Acceptance Criteria for Bond Quality of Strand for Pretensioned Prestressed Concrete Applications

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Donald R. Logan obtained his BS and MS degrees in structural engineering from Drexel University and the University of Pennsylvania, respectively. While a student at Drexel in Philadelphia, he witnessed the testing and construction of the Walnut Lane Memorial Bridge (1949-1950) and attended the prestressed concrete course given to Drexel students by Charles Zollman. In the mid-sixties, he was sales-engineering manager at Concrete Technology Corporation under the tutelage of Dr. Arthur Anderson and Robert Mast. He founded Stresscon Corporation in 1968, establishing a project management organizational structure directed toward design-build negotiated clients. In 1969, he co-founded the Colorado Prestressers Association. Since 1980, Mr. Logan has been deeply involved in researching strand slip, bond and development length.

In this test program, six samples of 0.5 in. (13 mm) diameter strand were obtained from precast, prestressed concrete producers from widely separated regions of North America to evaluate strand bond performance. A total of 216 tests were carried out on the specimens, including pull-out tests, end slip at prestress release and at 21 days, as well as development length tests. The pull-out test (Moustafa method) proved to be an accurate predictor of the general transfer and development characteristics of the strand in pretensioned, prestressed concrete applications. Based on the test results, the following major findings can be drawn: (1) The transfer and development lengths of strands with average pull-out capacity exceeding 36 kips (160 kN) were considerably shorter than predicted by the ACI transfer and development length equations; (2) Strands with average pull-out capacity less than 12 kips (53.3 kN) were unable to meet the ACI transfer length criteria, and failed prematurely in bond at the ACI development length, without noticeable warning deflection.

The transfer of prestressing force from strand to concrete at a predictable length, and the attainment of the full strand strength at nominal flexural capacity over a reliable development length, are fundamental requirements to the definition and performance of pretensioned, prestressed concrete.

The equations in the Commentary of the Building Code of the American Concrete Institute (ACI 318-95)[1] have been used for many years and are relied upon by the engineering community to accurately define transfer and development lengths.

Transfer length:

$$L_{tr} = f_{se} d_b / 3 \quad (1)$$

Development length:

$$L_{dev} = f_{se} d_b / 3 + (f_{ps} - f_{se}) d_b \quad (2)$$

where

d_b = diameter of prestressing strand

f_{se} = effective stress in prestressing strand after allowance of prestress losses

f_{ps} = stress in prestressing strand at calculated ultimate capacity of section

Eqs. (1) and (2) are depicted schematically in Fig. 1.

Despite the reliance on the ACI equations, there is substantial evidence that the capability of strand to bond to concrete varies considerably, depending on the source of supply of the strand. Most of the strand sources tested in this test series, as well as in other recent tests,[2] achieve transfer and development lengths that are shorter than the ACI equations predict. However, two sources of strand covered in this report were unable to meet the ACI transfer and development criteria. Indeed, this strand appeared to experience deterioration in bond over time resulting in significant increases in transfer lengths in just 21 days after release of the prestress force into the concrete beams tested.

In the past, the bond quality of the surface of the strand was generally not questioned, except that users were alerted to avoid contamination of strand by form oils during handling and to recognize the benefits of moderate weathering in enhancing bond.[3-6] Thus, there has never been a recognized test method nor a standard minimum requirement for the bond quality of strand used for pretensioned concrete applications. As a result, pretensioned, prestressed concrete producers and designers have no method to ensure that the strand produced by the different manufacturers actually transfers the prestressing force and develops the guaranteed ultimate tensile strength of the strand over the lengths calculated by the suggested ACI equations.

BACKGROUND

Some of the earliest evidence of significant variations in bond quality among strand sources began to emerge in the late 1980s and early 1990s.[7] The most significant event was the challenge to the bond quality of strand, in general, that resulted from tests conducted in 1986 at North Carolina State University (NCSU) by Cousins, Johnston and Zia.[8] The transfer length of the 0.5 in. (13 mm) diameter uncoated, non-weathered (as-received) strand used in these tests was as long as 64 in. (1626 mm), over twice the $50d_b$ length of 25 in. (635 mm) assumed by ACI 318-95, Section 11.4.4. The development length was also much greater than ACI 318-95, Section 12.9 requires.

Responding to these test results, the Federal Highway Administration (FHWA) required, as an interim measure, that the ACI development length equation be increased by 60 percent. Many test programs were then initiated to determine the "actual" transfer and development length of strand in pretensioned concrete. An excellent review by Buckner[9] discussed the wide variations in the results of recent tests as well as earlier tests. However, none of these tests considered the possibility that such variations may have been the result of significant differences in the bond quality of the strand produced by various strand manufacturers.

Having recently completed extensive research on Anderson/Anderson's[10] and Mast's[11] concepts regarding the relationship of end slip at release of prestress to transfer/development length of strand, the author was requested by the Precast/Prestressed Concrete Institute (PCI) to evaluate the results of the NCSU tests. It was immediately apparent that there was a significant difference between the reported end slip, 0.25 in. (6.4 mm), on the strand used in the NCSU tests and the end slip, less than 0.09 in. (2.3 mm), routinely observed on the saw-cut ends of wet-cast hollow-core slabs cast in the author's plant. Because the strands in these two cases were produced by different strand manufacturers, it was

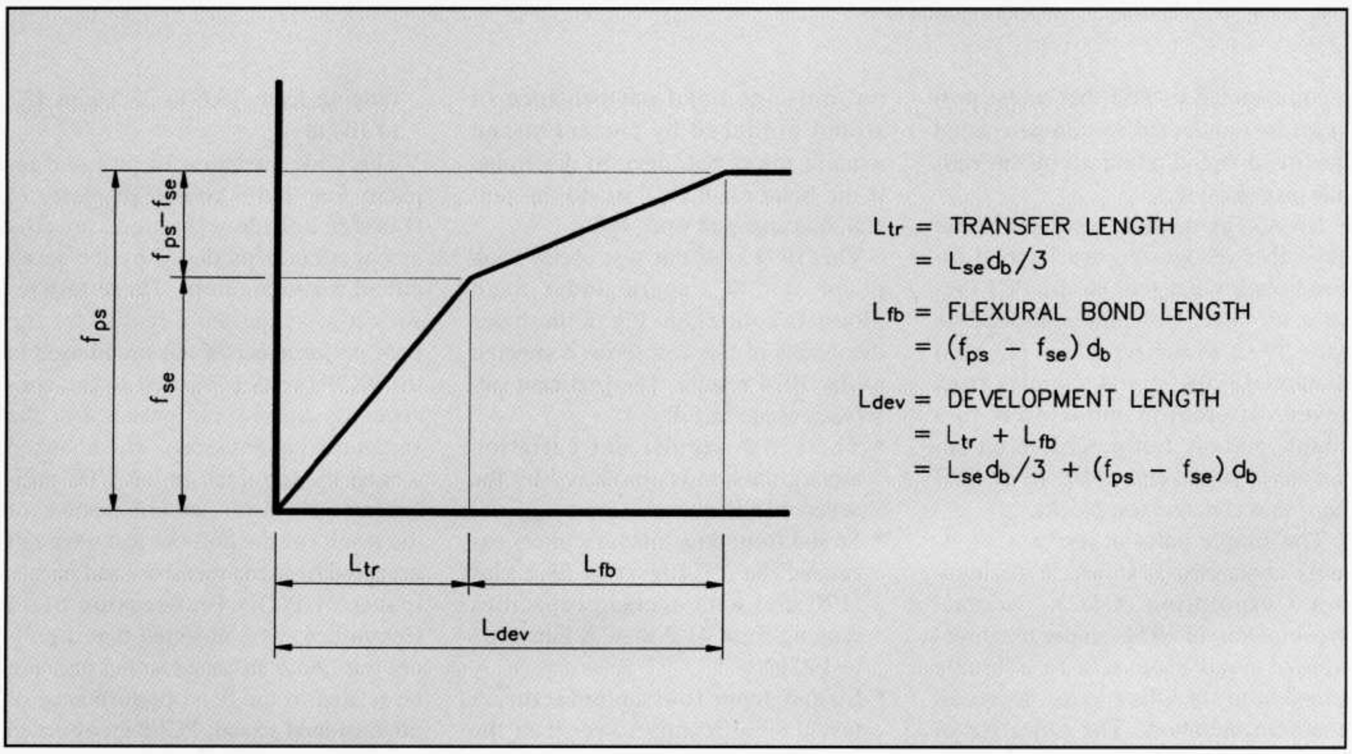
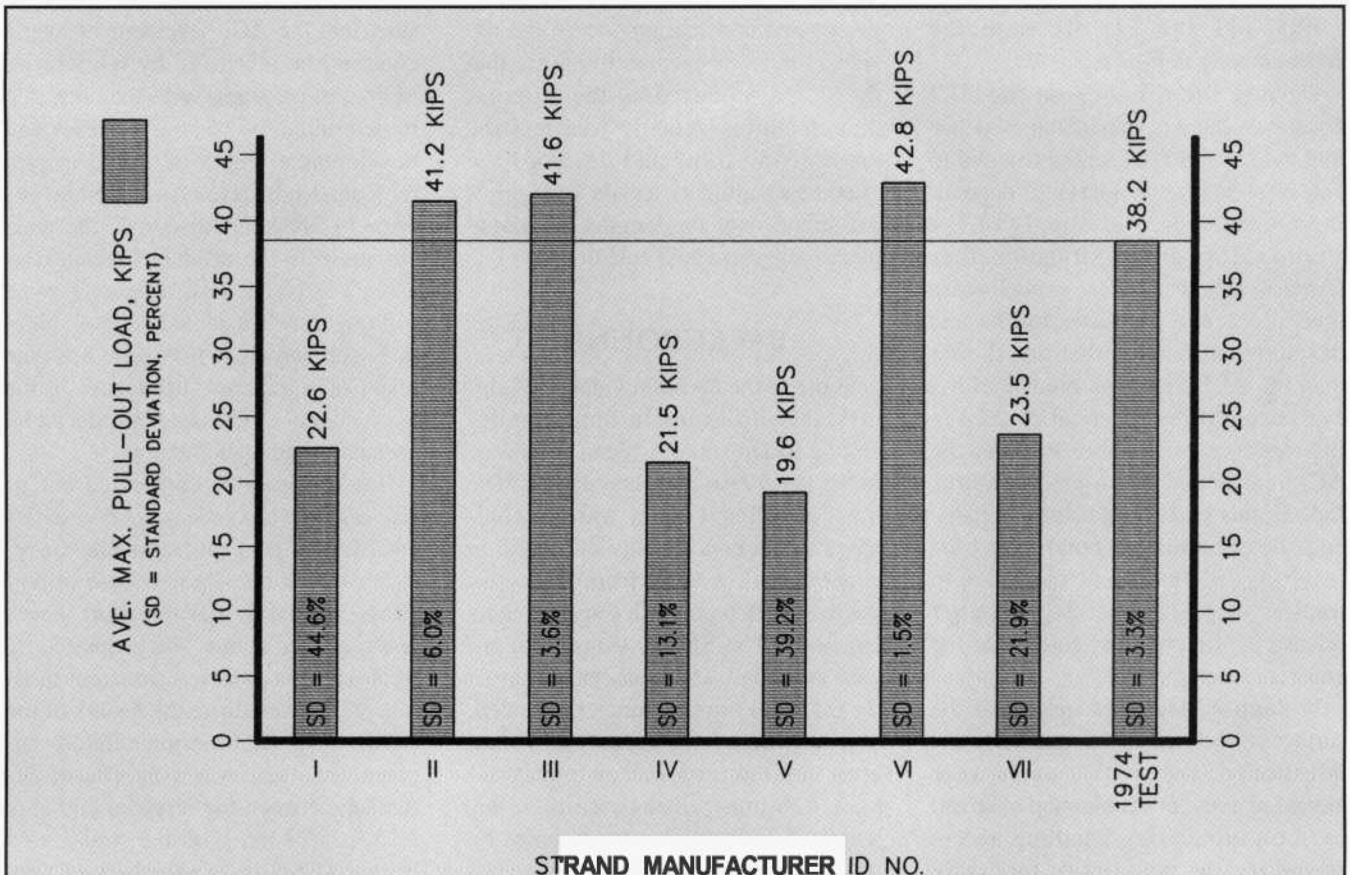


Fig. 1. Schematic depiction of strand transfer and development length equations from ACI 318-95, Section R12.9.



Notes:

(1) The above results are from the PCI-sponsored test conducted at Concrete Technology Corporation (CTC) and were supervised by Saad Moustafa in August 1992 (18 specimens per test).

(2) Strand specimens were embedded 18 in. (458 mm) into well vibrated concrete test blocks. Concrete was CTC's standard production mix. All strand was 0.5 in. (13 mm) in diameter.

