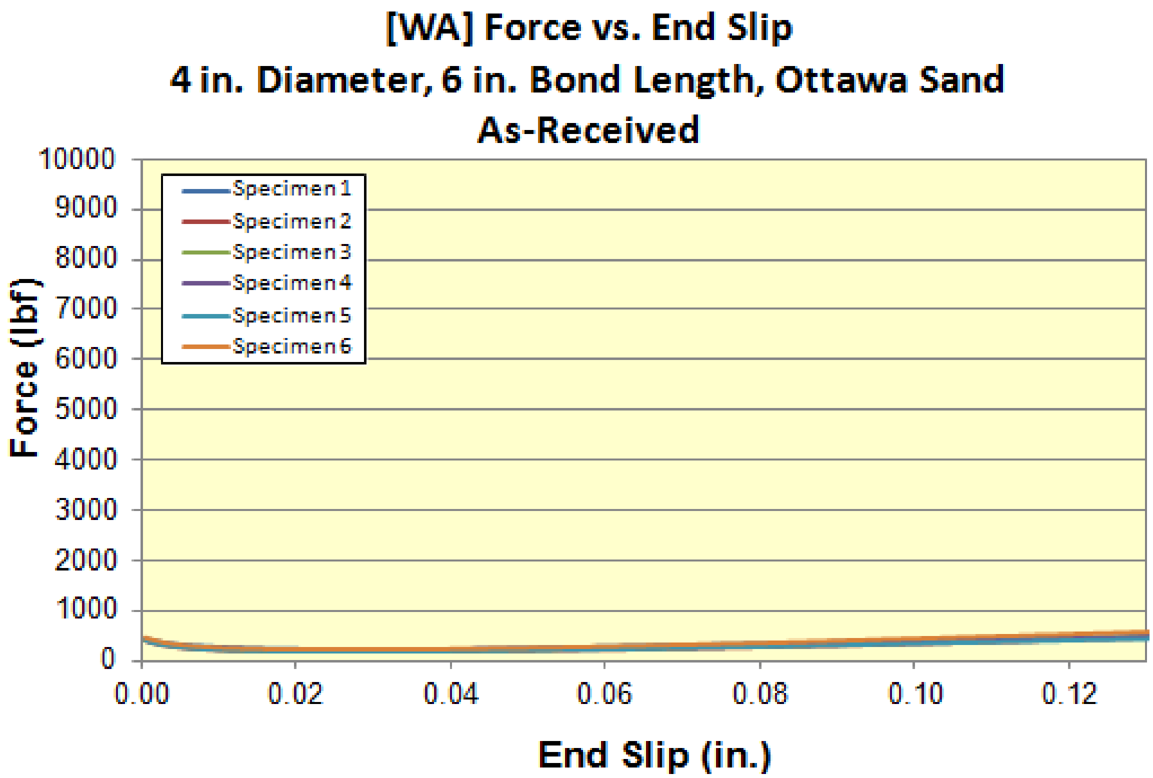

Figure E-1. As-received [WA] force vs. end-slip individual graphs

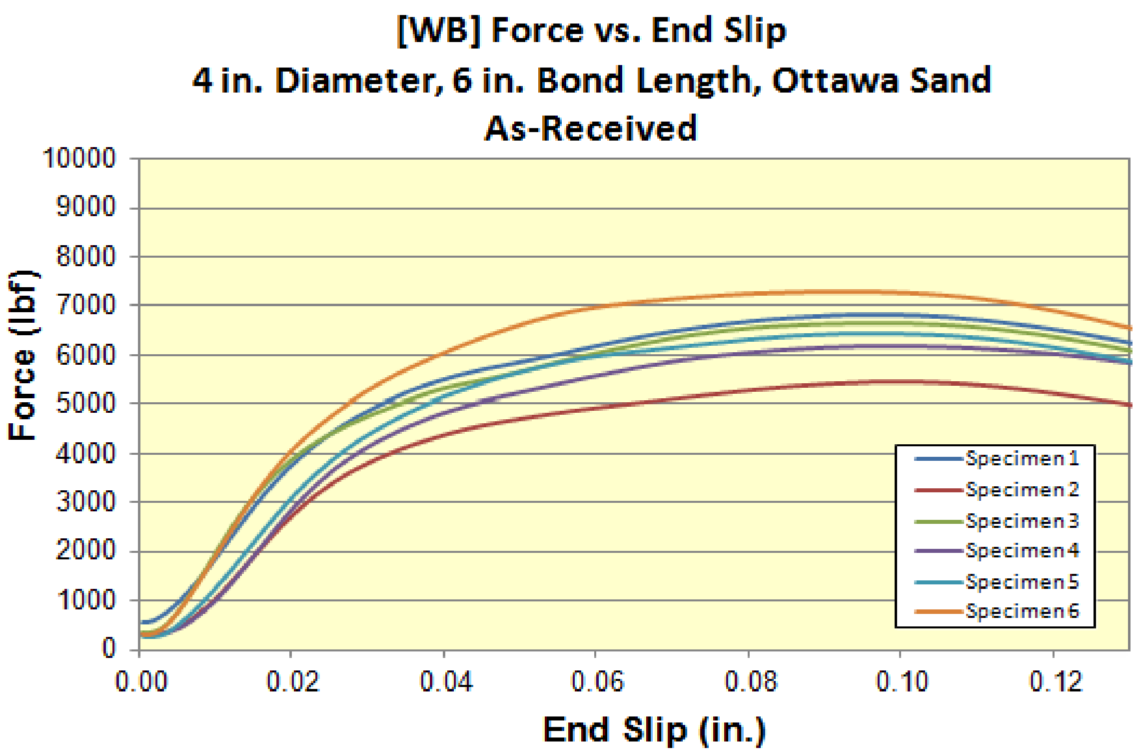

Figure E-2. As-received [WB] force vs. end-slip individual graphs

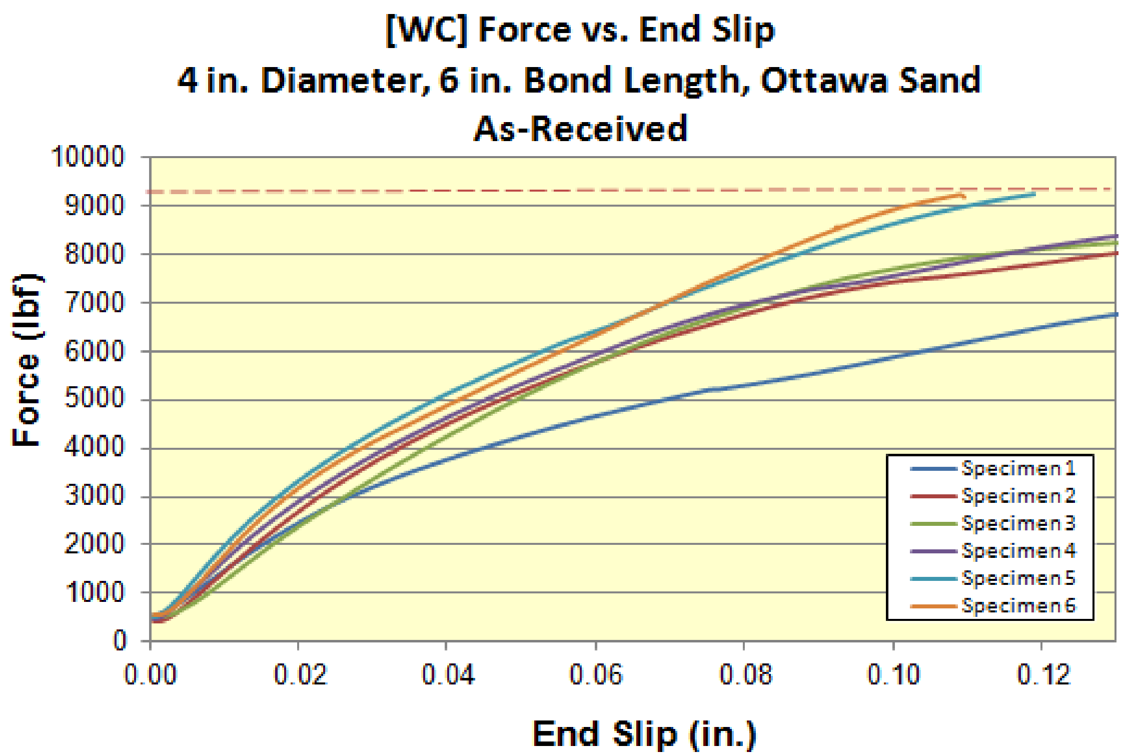

Figure E-3. As-received [WC] force vs. end-slip individual graphs

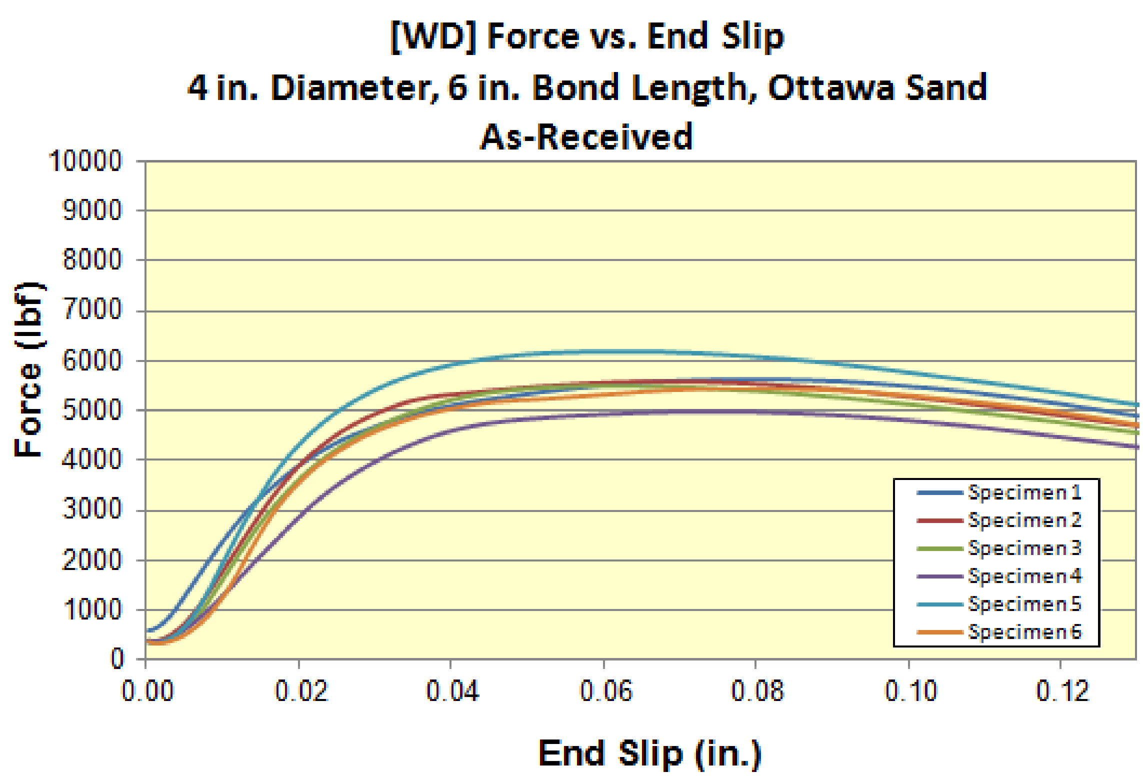

Figure E-4. As-received [WD] force vs. end-slip individual graphs

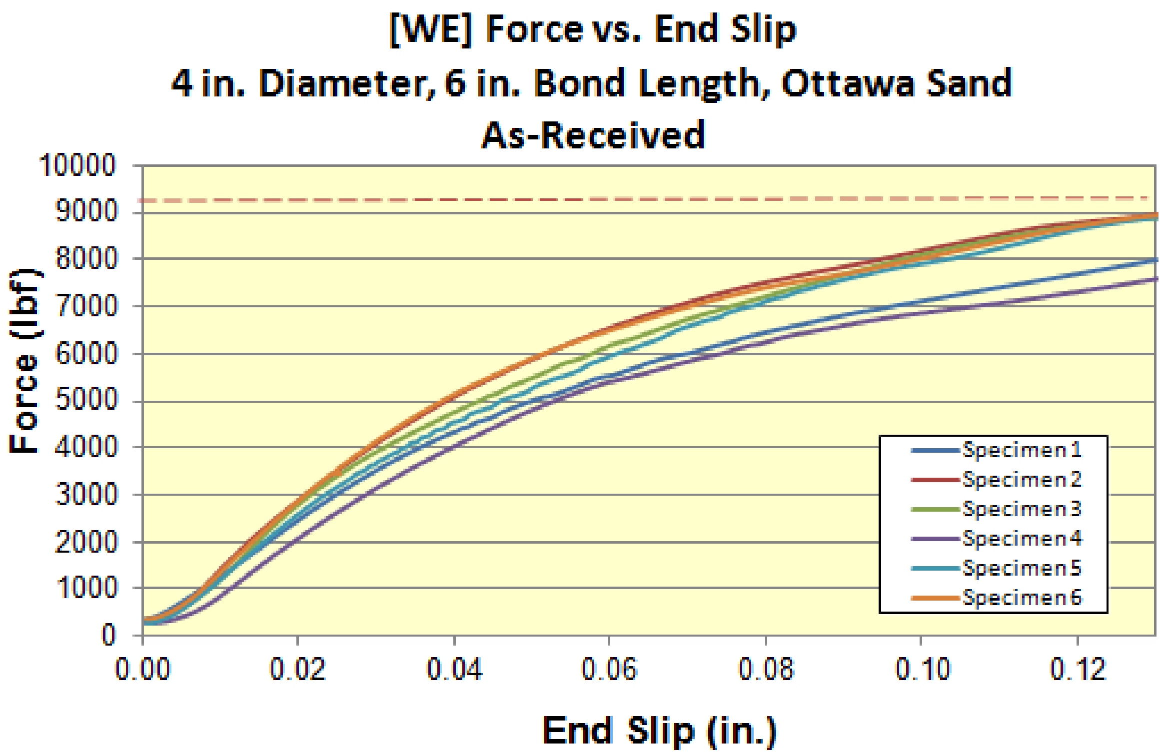

Figure E-5. As-received [WE] force vs. end-slip individual graphs

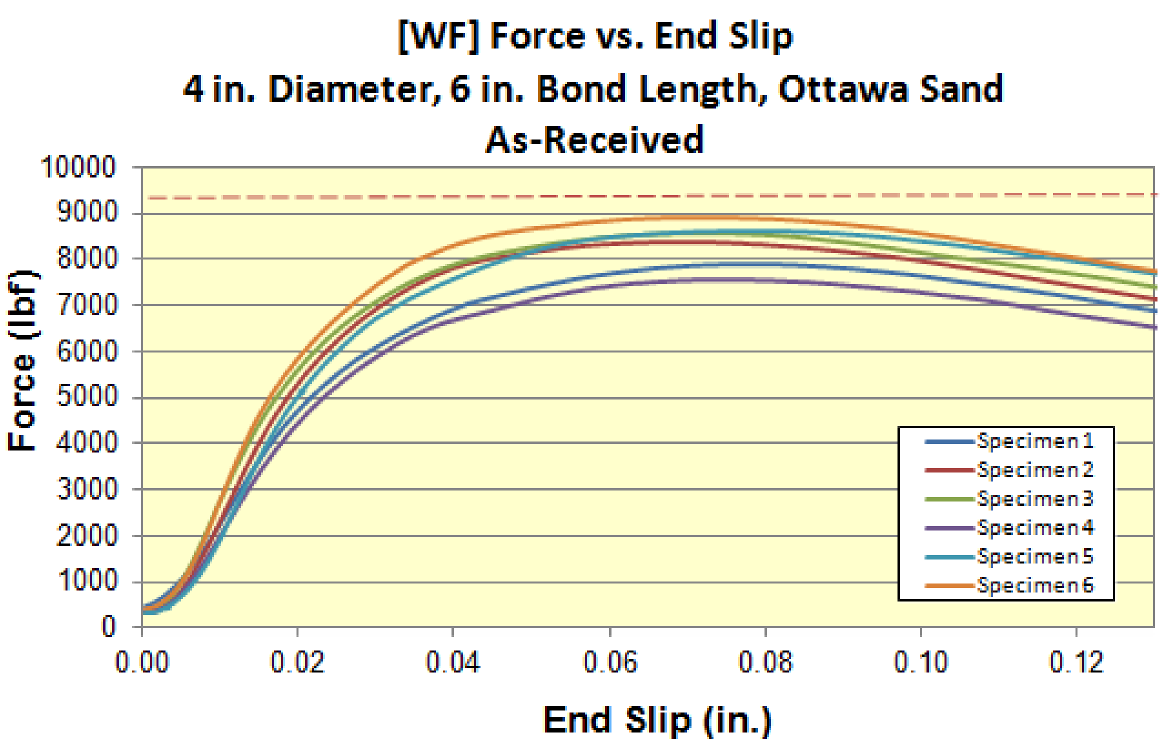

Figure E-6. As-received [WF] force vs. end-slip individual graphs

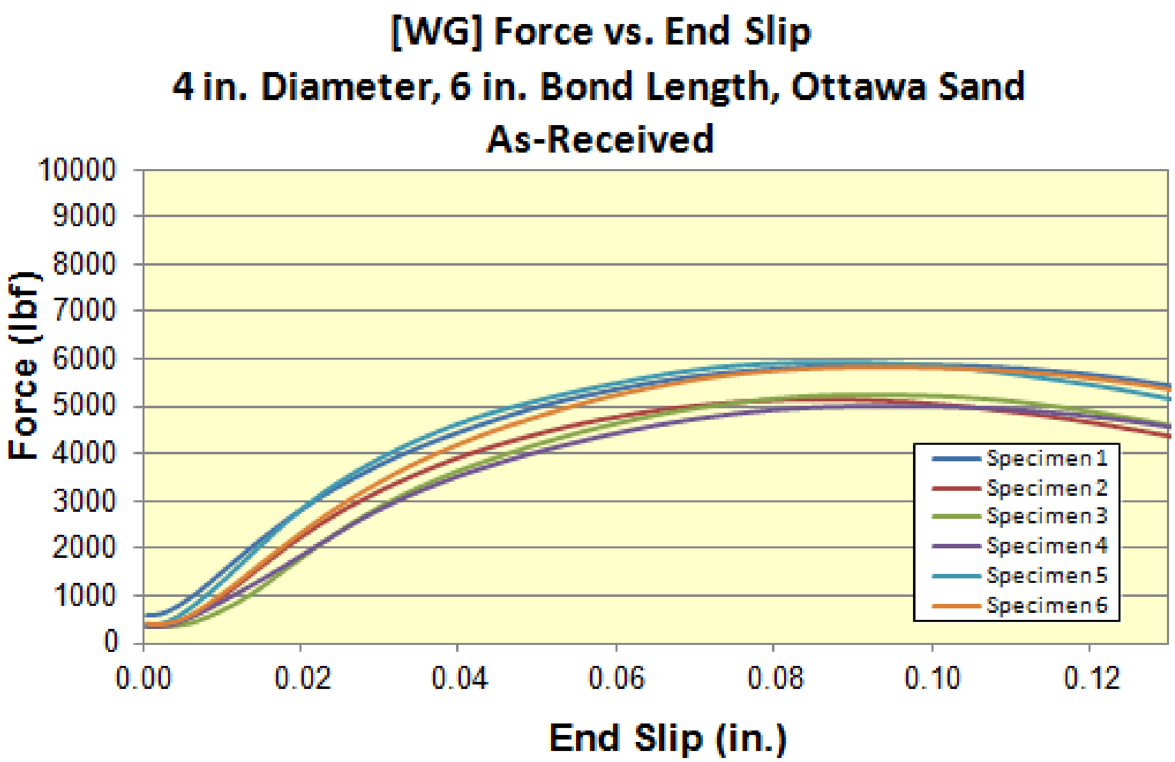

Figure E-7. As-received [WG] force vs. end-slip individual graphs

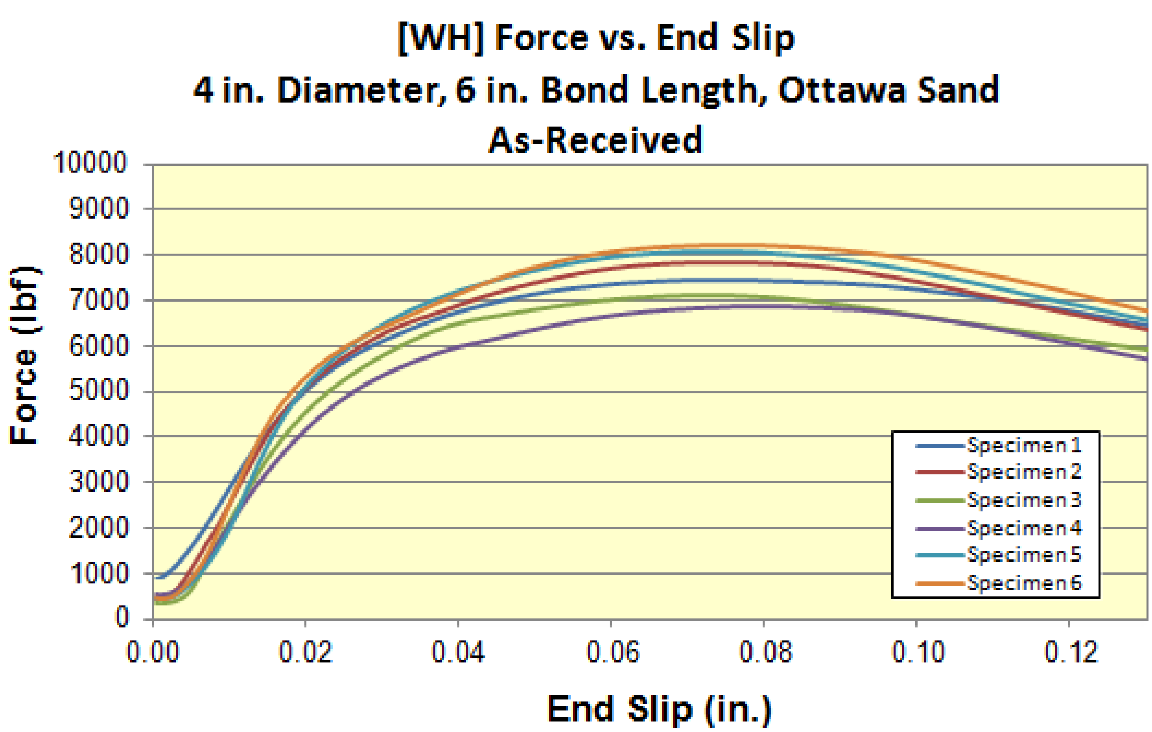

Figure E-8. As-received [WH] force vs. end-slip individual graphs

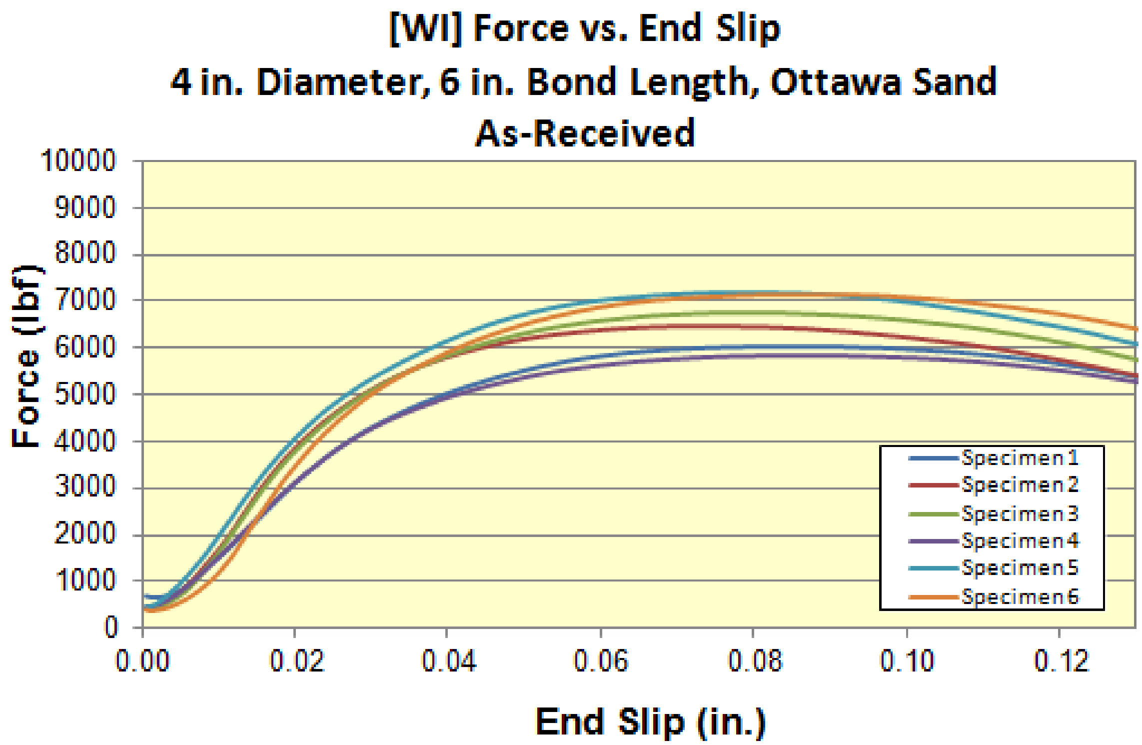

Figure E-9. As-received [WI] force vs. end-slip individual graphs

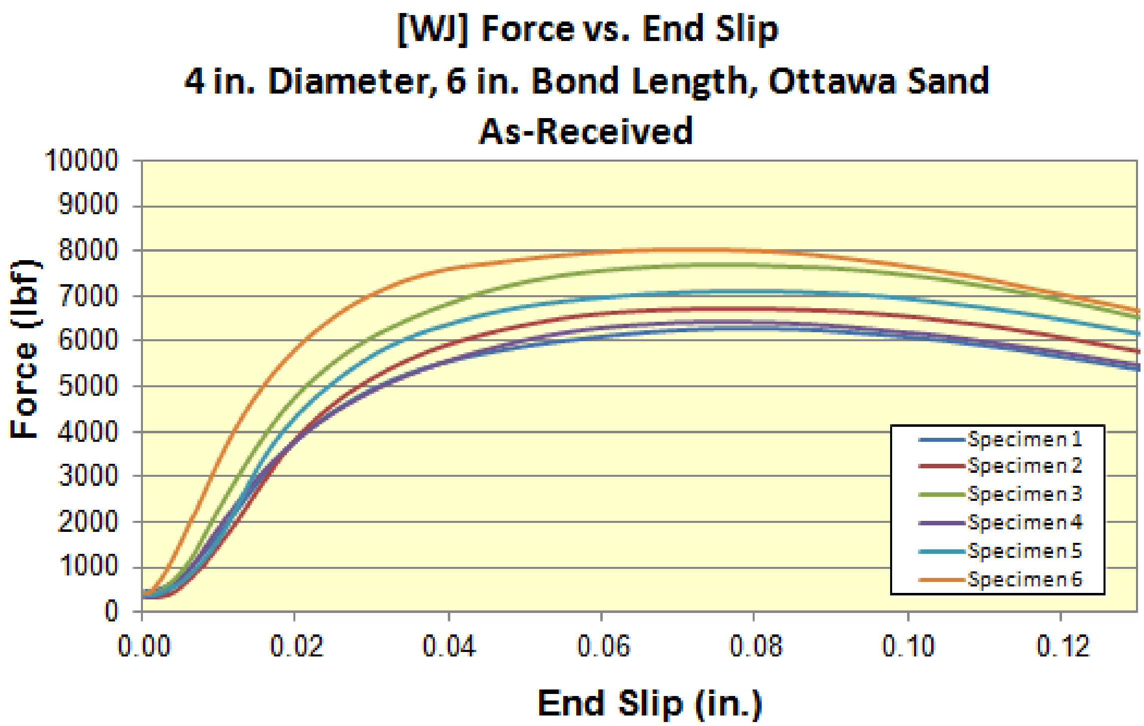

Figure E-10. As-received [WJ] force vs. end-slip individual graphs

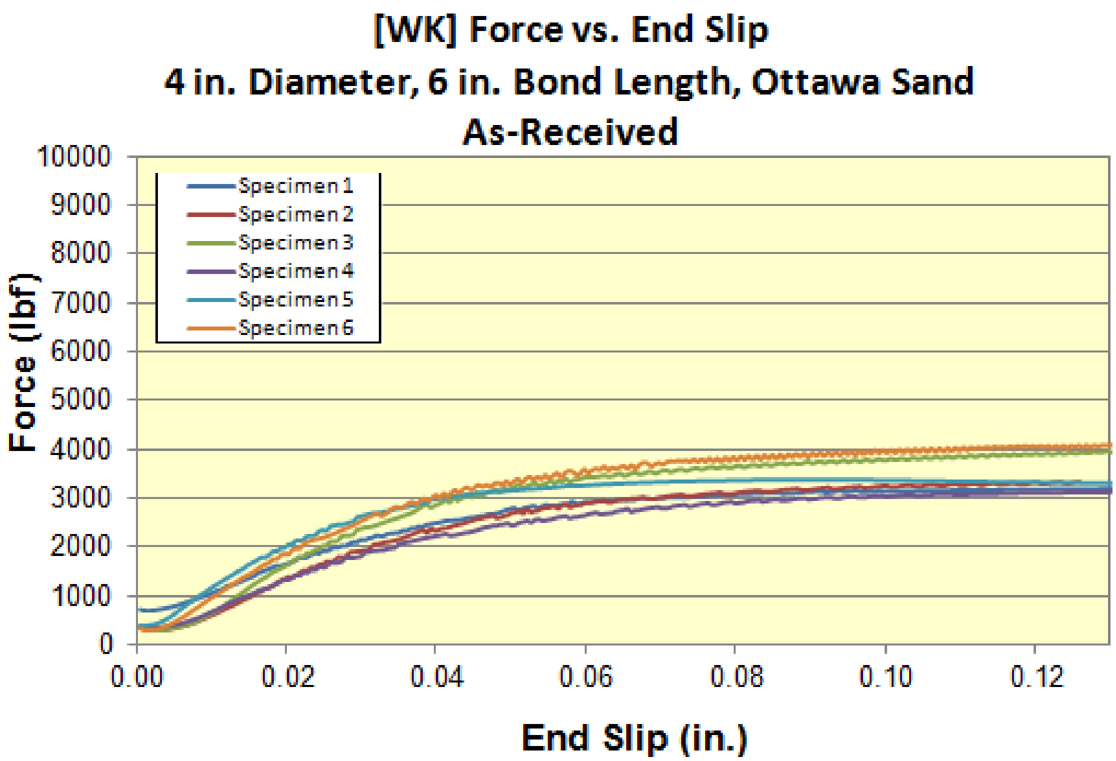

Figure E-11. As-received [WK] force vs. end-slip individual graphs

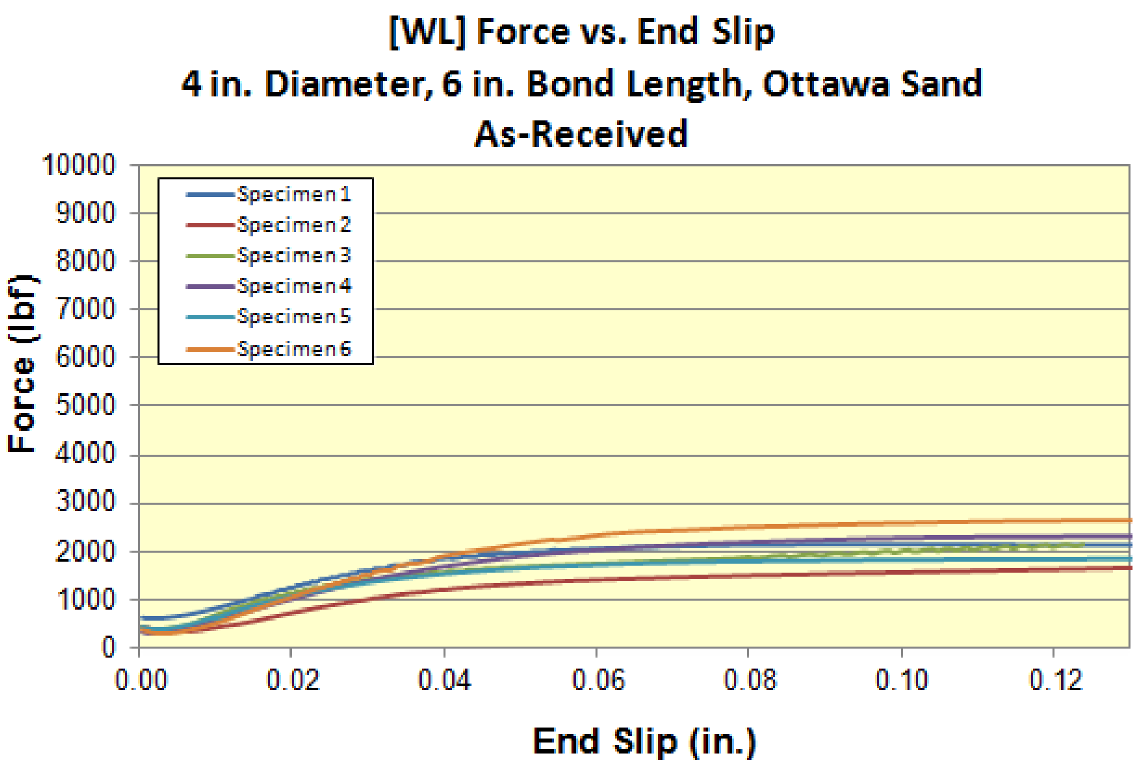

Figure E-12. As-received [WL] force vs. end-slip individual graphs

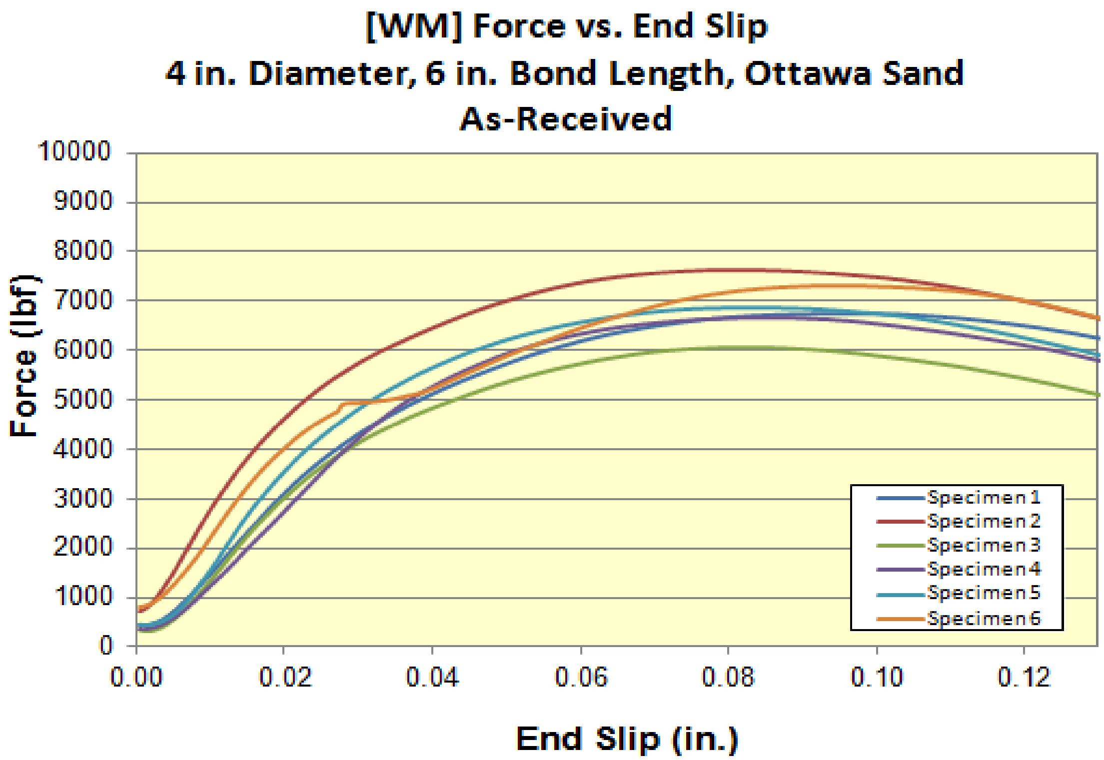

Figure E-13. As-received [WM] force vs. end-slip individual graphs

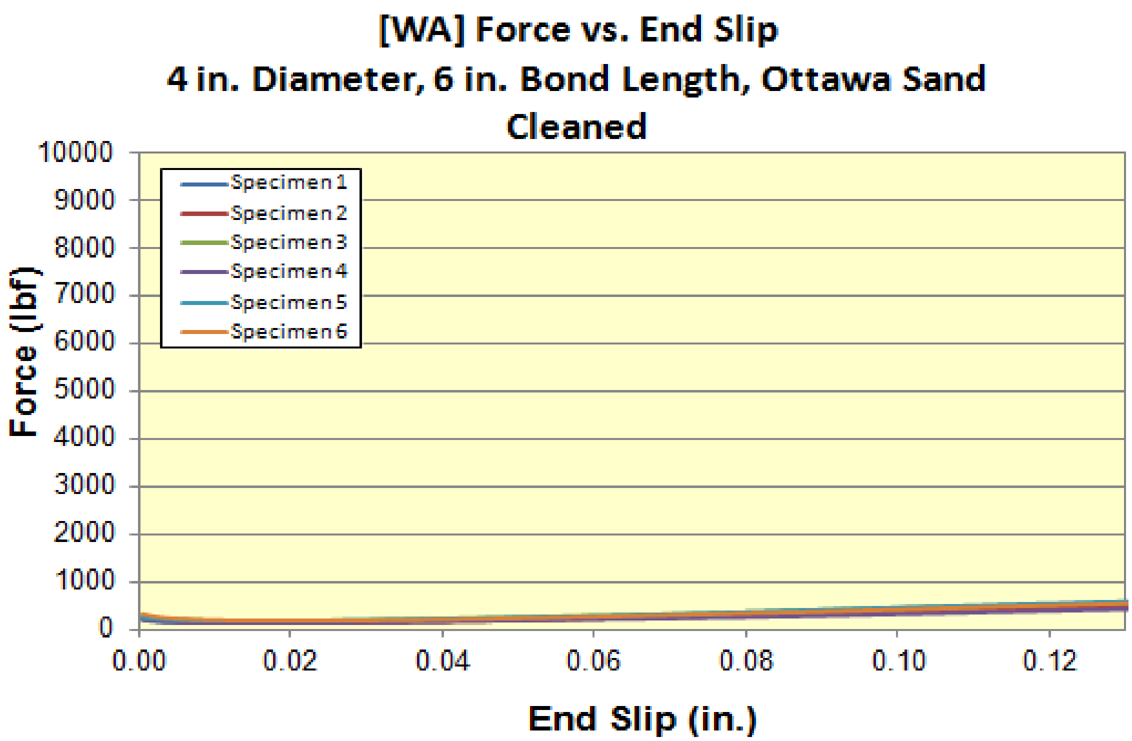

Figure E-14. Cleaned [WA] force vs. end-slip individual graphs

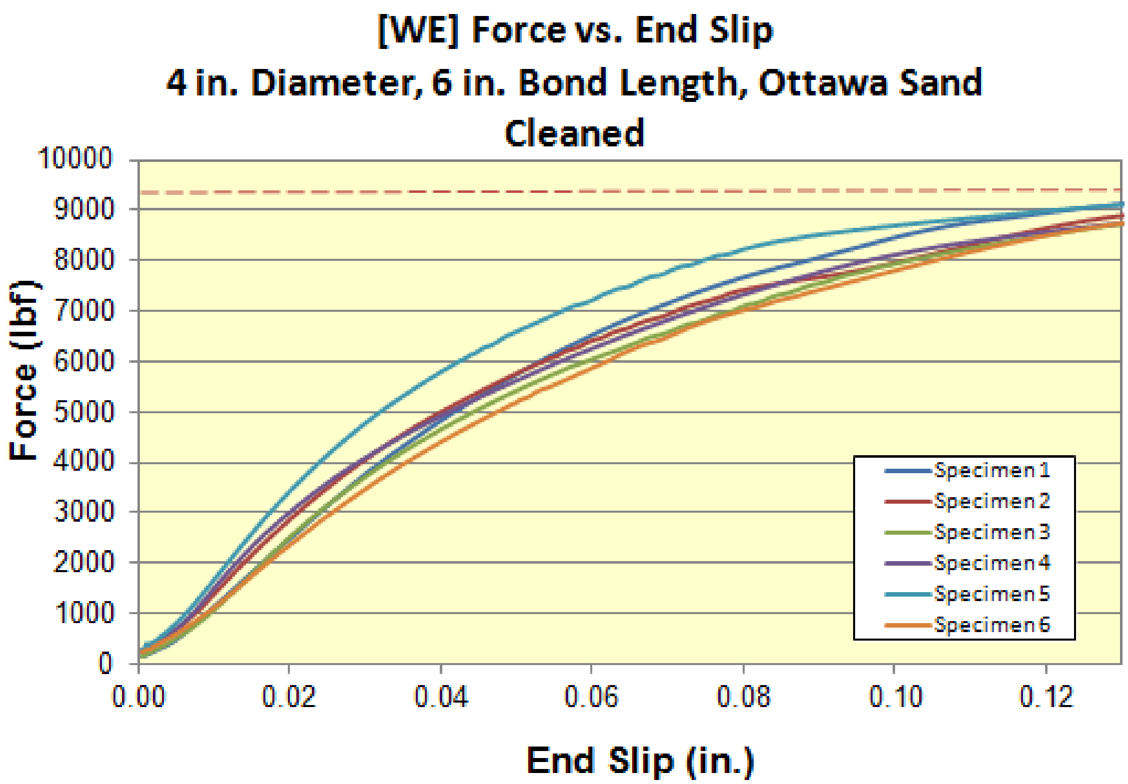

Figure E-15. Cleaned [WE] force vs. end-slip individual graphs

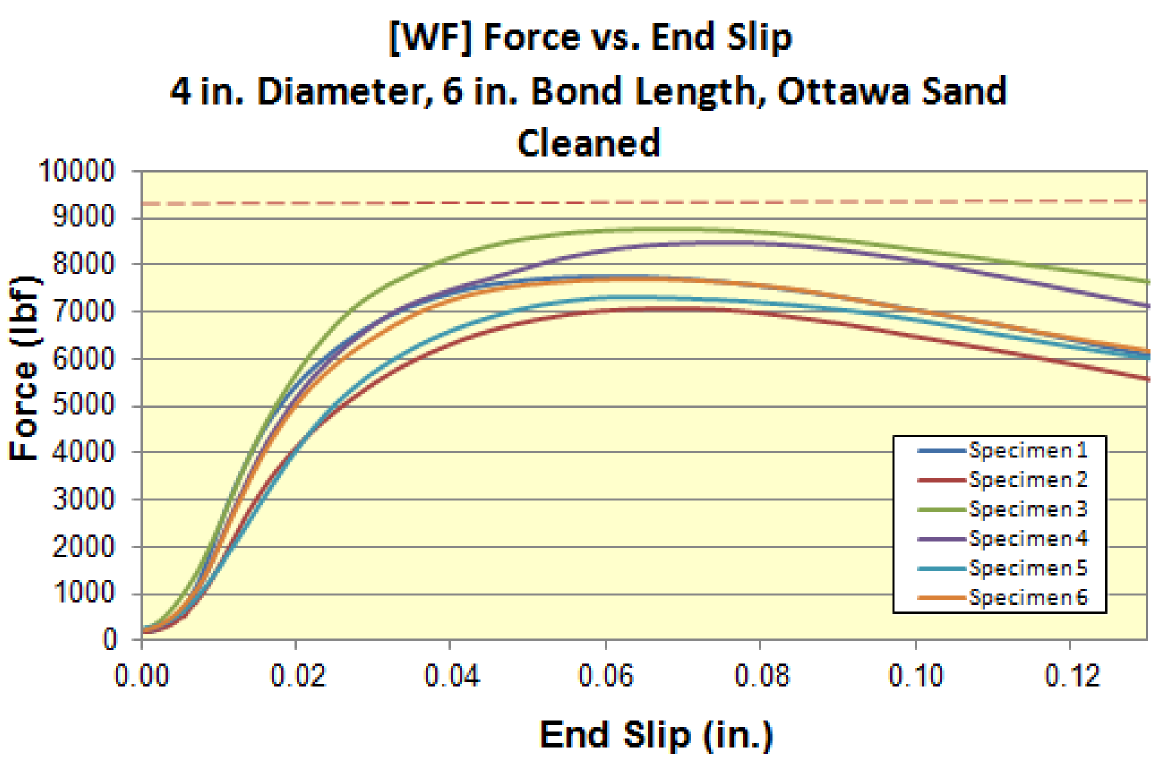

Figure E-16. Cleaned [WF] force vs. end-slip individual graphs

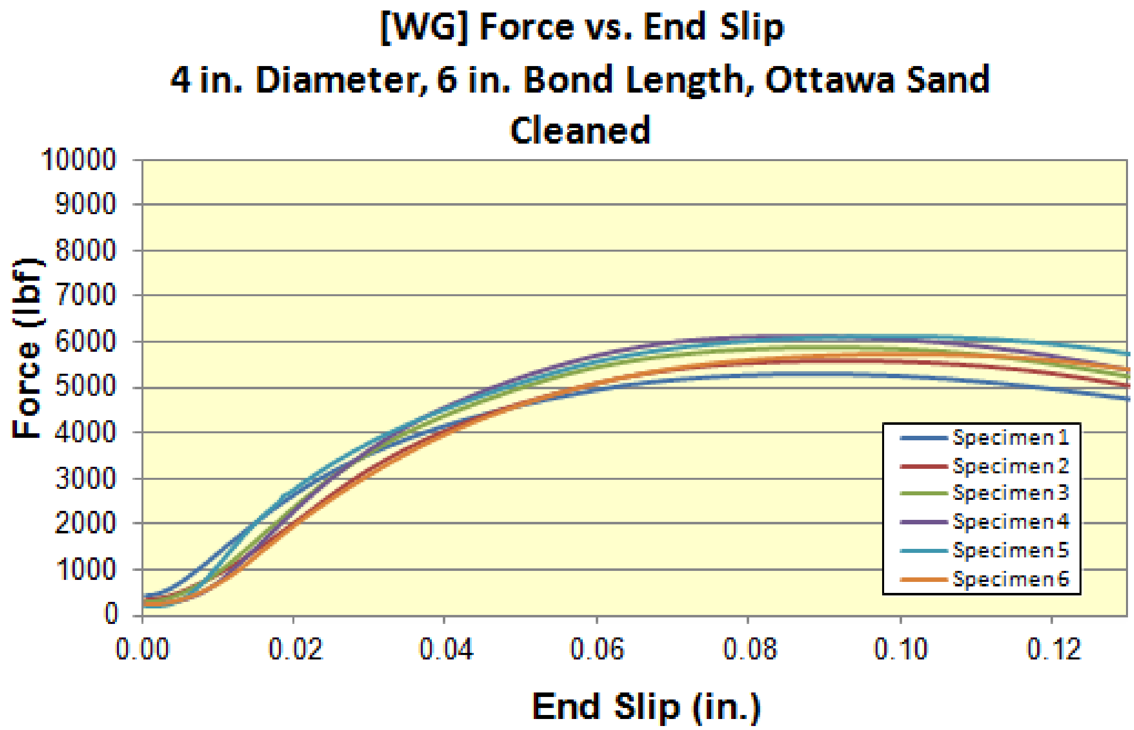

Figure E-17. Cleaned [WG] force vs. end-slip individual graphs

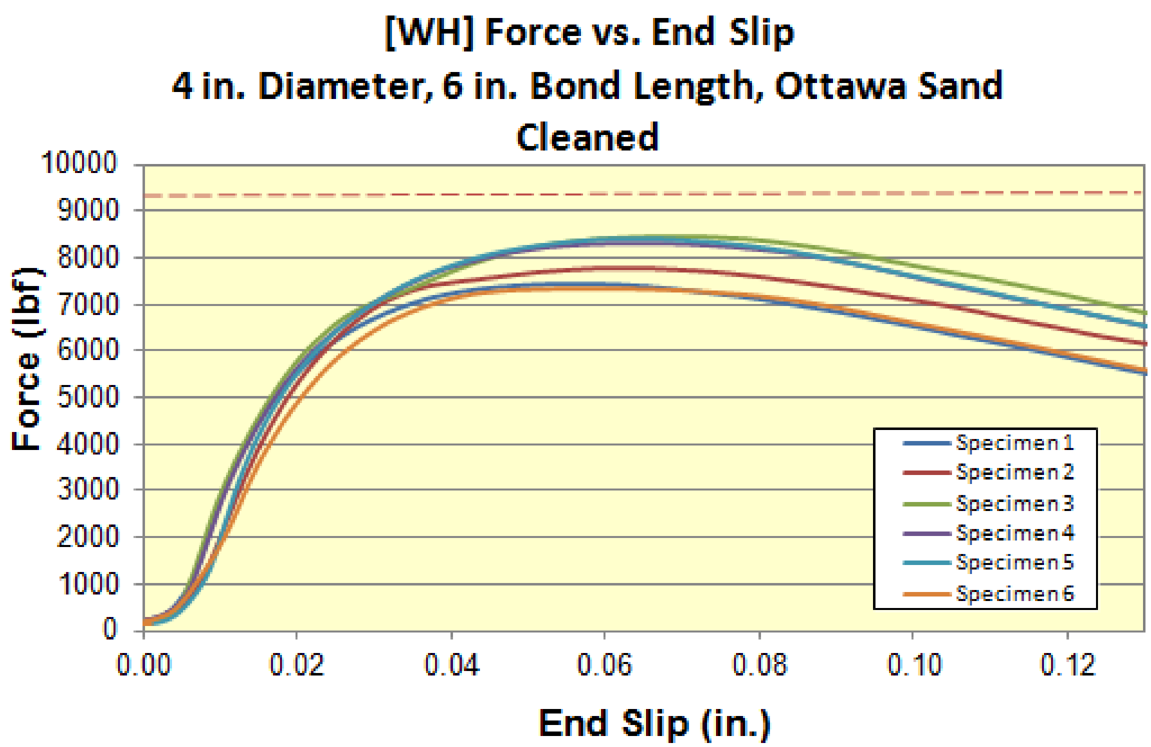

Figure E-18. Cleaned [WH] force vs. end-slip individual graphs

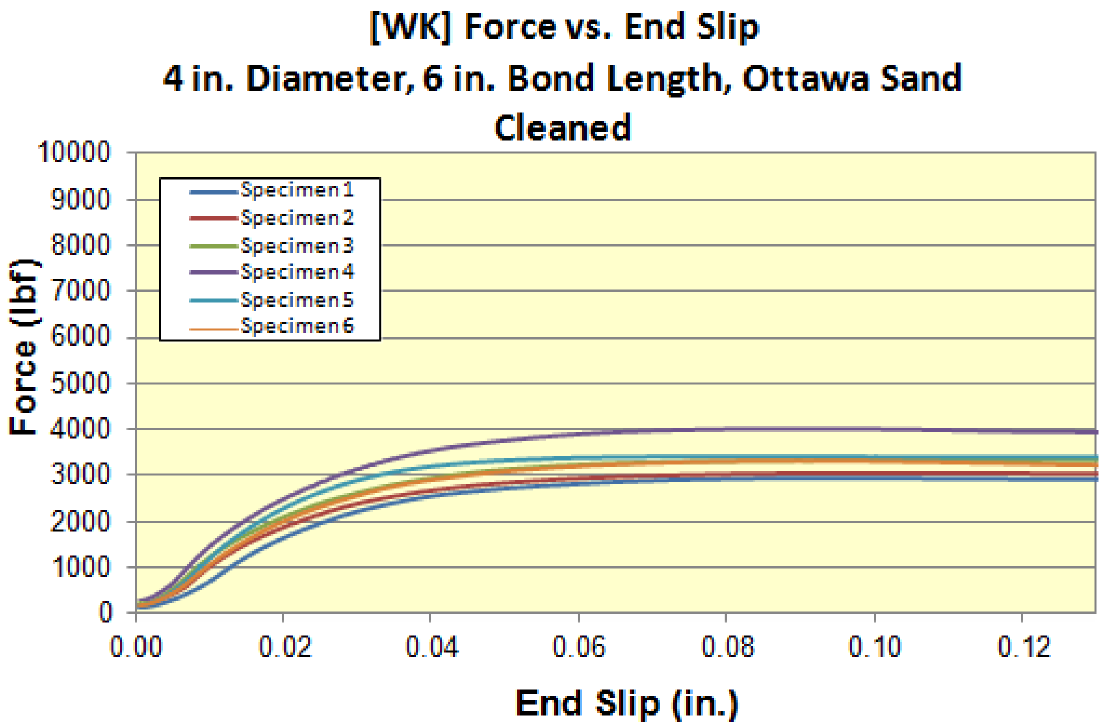

Figure E-19. Cleaned [WK] force vs. end-slip individual graphs

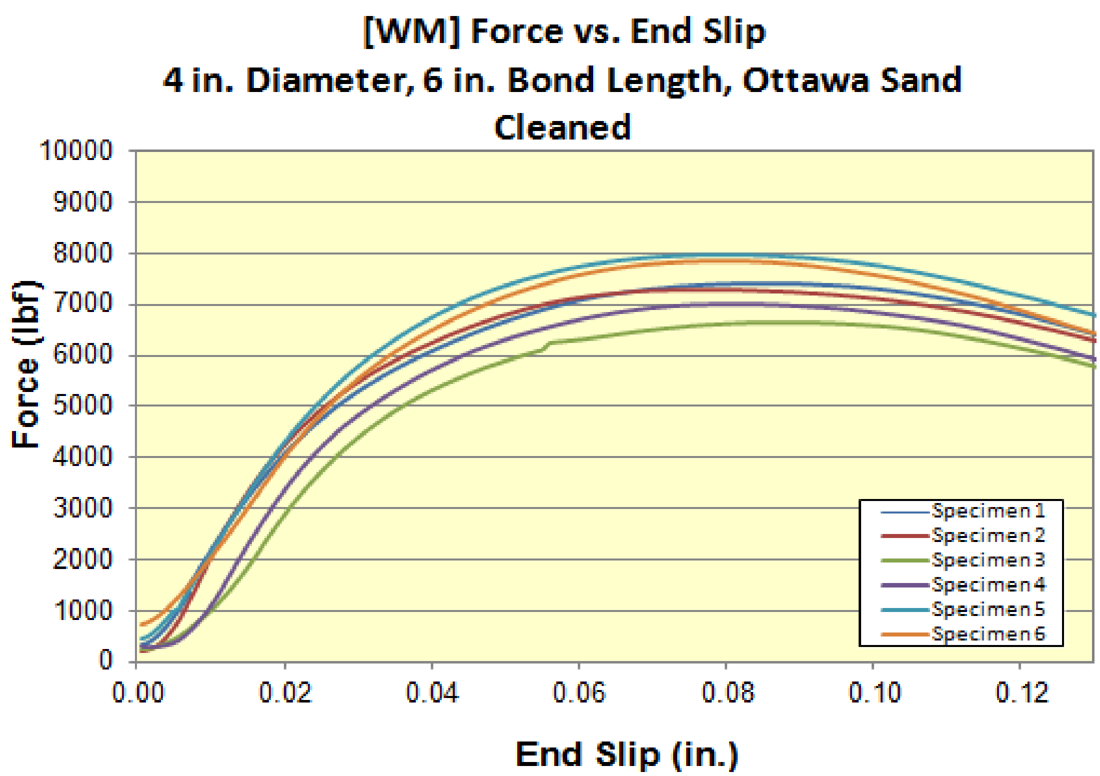

Figure E-20. Cleaned [WM] force vs. end-slip individual graphs

Appendix F.
Lab Phase, Wire; As-received Force at Certain End-slip Analysis

Table F-1. As-received wires, pullout force at 0.01-in. end slip

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Pullout Force at 0.01 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	247	22	8.8	16.3
[WB]	1496	447	29.9	11.6
[WC]	1557	224	14.4	8.8
[WD]	1576	370	23.5	11.1
[WE]	1166	177	15.2	7.4
[WF]	2286	417	18.2	8.5
[WG]	1012	261	25.7	11.8
[WH]	2200	303	13.8	7.5
[WI]	1508	233	15.5	10.1
[WJ]	1931	605	31.3	9.0
[WK]	817	225	27.6	14.0
[WL]	593	150	25.3	18.7

