Investigation of Standardized Tests to Measure the Bond Performance of Prestressing Strand

An experimental program was conducted to evaluate three different bond performance tests and their potential to predict the bond characteristics of seven-wire strands in pretensioned concrete applications. Simple pull-out tests, tensioned pull-out tests, and measured strand end slips were compared to companion transfer length measurements for 0.5 in. (12.7 mm) diameter, Grade 270 low-relaxation strands with varying surface conditions. Four strand surface conditions were tested: as-received, cleaned, silane treated, and weathered. Additionally, strands produced by three different manufacturers were tested in their as-received condition. Overall, end slip measurements provided an excellent correlation with measured transfer lengths. When data from other research projects were included, a statistical correlation of 0.95 was demonstrated between measured transfer lengths and strand end slips. From these results, strand end slips are determined to be the best predictor of pretensioned bond. Therefore, strand end slip measurements are recommended as a reliable standard measure to predict the bond performance of prestressing strands for pretensioned applications.

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Original code expressions for transfer length and development length were developed from testing performed in the 1950s and early 1960s on Grade 250, stress-relieved strand. Based on these early tests, the American Concrete Institute (ACI)[1] and the American Association of State Highway Transportation Officials (AASHTO)[2] adopted code provisions that remain in force today. However, since the 1950s, strand manufacturing processes have changed to produce strand more efficiently and economically.

Today, the strand production industry typically produces Grade 270, low-relaxation strands. It has been suggested that these advances in materials technology brought about by improved production methods could be the cause for the perceived changes in strand bond behavior over the last three decades.[3,4]

For example, contemporary seven-wire strand production employs induction heating to stress relieve strand whereas convection heating was used in earlier strand manufacturing processes. Convection heating created comparatively hotter surface temperatures on strand that may have burned off much of the surface residues remaining from the wire drawing process. By using induction heating, the strand is heated more efficiently than convection heating and surface temperatures are cooler.

Furthermore, convection heating employed combustion processes that may have aided in oxidizing impurities on strand surfaces. On the other hand, induction heating also lacks a combustion process where organic molecules and surface residues can be oxidized. As a result, more surface residues may remain on the strand.

First indications of increased transfer lengths were observed in bond tests performed by Cousins, Zia and Johnston in the mid-1980s.[5,6,7] Results from their research suggested that the current code provisions underestimated both transfer and development lengths for uncoated strands. Their research compared the bond performance of grit impregnated, epoxy-coated strands to the bond performance of uncoated, or bare, strands. Measured transfer lengths on bare strands exceeded ACI and AASHTO design recommendations for transfer lengths ($50d_b$) by more than 100 percent. The average transfer length of 0.5 in. (12.7 mm) strands was measured at 49.7 in. (1.26 m) or $99.4d_b$ with a maximum reported transfer length of 74 in. (1.88 m), or $148d_b$.

In response to these test results and also recognizing that standard practice was based on tests performed three decades ago on stress-relieved, Grade 250 strand, the Federal Highway Administration (FHWA) issued a memorandum restricting selected uses of pretensioned strands. The responding action by the FHWA completely disallowed the use of 0.6 in. (15.2 mm) strand in pretensioned concrete applications. Additionally, for all sizes of strands up to and including $^9/_{16}$ in. (14.3 mm) strands, the required development length was increased 60 percent. Today, parts of the FHWA moratorium still remain in effect although 0.6 in. (15.2 mm) strands are now fully accepted for pretensioned applications.

Undoubtedly, changes in strand production technology could have contributed to wide variations in bond characteristics and strand manufacturers should be sensitive and knowledgeable about how their unique manufacturing processes affect pretensioned bond. However, the authors do not believe that the concrete construction industry, and particularly the precast/prestressed concrete industry, should place restrictions on the manner in which seven-wire strands are produced.

Instead, as buyers of seven-wire strands, the pretensioned industry can specify and expect minimum bond performance requirements for seven-wire strands. ASTM A 416 only requires certain mechanical properties of the strand, including minimum strength, maximum relaxation, minimum elongation, and other variables.[8] Adequate bond, however, is no less essential to the integrity of prestressed concrete. Therefore, the creation of performance standards for the bond of prestressing strands is a rational response to any perceived problems throughout the industry.

A standard test for the bond of seven-wire strand in pretensioned concrete could benefit all parties involved. Strand manufacturers, producers of pretensioned concrete, designers and owners can benefit from the assurance of producing quality products that will perform as expected and as required by design. Strand manufacturers could use a performance test to monitor the quality of their strand production. Pretensioned producers could use a performance test to specify the quality of bond for the prestressing strand that they purchase. Designers would be able to specify materials and develop designs with relative assurance of the constructed product. Finally, owners and builders could select pretensioned concrete without concern for pretensioned bond.

BACKGROUND

The successful resolution of the pretensioned anchorage problem has been complicated by the wide variation in transfer length data obtained from several research programs over the past 40 years, beginning with work performed by Hanson, Kaar, and others.[9,10,11] Fig. 1 illustrates the transfer length data for 0.5 in. (12.7 mm) diameter strands reported since 1959. For each research program, high, low and average values for transfer length are illustrated. The data represented in Fig. 1 are also listed in Table 1. Despite the researchers' best efforts to control variables, the data clearly illustrate that each investigation produced transfer length data that are characterized by large variations, especially when compared to other researchers.

After reviewing the data, it should be concluded that transfer length measurements are characterized by a wide degree of scatter, and tests using seemingly identical strand and surface conditions may yield widely disparate results. Therefore, to certify the bond characteristics of a given prestressing strand in pretensioned concrete applications, a standardized and repeatable bond performance test must be developed.

The FHWA moratorium generated several research programs to study pretensioned bond. Beginning in the late 1980s, the University of Texas at Austin led by Ned Burns,[12-16] the Florida Department of Transportation led by Mohsen Shahawy,[17,18] McGill University led by Denis Mitchell,[19] Auburn University led by Thomas Cousins,[20] and the University of Tennessee led by Harold Deatherage[21,22] all developed research programs to investigate the bond of seven-wire strands. Results from these and other research programs indicated significant variation in measured transfer lengths. Shown in Fig. 1, the research generally indicates that wide variations can occur within the same research program. More importantly, even wider variations occur when data from all research are combined.

In a related issue, some investigators initially faulted the lubricants used to manufacture the strand, claiming that wire drawn with water soluble sodium stearates results in better bond characteristics than wire drawn with non-water soluble calcium stearates. However, empirical evidence does

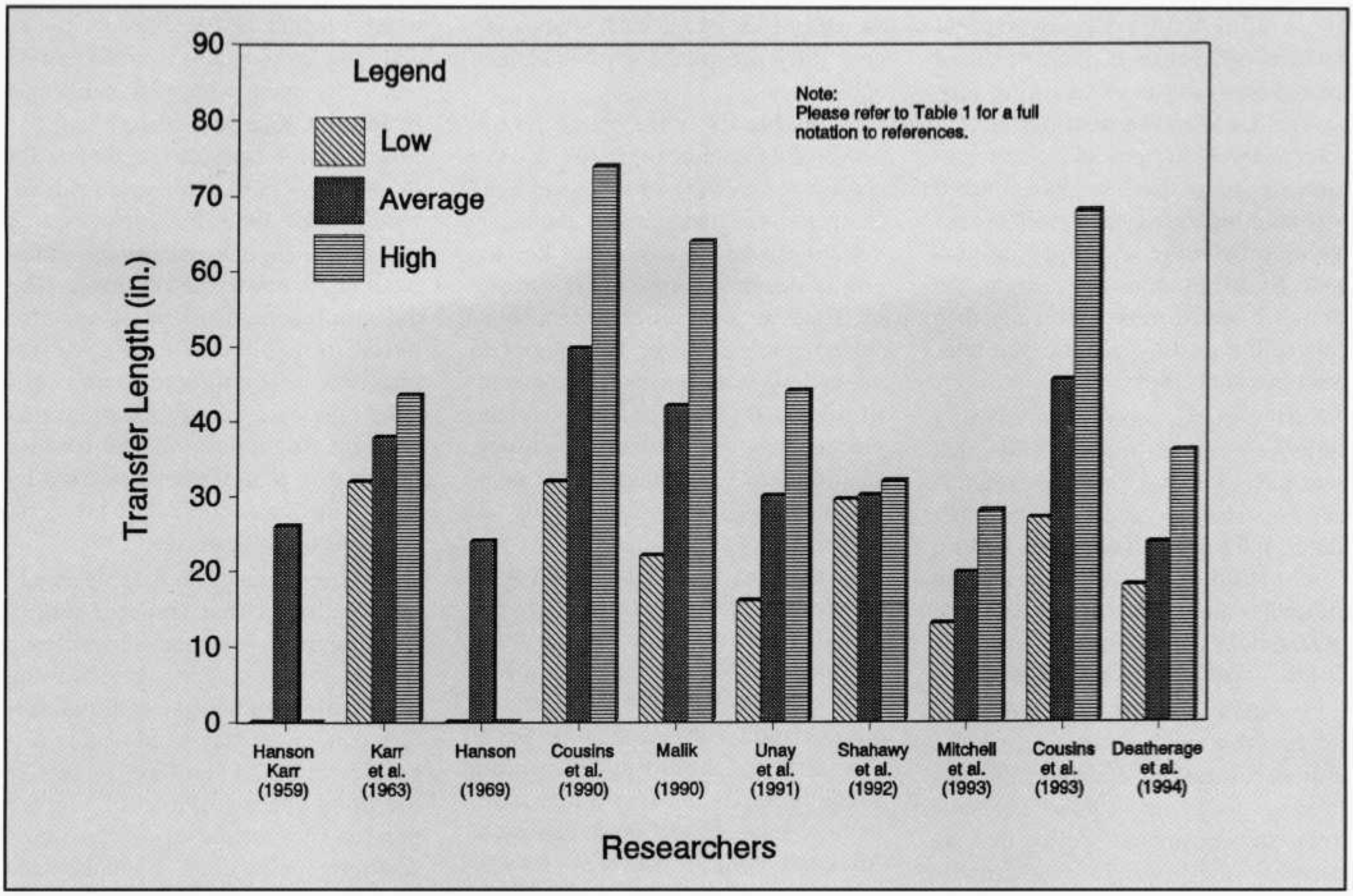


Fig. 1. Summary of transfer length data, uncoated, 0.5 in. (12.7 mm) strands

suggest that acceptable strand products can be manufactured using either of these lubricants.

Correlation of Strand End Slip With Transfer length

Some researchers have reported strand end slip measurements along with measuring transfer lengths of pretensioned members. In the manufacture of hollow-core slabs, the end slip (or "suck-in") of prestressing strands has been advocated as a measurement for the quality of pretensioned bond. Anderson and Anderson[23] and Brooks, Gerstle and Logan[24] reported results from flexural tests performed on hollow-core slab products with varying amounts of end slips. The tests consistently demonstrated that bond failures resulted in hollow-core slabs where excessive end slips were measured. Anderson and Anderson[23] reported that the ACI transfer length would be satis-

Table 1. Summary of [illegible] data, uncoated, 0.5 in. strand.

Researcher	Type of release	Average concrete release strength (psi)	Number of ends tested	Reported transfer lengths (in.)		
				Low	Average	High
Hanson and Kaar[9] (1959)	Flame cut	5310	17 beams	—	26*	—
Kaar et al.[10] (1963)	Flame cut	3440	10	32	37.9	43.5
Hanson[11] (1969)	Flame cut	4960	1 beam	—	24*	—
Cousins et al.[5,6] (1990)	Flame cut	4340	20	32	49.7	74
Malik[12] (1990) Russell and Burns[13]	Flame cut	3580		22		
Unay et al.[11] (1991) Russell and Burns[15,16]	Flame cut	4380	12	16	42	
Shahawy et al.[17,18] (1992)	Flame cut	5110	12	29.5	30.1	32
Mitchell et al.[19] (1993)	Gradual release	5870	34 14	13	30 19.7	28
Cousins et al.[20] (1993)	Flame cut	6510	27	27	45.4	68
Deatherage et al.[21,22] (1994)	Flame cut	4960	16	18	23.7	36

Note: 1 in. = 25.4 mm; 1 psi = 0.006895 MPa.

* Only the average value for transfer length was reported.

fied if the measured end slip was less than 0.10 in. (2.5 mm). Logan has since suggested that $^3/_{32}$ in. (2.3 mm) of "suck-in" would be acceptable.[25]

Fundamental mechanics and strain compatibility require that strand end slips are related to transfer length. Specifically, the transfer length of a pretensioned strand can be calculated based on the differences between concrete and steel strains throughout the transfer zone. When pretensioned strands are detensioned, strands slip into the concrete a finite distance. The total amount of end slip is given by the difference between steel and concrete strains, integrated over the transfer zone.

In other words, a theoretical relationship for end slip of a prestressing strand can be determined by accumulating concrete and steel strains over the transfer length.[15,16,21,23] The theoretical end slip of a strand can be calculated as follows:

$$L_{es} = \Delta_{ps} - \Delta_c = \int_0^{L_t}\left[\varepsilon_{si} - \varepsilon_s(x)\right]dx - \int_0^{L_t}\varepsilon_c(x)dx \qquad (1)$$

where

L_{es} = strand end slip
L_t = transfer length
4 = total elastic shortening of concrete through transfer zone
Δ_{ps} = total elastic shortening of strand through transfer zone
ε_{si} = initial steel strain, immediately prior to release
$\varepsilon_c(x)$ = concrete strain after transfer, varying with distance from end of member
$\varepsilon_s(x)$ = steel strain after transfer, varying with distance from end of member

Assuming a linear variation of steel and concrete strains in the transfer zone, as depicted in Fig. 2, Eq. (1) can be simplified to the following form:

$$L_{es} = \frac{L_t}{2}\left(\frac{f_{si}}{E_{ps}}\right) \qquad (2)$$

where

E_{ps} = modulus of elasticity of strand
f_{si} = steel stress just before detensioning

Eq. (2) can be rearranged as follows to calculate the transfer length from measured end slip:

$$L_t' = 2L_{es}\left(\frac{E_{ps}}{f_{si}}\right) \qquad (3)$$

where L_t' is the transfer length calculated from end slip.