(3) Strand specimens were in their "as received" condition and were protected from weathering.

Fig. 2. Pull-out capacity vs. strand manufacturer.

recommended to PCI that a test program be conducted to compare bond quality of strand produced by the various manufacturers.

No ASTM standard test method nor any other recognized test method for bond quality existed, so the PCI Prestressing Steel Committee decided, in early 1992, to subject 0.5 in. (13 mm) diameter 270K strand samples from seven different manufacturers to a simple pull-out test procedure on untensioned strand embedded 18 in. (457 mm) into concrete test blocks.

The simple pull-out test was originally conducted at Concrete Technology Corporation (CTC), Tacoma, Washington, in 1974[12] under the direction of Saad Moustafa to evaluate strand used for lifting loops in precast concrete members. The objective of the 1992 test series was to compare not only the bond performance of strand produced by current strand manufacturers but, also, to determine if the bond quality of strand, in general, had changed since 1974.

The 1992 pull-out test series took place at CTC, again under Saad Moustafa's direction. Fig. 2 illustrates the results of this test series compared to the 1974 results. The pertinent observations are as follows:

- There was significant variation among the strands produced by the seven manufacturers.
- Strand from three manufacturers exceeded the 1974 level of 38.2 kips (170 kN) with average capacities ranging from 41.2 to 42.8 kips (183 to 190 kN).
- Strand from four manufacturers tested significantly lower than the 1974 level with average capacities ranging from 19.6 to 23.5 kips (87 to 104 kN).

The wide variation in pull-out capacity implied a similar disparity in transfer and development lengths among strands produced by the seven strand manufacturers. These test results also suggested a reason for the poor performance of the strand used in the NCSU tests compared to the consistently superior performance of the strand used at Stresscon, which ranked among the top three in the CTC pull-out tests. However, the implications of the results of the pull-out test were not accepted by some members and participants of PCI's Prestressing Steel Committee, who objected that a pull-out test on untensioned strand may not be related to the bond performance of pretensioned strand. PCI then awarded a fellowship to the University of Oklahoma to perform tests to compare simple pull-out strength of pretensioned strand." The results from that research turned out to be inconclusive, and, in response, the testing program reported herein was developed.

OBJECTIVES AND SCOPE

In order to gain the expertise of prominent individuals having experience in bond research, the author assembled an advisory group consisting of Roger Becker, Robert Mast, Saad Moustafa, Donald Pellow, Bruce Russell, and Norman Scott.

Objectives

The mission of the advisory group was to:

1. Conceive, review and observe a test program to compare, in pretensioned, prestressed concrete flexural beam tests, the transfer and development lengths of strand from different sources.

2. Correlate the simple pull-out capacity of strand to its transfer and development lengths in the flexural beam tests.

3. Establish a minimum acceptable pull-out capacity for strand that reliably predicts satisfactory performance in flexural beam tests.

4. Evaluate the reliability of end slip measured at release of prestress as a predictor of flexural bond behavior.

5. Determine whether there are any obvious surface conditions and/or dimensional variations of strand samples that may give an immediate indication of the bond quality of strand.

Scope

Prior to the start of this test series, the following parameters were established:

1. Strand samples would be obtained directly from pretensioned concrete producers over a significantly wide region so that the test series would represent strand currently in general use in the fabrication of pretensioned concrete members.

2. Preliminary pull-out tests would be conducted to ensure that there was sufficient variation in pull-out capacity of the samples to enable evaluation of the relationship between such capacity and subsequent bond performance in pretensioned concrete flexural beam tests.

3. In order to reduce potential variables, the following constraints were established:

(a) Use only 0.5 in. (13 mm) diameter 270K strand.

(b) For all test blocks and beams, use Stresscon's standard structural concrete mix with Type III cement, natural sand, crushed gravel coarse aggregate, and a normal water-reducing admixture. No high range water reducing admixtures, air-entraining agents, fly ash, or other less common ingredients would be used.

(c) All strand specimens in pull-out test blocks and in test beams would be subject to identical casting conditions relative to concrete slump [2.5 to 3 in. (64 to 76 mm)], placement, vibration, finishing, and curing techniques.

(d) Release of prestress into the beam specimens would be sudden, rather than gradual, in order to simulate the most severe release conditions[6] in typical production situations.

(e) Both the pull-out tests and the release of prestress into the beam specimens would take place on the morning after the specimens were cast, at similar overnight strengths. The intent was to attain, in a typical production situation, a correlation between the pull-out capacity of strand in a test block and its transfer length (end slip at release) in the beam specimens.

(f) The pull-out test method would be the same method used by Moustafa in 1974 and in an ongoing series of tests conducted at CTC and Stresscon Corporation since 1990. This would enable a comparison of test results of this series with a broad data base of past results.

The resulting scope of the test program, on the six groups of 0.5 in. (13 mm) diameter strand chosen, is shown in Table 1.

DESCRIPTION OF TEST SPECIMENS

This section describes the strand samples, pull-out test specimens and beam specimens.

Strand Samples

Samples of 0.5 in. (13 mm) diameter strand were obtained from pretensioned, prestressed concrete producers from widely separated regions of North America, and thus represented market place strand generally available for use in the fabrication of pretensioned concrete members. Five of the six samples were provided by concrete producers from the midwest and mountain regions of the United States and from western Canada. The sixth sample represents strand commonly sold to Mexican and South American concrete producers. The strand samples were coded TW, TA, A, B, D and ER for identification purposes.

Two of the samples were sent by concrete producers who were concerned about apparent bond quality problems with the strand. One had noticed excessive initial end slip and subsequent growth of end slip in those strands. The other concrete producer noticed that a new source of strand had more visible residue than strand from his regular supplier. The other four samples had no reported bond problems. Five of the six samples were carefully wrapped and delivered to Stresscon in their

Table 1. Summary of various types of tests on 0.5 in. (13 mm) diameter strand from representative sources in North America.

Type of test	Tests per group	Total number of tests
Pull-out test (Moustafa method)	6	36
End slip at release of prestress	10	60
End slip at 21 days	10	60
Development length tests	10	60

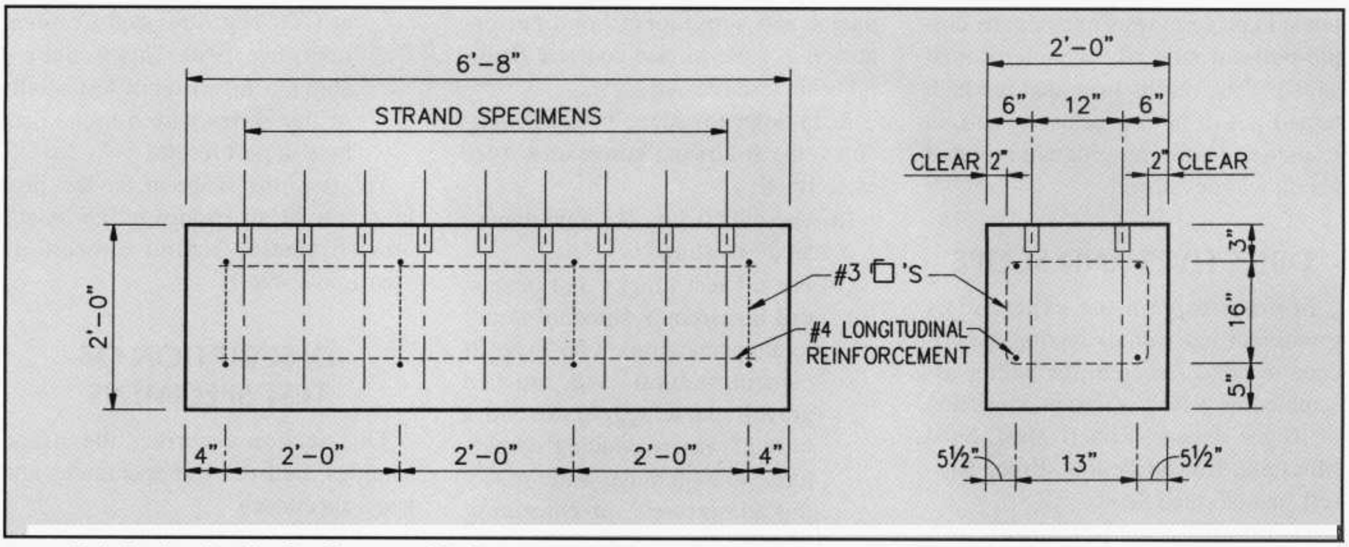


Fig. 3. Reinforcing details of pull-out test blocks.

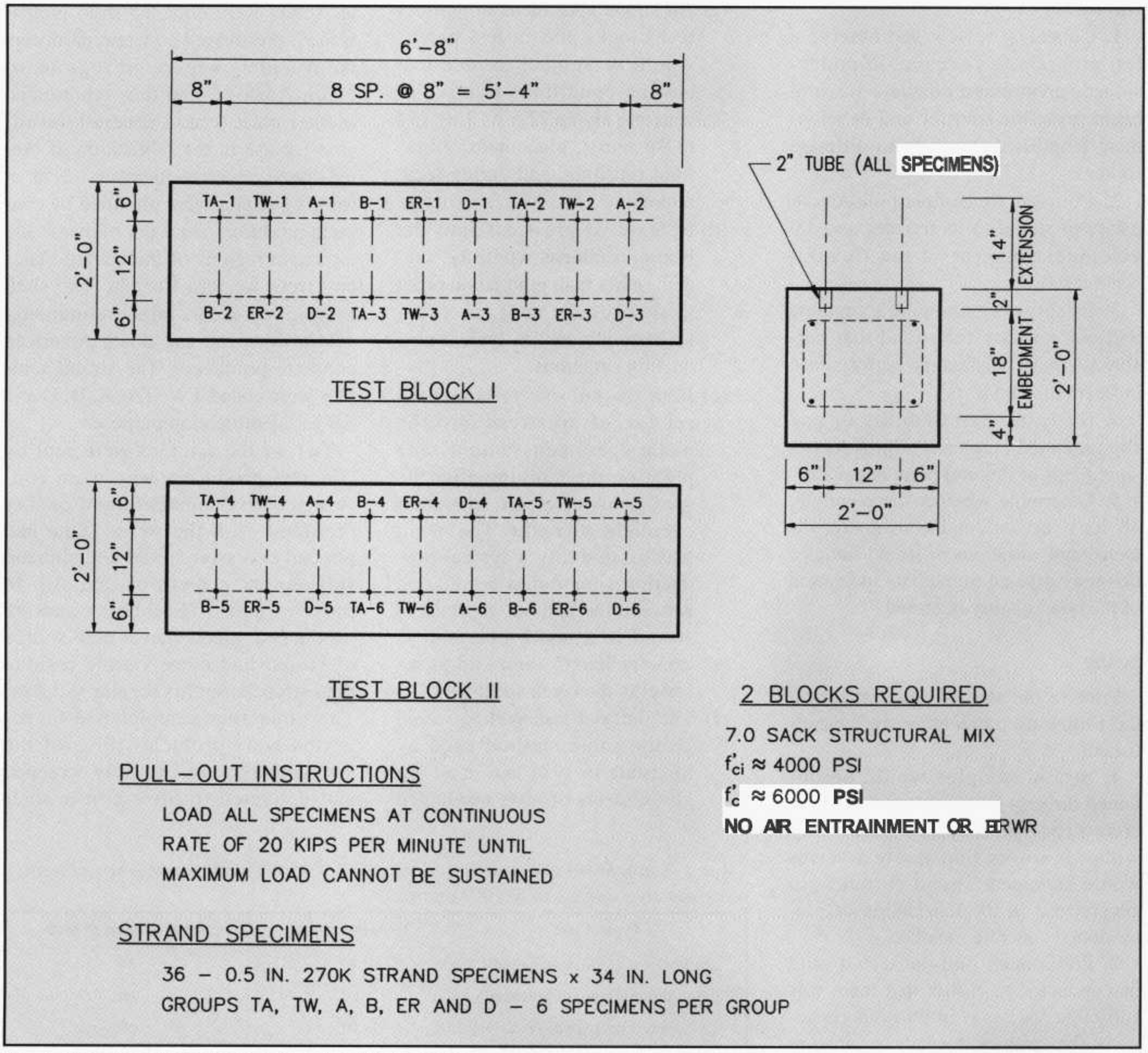


Fig. 4. Strand specimen layout of pull-out test blocks.

as-received condition. The sixth, coded TW, was taken from the same shipment as the TA group, but from a different reel of strand which had been put into use in that plant and had already developed a light coating of rust.

Typically, the strand samples were packaged in 250 ft (76 m) coils, and wrapped with waterproof covering for shipment to Stresscon. All samples were tagged with identification symbols, color coded, and separately stored inside a building at Stresscon, protected from weather. Preliminary pull-out tests were conducted and verified that the as-received strand samples covered a wide enough capacity range to enable detection of potential differences in bond quality in subsequent flexural beam tests.