Note: Sample Size = 6

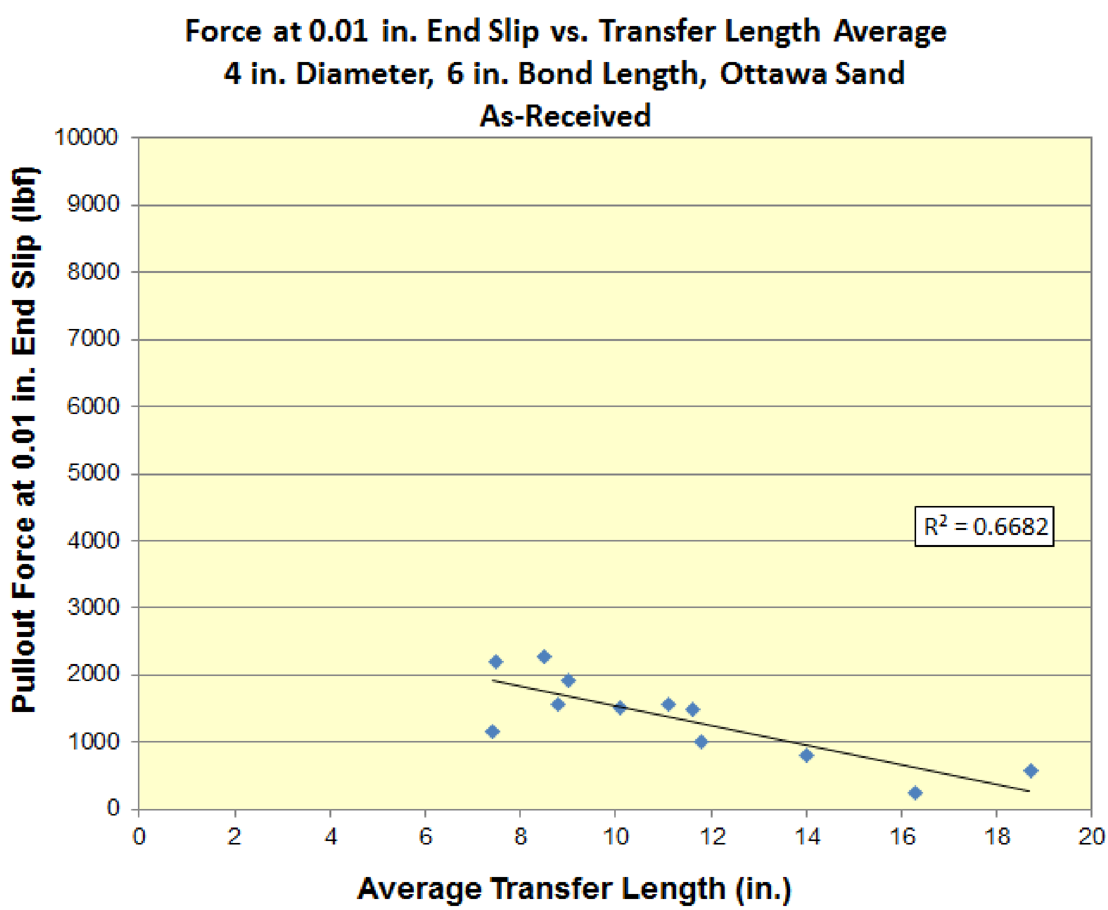

Figure F-1. As-received wires, pullout force at 0.01-in. end slip

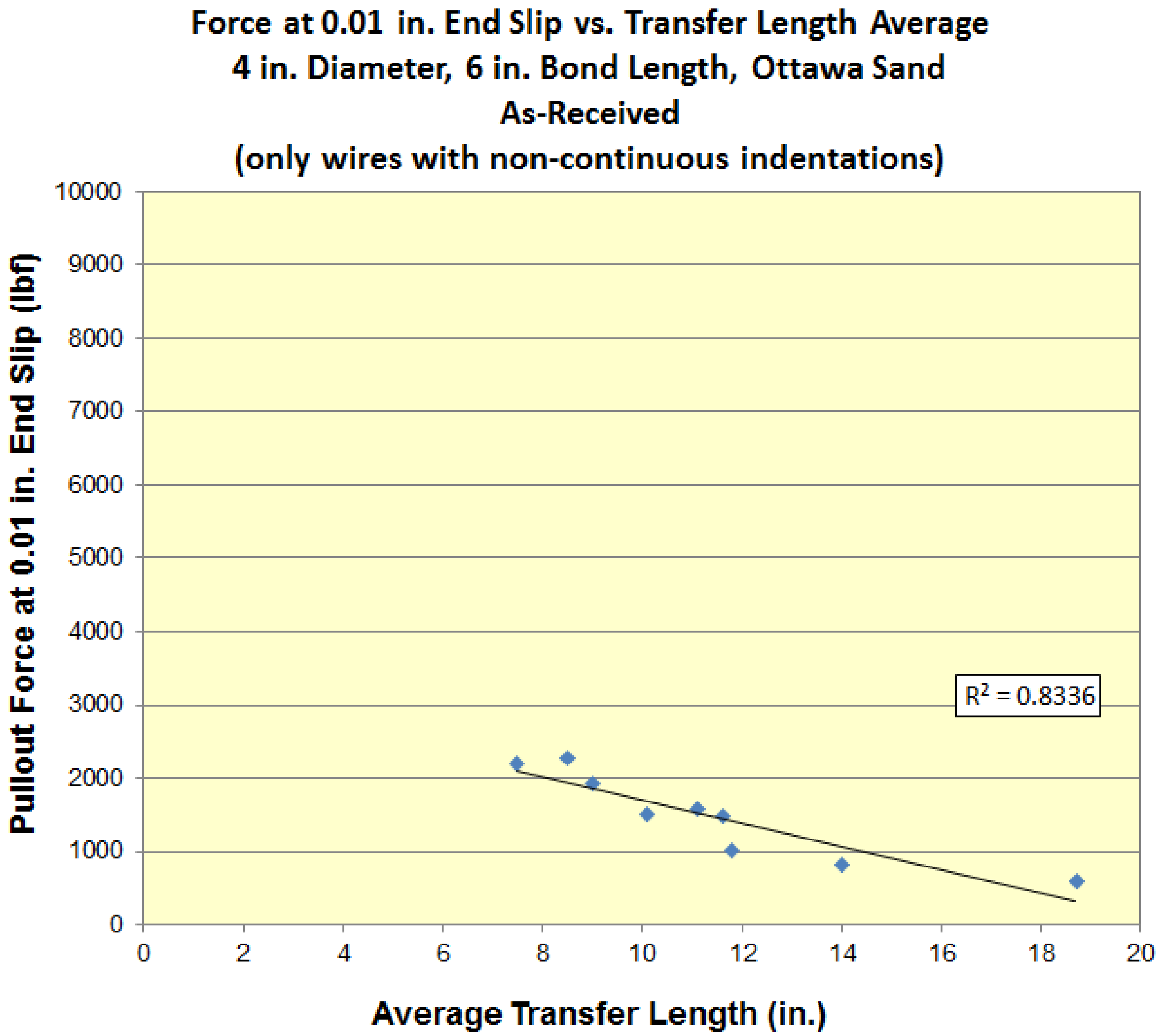

Figure F-2. As-received wires, pullout force at 0.01-in. end slip (individual-indents only)

Table F-2. As-received wires, pullout force at 0.02-in. end slip

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Pullout Force at 0.02 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	213	19	9.1	16.3
[WB]	3366	530	15.8	11.6
[WC]	2794	340	12.2	8.8
[WD]	3616	445	12.3	11.1
[WE]	2580	288	11.2	7.4
[WF]	5135	511	10.0	8.5
[WG]	2265	411	18.1	11.8
[WH]	4809	398	8.3	7.5
[WI]	3511	371	10.6	10.1
[WJ]	4315	729	16.9	9.0
[WK]	1625	247	15.2	14.0
[WL]	1014	175	17.2	18.7

Note: Sample Size = 6

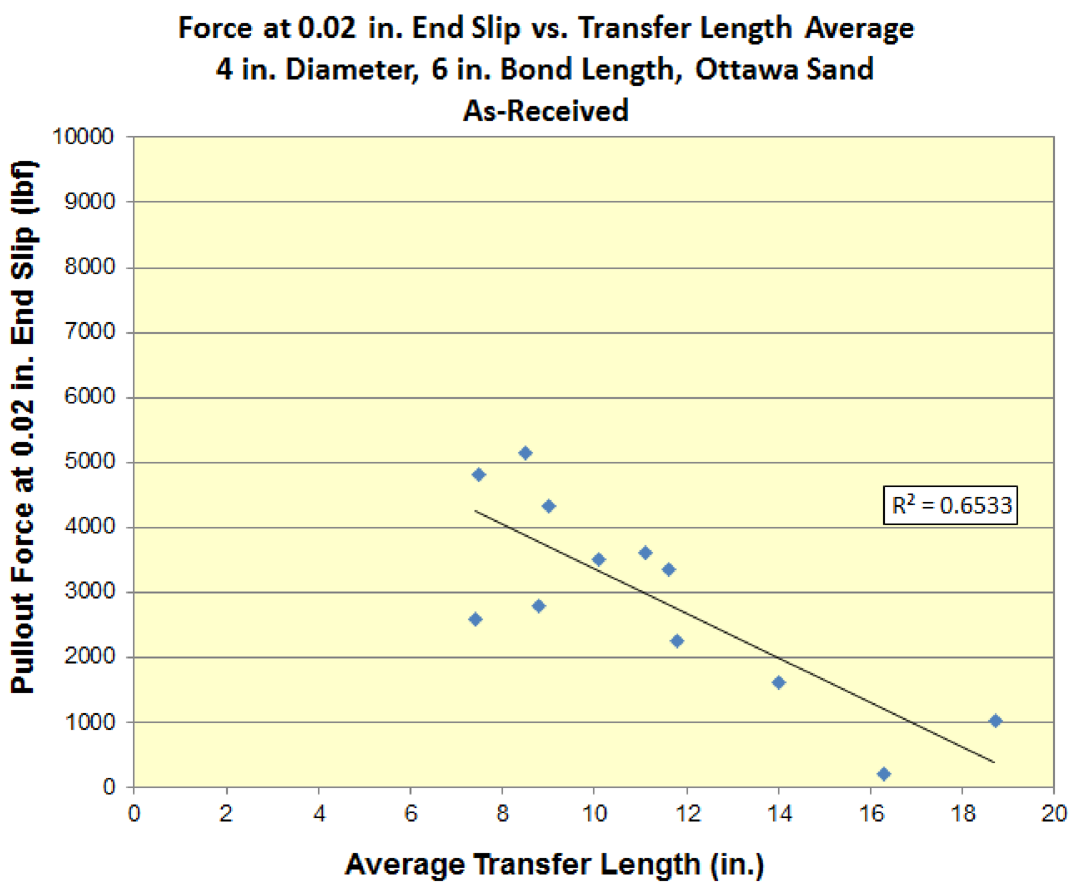

Figure F-3. As-received wires, pullout force at 0.02-in. end slip

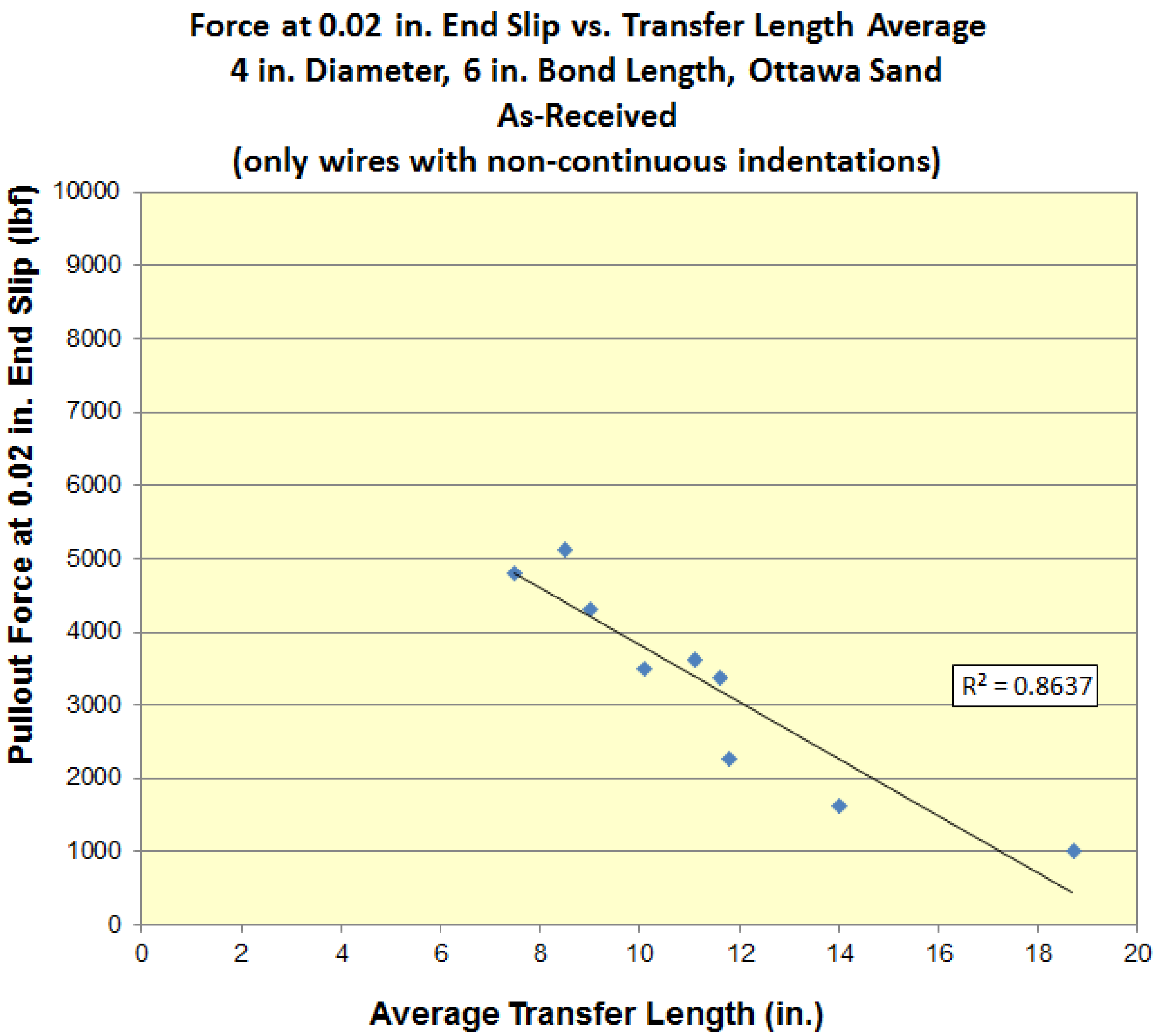

Figure F-4. As-received wires, pullout force at 0.02-in. end slip (individual-indents only)

Table F-3. As-received wires, pullout force at 0.03-in. end slip

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Pullout Force at 0.03 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	210	18	8.6	16.3
[WB]	4540	503	11.1	11.6
[WC]	3737	387	10.3	8.8
[WD]	4676	435	9.3	11.1
[WE]	3709	333	9.0	7.4
[WF]	6659	555	8.3	8.5
[WG]	3307	413	12.5	11.8
[WH]	6040	394	6.5	7.5
[WI]	4825	419	8.7	10.1
[WJ]	5601	752	13.4	9.0
[WK]	2240	314	14.0	14.0
[WL]	1371	191	13.9	18.7

Note: Sample Size = 6

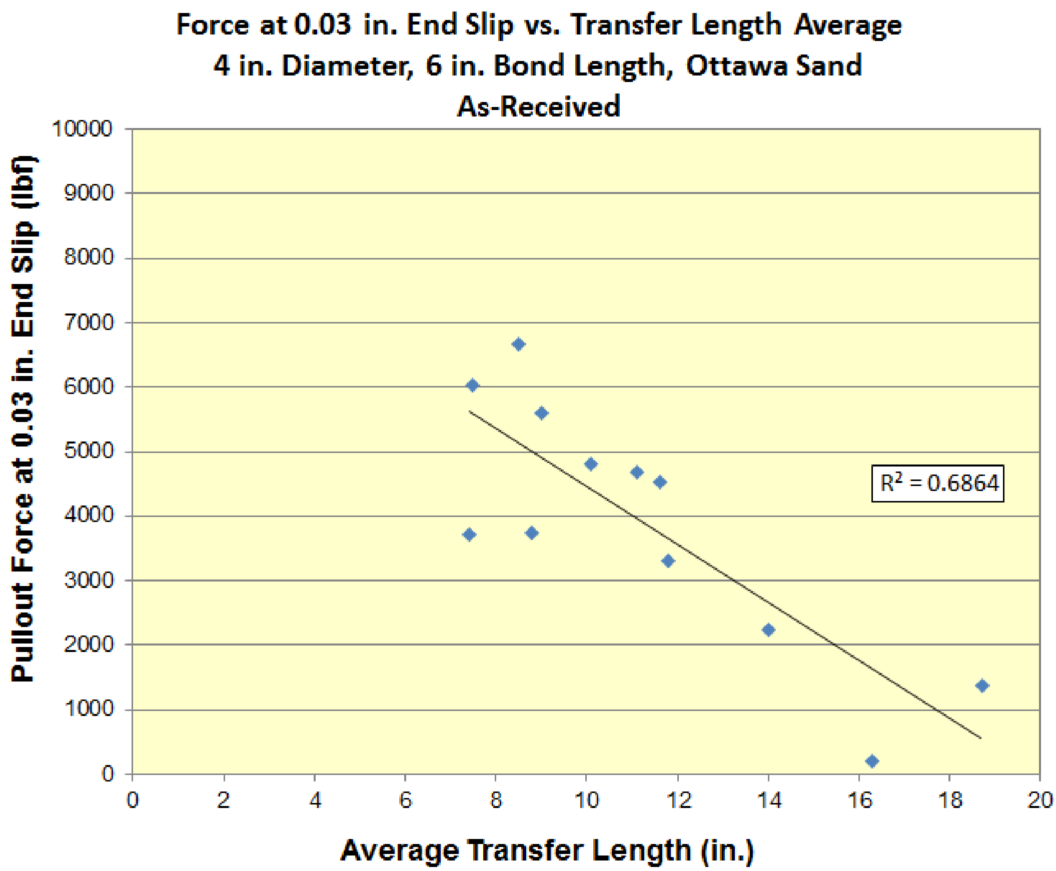

Figure F-5. As-received wires, pullout force at 0.03-in. end slip

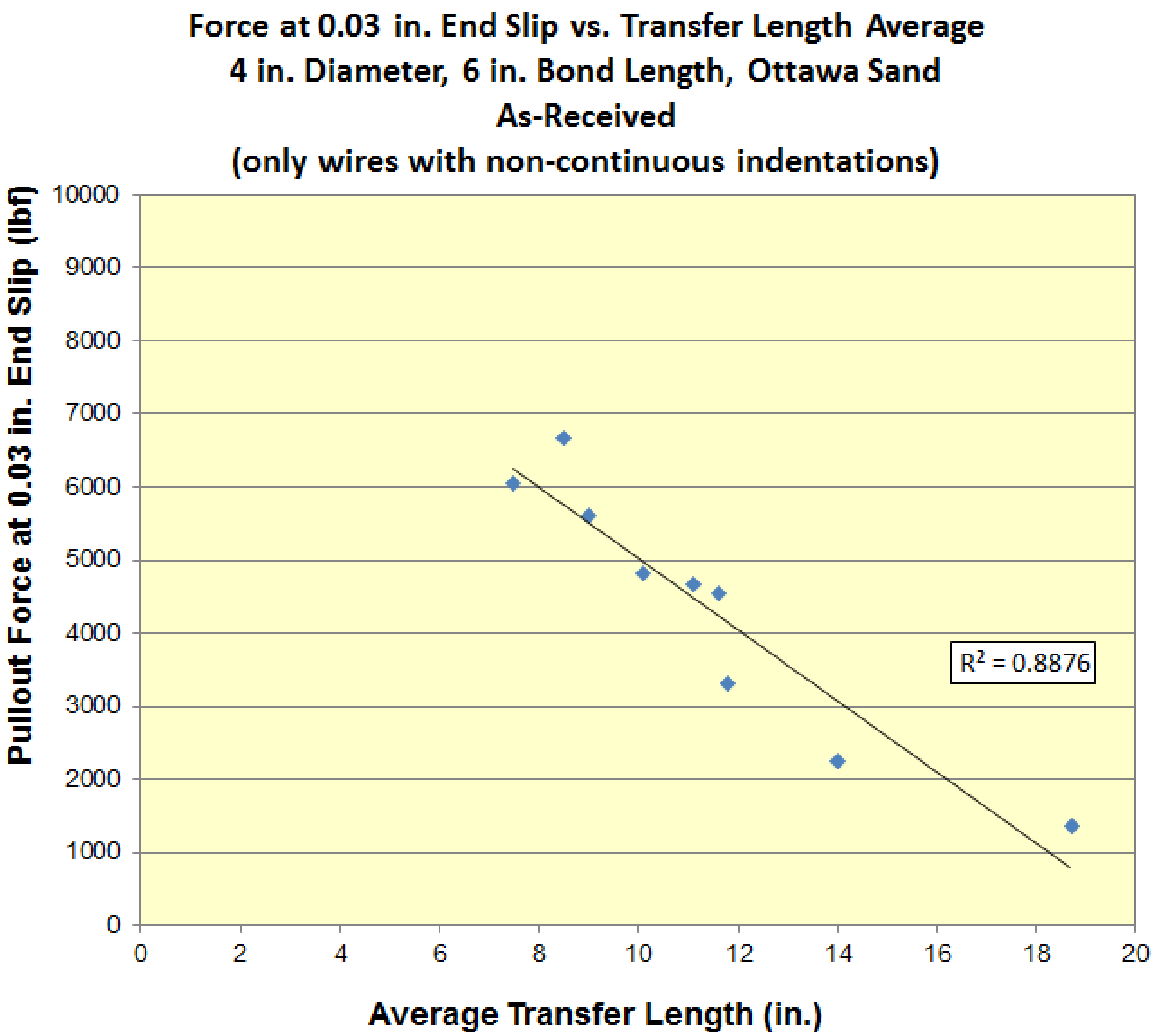

Figure F-6. As-received wires, pullout force at 0.03-in. end slip (individual-indents only)

Table F-4. As-received wires, pullout force at 0.04-in. end slip

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Pullout Force at 0.04 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	217	18	8.1	16.3
[WB]	5210	533	10.2	11.6
[WC]	4514	434	9.6	8.8
[WD]	5187	400	7.7	11.1
[WE]	4630	379	8.2	7.4
[WF]	7485	565	7.6	8.5
[WG]	4051	411	10.1	11.8
[WH]	6742	423	6.3	7.5
[WI]	5603	468	8.4	10.1
[WJ]	6291	728	11.6	9.0
[WK]	2653	333	12.5	14.0
[WL]	1614	219	13.6	18.7

Note: Sample Size = 6

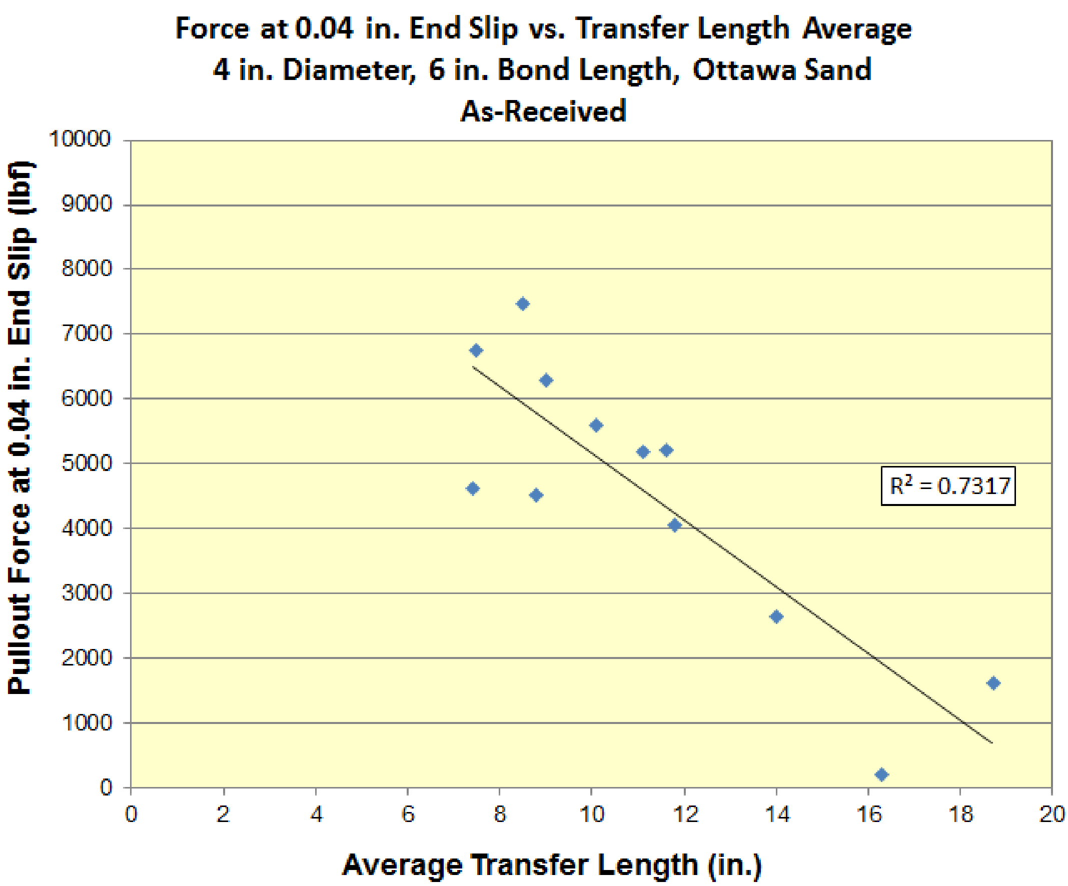

Figure F-7. As-received wires, pullout force at 0.04-in. end slip

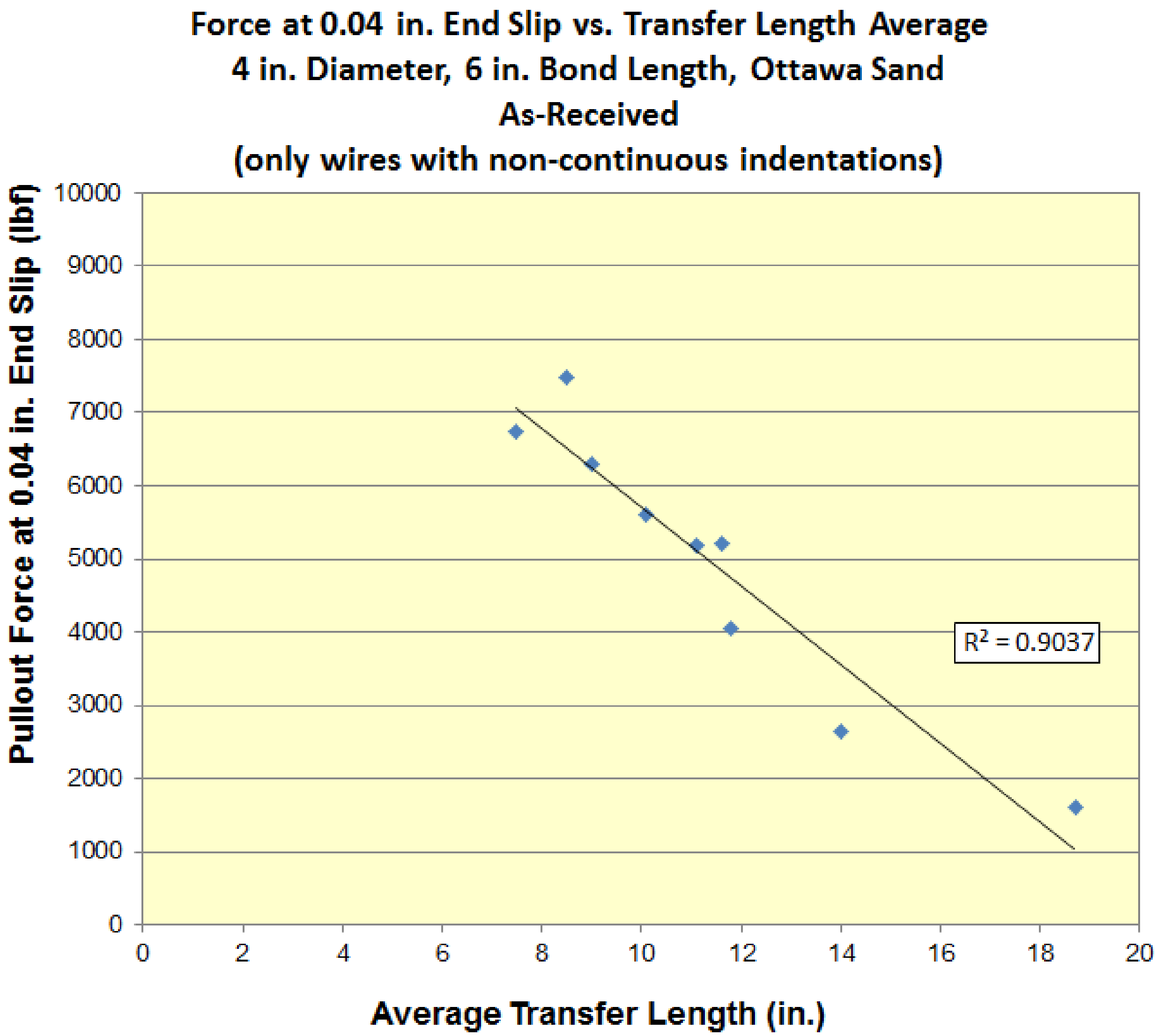

Figure F-8. As-received wires, pullout force at 0.04-in. end slip (individual-indents only)

Table F-5. As-received wires, pullout force at 0.05-in. end slip

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Pullout Force at 0.05 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	234	20	8.6	16.3
[WB]	5627	592	10.5	11.6
[WC]	5198	499	9.6	8.8
[WD]	5400	391	7.2	11.1
[WE]	5381	402	7.5	7.4
[WF]	7928	535	6.8	8.5
[WG]	4586	407	8.9	11.8
[WH]	7186	488	6.8	7.5
[WI]	6095	506	8.3	10.1
[WJ]	6682	687	10.3	9.0
[WK]	2919	306	10.5	14.0
[WL]	1773	260	14.7	18.7

Note: Sample Size = 6

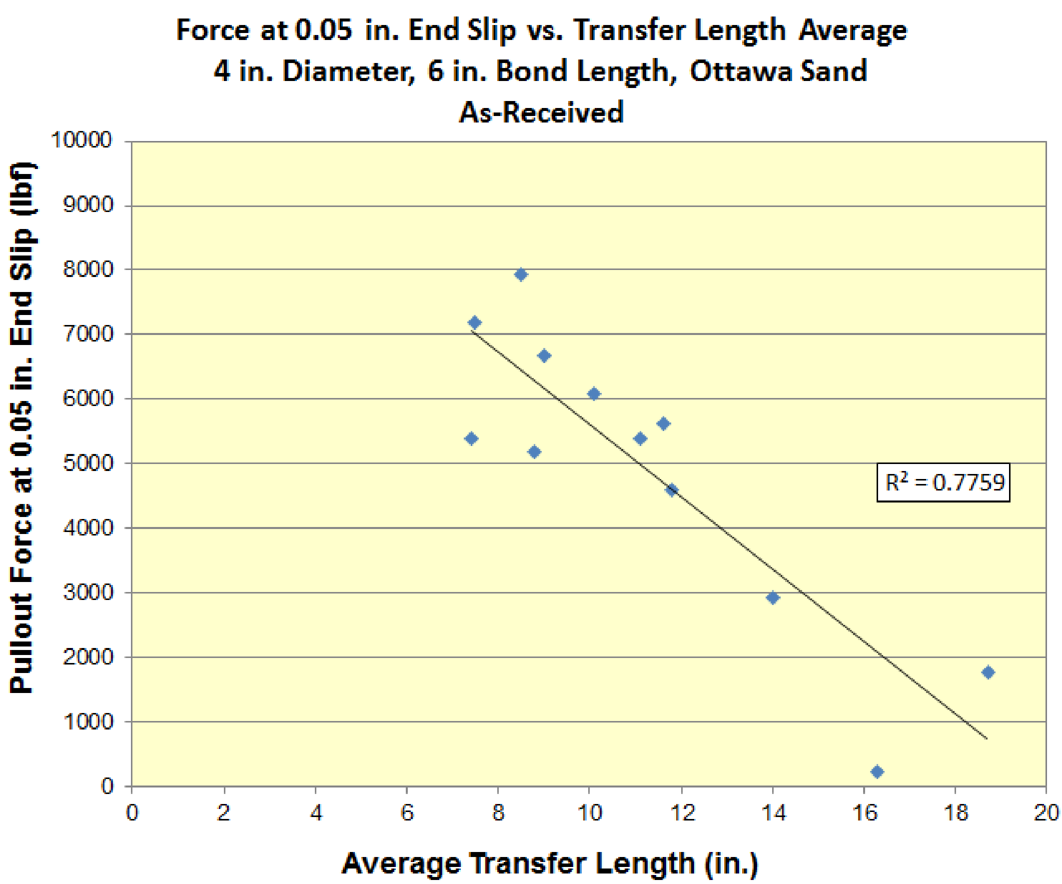

Figure F-9. As-received wires, pullout force at 0.05-in. end slip

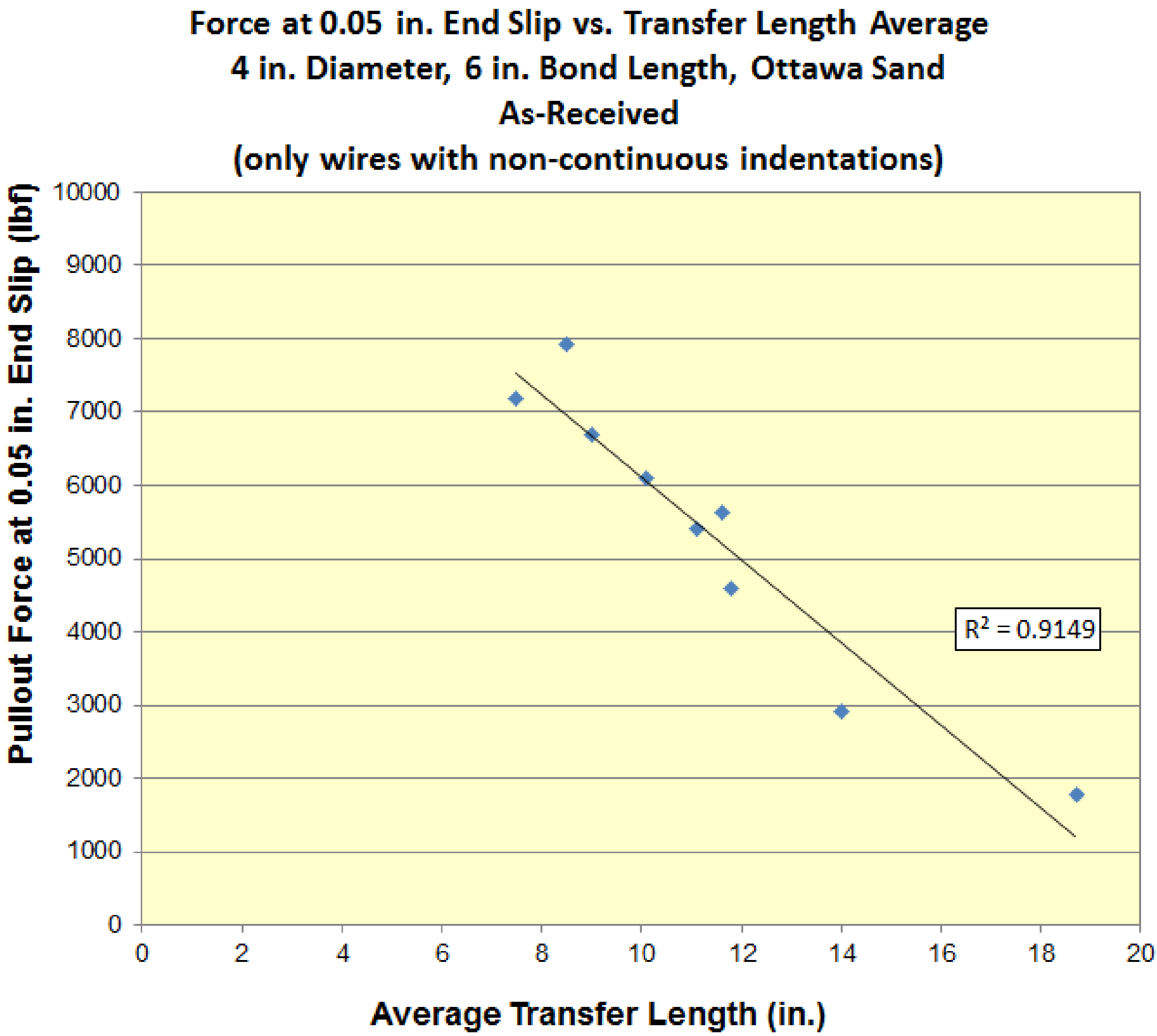

Figure F-10. As-received wires, pullout force at 0.05-in. end slip (individual-indents only)

Table F-6. As-received wires, pullout force at 0.06-in. end slip

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Pullout Force at 0.06 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	255	24	9.2	16.3
[WB]	5936	624	10.5	11.6
[WC]	5785	570	9.8	8.8
[WD]	5494	378	6.9	11.1
[WE]	6018	434	7.2	7.4
[WF]	8192	491	6.0	8.5
[WG]	4972	400	8.1	11.8
[WH]	7458	508	6.8	7.5
[WI]	6372	520	8.2	10.1
[WJ]	6899	664	9.6	9.0
[WK]	3111	320	10.3	14.0
[WL]	1878	289	15.4	18.7

Note: Sample Size = 6

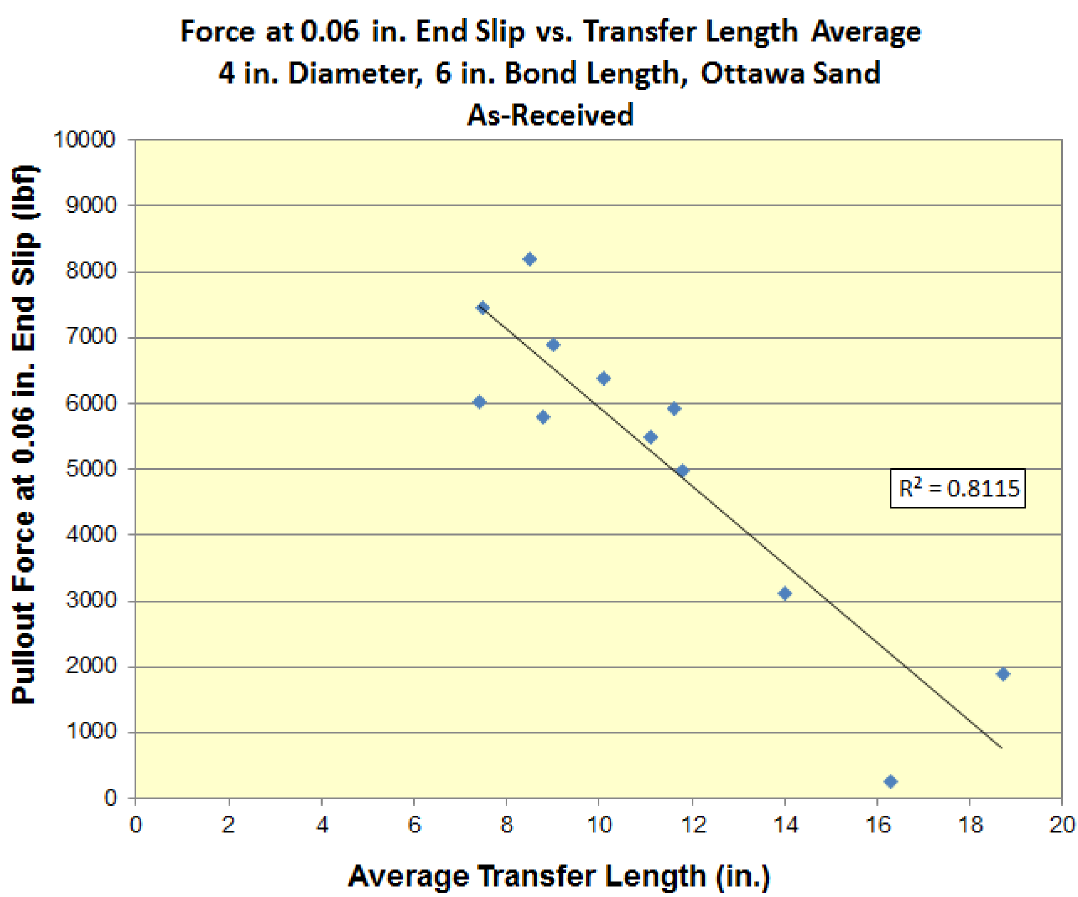

Figure F-11. As-received wires, pullout force at 0.06-in. end slip

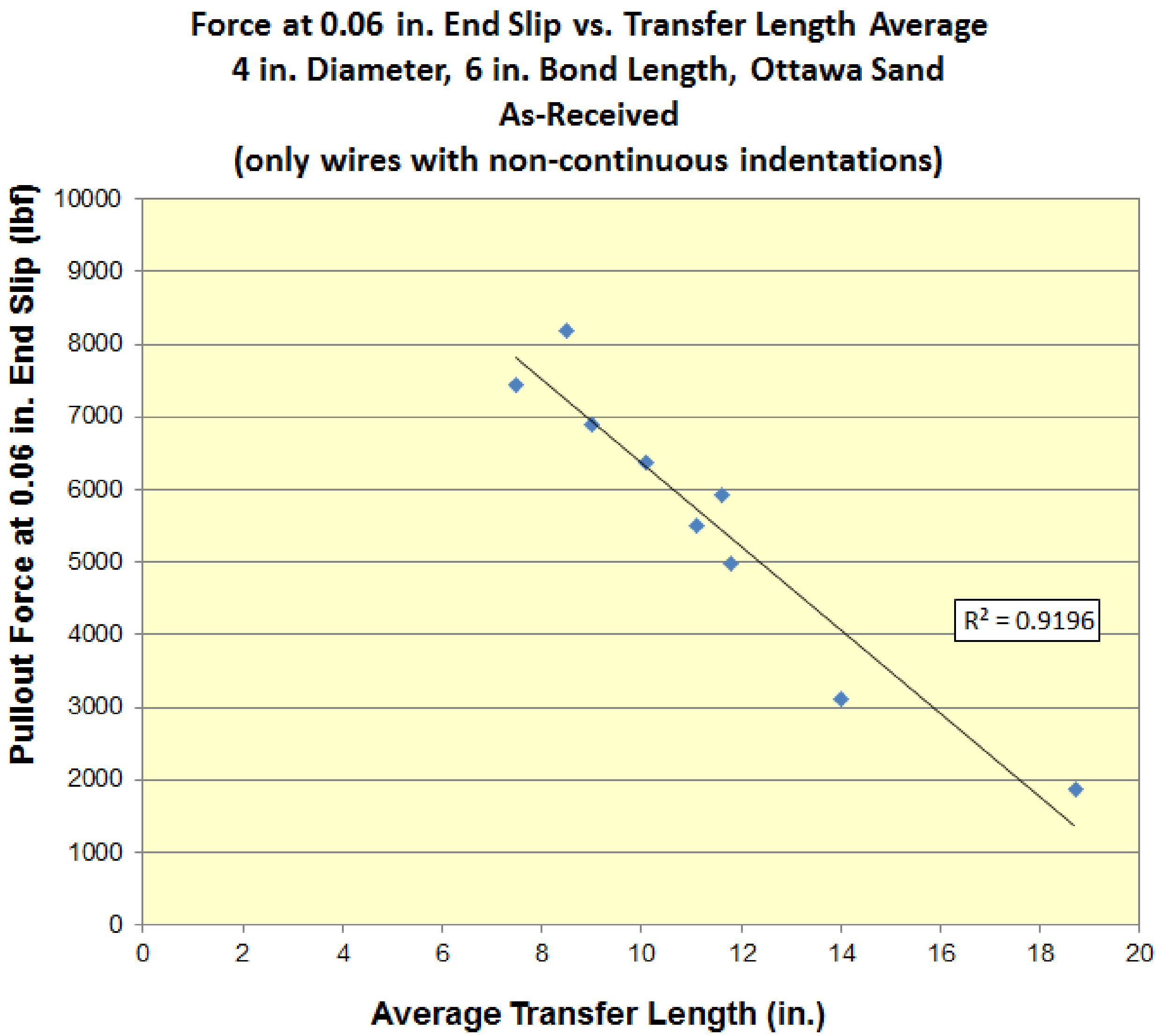

Figure F-12. As-received wires, pullout force at 0.06-in. end slip (individual-indents only)

Table F-7. As-received wires, pullout force at 0.07-in. end slip

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Pullout Force at 0.07 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	282	27	9.4	16.3
[WB]	6178	621	10.1	11.6
[WC]	6358	671	10.5	8.8
[WD]	5534	355	6.4	11.1
[WE]	6547	468	7.2	7.4
[WF]	8296	464	5.6	8.5
[WG]	5269	398	7.6	11.8
[WH]	7585	508	6.7	7.5
[WI]	6514	525	8.1	10.1
[WJ]	7009	645	9.2	9.0
[WK]	3227	322	10.0	14.0
[WL]	1951	311	15.9	18.7

Note: Sample Size = 6

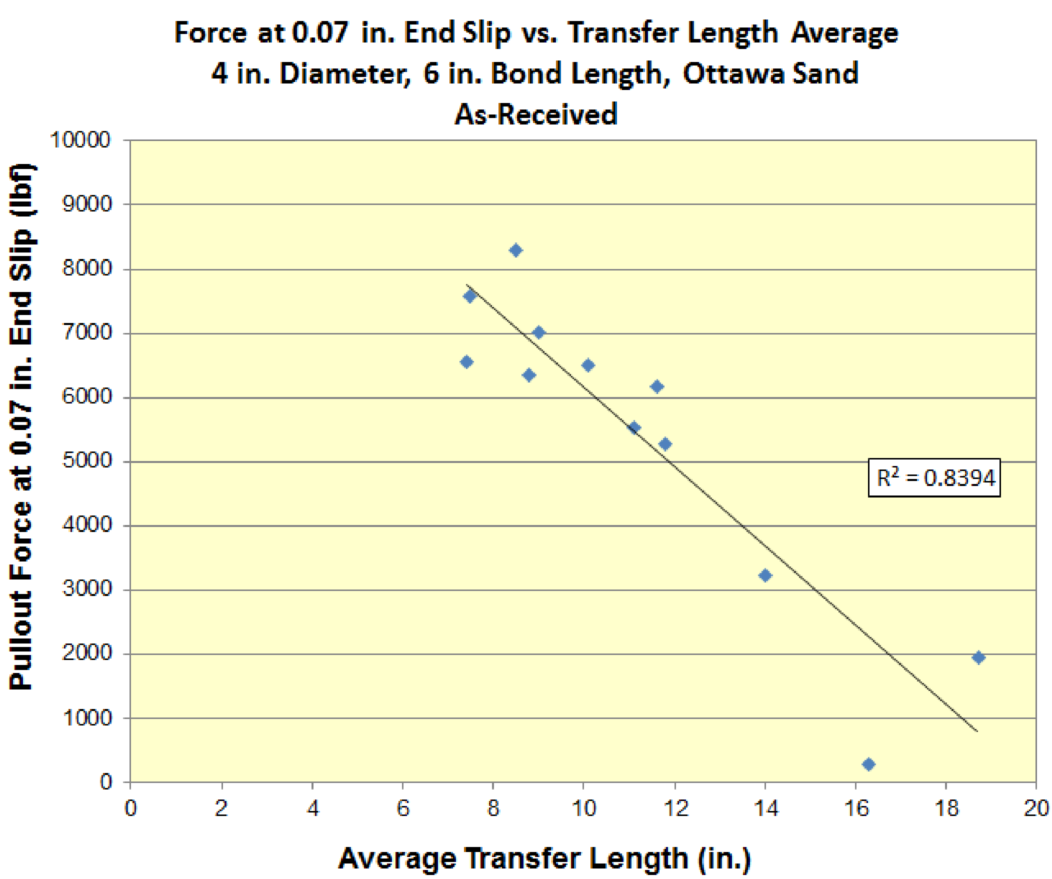

Figure F-13. As-received wires, pullout force at 0.07-in. end slip

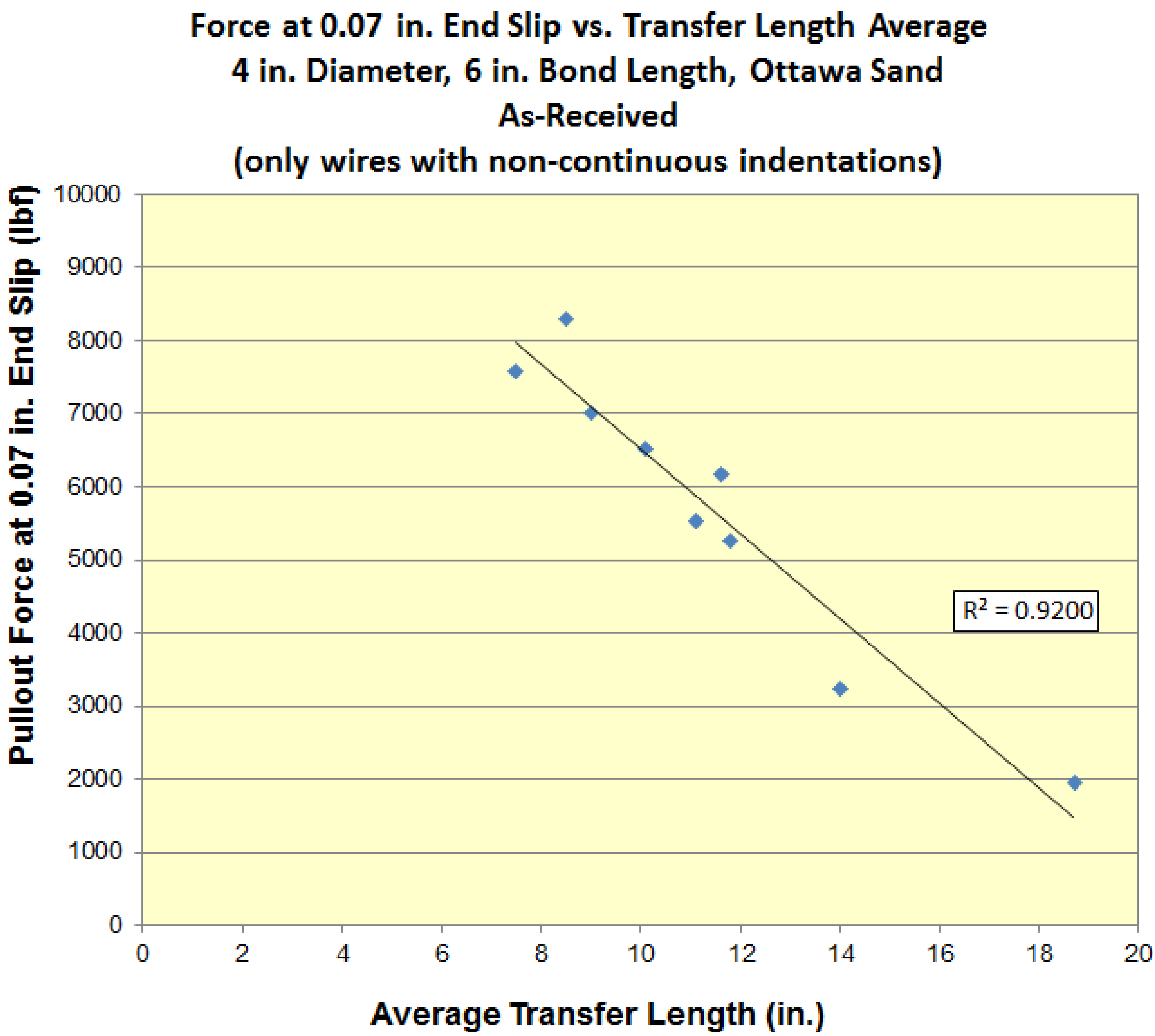

Figure F-14. As-received wires, pullout force at 0.07-in. end slip (individual-indents only)

Table F-8. As-received wires, pullout force at 0.08-in. end slip

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Pullout Force at 0.08 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	311	29	9.2	16.3
[WB]	6356	607	9.6	11.6
[WC]	6860	794	11.6	8.8
[WD]	5511	333	6.0	11.1
[WE]	6983	474	6.8	7.4
[WF]	8287	453	5.5	8.5
[WG]	5440	388	7.1	11.8
[WH]	7588	497	6.5	7.5
[WI]	6558	525	8.0	10.1
[WJ]	7025	628	8.9	9.0
[WK]	3324	348	10.5	14.0
[WL]	1999	318	15.9	18.7

Note: Sample Size = 6

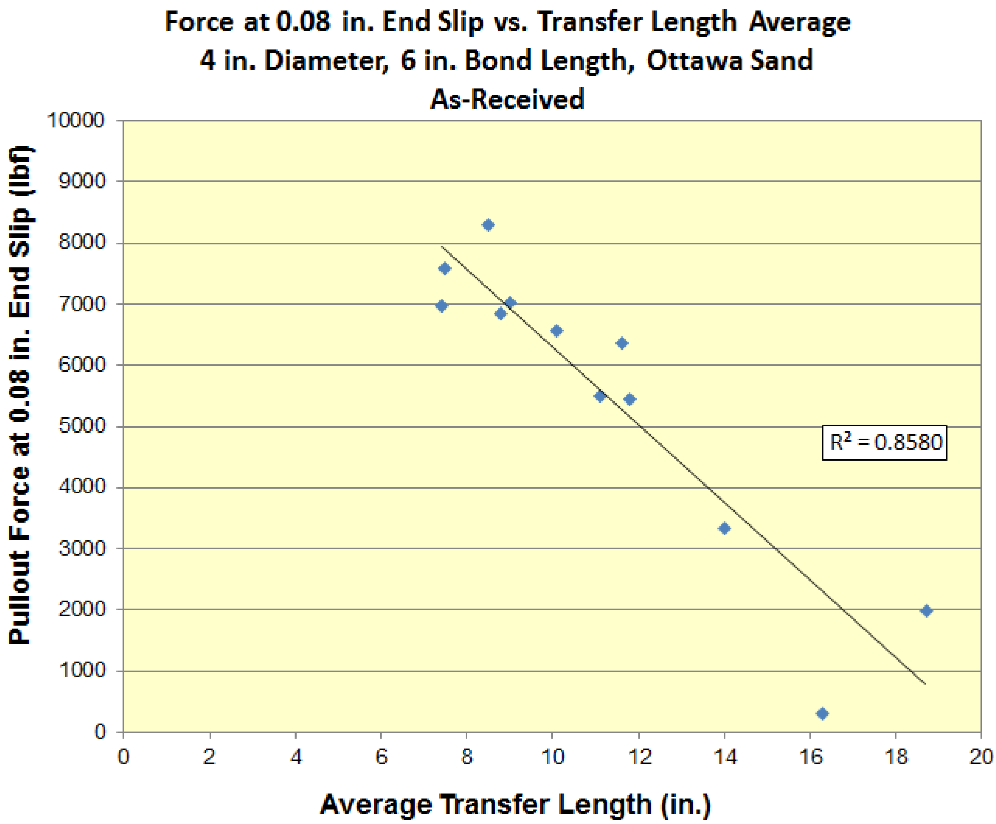

Figure F-15. As-received wires, pullout force at 0.08-in. end slip

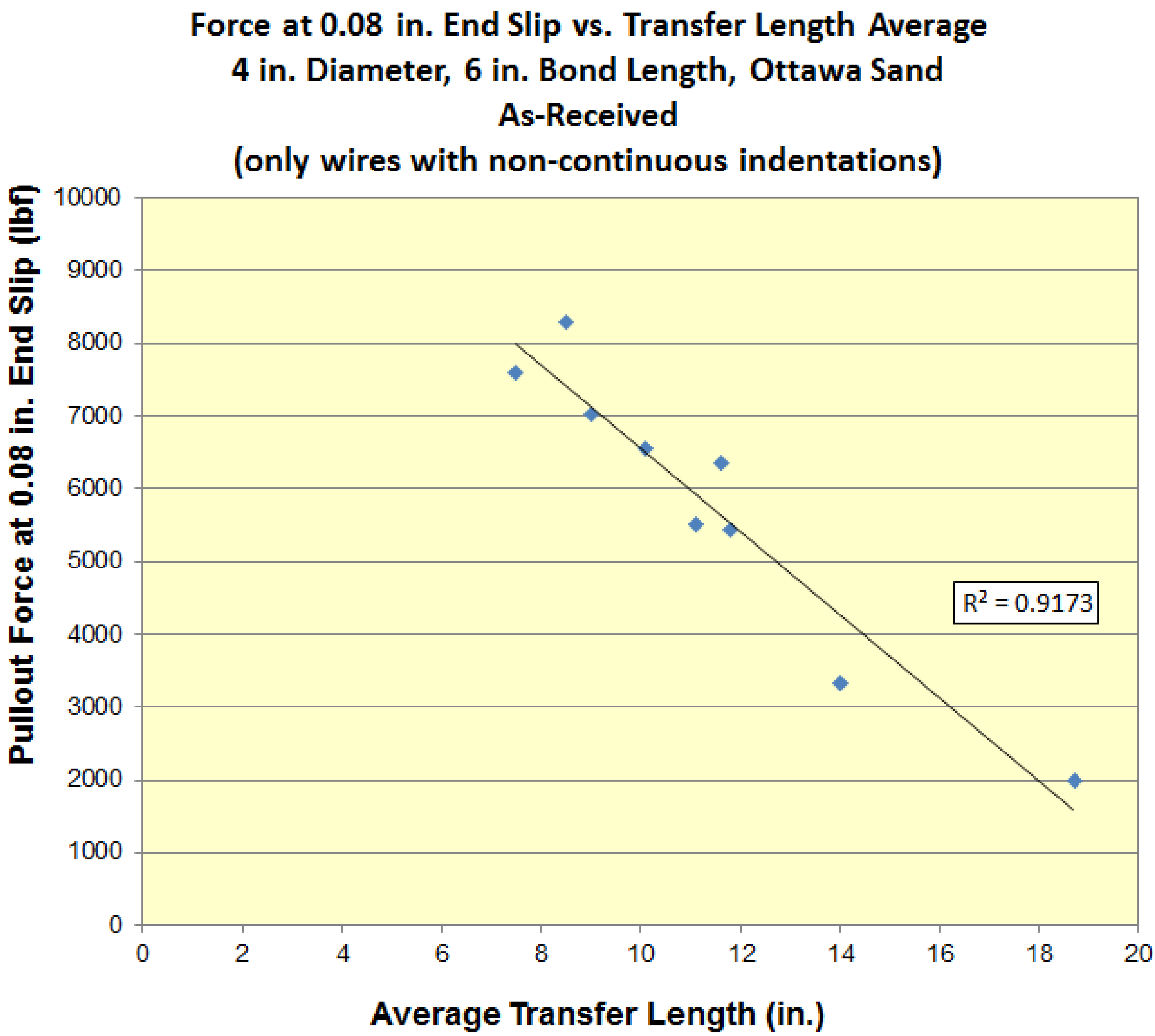

Figure F-16. As-received wires, pullout force at 0.08-in. end slip (individual-indents only)