The Fédération Internationale de la Précontrainte (FIP) also recognizes the value of measured end slip in assessing the transfer length of prestressing strands. In a technical report titled "Test for the Determination of Tendon Transmission Length Under Static Conditions," FIP recommends that strand end slip, or "draw-in" should be used to measure the transfer length, or "transmission length" of pretensioned prestressing strands. Although the FIP approach tends to be more theoretical than models developed in North America, a simplified approach is discussed. The section titled "Practical Appraisal" in the FIP report suggests that the relationship between end slip and transfer length should be taken as:

$$L_t = 3L_{es}\left(\frac{E_{ps}}{f_{si}}\right) \qquad (4)$$

The primary difference between the FIP equation and the relation originally developed by Anderson and Anderson[23] is that the FIP report assumes a parabolic distribution of concrete strains through the transfer zone whereas the North American approach assumes a linear distribution of concrete strains.[26]

Simple Pull-Out Tests to Assess Bond Performance

Simple pull-out tests were developed as a possible measurement to assess the strength of pretensioned strand. Resistance to strand pull-out must develop primarily through friction, just as pretensioned anchorage is developed to some degree. Arguments in favor of simple pull-out tests note that the friction between the strand and concrete is also an essential element to the bond of pretensioned strands. However, in pretensioned strand anchorage, the strands expand laterally against the surrounding hardened concrete as the strands are released, thus contributing significant

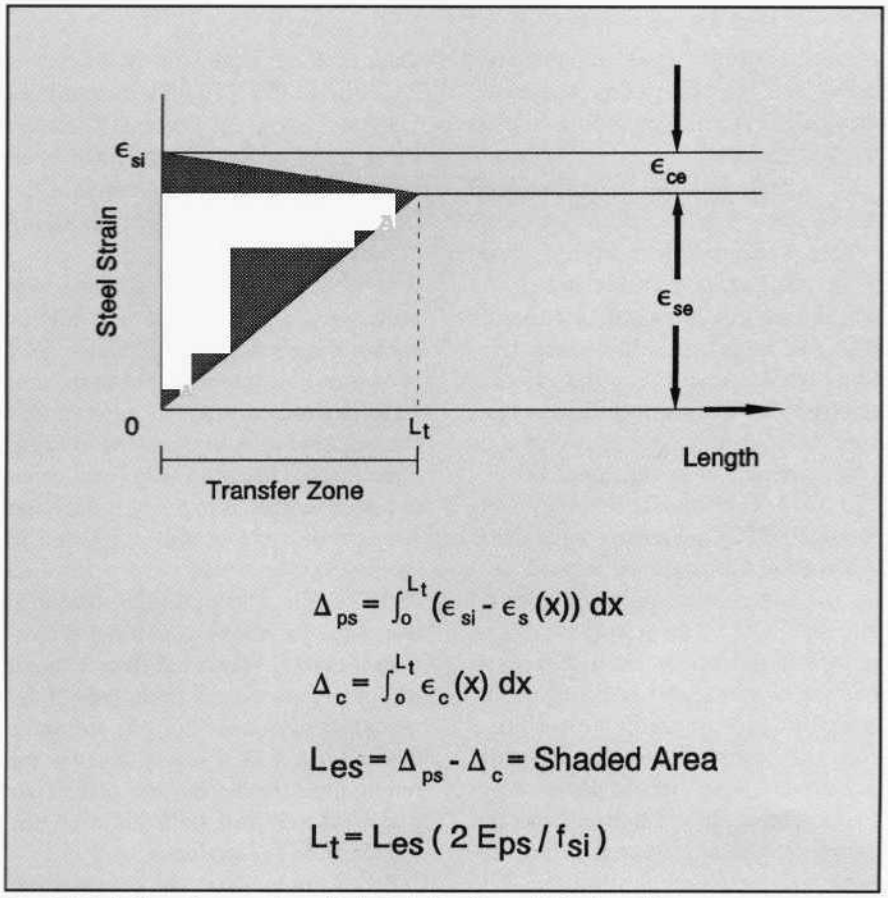


Fig. 2. Variation of concrete and steel strains through the transfer zone.

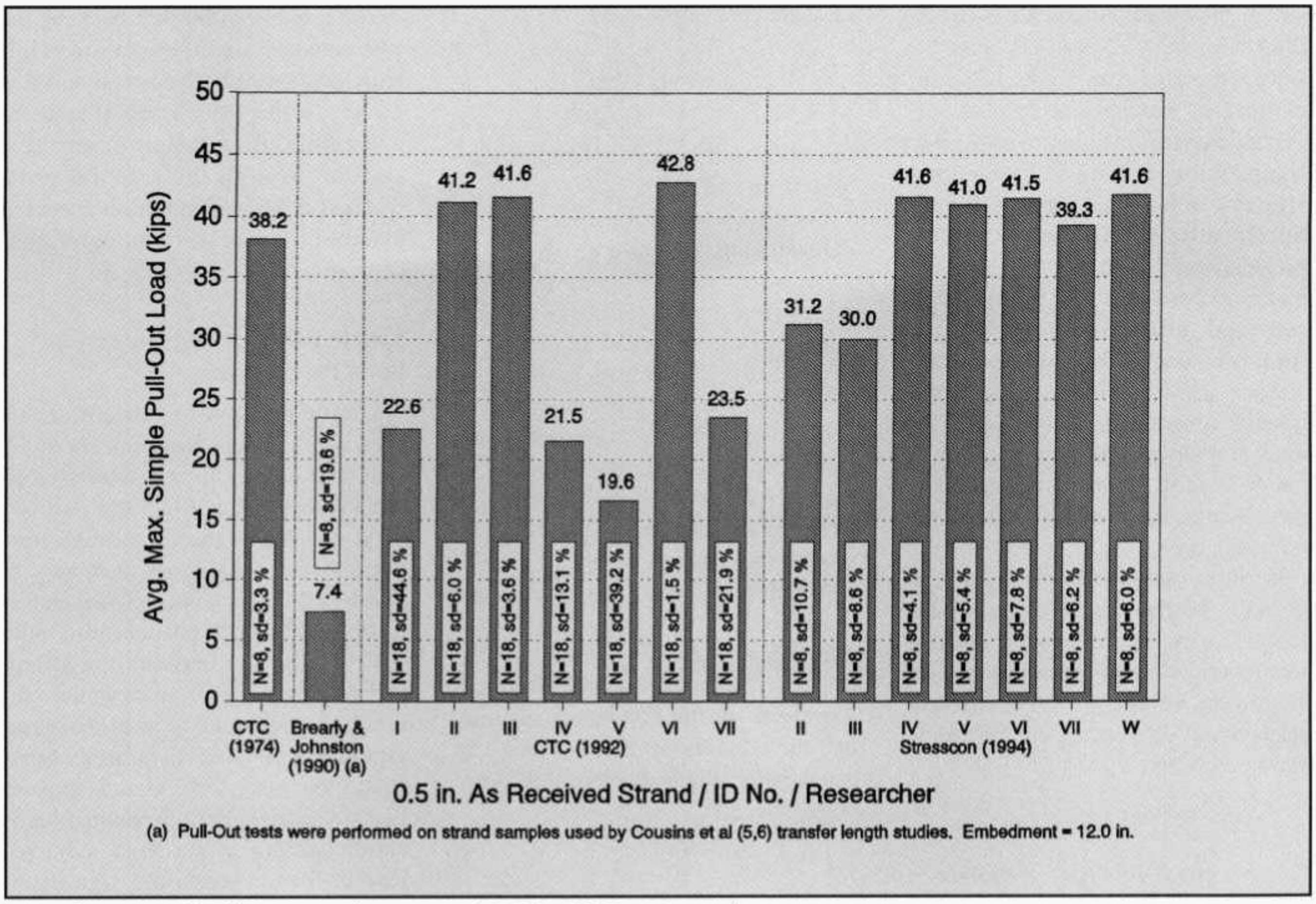


Fig. 3. Summary of pull-out strengths, uncoated, 0.5 in. (12.7 mm) strands.

normal forces that assist and strengthen the bond of pretensioned strands. This phenomenon is called "Hoyer's effect."

The simple pull-out of untensioned strands from concrete does not incorporate the wedging action from Hoyer's effect; in fact, the strand in a simple pull-out strand has a reducing diameter which should reduce frictional bond. Because Hoyer's effect is negated in the simple pull-out test, some individuals question its value as a measurement of pretensioned bond.

In 1974, Concrete Technology Corporation (CTC), under the supervision of Dr. Saad Moustafa, performed simple (no pretension) pull-out tests on bare, 0.5 in. (12.7 mm) strands with 18 in. (457 mm) embedment to determine their capacity for use as lifting loops. In these tests, strands were pulled from the concrete using an hydraulic jack driven by an electric powered hydraulic pump. Strand pull-out was accomplished in approximately 90 seconds, and less than 2 minutes. The average pull-out strength, or peak load, of these strands in pull-out was **38.2** kips (170 kN) with a standard deviation of about **3.3** percent. Recently, these 1974 pull-out tests have been used as a benchmark to compare the bond performance of strands being currently produced.[25]

In 1992, in response to a lifting loop failure at CTC and anchorage failures within the rock anchor industry, PCI sponsored simple pull-out tests that were performed at CTC, again under the supervision of Saad Moustafa. Specifically, the tests were conducted to assess variations in the pull-out bond strength of 1992 strands compared to the pull-out tests that were performed in 1974. The tests in 1992 established that some variations in pull-out performance existed between different strand manufacturers. Strand from three of the manufacturers had pull-out strengths that exceeded 1974 levels whereas the remaining strand from the other four manufacturers had pull-out strengths less than the 1974 values.[25]

Fig. **3** summarizes the results from these pull-out tests. Tests from CTC, labeled "CTC (1992)," are split into seven sets of data, I through VII, with each bar representing one strand manufacturer. Additionally, the results from the 1974 pull-out tests are shown in Fig. **3.**

In 1994, Donald R. Logan, chairman of Stresscon Corp., Colorado Springs, Colorado, conducted pull-out tests on an additional series of strands to assess variations in bond that could be caused by differences in common wire drawing lubricants. Pull-out tests were performed on seven series of strands, labeled II through VII and W in the "Stresscon (1994)" tests (see Fig. 3). In these tests, strands labeled II and III were manufactured using calcium stearate lubricants and strands labeled IV, V, VI and VII were manufactured using sodium stearate lubricants. Strand in test series "W" was weathered. From these tests, Logan suggested that strands made with sodium stearate lubricants out-performed calcium stearate lubricants for bond." However, significant evidence exists that suggests that strands made with calcium stearate lubricants can also achieve satisfactory bond.

Pull-out tests conducted by Brearly and Johnston[7,8] were performed on strand samples taken from the transfer length studies performed by Cousins et al.[5,6] However, these pull-out tests are not directly comparable to the pull-out tests performed by Moustafa and also by Logan. The Brearly and Johnston pull-out tests were performed on small, single strand pull-out specimens with only 12 in. (305 mm) of embedment, whereas the tests performed by Moustafa in 1974 and 1992 and by Logan in 1994 were performed on strand samples embedded in large concrete blocks with a total embedment length of 18 in. (457 mm).

The simple pull-out tests performed at CTC and Stresscon used similar testing procedures to one another. Significantly, each individual pull-out test was completed in 2 minutes or less. On the other hand, Brearly and Johnston applied pull-out loads much more slowly. Strand was pulled-out incrementally, and each new load increment was delayed until the strand had stopped slipping from the previous load increment. As evidenced most strongly by the tests reported in this article, the rate of pull-out appears to render a significant effect on the peak pull-out load. Slower pull-out rates apparently result in smaller pull-out forces and conversely, quicker pull-out rates apparently result in larger pull-out forces.

Tensioned Pull-Out Tests

Tensioned pull-out tests were envisioned as a pull-out test where the wedging action from Hoyer's effect would actively participate in resisting the pull-out of strand. In these tests, concrete was cast surrounding a strand that is initially pretensioned. Strand "pull-out" is achieved by relieving strand tension on one side of the specimen, and the bond force is calculated from the measured differences in strand tension on opposite sides of the specimen. By relieving tension on one side of the specimen, the strand diameter increases with Poisson's effect and the wedging action associated with Hoyer's effect is created in the test.

The tensioned pull-out test has been performed in different ways in the past, while creating the same effect. Cousins, Badeaux and Moustafa[29] performed tensioned pull-out tests in which the hardened concrete specimen was pushed down the length of an embedded pretensioned strand by means of an hydraulic actuator. As a result, strand tension was reduced on the leading side of the specimen while strand tension increased on the trailing side. The tensioned pull-out force reported for 0.5 in. (12.7 mm) diameter uncoated strand averaged 7.8 kips (34.7 kN) over an embedment length of 12 in. (305 mm).

Similarly, Abrishami and Mitchell[30] performed tensioned pull-out tests in which tension on one side of the hardened concrete is reduced via jacking bolts allowing for the participation of Hoyer's effect. They reported an average tensioned pull-out strength on 0.5 in. (12.7 mm) strands of 21.5 kips (95.6 kN) over an embedment length of 12 in. (305 mm).

EXPERIMENTAL PROGRAM

The authors' testing program was implemented to achieve the following research objective:

> Investigate three separate tests to assess the bond of prestressing strands to concrete, and determine which of these tests possesses the best potential for accurately measuring the bond performance of seven-wire steel prestressing strands.

Three types of test specimens were constructed and investigated: (1) transfer length specimens, (2) simple pull-out test blocks, and (3) tensioned pull-out specimens. Simple pull-out strengths, tensioned pull-out strengths and measured strand end slips are compared to the measured transfer lengths of companion specimens to determine which of the possible standardized tests provides the strongest correlation to pretensioned bond.

All of the test specimens were fabricated and the tests performed at the Fears Structural Engineering Laboratory (FSEL) on the campus at the University of Oklahoma (OU). For brevity in the following discussions, the testing program described in this paper is referred as the "OU tests."

Research Variables

The primary research variable was the strand surface condition. Altogether, tests were performed on four different surface conditions and on strand from three different manufacturers. Specimens and results are reported according to the surface conditions that were tested: as-received **(A)**, cleaned (C), silane treated **(S)**, and weathered **(W)**. Specimens containing strands from the three manufacturers are designated and reported as Manufacturer A, B or C. Table 2 tabulates the research variables, the types of tests performed and the number of tests performed for each surface condition. All tests were performed on 0.5 in. (12.7 mm), Grade 270 low-relaxation strands.

Table 2. Summary of testing program and research variables.

Strand manufacturer	Surface condition*	Number of tests performed		
		Transfer length (number of ends)	Simple pull-out	Tensioned pull-out
A	A	6	12	2
B	A	6	12	2
C	A	6	12	2
	C	6	12	2
	S	4	12	2
	W	6	12	2
Totals		34	72	12

* Key for strand surface conditions:
A = as-received
C = cleaned
S = silane treated, after cleaning
W = weathered, after cleaning

Table 3. Maximum pull-out bond strengths of preliminary test strands.

Strand surface condition	Maximum pull-out bond strength (kips)		Average pull-out bond strength (kips)
	Strand No. 1	Strand No. 2	
As-received	20.0	23.8	21.9
Cleaned	26.0	25.5	25.8
Weathered	32.6	31.8	32.2
Acid cleaned, silane treated	21.3	28.6	24.4
Acetone cleaned, silane treated	25.9	33.2	29.6
WD-40	6.4	8.2	7.3

: 1 kip = 4.448 kN.

Preliminary Pull-Out Tests to Evaluate Strand Surface Treatments

Prior to beginning the testing, prototype pull-out tests were performed to evaluate various types of strand surface treatments. One simple pull-out block was cast matching the pull-out blocks used in the experimental phase of the research. Twelve strands with six different surface conditions were tested and evaluated. The surface conditions and results from the pull-out tests are listed in Table 3. From these preliminary tests, it was determined that the "as-received (A)," cleaned (C), and weathered (W) surface treatments were suitable for testing.

The silane treated (S) (after cleaning with acid) surface condition was selected as the fourth surface treatment, intended to emulate a slightly lubricated or slightly poor bond surface condition. Results from the preliminary tests indicated that the silane treated strand possessed the best opportunity to observe consistent bond characteristics with lower pull-out strengths when compared to strand in the cleaned (C) or weathered (W) surface conditions.

The silane used for these tests was an alcohol based solution commonly used as a penetrating sealer for concrete. It has low viscosity, but possesses light lubricating characteristics due to its silicon based chemical characteristics. Silane was selected as the lubricant for these tests primarily because of its affinity to uniformly adhere to metallic surfaces due to its molecular attraction to free metals, and ultimately producing a consistent coating of lubricant along the entire length of the strand. The WD-40 treatment proved to be very slick as indicated by the low pull-out strengths and was believed to be unsuitable for these tests.

Strand Surface Conditions

Strand was obtained from three manufacturers (A, B, and C). Samples from each of these manufacturers were tested in the as-received (A) condition. These strands were placed in the desiccating chamber pictured in Fig. **4.** A dehumidifier operated continuously within the chamber constructed of lumber and plastic to prevent weathering of the strand during storage. Relative humidity was maintained at approximately 30 percent. Photographs of the strands in the "as-received (A)" condition are shown in Fig. **5**.