Pull-Out Test Specimens (Moustafa Method)

Short strand specimens, 34 in. (864 mm) in length, along with the 105 ft (32 m) samples for the beam tests, were saw-cut from each of the six 0.5 in. (13 mm) diameter 270K strand group coils, tagged and color coded for reliable identification, and replaced into storage before the next strand coil was opened for its saw-cutting of test specimens. Each of the 34 in. (864 mm) pull-out specimens from each group was inspected visually, subjected to the towel-wipe test for residue, and straightened to limit the bow (or sweep) to $^3/_8$ in. (9.5 mm).

The specimens were tied to light reinforcing bar cages into two test block forms (see Figs. 3 through 5). The specimens from all of the strand groups were arranged so that no strand specimen had any favored position in the test blocks and so that all would be subject to the same concrete placement and vibration techniques. The concrete mix used was Stresscon's standard 7.0-sack cement, sand and crushed gravel mix that is designed to attain 4000 psi (27 MPa) overnight (with heat curing), and 6000 psi (41 MPa) in 28 days. No high range water reducing admixtures were used. Embedment in the concrete was 18 in. (457 mm). Refer to Appendix E for concrete mix ingredients and proportions.

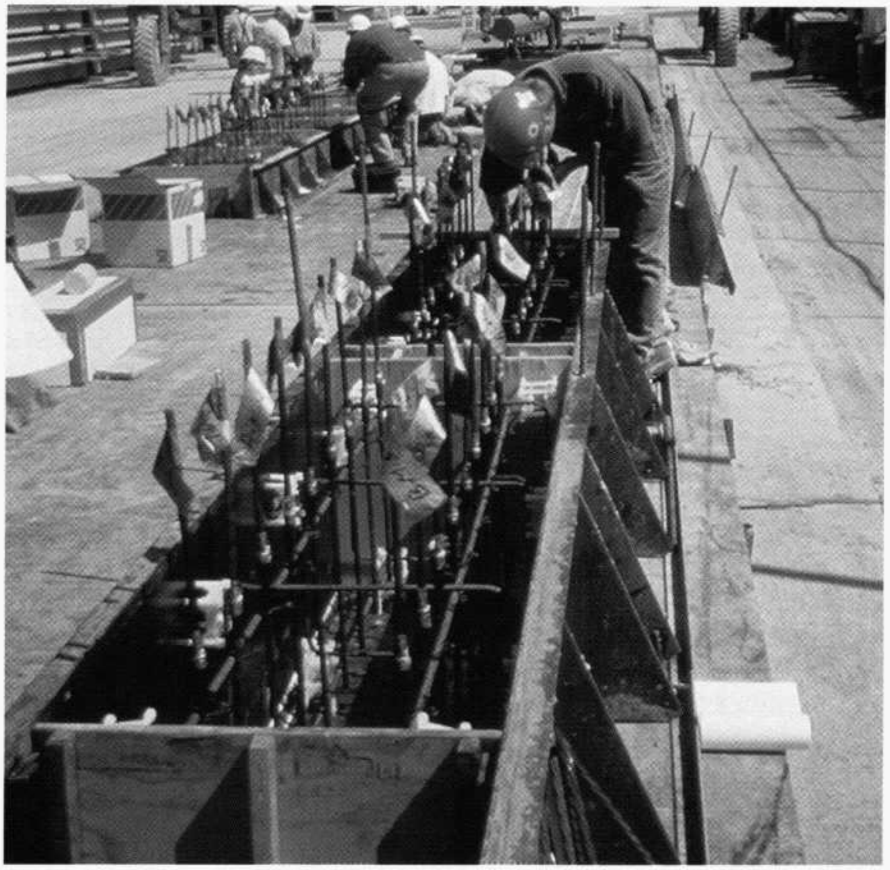


Fig. 5. Strand specimens in place, ready for casting pull-out test blocks (May 17, 1996).

Fig. 6. Completion of casting and finishing pull-out test blocks (May 17, 1996).

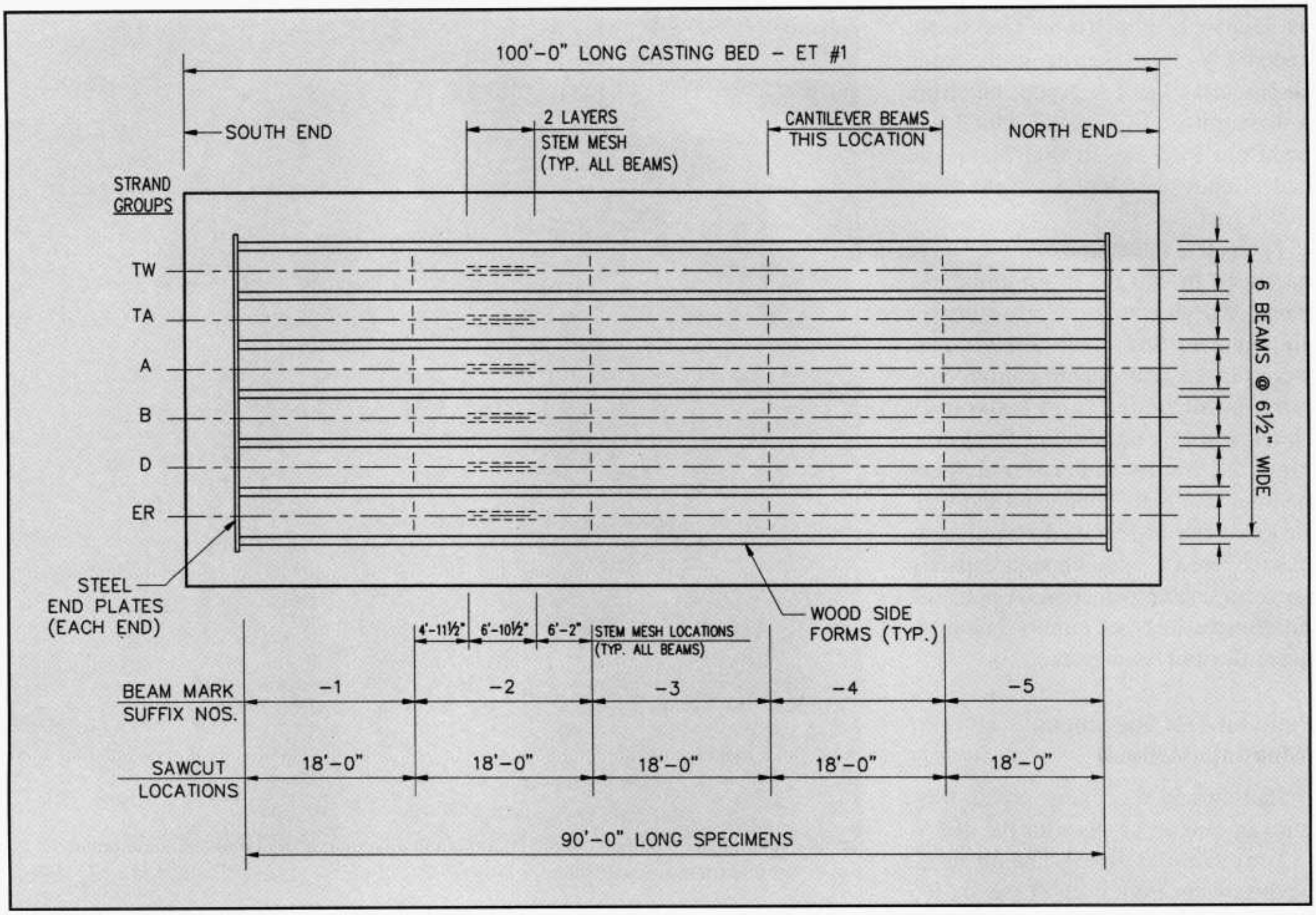


Fig. 7. Beam specimen layout (not to scale).

The two pull-out test blocks were cast the same day, with the same mix design and with the same placement techniques as the 30 transfer/development length test beams (see Fig. 6). All beams and blocks were heat cured overnight and attained average overnight concrete strengths of 4350 psi (30 MPa) for the test blocks and 4254 psi (29 MPa) for the test beams.

Beam Specimens

Four test load arrangements were devised for the beam specimens. The variable was the embedment length, L_e, from the end of the beam to the point of maximum moment. The embedment lengths used were as follows:

- 6.08 ft (1.85 m), the calculated strand development length tested in both the simple beam and cantilever conditions.
- 2.42 ft (0.74 m), the calculated strand transfer length tested in the cantilever condition.
- 4.83 ft (1.47 m), 80 percent of the calculated strand development length tested in the simple beam condition.

Beam specimens were designed to fail in flexure, rather than in shear, and

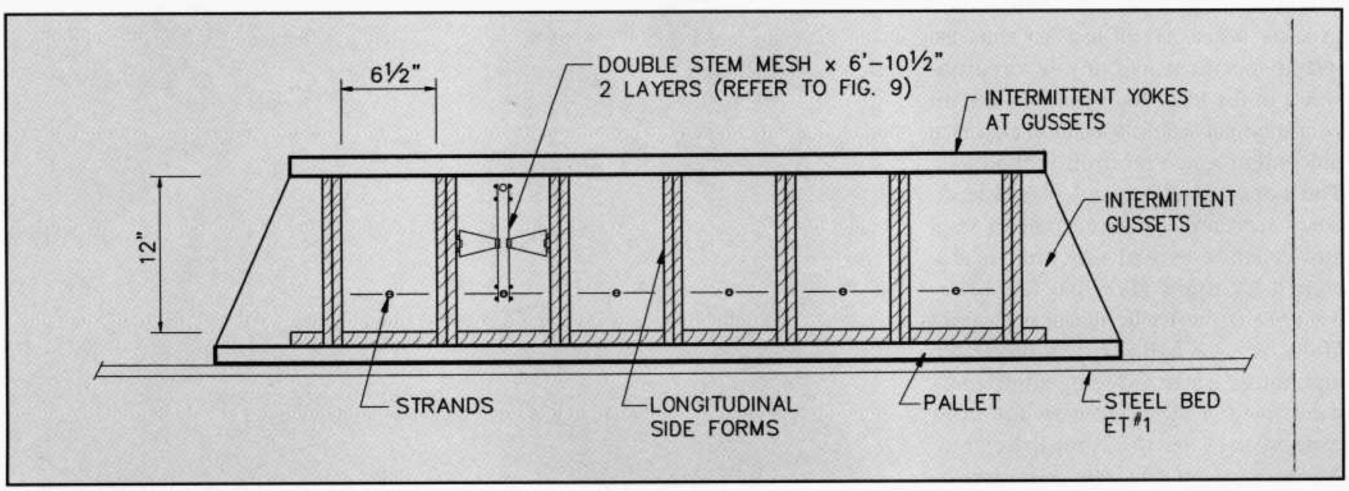


Fig. 8. Wood form for beam specimens.