Table F-9. As-received wires, pullout force at 0.09-in. end slip

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Pullout Force at 0.09 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	342	30	8.9	16.3
[WB]	6455	585	9.1	11.6
[WC]	7300	904	12.4	8.8
[WD]	5430	317	5.8	11.1
[WE]	7367	477	6.5	7.4
[WF]	8182	448	5.5	8.5
[WG]	5499	384	7.0	11.8
[WH]	7477	485	6.5	7.5
[WI]	6535	515	7.9	10.1
[WJ]	6955	612	8.8	9.0
[WK]	3377	338	10.0	14.0
[WL]	2041	321	15.7	18.7

Note: Sample Size = 6

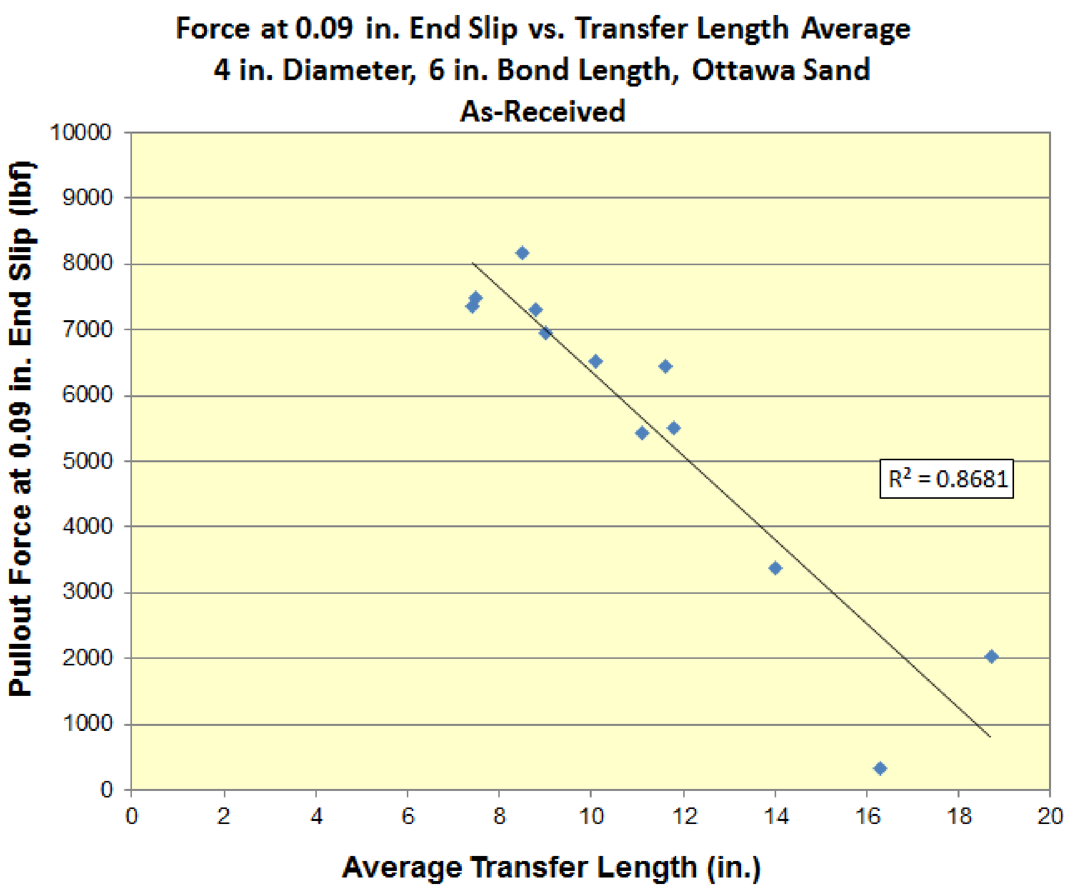

Figure F-17. As-received wires, pullout force at 0.09-in. end slip

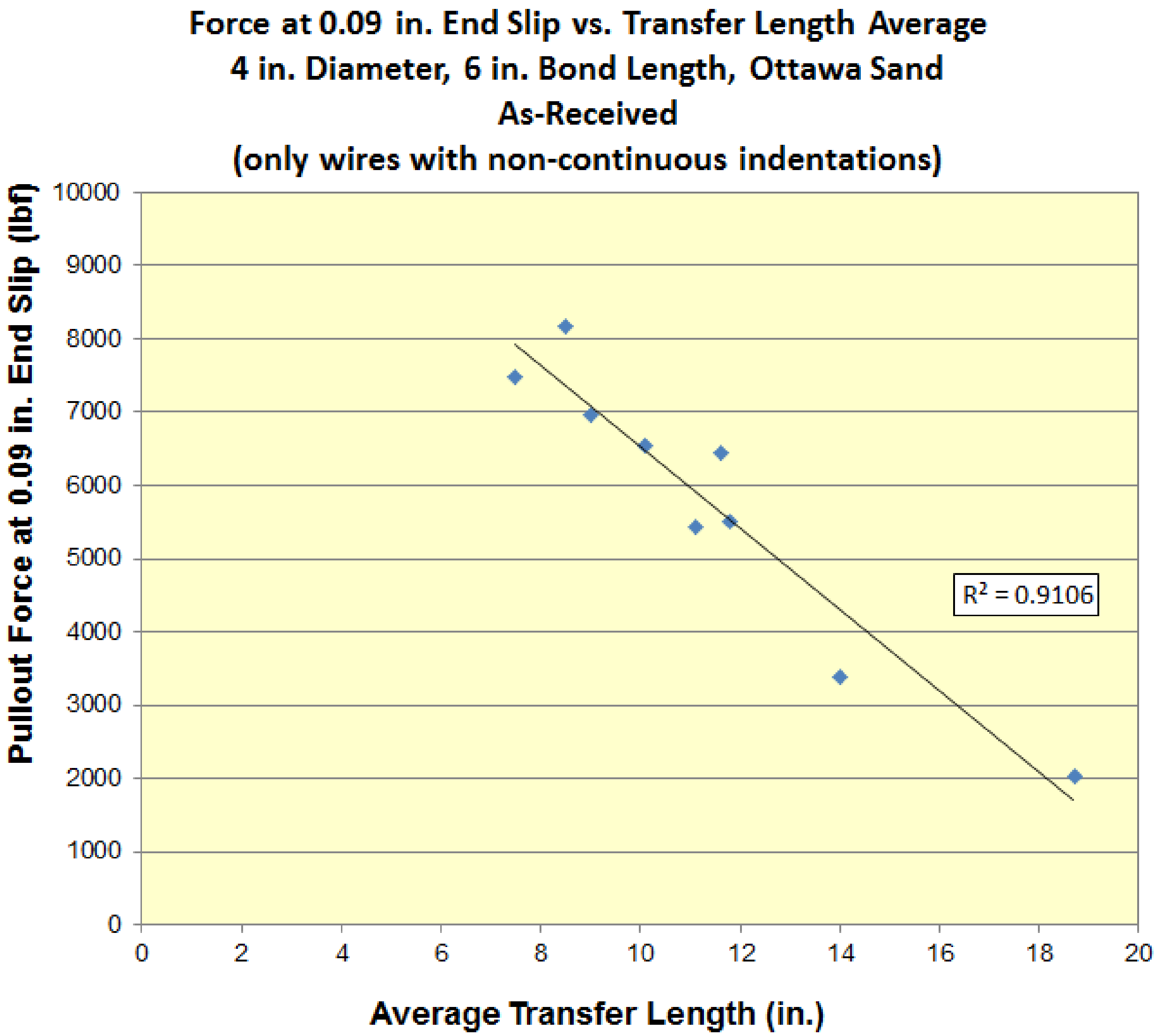

Figure F-18. As-received wires, pullout force at 0.09-in. end slip (individual-indents only)

Table F-10. As-received wires, pullout force at 0.10-in. end slip

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Pullout Force at 0.10 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	378	32	8.5	16.3
[WB]	6473	563	8.7	11.6
[WC]	7663	969	12.6	8.8
[WD]	5302	300	5.7	11.1
[WE]	7817	487	6.2	7.4
[WF]	7993	441	5.5	8.5
[WG]	5469	388	7.1	11.8
[WH]	7270	462	6.4	7.5
[WI]	6439	498	7.7	10.1
[WJ]	6814	591	8.7	9.0
[WK]	3434	347	10.1	14.0
[WL]	2067	323	15.6	18.7

Note: Sample Size = 6, WE = 5

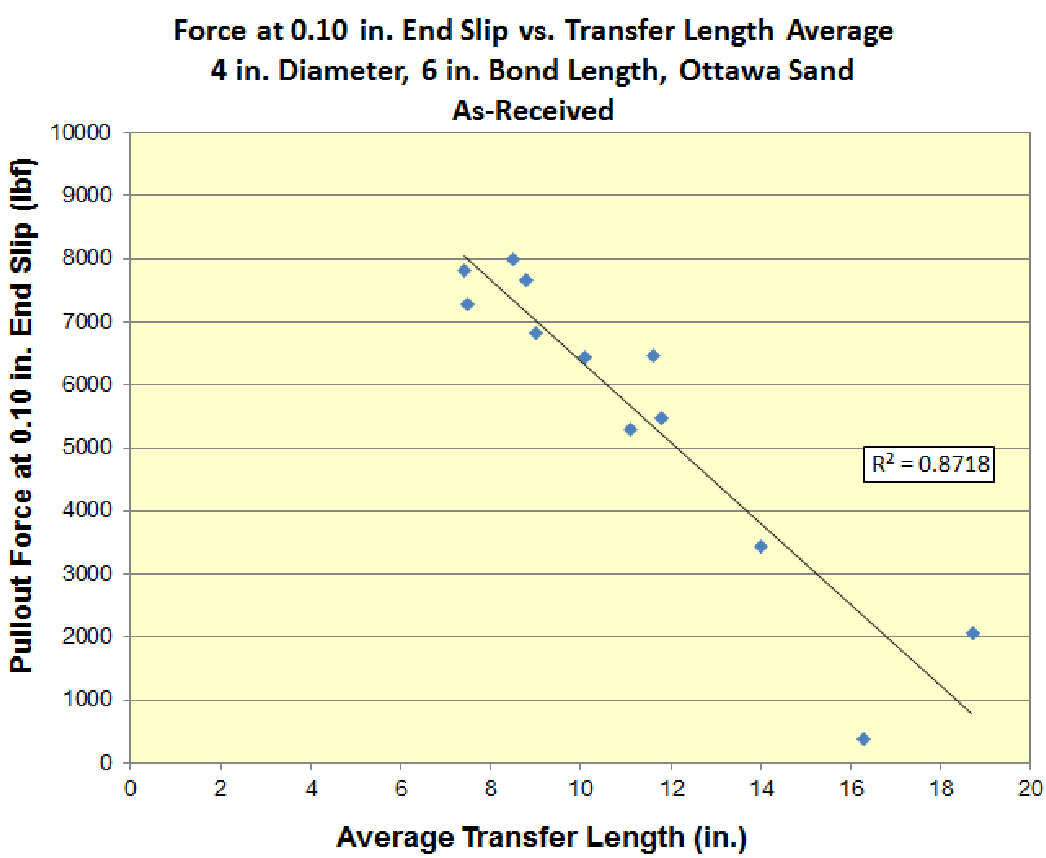

Figure F-19. As-received wires, pullout force at 0.10-in. end slip

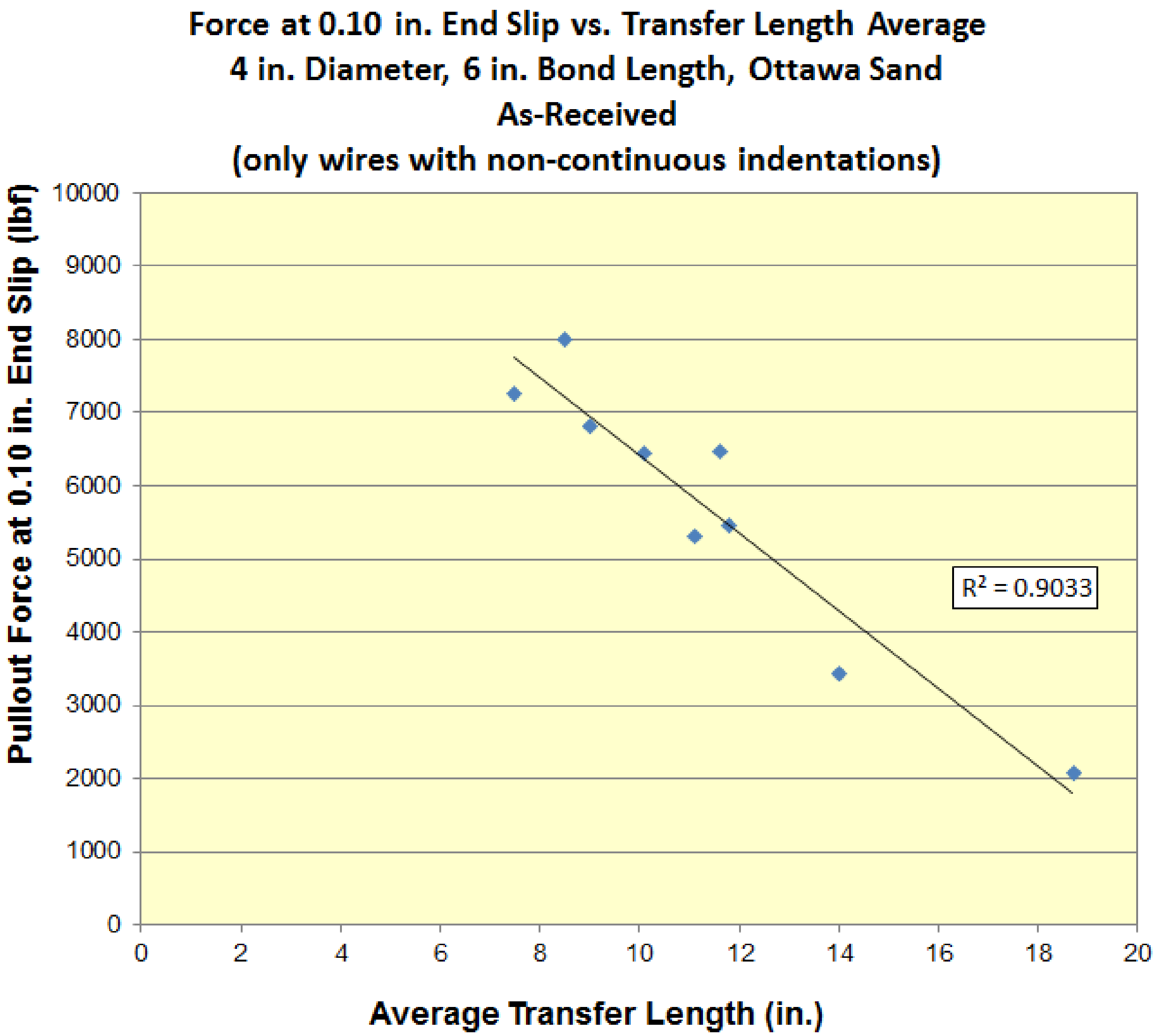

Figure F-20. As-received wires, pullout force at 0.10-in. end slip (individual-indents only)

Table F-11. As-received wires, pullout force at 0.11-in. end slip

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Pullout Force at 0.11 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	415	33	8.0	16.3
[WB]	6399	544	8.5	11.6
[WC]	7958	997	12.5	8.8
[WD]	5129	289	5.6	11.1
[WE]	8138	539	6.6	7.4
[WF]	7761	436	5.6	8.5
[WG]	5367	394	7.3	11.8
[WH]	6976	427	6.1	7.5
[WI]	6280	467	7.4	10.1
[WJ]	6592	558	8.5	9.0
[WK]	3460	375	10.8	14.0
[WL]	2091	323	15.4	18.7

Note: Sample Size = 6, WE = 5

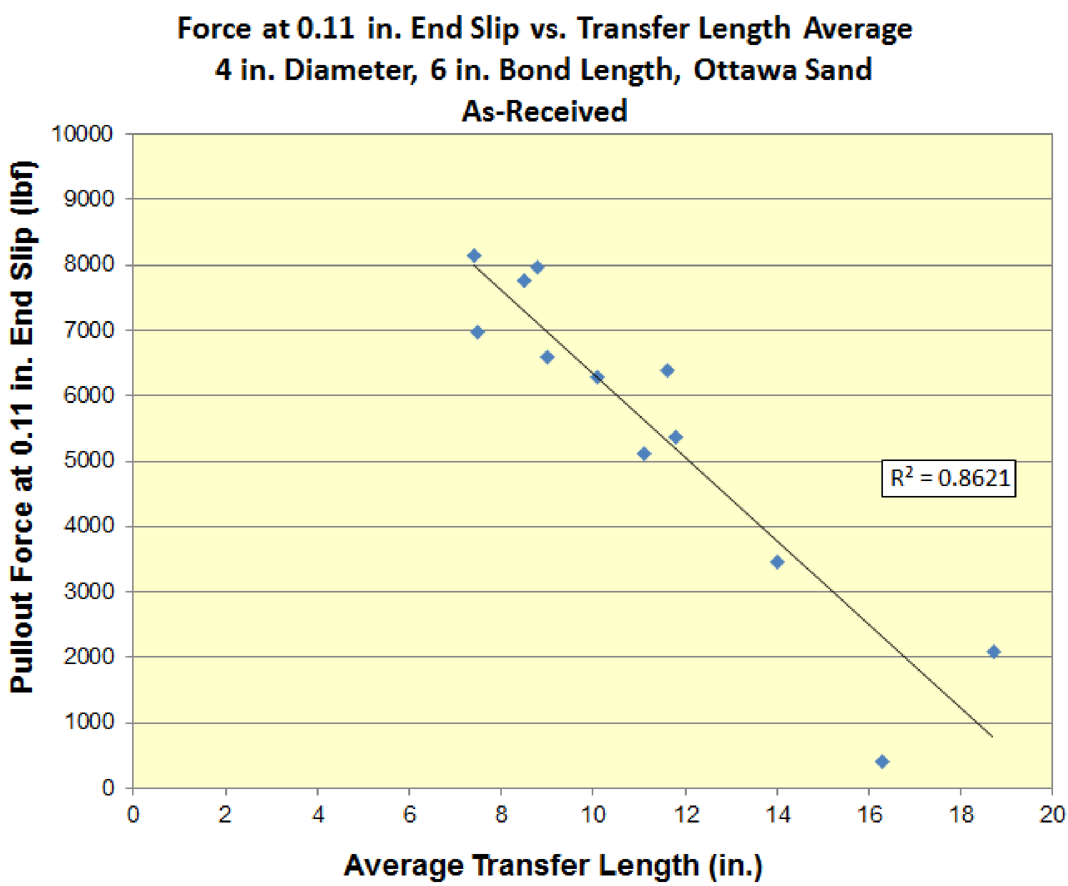

Figure F-21. As-received wires, pullout force at 0.11-in. end slip

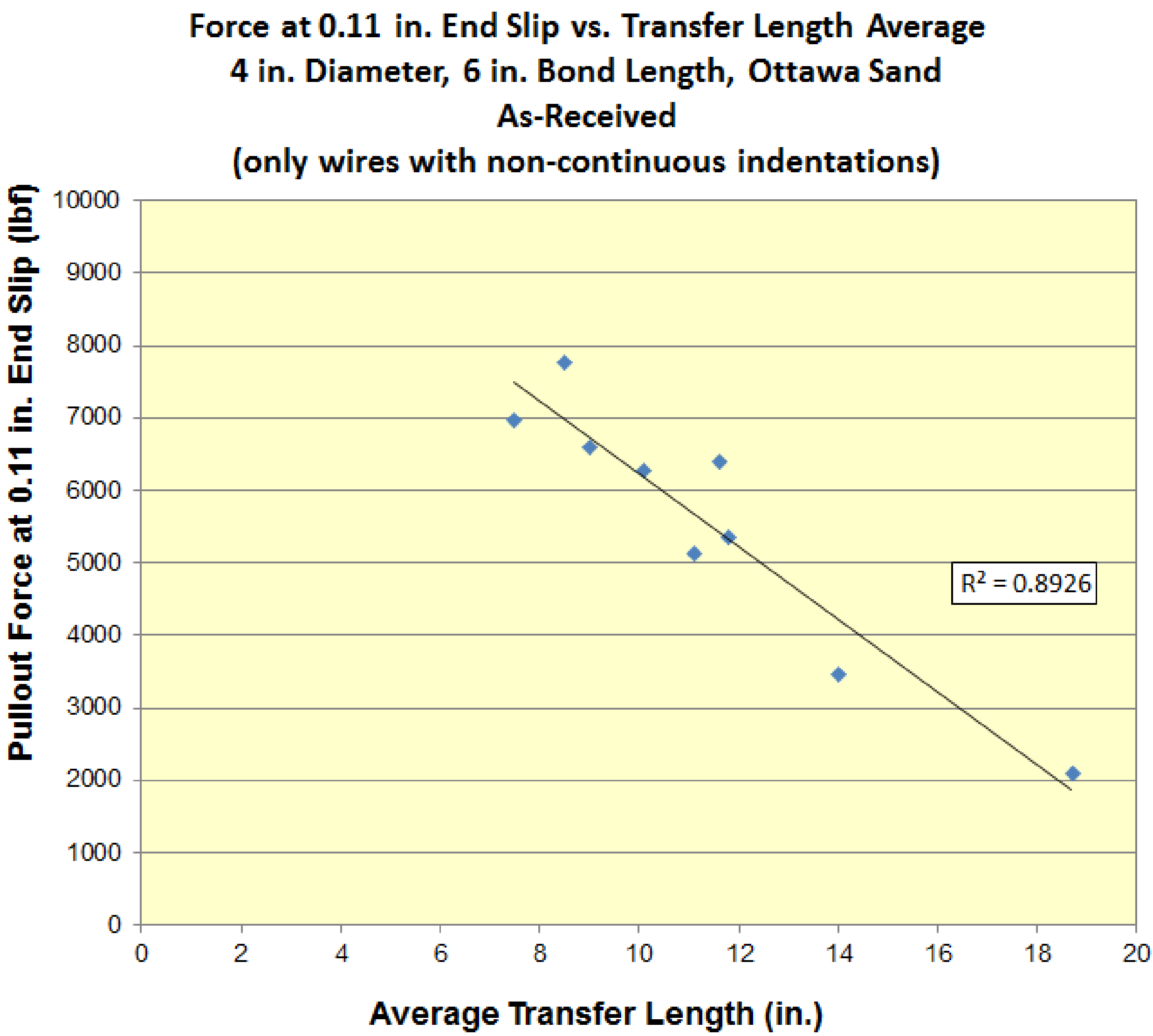

Figure F-22. As-received wires, pullout force at 0.11-in. end slip (individual-indents only)

Table F-12. As-received wires, pullout force at 0.12-in. end slip

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Pullout Force at 0.12 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	452	35	7.7	16.3
[WB]	6212	514	8.3	11.6
[WC]	7623	681	8.9	8.8
[WD]	4936	280	5.7	11.1
[WE]	8438	563	6.7	7.4
[WF]	7502	443	5.9	8.5
[WG]	5181	410	7.9	11.8
[WH]	6646	395	5.9	7.5
[WI]	6045	446	7.4	10.1
[WJ]	6315	523	8.3	9.0
[WK]	3488	382	10.9	14.0
[WL]	2114	319	15.1	18.7

Note: Sample Size = 6, WC = 4, WE = 5

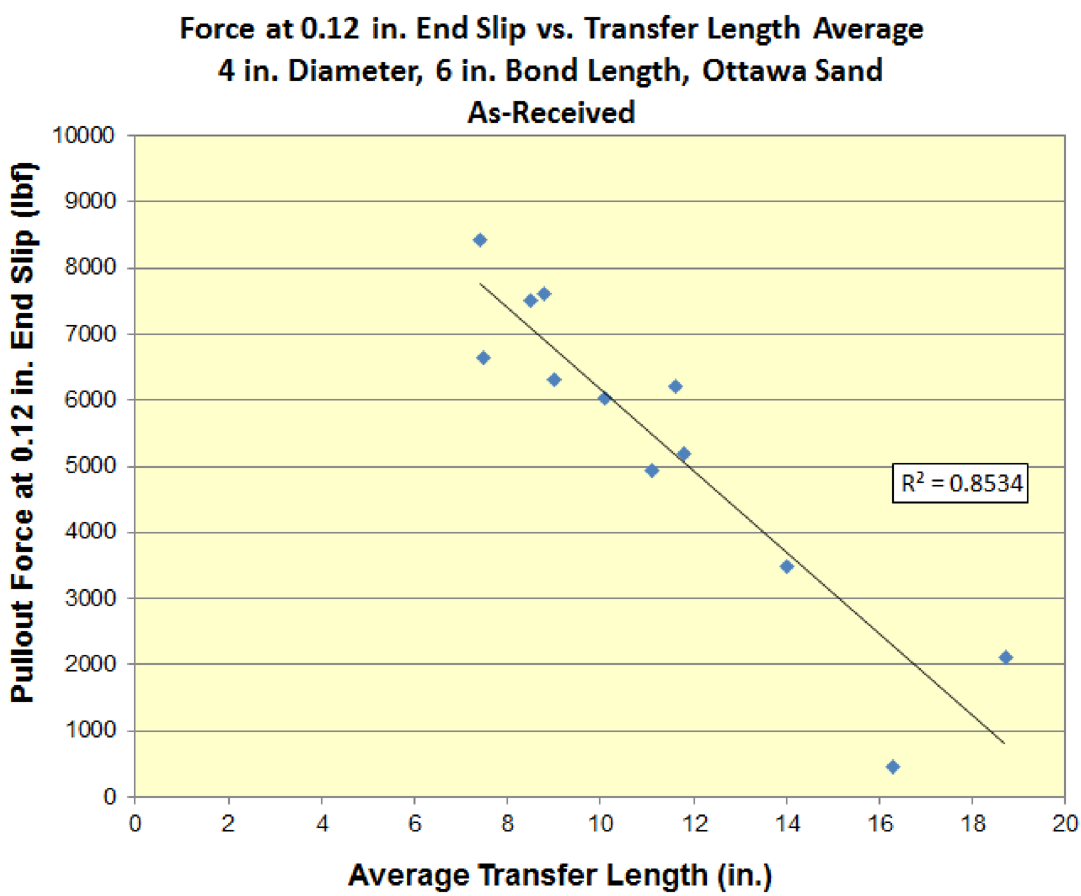

Figure F-23. As-received wires, pullout force at 0.12-in. end slip

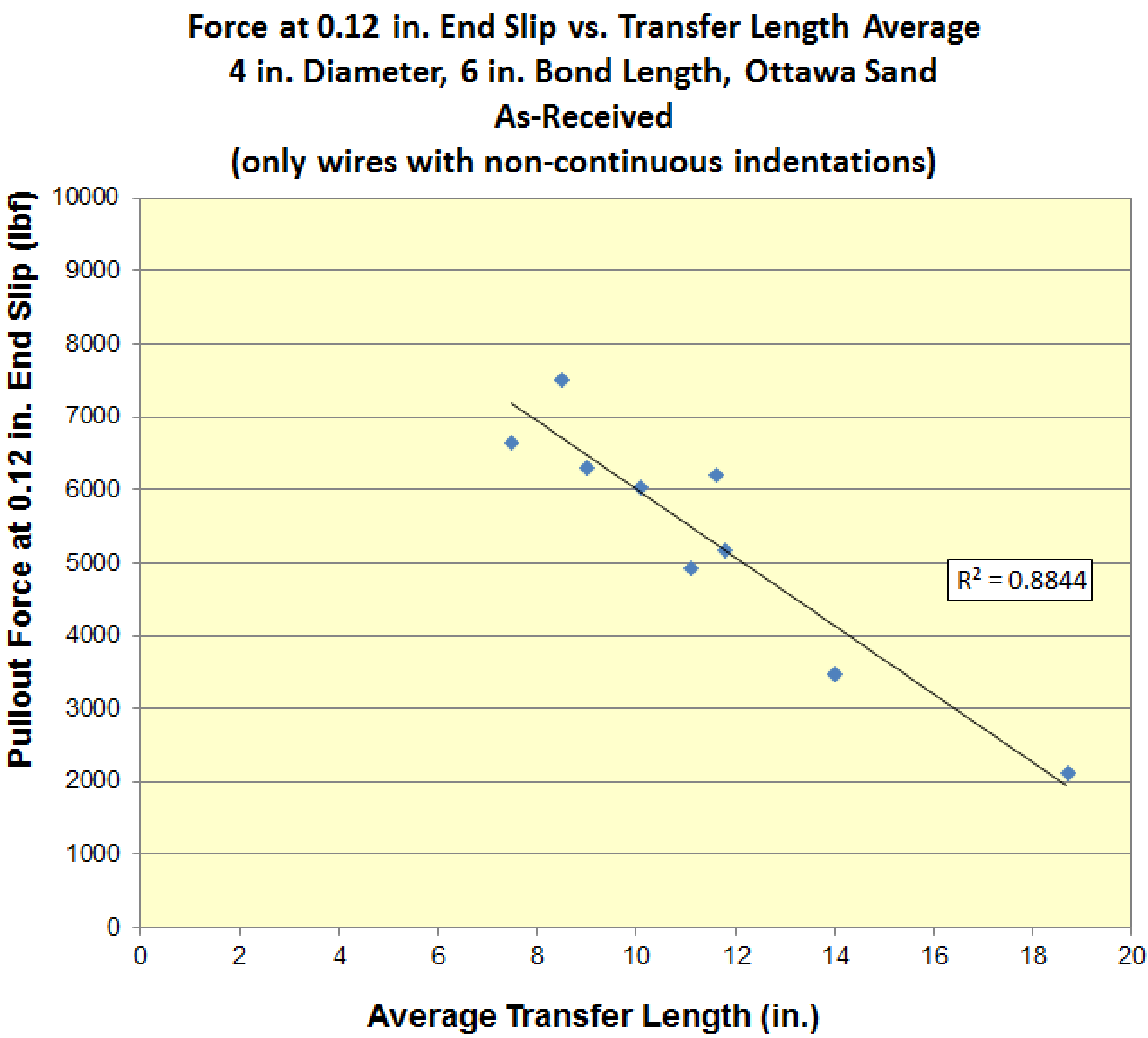

Figure F-24. As-received wires, pullout force at 0.12-in. end slip (individual-indents only)

Table F-13. As-received wires, pullout force at 0.13-in. end slip

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Pullout Force at 0.13 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	485	39	8.0	16.3
[WB]	5949	477	8.0	11.6
[WC]	7835	647	8.3	8.8
[WD]	4714	261	5.5	11.1
[WE]	8659	532	6.1	7.4
[WF]	7225	441	6.1	8.5
[WG]	4925	420	8.5	11.8
[WH]	6310	352	5.6	7.5
[WI]	5724	419	7.3	10.1
[WJ]	6004	478	8.0	9.0
[WK]	3506	394	11.2	14.0
[WL]	2119	315	14.9	18.7

Note: Sample Size = 6, WC = 4, WE = 5

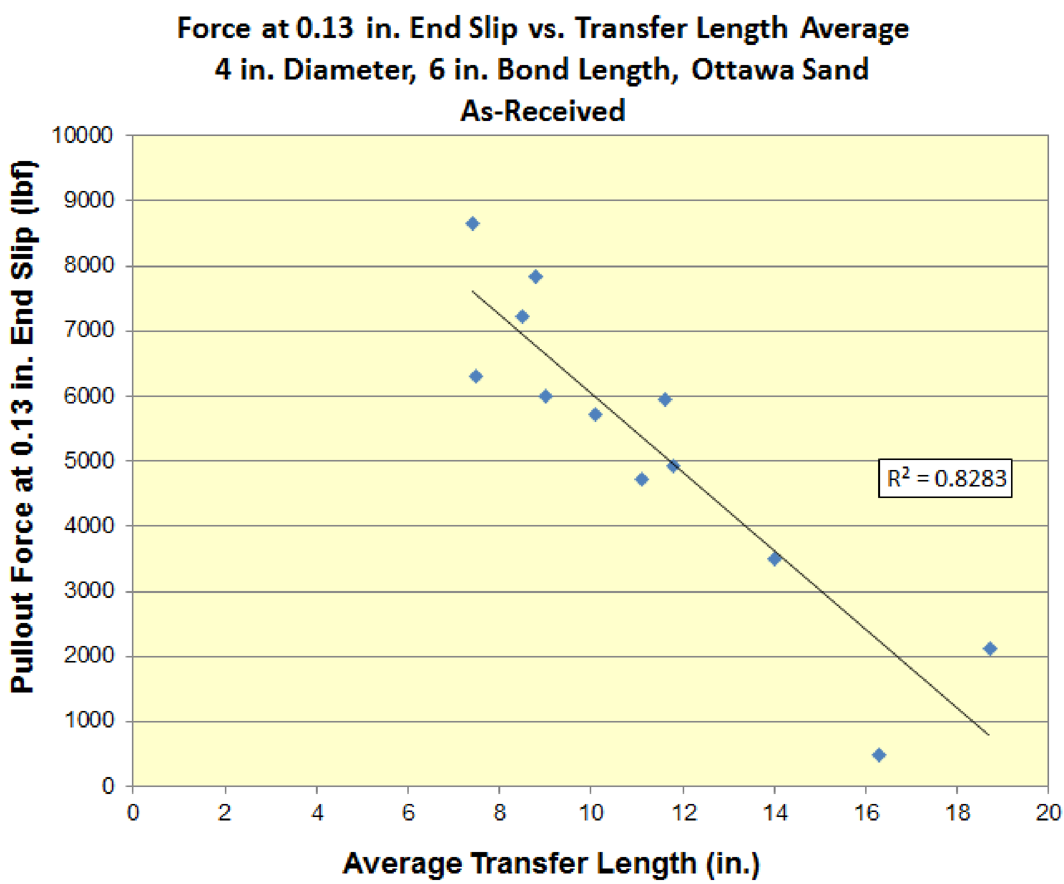

Figure F-25. As-received wires, pullout force at 0.13-in. end slip

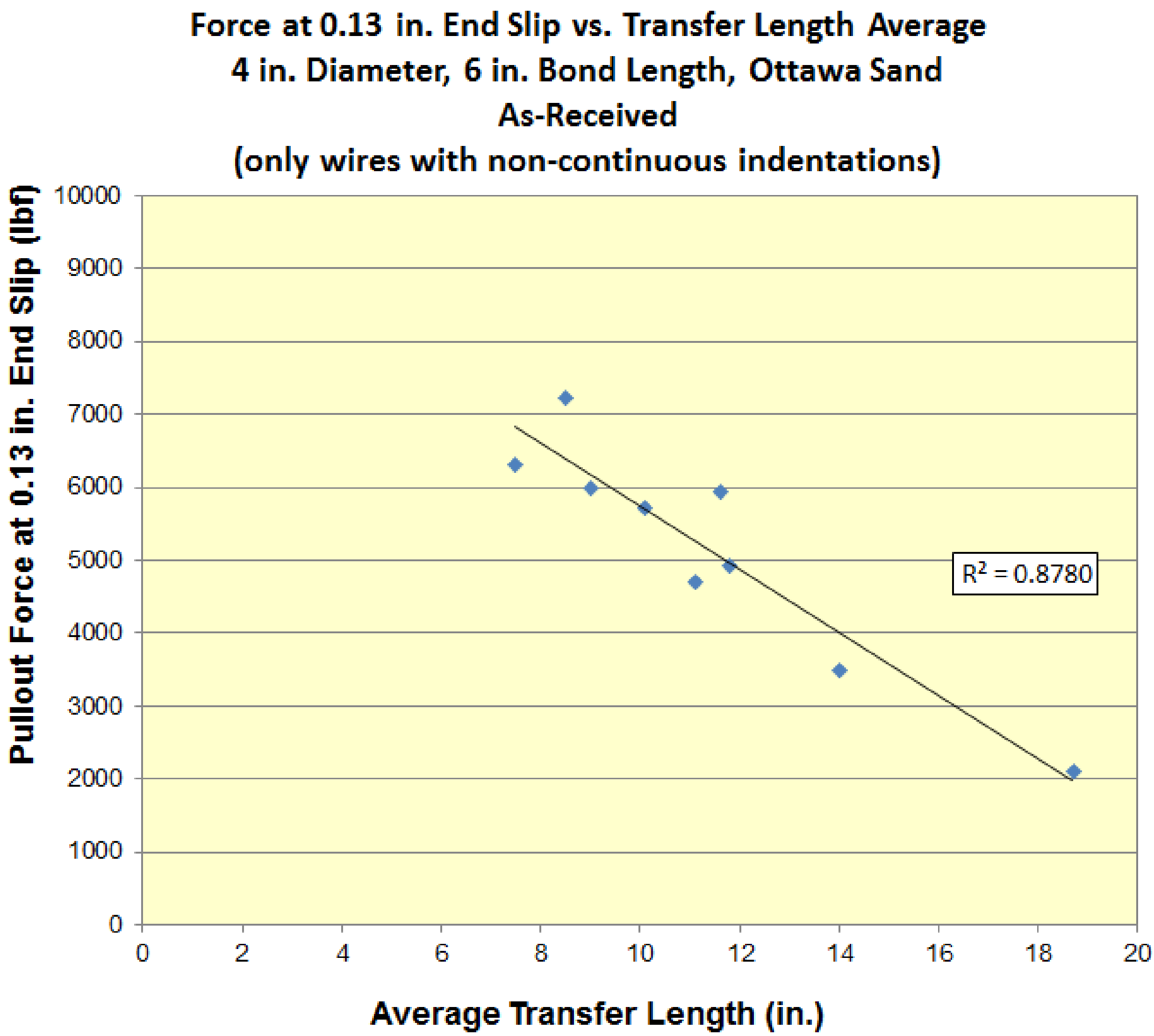

Figure F-26. As-received wires, pullout force at 0.13-in. end slip (individual-indents only)

Table F-14. As-received wires, maximum pullout force

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Maximum Pullout Force				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	487	42	8.7	16.3
[WB]	6481	570	8.8	11.6
[WC]	7646	967	12.6	8.8
[WD]	5555	357	6.4	11.1
[WE]	7674	526	6.9	7.4
[WF]	8312	459	5.5	8.5
[WG]	5505	385	7.0	11.8
[WH]	7605	497	6.5	7.5
[WI]	6567	522	8.0	10.1
[WJ]	7034	635	9.0	9.0
[WK]	3447	354	10.3	14.0
[WL]	2068	322	15.6	18.7

Note: Sample Size = 6

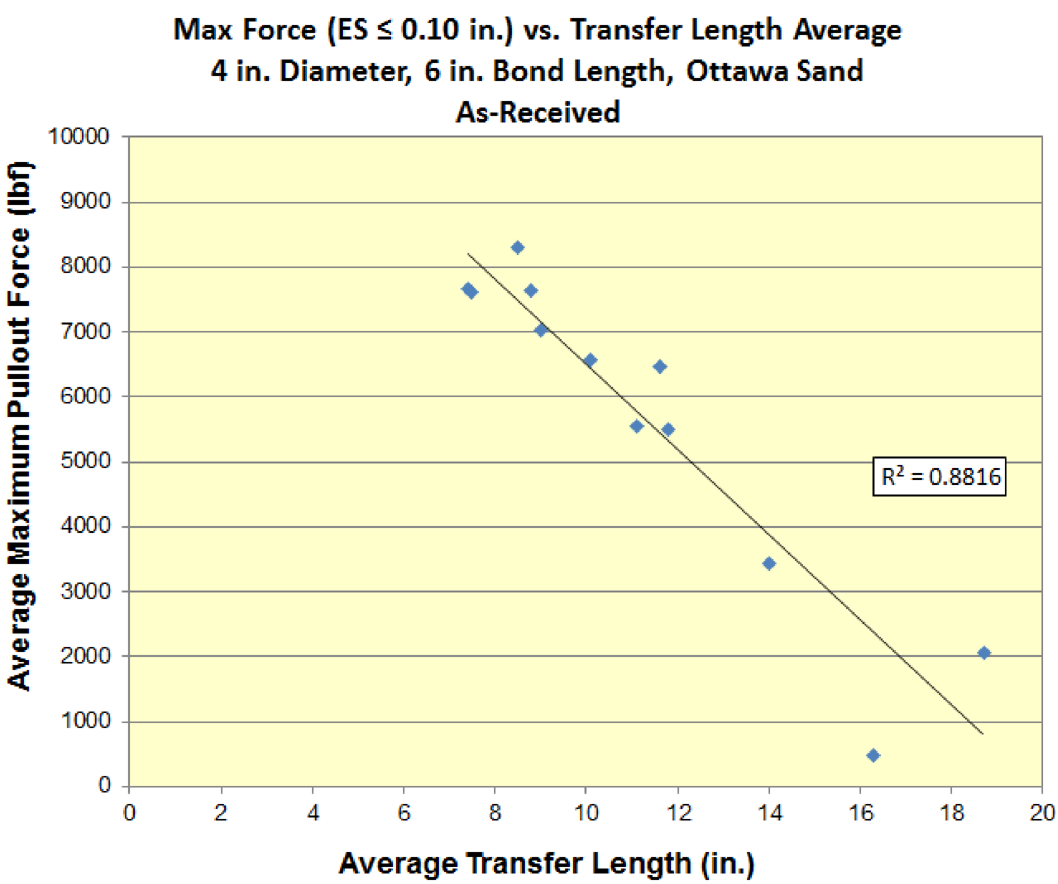

Figure F-27. As-received wires, maximum pullout force

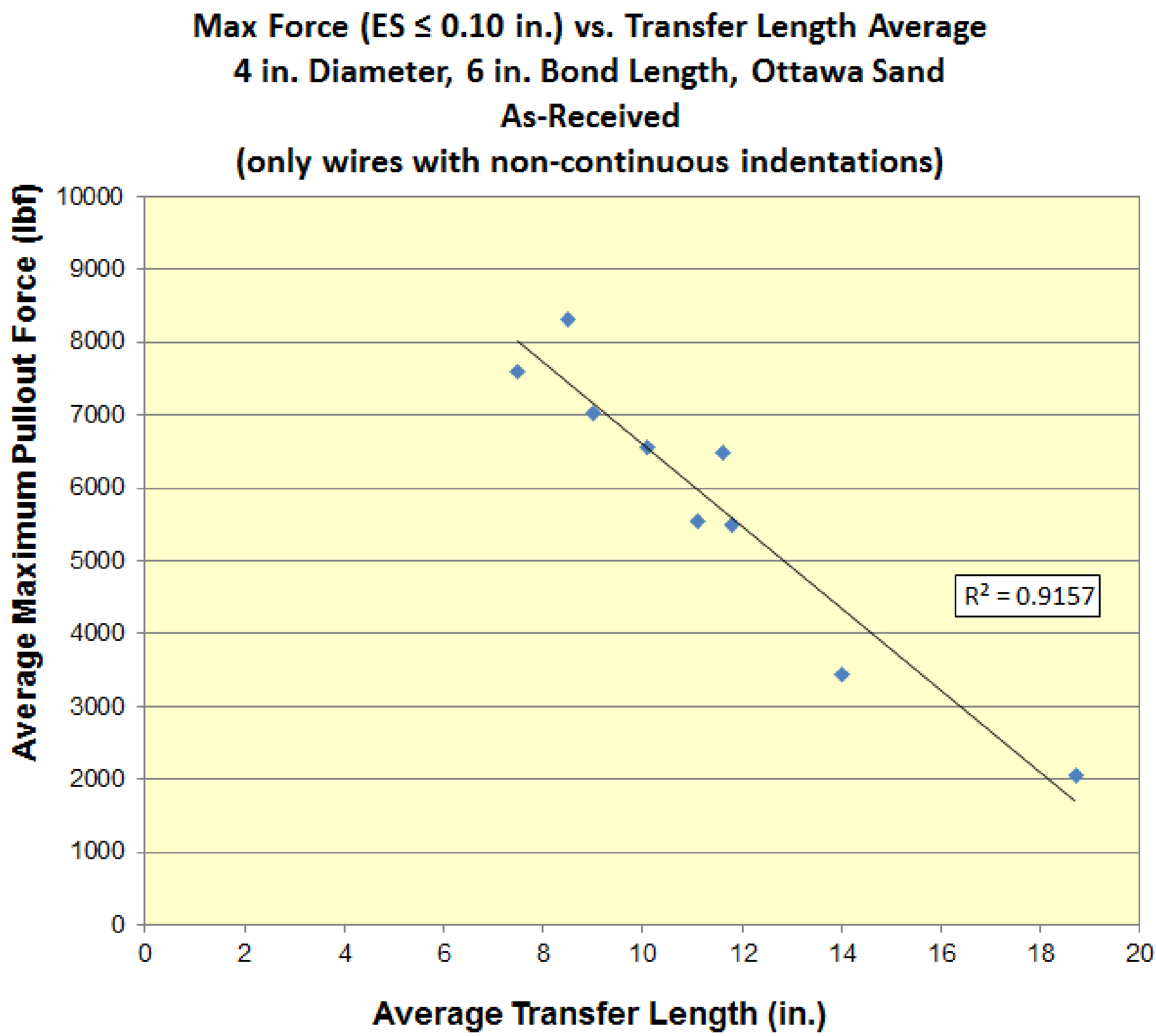

Figure F-28. As-received wires, maximum pullout force (individual-indents only)

Appendix G.
Lab Phase, Wire; As-received End Slips at Certain Force Analysis

Table G-1. As-received wires, end slip at 1000 lbf force

As-Received Wire Bond Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand End Slip at 1000 lbf of Force				
Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0075	0.00190	25.3	11.6
[WC]	0.0056	0.00114	20.2	8.8
[WD]	0.0067	0.00161	23.9	11.1
[WE]	0.0082	0.00133	16.1	7.4
[WF]	0.0055	0.00066	12.2	8.5
[WG]	0.0095	0.00231	24.3	11.8
[WH]	0.0050	0.00142	28.6	7.5
[WI]	0.0066	0.00106	16.1	10.1
[WJ]	0.0060	0.00148	24.8	9.0
[WK]	0.0117	0.00273	23.4	14.0
[WL]	0.0200	0.00495	24.8	18.7

Note 1: Sample Size = 6

Note 2: A blank entry means the wire didn't reach that force

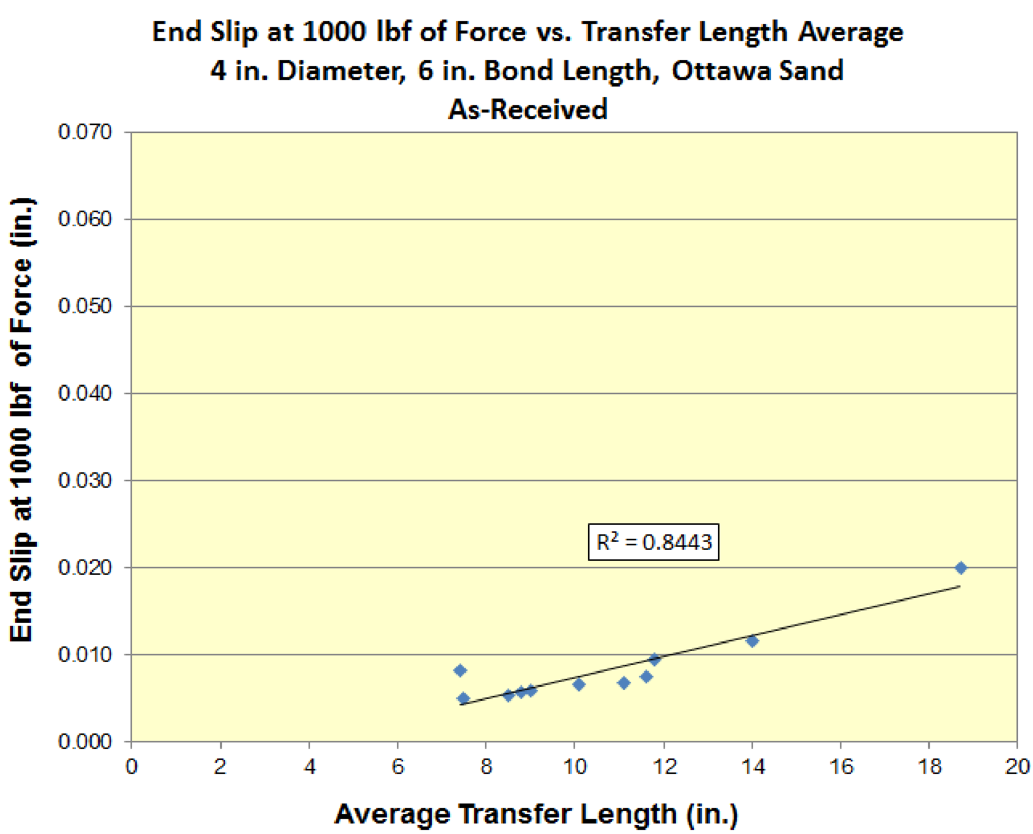

Figure G-1. As-received wires, end slip at 1000 lbf force

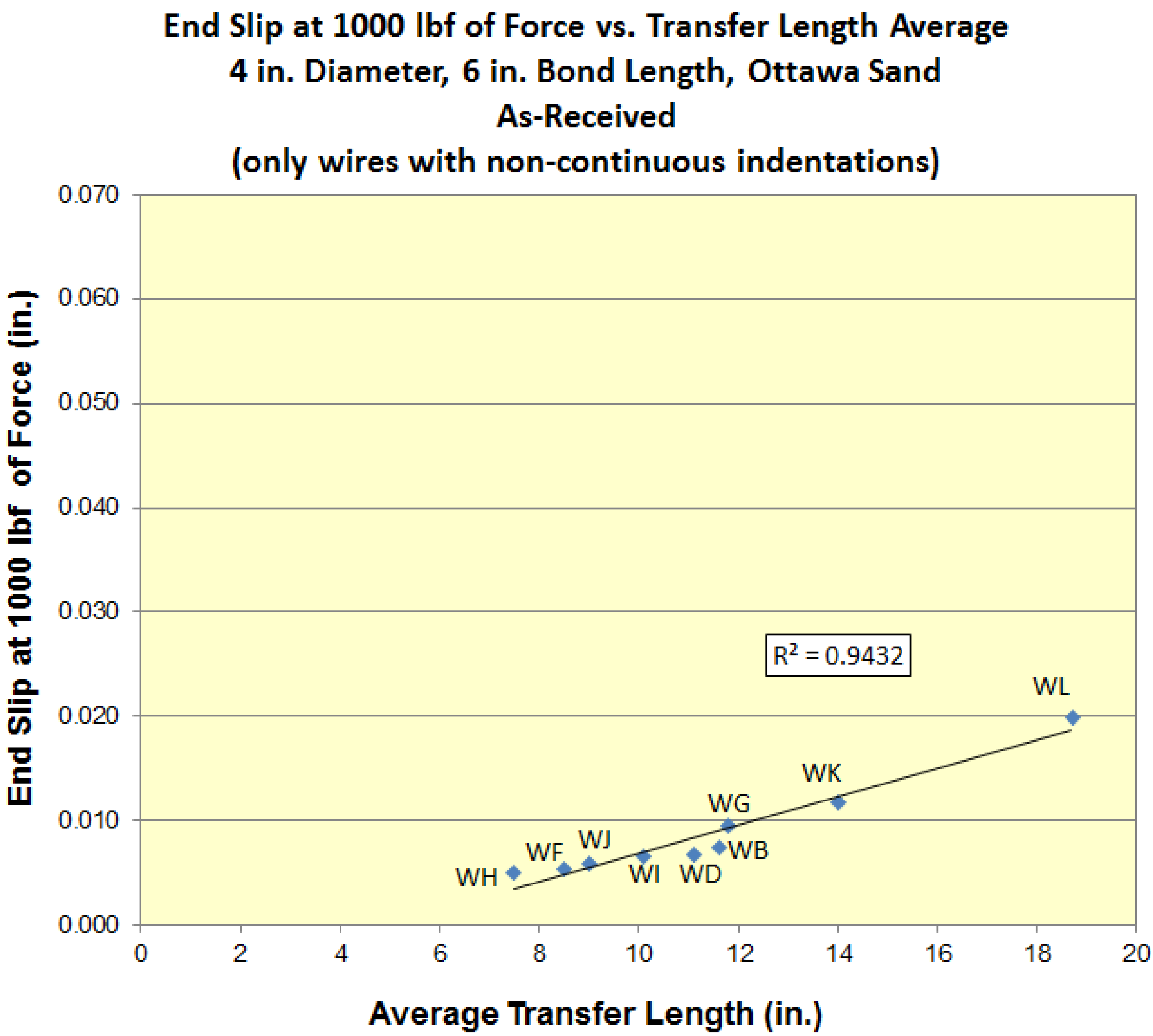

Figure G-2. As-received wires, end slip at 1000 lbf force (individual-indents only)

Table G-2. As-received wires, end slip at 1500 lbf force

As-Received Wire Bond Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand End Slip at 1500 lbf of Force				
Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0101	0.00208	20.6	11.6
[WC]	0.0093	0.00150	16.2	8.8
[WD]	0.0092	0.00173	18.9	11.1
[WE]	0.0118	0.00145	12.3	7.4
[WF]	0.0074	0.00074	10.0	8.5
[WG]	0.0136	0.00284	20.9	11.8
[WH]	0.0068	0.00121	17.7	7.5
[WI]	0.0093	0.00108	11.7	10.1
[WJ]	0.0081	0.00186	23.0	9.0
[WK]	0.0180	0.00342	19.1	14.0
[WL]	0.0400	0.01658	41.5	18.7