Strand from Manufacturer C was also tested in the cleaned (C), silane treated (S), and weathered (W) surface conditions. The cleaned surface condition was prepared by washing the strand with muriatic acid, rinsing with tap water, and then drying with paper towels. A slight discoloration (yellow haze) was observed on the strand surfaces immediately after the strand was dried. During drying, strand was held vertically to prevent water from collecting in the interstices of the strands. The silane treated (S), or lubricated, strand surface condition was achieved by first cleaning the strand with muriatic acid, rinsing and drying as described above, and then evenly spraying the strand with silane.

Weathered (W) strand samples were uniformly rusted by first clean-

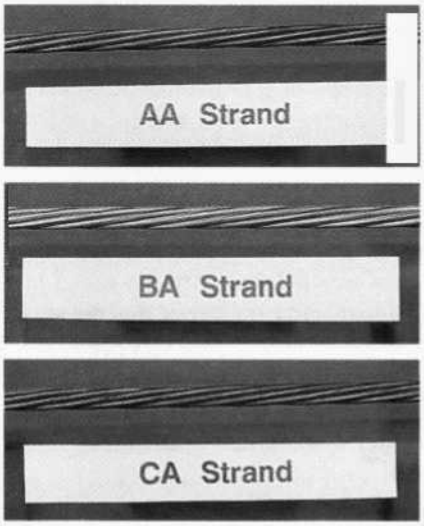


Fig. 5. Photographs of "as-received" strand.

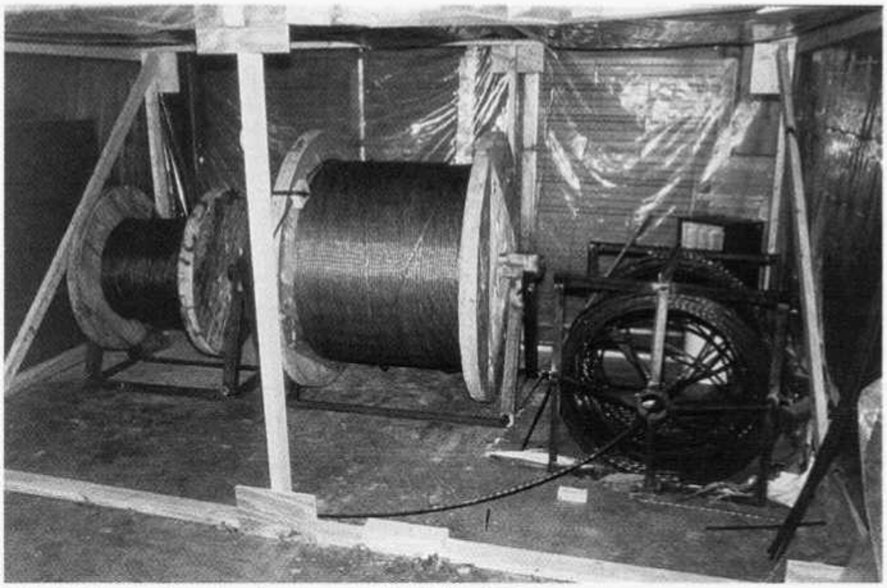


Fig. 4. Storage chamber for strand with dehumidifier.

ing the strand as described above, then placing the strand in an environmental chamber for 3 days. Temperature was maintained at about 73.4°F (23°C) and relative humidity was kept at approximately 75 percent. Additionally, the strands were misted with water three times each day. While weathering, the strand was placed in a frame constructed of lumber that could be turned periodically to ensure uniform weathering. The end result was strands that were covered with a surface coating of rust that was relatively uniform over the surface of the strands. Photographs of the strands in the cleaned (C), silane-treated (S) and weathered (W) surface conditions are pictured in Fig. 6.

As a benchmark, the strand samples are compared to the standards suggested by Sason.[31] Sason provides photographs in ascending degrees of weathering to help buyers, inspectors and engineers understand the structural implications of weathering on strand. Strands that were tested in the as-received (A) surface condition were all rated as "bright" strand and would most closely resemble strand condition "1," representing a "new strand with no rust [but with] a bright surface."

Similarly, strands that were cleaned (C) and silane treated (S) are most closely represented by surface condition "1," although the yellow surface haze suggests a small degree of shallow surface rusting. However, in no manner did the weathering on cleaned or silane treated strand approach the degree of weathering represented by strand surface "2." The weathered (W) strand for this testing program fits neatly between strand surface "3" and strand surface "4." More detailed photographs depicting the pattern of weathering are available in the final research report.[32]

Casting and Testing

One complete set of test specimens was cast for testing each strand surface condition, as outlined in Table 2. For each casting (and each strand surface condition), three transfer length beams, twelve simple pull-out tests and two tensioned pull-out tests were cast and tested. Additionally, end slips were measured on the transfer length beam specimens. Generally, the transfer length tests, end slip tests and tensioned pull-out tests were performed immediately during and after release of the pretensioned strands, approximately 48 hours after casting. The simple pull-out tests were generally performed on the third day after casting because of the time required to perform the tests.

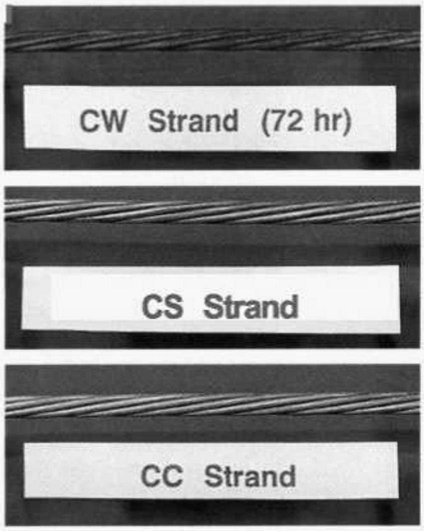


Fig. 6. Photographs of strand with varying surface conditions.

This sequence of casting and testing was adopted to ensure that variations in concrete batching would not affect the correlation between measured transfer lengths and the possible standardized tests. Strand surfaces were prepared, at most, 48 hours before casting to reduce the possibility that the surface condition would be altered with time (i.e., additional rusting or weathering).

Fabrication of Transfer length Beam Specimens

For each strand manufacturer and/or surface condition, three transfer length beams were cast and tested. These specimens were used to measure transfer lengths and their corresponding end slips. Each of the beams was constructed 17 ft (5.2 m) in length, except that the beams containing silane treated strands were made 24 ft (7.3 m) long to accommodate the longer transfer lengths; only two beams were cast with silane treated strands because of their longer length.

The cross section details are illustrated in Fig. 7. The cross section dimensions were 6 x 12 in. (152 x 305 mm) as shown. Each beam contained two 0.5 in. (12.7 mm) strands for tensile reinforcement and two #6 reinforcing bars in the compression zone. Closed loop stirrups were made with a smooth rod, 0.25 in. (6.4 mm) in diameter and were generally spaced on 6 in. (152 mm) centers, with the exception that in the interior 7 ft (2.1 m) of each beam, stirrups were spaced at 9 in. (229 mm) centers. Top compression steel was provided to ensure large strand strains at the flexural ultimate for beam tests that were reported by Paulsgrove and Russell.[33]

The transfer length specimens were fabricated using the following generalized procedure:

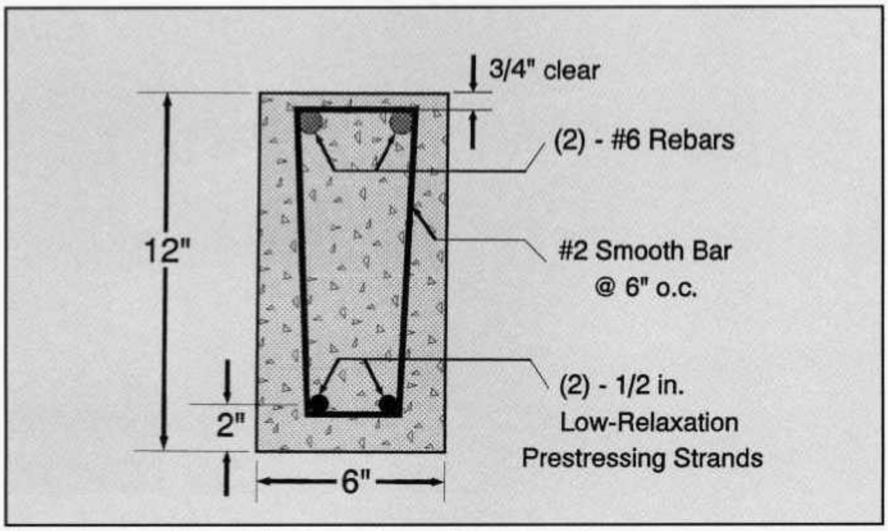


Fig. 7. Cross section details of transfer length beam specimens.

1. Prepare surfaces using methods described above.

2. Tension the strands to 75 percent of f_{pu}.

3. Verify strand tension with elongation measurements.

4. Place the mild steel reinforcement on the strands, including compression steel and the stirrups.

5. Set the forms.

6. Place the concrete, using internal vibrators to ensure consolidation.

7. Cure the concrete for 2 days by leaving the forms in place and covering the specimens with plastic.

Each of the transfer length specimens were labeled with a three-character identification code. The first character represents the strand manufacturer (A, B or C). The second character identifies the strand surface condition (A, C, S or W). The third character represents the individual specimen's location in the prestressing bed (1, 2 or 3). The location to the north (jacking) end is "1," location "2" is the middle beam and "3" denotes the south-most beam in each series. Three completed transfer length beam specimens are pictured in Fig. 8 with the view looking north.

Fabrication of Simple Pull-Out Specimens

For each casting (and each strand surface condition), one pull-out block was constructed. Each pull-out block measured 2 x 3 x 4 ft (0.61 x 0.91 x 1.22 m) and contained twelve strands for simple pull-out tests. Strands were patterned in a 4 x 3 grid and spaced 9 in. (229 mm) apart with an embedment length of 18 in. (457 mm). A schematic detail of the pull-out block design is shown in Fig. 9. In Fig. 10, Dallas R. Rose, 1993 Daniel P. Jenny Research Fellow, is shown at right casting concrete into the form for the simple pull-out block.

Of the twelve strands, six strands were treated to match the surface condition of the strands contained in the companion transfer length specimens. The remaining six strands were composed of three pairs of the remaining surface conditions (A, C, S, or W). For example, if the surface condition of the transfer length specimens was cleaned (C), then the pull-out block would contain six strands with cleaned (C) surface condition, two strands in the "as-received (A)" condition, two strands with silane (S) treatment, and two strands in the weathered (W) condition.

Each strand in the simple pull-out tests was labeled with a four-character identification number. The first two characters identify the strand manufacturer and strand surface condition in the companion transfer length specimens (AA, BA, CA, CC, CS, or CW). The third character identifies the individual strand surface condition (A, C, S, or W) and the last character identifies the test number for a given surface condition (1, 2, 3, 4, 5, or 6).

The simple pull-out tests were designed to replicate the pull-out tests that were performed by Moustafa at CTC and Logan at Stresscon. Towards that goal, the geometry of the pull-out block and the testing procedures were selected to imitate the earlier pull-out tests, i.e., the length of bond (embedment) was maintained at 18 in. (457 mm), the strands were cast vertically to prevent entrapped air from affecting the bond, the strands were cast in a relatively large pull-out block, and the concrete release strengths were targeted for approximately 4000 psi (28 MPa).

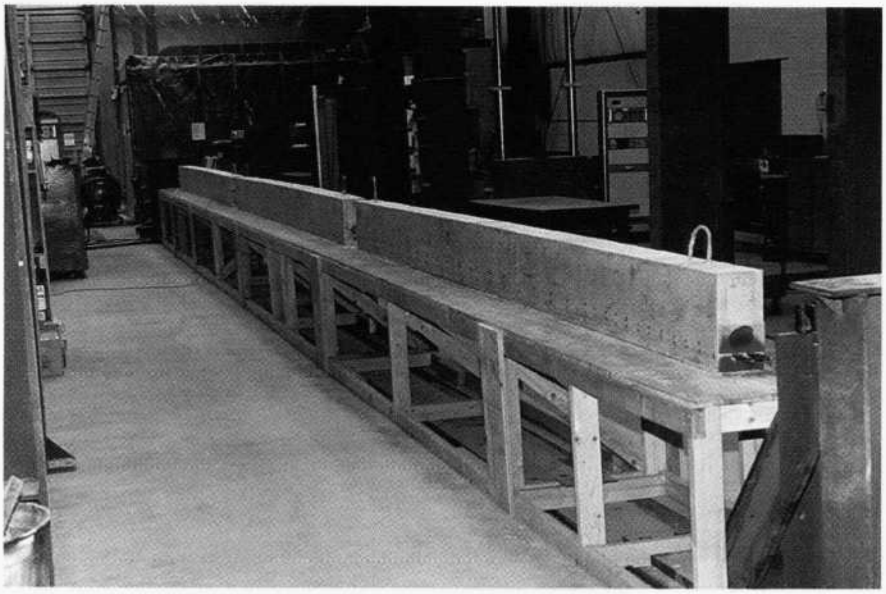


Fig. 8. Transfer length beams and prestressing bed at Fears Structural Laboratory, University of Oklahoma.

Fabrication of Tensioned Pull-Out Specimens

Two tensioned pull-out specimens were cast for each strand surface condition. Each specimen measured 5.5 in. (140 mm) square in cross section and 12 in. (305 mm) in length. The two specimens were cast in a tensioned pull-out prestressing bed and against a stiffened plate at midspan, as shown in the schematic in Fig. 11. The bond length of each tensioned pull-out specimen was 12 in. (305 mm). These tests were patterned after tests performed by Abrishami and Mitchell, who used 6 x 12 in. (152 x 305 mm) concrete cylinders as tensioned pull-out specimens.[30] However, in the OU tests, the testing frame allowed longer free strand lengths and more sensitive control of strand tension.

Each tensioned pull-out specimen was labeled with a three-character identification number. The first character represents the strand manufacturer (A, B, or C). The second character identifies the strand surface condition (A, C, S, or W). The third character designates the specimen number.

TEST PROCEDURES AND TEST RESULTS

This section describes the concrete mix design and strengths, the measurement of transfer lengths and strand end slips, simple pull-out tests, and tensioned pull-out tests.

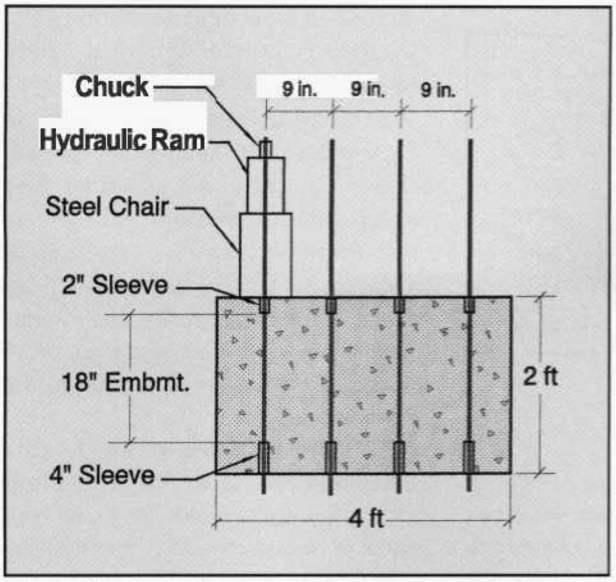


Fig. 9. Elevation schematic of simple pull-out blocks.

Fig. 10. Casting simple pull-out blocks.