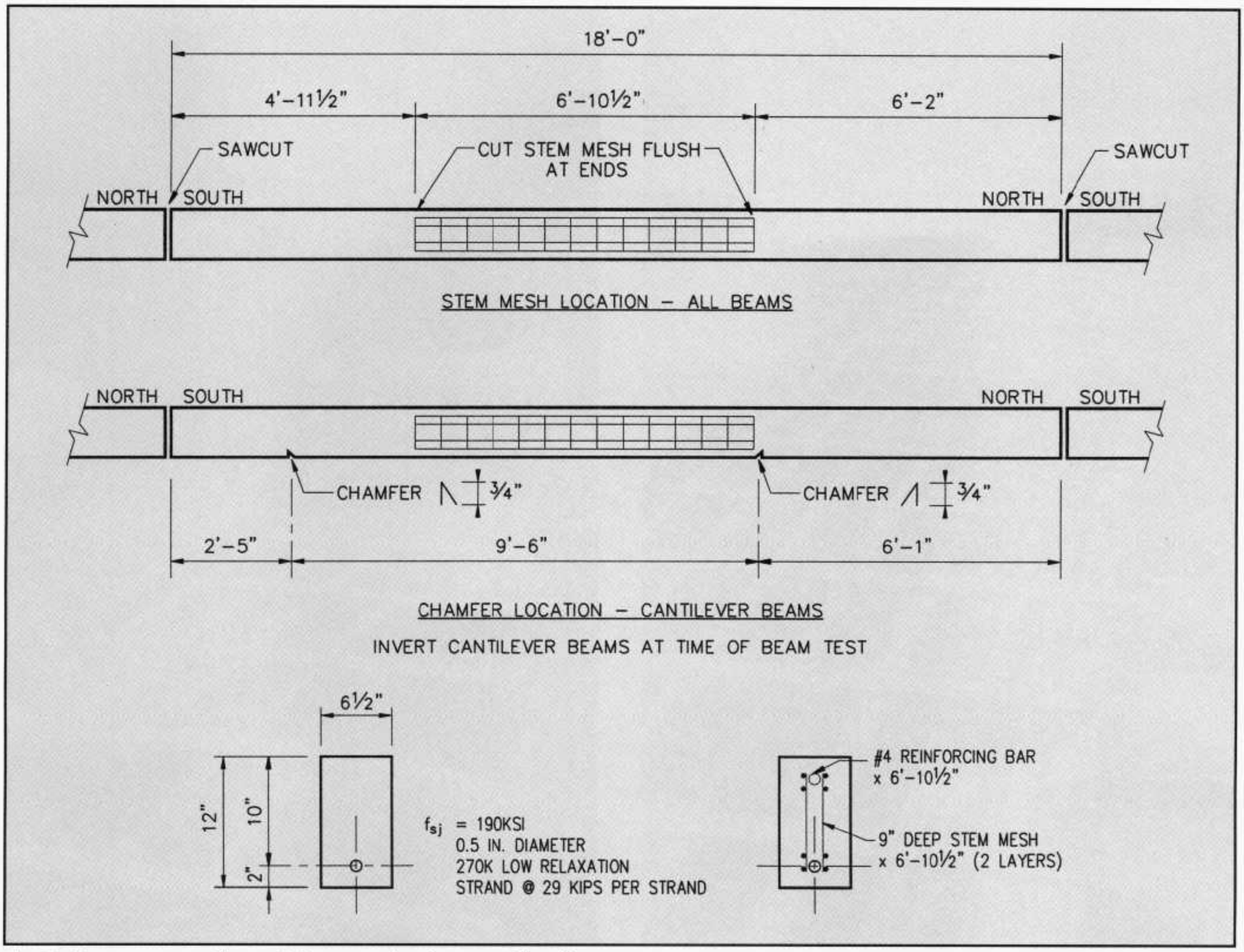


Fig. 9. Beam cross section, reinforcement and saw-cut locations.

to prevent concrete cracking (at ultimate load) within the transfer zone, for both the 4.83 and 6.08 ft (1.47 and 1.85 m) embedments. The beam cross section was 6.5 in. (165 mm) wide and 12 in. (305 mm) deep with the single strand centered at 2 in. (51 mm) from the bottom of the beam in its casting position. There was no shear reinforcement in the regions tested for strand development. The derivation of the ultimate capacity of the section, based on strain compatibility, is shown in Fig. A1 (see Appendix A).

Beams were cast in 90 ft (27.4 m) lengths in adjacent wood forms for each of the six strand groups. Figs. 7 through 9 show the configuration of the beams, cross section, layout of web reinforcement, and saw-cut locations. Beams were to be saw-cut into five 18 ft (5.49 m) lengths and were designed to permit development length tests at each end, providing two tests per beam, ten per group, for

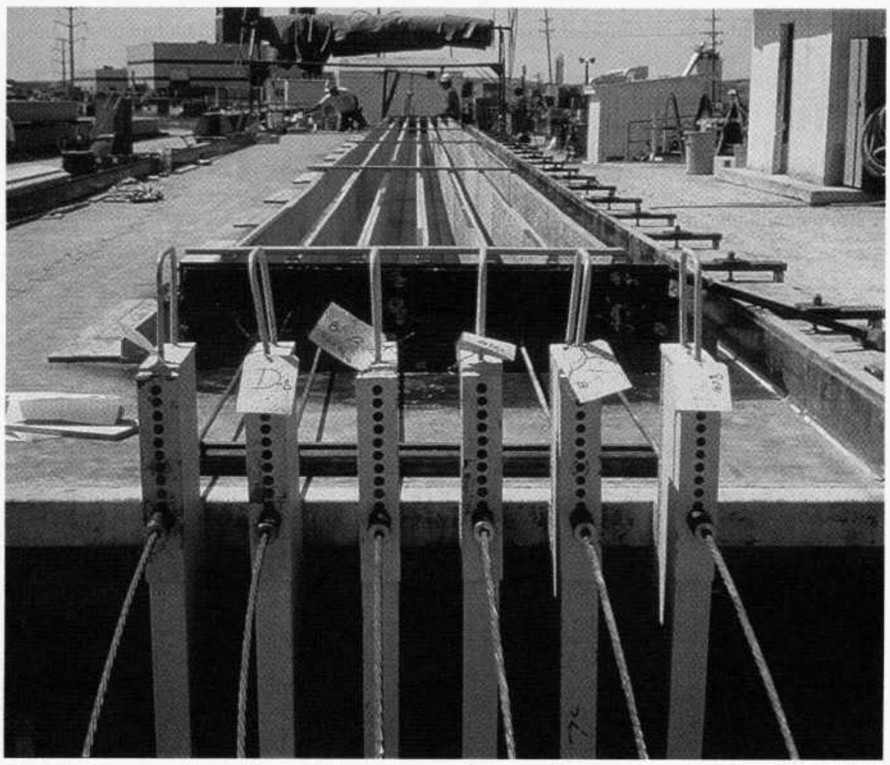


Fig. 10. Beam test specimens. ***Six*** **strand specimens after prestressing (May 17, 1996).**

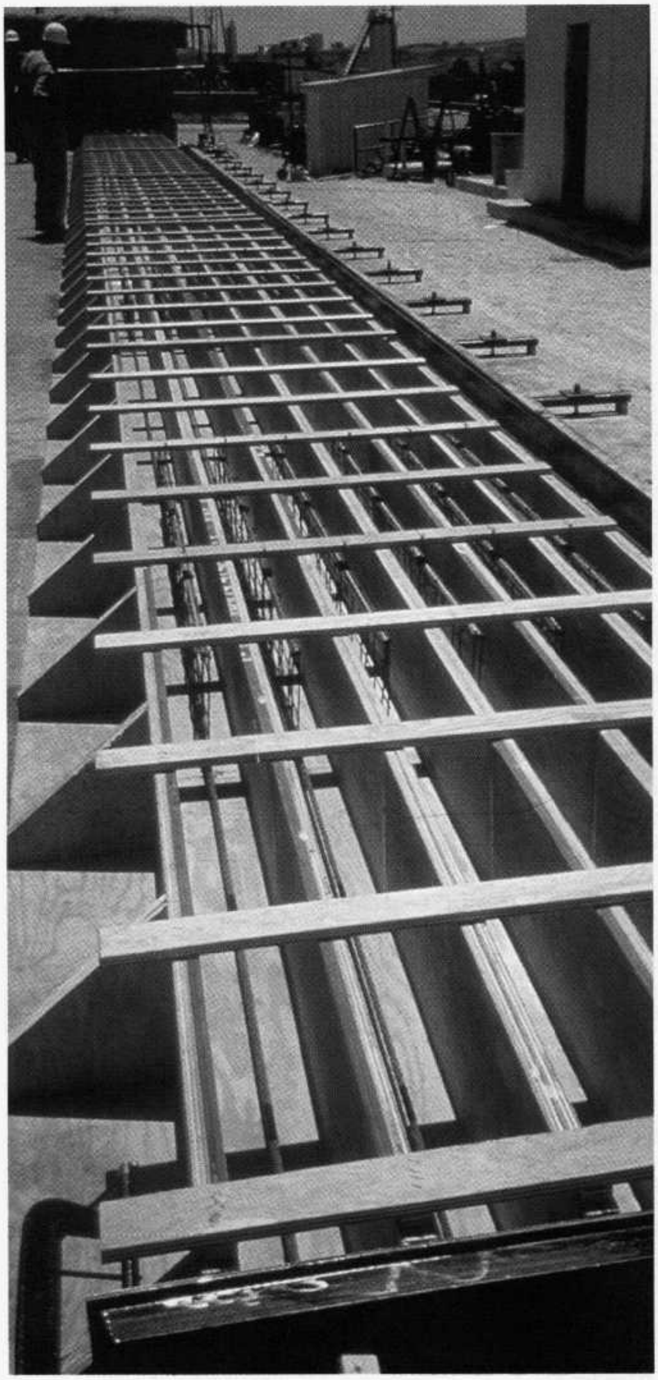


Fig. 11. Wood form, steel end plate, strand and web mesh in place, ready for concrete casting (May 17, 1996).

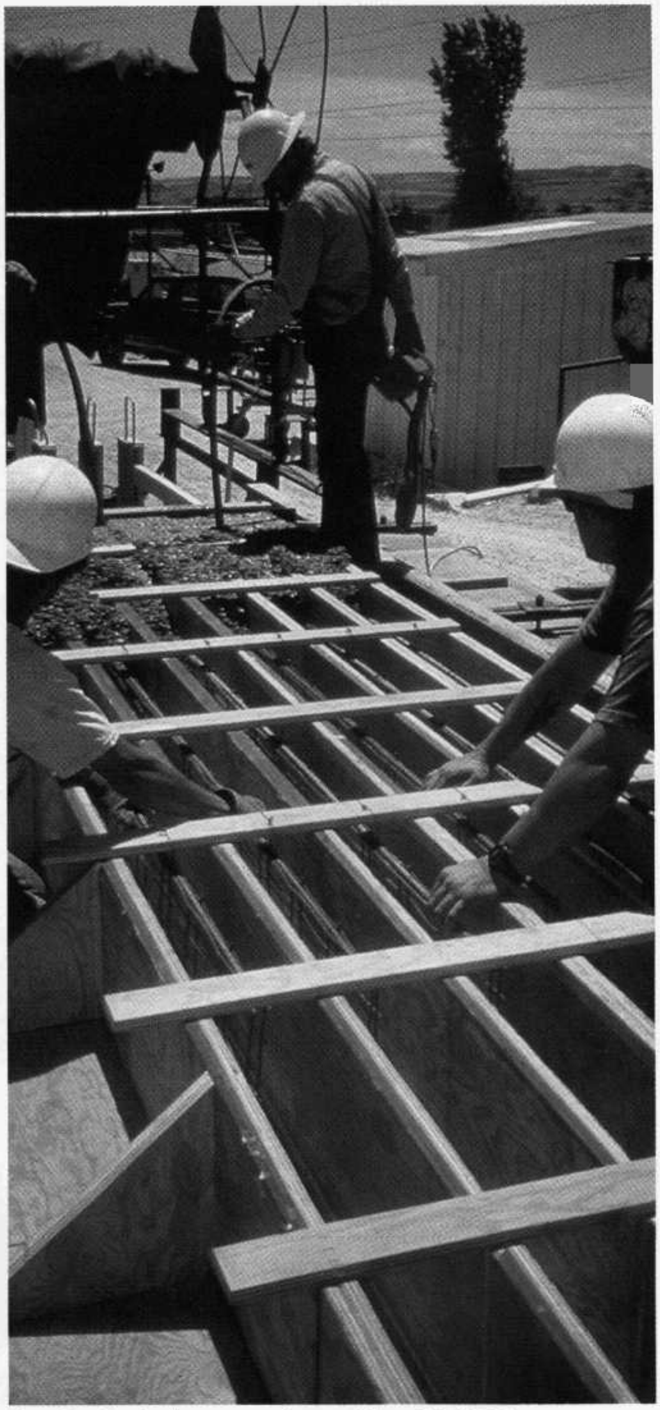


Fig. 12. Casting beam specimens (May 17, 1996).

a total of 60 development length tests.

The test beams were cast immediately after the pull-out blocks were cast. Concrete placement and vibration conformed closely to standard production techniques (see Figs. 10 through 12). Overnight heat curing was applied and prestress was released after it was established that companion heat-cured cylinders had attained an overnight strength of 4254 psi (29.3 MPa).

In order to simulate the most common production conditions, the release of prestress was sudden, rather than gradual.[6] Both ends of each 90 ft (27.4 m) test line were flame-cut simultaneously (see Fig. 13). Care was taken to avoid allowing any 90 ft (27.4 m) line to move during the flame-cutting operation. Then, each 90 ft (27.4 m) length was saw-cut into 18 ft (5.49 m) lengths (see Fig. 14).

The result was that, for each strand group, prestress was released by flame-cutting at two ends simulating a typical release for a fixed-form product such as a double tee, and by saw-cutting at eight ends simulating a typical release for a wet-cast hollow-core slab product. This resulted in the most severe release conditions for all ends of all beams.

Beams were stripped from the prestressing bed and handled with vacuum lifters in order to eliminate any lifting loops that might have otherwise disturbed the transfer and development length regions of the beams.