Note 1: Sample Size = 6

Note 2: A blank entry means the wire didn't reach that force

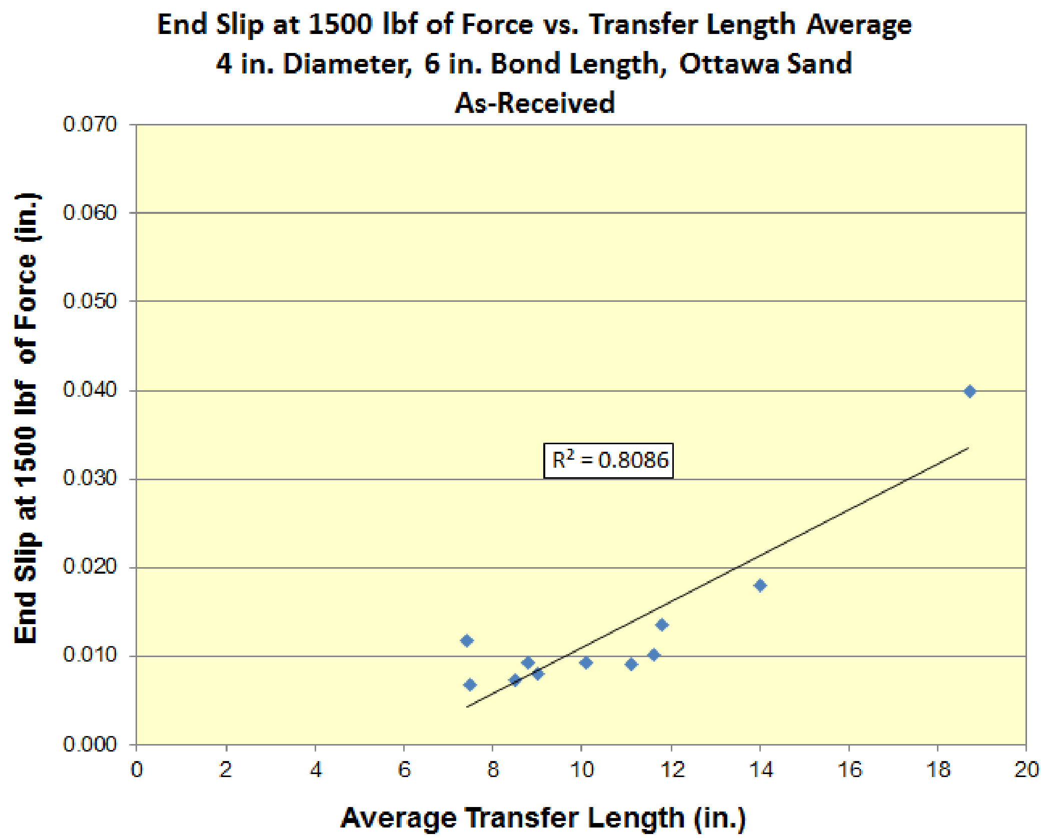

Figure G-3. As-received wires, end slip at 1500 lbf force

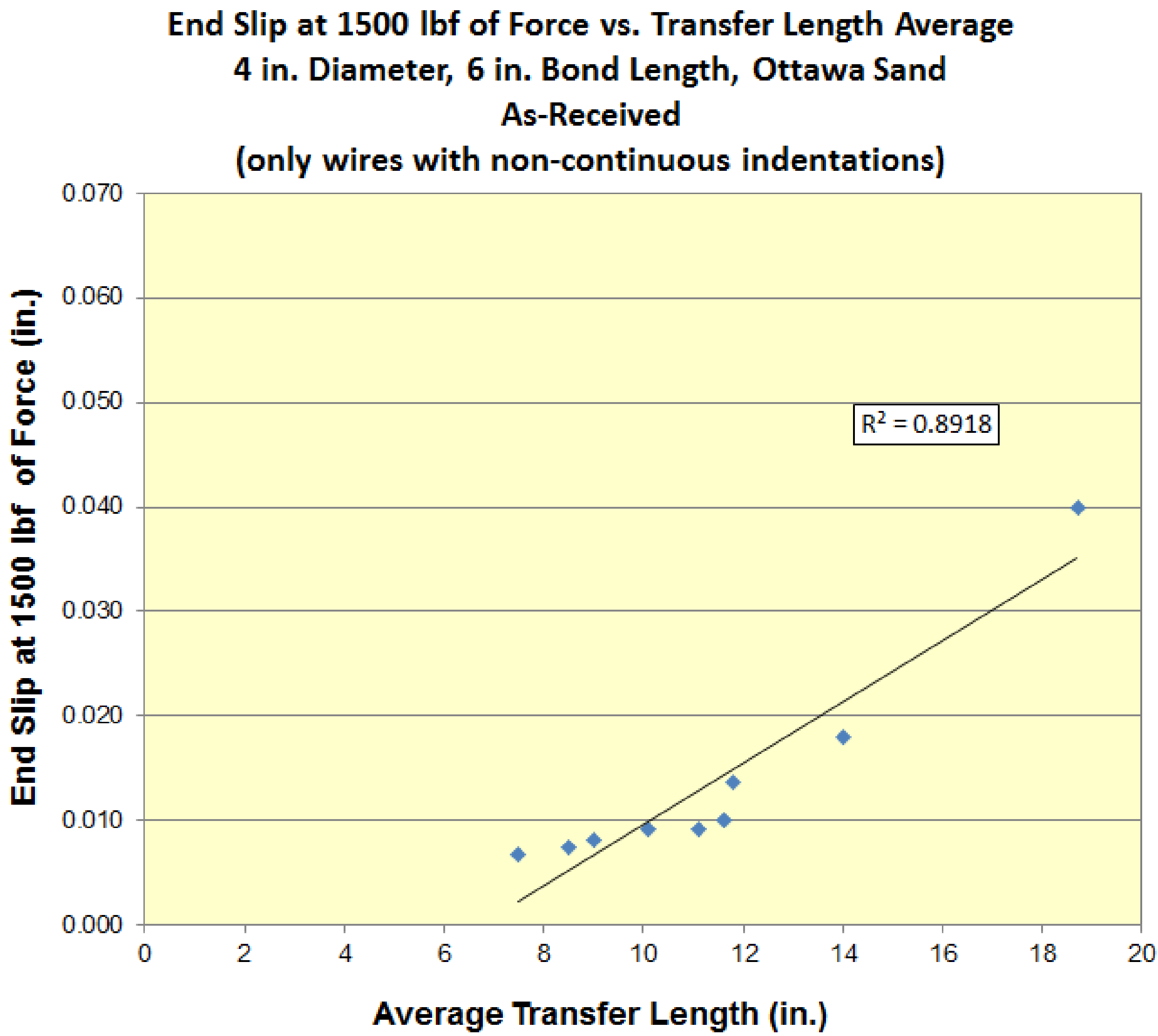

Figure G-4. As-received wires, end slip at 1500 lbf force (individual-indents only)

Table G-3. As-received wires, end slip at 2000 lbf force

As-Received Wire Bond Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand End Slip at 2000 lbf of Force				
Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0124	0.00235	19.0	11.6
[WC]	0.0130	0.00210	16.1	8.8
[WD]	0.0113	0.00190	16.9	11.1
[WE]	0.0152	0.00202	13.3	7.4
[WF]	0.0091	0.00081	9.0	8.5
[WG]	0.0175	0.00322	18.4	11.8
[WH]	0.0086	0.00106	12.4	7.5
[WI]	0.0119	0.00116	9.8	10.1
[WJ]	0.0100	0.00200	20.0	9.0
[WK]	0.0264	0.00510	19.3	14.0
[WL]	0.0647	0.02199	34.0	18.7

Note 1: Sample Size = 6, L = 4

Note 2: A blank entry means the wire didn't reach that force

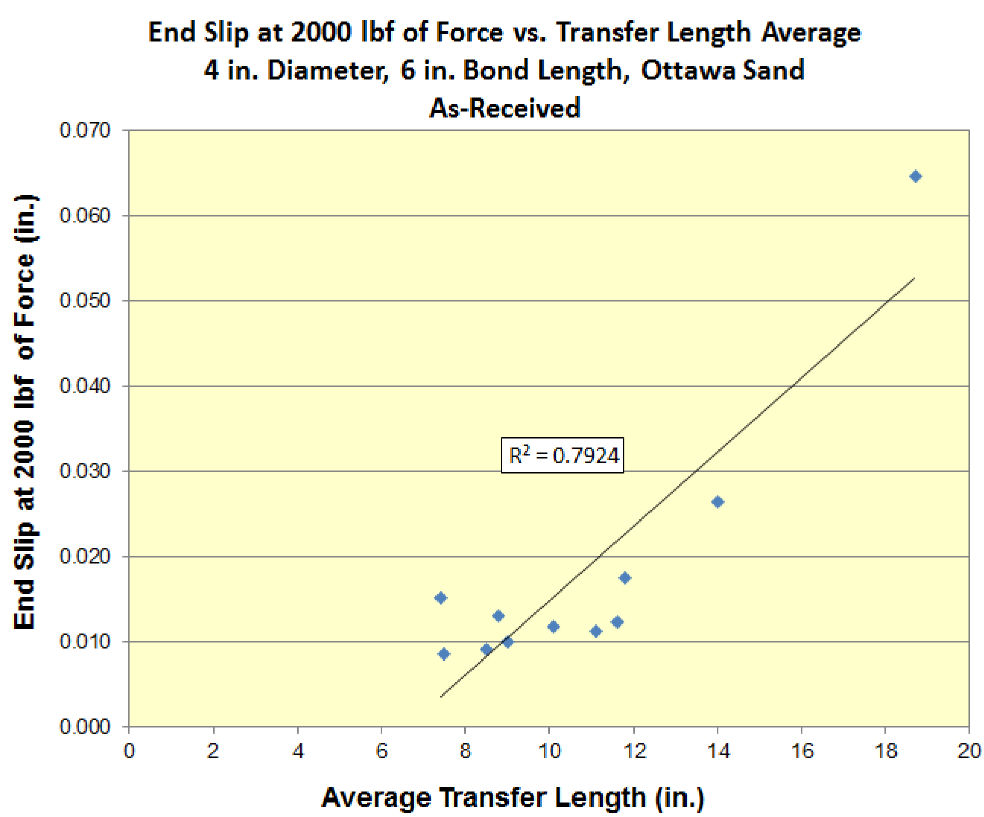

Figure G-5. As-received wires, end slip at 2000 lbf force

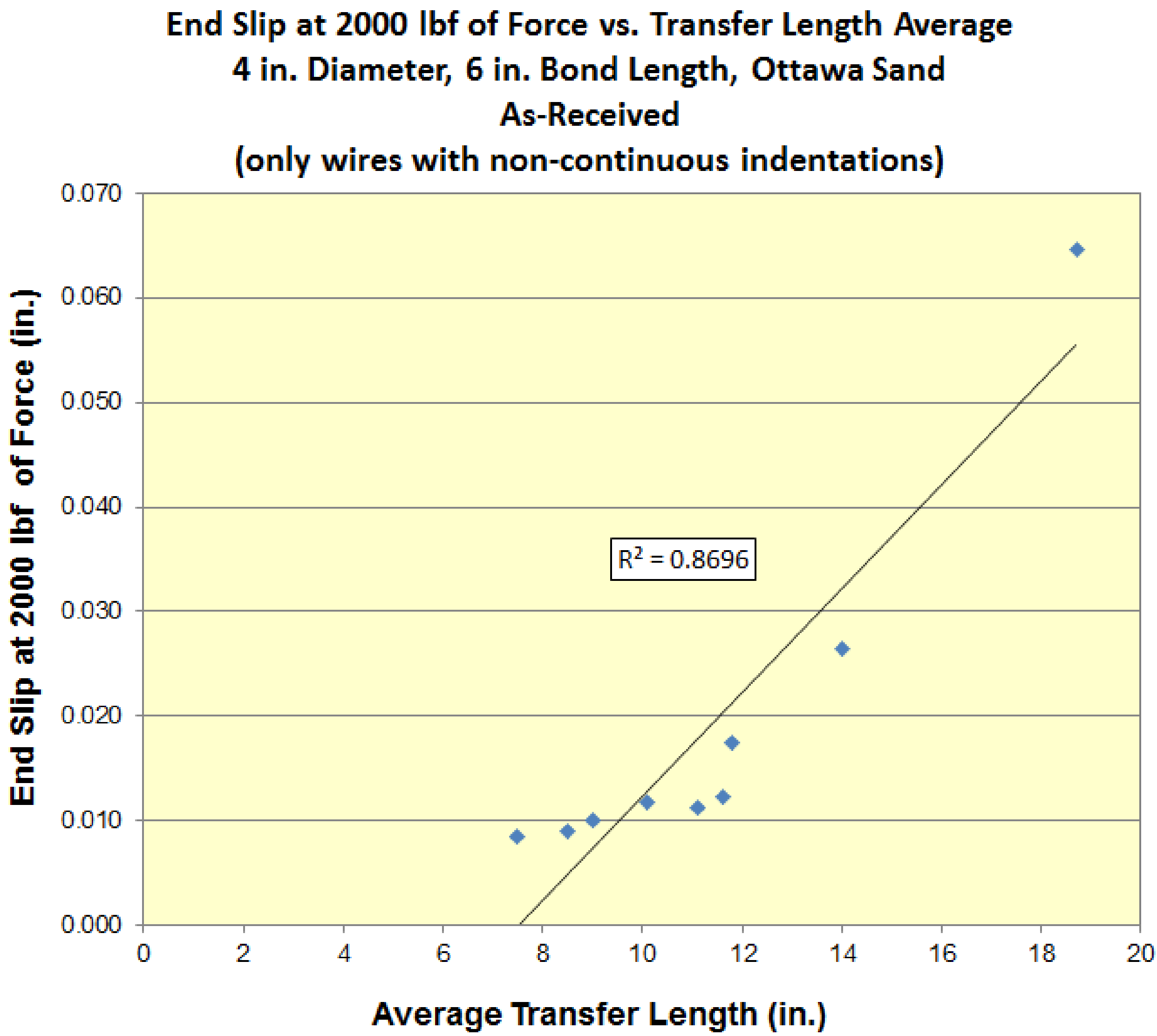

Figure G-6. As-received wires, end slip at 2000 lbf force (individual-indents only)

Table G-4. As-received wires, end slip at 2500 lbf force

As-Received Wire Bond Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand End Slip at 2500 lbf of Force				
Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0147	0.00269	18.3	11.6
[WC]	0.0171	0.00285	16.7	8.8
[WD]	0.0135	0.00226	16.7	11.1
[WE]	0.0191	0.00239	12.5	7.4
[WF]	0.0103	0.00103	10.0	8.5
[WG]	0.0218	0.00363	16.6	11.8
[WH]	0.0103	0.00109	10.6	7.5
[WI]	0.0144	0.00151	10.5	10.1
[WJ]	0.0118	0.00217	18.4	9.0
[WK]	0.0375	0.00835	22.3	14.0
[WL]				18.7

Note 1: Sample Size = 6
Note 2: A blank entry means the wire didn't reach that force

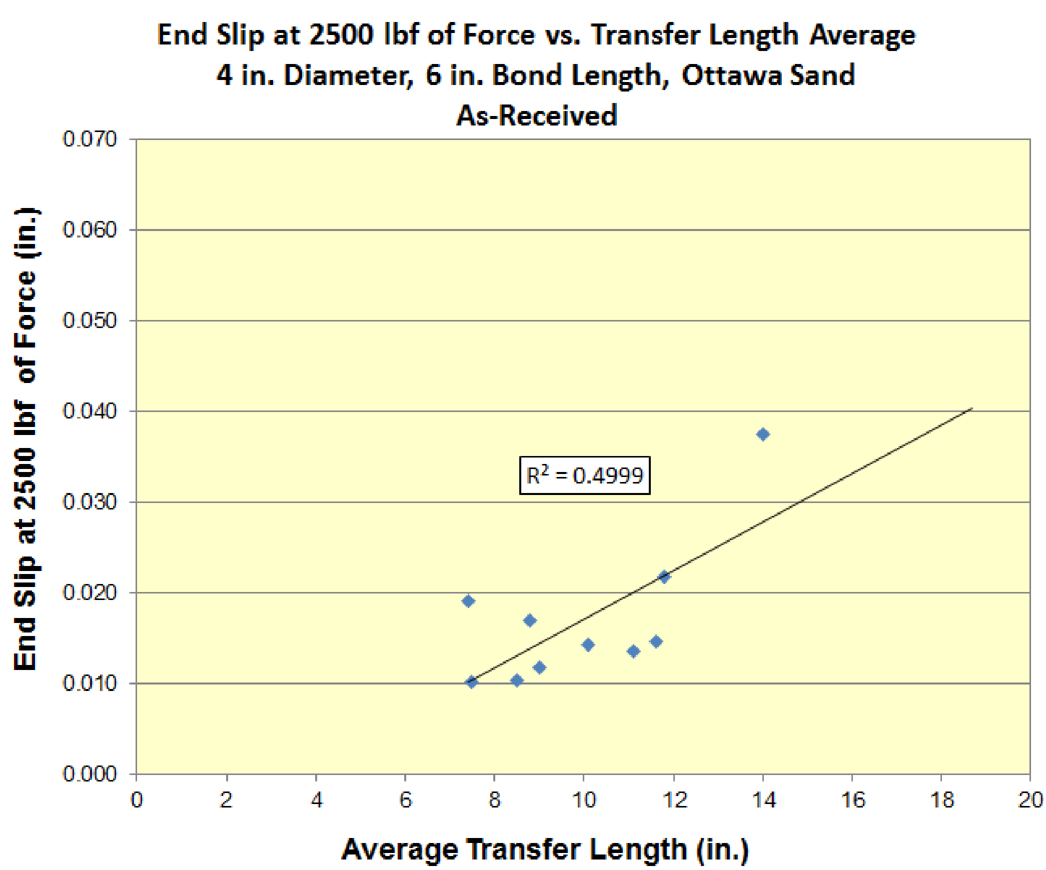

Figure G-7. As-received wires, end slip at 2500 lbf force

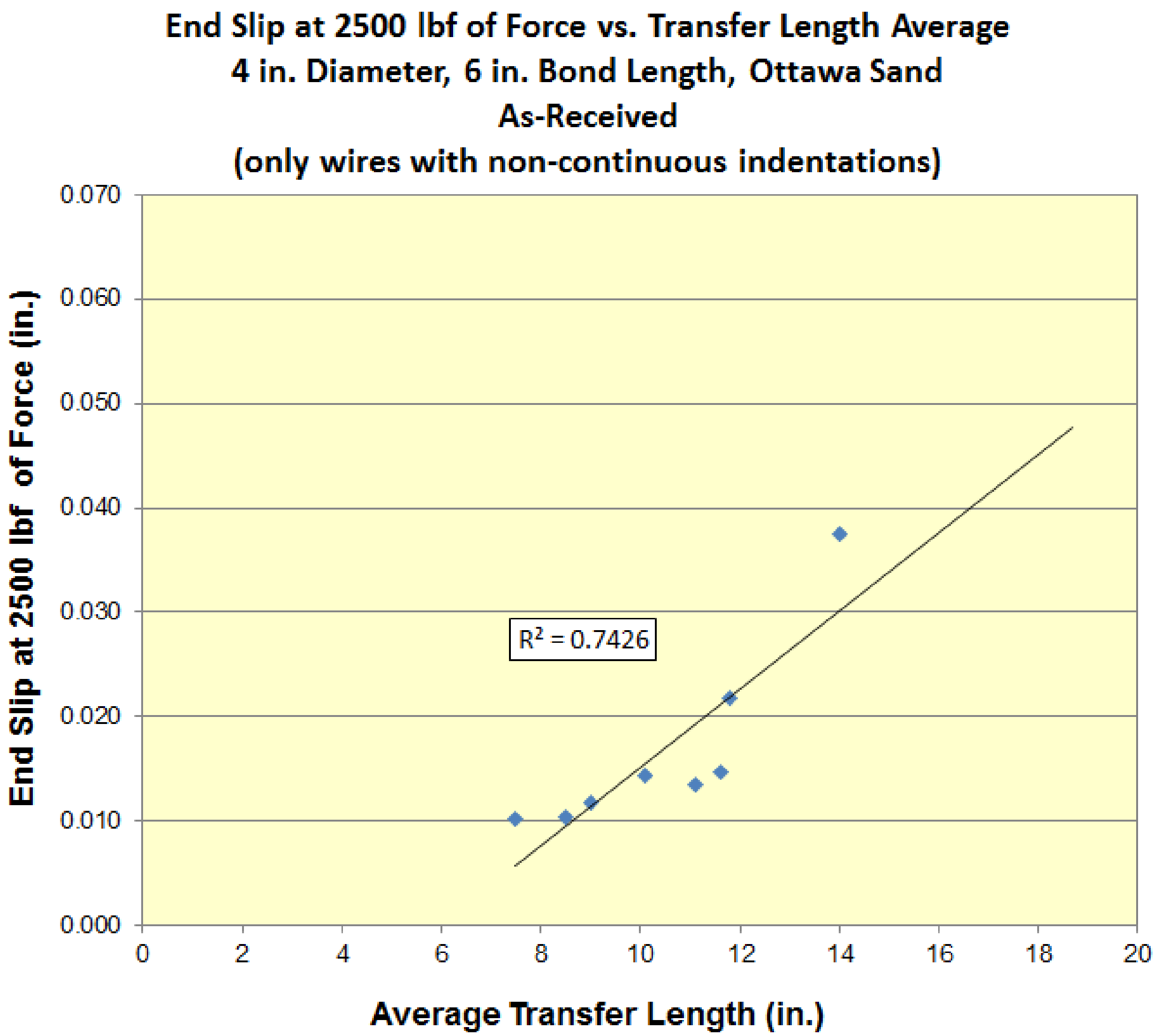

Figure G-8. As-received wires, end slip at 2500 lbf force (individual-indents only)

Table G-5. As-received wires, end slip at 3000 lbf force

As-Received Wire Bond Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand End Slip at 3000 lbf of Force				
Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0175	0.00310	17.7	11.6
[WC]	0.0219	0.00356	16.3	8.8
[WD]	0.0159	0.00248	15.6	11.1
[WE]	0.0231	0.00272	11.8	7.4
[WF]	0.0120	0.00117	9.7	8.5
[WG]	0.0265	0.00415	15.7	11.8
[WH]	0.0119	0.00108	9.1	7.5
[WI]	0.0168	0.00197	11.7	10.1
[WJ]	0.0137	0.00246	17.9	9.0
[WK]	0.0583	0.02030	34.8	14.0
[WL]				18.7

Note 1: Sample Size = 6

Note 2: A blank entry means the wire didn't reach that force

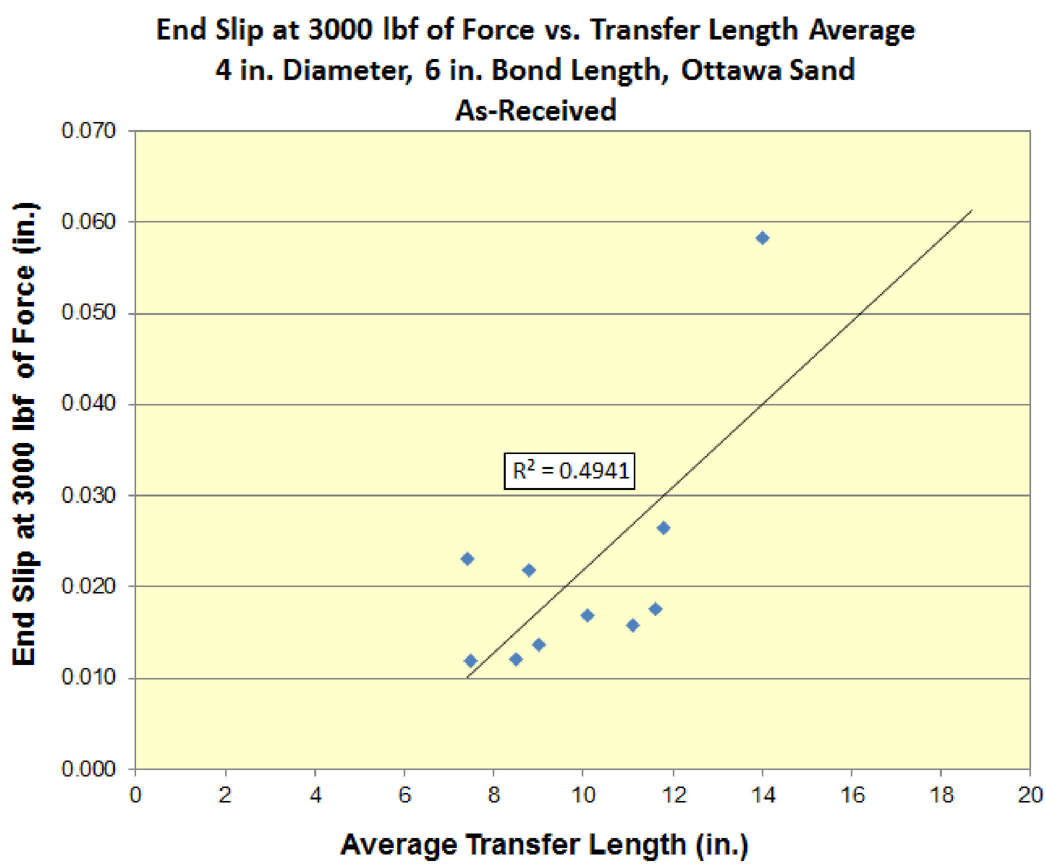

Figure G-9. As-received wires, end slip at 3000 lbf force

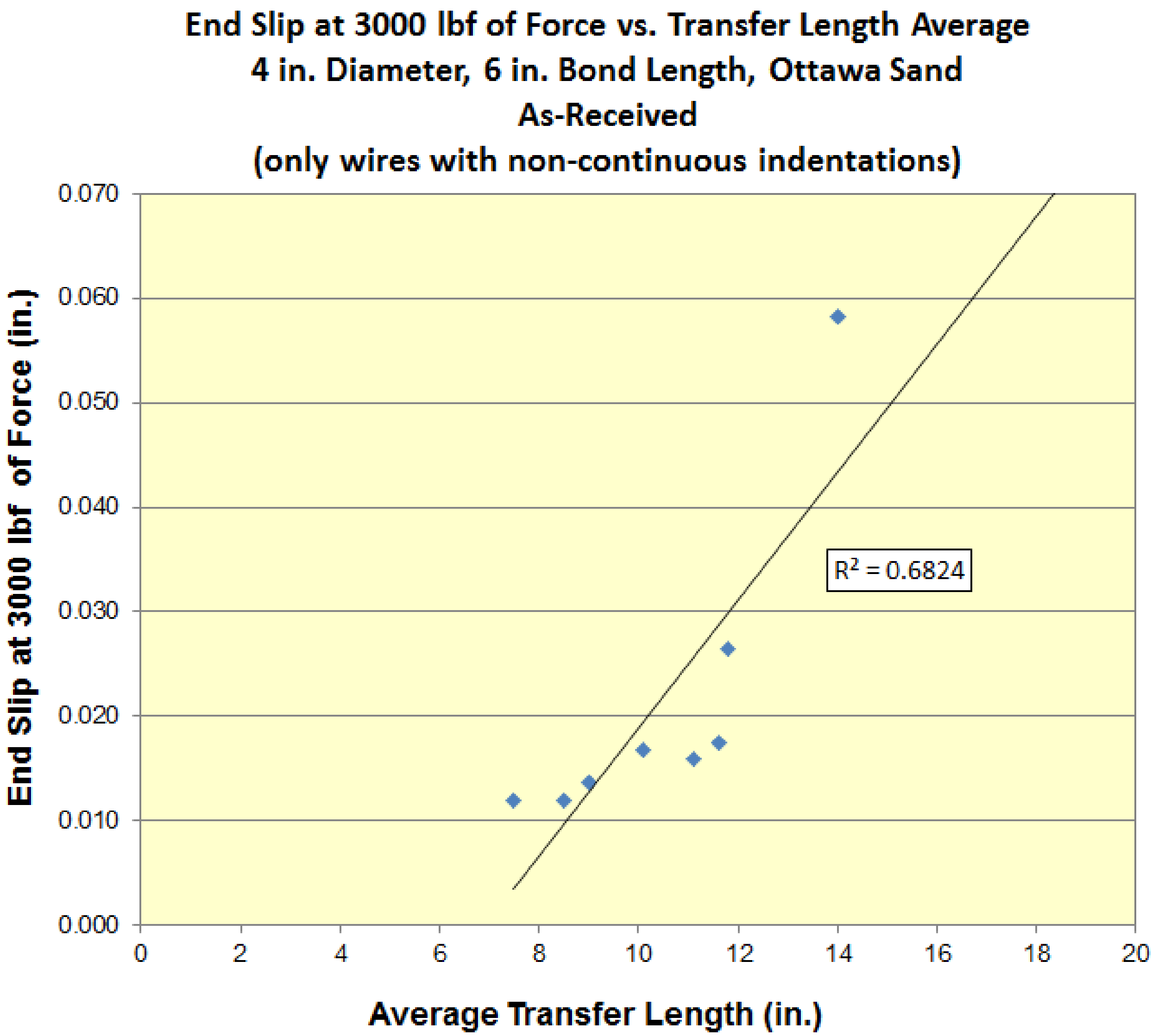

Figure G-10. As-received wires, end slip at 3000 lbf force (individual-indents only)

Table G-6. As-received wires, end slip at 3500 lbf force

As-Received Wire Bond Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand End Slip at 3500 lbf of Force				
Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0207	0.00372	17.9	11.6
[WC]	0.0273	0.00459	16.8	8.8
[WD]	0.0189	0.00294	15.5	11.1
[WE]	0.0276	0.00315	11.4	7.4
[WF]	0.0134	0.00135	10.0	8.5
[WG]	0.0322	0.00525	16.3	11.8
[WH]	0.0136	0.00140	10.2	7.5
[WI]	0.0196	0.00238	12.1	10.1
[WJ]	0.0158	0.00296	18.7	9.0
[WK]	0.0611	0.00449	7.3	14.0
[WL]				18.7

Note 1: Sample Size = 6, K = 2

Note 2: A blank entry means the wire didn't reach that force

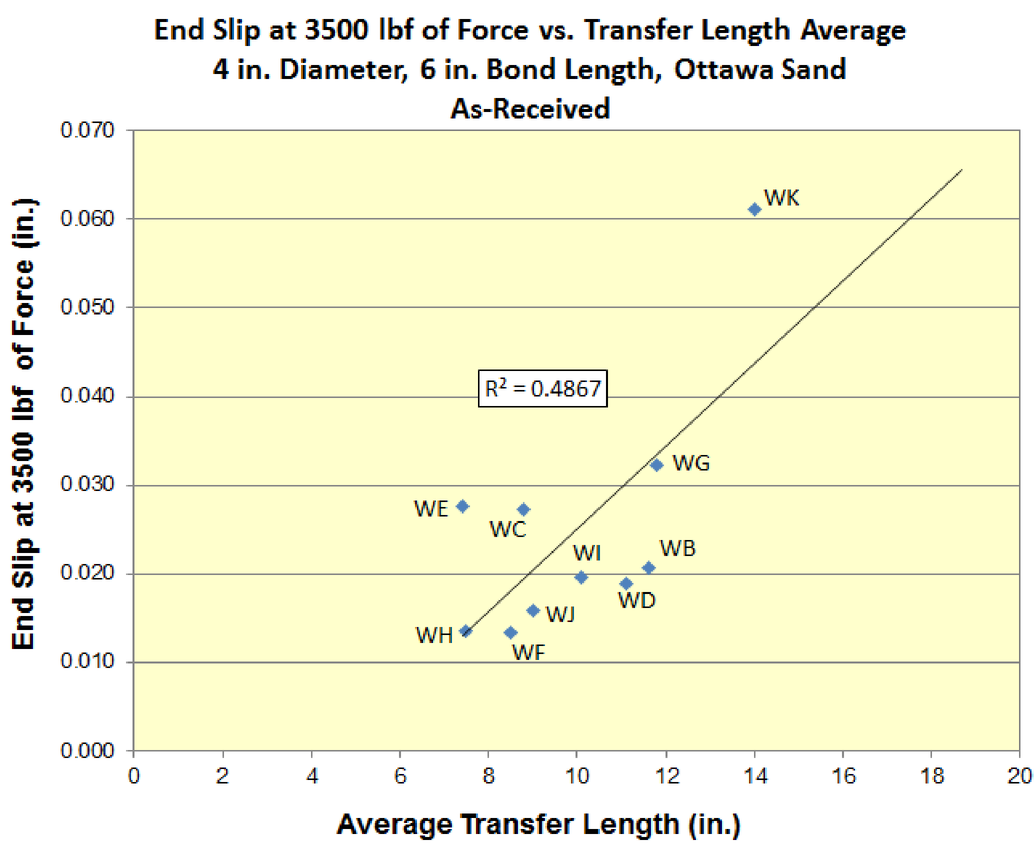

Figure G-11. As-received wires, end slip at 3500 lbf force

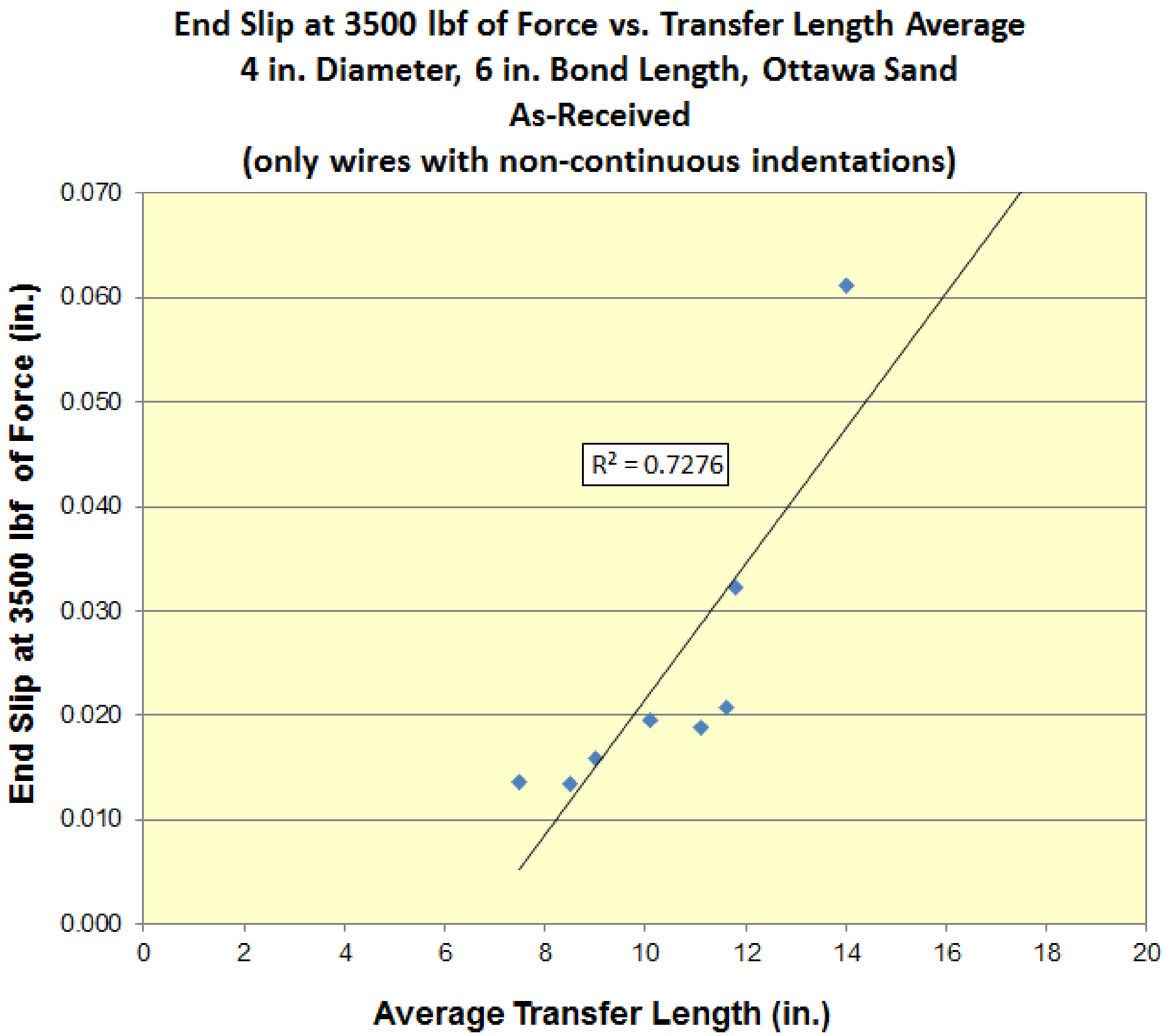

Figure G-12. As-received wires, end slip at 3500 lbf force (individual-indents only)

Table G-7. As-received wires, end slip at 4000 lbf force

As-Received Wire Bond Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand End Slip at 4000 lbf of Force				
Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0246	0.00465	18.9	11.6
[WC]	0.0335	0.00602	17.9	8.8
[WD]	0.0227	0.00375	16.5	11.1
[WE]	0.0325	0.00383	11.8	7.4
[WF]	0.0152	0.00157	10.3	8.5
[WG]	0.0394	0.00668	16.9	11.8
[WH]	0.0156	0.00187	12.0	7.5
[WI]	0.0230	0.00304	13.2	10.1
[WJ]	0.0182	0.00347	19.1	9.0
[WK]				14.0
[WL]				18.7

Note 1: Sample Size = 6

Note 2: A blank entry means the wire didn't reach that force

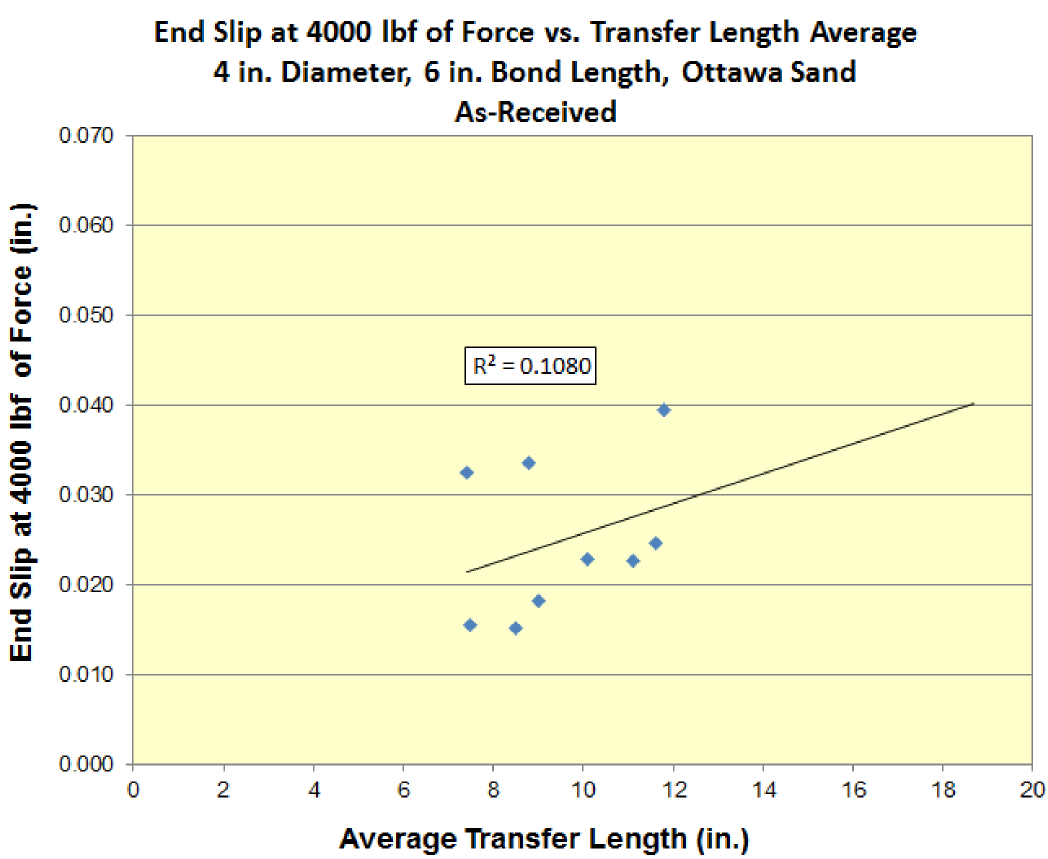

Figure G-13. As-received wires, end slip at 4000 lbf force

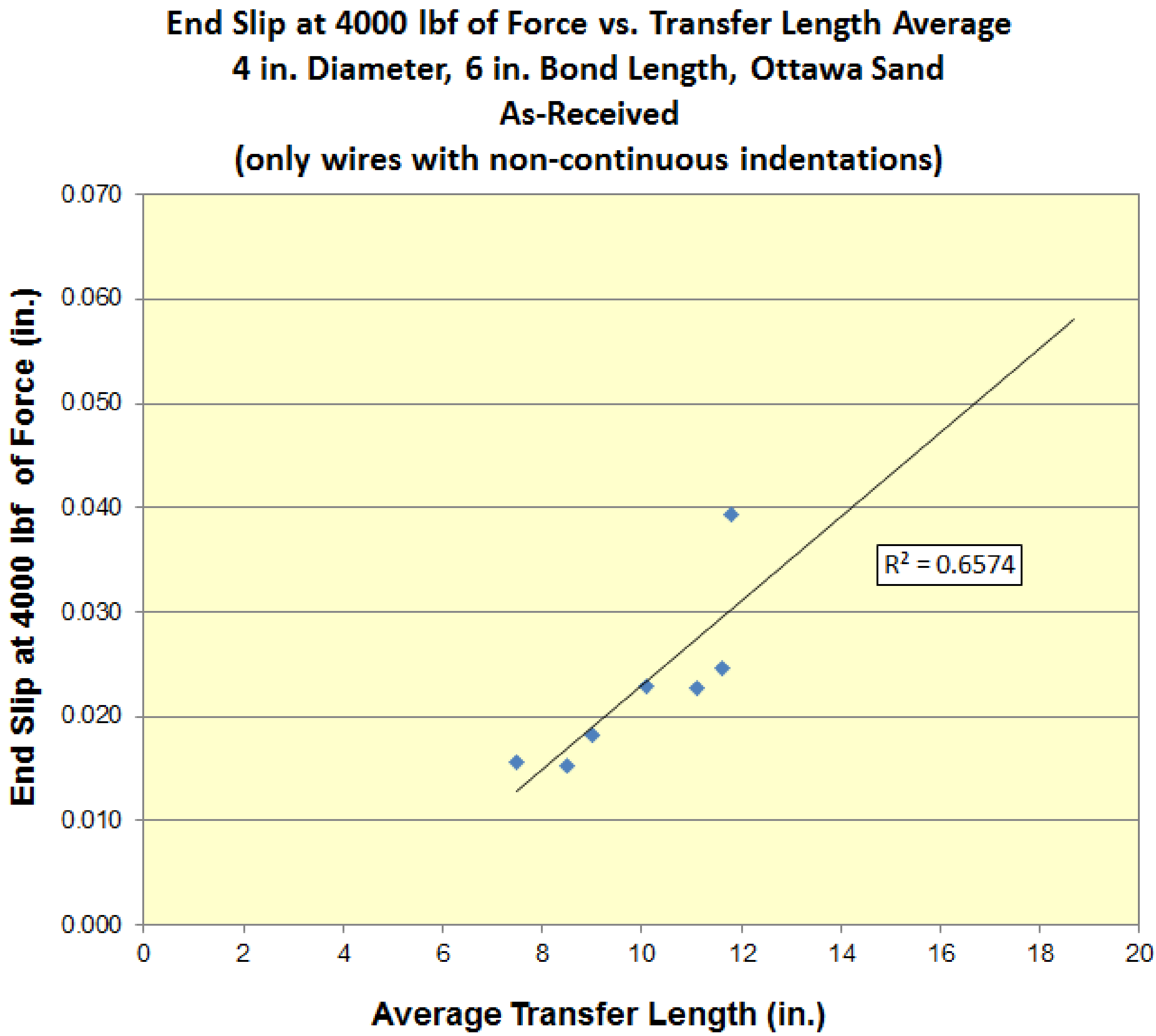

Figure G-14. As-received wires, end slip at 4000 lbf force (individual-indents only)

Table G-8. As-received wires, end slip at 4500 lbf force

As-Received Wire Bond Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand End Slip at 4500 lbf of Force				
Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0302	0.00664	22.0	11.6
[WC]	0.0406	0.00764	18.8	8.8
[WD]	0.0280	0.00523	18.7	11.1
[WE]	0.0382	0.00443	11.6	7.4
[WF]	0.0171	0.00192	11.2	8.5
[WG]	0.0488	0.00875	17.9	11.8
[WH]	0.0180	0.00224	12.5	7.5
[WI]	0.0271	0.00397	14.7	10.1
[WJ]	0.0213	0.00434	20.4	9.0
[WK]				14.0
[WL]				18.7

Note 1: Sample Size = 6

Note 2: A blank entry means the wire didn't reach that force

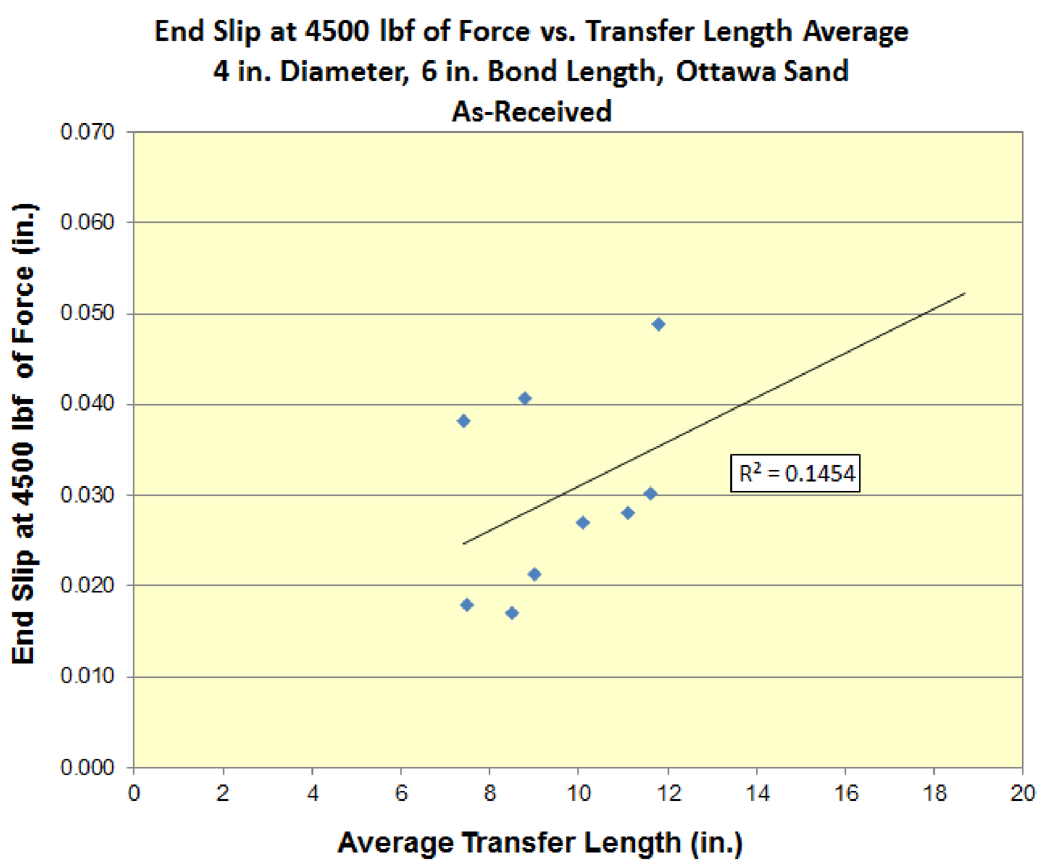

Figure G-15. As-received wires, end slip at 4500 lbf force

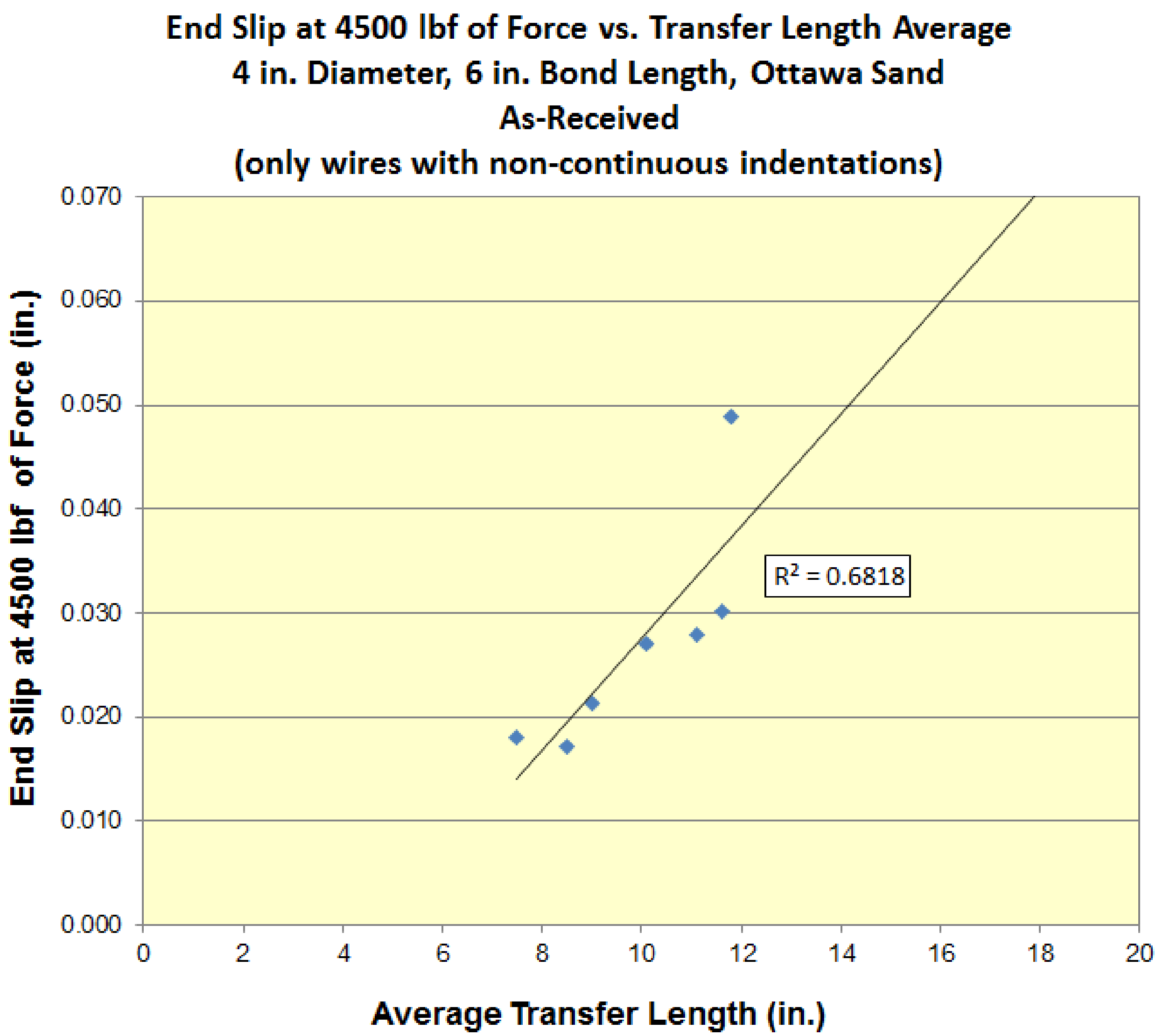

Figure G-16. As-received wires, end slip at 4500 lbf force (individual-indents only)

Table G-9. As-received wires, end slip at 5000 lbf force

As-Received Wire Bond Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand End Slip at 5000 lbf of Force				
Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0392	0.01206	30.7	11.6
[WC]	0.0483	0.00991	20.5	8.8
[WD]	0.0335	0.00489	14.6	11.1
[WE]	0.0447	0.00529	11.8	7.4
[WF]	0.0194	0.00244	12.6	8.5
[WG]	0.0630	0.01581	25.1	11.8
[WH]	0.0209	0.00278	13.3	7.5
[WI]	0.0324	0.00578	17.8	10.1
[WJ]	0.0252	0.00557	22.1	9.0
[WK]				14.0
[WL]				18.7

Note 1: Sample Size = 6, D = 5

Note 2: A blank entry means the wire didn't reach that force

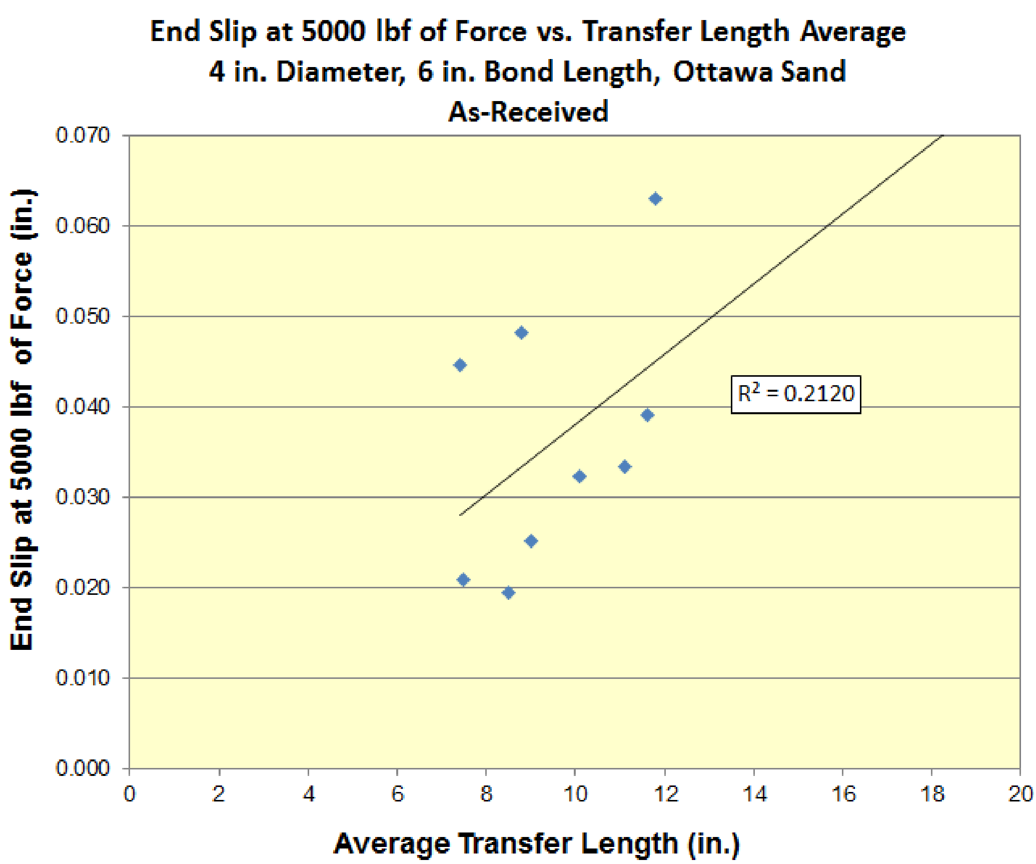

Figure G-17. As-received wires, end slip at 5000 lbf force

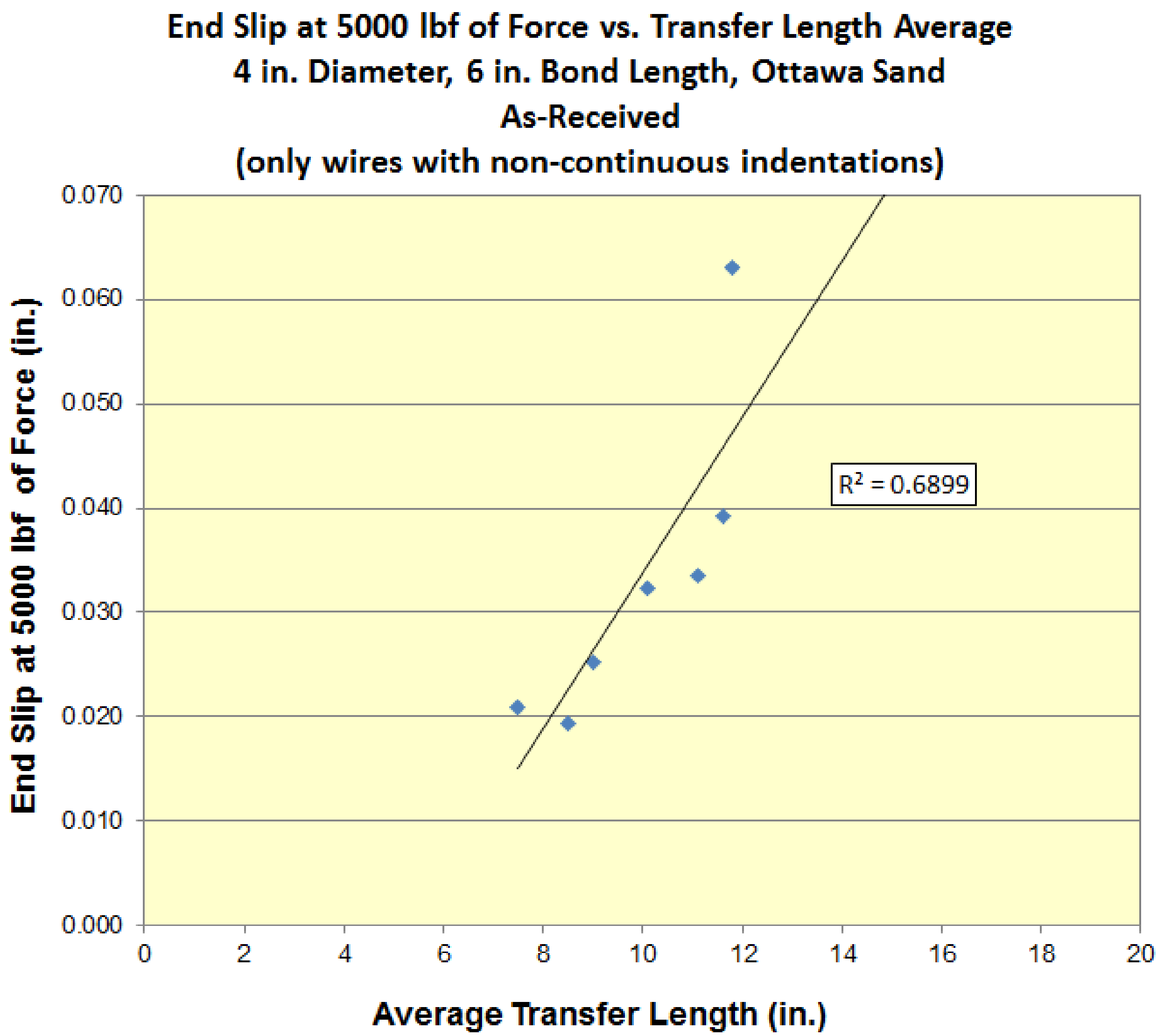

Figure G-18. As-received wires, end slip at 5000 lbf force (individual-indents only)