Concrete Mix Design and Strengths

A total of six concrete castings were performed, one for each variable of strand manufacturer and strand surface condition (AA, BA, CA, CC, CS, and CW). In each casting, three transfer length beams, one large simple pull-out block and two tensioned pull-out specimens were cast. The concrete mix design was held constant throughout the testing program.

The concrete strength was specified to have a release strength of 4000 psi (28 MPa) and a 28-day strength of 6000 psi (41 MPa). Six sacks of Type I cement were used per cu yd of concrete with nominal maximum size aggregate (MSA) of 3/4 in. (19 mm). Approximately 75 ounces per cu yd (2900 ml/m^3) of Daracem 100 High Range Water Reducer (W.R. Grace) was used to achieve a suitable workability. Slumps for each concrete batch were measured and ranged consistently between 7 and 8 in. (178 to 203 mm). Concrete strengths are listed in Table 4.

Measurement of Transfer Lengths and Strand End Slips

Transfer lengths were measured on each end of each transfer length beam specimen. End slips were also measured on each strand at each end of each beam specimen. Testing generally observed the following procedures:

1. After removal of forms, the detachable, mechanical strain gauge (DEMEC) target points were attached at 3.937 in. (100 mm) spacings, beginning approximately 1 in. (25 mm)

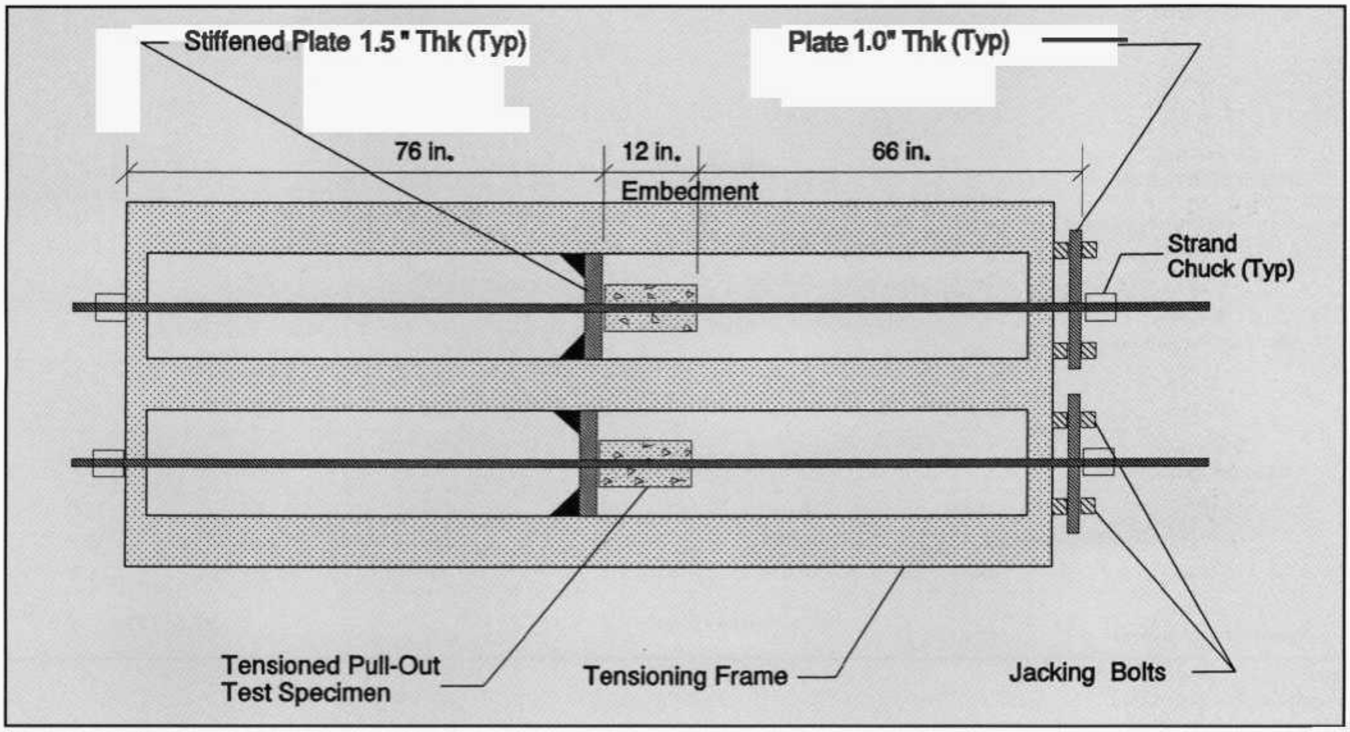


Fig. 11. Detail of tensioned pull-out testing frame.

Table 4. Concrete compressive strengths.

Strand manufacturer and surface condition	Compressive strength (psi)			
	Release	3 days	7 days	28 days
AA	4050*	4420	4790	5680
BA	4470*	4670	4690	6220
CA	3990†	—†	4480	4790
CC	4080*	4990	5130	6040
CS	4450*	4950	5610	6260
CW	4690*	5350	5680	6190

Note: 1 psi = 0.006895 MPa.

* Pretensioning released 2 days after casting.

† Pretensioning released 4 days after casting.

from the end of the beam. Targets were placed at the elevation matching the prestressing strands.

2. Initial strain measurements were made and recorded. Strain readings were taken by two individuals on both sides of the specimen. Therefore, the recorded strain reading is the average of four independent measurements. Complete transfer length data are found in the final report.[32]

3. Metal clamps were placed on each strand and initial end slip readings were taken and recorded. The clamps used to measure end slips are pictured in Fig. 12.

4. Strands were detensioned by flame cutting. Generally, the strands were cut at the north end of each set of beams. Locations for flame cutting are noted in Table 5.

5. Final strain measurements were taken and recorded. Strain readings were taken by two individuals on both sides of the specimen. Concrete surface strains are given by the difference between initial and final DEMEC read-

Table 5. Measured transfer lengths and end slips.

Beam	End slip (in.)				Transfer length (in.)	
	North		South			
	West	East	West	East	North	South
AA-1	0.055	0.066	0.064	0.056	12.2	19.1
AA-2	0.072	0.067	0.072	0.075	17.3	19.9
AA-3	0.074	0.061	§	§	18.2	28.0*
AA average (standard deviation)	**0.066 (0.007)**				**19.1 (5.1)**	
BA-1	0.061	0.052	0.074	0.071	14.3	15.1
BA-2	0.039	0.055	0.051	0.058	10.5	15.9
BA-3	0.054	0.067	§	§	12.1	26.4*
BA average (standard deviation)	**0.058 (0.010)**				**15.7 (5.6)**	
CA-1	§	§	0.054	0.070	18.3*	15.7
CA-2	0.046	0.049	0.051	0.060	11.5	15.8
CA-3	0.056	0.059	0.051	0.053	9.9	15.3
CA average (standard deviation)	**0.055 (0.007)**				**14.4 (3.1)**	
CC-1	§	§	0.057	0.052	28.1*	13.6
CC-2	0.053	0.059	0.041	0.043	13.6	13.2
CC-3	0.038	0.033	0.041	0.053	8.4	15.2
CC average (standard deviation)	**0.047 (0.009)**				**15.4 (6.7)**	
CS-1†	0.252	0.488	§	§	33.2	88.1*
CS-2†	§	§	0.124	0.197	122.4*	19.4
CS average (standard deviation)	**0.265 (0.157)**				**65.8 (48.0)**	
CW-1	0.048	0.046	0.039	0.044	11.7	12.0
CW-2	0.047	0.045	0.043	0.046	10.1	13.8
CW-3	0.042	0.038	§	§	9.3	18.2*
CW average (standard deviation)	**0.044 (0.003)**				**12.5 (3.2)**	

Note: 1 in. = 25.4 mm.

* End adjacent to flame cutting.

† Pretensioning force not fully transferred into the concrete.

§ Not available due to damage of clamping device during detensioning.

Fig. 12. Metal clamps attached to strands used to measure strand end slip.

Fig. 13. DEMEC strain gauge and targets.

ings and converted to normal strain using the instrument calibration supplied by the instrument manufacturer.

6. Final end slip measurements were made and recorded. The total strand end slip is determined by the difference between initial and final measurements, less the calculated elastic shortening of the "free" strand.

The DEMEC gauge and target points are shown in the photograph of Fig. 13. The DEMEC targets are manufactured from stainless steel specifically for use with the DEMEC gauge to measure concrete surface strains. The gauge itself and the target points were manufactured by the Hayes Manufacturing Co. in the United Kingdom. The gauge length of the instrument was 7.874 in. (200 mm) with an accuracy of about ±25 microstrains. The accuracy of the measuring device is established by assessing the variance in the collected strain data.

Concrete surface strains were recorded and plotted for each transfer length beam specimen. A typical plot of concrete surface strains is illustrated in Fig. 14. The transfer lengths were determined using the 95 Percent Average Maximum Strain (95 percent AMS) method described in detail by Russell and Burns.[15,16] Using a plot of concrete surface strains for each specimen, transfer lengths were determined for each end of each specimen.

Results from the transfer length tests are listed in Table 5. The data indicate that all of the as-received (A) strands, performed satisfactorily for pretensioned transfer with all of the measured transfer lengths, on average, less than the ACI and AASHTO design recommendations. Strand from Manufacturer A required, on average, 19.1 in. (485 mm) or $38.2d_b$ to transfer its forces into the concrete whereas strand from Manufacturers B and C required transfer lengths of 15.7 and 14.4 in. (399 and 366 mm), or $31.4d_b$ and $28.8d_b$, respectively.

The data also demonstrate that the transfer lengths measured immediately adjacent to the flame cut location are notably longer than the transfer lengths measured at other locations. On average, the transfer lengths adjacent to the location of detensioning were approximately 60 percent longer than all others measured.

For strands that were acid cleaned (CC), the average transfer length was measured as 15.4 in. (391 mm) or 30.3 d_b, slightly longer than as-received strands from Manufacturers B and C (BA and CA). The shortest transfer lengths were measured on weathered (CW) strands with an average transfer length of only 12.5 in. (318 mm) or $25d_b$. Thus, the weathered strands demonstrated superior bond character-

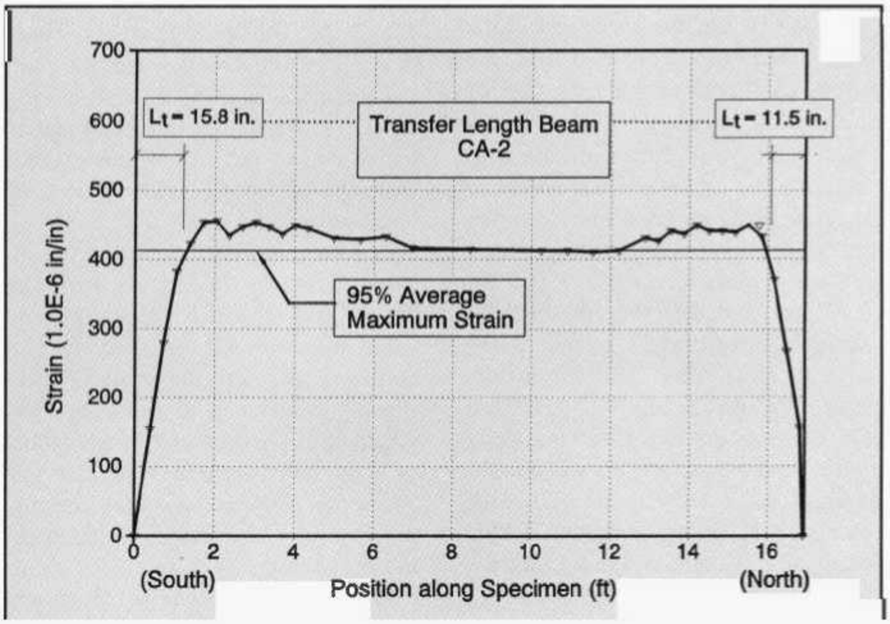


Fig. 14. Plot of typical concrete surface strains.

istics when compared to the other surface treatments.

The silane treated (CS) strands demonstrated extremely poor pretensioned bond characteristics. The transfer length values are listed in the table with an average of 65.8 in. (1671 mm) or $131.6d_b$. More importantly, the transfer length data demonstrate that full precompression strains were not achieved for these specimens, indicating that the silane treated (CS) strands were unable to completely transfer their prestressing forces to the concrete because of poor bond. Typically, concrete strains were measured at approximately 400 microstrains for the fully prestressed transfer length beams, as shown in Fig. 14. However, for the beams made with silane treated strands, the maximum concrete strain measured only 175 microstrains.

Table 5 also presents the measured strand end slips. Strand end slips are listed for each end of each strand. These data were measured using a metal clamp tightened onto each strand and located about 1.0 in. (25 mm) from the end of the transfer length beam. A Plexiglas plate was glued to the end of each specimen, as pictured in Fig. 12. The distance from the metal clamp to the Plexiglas was measured with an inside micrometer before and after release of the pretensioning force. The difference in the measurements represents the gross end slip value. The elastic shortening of the strand between the face of the concrete and the metal clamp was subtracted from the gross end slip to provide the net, or true, end slip readings.

Generally, the data indicate that longer strand end slips correspond to longer transfer lengths. For example, end slip measurements on silane treated strands averaged 0.265 in. (6.73 mm) whereas the end slips on weathered strands averaged only 0.044 in. (1.12 mm). These end slip results generally indicate that silane treated (CS) strands exhibited considerably worse bond characteristics when compared to the bond characteristics of other strand surface conditions. This observation is verified by the comparison of average transfer lengths.

End slip measurements are not available on member ends that were adjacent to the location of flame cutting. At release, the hose clamps that were attached to the strands were damaged at the ends where flame cutting was performed, and end slip readings were not possible.

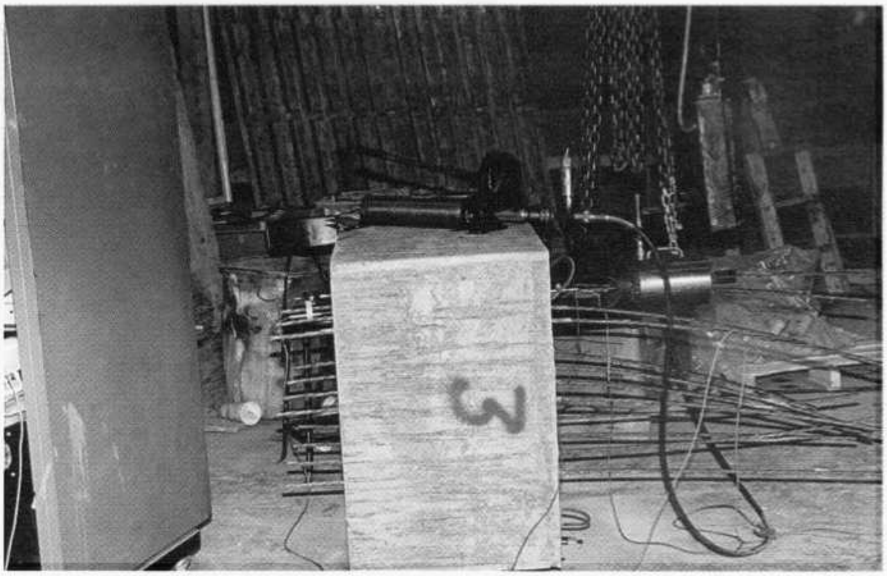


Fig. 15. Pull-out block being readied for testing.