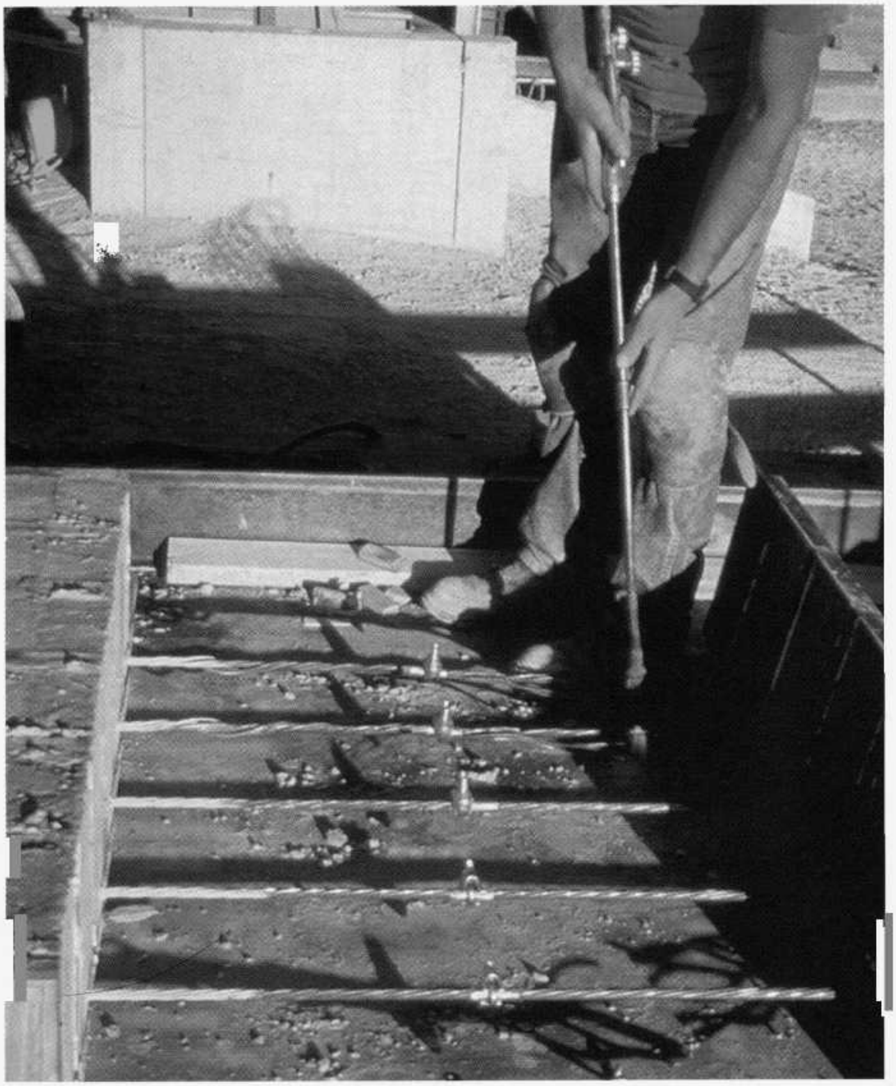


Fig. 13. Release of prestress force by flame-cutting at ends of 90 ft (27.4 m) beam length (May 18, 1996).

TEST PROCEDURES AND RESULTS

This section describes the pull-out test, transfer length and development length test methods, together with the major results of the investigation.

Pull-Out Test

Pull-out tests were conducted under the surveillance of Saad Moustafa on the morning after the test blocks were cast, at the overnight concrete strength indicated, and were observed and recorded by advisory group members Bruce Russell and Donald Logan. Figs. **15, 16** and **17** show the techniques used to apply the pull-out load to each strand sample. Appendix E describes in detail the complete procedure for conducting the pull-out test used in this test series (Moustafa method).

Fig. **18** compares the average pull-out capacity and standard deviation of each group with the **1974** benchmark.[12] Groups TW, TA, A, and B (six specimens per group) tested above **36** kips **(160** kN) average maximum pull-out capacity, **36.8** to **41.6** kips **(163** to **185** kN), and all except one of the 24 specimens appeared to bond well and failed abruptly after about **0.5** to 2 in. **(13** to **51** mm) movement.

Fig. 14. Release of prestress force by saw-cutting at ends of each 18 ft (5.49 m) beam length (May 18, 1996).

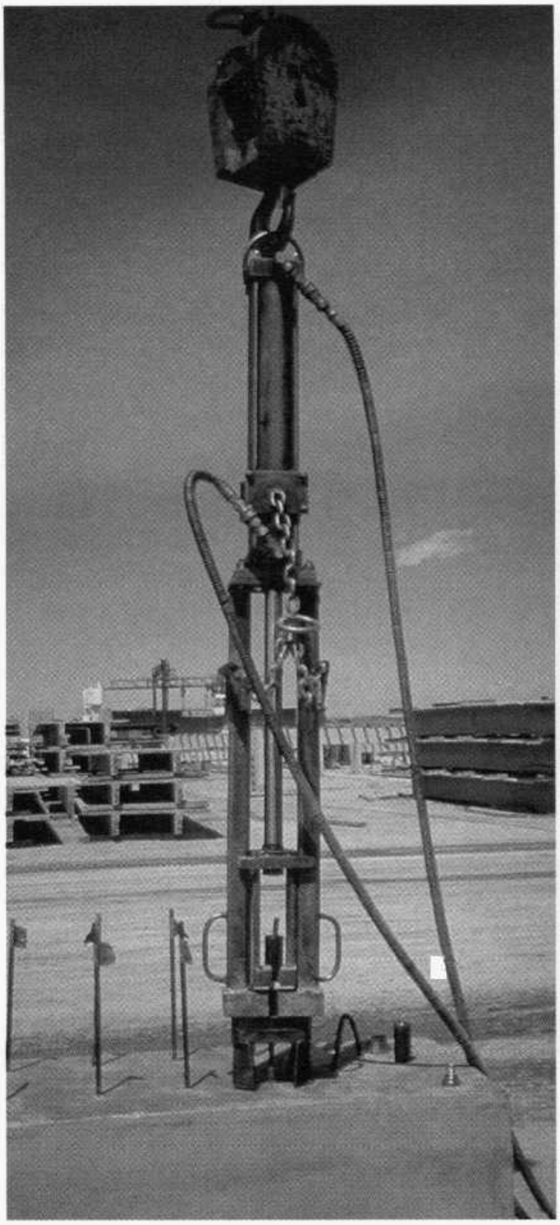


Fig. 15. Pull-out load applied with single strand jack (preliminary pull-out test series).

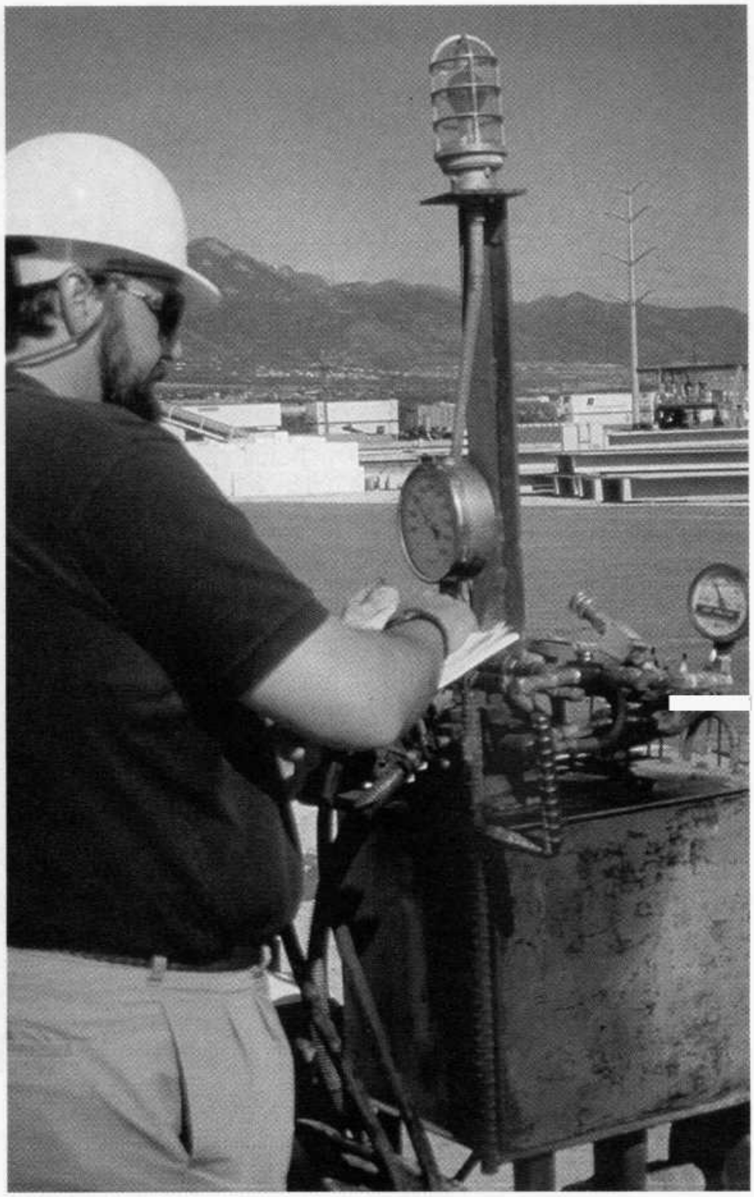


Fig. 16. Advisory group member Bruce Russell applying load at 20 kips per minute (89 kN/minute) and recording maximum pull-out load (May 18, 1996).

Two Groups, D and ER, only reached average maximum loads of 11.2 and 10.7 kips (49.7 and 47.5 kN), 30 percent of the 1974 benchmark level, and began to pull-out slowly from the test block at an applied load of only 7 kips (31 kN). Maximum load was reached after about 6 to 8 in. (152 to 203 mm) withdrawal, without the sudden impact associated with the other groups, and there appeared to be little paste bond between the strand and the concrete.

Table B1 in Appendix B provides more detailed information regarding the specific behavior of each of the 36 specimens in the pull-out test.

End Slip (Transfer length) Concept, Procedures and Results

Transfer length was measured indirectly from the measured end slip of the strand into the concrete at the end of the beam[10,11,14] (see Fig. 19). This simplified version is calculated using the familiar equation:

$$A = PUAE = fL/E \qquad (3)$$

or

$$\Delta = \text{avg}\, f_{si} L_{tr} / E_{ps} \qquad (4)$$

where

A = measured end slip, in.
avg f_{si} = average initial strand stress, over the transfer length, after release of prestress, ksi
L_{tr} = transfer length, in.
E_{ps} = elastic modulus of strand, ksi

Assuming a straight line variation in the strand stress from zero at the end of the beam to full prestress at the transfer length, L_{tr}, end slip can be expressed in terms of the reduction of the stress in the strand due to release of prestress as:

$$A = 0.5 f_{si} L_{tr} / E_{ps} \qquad (5)$$

Therefore, the implied transfer length, based on end slip, is:

$$L_{tr} = \Delta E_{ps} / (0.5 f_{si}) \qquad (6)$$

For this test series, the following values were used:

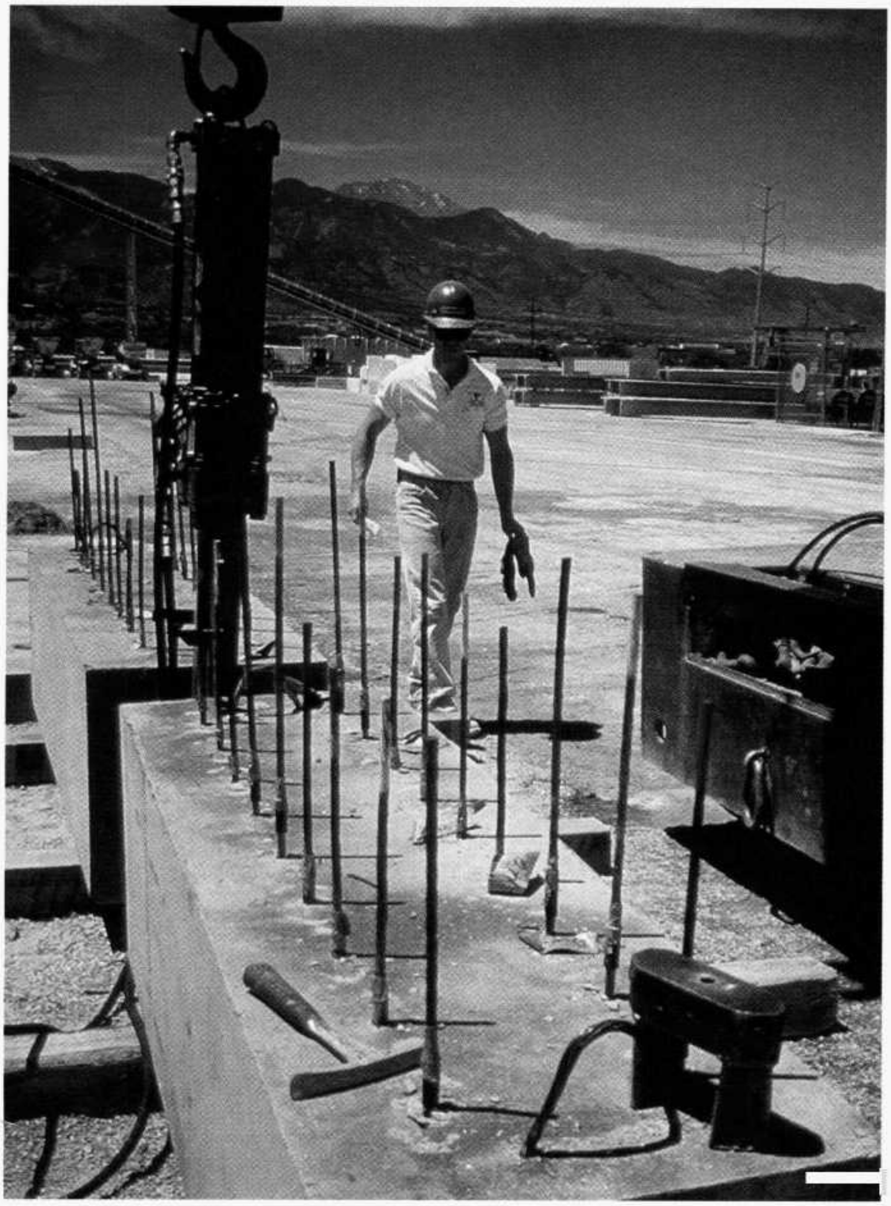


Fig. 17. Strand Groups D and ER pulled out 6 to 8 in. (152 to 203 mm) at 12 **kips** (53 kN) maximum load. Other groups exceeded 36 **kips** (160 kN) with less than 2 in. (51 mm) pull-out (May 18, 1996).