Table G-10. As-received wires, end slip at 5500 lbf force

As-Received Wire Bond Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand End Slip at 5500 lbf of Force				
Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0532	0.02179	41.0	11.6
[WC]	0.0575	0.01420	24.7	8.8
[WD]	0.0566	0.01550	27.4	11.1
[WE]	0.0520	0.00670	12.9	7.4
[WF]	0.0220	0.00300	13.7	8.5
[WG]	0.0642	0.00316	4.9	11.8
[WH]	0.0247	0.00359	14.5	7.5
[WI]	0.0401	0.00895	22.3	10.1
[WJ]	0.0304	0.00753	24.8	9.0
[WK]				14.0
[WL]				18.7

Note 1: Sample Size = 6, D = 5, G = 3

Note 2: A blank entry means the wire didn't reach that force

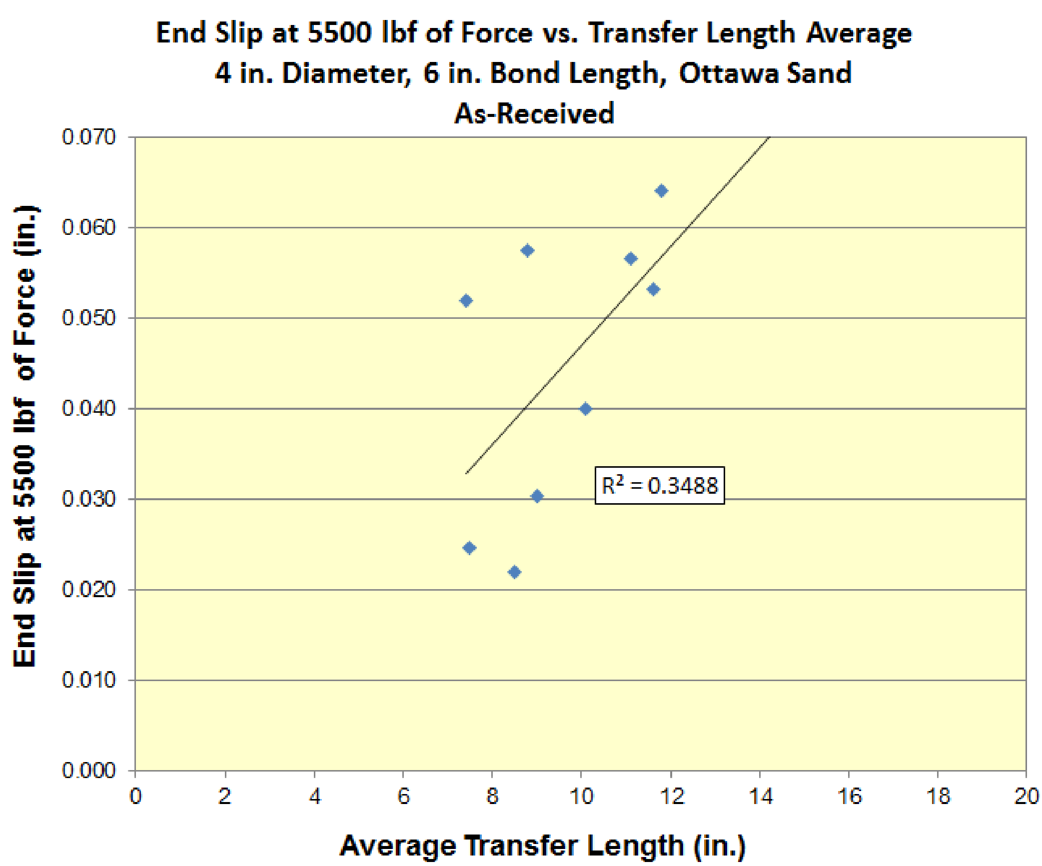

Figure G-19. As-received wires, end slip at 5500 lbf force

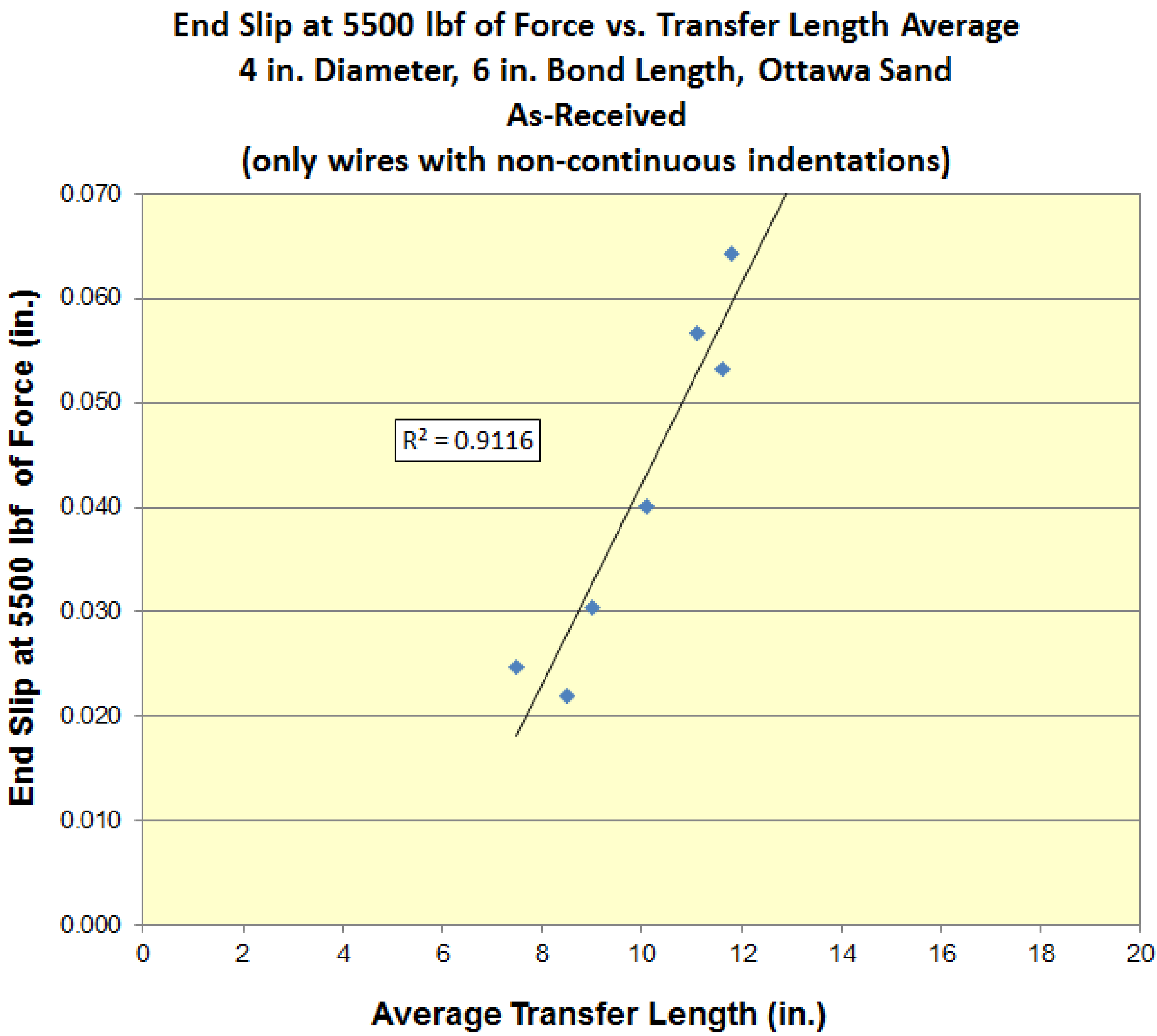

Figure G-20. As-received wires, end slip at 5500 lbf force (individual-indents only)

Table G-11. As-received wires, end slip at 6000 lbf force

As-Received Wire Bond Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand End Slip at 6000 lbf of Force				
Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0580	0.01245	21.5	11.6
[WC]	0.0667	0.01729	25.9	8.8
[WD]	0.0980	0.05509	56.2	11.1
[WE]	0.0606	0.00873	14.4	7.4
[WF]	0.0253	0.00375	14.8	8.5
[WG]				11.8
[WH]	0.0299	0.00540	18.0	7.5
[WI]	0.0479	0.01331	27.8	10.1
[WJ]	0.0383	0.01165	30.4	9.0
[WK]				14.0
[WL]				18.7

Note 1: Sample Size = 6, B = 5, D = 2, I = 5

Note 2: A blank entry means the wire didn't reach that force

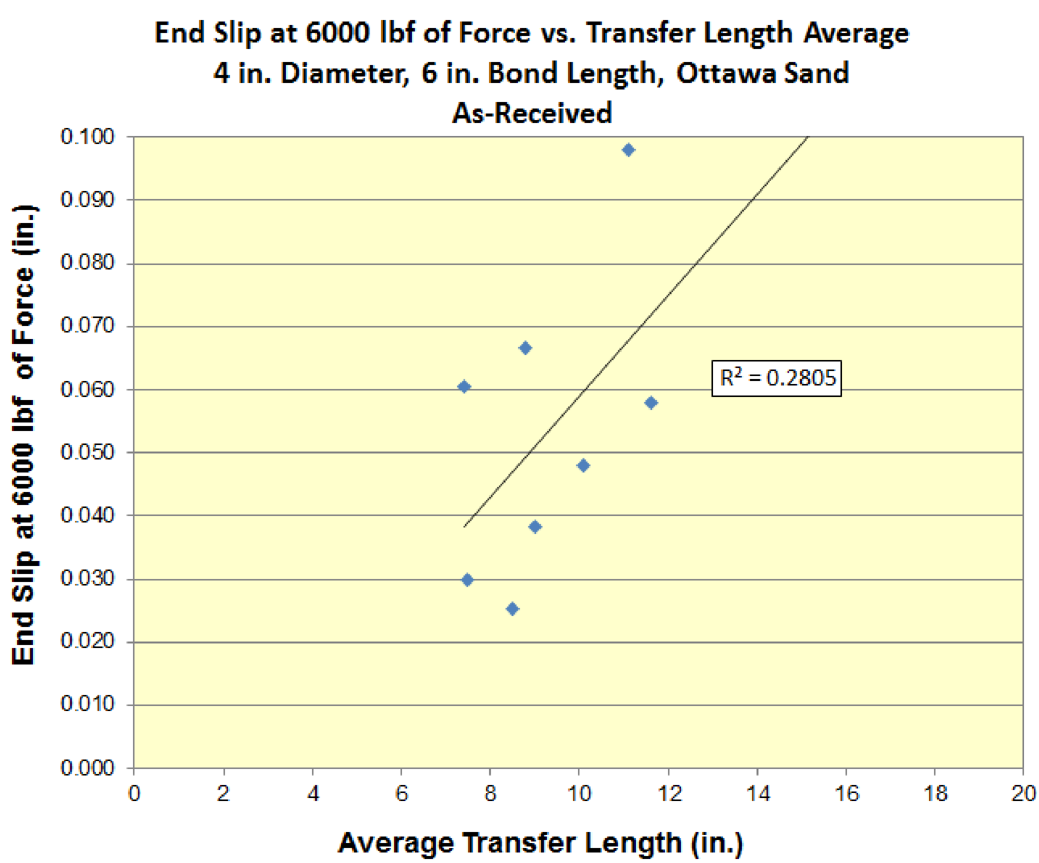

Figure G-21. As-received wires, end slip at 6000 lbf force

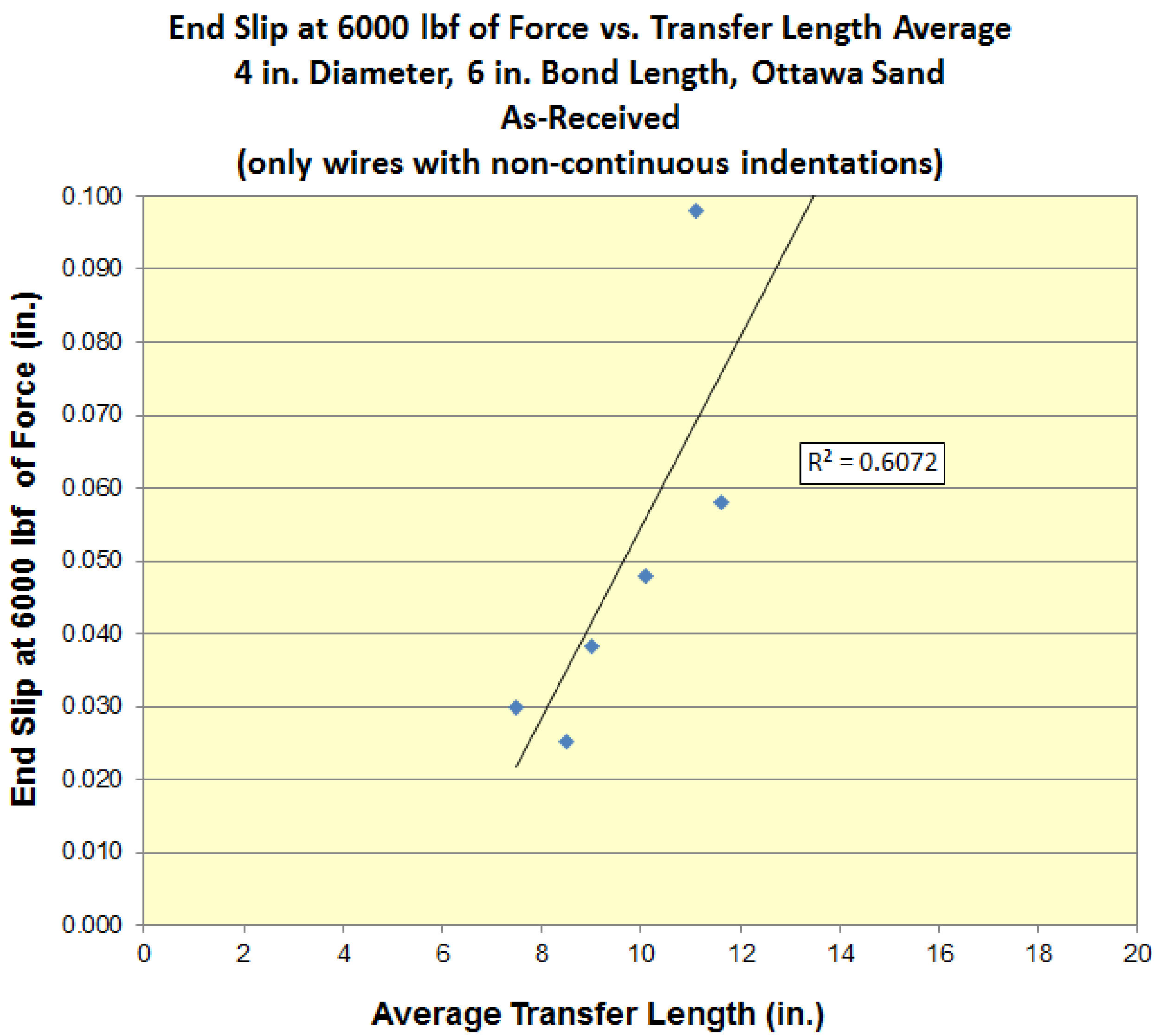

Figure G-22. As-received wires, end slip at 6000 lbf force (individual-indents only)

Appendix H.
Lab Phase, Wire; As-received vs. Cleaned Analysis

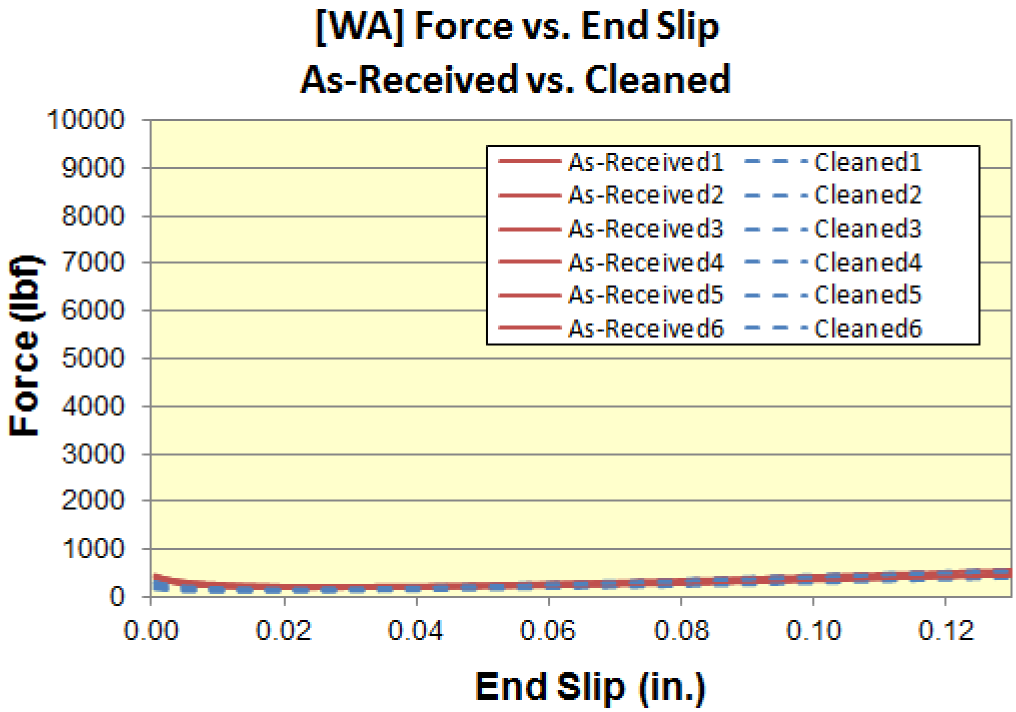

Figure H-1. [WA] force vs. end-slip individual graphs, As-received vs. cleaned

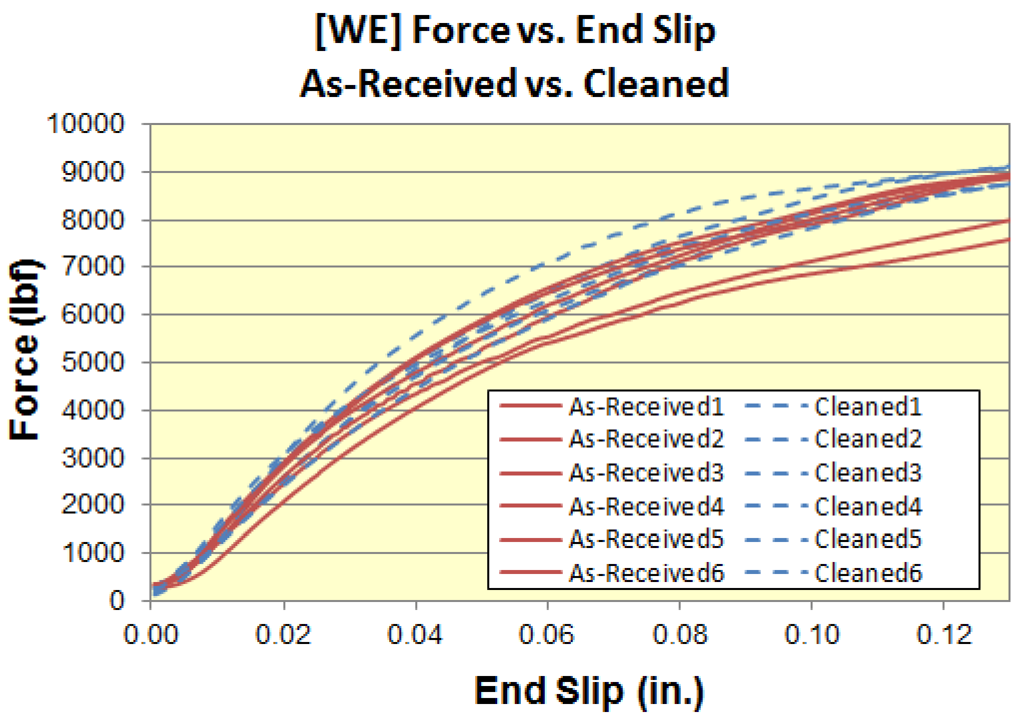

Figure H-2. [WE] force vs. end-slip individual graphs, As-received vs. cleaned

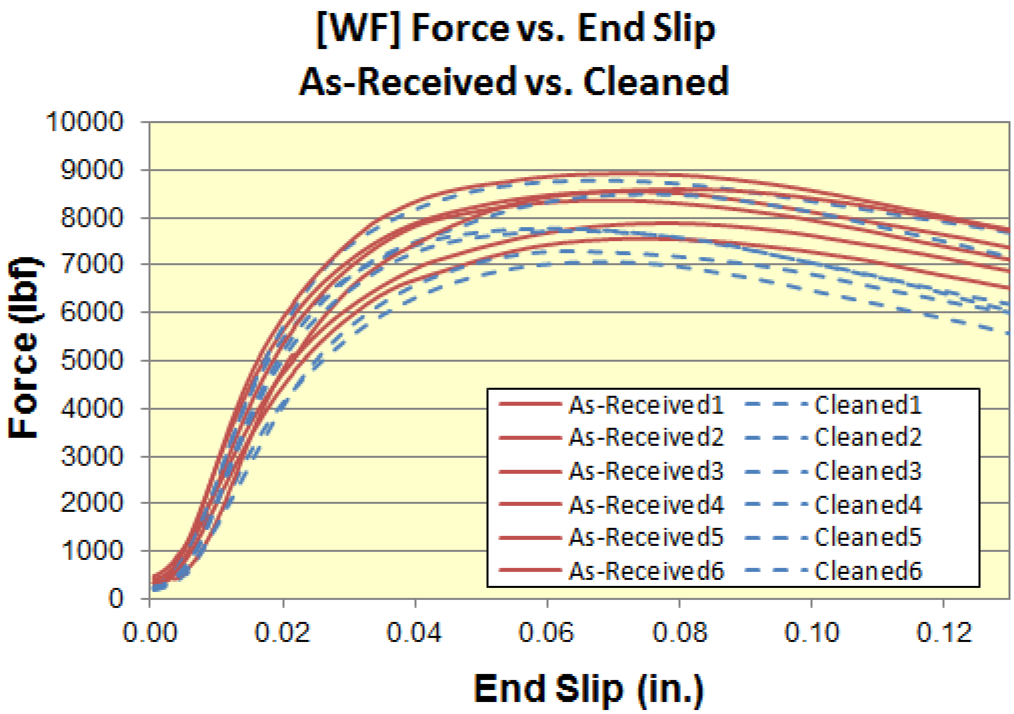

Figure H-3. [WF] force vs. end-slip individual graphs, As-received vs. cleaned

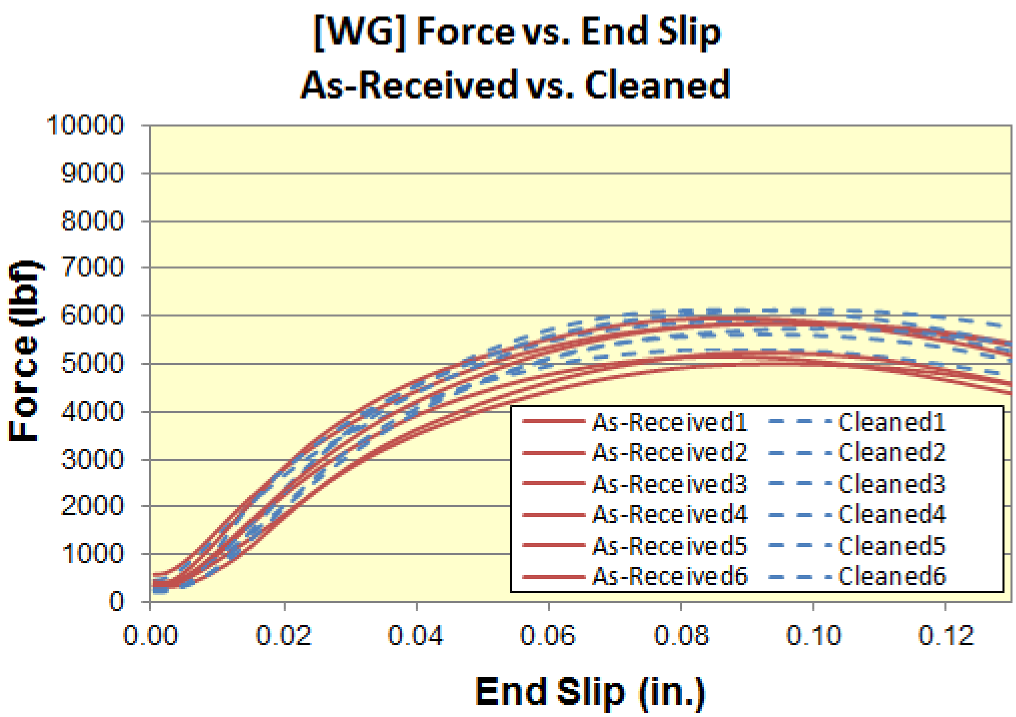

Figure H-4. [WG] force vs. end-slip individual graphs, As-received vs. cleaned

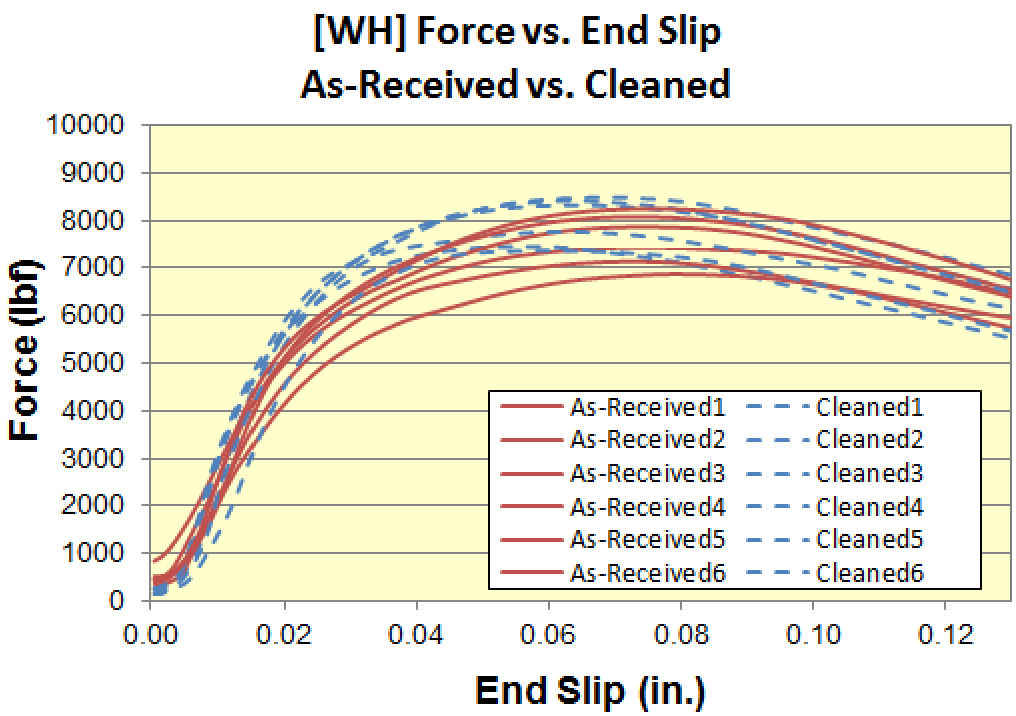

Figure H-5. [WH] force vs. end-slip individual graphs, As-received vs. cleaned

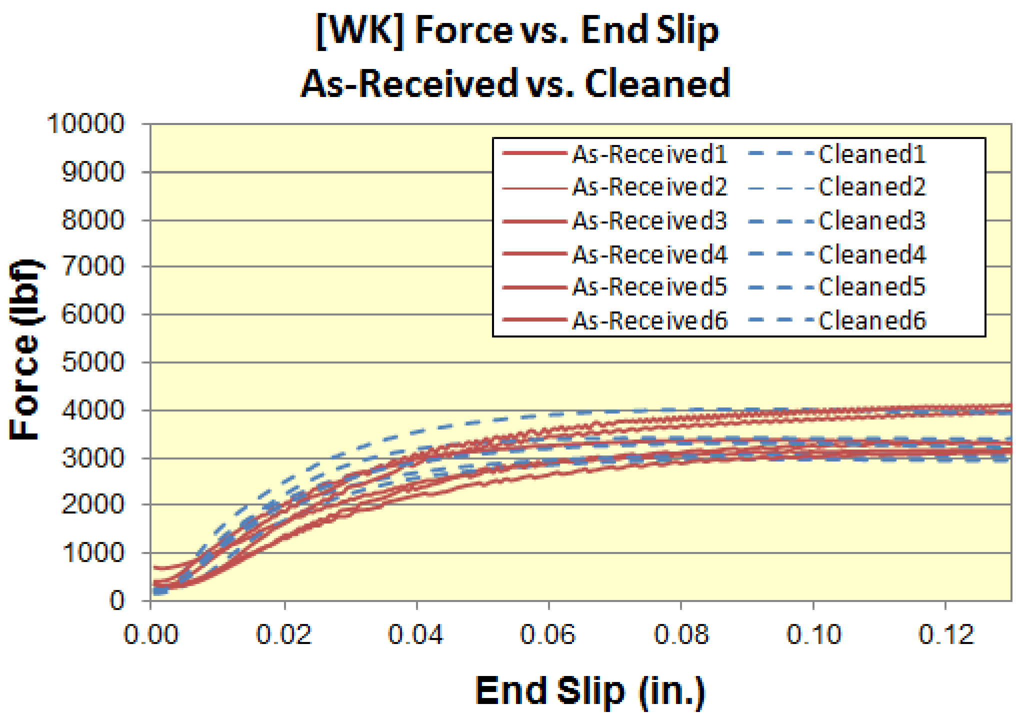

Figure H-6. [WK] force vs. end-slip individual graphs, As-received vs. cleaned

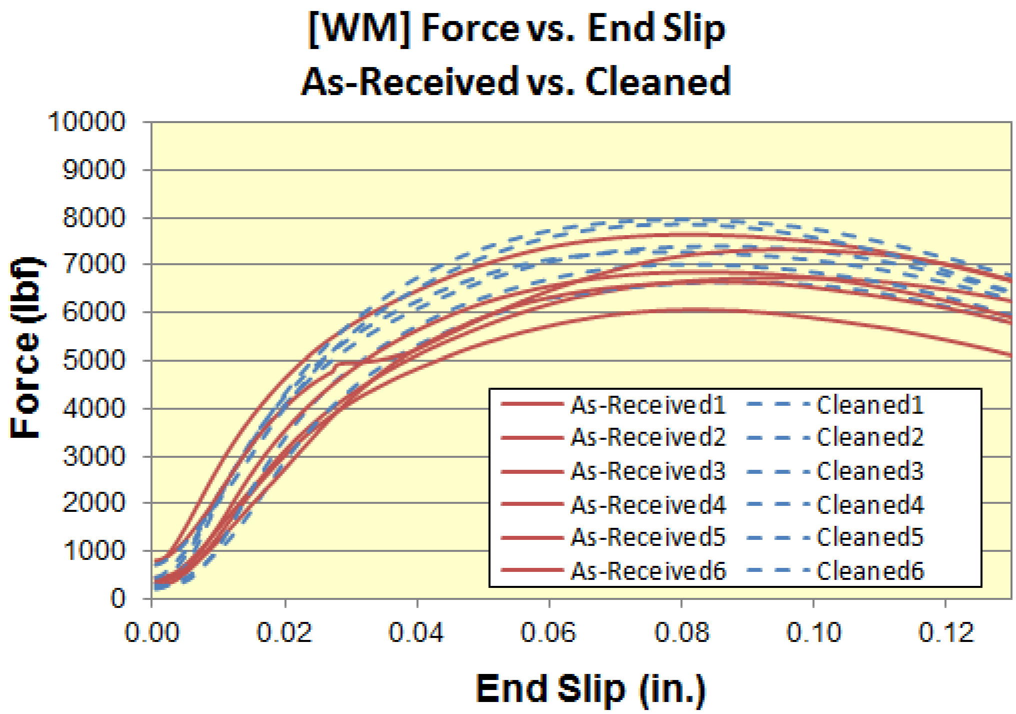

Figure H-7. [WM] force vs. end-slip individual graphs, As-received vs. cleaned

Appendix I.
Standard Test Method for Evaluating the Bond Quality of 5.32-mm-Diameter Prestressing Wire

1. Scope

This test method describes procedures for determining the bond of 5.32-mm-diameter steel prestressing wires. The bond determined by this test method is stated as the tensile force needed to pull the wire through the cured mortar in a cylindrical steel casing. The result of the test is the maximum tensile force measured on the loaded-end of the wire recorded at a free-end-slip less than or equal to 0.10 in.

This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Reference Documents

ASTM A881

ASTM C109

ASTM C150

ASTM C192

ASTM C230

ASTM C511

ASTM C778

ASTM C1437

3. Terminology

Bond – The adhesion of wire to mortar or concrete.

Bond breaker – A product wrapped around wire to prevent wire-to-mortar bond over the installed length. Duct tape is commonly used for this purpose.

Mortar – A mixture of cement, fine aggregate, and water.

Wire – All references to wire in this test method shall be assumed to be 5.32-mm-diameter, low-relaxation, indented prestressing steel wire conforming to ASTM A881.

Test specimen – An assembly consisting of one steel casing, one sample of wire, and mortar.

4. Summary of Test Method

Six samples of 5.32-mm-diameter steel prestressing wire are selected from a single continuous length for testing. Each wire sample is cast into a steel casing with a bonded length of 6-in. A mortar mixture is recommended, but is not prescribed. The fine aggregate source is prescribed, but the cement source is not. Testing on the six specimens begins shortly after the mortar-cube compressive strength reaches 4500 psi and ends before the strength reaches 5000 psi. A specified, force-controlled loading rate is applied at the bottom of the wire while the applied load and free-end-slip at the opposite (top) end is continuously monitored and recorded. The maximum pullout force occurring at an end slip less than or equal to 0.10-in. is recorded as the "test result." One complete test is comprised of the average of these six specimens.

5. Apparatus

A position transducer – generally an LVDT – with a minimum precision of 0.001-in.

A tensile testing machine with the following functionality:

- Force-controlled loading rate
- Gripping device without torsional restraint. This is commonly accomplished by providing a thrust bearing to allow rotation.
- Rigid testing frame. An example of the frame used for test development is shown in Figure .

6. Sampling of Wire

Samples of wire approximately 20-in. long will be taken from the same coil of prestressing wire. A minimum of six wire specimens are required, but more are permitted.

7. Mortar Requirements

Materials:

- Sand – The sand shall be silica sand from the Ottawa, Illinois region and conforming to ASTM C778. The sand shall come from natural sources. Manufactured sand is not permitted.
- Cement – The cement shall conform to ASTM C150 requirements for Type III cement.
- Water – The water shall be potable.
- Admixtures – Admixtures shall not be used.

Mixing procedure:

Mixing procedure will conform to ASTM C192 except no coarse aggregates or admixtures are allowed.

Strength:

Mortar strength will be evaluated according to ASTM C109 using 2-in. mortar cubes. Brass molds shall be used. Testing of the pullout specimens may begin after the 2-in. mortar cube compressive strength reaches 4500 psi. If the mortar strength reaches 5000 psi before the conclusion of the test, then the test is invalid and must be performed again.

Mix proportions:

The proportions and bath weights listed are recommended, but not prescribed. Any mixture conforming to the flow and strength requirements listed in the previous sub-section are allowed.

Table shows a mortar with a water-to-cement ratio (w/c) of 0.425 and an oven-dry sand-to-cement (s/c) ratio of 2.0.

Table I-1. Recommended batch weights

Material	Proportional Weight
ASTM C150 Type III Cement	1.0
ASTM C778 Ottawa Sand (Oven-Dry)	2.0
Water	0.425

8. Preparation of Test Specimens

Materials:

- Wire samples – Requirements as defined in Section 6.
- Mortar – Requirements as defined in Section 7.
- Bottom bond breaker – A 1-in. wide ± 0.125-in. strip of woven cloth adhesive tape (duct tape) shall be used as a bottom bond breaker. The length of bond breaker should be no less than 5-in. before application. The bond breaker shall be wrapped around the wire snugly.
- Top bond breaker – A 2-in. wide ± 0.125-in. strip of duct tape shall be used as a top bond breaker. The length of bond breaker should be no less than 3-in. before application. The bond breaker shall be wrapped around the wire snugly. The top bond breaker shall extend past the top mortar surface approximately 1 in. to ensure the exact bond length desired in case of settlement. The distance between the top and bottom bond breaker (embedment length) shall be maintained at 6-in. ± 0.0625 in.

- Steel casing – Each individual wire specimen shall be cast in a 4-in.-outer-diameter steel tube, approximately 1/8-in. wall thickness (11 gauge), and a total length of 8 in. A 6-in. x 6-in. x 3/16-in. thick steel plate is tack-welded to the bottom of the tube. The remaining contact surface shall be caulked to prevent any leakage. A schematic of the wire pullout specimen is shown in Figure Figure . The bottom plate shall have a 1/4-in.-diameter hole drilled in the center to allow the steel wire to pass through.

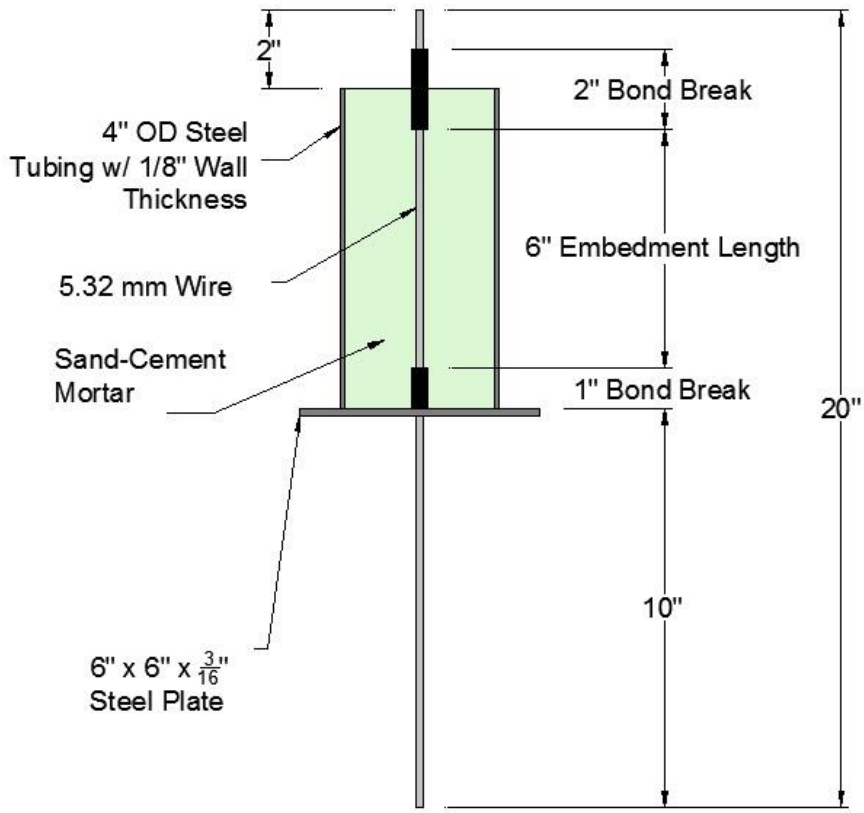

Figure I-1. Schematic of wire pullout test specimen

- Specimen assembly – Each wire specimen will be cast into a steel casing in the vertical position. The wires shall be held centered (concentrically ± 1/8-in.) in the steel tube using an additional fixture and rebar tie wire. The additional fixture can be removed after the mortar has cured and prior to testing.
- Consolidation – The pullout specimens shall be filled in two lifts and consolidated using internal vibration between each lift. The first lift should be filled to approximately 50% of the can height and the second lift to approximately 90% of the can height. The remaining 10% of mortar shall be added and smoothed using a hand trowel.
- Curing – The pullout test specimens shall be cured so that the relative humidity of the exposed top surface is greater than or equal to 90% for the duration of curing. The 2-in. mortar cubes shall be cured at 100% relative humidity. The specimens and cubes shall be stored in a temperature- and humidity-controlled room maintained at a temperature of

73.5 ± 3.5 °F and a relative humidity above 50%. These parameters can be accomplished without the use of a moist room or closet. As such, a moist room or closet is allowed, but not required. The test specimens shall be cured in an environment free of vibrations.

9. Test Set-up

- Test frame – The specimens shall be tested in a frame as described in Section 5. A schematic of the test frame used for test development is shown in Figure .

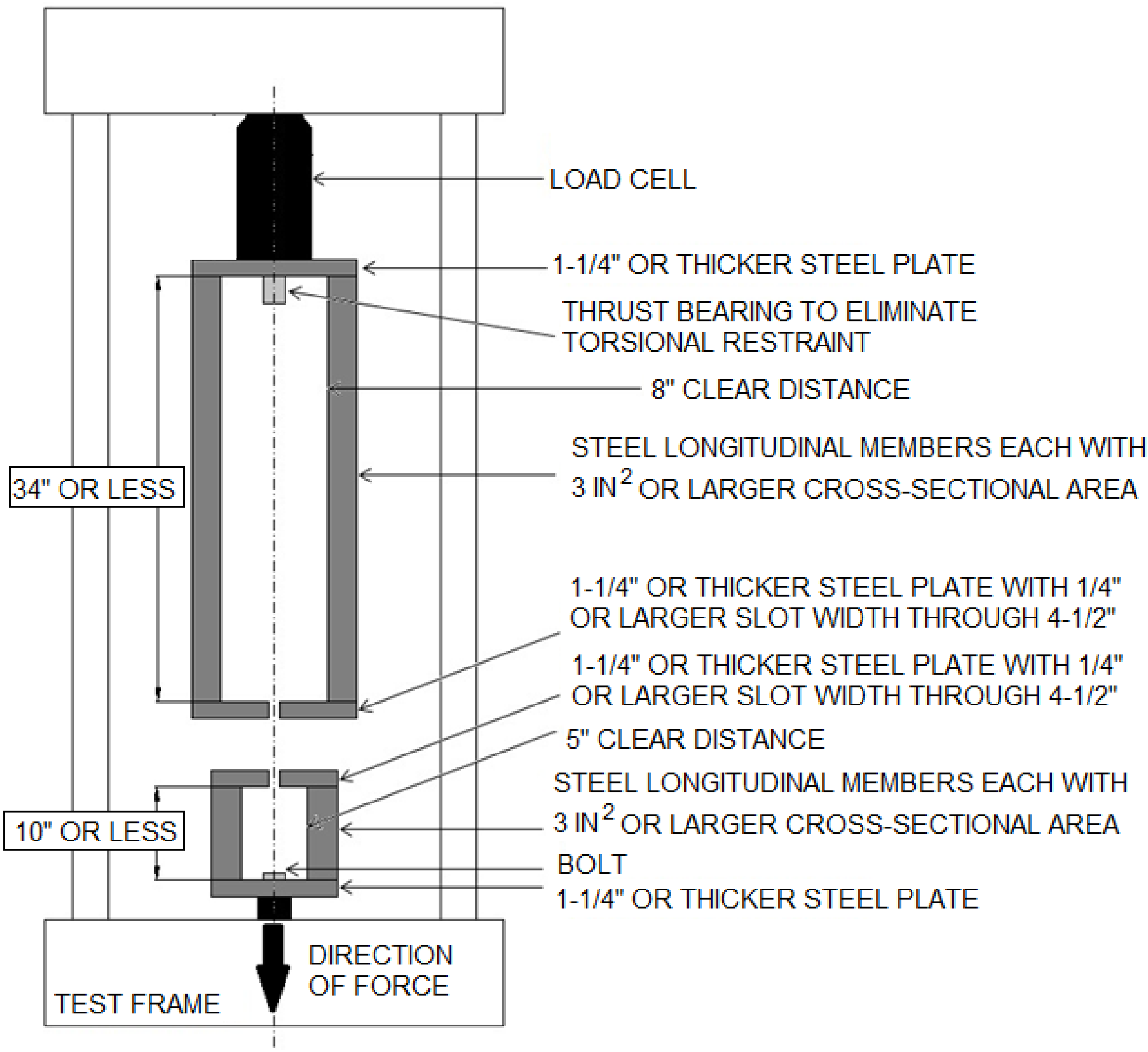

Figure I-2. Schematic of pullout test frame

- Free-end-slip measurement – A position transducer, generally an LVDT, shall be installed to measure the free-end-slip of the wire relative to the hardened mortar surface. The position transducer shall be centered on the wire. A picture of the setup used for test development is shown in Figure .

Figure I-3. LVDT and magnetic base setup used for test development

- Wire gripping – The wire shall be gripped by a chucking device. The free length between the bottom of the plate of the steel casing and the top of the chucking device shall be a minimum of 7-in. The test shall be free from torsional restraint.

10. Test Procedure

- Test start – The test specimens shall be removed from the temperature- and humidity-controlled environment, and testing may begin once the mortar strength reaches 4500 psi as evaluated by the 2-in. mortar cubes. This mortar strength is defined as the average of at least two individual 2-in. mortar cubes.
- Mortar strength – The mortar strength shall be tested at the beginning of the test and at the end of the test. Technicians are encouraged to monitor the mortar strength intermittently by using an extra mortar cube that was made.
- Force rate – Load shall be applied to the strand by displacement of the chucking device. A force-controlled rate of 2000 lbf/min. ± 100 lbf/min. shall be maintained after the chuck has been initially seated.
- Test result – The maximum pullout force occurring at an end slip less than or equal to 0.10-in. shall be recorded. This force should be rounded to the nearest 10 lbf.
- Acceptance of test result – If the hardened mortar exhibits cracking visible to normal or corrected vision in two or more of the six test specimens, the entire batch of six specimens shall be discarded and new specimens prepared.

11. Report

The following items shall be reported concisely:

- Identification of the wire tested (coil number, manufacturer, original manufacture date, manufacture location).
- Size and indentation pattern of wire.
- Date and time of batching. Batching time is reported as the time the mortar is finished being mixed. Batching time can be reported to the nearest five minutes.
- Batch weights and origin of constituent materials.
- Concrete temperature at the time mortar is finished mixing.
- Date and time of testing. Time of testing is reported as the time the load begins to be applied to the specimen. Testing time can be reported to the nearest five minutes.
- Six individual test results.
- Average test result.
- Individual mortar cube compressive strengths and times performed. Time performed should be reported as the time load is first applied to the specimen, rounded to the nearest minute.
- Average of beginning and ending mortar strengths.

12. Precision and Bias

No statement is made on the precision and bias of these test methods since the test results indicate only whether there is conformance to given criteria and no generally accepted method for determining precision of this test method is currently available. General guidelines provided herein for the specimens, instrumentation, and procedures make the results intractable to calculation of meaningful values by statistical analysis for precision at this time.

Since there is no accepted reference material suitable for determining the bias in this test method, no statement on bias is made.

Appendix J.
Lab Phase, Strand; As-received and Cleaned Batch Summaries

FRA DATA SHEET

Batch Name:	Strand Batch 1		Performed By:	Matthew Arnold
Batch Date:	9/4/2012			
Batch Time:	10:15am			

Mix proportions	# of cans	
	12	Actual
Dolese Sand (lb	243.19	243.19
Type III Monarch Cement (lbf)	86.85	86.85
Water (lbf)	39.95	39.95
Total (lbf)	370.0	370.0

		Wt. of Sand
Sieved Dolese Sand	#4	7.30
	#8	24.32
	#16	60.80
	#30	72.96
	#50	60.80
	#100	12.16
	#200	4.86
	Σ	243.19

Flow Table Value :	122
Water Added (± lbf	0
Concrete Temp :	75.1 °F
Room Temp / Humid:	72.9 °F / 61 %H

w/c: 0.46
s/c: 2.80
Avg Cub 4570 psi

Test Date: 9/5/2012 Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:08a	22 hr	1	16915	4229	10:31a	24.25 hr	9	18440	4610
8:10a		2	17280	4320	10:46a	24.5 hr	10	17900	4475
8:39a	22.5 hr	3	18030	4508	11:02a	24.75 hr	11	18675	4669
8:41a	22.75 hr	4	16875	4219	11:04a		12	18695	4674
9:24a	23.25 hr	5	18225	4556					
9:26a		6	17955	4489					
10:06a	23.75 hr	7	17995	4499					
10:13a	24 hr	8	18180	4545					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
9:37a	1	[SA]-OK-	1	18539	9:44a	2	[SA]-OK-	1clean	14377
9:51a	3	[SB]-OK-	1	17055	9:58a	4	[SB]-OK-	1clean	19254
10:05a	5	[SC]-OK-	1	11611	10:12a	6	[SC]-OK-	1clean	6668
10:19a	7	[SD]-OK-	1	15319	10:25a	8	[SD]-OK-	1clean	14425
10:31a	9	[SE]-OK-	1	16012	10:37a	10	[SE]-OK-	1clean	17502
10:44a	11	[SF]-OK-	1	18097 *	10:51a	12	[SF]-OK-	1clean	16635

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure J-1. As-received and cleaned strands, batch summary #1 (16-in. bond length)

FRA DATA SHEET

Batch Name:	Strand Batch 2	Performed By:	Matthew Arnold
Batch Date:	9/6/2012		
Batch Time:	10:14am		

Mix proportions	# of cans	
	12	Actual
Dolese Sand (lb	243.19	243.19
Type III Monarch Cement (lbf)	86.85	86.85
Water (lbf)	39.95	39.95
Total (lbf)	370.0	370.0

		Wt. of Sand
Sieved Dolese Sand	#4	7.30
	#8	24.32
	#16	60.80
	#30	72.96
	#50	60.80
	#100	12.16
	#200	4.86
	Σ	243.19

Flow Table Value :	121
Water Added (± lbf	0
Concrete Temp :	76.2 °F
Room Temp / Humid:	73.1 °F / 52 %H

w/c: 0.46

s/c: 2.80

Avg Cub 4598 psi

Test Date: 9/7/2012 Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:27a	22.25 hr	1	16925	4231	10:41a	24.5 hr	9	18355	4589
8:31a		2	17690	4423	11:00a	24.75 hr	10	19415	4854
9:26a	23.25 hr	3	17905	4476	11:16a	25 hr	11	18520	4630
9:28a		4	17995	4499	11:18a		12	18470	4618
9:39a	23.5 hr	5	18080	4520					
9:52a		6	18345	4586					
10:05a	23.75 hr	7	18295	4574					
10:13a		8	18565	4641					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
10:58a	11	[SA]-OK-	2	17666	11:04a	12	[SA]-OK-	2clean	14553
9:44a	1	[SB]-OK-	2	15587	9:51a	2	[SB]-OK-	2clean	16899
9:58a	3	[SC]-OK-	2	10624	10:04a	4	[SC]-OK-	2clean	9962
10:11a	5	[SD]-OK-	2	15491	10:17a	6	[SD]-OK-	2clean	16000
10:23a	7	[SE]-OK-	2	21384 *	10:32a	8	[SE]-OK-	2clean	21016 *
10:40a	9	[SF]-OK-	2	17750	10:49a	10	[SF]-OK-	2clean	18204 *

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure J-2. As-received and cleaned strands, batch summary #2 (16-in. bond length)

FRA DATA SHEET

Batch Name:	Strand Batch 3	Performed By:	Matthew Arnold
Batch Date:	9/11/2012		
Batch Time:	10:18am		

Mix proportions	# of cans	
	12	Actual
Dolese Sand (lb	243.19	243.19
Type III Monarch Cement (lbf)	86.85	86.85
Water (lbf)	39.95	39.95
Total (lbf)	370.0	370.0

		Wt. of Sand
Sieved Dolese Sand	#4	7.30
	#8	24.32
	#16	60.80
	#30	72.96
	#50	60.80
	#100	12.16
	#200	4.86
	Σ	243.19

Flow Table Value :	119
Water Added (± lbf	0
Concrete Temp :	75.9 °F
Room Temp / Humid:	73.1 °F / 49 %H

w/c: 0.46
s/c: 2.80
Avg Cub 4607 psi

Test Date: 9/12/2012 Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:28a	22.25 hr	1	16255	4064	10:58a		9	18760	4690
8:30a		2	17130	4283	11:06a	24.75 hr	10	18380	4595
9:38a	23.25 hr	3	18225	4556	11:08a		11	18665	4666
9:40a		4	18555	4639	11:10a	25 hr	12	18995	4749
9:58a	23.5 hr	5	17695	4424					
10:17a	24 hr	6	18200	4550					
10:26a		7	18420	4605					
10:52a	24.5 hr	8	18045	4511					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
10:38a	9	[SA]-OK-	3	17800	10:45a	10	[SA]-OK-	3clean	15699
10:51a	11	[SB]-OK-	3	19729	10:58a	12	[SB]-OK-	3clean	21541
9:46a	1	[SC]-OK-	3	6151	9:51a	2	[SC]-OK-	3clean	5681
9:56a	3	[SD]-OK-	3	14814	10:02a	4	[SD]-OK-	3clean	16880
10:09a	5	[SE]-OK-	3	17023	10:15a	6	[SE]-OK-	3clean	15830
10:22a	7	[SF]-OK-	3	18203 *	10:30a	8	[SF]-OK-	3clean	18217 *

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure J-3. As-received and cleaned strands, batch summary #3 (16-in. bond length)

FRA DATA SHEET

Batch Name: Strand Batch 4 — Performed By: Matthew Arnold

Batch Date: 9/13/2012

Batch Time: 10:11am

Mix proportions	# of cans	
	12	Actual
Dolese Sand (lb	243.19	262.92
Type III Monarch Cement (lbf)	86.85	93.89
Water (lbf)	39.95	43.19
Total (lbf)	370.0	400.0

		Wt. of Sand
Sieved Dolese Sand	#4	7.30
	#8	24.32
	#16	60.80
	#30	72.96
	#50	60.80
	#100	12.16
	#200	4.86
	Σ	243.19

Flow Table Value : 118

Water Added (± lbf 0

Concrete Temp : 75.2 °F

Room Temp / Humid: 71.3 °F / 56 %H

w/c: 0.46

s/c: 2.80

Avg Cub 4598 psi

Test Date: 9/14/2012 — Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:38a	22.5 hr	1	16980	4245	10:07a	24 hr	9	17805	4451
8:42a		2	18465	4616	10:26a	24.25 hr	10	19060	4765
8:56a	22.75 hr	3	18190	4548	10:28a		11	18585	4646
9:06a	23 hr	4	18390	4598	10:30a		12	18495	4624
9:21a	23.25 hr	5	18690	4673					
9:36a	23.5 hr	6	17570	4393					
9:47a		7	18990	4748					
9:54a	23.75 hr	8	18720	4680					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
9:46a	7	[SA]-OK-	4	15920	9:53a	8	[SA]-OK-	4clean	16113
9:59a	9	[SB]-OK-	4	18273	10:06a	10	[SB]-OK-	4clean	21611 *
10:12a	11	[SC]-OK-	4	5985	10:18a	12	[SC]-OK-	4clean	8335
9:08a	1	[SD]-OK-	4	14347	9:14a	2	[SD]-OK-	4clean	112861
9:20a	3	[SE]-OK-	4	14219	9:26a	4	[SE]-OK-	4clean	20870 *
9:32a	5	[SF]-OK-	4		9:38a	6	[SF]-OK-	4clean	18211 *

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure J-4. As-received and cleaned strands, batch summary #4 (16-in. bond length)

FRA DATA SHEET

Batch Name: Strand Batch 5
Batch Date: 9/27/2012
Batch Time: 10:18am
Performed By: Matthew Arnold