Simple Pull-Out Tests

The simple pull-out tests were performed 3 days after casting. The testing procedure for each strand is outlined in the following steps:

1. After removal of the forms, the pull-out block was turned on its side so that both the "free end" of the strand and the "jacking end" of the strand were easily accessed for instrumentation (shown in Figs. 15, 16 and 17). [Note: The "jacking end" refers to that end of the strand where the pull-out force was applied through the hydraulic actuator. The "free end" refers to the end of the strand that extends from the pull-out block opposite the "jacking end."]

2. Linear potentiometers were attached to the strand on both the "free" end and the "jacking" end using aluminum clamps specially machined to attach to the strands. Additionally, a mechanical dial gauge was attached to the free end of the strand as a backup to electronic readings. These instruments measured the displacement of the strand with respect to the concrete.

3. Load was applied incrementally to the strand, stopping at regular intervals to record data. Load and strand slip data were recorded at regular increments of "free end" slip.

4. Strands were pulled from the block until the free end strand slip exceeded 1.0 in. (25 mm). Using this method, each pull-out test required approximately 15 to 20 minutes to complete.

Pull-out load was applied to the "jacking end" of each strand through a hydraulic actuator shown in Fig. 16 and powered by a manual hydraulic pump. The strands were pulled in a continuous manner until the free end slip exceeded 1 in. (25.4 mm), and load was recorded at regular intervals of free end slip, i.e., 0.001, 0.005, 0.010, 0.025, 0.050, 0.075, 0.10, 0.25, 0.50, 0.75, and 1.00 in. (0.03, 0.13, 0.25, 0.64, 1.27, 1.91, 2.54, 6.35, 12.70, 19.05, and 25.40 mm). Loads were measured by a pressure transducer that monitored hydraulic pressure and recorded loads electronically. Strand slip data were recorded electronically by linear potentiometers and manually by observations of the dial gauge. Progress of the tests and plots of the loads and strand slips were available in "real time" from the data acquisition system used at FSEL.

Results from the simple pull-out tests are tabulated in Table 6. For each simple pull-out test, Table 6 lists the simple pull-out load that corresponded to a free end slip of 0.005 in. (0.13 mm). The maximum pull-out force achieved during each test was also recorded.

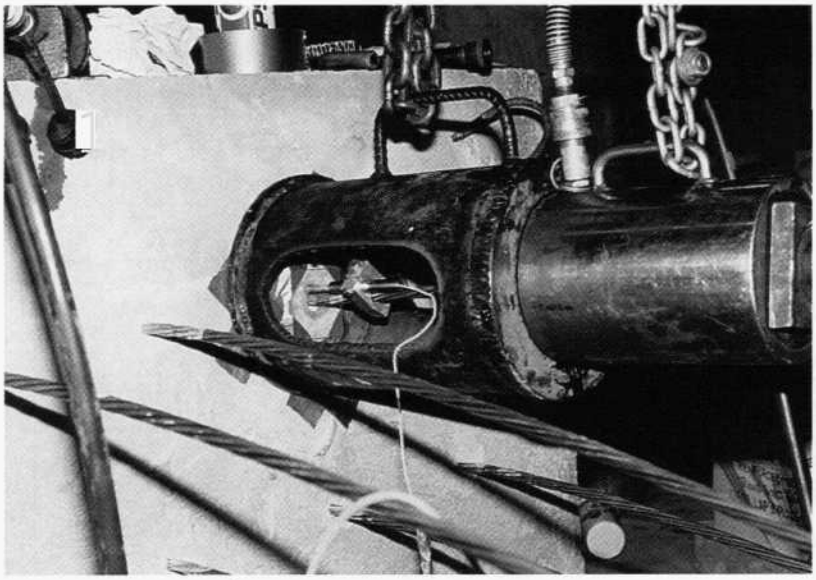


Fig. 16. Jacking end of simple pull-out specimen.

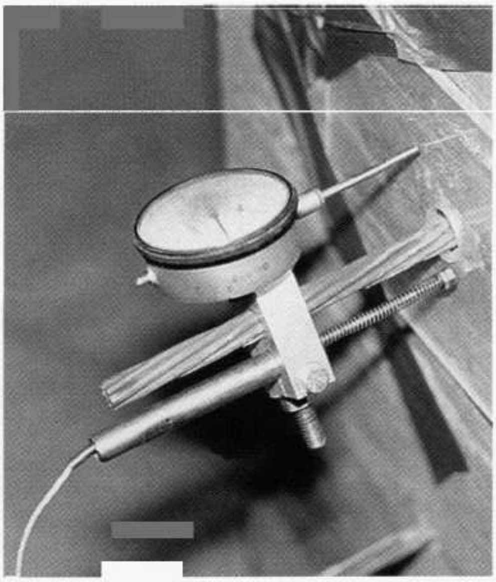


Fig. 17. Free end of simple pull-out specimen.

The pull-out loads vs. "free end" slip and "jacking end" slip are plotted in Fig. 18(a) through Fig. 18(f). Each plot represents the typical results for each strand condition. For example, Fig. 18(b) plots results from the simple pull-out test conducted on Specimen BA-A1, which represents a typical pull-out test for as-received **(A)** strand from Manufacturer **B.** For Specimen BA-A1, general bond slip [defined by a free end slip of 0.005 in. (0.13 mm)] occurred at a pull-out load of 19.7 kips (88 kN) and the maximum pull-out load was 27.8 kips **(124** kN).

End slips were measured on the jacking end immediately upon application of load corresponding to the elastic lengthening of the strand between the concrete surface to the point where the deflection instruments are attached to the strand. Conversely, free end slips remain at zero until general bond slip has ensued along the entire embedded length. Similar plots of load vs. strand slip for all the pull-out

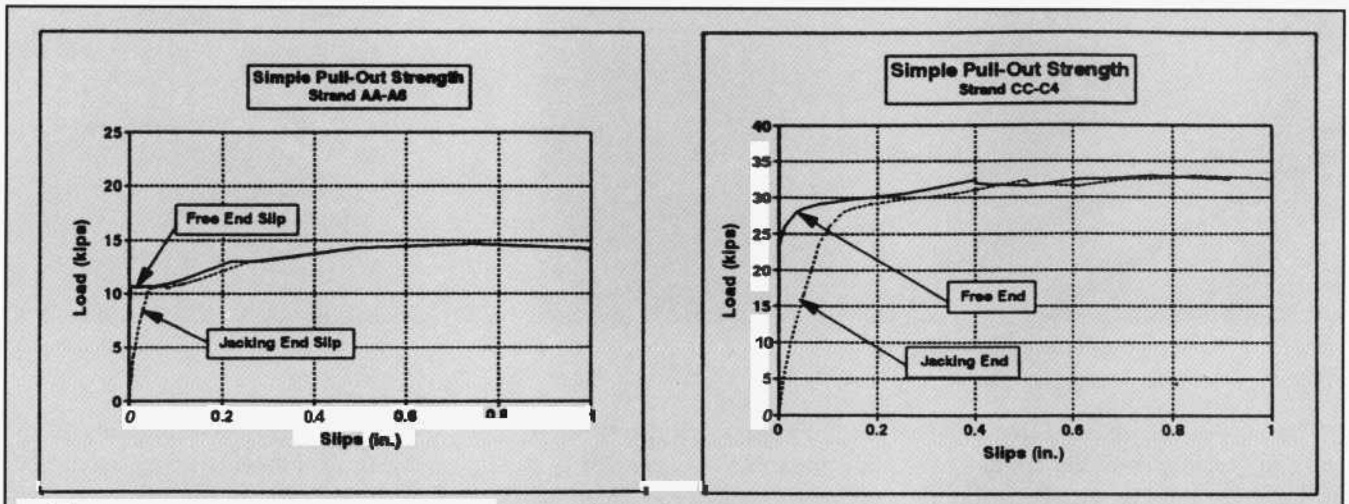
Table 6. Simple pull-out bond strengths.

Strand manufacturer and surface condition	Test number	Pull-out strength (kips)		Strand manufacturer and surface condition	Test number	Pull-out strength (kips)	
		at 0.005 in.*	at maximum			at 0.005 in.*	at maximum
AA	1	11.5	16.2	CC	1	23.0	31.9
	2	10.1	13.3		2	26.1	33.5
	3	7.3	14.7		3	26.2	36.9
	4	10.7	16.3		4	24.7	33.1
	5	12.1	16.5		5	18.2	27.8
	6	10.7	14.6		6	26.8	35.2
AA average (standard deviation)		**10.4 (1.7)**	**15.3 (1.3)**	**CC average (standard deviation)**		**24.2 (3.2)**	**33.1 (3.1)**
BA	1	19.7	27.8	CS	1	9.3	28.5
	2	19.0	25.8		2	19.4	30.8
	3	21.5	28.8		3	17.5	31.8
	4	21.9	28.0		4	18.2	35.6
	5	17.7	28.7		5	22.5	28.4
	6	18.7	25.2		6	17.9	29.0
BA average (standard deviation)		**19.8 (1.6)**	**27.4 (1.5)**	**CS average (standard deviation)**		**17.4 (4.4)**	**30.7 (2.8)**
CA	1	23.8	33.2	CW	1	31.2	37.6
	2	25.4	34.4		2	37.1	37.6
	3	25.6	31.2		3	35.9	37.5
	4	21.9	30.1		4	40.6	40.9
	5	23.5	31.0		5	37.0	37.7
	6	22.9	31.7		6	36.3	37.7
CA average (standard deviation)		**23.9 (1.4)**	**31.9 (1.6)**	**CW average (standard deviation)**		**36.4 (3.0)**	**38.2 (1.3)**

Note: 1 in. = 25.4 mm; 1 kip = 4.448 kN.
* Free end slip = *0.005* in.

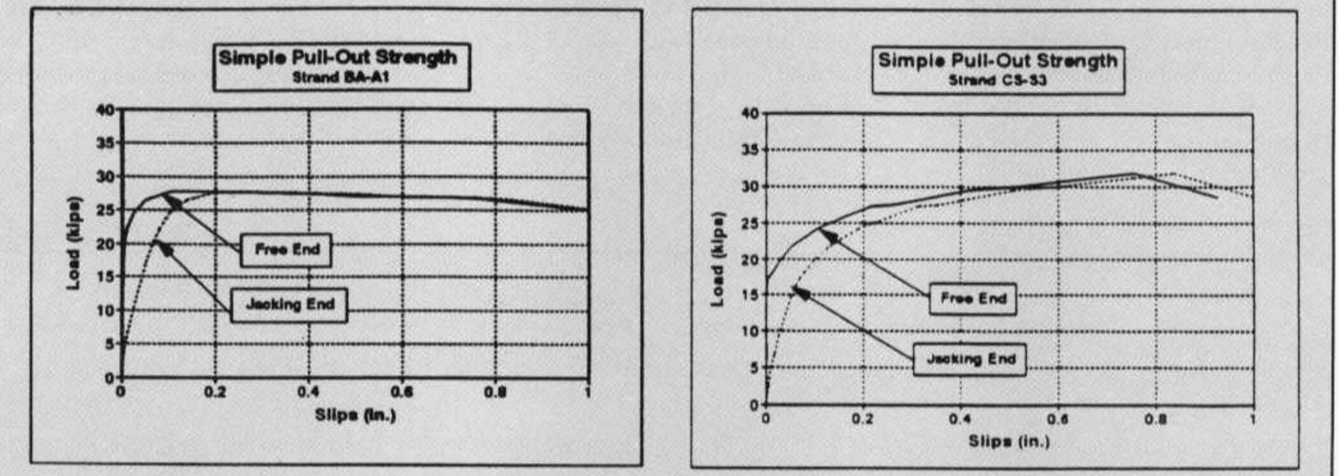
tests are available in the research report along with the recorded data.[32]

The plot in Fig. 19 shows the "average" pull-out load vs. the "average" free end slip for each of the six different surface conditions/strand manufacturers. Once again, the weathered (W) strands demonstrated the largest bond strength. However, silane treated ***(S)*** strands possessed remarkably strong pull-out resistance, after the initial free end slip had occurred. As-received strands from Manufacturer A (AA) achieved the lowest pull-out strengths, reaching **only** about 50 percent of the pull-out strength compared to as-received strands from Manufacturers B and C (BA and CA). This result



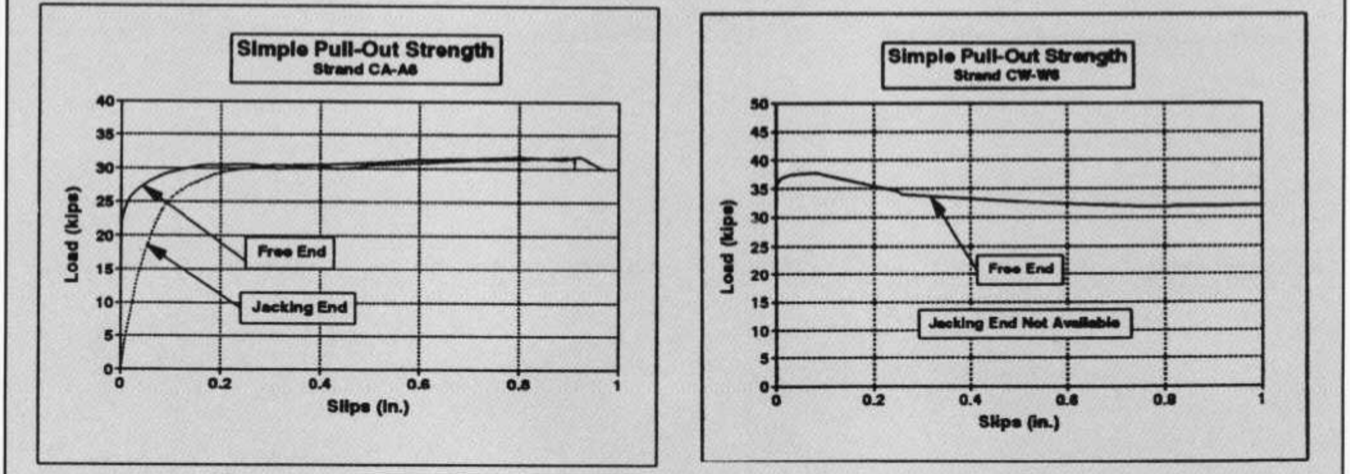
(a) Test AA–A6

(d) Test CC–C4



(b) Test BA–A1

(e) Test CS–S3



(c) Test CA–A6

(f) Test CW–W6

Fig. 18. Typical load vs. slips for simple pull-out tests.

demonstrates that some significant variations in pull-out strength can exist in the bond quality of "as-received (A)" strands.

Each strand surface condition achieved higher pull-out strengths after the initial slip at the free ends, and the pull-out force increased slightly with increasing slips. For the most part, the maximum pull-out load was reached before the maximum free end slip of 1.0 in. (25 mm) was achieved. The weathered (W) strand achieved its highest pull-out strength just after the free end of the strand slipped, and pull-out load declined with increasing free end slips.

The silane treated strand (CS) exhibited notable differences from the other strand surface treatments. For these strands, the initial free end slips occurred at significantly smaller pull-out loads than the other surface treatments. However, as shown in Fig. 19, the silane treated strands were able to achieve similar maximum pull-out capacities when compared to the other strand surface treatments.

Tensioned Pull-Out Tests

The tensioned pull-out strength of each strand was determined by gradually releasing tension on one side of the specimen through the jacking bolts. By relieving strand tension on one side of the specimen, Hoyer's effect contributed to the bond strength of the strand. The tensioned pull-out testing frame is pictured in Fig. 20.

Results from the tensioned pull-out tests are listed in Table 7. The tensioned pull-out strength of each strand was evaluated at a free end slip of

Table 7. Summary of tensioned pull-out bond loads.