E_{ps} = 28,500 ksi (196500 MPa)

f_{si} = 0.98f (jacking) = 0.98 x 189

= 185 ksi (1276 MPa)

From Eq. (6):

L_{tr} = A x 28,500/(0.5 x 185)

= 3084 in. (3084 mm)

Ref. 13 provides a more detailed and exact analysis of this relationship and also accounts for the effects of concrete strain.

The applicable ACI equation for transfer length is related to the effective stress in the strand at the time of application of ultimate load, rather than the logical choice of initial prestress at transfer. Therefore, because the test would take place in 21 days, it was assumed that some additional loss would occur and the effective prestress, f_{se}, would be approximately equal to 175 ksi (1207 MPa). According to ACI 318 R12.9,[1] the expression for transfer length for strand diameter d_b = 0.5 in. (13 mm) is:

$L_{tr} = d_b f_{se}/3$ = 0.5 × 17513

= 29 in. (737 mm)

Strand slip measurements were taken immediately upon release of prestress on the morning of May 18, 1996, the day after the beams were cast, providing the initial (overnight) transfer lengths for each end of each beam. These initial measurements were taken by Stresscon engineer Craig Cason, and checked by Advisory Group member Bruce Russell.

For the flame-cut ends, the steel form plate was moved several feet away from the beam ends. A mark was then scribed, prior to flame-cutting, onto the strand at 1 in. (25 mm) from the formed face of the concrete at both ends of each of the 90 ft (27.4 m) beam lengths. After flame-cutting, the distance that the scribed mark moved was recorded as the initial end slip (see Fig. 20).

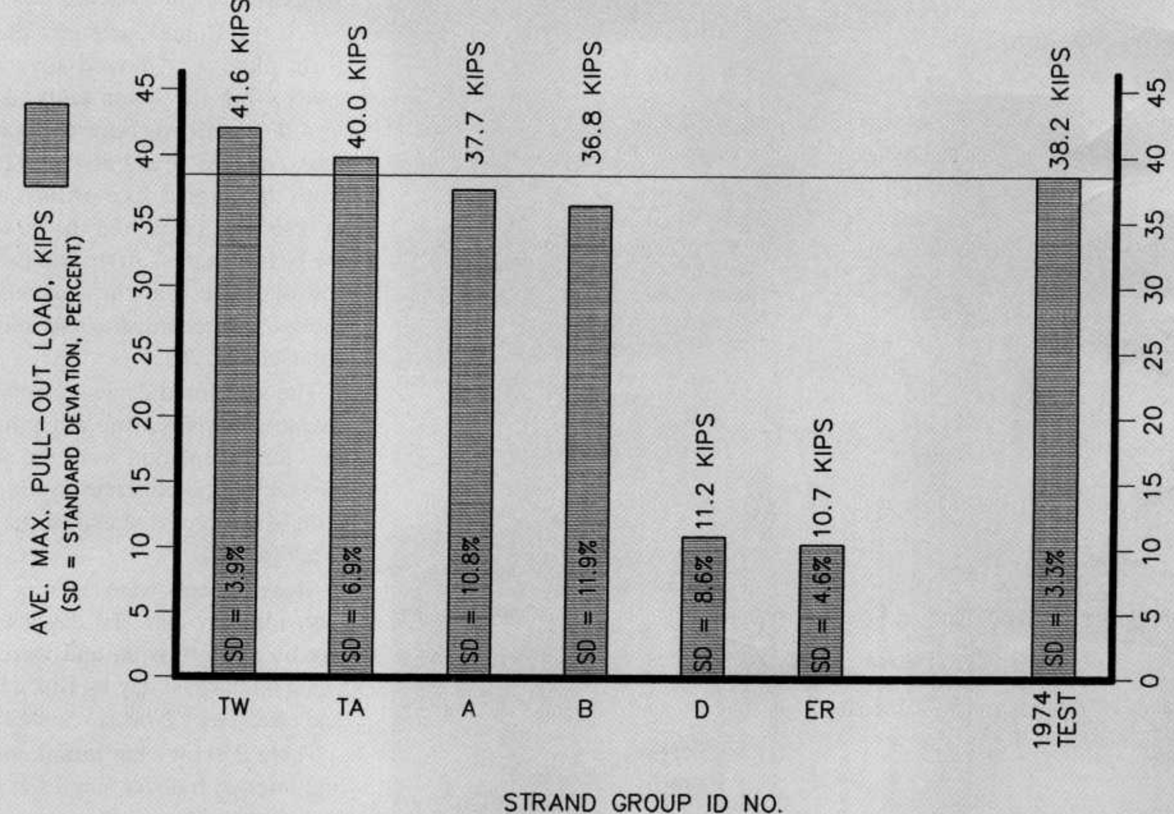
The slip for the saw-cut ends was measured by inserting a depth gauge into the indentation from the saw-cut surface of the concrete to the center wire of the recessed end of the strand (see Fig. 21).

Measurements were taken on the 7th day, 14th day and 21st day after casting by Craig Cason, and were taken again on the 21st day by Bruce Russell and checked by Norman Scott.

Table 2 shows the initial end slips and inferred transfer lengths at release of prestress. Despite the severe release conditions, the overnight transfer lengths were generally shorter than the 29 in. (737 mm) length predicted by the ACI equation. For Strand Groups TW, TA, A, and B, the transfer length averaged less than 15 in. (381 mm), Group D averaged 24 in. (610 mm), and Group ER averaged 34 in. (864 mm). Group ER was the only group that exceeded the predicted ACI length. Although the transfer lengths of the groups that performed so poorly in the pull-out tests did not appear to be excessive, the single result of 53 in. (1364 mm) on one of the strands in Group ER was a cause for concern.

Then, as subsequent weekly end slip measurements were taken, it quickly became apparent that the transfer lengths of Groups D and ER were increasing significantly. In 21 days, the average transfer length for Group D increased from 24 to 40 in. (610 to 1016 mm) and Group ER increased from 34 to 48 in. (864 to 1219 mm), both well beyond the 29 in. (737 mm) predicted by the ACI equation. For more specific information, refer to Table 2.

Until this test series, it was assumed that initial strand slip at transfer of prestress was stable and was a reliable



Notes:

(1) The above results are from the strand bond tests conducted at Stresscon Corporation and supervised by Saad Moustafa in May 1996 (six specimens per test).

(2) Strand specimens were embedded 18 in. (457 mm) into well vibrated concrete test blocks. Concrete was Stresscon's standard production mix. All strand was 0.5 in. (13 mm) in diameter.

(3) All strand specimens, except TW, were in their "as received" condition and were protected from weathering.

Fig. 18. Pull-out capacity **vs.** strand group.

indicator of the overall bond performance of strand in pretensioned concrete. The subsequent growth of the implied transfer length of the Group D strand from 24 to 40 in. (610 to 1016 mm) in just 21 days demonstrated that this is a seriously unconservative assumption. (Note: End slip due to prestress remains a reliable tool for measuring transfer length at any age of a structural member, and, as will be shown later in this report, end slip measured just prior to a beam test appears to be a reliable predictor of development length as well.)

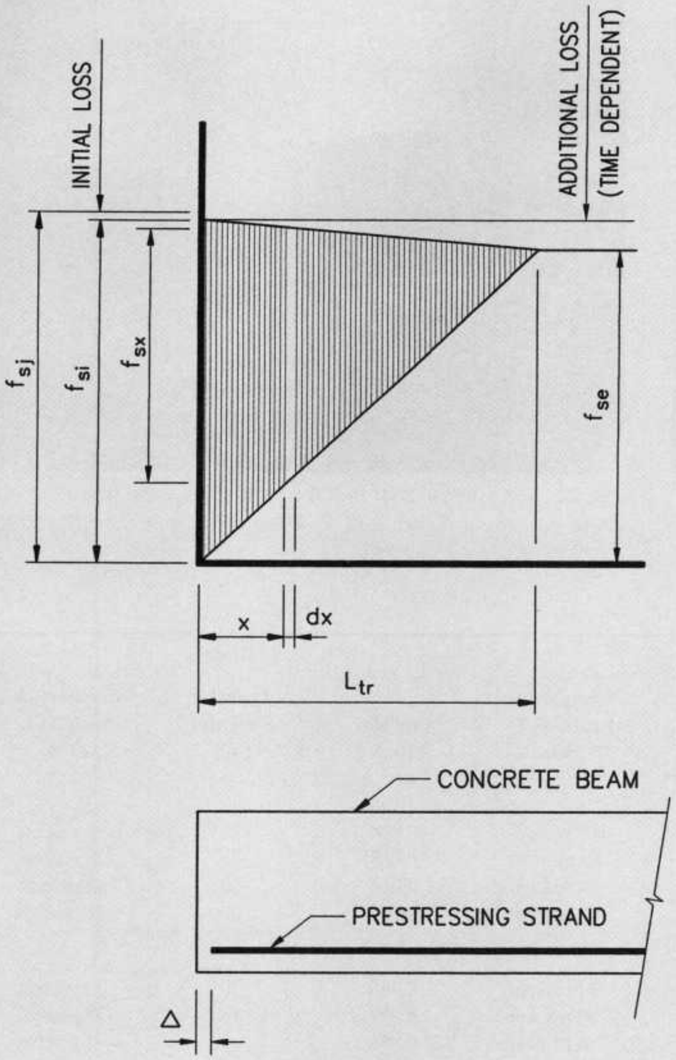
There was some growth in the end slips of Groups TW, TA, A, and B, but averages of the implied transfer lengths of all of these groups remained well below the transfer length predicted by the ACI equation. In addition, their end slips appeared to stabilize shortly after the initial release of prestress.

As a further check on the stability of strand having a pull-out capacity consistently exceeding 36 kips (160 kN), several hundred hollow-core slabs stored in the author's plant, ranging from one week to three years in age, were then checked for end slip at the saw-cut ends. No end slip in this group of over 4000 strand ends exceeded the 0.09 in. (2.3 mm) limit established for compliance with the ACI equation, and very few were greater than the typical 0.06 in. (1.5 mm) slip observed at release of prestress, indicating an implied transfer length of approximately 20 in. (508 mm) after slip is stabilized for the strands used in these products. The typical pull-out capacity of this strand has consistently ranged from 37 to 41 kips (164 to 182 kN) over the past four years of such testing.

Development length Test Procedures and Results

The development length computed by the ACI equation' is based on the stress in the strand, f_{ps}, at the calculated ultimate moment capacity of the section, as well as the effective prestress in the strand at the time of the test, f_{se}. The calculated ultimate capacity was based on a traditional strain compatibility analysis (Tadros stress-strain curve[15]), limiting the concrete strain to 0.003. The calculated f_{ps} on this basis is 263 ksi (1813 MPa), as derived in Appendix A (see Fig. A1).