Mix proportions	# of cans	
	12	Actual
Dolese Sand (lb	243.19	243.19
Type III Monarch Cement (lbf)	86.85	86.85
Water (lbf)	39.95	39.95
Total (lbf)	370.0	370.0

		Wt. of Sand
Sieved Dolese Sand	#4	7.30
	#8	24.32
	#16	60.80
	#30	72.96
	#50	60.80
	#100	12.16
	#200	4.86
	Σ	243.19

Flow Table Value : 117
Water Added (± lbf: 0
Concrete Temp : 74.5 °F
Room Temp / Humid: 70.2 °F / 55 %H

w/c: 0.46
s/c: 2.80
Avg Cub 4602 psi

Test Date: 9/28/2012
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:58a	22.75 hr	1	17985	4496	10:28a	24.25 hr	9	18770	4693
9:06a		2	18180	4545	10:36a		10	17885	4471
9:08a		3	18125	4531	10:48a	24.5 hr	11	18920	4730
9:34a	23.25 hr	4	18565	4641	10:50a		12	18435	4609
9:50a	23.5 hr	5	18100	4525					
10:04a	23.75 hr	6	17870	4468					
10:06a		7	18525	4631					
10:20a	24 hr	8	19180	4795					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
9:49a	5	[SA]-OK-	5	15635	9:56a	6	[SA]-OK-	5clean	16316
1);02a	7	[SB]-OK-	5	17660	10:12a	8	[SB]-OK-	5clean	21500 *
10:19a	9	[SC]-OK-	5	11677	10:24a	10	[SC]-OK-	5clean	9886
10:30a	11	[SD]-OK-	5	13892	10:36a	12	[SD]-OK-	5clean	11880
9:20a	1	[SE]-OK-	5	16053	9:26a	2	[SE]-OK-	5clean	20916 *
9:33a	3	[SF]-OK-	5	18203 *	9:42a	4	[SF]-OK-	5clean	18210 *

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure J-5. As-received and cleaned strands, batch summary #5 (16-in. bond length)

FRA DATA SHEET

Batch Name:	Strand Batch 6	Performed By:	Matthew Arnold
Batch Date:	10/11/2012		
Batch Time:	10:48am		

Mix proportions	# of cans	
	12	Actual
Dolese Sand (lb	243.19	243.19
Type III Monarch Cement (lbf)	86.85	86.85
Water (lbf)	39.95	39.95
Total (lbf)	370.0	370.0

		Wt. of Sand
Sieved Dolese Sand	#4	7.30
	#8	24.32
	#16	60.80
	#30	72.96
	#50	60.80
	#100	12.16
	#200	4.86
	Σ	243.19

Flow Table Value :	118
Water Added (± lbf	0
Concrete Temp :	73.1 °F
Room Temp / Humid:	69.3 °F / 48 %H

w/c: 0.46

s/c: 2.80

Avg Cube 4639 psi

Test Date: 10/12/2012 Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
9:20a	22.5 hr	1	17505	4376	11:26a	24.75 hr	9	18775	4694
9:28a	22.75 hr	2	17610	4403	11:36a		10	19730	4933
9:56a	23 hr	3	17925	4481	11:50a	25 hr	11	18460	4615
10:22a	23.5 hr	4	18195	4549	11:52a		12	17940	4485
10:24a		5	18325	4581					
10:48a	24 hr	6	18340	4585					
11:04a	24.25 hr	7	18700	4675					
11:16a	24.5 hr	8	18315	4579					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
10:45a	3	[SA]-OK-	6	17143	10:53a	4	[SA]-OK-	6clean	14891
11:00a	5	[SB]-OK-	6	15962	11:06a	6	[SB]-OK-	6clean	19492
11:14a	7	[SC]-OK-	6	10776	11:20a	8	[SC]-OK-	6clean	8468
11:24a	9	[SD]-OK-	6	13261	11:30a	10	[SD]-OK-	6clean	11623
11:35a	11	[SE]-OK-	6	20818 *	11:42a	12	[SE]-OK-	6clean	20819 *
10:29a	1	[SF]-OK-	6	18100 *	10:36a	2	[SF]-OK-	6clean	17316

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure J-6. As-received and cleaned strands, batch summary #6 (16-in. bond length)

FRA DATA SHEET

Batch Name:	Strand Batch 1 (9 in.)	Performed By:	Matthew Arnold
Batch Date:	11/1/2012		
Batch Time:	9:40am		

Mix proportions	# of cans	
	12	Actual
Dolese Sand (lb	164.32	164.32
Type III Monarch Cement (lbf)	58.69	58.69
Water (lbf)	27.00	27.00
Total (lbf)	250.0	250.0

		Wt. of Sand
Sieved Dolese Sand	#4	4.93
	#8	16.43
	#16	41.08
	#30	49.30
	#50	41.08
	#100	8.22
	#200	3.29
	Σ	164.32

Flow Table Value :	117
Water Added (± lbf	0
Concrete Temp :	73 °F
Room Temp / Humid:	69.3 °F / 43 %H

w/c: 0.46

s/c: 2.80

Avg Cub 4630 psi

Test Date:	11/2/2012	Performed By:	Matthew Arnold

Time	Since Batch	Spec.	Max Load	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:22a	22.75 hr	1	18200	4550	9:41a		9	18665	4666
8:24a		2	18130	4533	9:58a	24.25hr	10	18870	4718
8:40a	23 hr	3	18430	4608	10:00a		11	18245	4561
8:58a	23.25 hr	4	18710	4678	10:02a		12	18475	4619
9:09a	23.5 hr	5	18817	4704					
9:22a	23.75 hr	6	18490	4623					
9:30a		7	18195	4549					
9:34a	24 hr	8	18990	4748					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
8:43a	1	[SA]-OK-	1 (9 in.)	9248	9:19a	7	[SA]-OK-	2	10764
8:48a	2	[SB]-OK-	1 (9 in.)	10823	9:25a	8	[SB]-OK-	2	11318
8:56a	3	[SC]-OK-	1 (9 in.)	5954	9:30a	9	[SC]-OK-	2	6260
9:01a	4	[SD]-OK-	1 (9 in.)	7898	9:36a	10	[SD]-OK-	2	9529
9:07a	5	[SE]-OK-	1 (9 in.)	1068	9:41a	11	[SE]-OK-	2	12027
9:13a	6	[SF]-OK-	1 (9 in.)	16561	9:47a	12	[SF]-OK-	2	12684

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure J-7. As-received and cleaned strands, batch summary #1 (9-in. bond length)

FRA DATA SHEET

Batch Name: Strand Batch 2 (9 in.)   Performed By: Matthew Arnold

Batch Date: 11/6/2012

Batch Time: 10:12am

Mix proportions	# of cans	
	12	Actual
Dolese Sand (lb	164.32	164.32
Type III Monarch Cement (lbf)	58.69	58.69
Water (lbf)	27.00	27.00
Total (lbf)	250.0	250.0

		Wt. of Sand
Sieved Dolese Sand	#4	4.93
	#8	16.43
	#16	41.08
	#30	49.30
	#50	41.08
	#100	8.22
	#200	3.29
	Σ	164.32

Flow Table Value : 115

Water Added (± lbf: 0

Concrete Temp : 72.6 °F

Room Temp / Humid: 70.4 °F / 45 %H

w/c: 0.46

s/c: 2.80

Avg Cube 4663 psi

Test Date: 11/7/2012   Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:32a	22.25 hr	1	18495	4624	9:51a	23.75 hr	9	19250	4813
8:34a		2	18495	4624	10:07a	24 hr	10	18540	4635
8:46a	22.5 hr	3	18425	4606	10:09a		11	18890	4723
9:03a	22.75 hr	4	18140	4535	10:12a		12	18530	4633
9:14a	23 hr	5	19650	4913					
9:26a	23.25 hr	6	18555	4639					
9:34a	23.5 hr	7	18630	4658					
9:42a		8	18240	4560					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
9:20a	5	[SA]-OK-	3	10180	9:50a	11	[SA]-OK-	4	9600
9:25a	6	[SB]-OK-	3	10383	9:55a	12	[SB]-OK-	4	10623
8:57a	1	[SC]-OK-	3	4840	9:30a	7	[SC]-OK-	4	6323
9:02a	2	[SD]-OK-	3	9671	9:35a	8	[SD]-OK-	4	10261
9:08a	3	[SE]-OK-	3	11478	9:40a	9	[SE]-OK-	4	11802
9:13a	4	[SF]-OK-	3	16200	9:45a	10	[SF]-OK-	4	12184

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure J-8. As-received and cleaned strands, batch summary #2 (9-in. bond length)

FRA DATA SHEET

Batch Name: Strand Batch 3 (9 in.) — Performed By: Matthew Arnold

Batch Date: 11/13/2012

Batch Time: 10:14am

Mix proportions	# of cans	
	12	Actual
Dolese Sand (lb	164.32	164.32
Type III Monarch Cement (lbf)	58.69	58.69
Water (lbf)	27.00	27.00
Total (lbf)	250.0	250.0

		Wt. of Sand
Sieved Dolese Sand	#4	4.93
	#8	16.43
	#16	41.08
	#30	49.30
	#50	41.08
	#100	8.22
	#200	3.29
	Σ	164.32

Flow Table Value : 115.5

Water Added (± lbf: 0

Concrete Temp : 70.8 °F

Room Temp / Humid: 68.8 °F / 46 %H

w/c: 0.46

s/c: 2.80

Avg Cub 4669 psi

Test Date: 11/14/2012 — Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:54a	22.75 hr	1	18700	4675	10:02a		9	18735	4684
9:00a		2	18265	4566	10:17a	24 hr	10	18870	4718
9:05a		3	18490	4623	10:19a		11	19440	4860
9:13a	23 hr	4	18985	4746	10:22a		12	18695	4674
9:27a	23.25 hr	5	18530	4633					
9:40a	23.5 hr	6	18600	4650					
9:47a		7	18125	4531					
9:56a	23.75 hr	8	18700	4675					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
9:18a	3	[SA]-OK-	5	7995	9:50a	9	[SA]-OK-	6	11715
9:23a	4	[SB]-OK-	5	11245	9:55a	10	[SB]-OK-	6	9885
9:29a	5	[SC]-OK-	5	5732	10:00a	11	[SC]-OK-	6	6012
9:34a	6	[SD]-OK-	5	9936	10:05a	12	[SD]-OK-	6	9260
9:07a	1	[SE]-OK-	5	11579	9:39a	7	[SE]-OK-	6	11041
9:12a	2	[SF]-OK-	5	11195	9:44a	8	[SF]-OK-	6	14120

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure J-9. As-received and cleaned strands, batch summary #3 (9-in. bond length)

Appendix K.
Lab Phase, Strand; As-received and Cleaned Individual Pullout Graphs

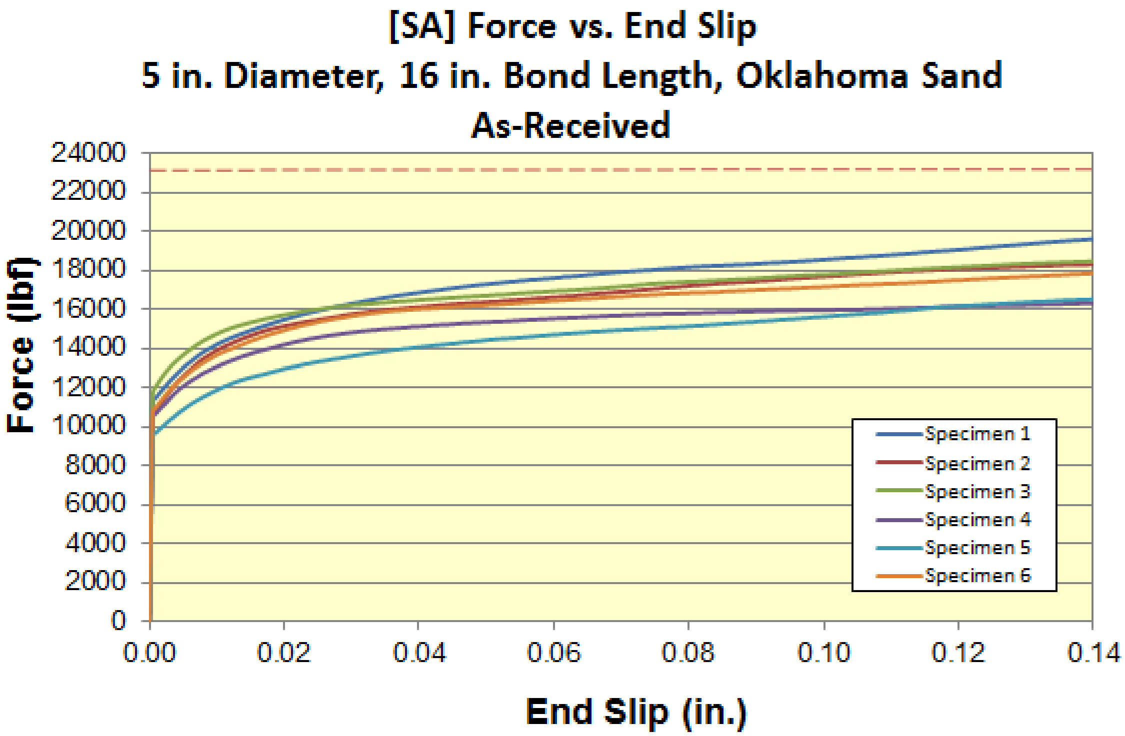

Figure K-1. As-received [SA] force vs. end-slip individual graphs (16-in. bond length)

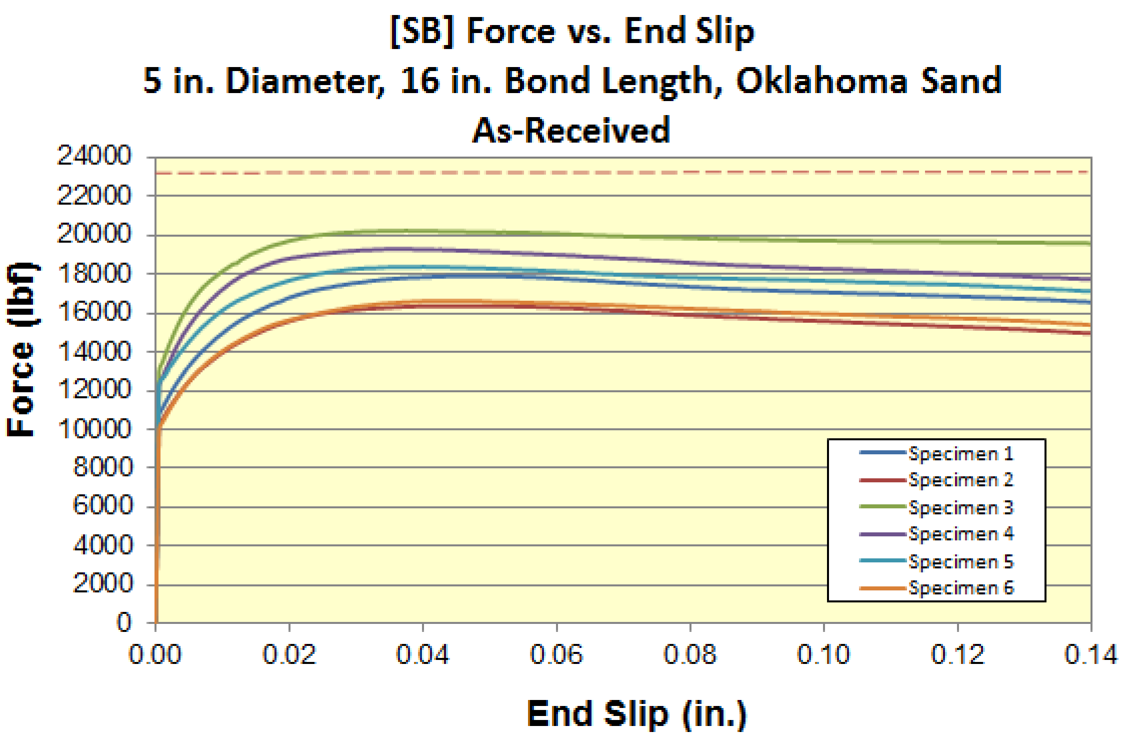

Figure K-2. As-received [SB] force vs. end-slip individual graphs (16-in. bond length)

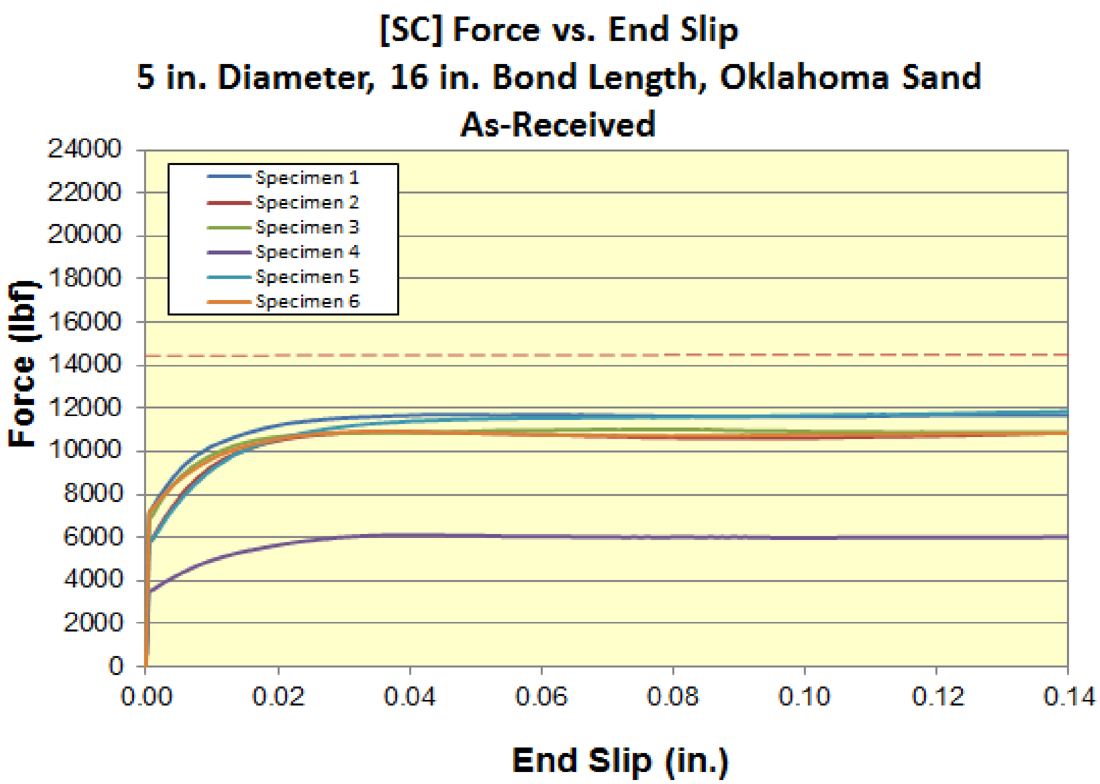

Figure K-3. As-received [SC] force vs. end-slip individual graphs (16-in. bond length)

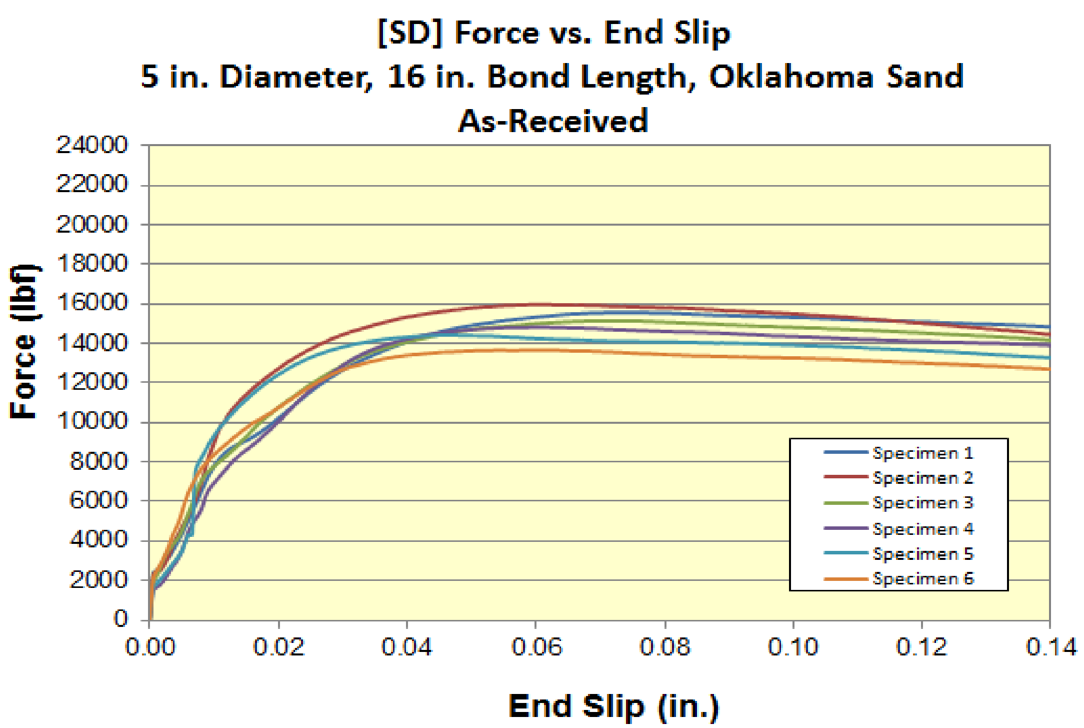

Figure K-4. As-received [SD] force vs. end-slip individual graphs (16-in. bond length)

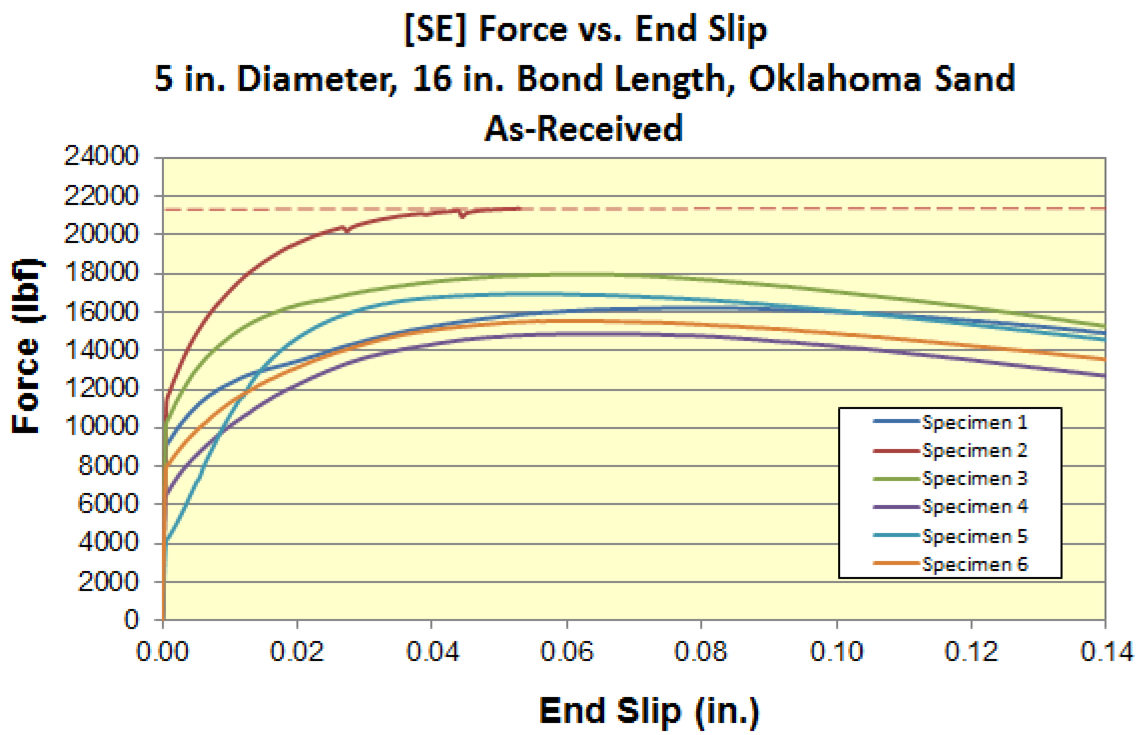

Figure K-5. As-received [SE] force vs. end-slip individual graphs (16-in. bond length)

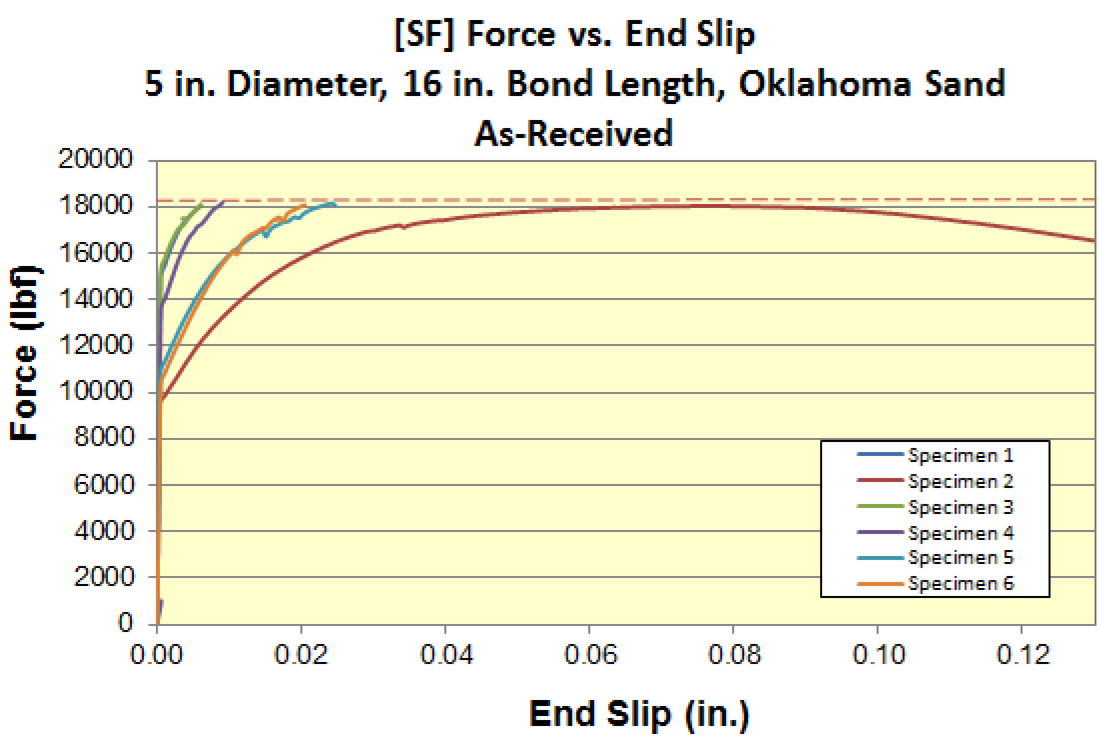

Figure K-6. As-received [SF] force vs. end-slip individual graphs (16-in. bond length)

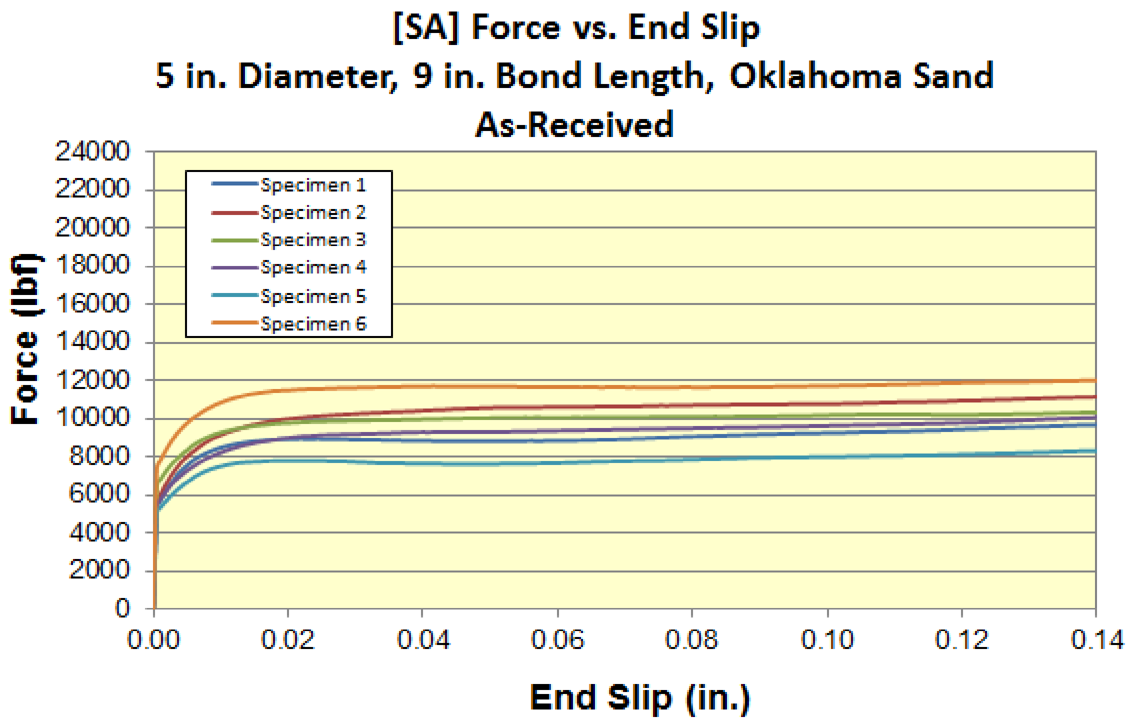

Figure K-7. As-received [SA] force vs. end-slip individual graphs (9-in. bond length)

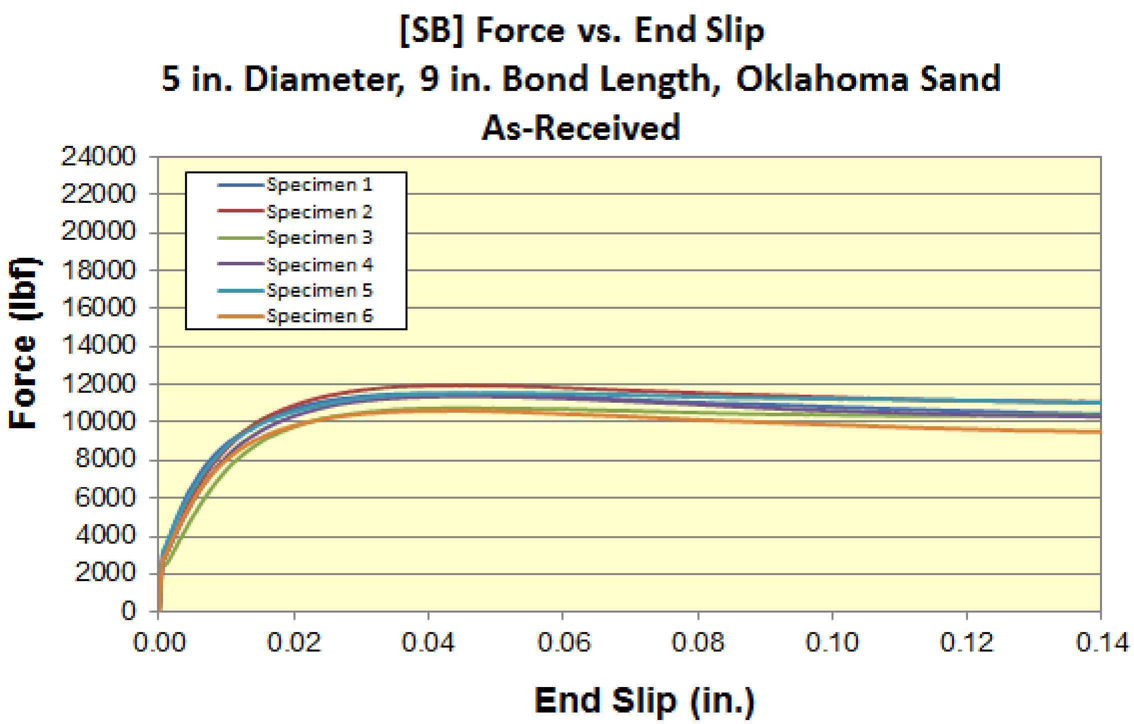

Figure K-8. As-received [SB] force vs. end-slip individual graphs (9-in. bond length)

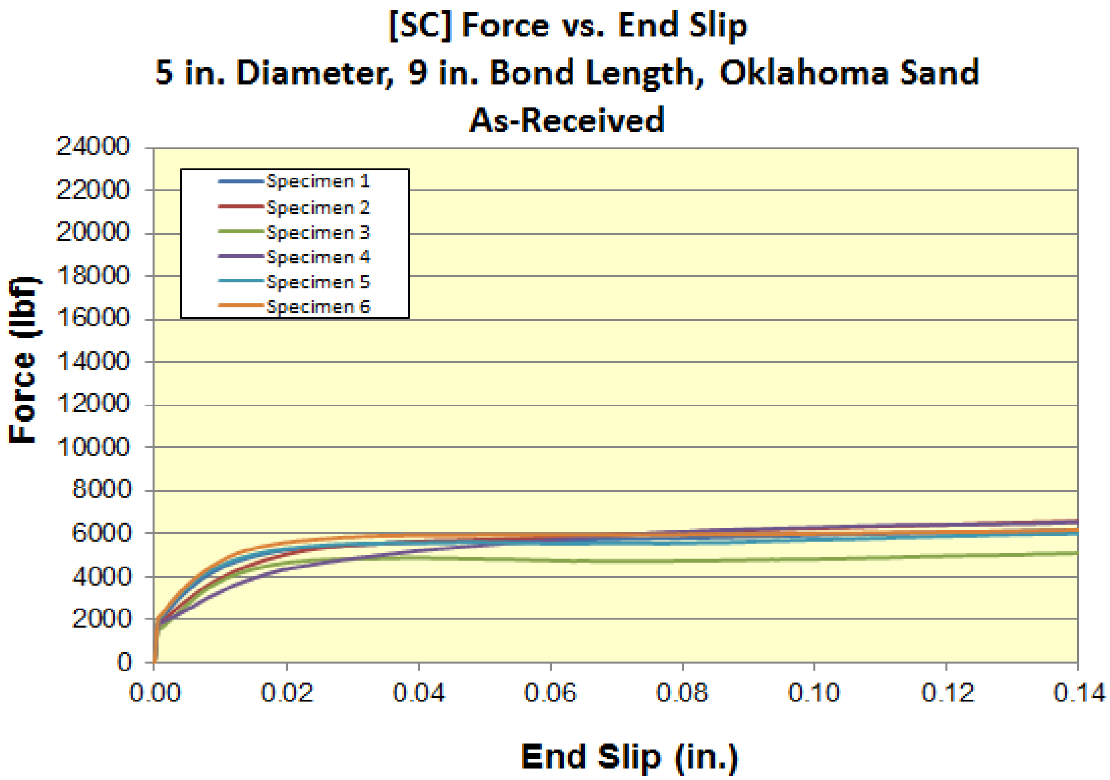

Figure K-9. As-received [SC] force vs. end-slip individual graphs (9-in. bond length)

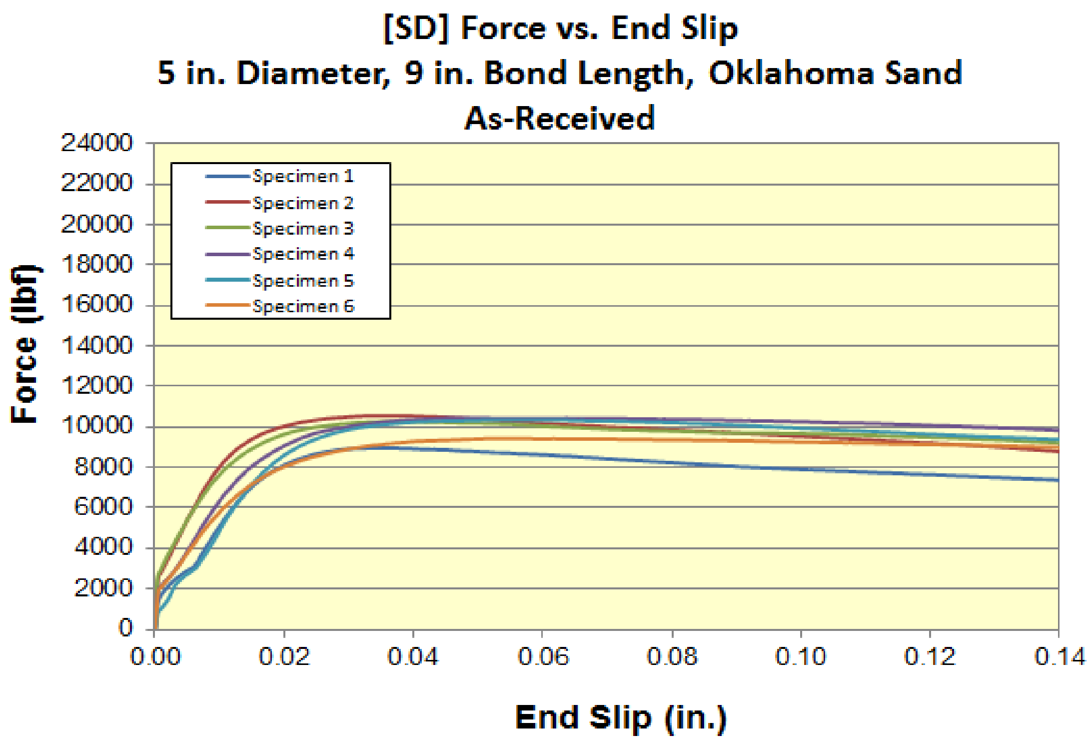

Figure K-10. As-received [SD] force vs. end-slip individual graphs (9-in. bond length)

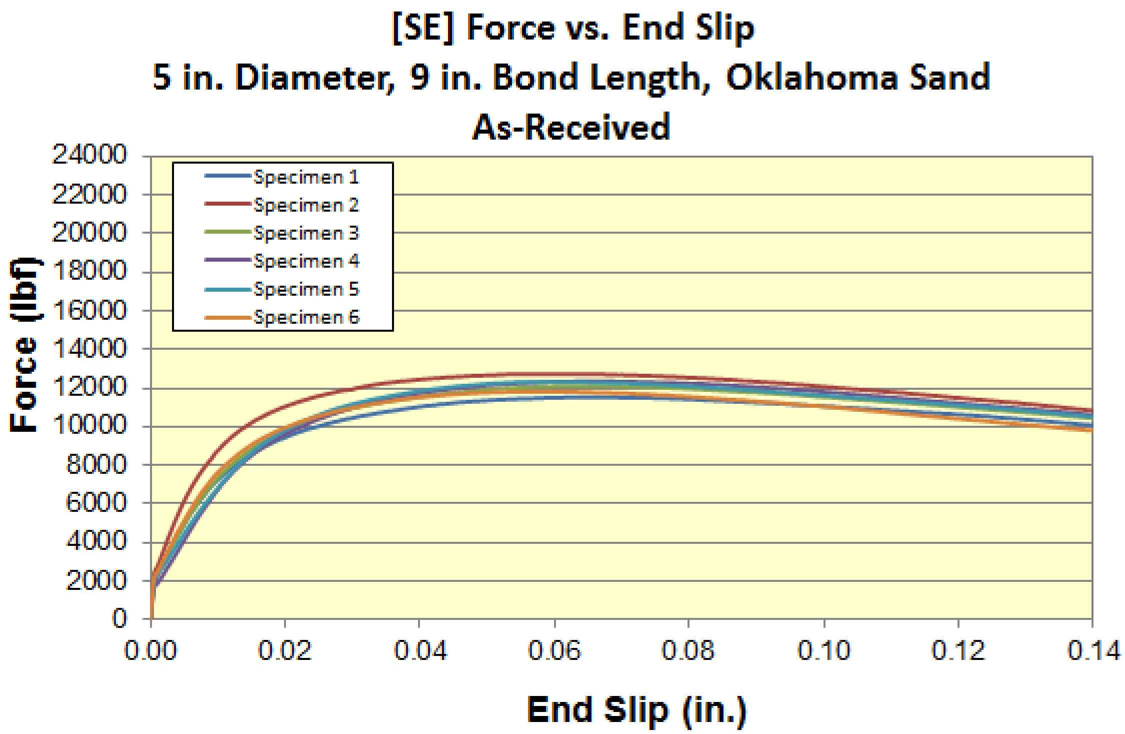

Figure K-11. As-received [SE] force vs. end-slip individual graphs (9-in. bond length)

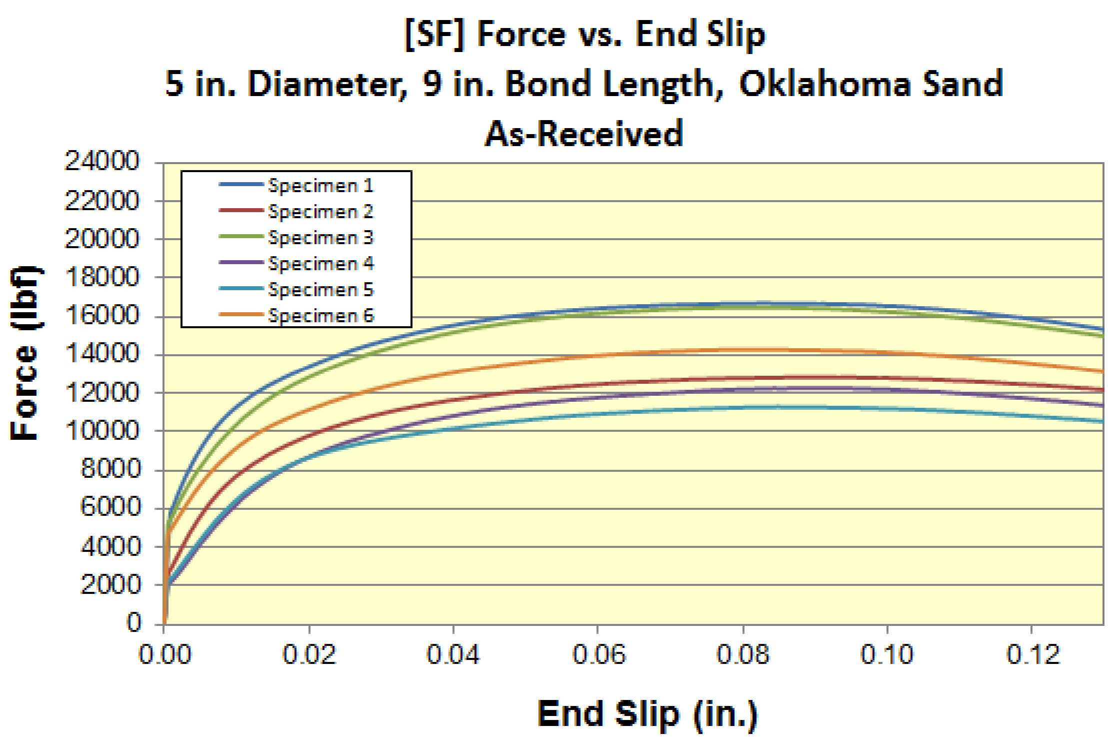

Figure K-12. As-received [SF] force vs. end-slip individual graphs (9-in. bond length)

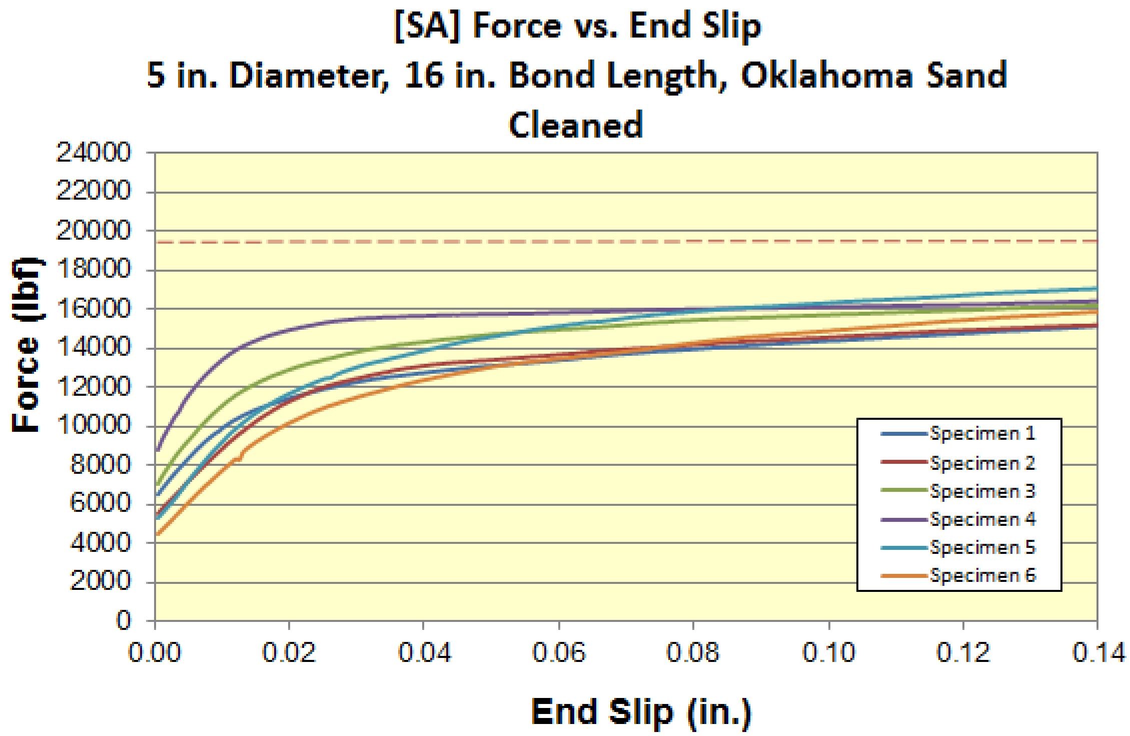

Figure K-13. Cleaned [SA] force vs. end-slip individual graphs (16-in. bond length)

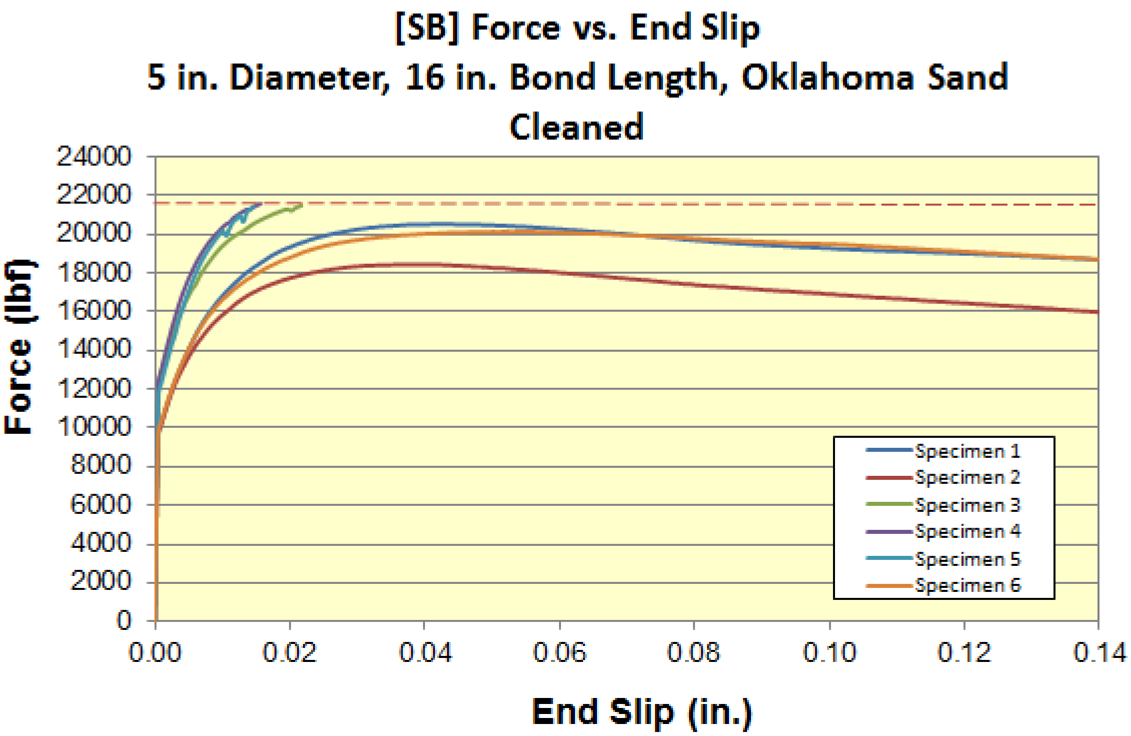

Figure K-14. Cleaned [SB] force vs. end-slip individual graphs (16-in. bond length)

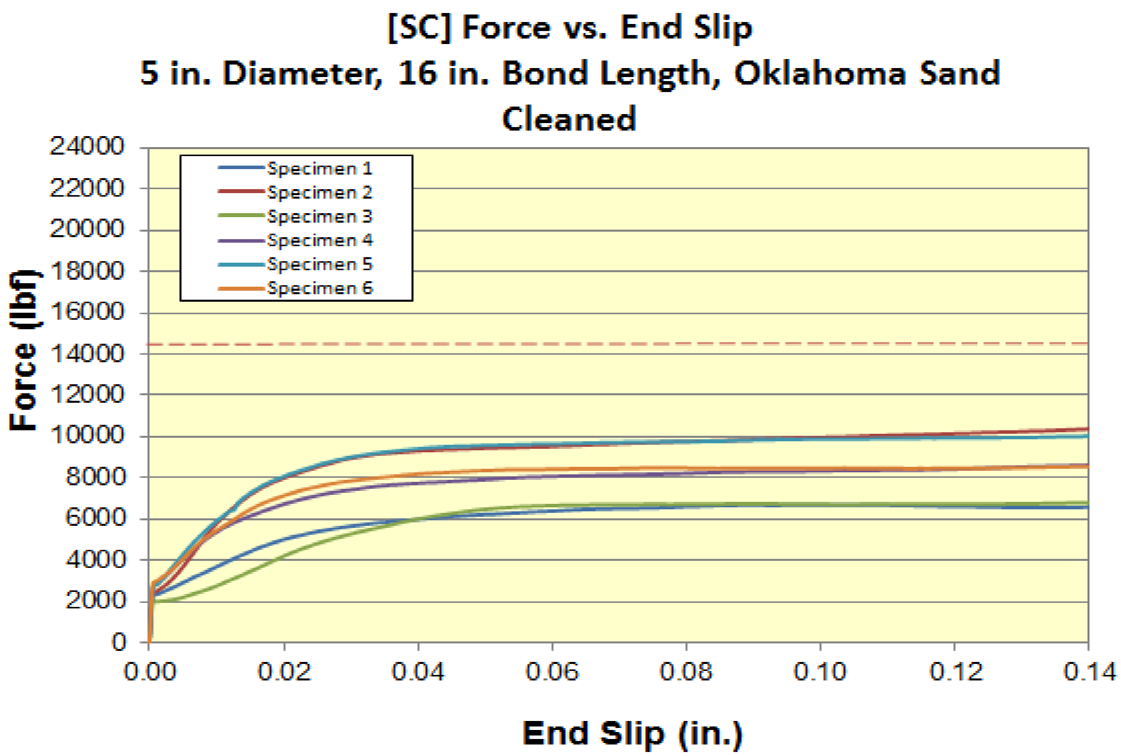

Figure K-15. Cleaned [SC] force vs. end-slip individual graphs (16-in. bond length)

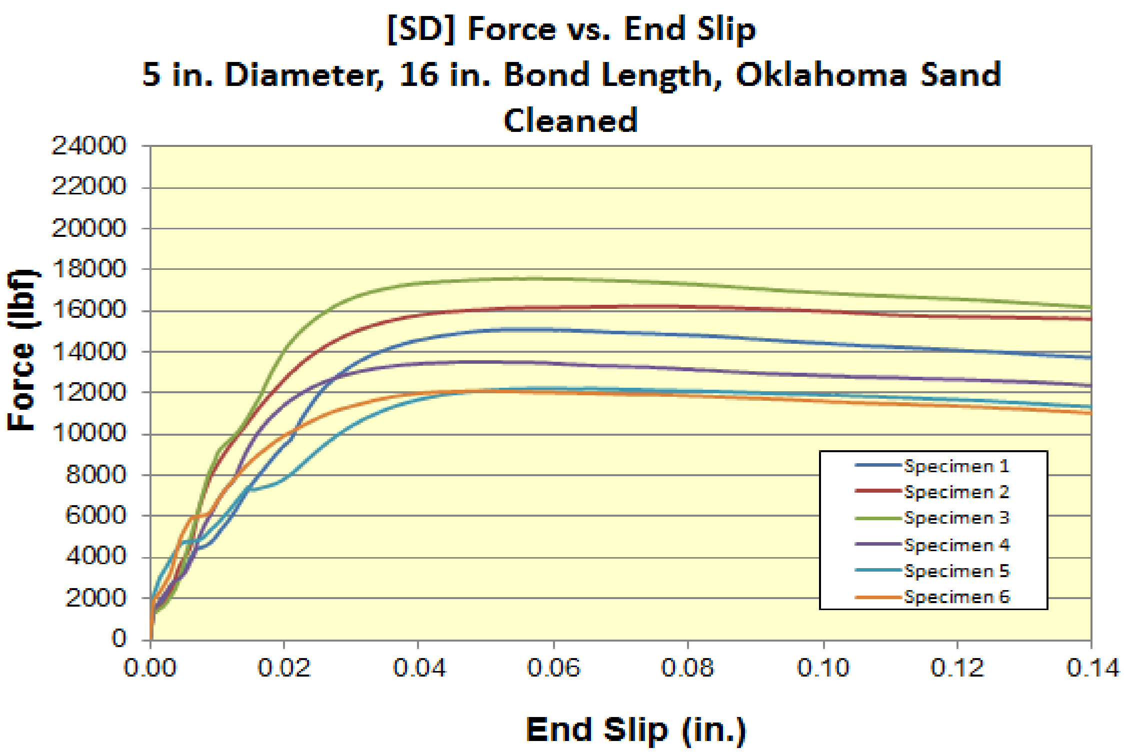

Figure K-16. Cleaned [SD] force vs. end-slip individual graphs (16-in. bond length)

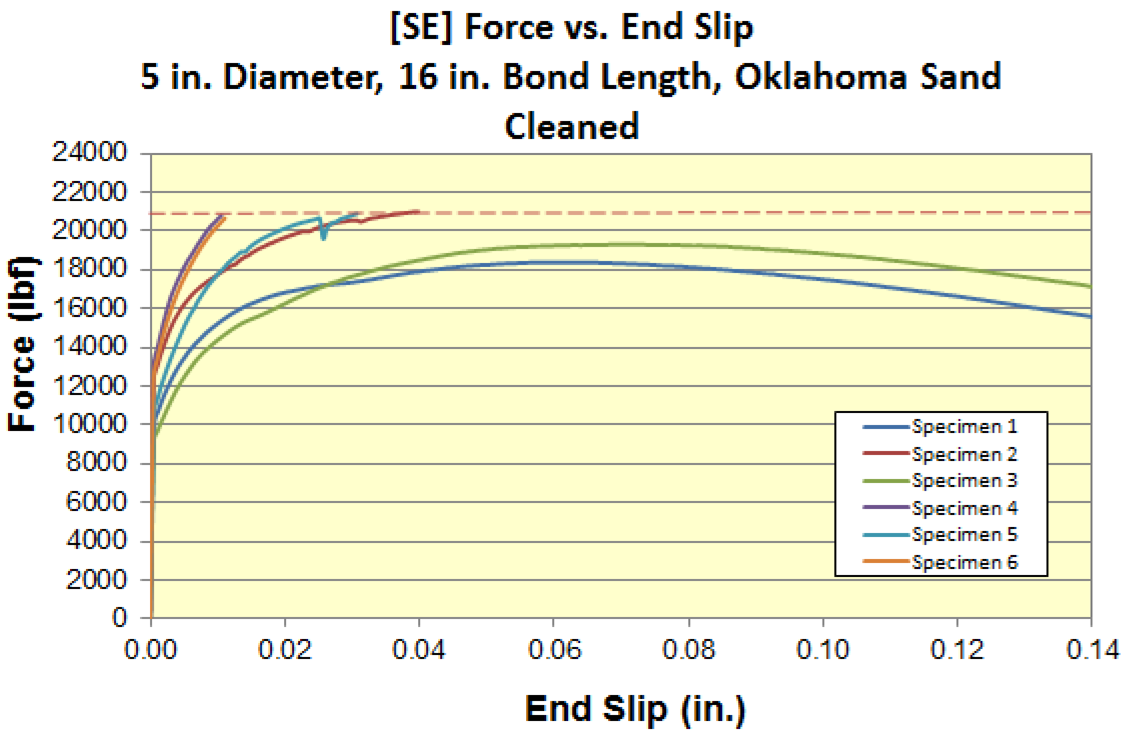

Figure K-17. Cleaned [SE] force vs. end-slip individual graphs (16-in. bond length)