Strand manufacturer and surface condition	Test number	Bond force at "free" end slip = 0.005 in. (kips)	Maximum pull-out bond force (kips)	"Free" end slip at maximum bond force (in.)
AA	1	5.8	12.2	0.283
	2	5.7	12.5	0.273
AA average (standard deviation)		**5.8 (0.1)**	**12.4 (0.2)**	—
BA	1	12.3	20.2	0.135
	2	17.2	22.2	0.101
BA average (standard deviation)		**14.8 (3.5)**	**21.2 (1.4)**	—
CA	1	*	*	*
	2	7.5	23.9	0.041
CA average (standard deviation)		**7.5**	**23.9**	—
CC	1	5.6	10.6	0.332
	2	6.6	10.2	0.329
CC average (standard deviation)		**6.1 (0.7)**	**10.4 (0.3)**	—
CS	1	3.0	12.2	0.197
	2	3.3	11.9	0.267
CS average (standard deviation)		**3.2 (0.2)**	**12.0 (0.3)**	—
CW	1	†	27.9	†
	2	†	27.6	†
CW average (standard deviation)		—	**27.8 (0.2)**	—

Note: 1 in. = 25.4 mm; 1 kip = 4.448 kN; 1 ksi = 6.895 MPa.

* Test No. 1 was omitted from the average because the initial prestress force was 13.9 kips.

† No free end slip was observed. 27.9 and 27.6 kips represent the full pretension force in each strand.

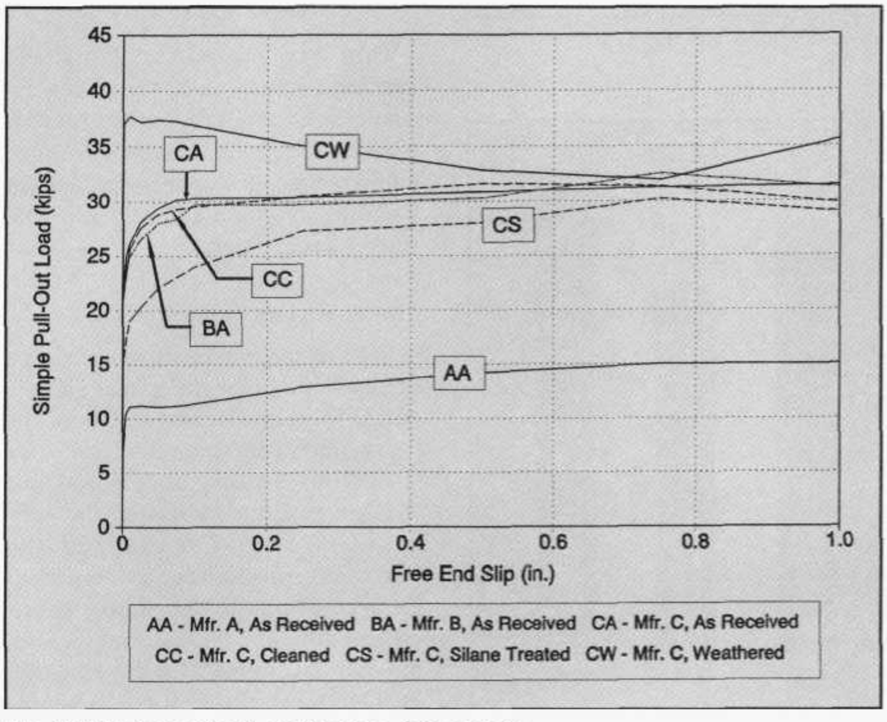


Fig. 19. Summary of pull-out loads vs. free end slip.

Fig. 20. Tensioned pull-out test frame.

Table 8. Comparison of average bond stresses.

Strand manufacturer and surface condition	Average bond stress (kips per in.)		
	Transfer bond stress*	Simple pull-out bond stress at maximum force†	Tensioned pull-out bond stress (maximum)§
AA	1.44	0.85	1.03
BA	1.75	1.52	1.77
CA	1.91	1.77	1.99
CC	1.79	1.84	0.87
CS	0.42	1.71	1.00
CW	2.20	2.12	2.32

Note: 1 in. = 25.4 mm; 1 ksi = 6.895 MPa.
* (180 ksi x 0.153 sq in.) ÷ transfer length
† Pull-out strength at maximum ÷ 18 in.
§ Bond force at maximum ÷ 12 in.

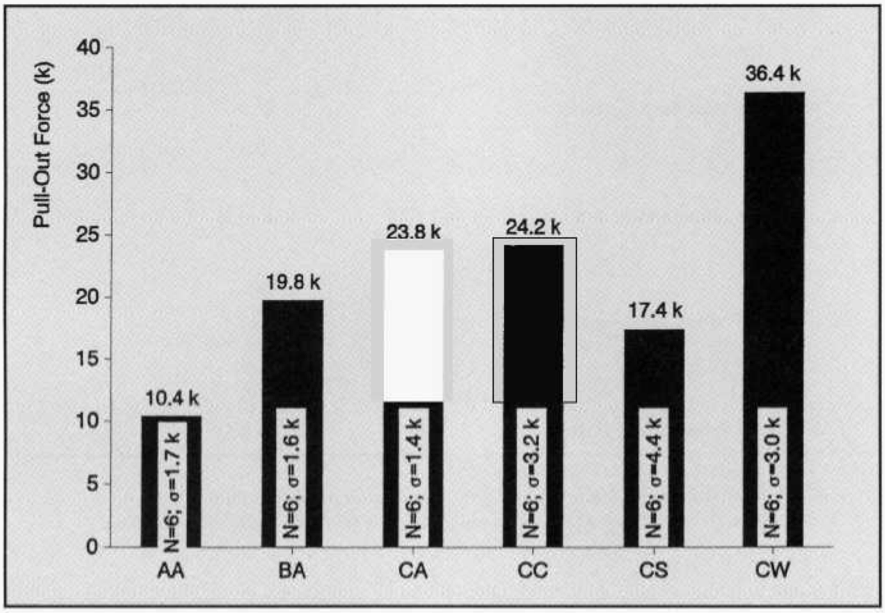


Fig. 21. Simple pull-out force at free end slip of 0.005 in. (0.127 mm).

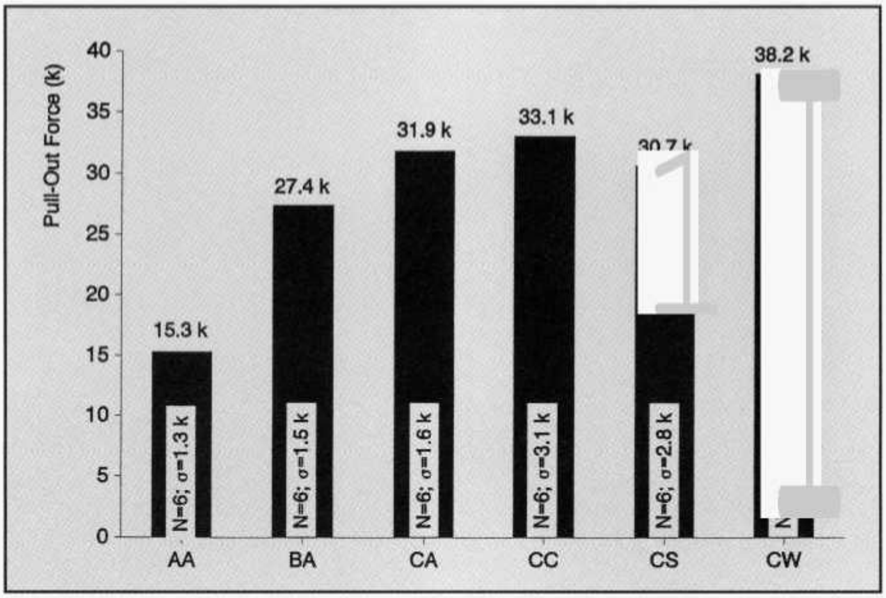


Fig. 22. Simple pull-out test, peak pull-out force.

0.005 in. (0.127 mm) and at peak bond force. Linear potentiometers were used to measure the strand slips on either side of the specimen. Load cells and electrical resistance strain gauges (ERSGs) were used to measure the tension on either side of the specimen.

In general, the bond strengths from the tensioned pull-out tests correspond to the trends noted in the transfer lengths and the simple pull-out tests. For example, the weathered (W) strands possessed the largest tensioned pull-out force of nearly 28 kips (125 kN) whereas the silane treated strands exhibited one of the poorest tensioned bond strengths of only 12 kips (53 kN).

However, some of the results tend to reverse trends from the transfer length tests or the simple pull-out tests. For example, the tensioned pull-out strength of the cleaned strands measured only 50 percent of the bond strength of the as-received strands from Manufacturers B and C (BA and CA), whereas the transfer lengths and the simple pull-out strengths from these three strand groups were all very similar. From these results and because the test is very difficult to perform, the tensioned pull-out test is not perceived as a feasible or practical standard test for bond performance.

DISCUSSION OF TEST RESULTS

This section discusses the strand surface conditions, simple pull-out strengths, simple pull-out strength vs. measured transfer length, tensioned pull-out strength vs. measured transfer length, and strand end slip vs. measured transfer length.

Strand Surface Conditions

Each of the bond performance tests demonstrated that the strand surface condition significantly affects the bond performance of seven-wire strands by increasing or decreasing the friction generated between the concrete and steel. For example, the weathered strands produced the shortest average transfer length, the smallest end slips, the highest average simple pull-out strengths, and the highest average tensioned pull-out strengths when compared to the other strand

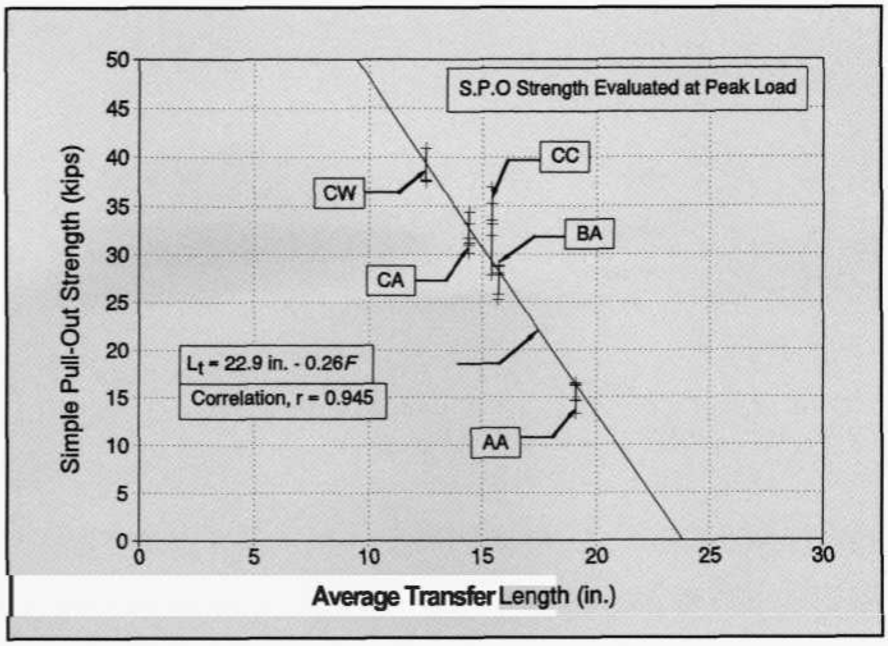


Fig. 23. Simple pull-out strengths vs. average transfer lengths.

surface conditions. Average bond stresses for each of the strand surface conditions and for each type of test performed are listed in Table 8.

Conversely, deliberate lubrication of the strand was found to adversely affect bond performance, particularly in the pretensioned transfer length specimens. In the transfer length specimens, the silane treated strands were unable to transfer their prestressing forces into the concrete, and the average maximum concrete surface strain measured on the silane treated transfer length specimens was less than 40 percent of that measured for all other surface conditions.

In Table 8, the average bond stress for each of the performance tests is listed for each strand surface condition. The data clearly indicate that the weathered strands exhibited higher bond capacities than the other strand surface conditions with bond stresses for weathered strands exceeding 2.12 kips per in. (371 N/mm) for all of the performance tests. The silane treated strands exhibited the lowest overall bond capacity with a transfer bond stress of only 0.42 kips per in. (74 N/mm), although the silane treated strand demonstrated considerably higher bond stress in the simple pull-out test.

Simple Pull-Out Strengths

The simple pull-out strengths of the different strand manufacturers and surface conditions are compared in Figs. 21 and 22, and represent the data given in Table 6. Fig. 21 illustrates the pull-out forces that correspond to a "free end" slip of 0.005 in. (0.13 mm). These data present the tendency of the strand to initiate general strand slip over the entire bonded length. The figure clearly indicates that the weathered (W) strands had the highest initial resistance to pull-out [36.4 kips (162 kN)] whereas the AA strands had the least initial resistance to strand pull-out [10.4 kips (46.3 kN)]. The silane treated (S) strands had a relatively low initial pull-out strength and general bond slip ensued at only 17.4 kips (77 kN).

Fig. 22 depicts the maximum pull-out force that was achieved during the pull-out tests. Again, the weathered strands produced the largest resistance to strand pull-out with an average of pull-out strength of 38.2 kips (170 kN), which represents only a small increase of pull-out force beyond the pull-out force measured at 0.005 in. (0.13 mm) of free end slip.

In contrast, the other strand surface treatments demonstrated the ability to increase the pull-out force after initial slips were measured. For Specimens AA, BA, CA and CC, the maximum pull-out load exceeded the initial pull-out load [at 0.005 in. (0.13 mm) of "free end" slip] by 34 to 47 percent.

The silane treated strands stand out in this comparison. These strands demonstrated relatively small resistance to the initial pull-out where only 17.4 kips (77 kN) was required to generate 0.005 in. (0.13 mm) of "free end" slip. However, with additional pull-out, the maximum pull-out force for the silane treated strands was 30.7 kips (137 kN), representing an increase of 76 percent. Furthermore, the maximum pull-out strength of the silane treated strands exceeded two of the three "as-received" strand samples. These data indicate that the silane treated strands generated little or no adhesion bond, yet the strands were able to generate significant amounts of friction or mechanical wedging as strand pull-out continued.

For each strand surface condition, the pull-out strengths were relatively consistent. Table 6 and Figs. 21 and 22 list the standard deviations for each group of strands. For each group of six strands, coefficients of variation were generally less than 10 percent, leading to the conclusion that the pull-out test procedures used in this test series provided reliable and repeatable results for pull-out capacity.

Simple Pull-Out Strength vs. Measured Transfer Lengths

With the data from silane treated strands omitted, the plot in Fig. 23 illustrates the trend that larger pull-out loads correspond to shorter transfer lengths. For each strand surface condition, the maximum pull-out strengths from each of the six pull-out tests are plotted against the average transfer length. The plot of 30 data points illustrates a trend where higher pull-out strengths correspond to shorter transfer lengths. From these data, the correlation between transfer length and pull-out strength is 0.945. Linear regression suggests the relationship shown in the figure:

$$L_t = 22.9 \text{ in.} - 0.26F \qquad (5)$$

where F represents the maximum strand pull-out force.