Assuming f_{se} = 175 ksi (1207 MPa) after 21 days, the required develop-



PRESTRESSING STEEL STRESSES

f_{sj} = JACKING STRESS

f_{si} = INITIAL STRESS, AFTER INITIAL LOSS AT TRANSFER OF PRESSURES

f_{se} = EFFECTIVE PRESTRESS, VARIES WITH AGE OF MEMBER

f_{sx} = VARYING REDUCTION OF PRESTRESS LEVEL DUE TO RELEASE OF PRESTRESS. VARIES FROM f_{si} AT END OF BEAM TO ZERO AT L_{tr}

DEFINITIONS

Δ = MEASURED STRAND SLIP DUE TO RELEASE OF PRESTRESS

L_{tr} = TRANSFER LENGTH

E_{ps} = ELASTIC MODULUS OF PRESTRESING STEEL

ASSUMING A LINEAR VARIATION IN THE REDUCTION OF STEEL STRESS DUE TO RELEASE OF PRESTRESS, THROUGH CUTTING OF THE STRAND, AND IGNORING THE MINOR CONCRETE STRAIN IN THE L_{tr} REGION:

$$\Delta = \frac{\text{AVE. } f_{sx} L_{tr}}{E_{ps}} = \frac{0.5 \, f_{si} \, L_{tr}}{E_{ps}}$$

THEREFORE, FOR ANY MEASURED STRAND SLIP, Δ

$$L_{tr} = \Delta E_{ps} / (0.5 f_{si})$$

Fig. 19. Relationship of end slip to transfer length.

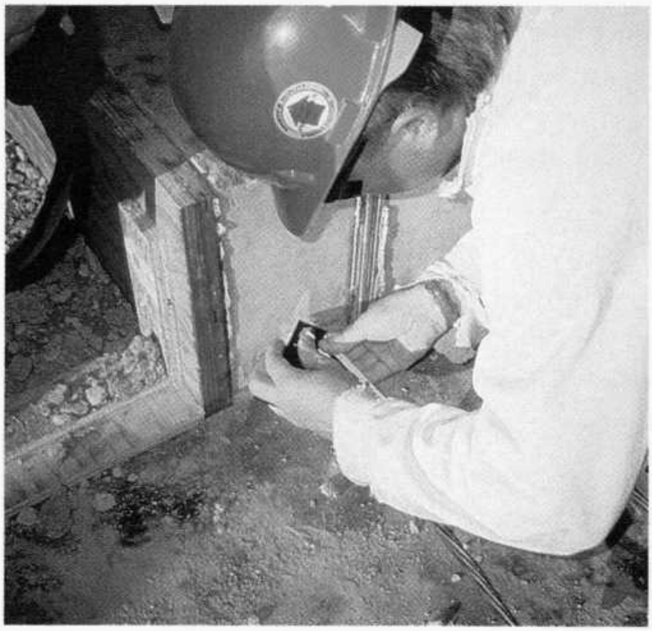


Fig. 20. Measurement of initial strand slip at release of prestress, flame-cut end (May 18, 1996).

Fig. 21. Measurement of initial strand slip at release of prestress, saw-cut end, June 7, 1996 (similar at May 18, 1996).

Table 2. Strand slip due to release of prestress force.*

Strand group	Pull-out capacity	At release			At 21 days		
		End slip (in.)	Transfer length (in.)	Comparison with ACI 29 in.	End slip (in.)	Transfer length (in.)	Comparison with ACI 29 in.
TW	**41.6 kips**						
Maximum recorded		0.078	24	-17 percent	0.080	25	-15 percent
Average flame-cut		0.068	21	-28 percent	0.068	21	-28 percent
Average saw-cut		0.043	13	-54 percent	0.064	20	-32 percent
Combined average		0.050	15	-47 percent	0.065	20	-31 percent
TA	**40.0 kips**						
Maximum recorded		0.062	19	-34 percent	0.066	20	-30 percent
Average flame-cut		0.047	14	-50 percent	0.059	18	-38 percent
Average saw-cut		0.041	13	-56 percent	0.056	17	-41 percent
Combined average		0.042	13	-55 percent	0.057	17	-40 percent
A	**37.7 kips**						
Maximum recorded		0.063	19	-33 percent	0.105	32	+12 percent
Average flame-cut		0.047	14	-50 percent	0.066	20	-30 percent
Average saw-cut		0.049	15	-48 percent	0.081	25	-14 percent
Combined average		0.049	15	-48 percent	0.079	24	-16 percent
B	**36.8 kips**						
Maximum recorded		0.063	19	-33 percent	0.072	22	-24 percent
Average flame-cut		0.055	17	-42 percent	0.068	21	-28 percent
Average saw-cut		0.045	14	-52 percent	0.058	18	-38 percent
Combined average		0.047	14	-50 percent	0.060	18	-36 percent
D	**11.2 kips**						
Maximum recorded		0.109	34	+16 percent	0.160	49	+70 percent
Average flame-cut		0.094	29	-0 percent	0.156	48	+66 percent
Average saw-cut		0.074	23	-21 percent	0.122	38	+30 percent
Combined average		0.078	24	-17 percent	0.129	40	+37 percent
ER	**10.7 kips**						
Maximum recorded		0.172	53	+83 percent	0.188	58	+100 percent
Average flame-cut		0.117	36	+24 percent	0.149	46	+58 percent
Average saw-cut		0.109	34	+16 percent	0.157	48	+67 percent
Combined average		0.111	34	+18 percent	0.156	48	+66 percent

Note: 1 in. = 25.4 mm; 1 kip = 4.44 kN.

* Transfer length, according to ACI equation = 29 in., for test conditions.

ment length according to the ACI Code equation' in Section R12.9 is:

$$L_{dev} = d_b f_{se}/3 + d_b(f_{ps} - f_{se})$$
$$= 0.5(175/3) + 0.5\ (263 - 175)$$
$$= 73 \text{ in.} = 6.08 \text{ ft } (1.85 \text{ m})$$

Four different types of development length tests were conducted on each of the six strand groups, as shown in Table 3. Refer also to Figs. 22 and 23.

The 60 tests were conducted on June 8 and 9, 1996, the 22nd and 23rd days after the beam specimens were cast. Figs. 22 through 28 illustrate the load test layouts, testing procedures and observations during the tests. The tests were conducted by advisory group members Roger Becker, Donald Logan, Don Pellow, Bruce Russell, and Norman Scott, along with observers Simon Harton and Mark Brooks.

Table 4 gives the results of the flexural beam development length tests for each of the strand groups and shows the failure load, the mode of failure, and the degree of warning deflection prior to failure.

Strand Groups TW, TA, A, and B, with pull-out capacities exceeding 36 kips (160 kN), performed extremely well in the development length tests. All failures were flexural in the 6.08 and 4.83 ft (1.85 and 1.47 m) embedment tests. No end slip occurred during testing, and there was ample warning deflection prior to failure. (Refer to Appendix C, Tables C1 to C6, for detailed information regarding each of the 60 load tests.)

In most cases, failure was the result of the strand breaking in tension at stress levels well above the 270 ksi (1862 MPa) guaranteed ultimate strength of these strands (see Figs. 25 through 27). Because the strand stress was so high, this test series represents an extremely severe test of the bond capacity of these strand groups. Group TA surpassed all other groups in bond capacity by failing in flexure (strand break) with only 29 in. (737 mm) of embedment in the short cantilever test.

Conversely, Strand Groups D and ER, which had pull-out capacities less than 12 kips (53.3 kN), performed poorly in all flexural beam tests and at all embedment lengths. All failures were due to loss of bond between the steel and concrete. There was usually only one crack, directly under the applied test load, and bond failure occurred upon or shortly after the formation of that crack. The crack opened wide and the end slip of the strand at failure generally matched the width of the crack at the level of the strand. There was no obvious warning deflection prior to failure, making this a seriously undesirable mode of failure for these strands (see Fig. 28).

The bond failure of the D and ER strand groups appeared to be the result of their inability to recover flexural bond to the concrete in the region immediately adjacent to the location of the first crack, where the strand stress and demand on bond capacity increase sharply at cracking. As the load is sustained or increases slightly, the paste bond appears to break down progressively toward the end of the beam until this loss of bond reaches the pre-

Table 3. Embedment lengths of six strand groups for simple span and cantilever load conditions.

Load condition	Embedment length L_e	Number of tests per group
Simple span	L_e = ACI development length (6.08 ft)	4
Simple span	L_e = 80 percent of ACI L_{dev} (4.83 ft)	4
Cantilever	L_e = ACI development length (6.08 ft)	1
Cantilever	L_e = ACI transfer length (2.42 ft)	1

Note: 1 ft = 0.3048 m.

Table 4. Flexural beam development length tests.

Group	Failure mode (average)	f_{ps}	Warning deflection (average)
	Simple span 12.87 ft; L_e = 6.08 ft		
TW	Flexure/strand break	280 ksi	2 in.
TA	Flexure/strand break	283 ksi	2 in.
A	Flexure/strand break	278 ksi	2 in.
B	Flexure/strand break	277 ksi	2.5 in.
D	Bond	220 ksi	0.1 in.
ER	Bond	205 ksi	0.1 in.
	Cantilever span 5.75 ft; L_e = 6.08 ft		
TW	Flexure/strand break	286 ksi	5.5 in.
TA	Flexure/concrete spall	286 ksi	5.5 in.
A	Flexure/concrete spall	282 ksi	5 in.
B	Flexure/concrete spall	282 ksi	5 in.
D	Bond	230 ksi	0.6 in.
ER	Bond	208 ksi	0.6 in.
	Cantilever span 2.08 ft; L_e = 2.42 ft		
TW	Concrete split/bond	250 ksi	1.2 in.
TA	Flexure/strand break	278 ksi	2 in.
A	Flexure/concrete crush	223 ksi	4.5 in.
B	Flexure/concrete crush	262 ksi	3.5 in.
D	Bond	107 ksi	0.1 in.
ER	Bond	96 ksi	0.1 in.
	Simple span 11.37 ft; L_e = 4.83 ft		
TW	Flexure/strand break	284 ksi	1.7 in.
TA	Flexure/strand break	284 ksi	1.6 in.
A	Flexure/strand break	286 ksi	2 in.
B	Flexure/strand break	278 ksi	2 in.
D	Bond	179 ksi	0.1 in.
ER	Bond	177 ksi	0.1 in.

Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 ksi = 6.895 MPa.

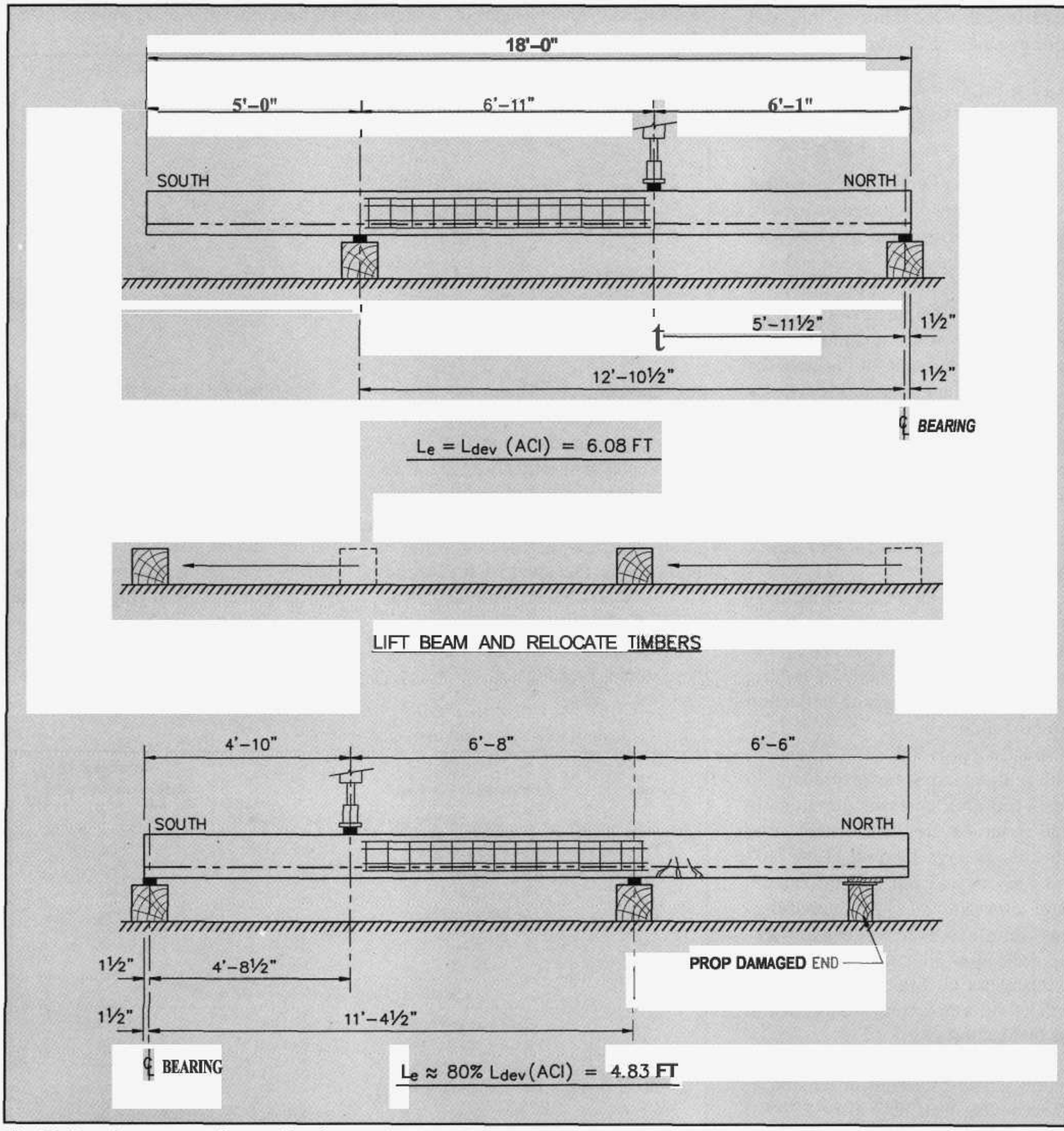


Fig. 22. Development test layout (simple spans).

stress transfer region, whereupon the mechanical bond in the transfer region is not able to hold the increased load in the strand.