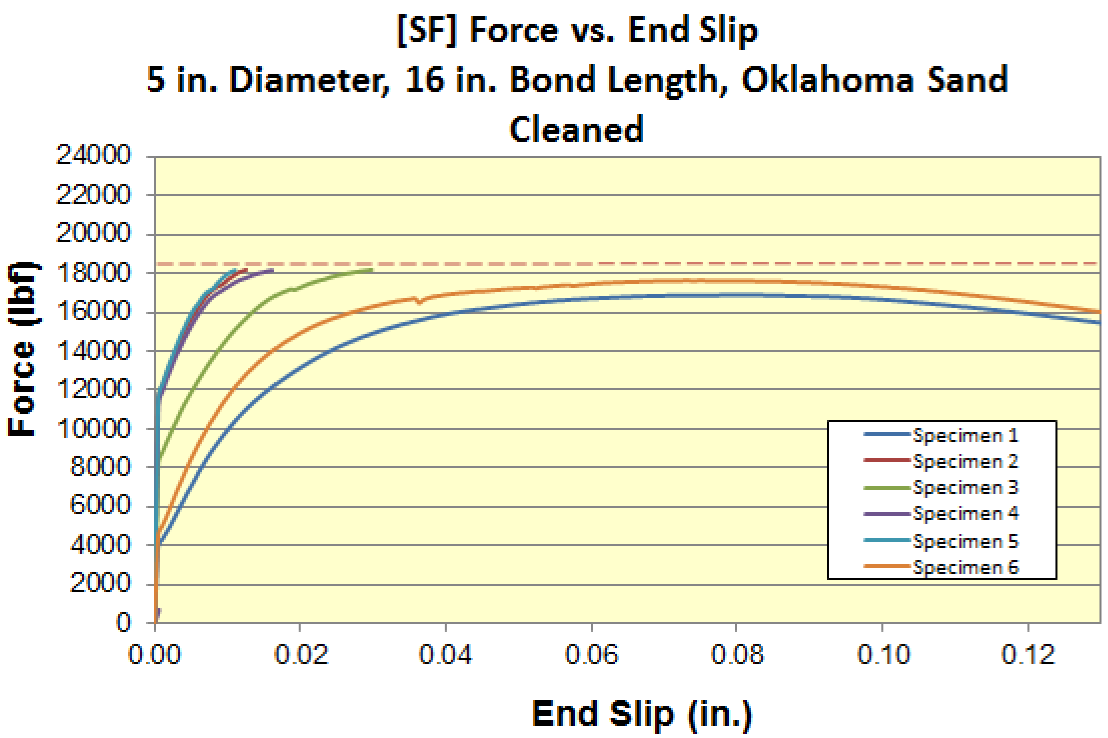

Figure K-18. Cleaned [SF] force vs. end-slip individual graphs (16-in. bond length)

Appendix L.
Lab Phase, Strand; As-received vs. Cleaned Analysis

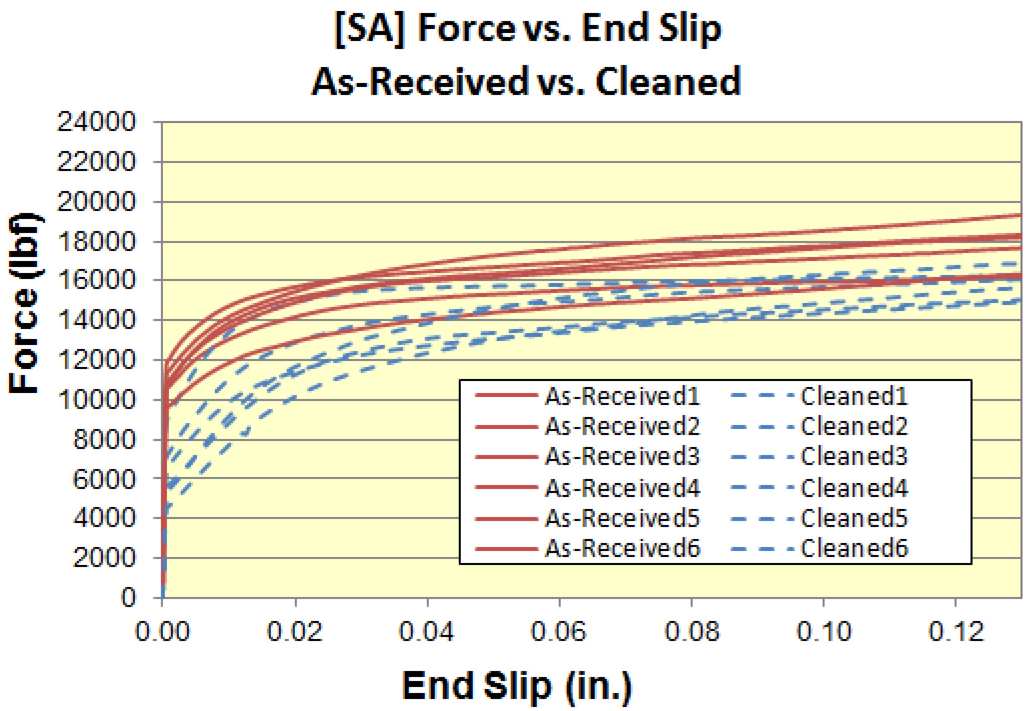

Figure L-1. [SA] force vs. end-slip individual graphs, As-received vs. cleaned

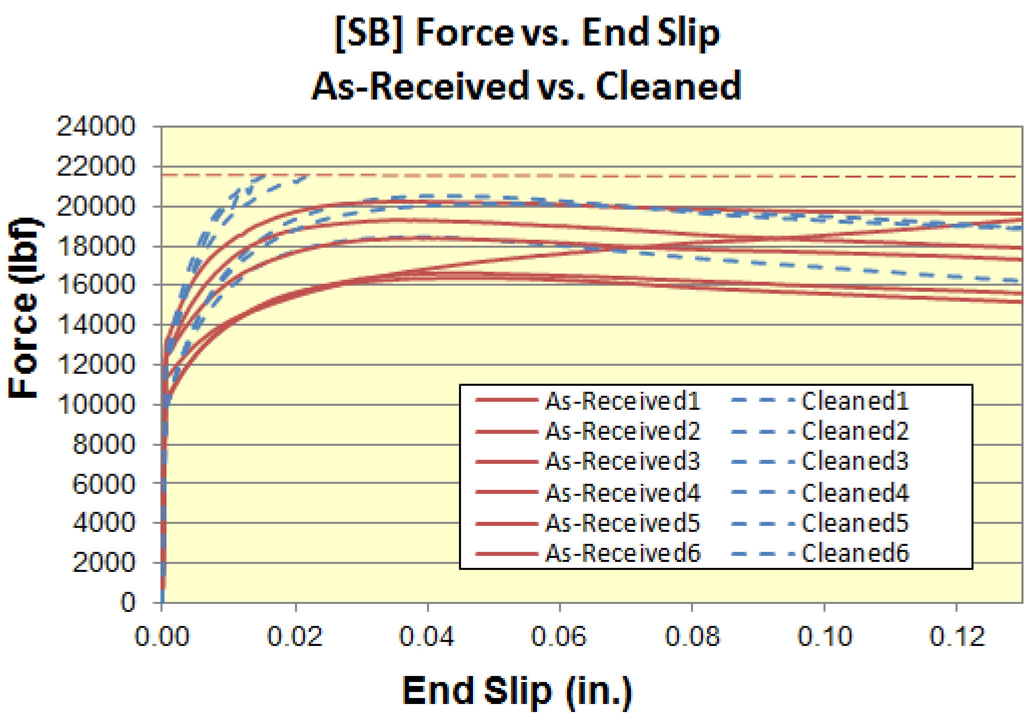

Figure L-2. [SB] force vs. end-slip individual graphs, As-received vs. cleaned

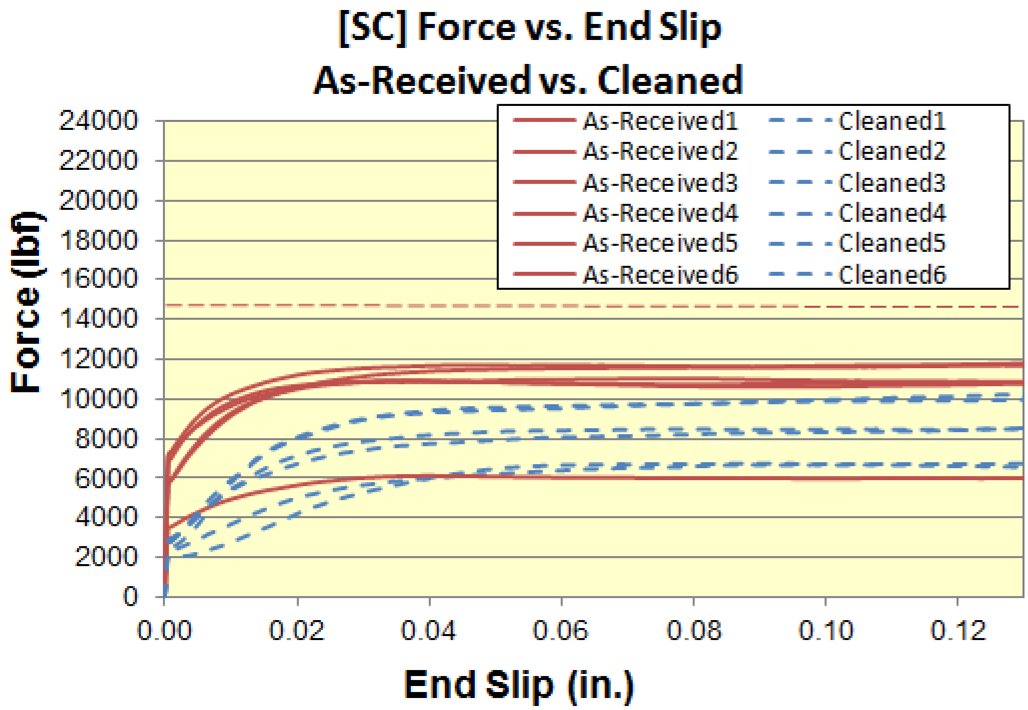

Figure L-3. [SC] force vs. end-slip individual graphs, As-received vs. cleaned

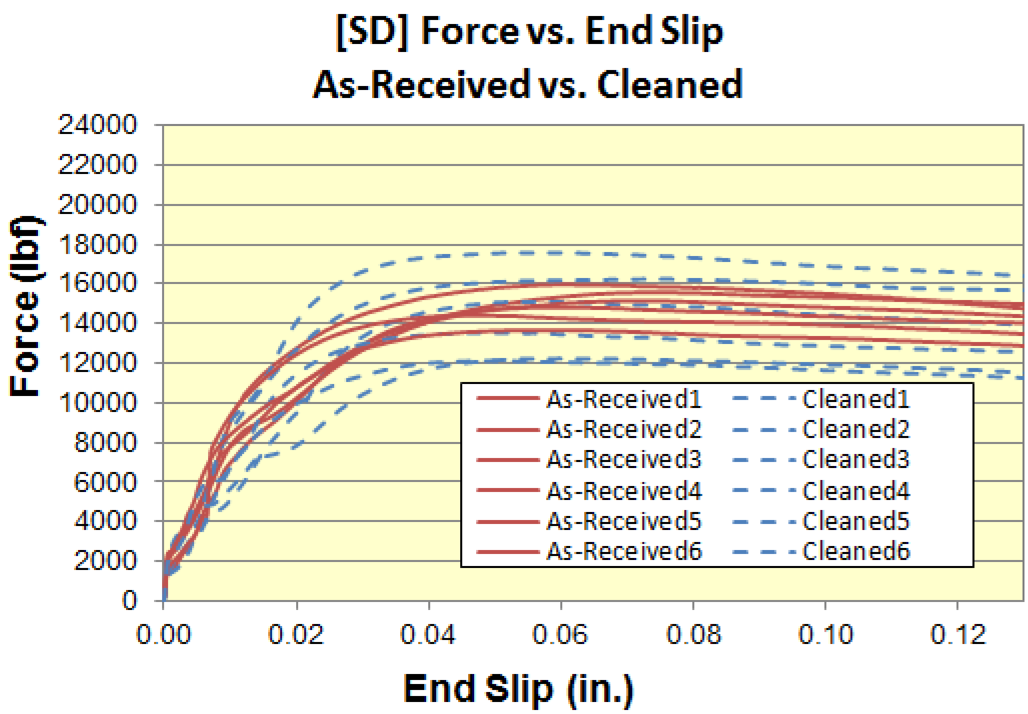

Figure L-4. [SD] force vs. end-slip individual graphs, As-received vs. cleaned

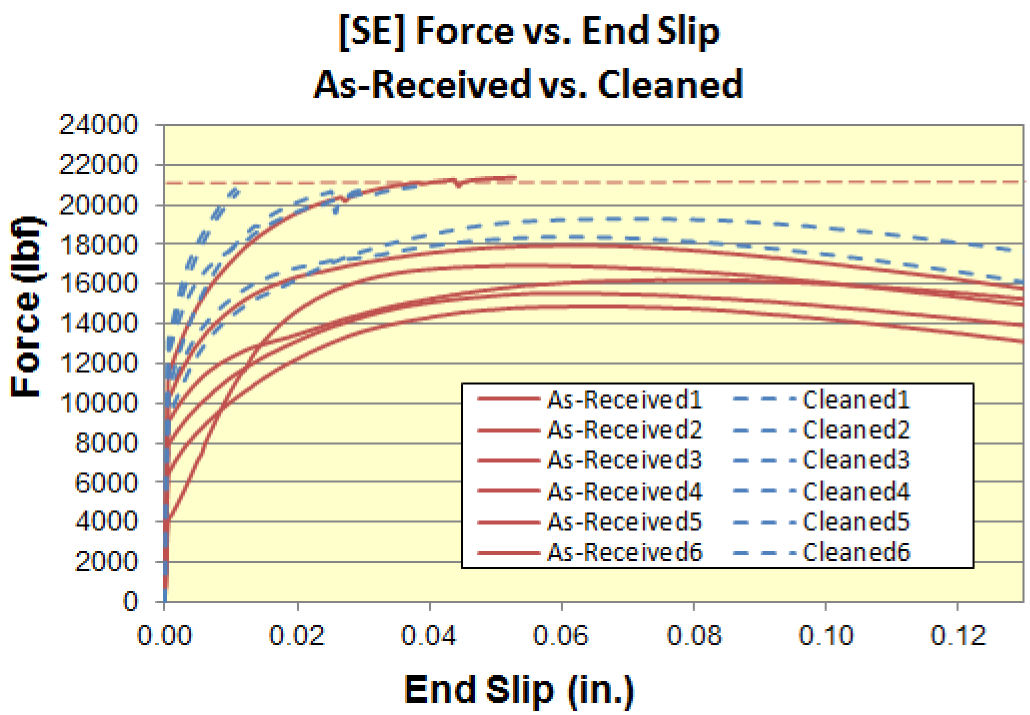

Figure L-5. [SE] force vs. end-slip individual graphs, As-received vs. cleaned

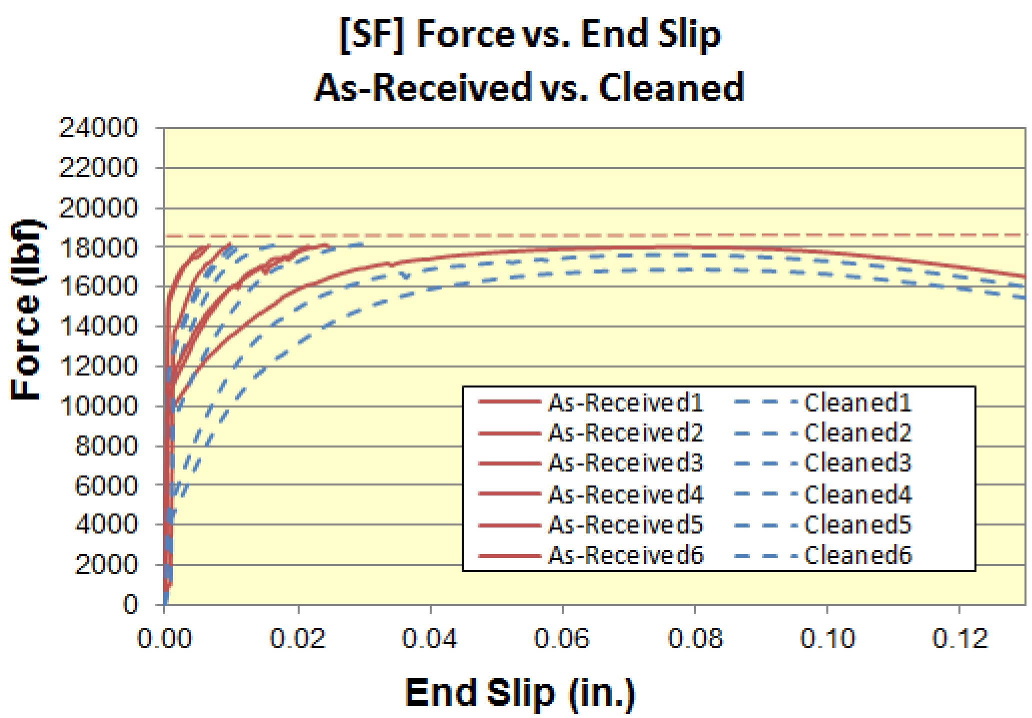

Figure L-6. [SF] force vs. end-slip individual graphs, As-received vs. cleaned

Appendix M.
Plant Phase, Wire and Strand; Batch Summaries

FRA PULLOUT DATA SHEET AT CXT

Reinforcement:	[WA]	Performed By:	Matthew Arnold
Batch Date:	1/4/2013		
Batch Time:	2:56pm		

Concrete Properties

Slump:	
Air Content:	
Unit Weight:	
Concrete Temp:	
Avg. Comp. Str. @ time of testing (psi):	5884

Test Date:	1/5/2013	Performed By:	Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
2:38a	11.75	1	79595	6339	4:19a	13.5	6	76355	6081
2:47a	11.75	2	68085	5423			7		0
3:08a	12.25	3	66375	5286			8		0
3:54a	13	4	79330	6318			9		0
4:07a	13.25	5	73540	5857			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
3:09a	1	WA - 1	1095	Cylinder #4's wrap was tightened by the QC guy Couldn't run pullout #5 because the can topper was badly bent
3:19a	2	WA - 2	945	
3:32a	3	WA - 3	692	
3:53a	4	WA - 4	943	All specimens and cylinders were covered while curing.
-	5	WA - 5	-	
4:17a	6	WA - 6	943	6" bond length

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M-1. As-received [WA] batch summary at CXT

FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WB] Performed By: Matthew Arnold

Batch Date: 1/6/2013

Batch Time: 9:30am

Concrete Properties

Slump:

Air Content:

Unit Weight:

Concrete Temp:

Avg. Comp. Str. @ time of testing (psi): 6585

Test Date: Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
7:37p	10	1	77735	6191			6		0
7:42p	10.25	2	79705	6348			7		0
8:36p	11	3	85570	6815			8		0
8:53p	11.5	4	87450	6965			9		0
8:59p	11.5	5	82935	6605			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
7:52p	1	WB-8	5252	All specimens and cylinders were covered while curing.
8:22p	2	WB-2	5482	
8:34p	3	WB-3	5415	6" bond length
8:43p	4	WB-4	5397	
8:50p	5	WB-5	5052	
8:58p	6	WB-6	4803	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M-2. As-received [WB] batch summary at CXT

FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WC]

Batch Date: 1/13/2013

Batch Time: 11:00am

Performed By: Matthew Arnold

Concrete Properties

Slump:

Air Content:

Unit Weight:

Concrete Temp:

Avg. Comp. Str. @ time of testing (psi): 6607

Test Date: 1/14/2013

Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
12:32a	13.5	1	83205	6627			6		0
12:37a	13.5	2	81405	6483			7		0
1:36a	14.5	3	84400	6722			8		0
1:39a	14.5	4	82835	6597			9		0
		5		0			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
12"44a	1	WC-1	7480	All specimens and cylinders were covered while curing.
1:04a	3	WC-2	8665	
1:20a	5	WC-3	7497	6" bond length
1:33a	7	WC-4	9249 *	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M-3. As-received [WC] batch summary at CXT

FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WD]
Batch Date: 1/10/2013
Batch Time: 8:15am

Performed By: Matthew Arnold

Concrete Properties

Slump:
Air Content:
Unit Weight:
Concrete Temp:
Avg. Comp. Str. @ time of testing (psi): 5965

Test Date: 1/10/2013

Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
6:11p	10	1	71150	5667	8:09p	12	6	76715	6110
6:26p	10.25	2	75355	6002			7		0
7:07p	10.75	3	75465	6010			8		0
7:33p	11.25	4	75220	5991			9		0
8:05p	11.75	5	75485	6012			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
6:38p	1	WD-1	5900	All specimens and cylinders were uncovered while curing.
6:52p	3	WD-2	6119	
7:10p	5	WD-3	4373	6" bond length
7:22p	7	WD-4	5896	
7:40p	9	WD-5	5356	
7:53p	11	WD-6	5112	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M-4. As-received [WD] batch summary at CXT

FRA PULLOUT DATA SHEET AT CXT

Reinforcement:	[WE]	Performed By:	Matthew Arnold
Batch Date:	1/15/2013		
Batch Time:	1:30pm		

Concrete Properties

Slump:	
Air Content:	
Unit Weight:	
Concrete Temp:	
Avg. Comp. Str. @ time of testing (psi):	5924

Test Date:	1/15/2013	Performed By:	Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
1:19a	11.75	1	73145	5826	3:29a	14	6	77170	6146
1:24a	12	2	67510	5377			7		0
2:21a	12.75	3	78725	6270			8		0
2:57a	13.5	4	78125	6222			9		0
3:22a	13.75	5	71595	5702			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
1:41a	1	WE-1	8672	All specimens and cylinders were covered while curing.
1:58a	3	WE-2	8756	
2:25a	5	WE-3	8147	6" bond length
2:43a	7	WE-4	8845	
2:58a	9	WE-5	8715	
3:12a	11	WE-6	8946	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M-5. As-received [WE] batch summary at CXT

FRA PULLOUT DATA SHEET AT CXT

Reinforcement:	[WF]	Performed By:	Matthew Arnold
Batch Date:	1/12/2013		
Batch Time:	11:15am		

Concrete Properties

Slump:	
Air Content:	
Unit Weight:	
Concrete Temp:	
Avg. Comp. Str. @ time of testing (psi):	5190

Test Date:	1/12/2013	Performed By:	Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
10:09p	11	1	62180	4952	12:08a	13	6	67760	5397
10:14p	11	2	60535	4821			7		0
10:57p	11.75	3	65150	5189			8		0
11:29p	12.25	4	66425	5290			9		0
12:02a	12.75	5	68930	5490			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
10:23p	1	WF-1	6397	All cylinders were covered while curing.
10:44p	3	WF-2	6952	All specimens were uncovered while curing.
11:00p	5	WF-3	6255	6" bond length
11:15p	7	WF-4	5642	
11:34p	9	WF-5	7053	
11:48p	11	WF-6	7861	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M-6. As-received [WF] batch summary at CXT

FRA PULLOUT DATA SHEET AT CXT

Reinforcement:	[WG]	Performed By:	Matthew Arnold
Batch Date:	1/10/2013		
Batch Time:	8:15am		

Concrete Properties

Slump:	
Air Content:	
Unit Weight:	
Concrete Temp:	
Avg. Comp. Str. @ time of testing (psi):	5965

Test Date: 1/10/2013 Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
6:11p	10	1	71150	5667	8:09p	12	6	76715	6110
6:26p	10.25	2	75355	6002			7		0
7:07p	10.75	3	75465	6010			8		0
7:33p	11.25	4	75220	5991			9		0
8:05p	11.75	5	75485	6012			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
6:45p	2	WG-1	5576	All specimens and cylinders were uncovered while curing.
6:58p	4	WG-2	5739	
7:15p	6	WG-3	4962	6" bond length
7:28p	8	WG-4	5387	
7:46p	10	WG-5	5428	
7:58p	12	WG-6	6234	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M-7. As-received [WG] batch summary at CXT

FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WH]
Batch Date: 1/12/2013
Batch Time: 11:15am

Performed By: Matthew Arnold

Concrete Properties

Slump:
Air Content:
Unit Weight:
Concrete Temp:

Avg. Comp. Str. @ time of testing (psi): 5190

Test Date: 1/12/2013

Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
10:09p	11	1	62180	4952	12:08a	13	6	67760	5397
10:14p	11	2	60535	4821			7		0
10:57p	11.75	3	65150	5189			8		0
11:29p	12.25	4	66425	5290			9		0
12:02a	12.75	5	68930	5490			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
10:33p	2	WH-1	8103	All cylinders were covered while curing.
10:50p	4	WH-2	5750	All specimens were uncovered while curing.
11:09p	6	WH-3	5652	6" bond length
11:22p	8	WH-4	5884	
11:41p	10	WH-5	6391	
11:55p	12	WH-6	7928	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M-8. As-received [WH] batch summary at CXT

FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WI]
Batch Date: 1/7/2013
Batch Time: 12:00pm

Performed By: Matthew Arnold

Concrete Properties

Slump:
Air Content:
Unit Weight:
Concrete Temp:
Avg. Comp. Str. @ time of testing (psi): 4651

Test Date:

Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
8:30p	8.5	1	53410	4254	10:05p	10	6	58335	4646
8:35p	8.5	2	53345	4249	10:13p	10	7	61080	4865
9:05p	9	3	61355	4887			8		0
9:12p	9.25	4	61125	4868			9		0
9:37p	9.5	5	60110	4787			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
9:13p	1	WI-1	5322	All specimens and cylinders were uncovered while curing.
9:21p	2	WI-2	4877	
9:27p	3	WI-3	4956	6" bond length
9:49p	4	WI-4	5137	
9:56p	5	WI-5	5335	
10:05p	6	WI-6	5425	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M-9. As-received [WI] batch summary at CXT

FRA PULLOUT DATA SHEET AT CXT

Reinforcement:	[WJ]		Performed By:	Matthew Arnold
Batch Date:	1/8/2013			
Batch Time:	9:15pm			

Concrete Properties

Slump:	
Air Content:	
Unit Weight:	
Concrete Temp:	
Avg. Comp. Str. @ time of testing (psi):	5532

Test Date:	1/8/2013	Performed By:	Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
6:35p	9.25	1	60450	4814	7:56p	10.75	6	72385	5765
6:45p	9.5	2	66400	5288			7		0
6:51p	9.5	3	67940	5411			8		0
7:35p	10.25	4	69615	5544			9		0
7:52p	10.75	5	70950	5651			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
7:02p	1	WJ-1	6582	All specimens and cylinders were uncovered while curing.
7:11p	2	WJ-2	6889	
7:19p	3	WJ-3	7202	6" bond length
7:29p	4	WJ-4	6413	
7:35p	5	WJ-5	6412	
7:44p	6	WJ-6	7237	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M-10. As-received [WJ] batch summary at CXT

FRA PULLOUT DATA SHEET AT CXT

Reinforcement:	[WL]	Performed By:	Matthew Arnold
Batch Date:	1/16/2013		
Batch Time:	11:45am		

Concrete Properties

Slump:	
Air Content:	
Unit Weight:	
Concrete Temp:	
Avg. Comp. Str. @ time of testing (psi):	6536

Test Date:	1/16/2013	Performed By:	Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
11:45p	12	1	79660	6344	1:27a	13.75	6	86635	6900
11:51p	12	2	75130	5984			7		0
12:27a	12.75	3	83555	6655			8		0
1:01a	13.25	4	85405	6802			9		0
1:18a	13.5	5	82030	6533			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
11:53p	1	WL-1	3894	All specimens and cylinders were uncovered while curing.
12:09a	3	WL-2	3065	
12:35a	5	WL-3	3019	6" bond length
12:49a	7	WL-4	3484	
1:04a	9	WL-5	3764	
1:19a	11	WL-6	3454	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M-11. As-received [WL] batch summary at CXT

FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WM]

Batch Date: 1/18/2013

Batch Time: 8:30am

Performed By: Matthew Arnold

Concrete Properties

Slump:

Air Content:

Unit Weight:

Concrete Temp:

Avg. Comp. Str. @ time of testing (psi): 6245

Test Date: 1/18/2013

Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
6:16p	9.75	1	72710	5791			6		0
6:38p	10.25	2	77110	6141			7		0
7:04p	10.5	3	79980	6370			8		0
7:21p	10.75	4	81575	6497			9		0
7:28p	11	5	80710	6428			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
6:40p	1	WM-1	5626	All cylinders were covered while curing.
6:49p	2	WM-2	7031	All specimens were uncovered while curing.
6:56p	3	WM-3	6570	6" bond length
7:07p	4	WM-4	7632	
7:14p	5	WM-5	7642	
7:24p	6	WM-6	7525	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M-12. As-received [WM] batch summary at CXT

FRA PULLOUT DATA SHEET AT CXT

Reinforcement:	[SA]	Performed By:	Matthew Arnold
Batch Date:	1/15/2013		
Batch Time:	1:30pm		

Concrete Properties

Slump:	
Air Content:	
Unit Weight:	
Concrete Temp:	
Avg. Comp. Str. @ time of testing (psi):	5924

Test Date:	1/15/2013	Performed By:	Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
1:19a	11.75	1	73145	5826	3:29a	14	6	77170	6146
1:24a	12	2	67510	5377			7		0
2:21a	12.75	3	78725	6270			8		0
2:57a	13.5	4	78125	6222			9		0
3:22a	13.75	5	71595	5702			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
1:53a	2	SA-1	4564	All specimens and cylinders were covered while curing.
2:15a	4	SA-2	4043	
2:35a	6	SA-3	3196	4" bond length
2:52a	8	SA-4	3410	
3:07a	10	SA-5	4507	
3:23a	12	SA-6	4526	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M-13. As-received [SA] batch summary at CXT

FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [SB]
Batch Date: 1/16/2013
Batch Time: 11:45am

Performed By: Matthew Arnold

Concrete Properties

Slump:
Air Content:
Unit Weight:
Concrete Temp:
Avg. Comp. Str. @ time of testing (psi): 6536

Test Date: 1/16/2013

Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
11:45p	12	1	79660	6344	1:27a	13.75	6	86635	6900
11:51p	12	2	75130	5984			7		0
12:27a	12.75	3	83555	6655			8		0
1:01a	13.25	4	85405	6802			9		0
1:18a	13.5	5	82030	6533			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
12:01a	2	SB-1	7391	All specimens and cylinders were uncovered while curing.
12:16a	4	SB-2	7532	
12:40a	6	SB-3	7474	6" bond length
12:54a	8	SB-4	7199	
1:11a	10	SB-5	7868	
1:28a	12	SB-6	7800	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M-14. As-received [SB] batch summary at CXT

FRA PULLOUT DATA SHEET AT CXT

Reinforcement:	[SC]	Performed By:	Matthew Arnold
Batch Date:	1/13/2013		
Batch Time:	11:00am		

Concrete Properties

Slump:	
Air Content:	
Unit Weight:	
Concrete Temp:	
Avg. Comp. Str. @ time of testing (psi):	6607

Test Date:	1/14/2013	Performed By:	Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
12:32a	13.5	1	83205	6627			6		0
12:37a	13.5	2	81405	6483			7		0
1:36a	14.5	3	84400	6722			8		0
1:39a	14.5	4	82835	6597			9		0
		5		0			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
12:58a	2	SC-1	3983	All specimens and cylinders were covered while curing.
1:12a	4	SC-2	2643	
1:27a	6	SC-3	2171	4" bond length
1:42a	8	SC-4	2319	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M-15. As-received [SC] batch summary at CXT