While these data provide a statistical correlation between the transfer length and pull-out strength, it is difficult to assign meaningful physical relationships to the data. For example, the lin-

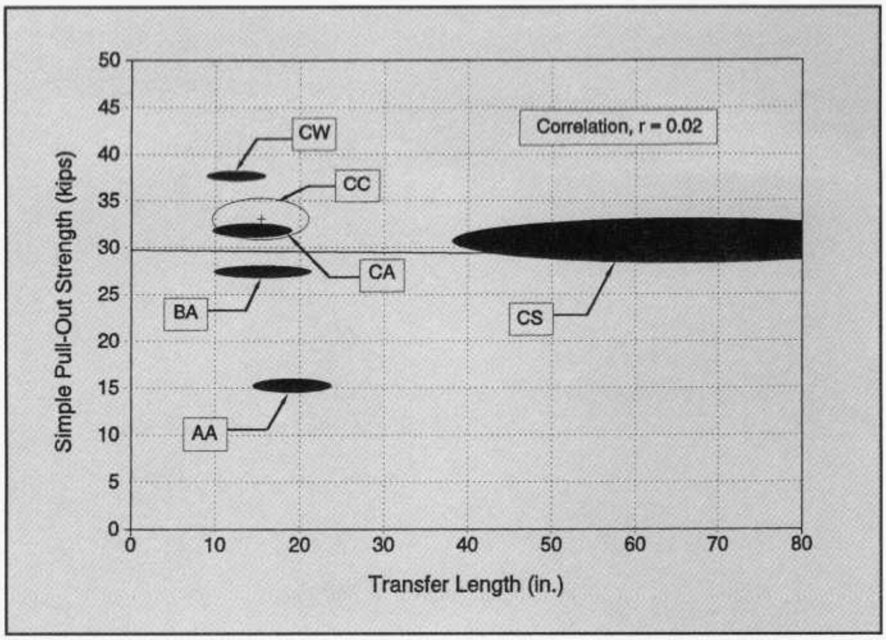


Fig. 24. Simple pull-out strengths vs. transfer lengths including data from silane treated strands.

merit in evaluating pretensioned bond, the use of these data require extrapolation that could lead to impractical application. For explanation, either the linear regression indicates that adequate transfer lengths can be obtained with zero pull-out strength, or a threshold value must be chosen from the data. Unfortunately, a suitable and sensible threshold value cannot be developed from these data.

Secondly, the trend between pull-out strength and transfer length only appears when the data from the silane treated strands are ignored. Strands treated with silane exhibited relatively high pull-out bond strength whereas these same surface treatments significantly reduced the strands' pretensioned bond capacity. If the bond performance of the silane treated strand had been evaluated by the simple pull-out test, the strand would have been accepted for pretensioned applications when, in fact, the silane treated strands were unable to transmit pretensioning forces into the concrete. Therefore, these data do not demonstrate any meaningful correlation between pretensioned bond and simple pull-out strength.

ear regression equation suggests that strands with zero pull-out strength would possess transfer lengths less than 25 in. (635 mm). However, engineering judgment contradicts this conclusion. Instead, one would expect that strands with zero pull-out strength would exhibit very little or no pretensioned bond capacity coupled with excessively long transfer lengths.

As an alternative method, this equation would determine a threshold, or minimum pull-out strength from the data. However, this approach is also problematic. If the threshold value is selected based on a minimum transfer length, then even a short transfer length requirement of 20 in. (508 mm) leads to a relatively small threshold value for pull-out strength, approximately 13 kips (58 kN).

An additional problem is illustrated when silane treated data are included, shown in Fig. 24. As presented, the inclusion of the silane treated data severely diminishes the correlation between the simple pull-out strengths and measured transfer lengths. If the data from silane treated strands are included in the analysis, one must conclude that the simple pull-out test does not reliably predict the bond performance for pretensioned concrete applications.

In Fig. 24, data for each strand surface condition is represented by an ellipse. The center of each ellipse represents the average value of pull-out strength vs. the average transfer length. The boundaries of each ellipse outline the data plus or minus one standard deviation distant from the average values. The tendency of each ellipse to become relatively flat suggests that greater variation exists in the transfer lengths than the pull-out strengths.

Fig. 24 also illustrates that the increase in pull-out strength is insensitive to the decrease in transfer length, with the silane data ignored. In other words, a relatively large variation in pull-out force resulted in a relatively small variation in transfer length. Comparing weathered strand (CS) to the AA strand, weathered strand had 2.5 times the pull-out strength of the AA strand yet the AA strand possessed a transfer length of 19.2 in. (488 mm), which is considered acceptable under current practice.

In evaluating the prospects of the simple pull-out test for use as a performance standard, these data present two dilemmas, both of which are difficult to reconcile. First, although the data (with data from silane treated strands omitted) demonstrate a definite trend that higher pull-out strengths correspond to shorter transfer lengths, thus indicating that the simple pull-out test possesses some

Tensioned Pull-Out Strength vs. Measured Transfer length

Current bond theory emphasizes the importance of the wedging action that results from Hoyer's effect. Further, Hoyer's effect suggests that the bond stresses measured in transfer length tests and tensioned pull-out tests should exceed the bond stresses measured from simple pull-out tests. Unlike the simple pull-out tests, the tensioned pull-out test allows Hoyer's effect to contribute to bond which accurately reflects the bond mechanisms acting in a pretensioned concrete member. However, the data suggest that the tensioned pull-out test did not perform as expected and the results obtained are inconsistent. For the cleaned (C) and silane treated (S) strands, the average bond stress from the tensioned pull-out tests was approximately one-half of the average bond stress from the simple pull-out tests, as shown in Table 8.

Furthermore in Fig. 25, the tensioned pull-out strengths are plotted against the average transfer lengths where the data display only a weak correlation between the tensioned pull-out strengths and the transfer lengths. Overall, these data demonstrate that the tensioned pull-out test may not be a reliable indicator of strand bonding capacity, although the disparities in bond strength may be attributable to inconsistent concrete curing conditions that may have resulted in lower concrete strengths for the tensioned pull-out specimens.

In summary, no matter the cause for inconsistent data, the tensioned pull-out tests were difficult to perform and require special apparatus and equipment for testing. Therefore, the tensioned pull-out test is not recommended for use as a bond performance test for prestressing strand.

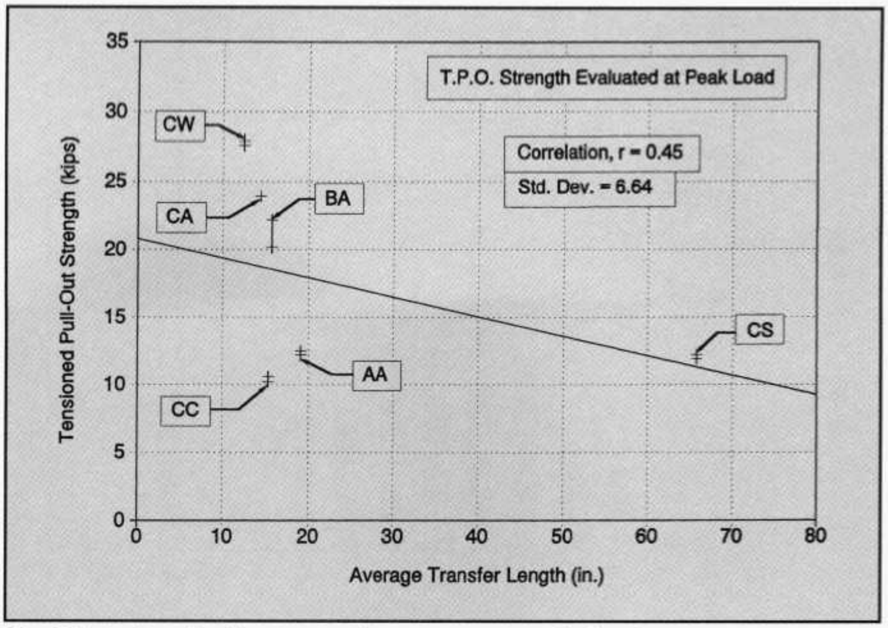


Fig. 25. Tensioned pull-out strengths vs. average transfer lengths.

Strand End Slip vs. Measured Transfer length

As noted earlier, a direct mechanical relationship exists between strand end slips and measured transfer lengths. In Fig. 26, data from the OU tests are included with data reported by Deatherage and Burdette[21,22] and Unay et al.[14] The plot dramatically illustrates the strong correlation between end slips and transfer lengths. Regression analysis further demonstrates that the transfer lengths are directly proportional to end slips and that the relationship is defined by a proportionality coefficient of 297.5 (unitless).

The plot also shows how closely the regression analysis fits with the theoretically derived relationship from Eq. (3) which defines a proportionality constant of 292.3. The prestress modulus was taken as 28,500 ksi (196.5 GPa) and the initial prestress, just prior to release was taken as 195 ksi (1344 MPa).

More substantially, these data demonstrate that measured strand end slips can be used to calculate the actual transfer length for a given prestressing strand, using the theoretically derived expression given by Eq. (3). This correlation is perhaps more significant after considering that each of the experimental programs used different techniques to acquire the end slip measurements, suggesting that the end slip correlation is adequately robust to survive approximate and perhaps even inaccurate measuring techniques. As more refined and more accurate methods of measuring end slip are employed, the correlation between measured end slips and transfer lengths should improve.

[Authors' Note: The transfer lengths reported by Deatherage and Burdette were determined from the bilinear intersection method. The transfer lengths reported by Russell and Burns were determined by the 95 percent AMS method described in the reference source, which is the same method employed for determining transfer lengths in the OU research. For others that wish to perform similar comparisons with additional data, a reliable and repeatable method must be established to determine the measured transfer length. Some methods for determining transfer lengths can be heavily influenced by arbitrary interpretation of concrete surface strains, and it is important to tangibly and purposely avoid methods where significant arbitrary interpretation of the strain data is required. The authors recommend the use of the 95 percent AMS method to eliminate variability in data analysis.]

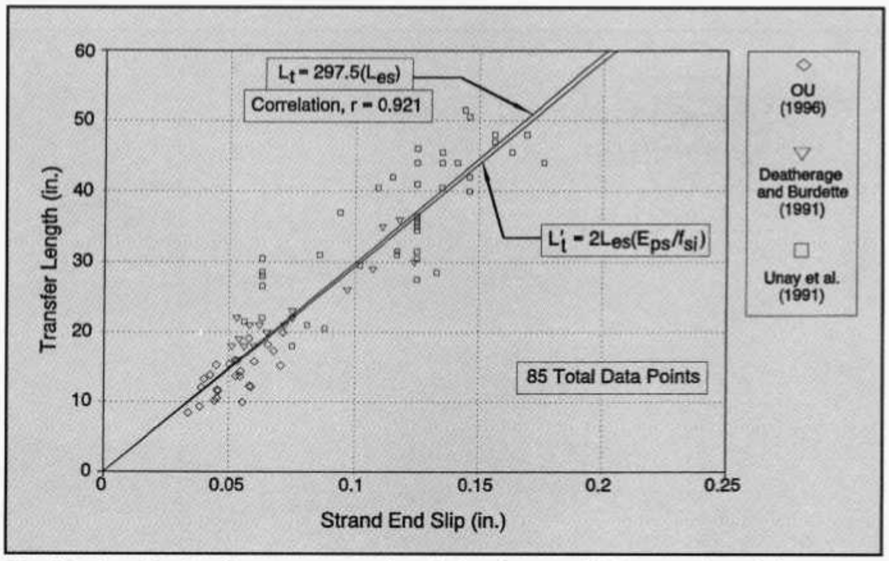


Fig. 26. Transfer lengths vs. measured end slips from multiple experimental programs.

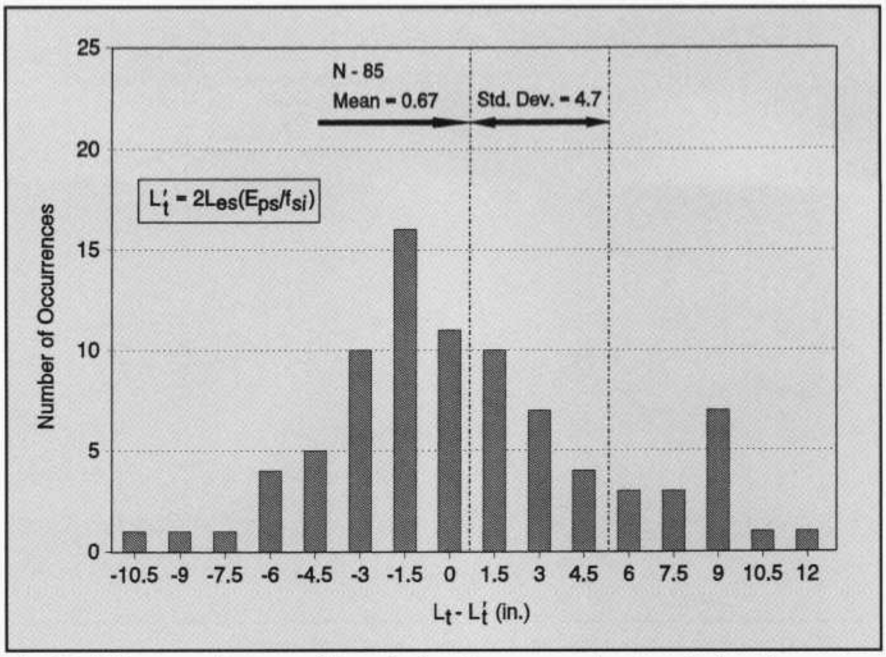


Fig. 27. Histogram of measured transfer lengths compared to transfer lengths calculated from end slip ($L_t - L'_t$).

The data from the three research projects consist of 85 data points. For each of the data points, the measured transfer length (L_t) was compared to the transfer length computed from end slip measurements (L'_t). To determine the consistency of the data, the differences in measured and computed transfer lengths were charted in the histogram pictured in Fig. 27. The histogram plots the incidence of difference between the measured transfer length and the calculated transfer length ($L_t - L'_t$) for each of the 85 data points.

As shown in the figure, the average difference between calculated end slip and measured end slip is about 0.7 in. (17 mm), which recognizes that Eq. (3) is not the "best fit" curve. The standard deviation is 4.7 in. (119 mm). Assuming normally distributed data, these data indicate that the transfer length computed from end slip measurements would fit in the range from -4.0 to +5.4 in. (-102 to +137 mm) in about 68 percent of the cases.

The strong correlation between end slip and transfer length suggests that a simple design relationship predicting transfer length from end slips can be developed that is reasonably accurate and reliable. These data lead to the following relationship between transfer length and measured end slips:

$$L'_t = 2L_{es}\left(\frac{E_{ps}}{f_{si}}\right) + 5.4 \text{ in.} \qquad (6)$$

which is derived from the theoretical relationship of Eq. (3) plus the mean difference of 0.7 in. (17 mm) plus one standard deviation of 4.7 in. (119 mm).

A line representing Eq. (6) is illustrated on the plot of measured transfer length vs. end slip in Fig. 28. Eq. (6) represents a line, parallel to the relationship given in Eq. (3), that is conservative to a large portion of the data. As illustrated, the transfer lengths obtained from Eq. (6) provide an upper bound for approximately 85 percent of the reported transfer lengths. (For these data, the mean value plus one standard deviation exceeds 70 data points, or about 82 percent of the 85 data points.)

If more confidence is required than that provided by Eq. (6), then the constant 5.4 could be replaced by 10.1 in. (257 mm), which represents 2.0 standard deviations from the average, thereby providing an upper bound for about 99 percent of the reported transfer lengths. In either case, the rational use of measured end slip can provide a conservative, yet realistic, estimate of transfer length for prestressing strands.

Consider the following example: Strands with a modulus of 28,500 ksi (196.5 GPa) and an initial prestress of 195 ksi (1344 MPa) are released and strand end slips of 0.07 in. (1.8 mm) are measured. Eq. (3) predicts that the most likely transfer length would be 20.5 in. (520 mm). Furthermore, Eq. (6) calculates that an estimated transfer length of 25.9 in. (658 mm) would exceed the actual transfer length in about 85 percent of the cases. If 2.0 standard deviations are needed for safety, the same end slip would correspond to an estimated transfer length of 30.6 in. (777 mm) or less, in 99 percent of the cases. In this manner, the appropriate reliability for transfer lengths can be built into the design codes.

Also, these relationships could be used to determine an allowable end slip for a specific transfer length re-

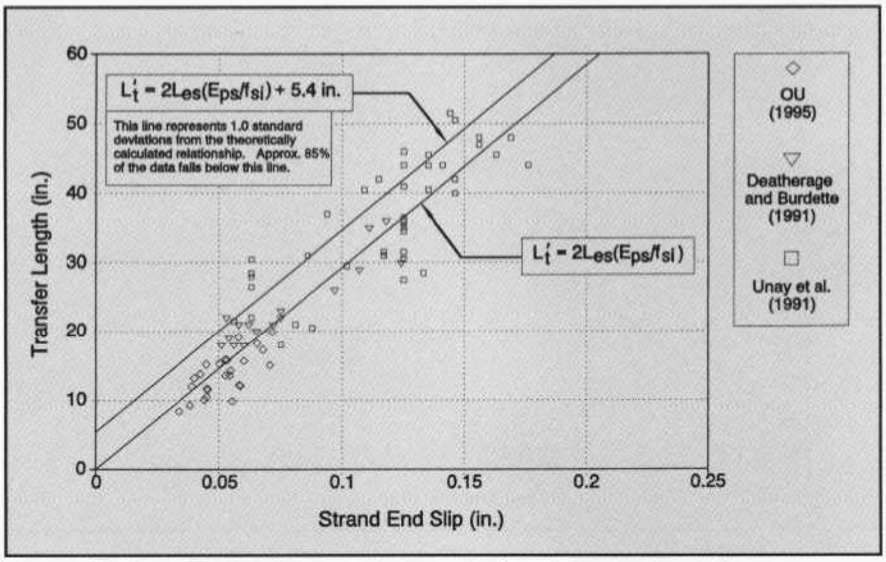


Fig. 28. Design guideline for estimating transfer length from end slip data.

quired by a unique design application. For example, if a transfer length of 40 in. (1016 mm) is required in the design of a pretensioned member, then the measured strand end slip should not exceed 0.121 in. (3.1 mm) to provide a reasonable guarantee of bond performance [using Eq. (6)]. Alternatively, if a transfer length of 30 in. (762 mm) is required, then the measured strand slips should not exceed 0.09 in. (2.2 mm).

These examples are intended to provide practical examples of the manner in which the end slip/transfer length relationship can be used to develop a safe and accurate assessment of the bond performance for a particular sample of prestressing strand. In very real terms, these data suggest that a standardized end slip test could be developed to assess the bond performance of strands intended for use in pretensioned concrete applications.

COMPARISON WITH OTHER TESTING PROGRAMS

To place this research in perspective, readers should note that the research described in this paper was performed from the fall of 1993 to the fall of 1994. At that time, standard procedures for pull-out tests were not yet established. Only when pull-out strengths from this testing program challenged results from other testing programs were concerted efforts made to identify and standardize pull-out test procedures. As a result, the "Moustafa Test" procedure was developed and published by PCI, and reprinted in the PCI JOURNAL by Logan.[25,27,34]

When the pull-out test results from the OU research are compared to pull-out values reported from the 1974 CTC tests, the 1992 CTC tests, and the 1994 Stresscon tests, significant differences are apparent. From the 1974 CTC tests, the average pull-out strength of 38.2 kips (170 kN) had been suggested as a benchmark for satisfactory bond performance. Furthermore, the 1972 CTC and the 1994 Stresscon tests provided evidence that this benchmark was attainable (these testing programs did not include testing to relate the pull-out strength to pretensioned bond).

However, the research performed at OU demonstrated that pull-out values as low as 15.3 kips (68 kN) could provide adequate pretensioned bond, which is far below the previous benchmark of 38.2 kips (170 kN). Furthermore, only one of the strand surfaces tested (weathered strand) achieved the "benchmark" pull-out strength of 38.2 kips (170 kN). Yet all of the strand surfaces, with the exception of silane, achieved adequate pretensioned bond. Therefore, the various participants in the research program, including members of the PCI Strand Bond Task Force, scrutinized the differences between the pull-out tests and procedures to determine the possible sources for differences between the various test results.

In developing the pull-out tests for the OU research, the tests were designed to replicate the earlier pull-out tests that were performed at CTC. Towards that goal, the testing geometry and many of the procedures were repeated. For example, the length of bond embedment was maintained at 18 in. (457 mm), the strands were cast vertically to prevent the collection of bleed water and entrapped air from affecting bond, the relatively large size of the pull-out block was maintained, a 2 in. (50 mm) bond break was provided at the concrete surface to prevent edge effects and reduce confinement effects, and the concrete strength at 1 day was targeted at 4000 psi (28 MPa). These were all design choices made in an attempt to repeat the earlier pull-out testing.

However, some significant differences in testing procedures did exist between the testing programs. For instance in the OU tests, strand samples pass completely through the concrete block so that the slip on the strands' "free" ends could be measured and so that general bond slip could be detected. In the CTC tests, the strand end was embedded in the concrete and "free end" slips were unavailable. Also in the OU tests, strand slip data were meticulously collected both electronically and manually so that the pull-out force vs. slip relationships could be examined. The collection of slip data effectively slowed the rate of pull-out loading, and the OU pull-out tests were completed in 15 to 20 minutes. In the Stresscon CTC tests, slip measurements were not taken and each pull-out test was completed in 2 minutes or less. Additionally, different styles of hydraulic actuators were used to pull the strand from the concrete, which could contribute to variations in pull-out force depending on the effects of restraining strand twisting.

After examination and discussion, it was concluded that the variation in pull-out rate was the most identifiable and substantive difference between the testing programs that could account for the differences in the results. The Stresscon and CTC tests affected a relatively fast loading rate, loading the strands from zero pull-out force to their pull-out capacity in 2 minutes or less. Further, it is believed that this loading rate resulted in relatively higher pull-out strengths than the OU tests.

In fact, by using a rapid pull-out rate the pull-out strengths of the untensioned strands approached the breaking strengths of the strands in many cases. These large pull-out strengths, on the order of 38 to 40 kips (170 to 178 kN), generated over an 18 in. (457 mm) embedment length exceeds the bond stresses generated in the transfer zone of a pretensioned concrete member where only approximately 70 percent of the strands' breaking strength, i.e., about 28 kips (125 kN), is achieved over a transfer length of roughly 25 to 30 in. (630 to 762 mm).

In the tests conducted by Brearly and Johnston, a relatively slow loading rate was applied to the strands which resulted in relatively low pull-out strengths. In their tests, loads were applied incrementally. In fact, the bond creep was allowed to cease before the next load increment was applied. The authors report that each pull-out test required about 20 minutes to perform. As shown in Table 3, the relatively low pull-out strengths are consistent with slower pull-out rates.

When viewed collectively, the results reported by Logan, Moustafa, and this study provide evidence that the loading rate significantly affected the pull-out strength of prestressing strand. From these results, it is imperative that the loading rate for an otherwise simple pull-out test must be controlled to provide repeatable and reliable results when using simple pull-out tests as a performance criterion.

Discussions led to the recommendation that a formalized testing procedure for simple pull-out tests be instituted. This test, called the "Moustafa Test," is described by Logan.[25,34] Additionally, it is recommended that all future pull-out testing be performed using the "Moustafa Test" procedures so that results from bond tests can be compared to one another.

Regarding the OU tests, despite the differences in pull-out strengths from earlier test results, the trends of pull-out strength vs. transfer length are largely preserved, and strands with comparatively strong pull-out exhibit shorter transfer lengths.

Additionally, the data indicate that the pull-out rate does not affect the standard deviation in pull-out strengths. In the OU research, the largest standard deviation was 9.4 percent on the cleaned strand with only 3.4 percent on the weathered strands. Similarly, standard deviations from the Stresscon 1994 tests (see Fig. *3)* ranged between 4.1 and 10.7 percent. With these minimal differences in statistical variations, the rate of loading cannot be said to affect the noted trends in comparing the pull-out strengths vs. transfer length, despite the influence of loading rate on the measured pull-out strength.

In comparing the results from end slip measurements, Logan measured dramatic time dependent increases in strand slips after the initial strand slip measurements were taken. Logan found that strand end slips increased as much as 75 percent over the 21 days immediately following pretensioned release. He concluded that end slip measurements should not be used immediately after release to assess the quality of pretensioned bond.[34]

In general, the gradual suck-in of strand can be expected for all pretensioned members and end slip measurements may be required as time goes by. However, research available in the literature suggests that transfer lengths (and end slips) typically increase approximately 10 percent over time.[10] Time dependent increases in transfer length or strand end slips like those reported by Logan have not been previously noted.

Certainly, the observed "bond creep," indicated by increasing strand slips, is arguably a function of bond quality. Strands with adequate bond did not display tendencies for bond creep whereas strand with poor bond tended to continue slipping over time. On the other hand, significant bond creep in strand slip has been observed only in saw cut products. The observed bond creep may be caused, in part, by the relatively small amount of strain energy released when saw cutting.

When pretensioned strands are released by saw cutting, the entire strand is typically encased in hardened concrete. The amount of strain energy released is limited to the energy contained within the few inches of strand immediately adjacent to the saw cut. The amount of energy released is relatively small because the length of affected strand is relatively short, compared to pretensioned products where strands extend several feet out from the ends of the members.

In pretensioned products such as bridge beams and double tees, relatively large lengths of "free" strand in air extend from the ends of the concrete. As these free lengths of strand are detensioned, much larger amounts of strain energy are released compared to saw cut products. The release of energy is manifested by sound energy as the strands are cut, by kinetic energy of quick and violent movement of the pretensioned strands, and sometimes by displacements of the pretensioned products in the prestressing beds. Also, the flame cutting of pretensioned strands releases a shock wave that can violently impact the concrete in ways that saw cutting cannot, even to the extent that concrete can be cracked in unexpected ways.[13]

When the larger amounts of energy are released upon detensioning, the likelihood for large and immediate end slips upon release is increased. As a result, larger transfer lengths and end slips are expected to be measured on flame cut ends because the impact of the strands' energy effectively lengthens the transfer length. In this sense, the saw cutting of strands represents a more gradual release than flame cutting. Thus time dependent increases in strand slip are more likely to be large and significant in saw cut products.

SUMMARY OF TEST RESULTS

Here, the principal results of the simple pull-out tests, tensioned pull-out tests and strand end slip measurements are summarized.

Simple Pull-Out Tests

Overall, the simple pull-out strength demonstrated a statistical correlation to measured transfer lengths, as long as the data from the silane treated strands are ignored. Unfortunately, when the data from silane treated strands are included, the simple pull-out test was found to be a poor evaluator of pretensioned bond. Furthermore, even when the statistical correlation between pull-out strength and transfer length is considered, the data acquired in this research do not present a clear threshold value for a required pull-out strength. This is because all of the measured transfer lengths were relatively short.

Therefore, it is concluded that these data do not demonstrate any meaningful correlation between simple pull-out tests and pretensioned bond. At best, the data from this research program should be described as inconclusive regarding the value of the simple pull-out test.

On the other hand, the tests performed by Logan[34] demonstrate that the simple pull-out test using the "Moustafa Test" procedure may be a useful indicator of pretensioned bond performance. Therefore, the simple pull-out test merits additional consideration simply because it can be performed fairly easily and because this research does indicate an apparent relationship between simple pull-out strength and transfer length.

A more concerted testing program, with controlled loading rates and controlled testing procedures may improve the reliability of the simple pull-out tests. Therefore, the authors are recommending that additional pull-out tests be performed at consistent pull-out rates and procedures to determine if a stronger correlation between pull-out strength and transfer length can be established.

Tensioned Pull-Out Tests

The tensioned pull-out test proved to be difficult to perform. Additionally, the results from the tensioned pull-out test are inconsistent with other tests, probably because of the difficulty inherent in performing the test. Careful curing of the tensioned pull-out specimens must be ensured to achieve concrete strengths and concrete maturity consistent with the companion test specimens. For these reasons, and because the tensioned pull-out test does not appear to provide significantly better correlations to pretensioned bond, the tensioned pull-out test is not recommended as a test to assess the bond performance of prestressing strand.

Strand End Slip Measurements

Of the three bond performance tests, measured strand end slips provide the best correlation to transfer length. Data from the OU tests were combined with data gathered from two other testing programs. Even though each research program employed different procedures and instruments for measuring strand end slip, the resulting correlation between strand end slip and transfer length was found to be excellent. Therefore, measuring strand end slips is recommended to readers as a reliable and repeatable method to evaluate the quality of strand bond. Additionally, the industry is encouraged to develop a standardized test for strand end slip.

CONCLUSIONS

1. Strand end slips provided a reliable and repeatable indication of transfer length. The data indicate that measured end slips closely predict the transfer lengths of pretensioned strands. Through this research, it was found that transfer lengths can be reliably predicted by the theoretically derived relationship given by:

$$L_t' = 2L_{es}\left(\frac{E_{ps}}{f_{si}}\right) \qquad (3)$$

2. This research demonstrates that the measurement of strand end slip is the most reliable assessment for the performance of strand bond in pretensioned concrete applications, when compared to simple pull-out tests and tensioned pull-out tests.

3. The following expression can be used to assess pretensioned bond performance relative to specific transfer length requirements:

$$L_t' = 2L_{es}\left(\frac{E_{ps}}{f_{si}}\right) + 5.4 \text{ in.} \qquad (6)$$

For example, using Eq. (6) to ensure a transfer length of 25 in. (635 mm) or less, a maximum end slip of 0.07 in. (1.8 mm) should be measured. Similarly, to ensure a transfer length of 40 in. (1016 mm), a maximum end slip of 0.12 in. (3.1 mm) should be measured.

4. The use of strand end slip measurements to evaluate pretensioned bond provides results which are independent of strand surface condition, strand diameter, flame cut location, and concrete strength.

5. These data do not support a strong correlation between simple pull-out strengths and pretensioned bond. Instead, silane treated strands demonstrated extremely poor pretensioned bond in the transfer length specimens whereas silane treated strands exhibited relatively large pull-out strengths. Furthermore, where data from the silane treated strands are omitted, the remaining data do not demonstrate any clear or useful relationships between pull-out strength and transfer length.

6. For future evaluations **of** a simple pull-out test, standardized testing procedures must be adopted and include a standardized loading rate, standardized concrete mixtures and standardized geometry.

7. In its current state, the tensioned pull-out test cannot be used to consistently evaluate pretensioned bond.

8. The surface condition affects the bond performance of pretensioned strand. A roughened surface enhances bond whereas a lubricated surface hinders the bond performance.

9. The transfer lengths can increase by as much as 60 percent when located immediately adjacent to flame cutting.

RECOMMENDATIONS

1. The measured end slip can and should be employed as a reasonable assessment of transfer length, using a theoretical relationship between end slip and transfer length. The authors recommend that Eq. (3) from this paper be used because of its simplicity.

2. A standardized test, measuring the end slip of pretensioned strand after release should be developed and adopted to assess the bond performance of pretensioned strand.

3. Criteria should be developed that would codify acceptable transfer lengths for specific applications, and accordingly, criteria for strand acceptances could be developed based on strand end slip.

4. Testing should continue towards developing a standardized performance test for end slip. The testing should be coordinated and point towards specific goals tailored toward providing a safe and reliable anchorage of pretensioned strands.

5. Testing should continue towards developing a reliable simple pull-out test. Standardized tests using the "Moustafa Test" must proceed and results should be evaluated and compared to pretensioned transfer and development lengths of prestressing strand. Logan's tests demonstrated much promise towards this goal and efforts should be continued and supported.

ACKNOWLEDGMENTS

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