Appendix N.
Plant Phase, Wire and Strand; Individual Pullout Graphs

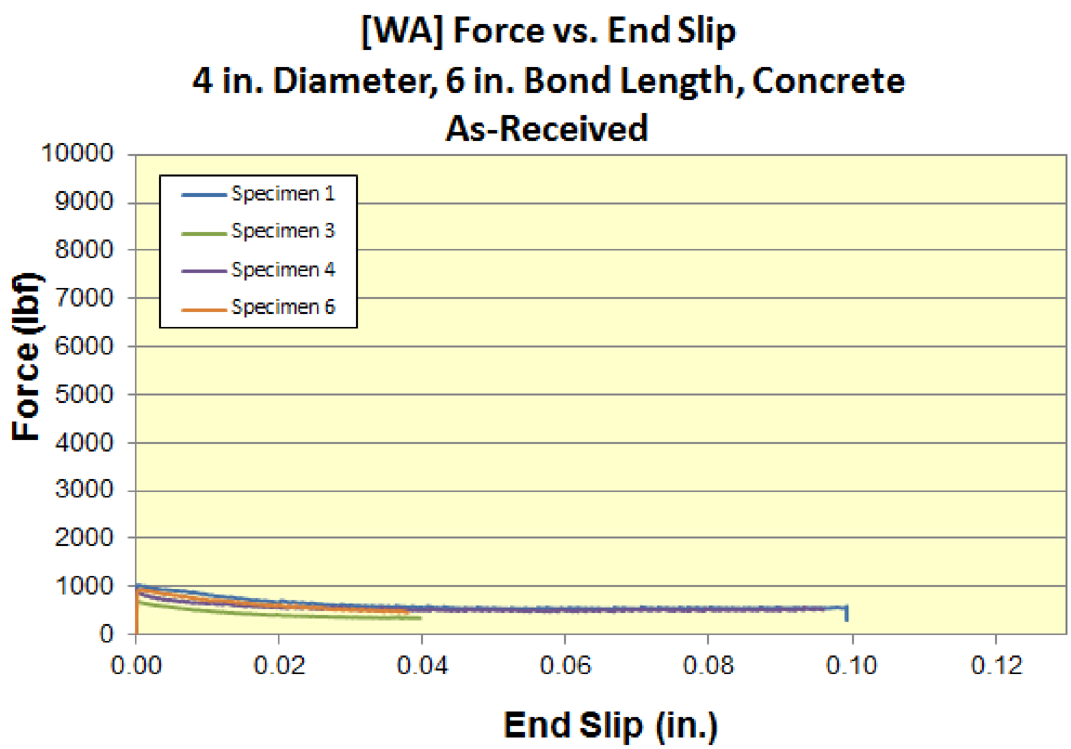

Figure N-1. As-received [WA] force vs. end-slip individual graphs at CXT

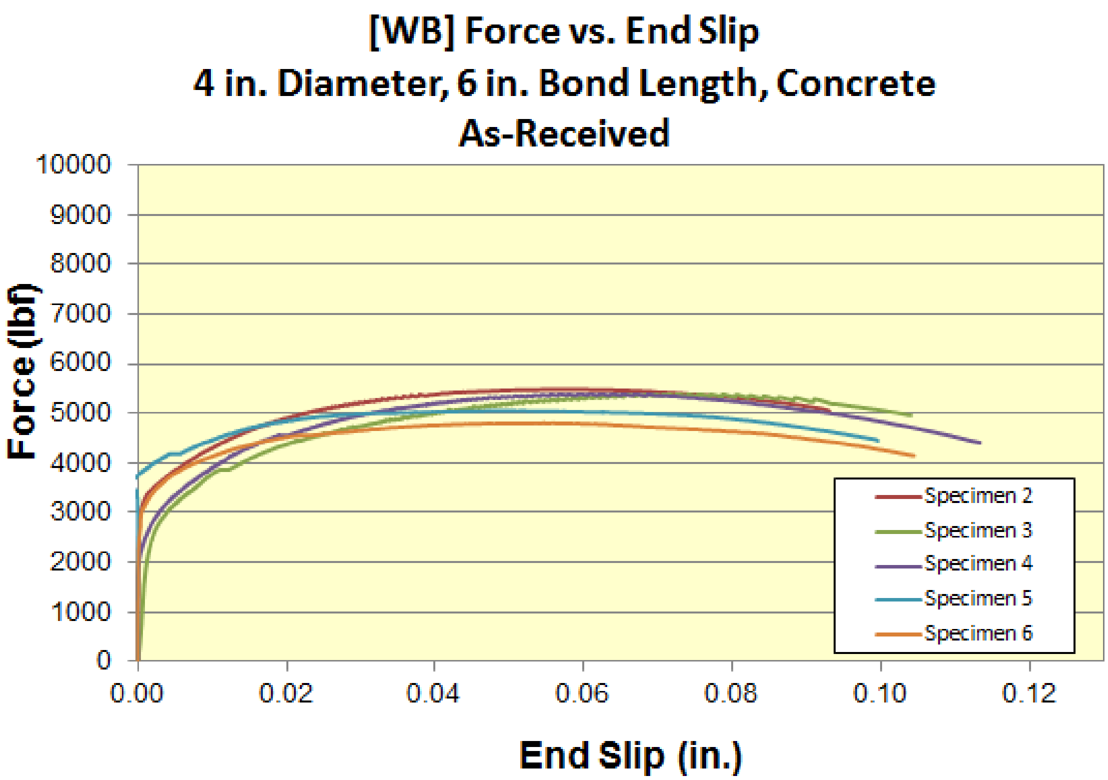

Figure N-2. As-received [WB] force vs. end-slip individual graphs at CXT

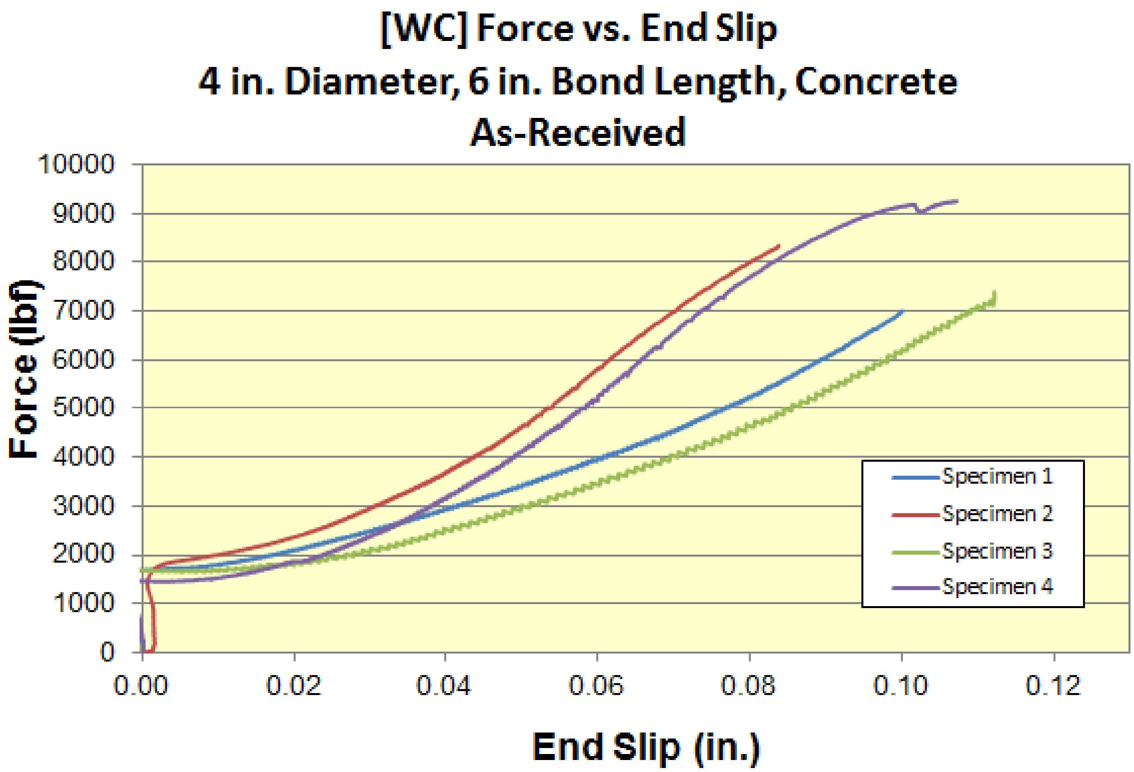

Figure N-3. As-received [WC] force vs. end-slip individual graphs at CXT

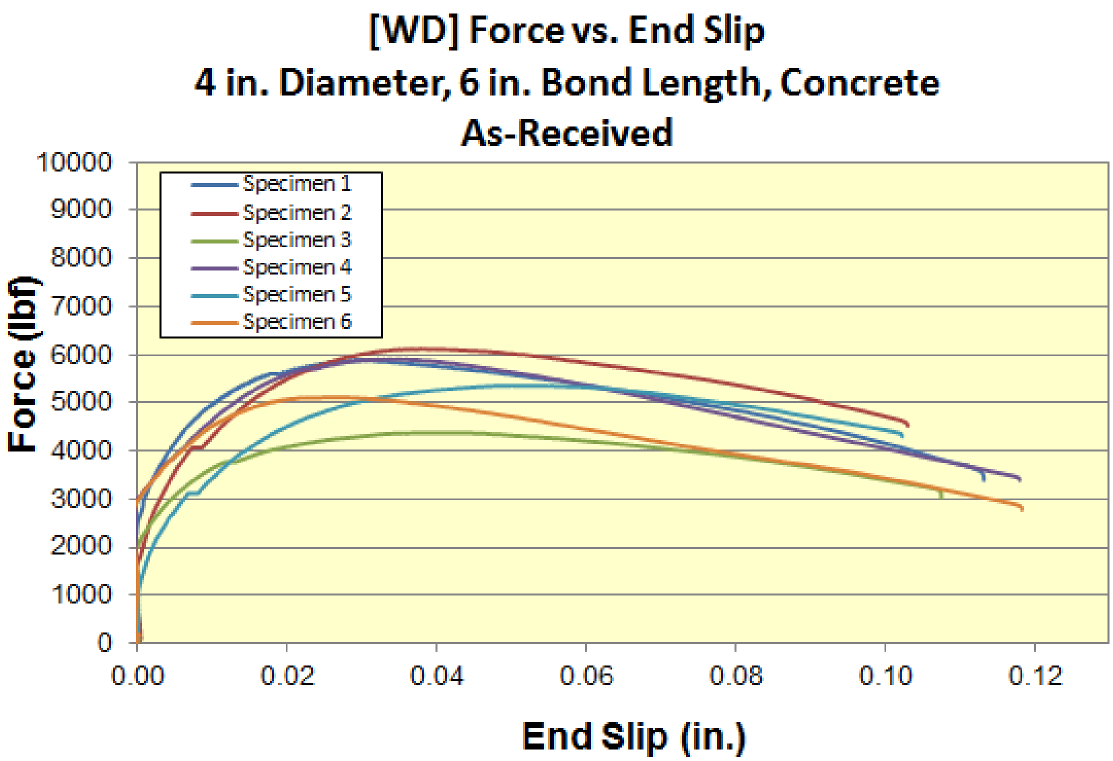

Figure N-4. As-received [WD] force vs. end-slip individual graphs at CXT

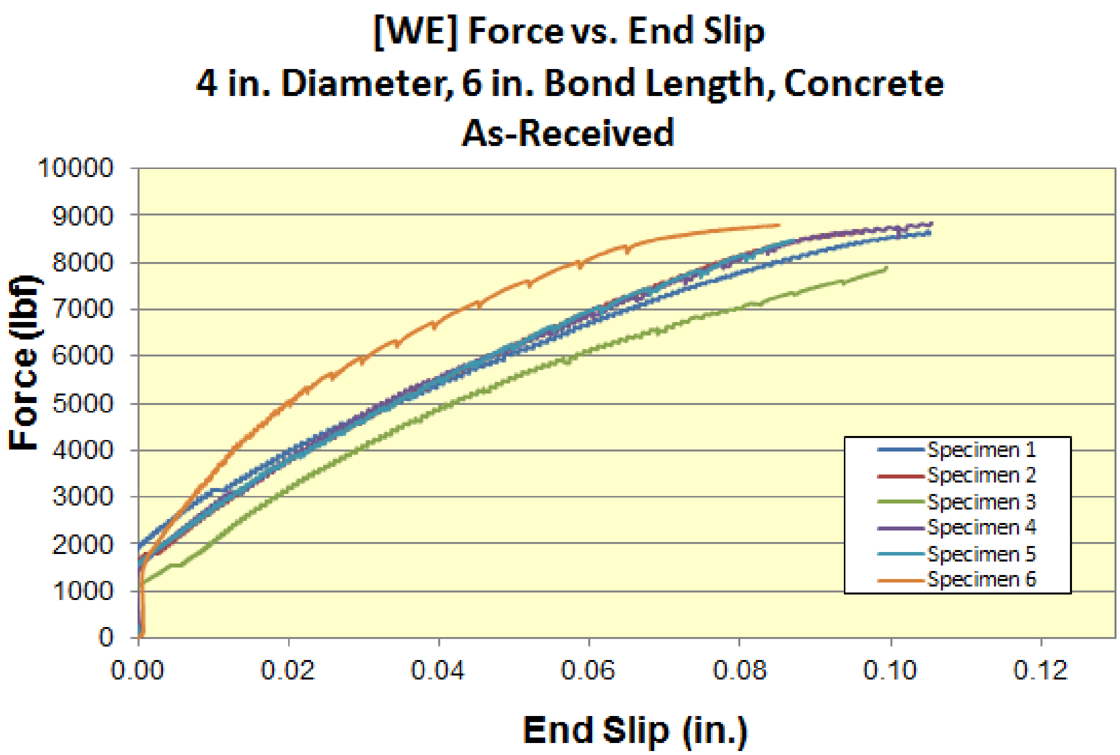

Figure N-5. As-received [WE] force vs. end-slip individual graphs at CXT

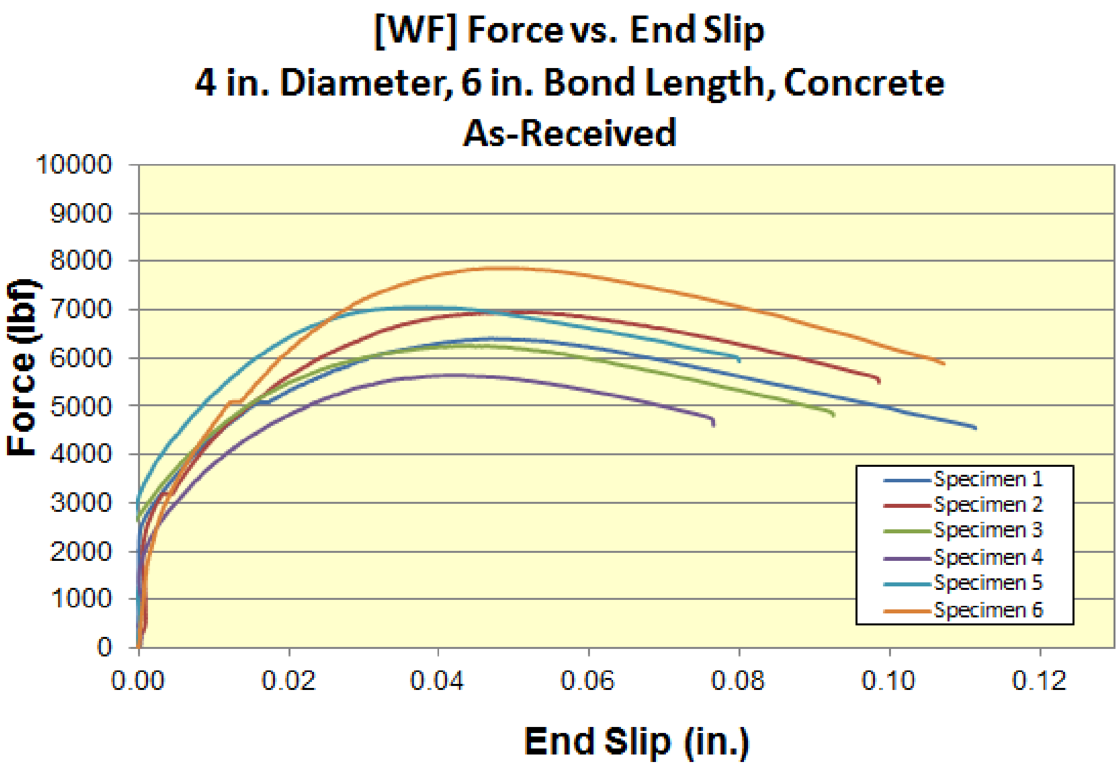

Figure N-6. As-received [WF] force vs. end-slip individual graphs at CXT

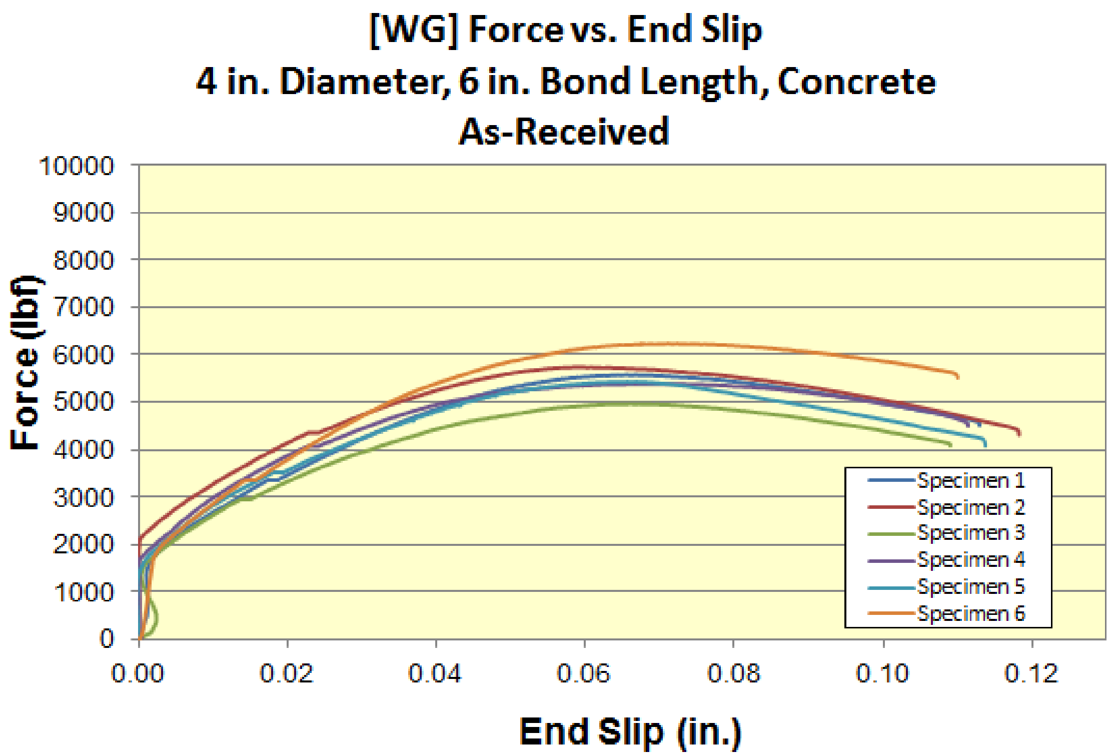

Figure N-7. As-received [WG] force vs. end-slip individual graphs at CXT

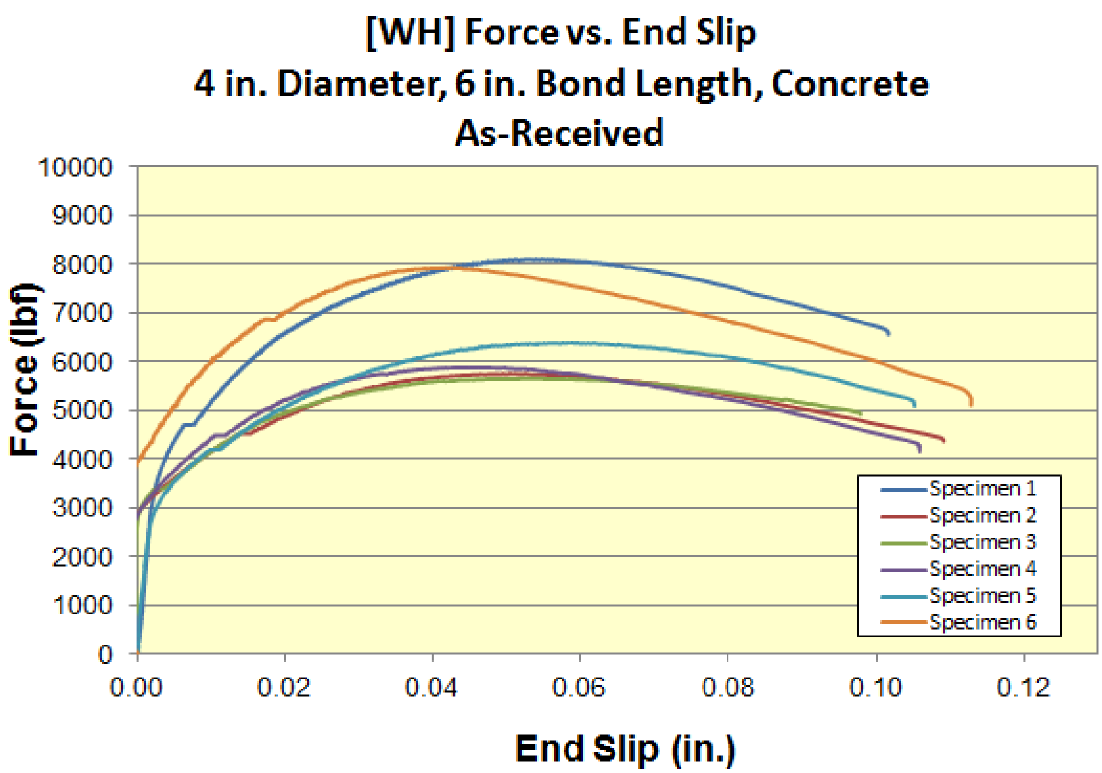

Figure N-8. As-received [WH] force vs. end-slip individual graphs at CXT

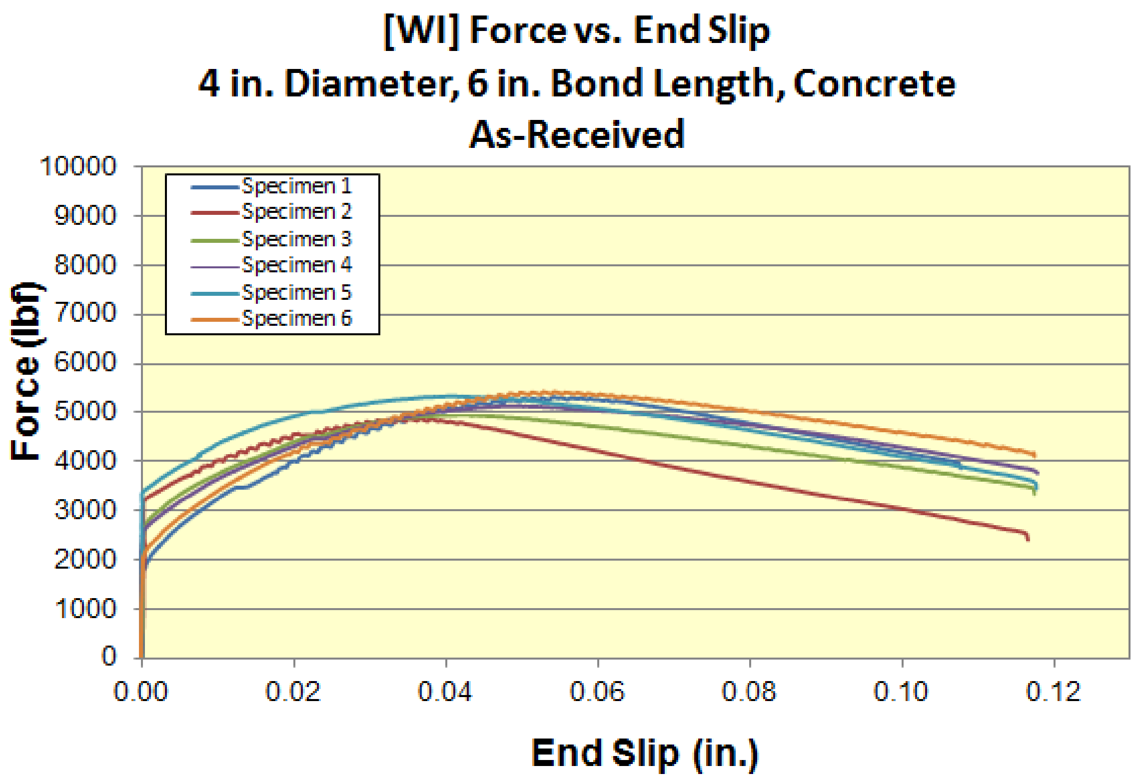

Figure N-9. As-received [WI] force vs. end-slip individual graphs at CXT

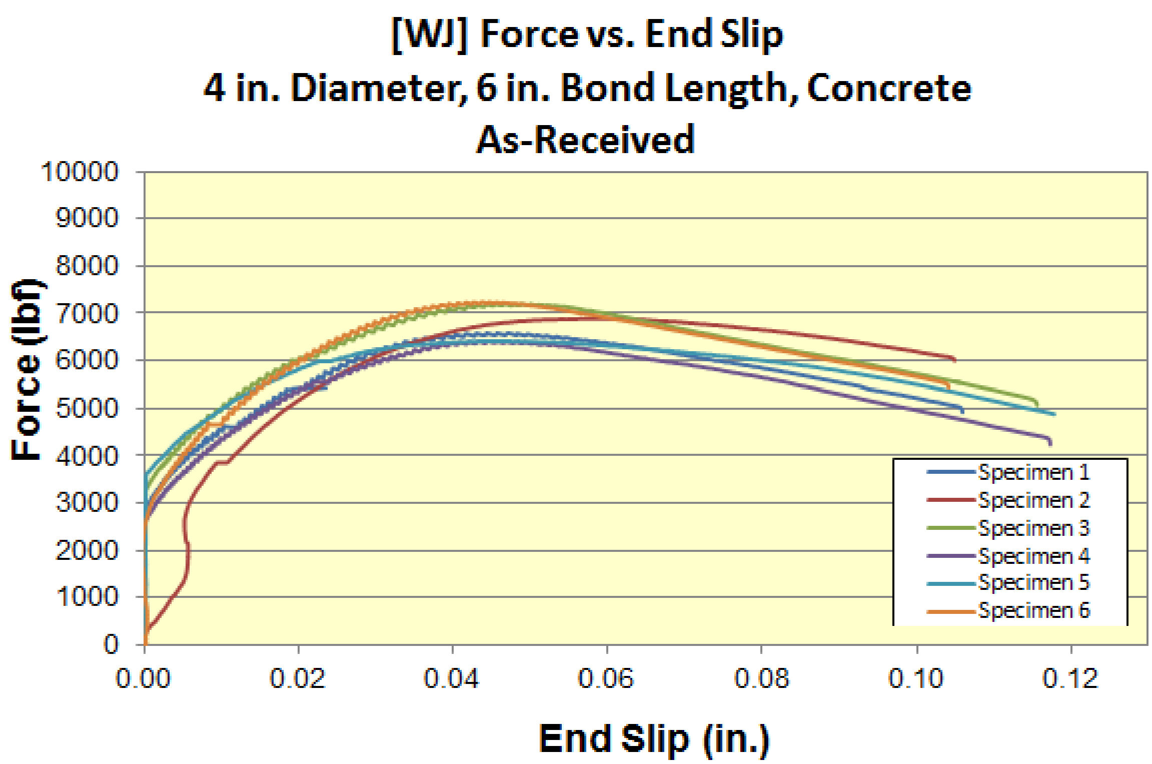

Figure N-10. As-received [WJ] force vs. end-slip individual graphs at CXT

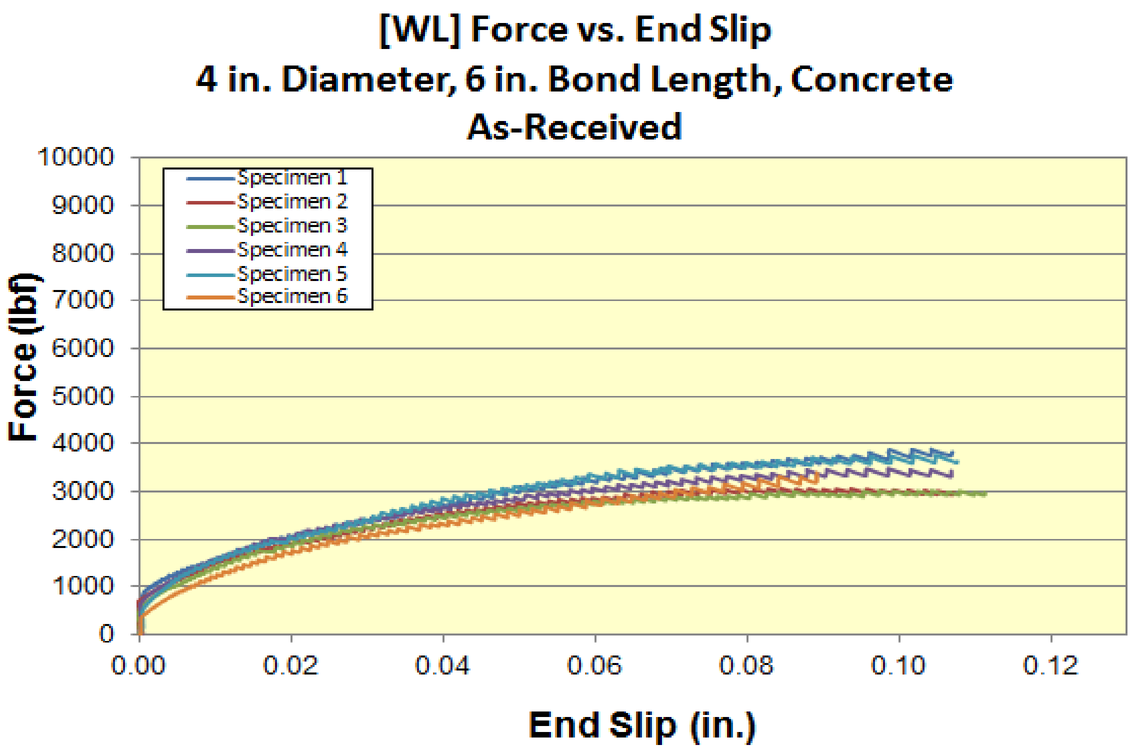

Figure N-11. As-received [WL] force vs. end-slip individual graphs at CXT

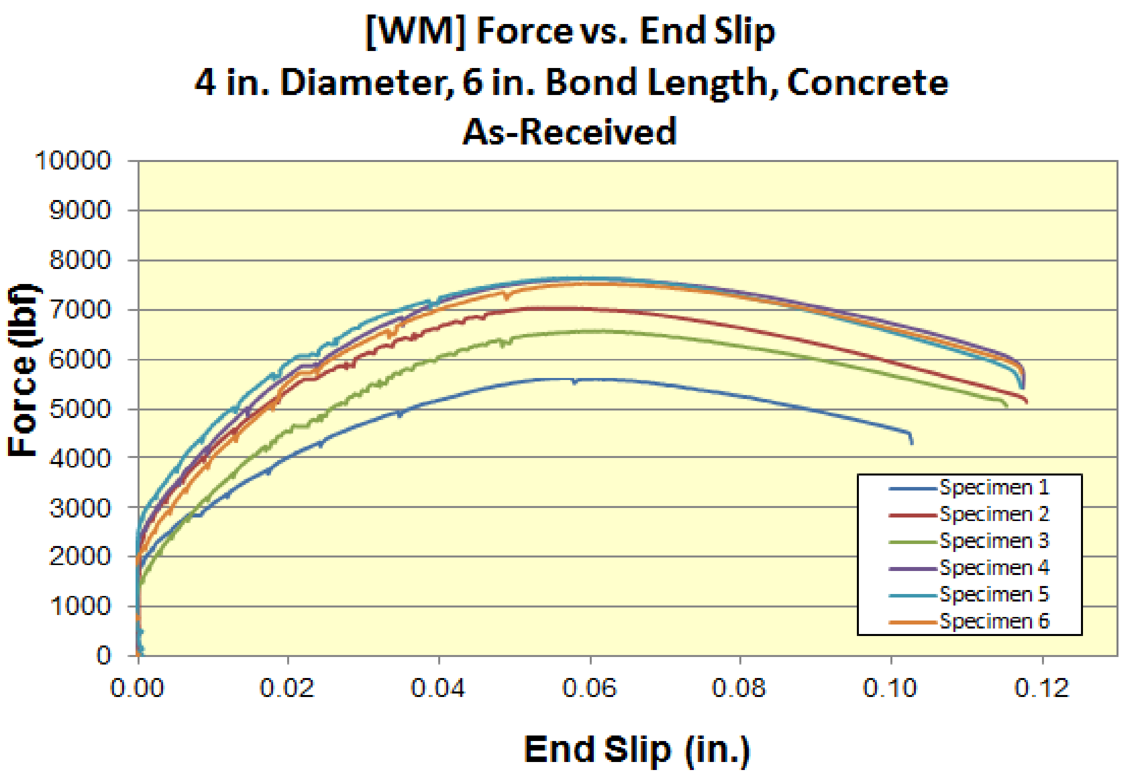

Figure N-12. As-received [WM] force vs. end-slip individual graphs at CXT

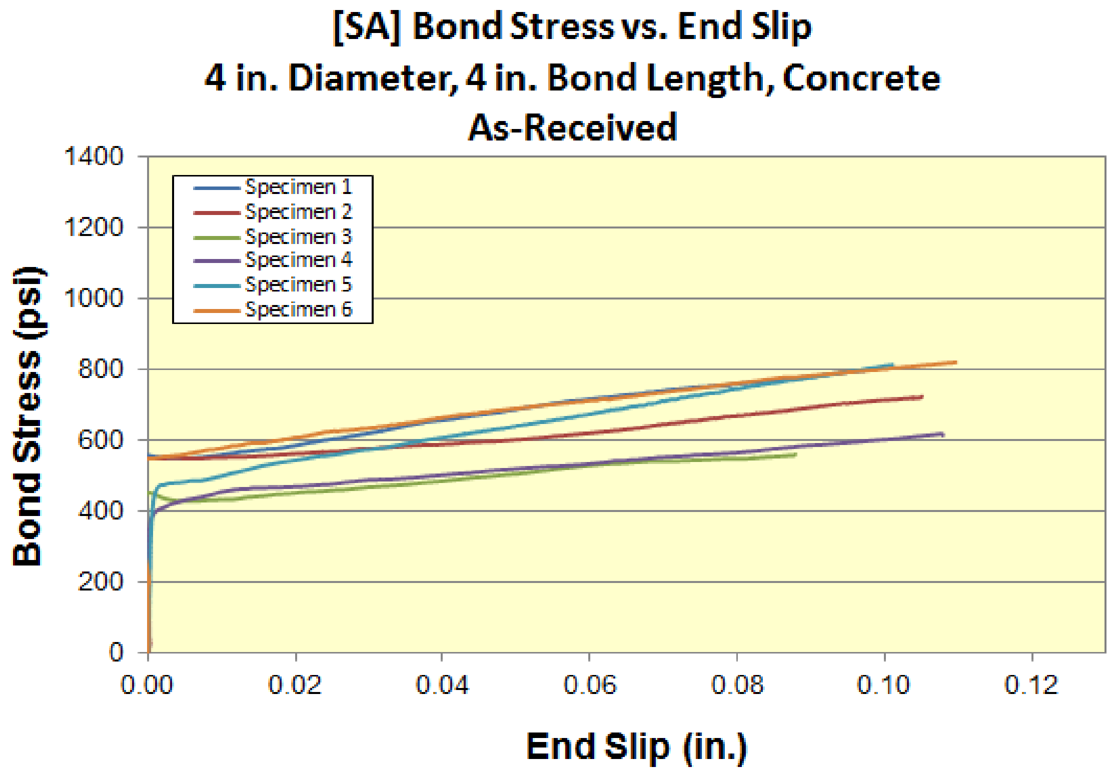

Figure N-13. As-received [SA] force vs. end-slip individual graphs at CXT

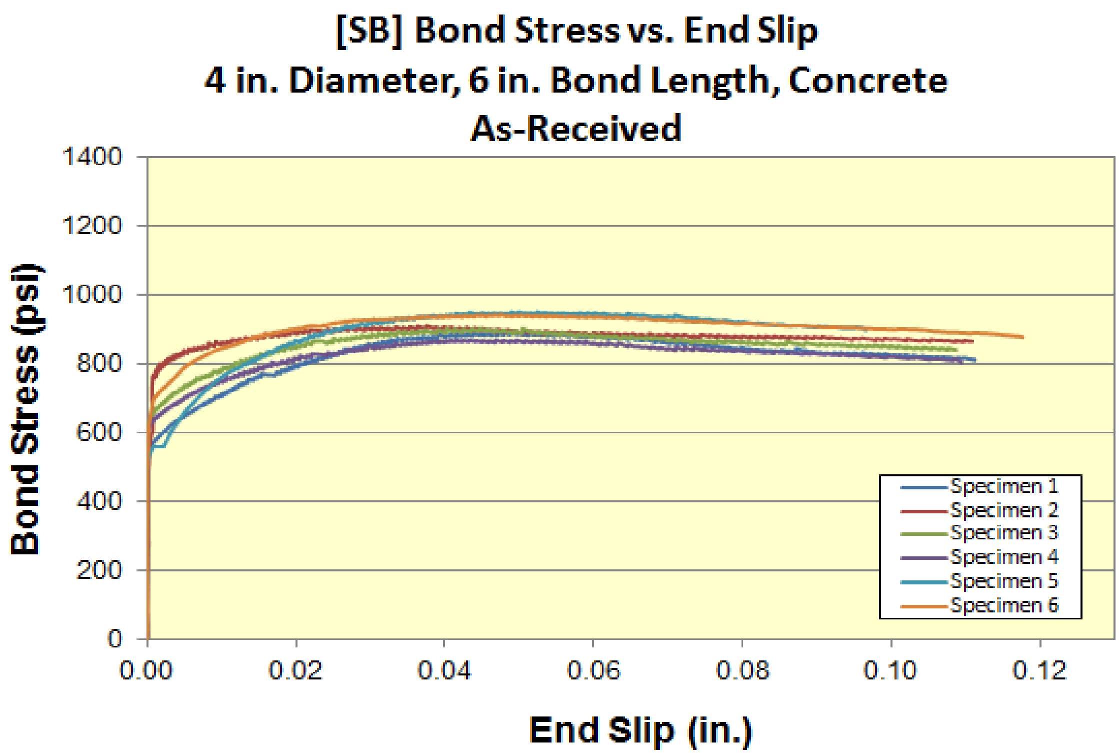

Figure N-14. As-received [SB] force vs. end-slip individual graphs at CXT

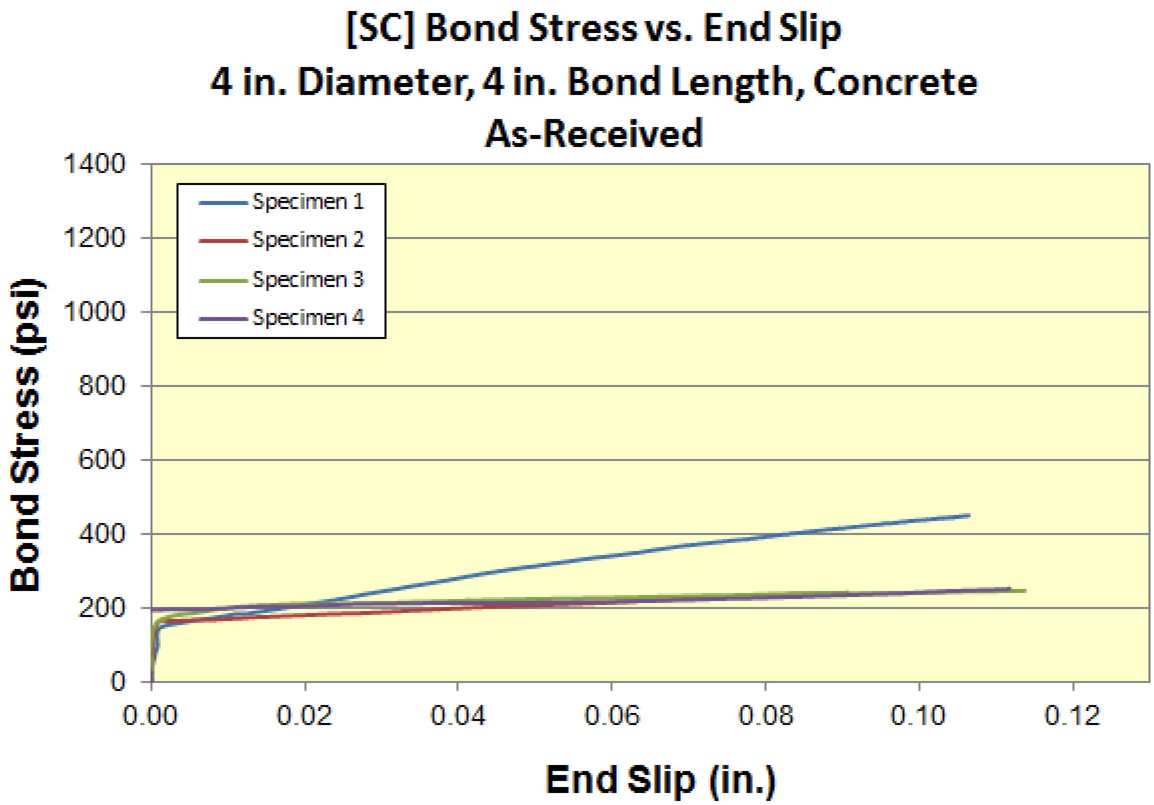

Figure N-15. As-received [SC] force vs. end-slip individual graphs at CXT

Appendix O.
Lab and Plant Phases; Individual Pullout Data Comparison

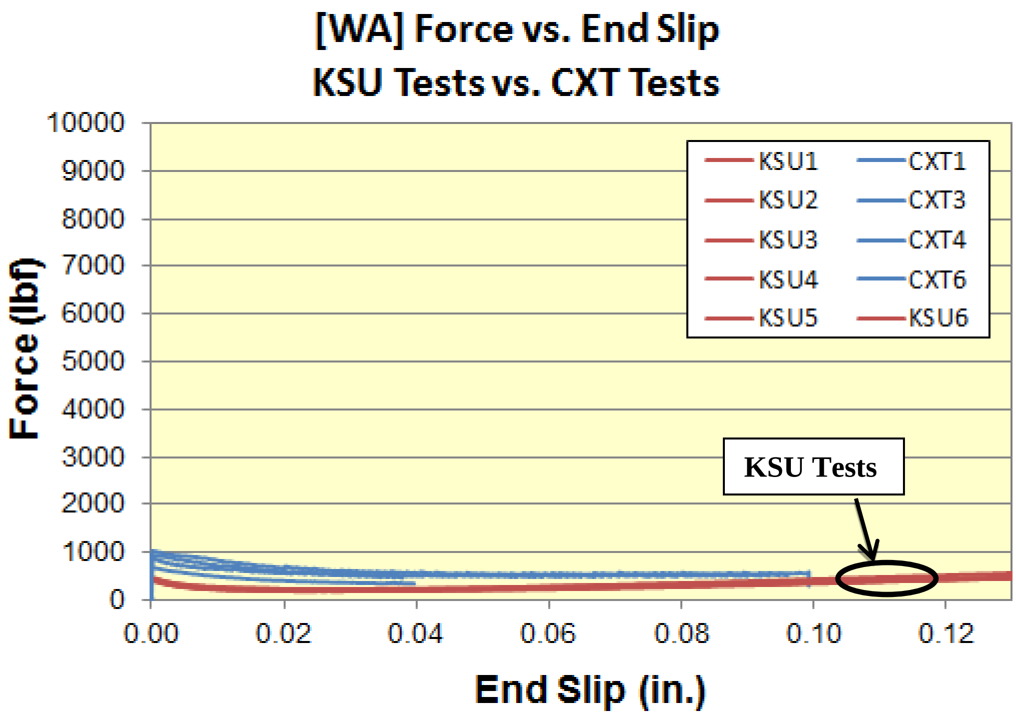

Figure O-1. [WA] force vs. end-slip individual graphs, KSU vs. CXT

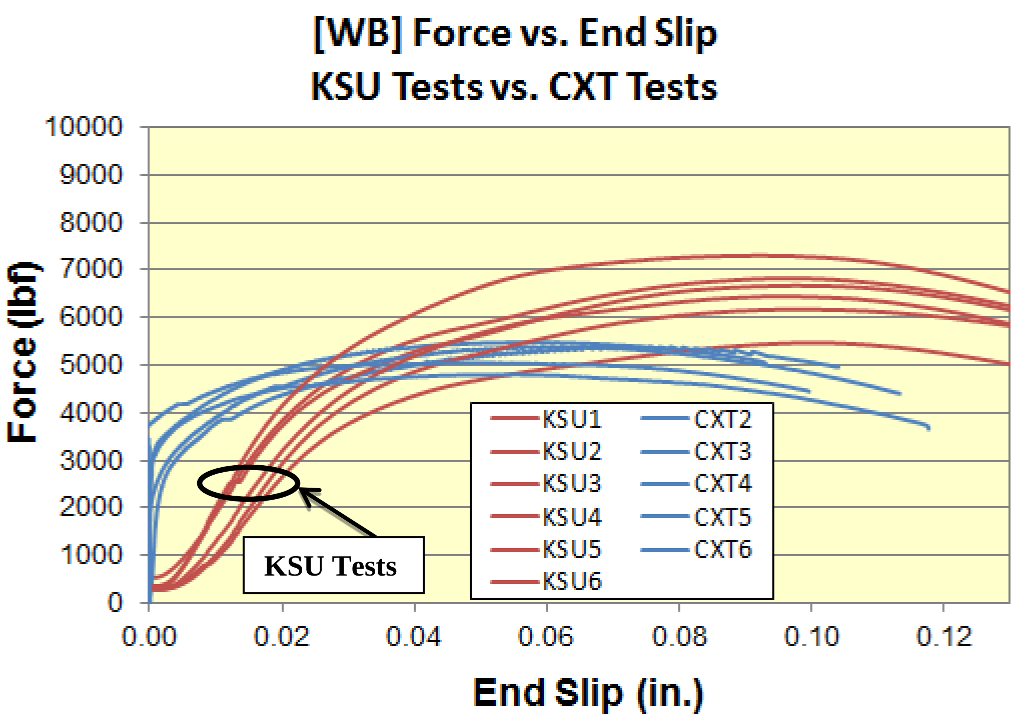

Figure O-2. [WB] force vs. end-slip individual graphs, KSU vs. CXT

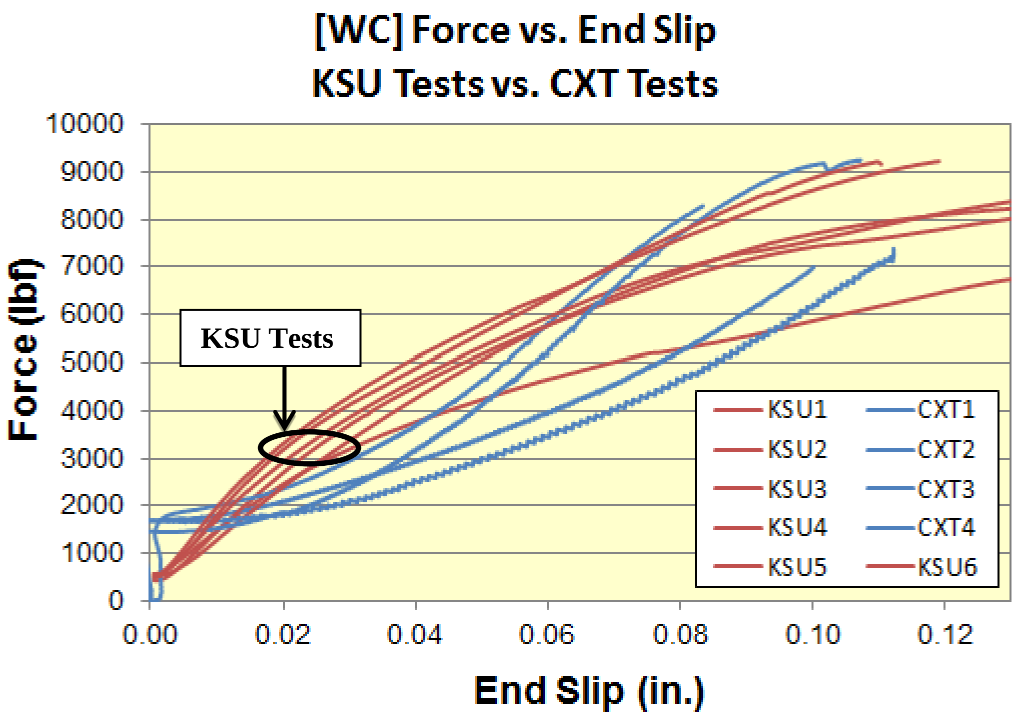

Figure O-3. [WC] force vs. end-slip individual graphs, KSU vs. CXT

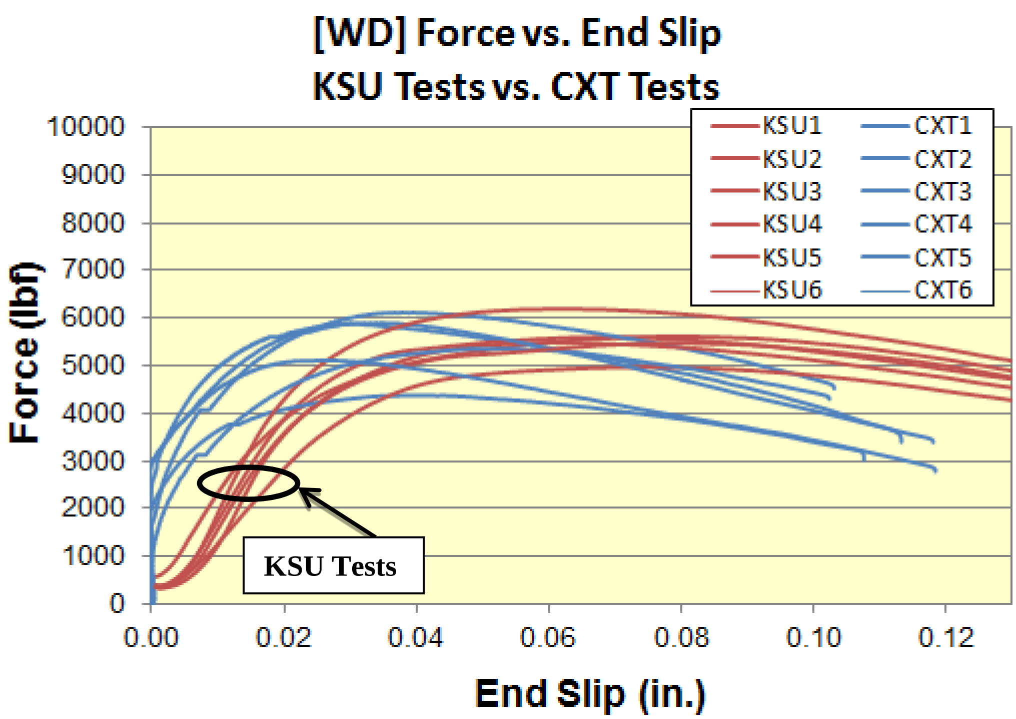

Figure O-4. [WD] force vs. end-slip individual graphs, KSU vs. CXT

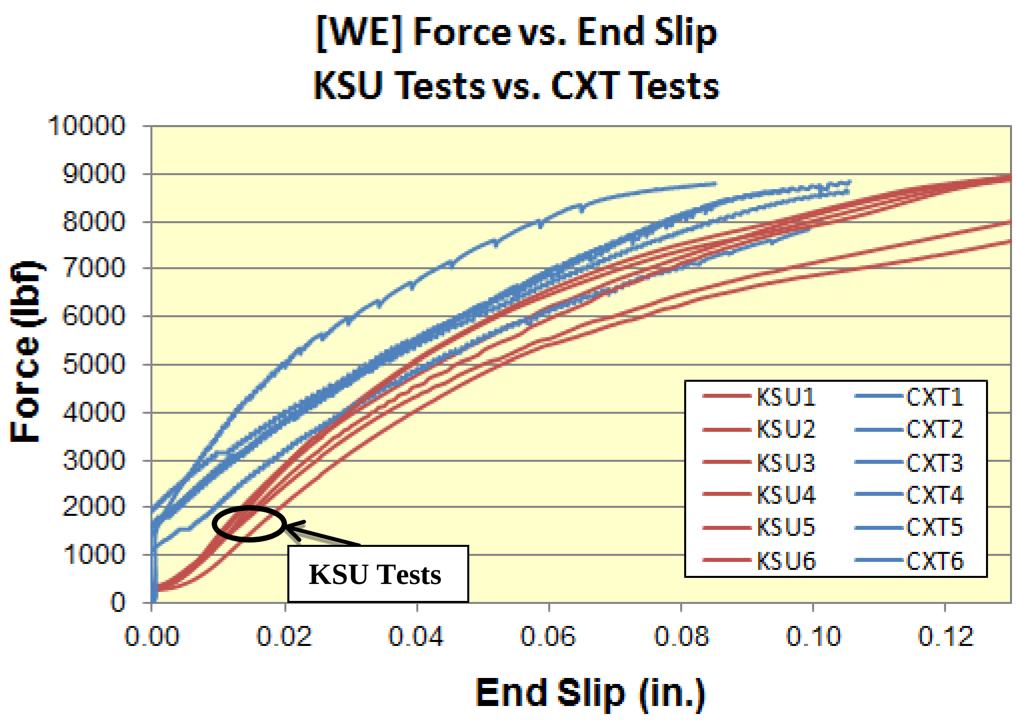

Figure O-5. [WE] force vs. end-slip individual graphs, KSU vs. CXT

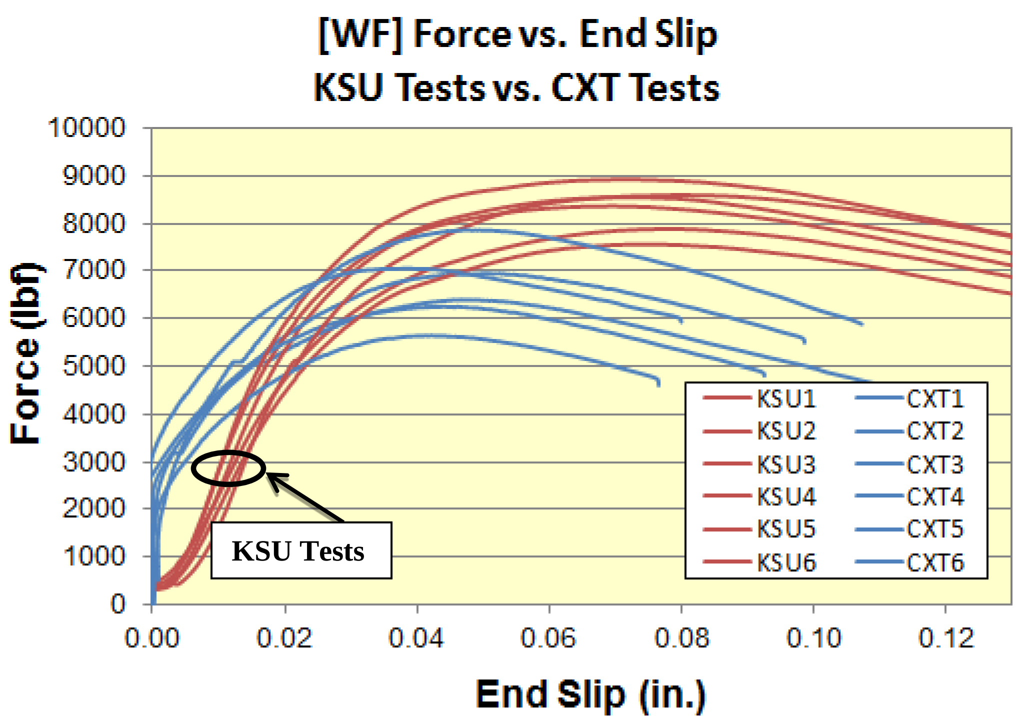

Figure O-6. [WF] force vs. end-slip individual graphs, KSU vs. CXT

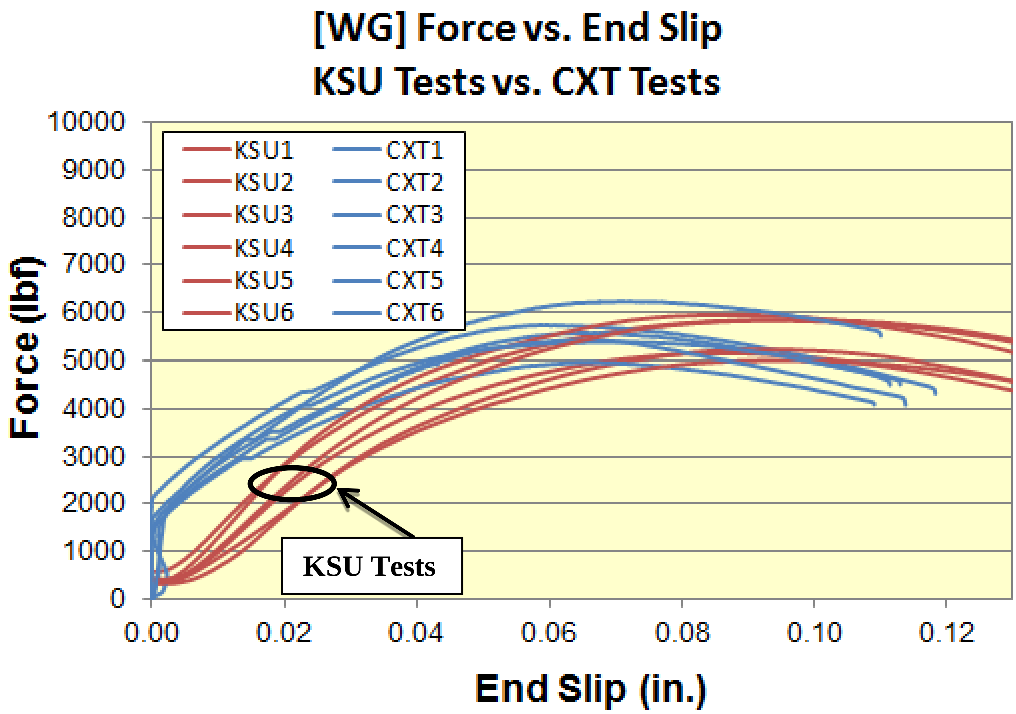

Figure O-7. [WG] force vs. end-slip individual graphs, KSU vs. CXT

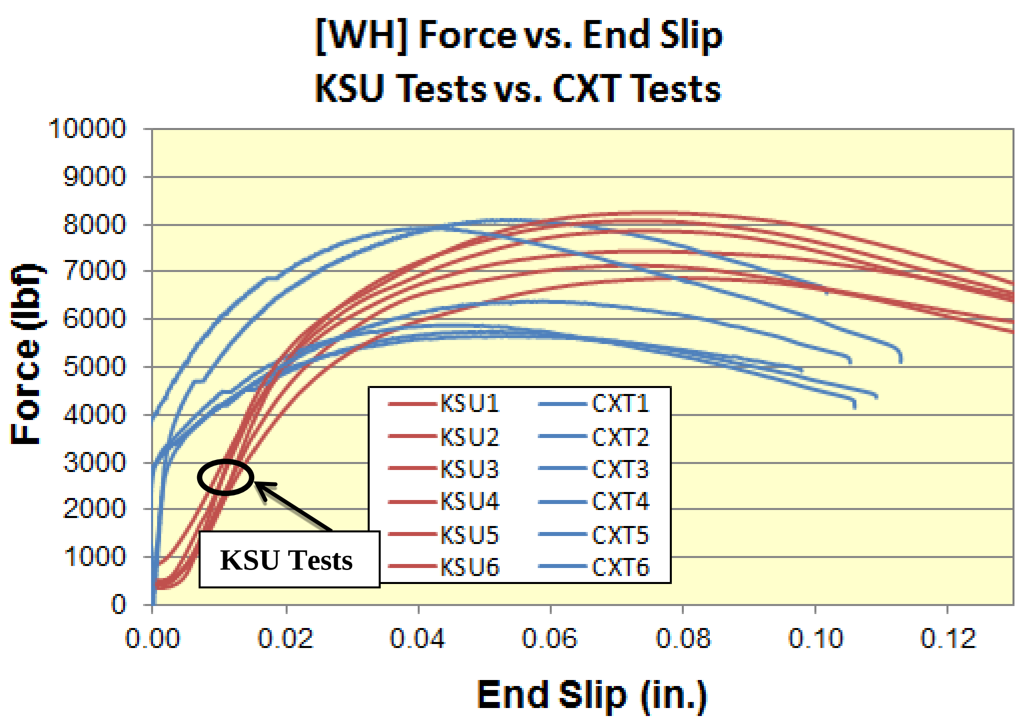

Figure O-8. [WH] force vs. end-slip individual graphs, KSU vs. CXT

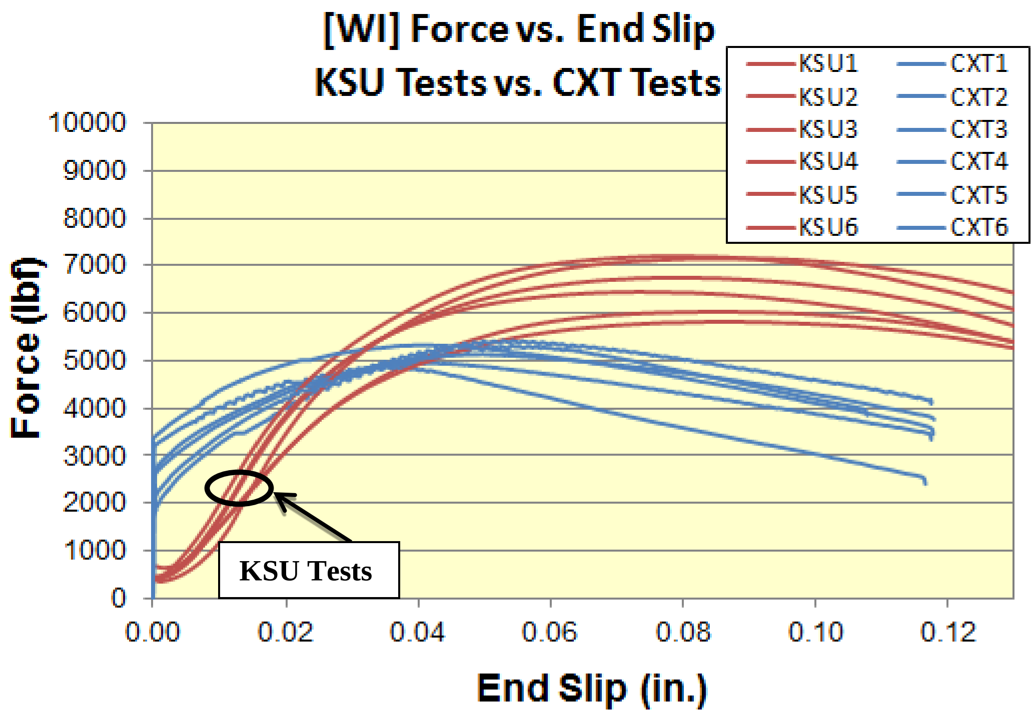

Figure O-9. [WI] force vs. end-slip individual graphs, KSU vs. CXT

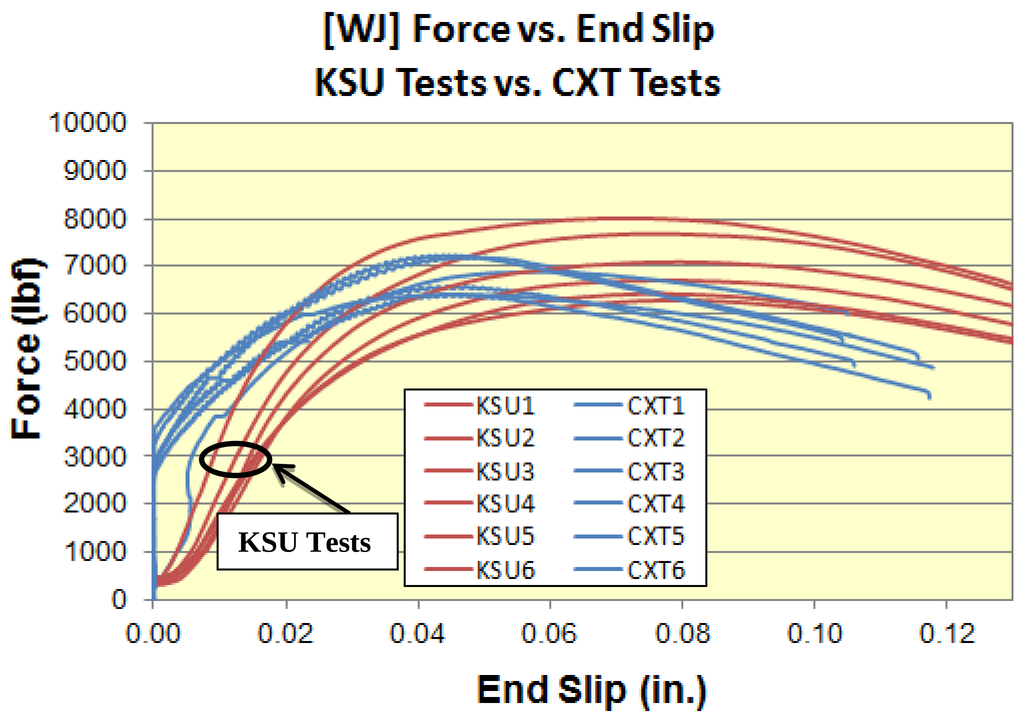

Figure O-10. [WJ] force vs. end-slip individual graphs, KSU vs. CXT

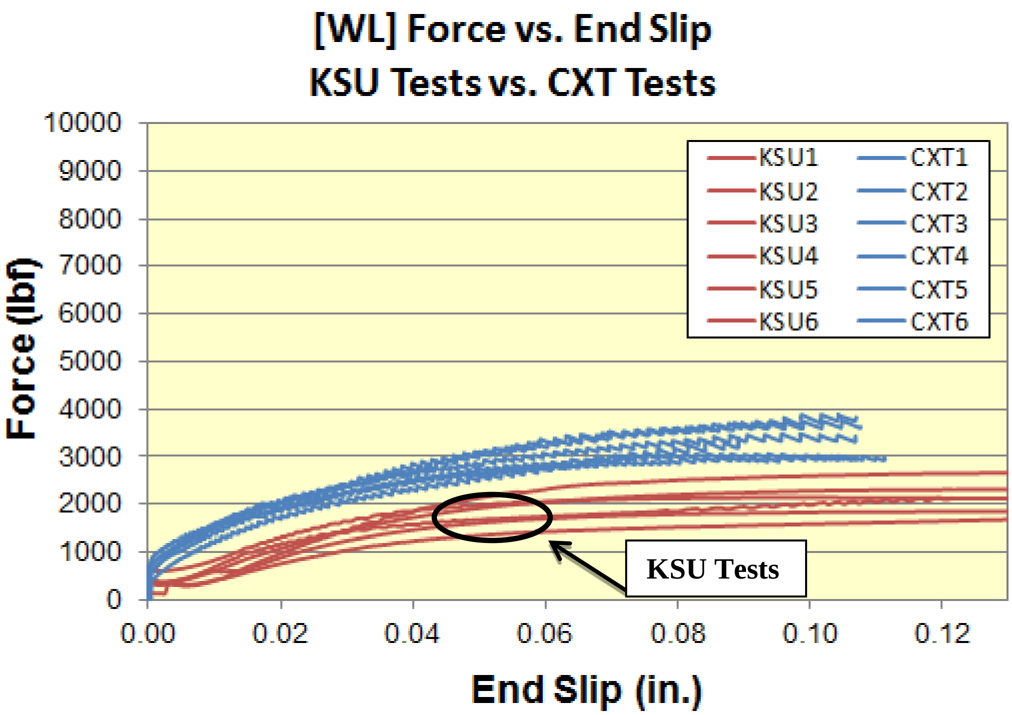

Figure O-11. [WL] force vs. end-slip individual graphs, KSU vs. CXT

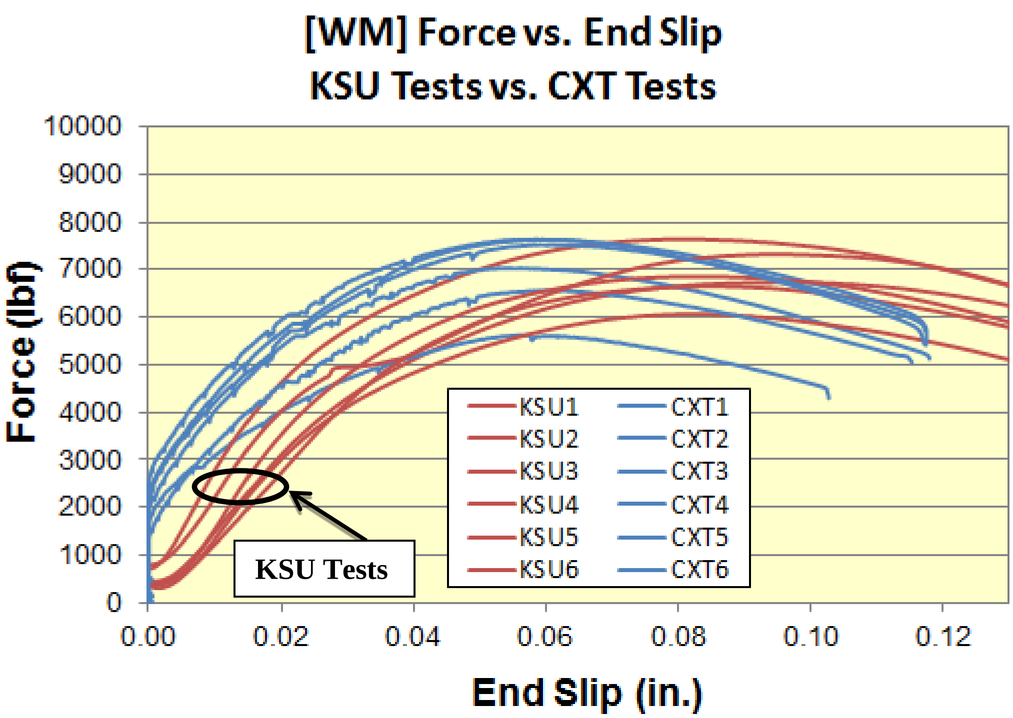

Figure O-12. [WM] force vs. end-slip individual graphs, KSU vs. CXT

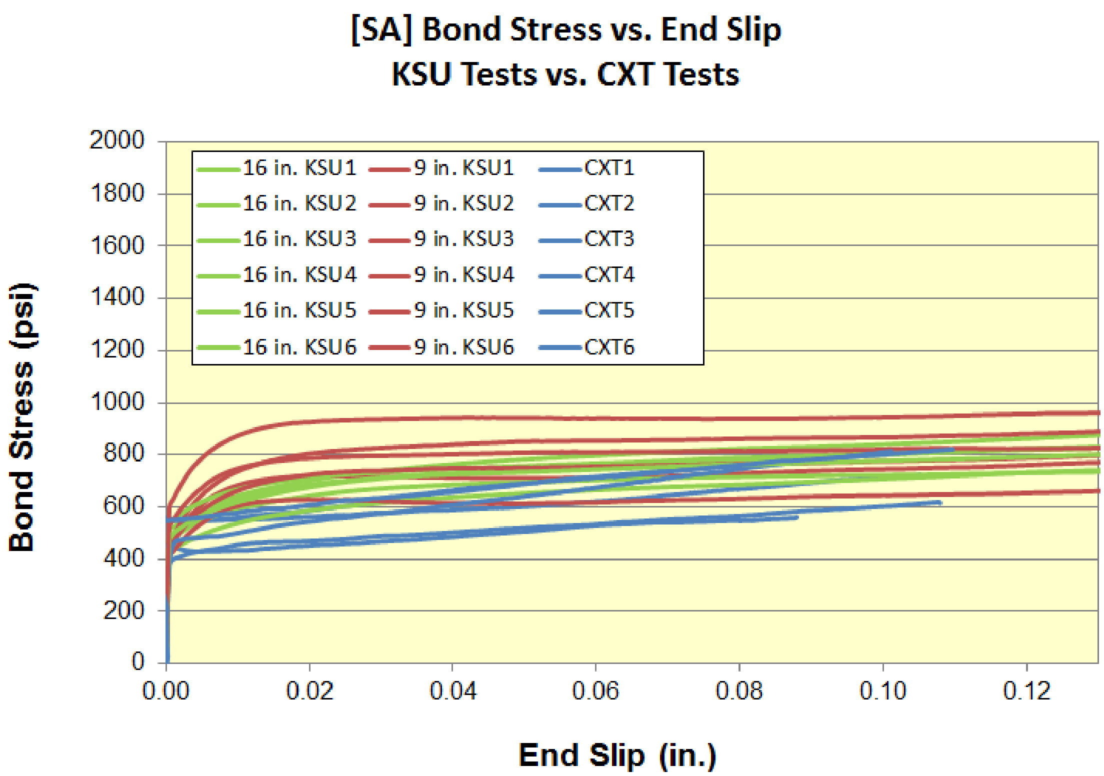

Figure O-13. [SA] force vs. end-slip individual graphs, KSU vs. CXT

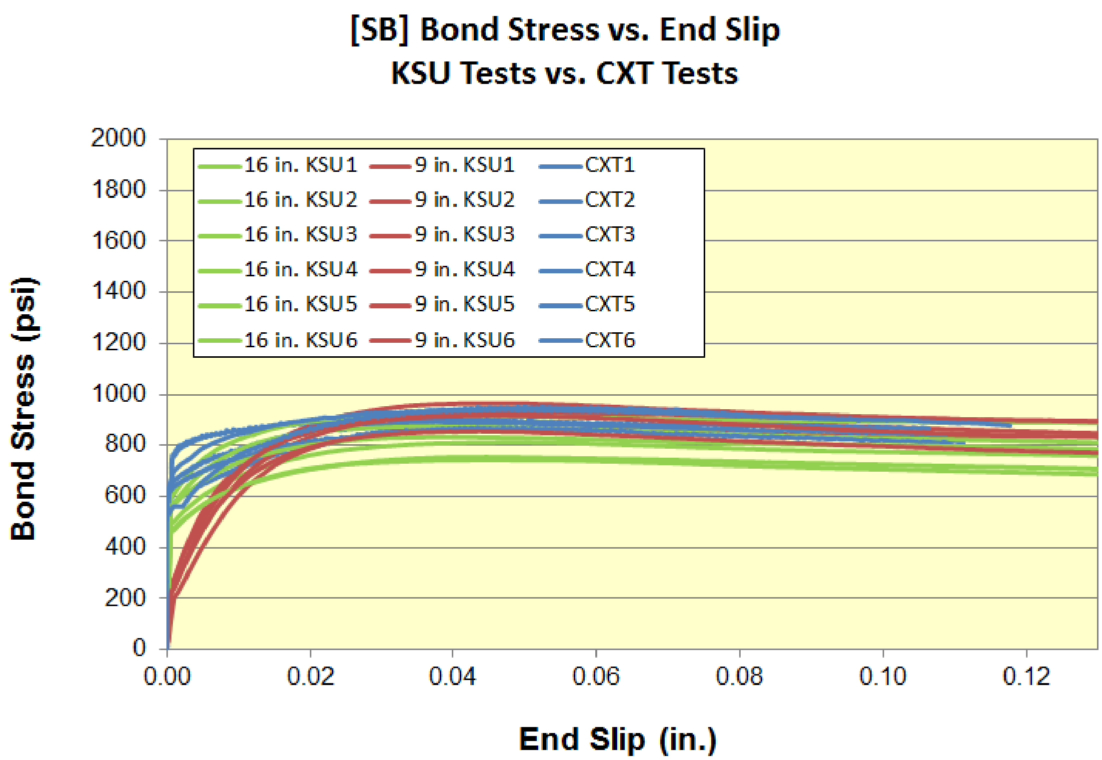

Figure O-14. [SB] force vs. end-slip individual graphs, KSU vs. CXT

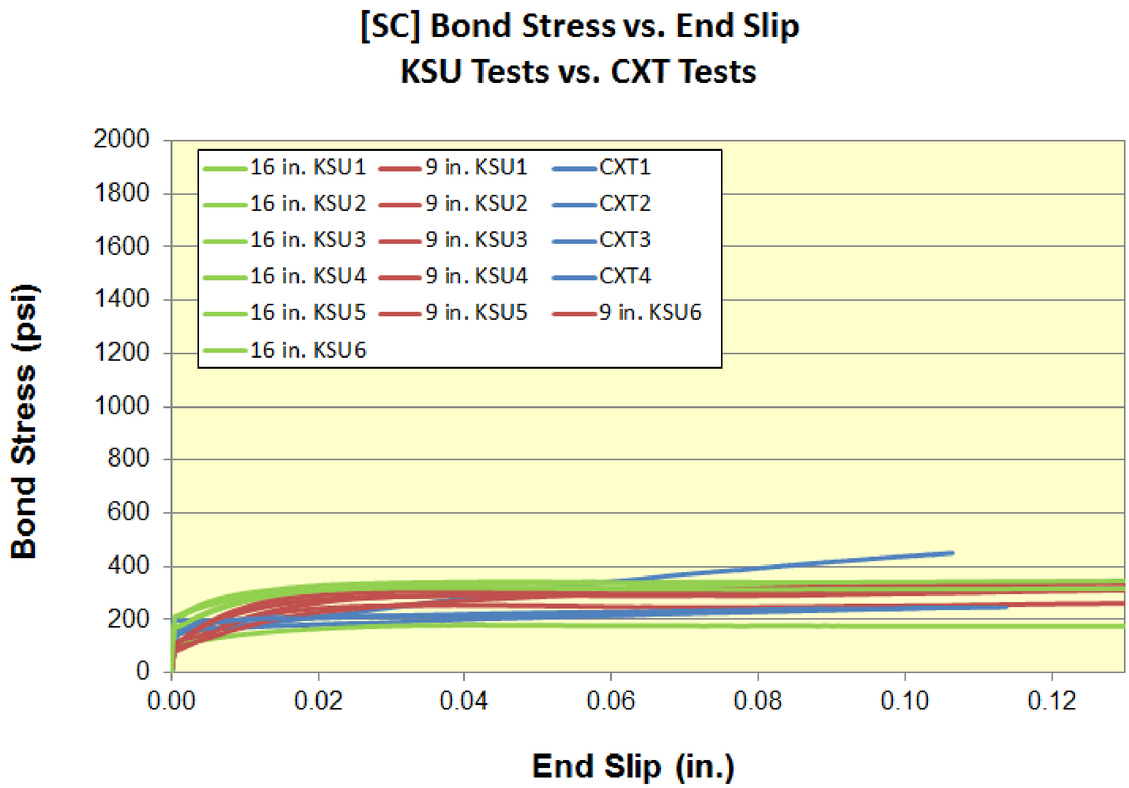

Figure O-15. [SC] force vs. end-slip individual graphs, KSU vs. CXT

Appendix P.
Mill Certification Tests for Cement Used in All Lab Pullout Tests

THE MONARCH Cement Company

MANUFACTURERS OF PORTLAND CEMENTS

SINCE 1908

PHONE: (620) 473-2222
FAX: (620) 473-3112

449 1200 STREET
P.O. BOX 1000
HUMBOLDT, KANSAS 66748-0900

CERTIFIED MILL TEST REPORT - Results of tests on typical samples - **Type III**

Date of Shipment
Consigned to

From: Humboldt Plant
Car or Trailer

Destination

PHYSICAL TESTS

Per cent passing 325 Sieve	98.5	Air Content	6.8
Blaine Surface Area	5490	Autoclave Expansi	-0.044

	Setting Time Gillmore	
Initial	2:30	Hrs./Min.
Final	3:55	Hrs./Min.

Compressive Strength
1:2.75 Graded Sand

24 Hrs.	3 Days	7 Days
3090	4358	5098

CHEMICAL ANALYSIS

Silicon dioxide	21.67	Loss on ignition	1.63
Ferric oxide	3.49	Insoluble residue	0.07
Aluminum oxide	4.44	Free lime	0.77
Calcium oxide	63.55	Sodium oxide	0.11
Magnesium oxide	1.83	Potassium oxide	0.50
Sulphur trioxide	3.13	Alkalies (equiv.)	0.44

POTENTIAL CALCULATED COMPOUNDS

Tricalcium silicate	50.3	Tricalcium aluminate	5.9
Dicalcium silicate	24.2	Tetracalcium aluminoferrite	10.6

The cement in this shipment meets standard requirements in the current specifications of the Federal Government and the American Society for Testing and Materials for Type III Portland Cement. All test methods conform to ASTM Test Methods: Chemical C-114, Blaine C-204, Soundness C-151, Gillmore C-266, Compressive Strength C-109, Air Content C-185 and C150.

Date: 6/1/2012

Calvin D. Parker
Calvin D. Parker
Quality Control Supervisor

Abbreviations and Acronyms

ASTM	American Society for Testing Materials
C.V.	Coefficient of Variation
CXT	CXT Concrete Ties
FRA	Federal Railroad Administration
KSU	Kansas State University
LVDT	Linear Variable Differential Transformer
MW	Midwest Sand
NASP	North American Strand Producers
NCHRP	National Cooperative Highway Research Program
PTI	Post-Tensioning Institute
STSB	Standard Test for Strand Bond