APPLICABILITY OF MAST'S STRAND SLIP THEORY

In **1980,** Robert Mast suggested to the author that the factors which affect initial strand slip (transfer length) upon transfer of prestress may have a proportional effect on flexural bond length. If so, in cases where such strand slip can be measured, that slip can be utilized to modify the ACI equation for not only transfer length, but also to modify the flexural bond length equation. Therefore, development length can be predicted from measured strand slip due to transfer of prestress.

Mast's slip theory was tested and verified in the mid **1980s** for strands with excess strand slip (transfer length greater than that predicted by the ACI equation). That test program was conducted at the University of Colorado and was the subject of a report by Brooks, Gerstle and Logan."

The current test program afforded another opportunity to evaluate this concept, but on this occasion, end slips due to release of prestress implied transfer lengths both shorter than and longer than those predicted by the ACI equations. Advisory group member Roger Becker, who conducted research on Mast's slip theory at the

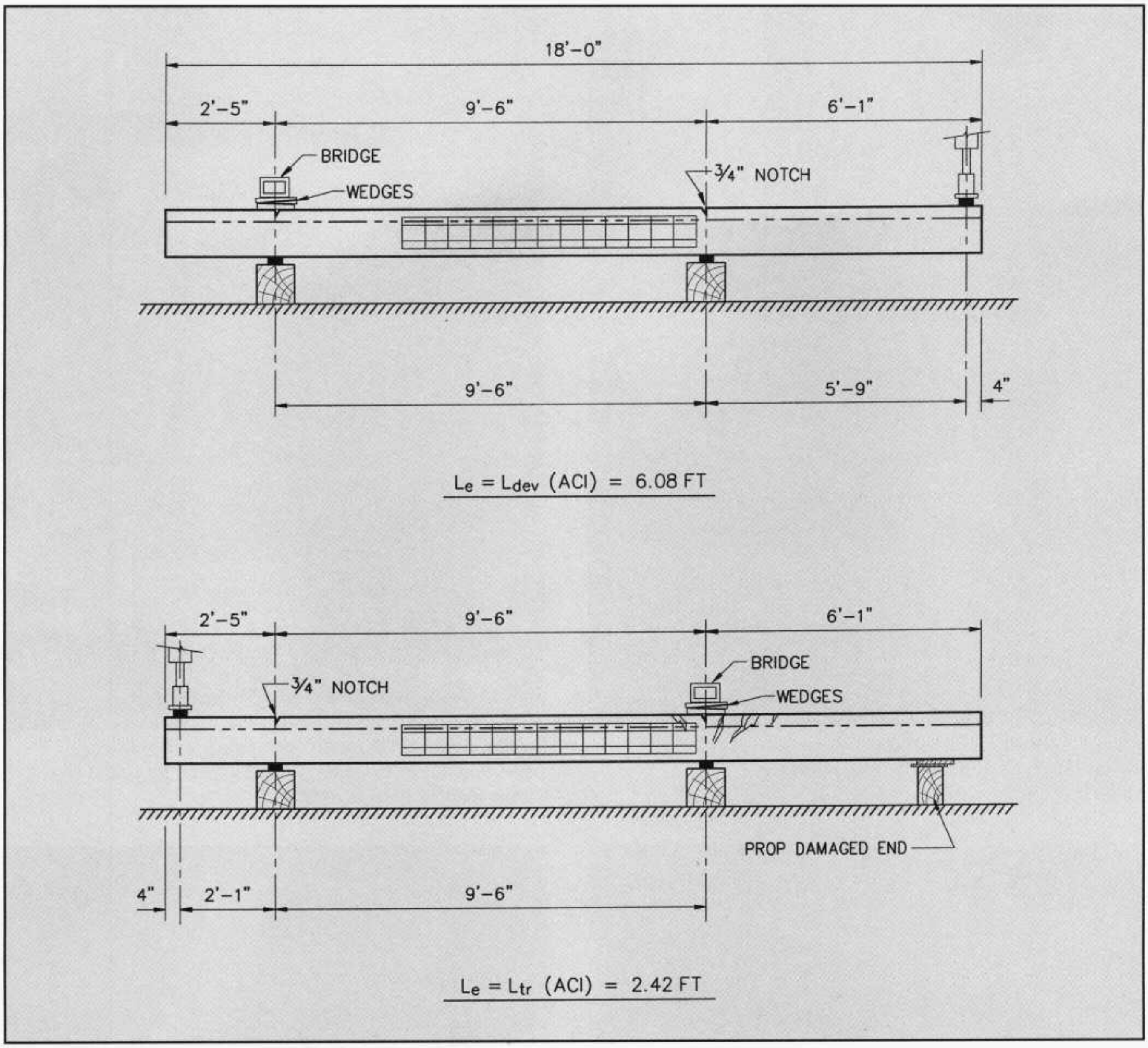


Fig. 23. **Development test layout (cantilevers).**

University of Wisconsin, Milwaukee, in the early 1980s, analyzed the results of this test series and found excellent correlation with Mast's concept.

Fig. 29 illustrates Mast's slip theory as it applies to the simple beam conditions tested in this series for strand slips due to release of prestress. Three conditions are illustrated

End slip = 0.09 in. (2.3 mm)
L_{dev} = ACI L_{dev}

End slip < 0.09 in. (2.3 mm)
L_{dev} < ACI L_{dev}

End slip > 0.09 in. (2.3 mm)
L_{dev} > ACI L_{dev}

In all three cases, the nominal capacity, M_n, remains the same, but the transfer lengths and flexural bond

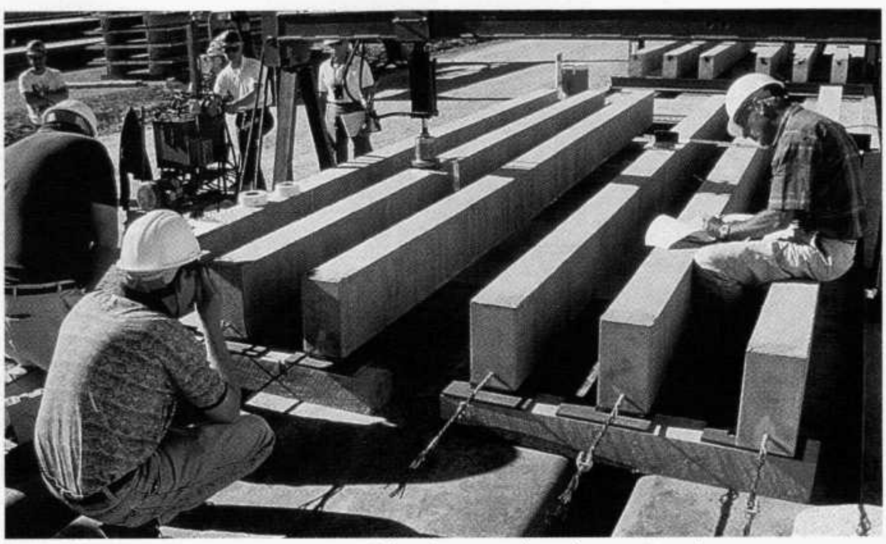


Fig. 24. First six-beam line at **start of development length test. Simple span,** L_e **= 6.08 ft (1.85 m)** (June 8, **1996).**

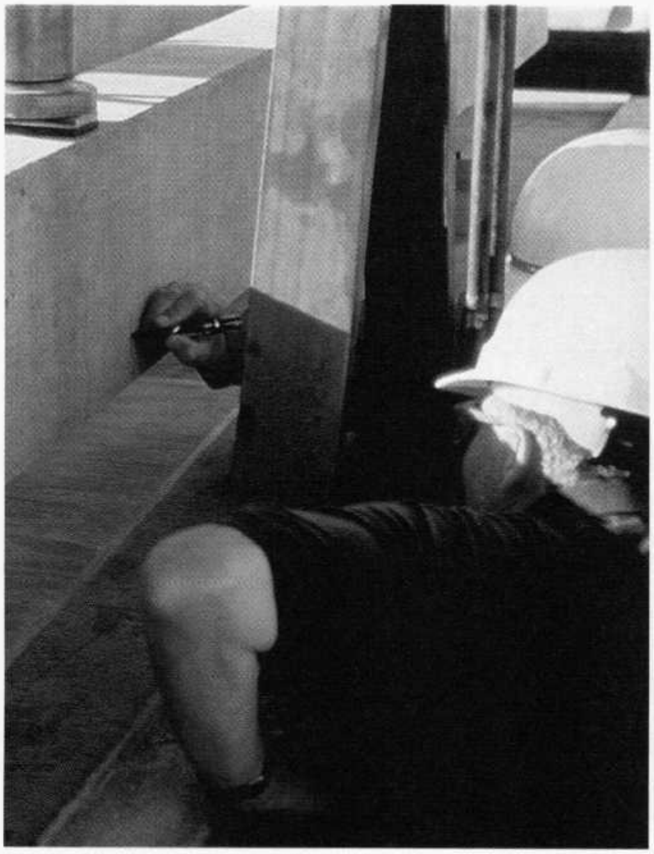


Fig. 25. Detecting and marking first cracks, Beam TW-5, L_e = 6.08 ft (1.85 m) north end (June 8, 1996).

Fig. 26. Beam TW-5 (north end) approaching failure, deflection = 2 in. (51 mm). Observing end for strand slip during loading (June 8, 1996).

Fig. 27. Strand break, Beam TW-5 (north end). Energy release from 43 kip (191 kN) load in strand caused 6.08 ft (1.85 m) beam end to rebound 6 in. (152 mm) to north (June 8, 1996).

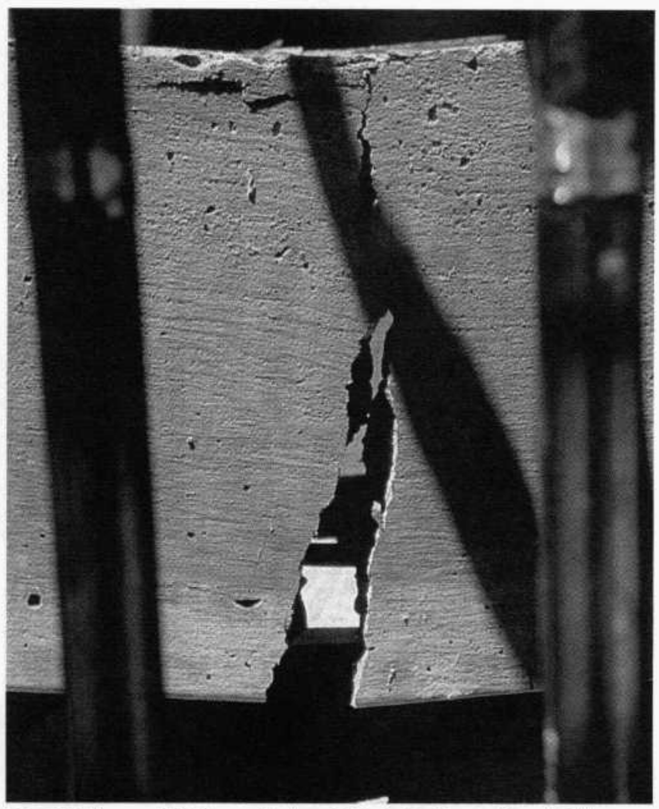


Fig. 28. Beam ER-2 (south) L = 4.58 ft (1.40 m). Bond failure occurred upon formation of first crack. Deflection = 0.1 in. (2.54 mm) prior to sudden failure. Strand slip at end = crack width (June 9, 1996).

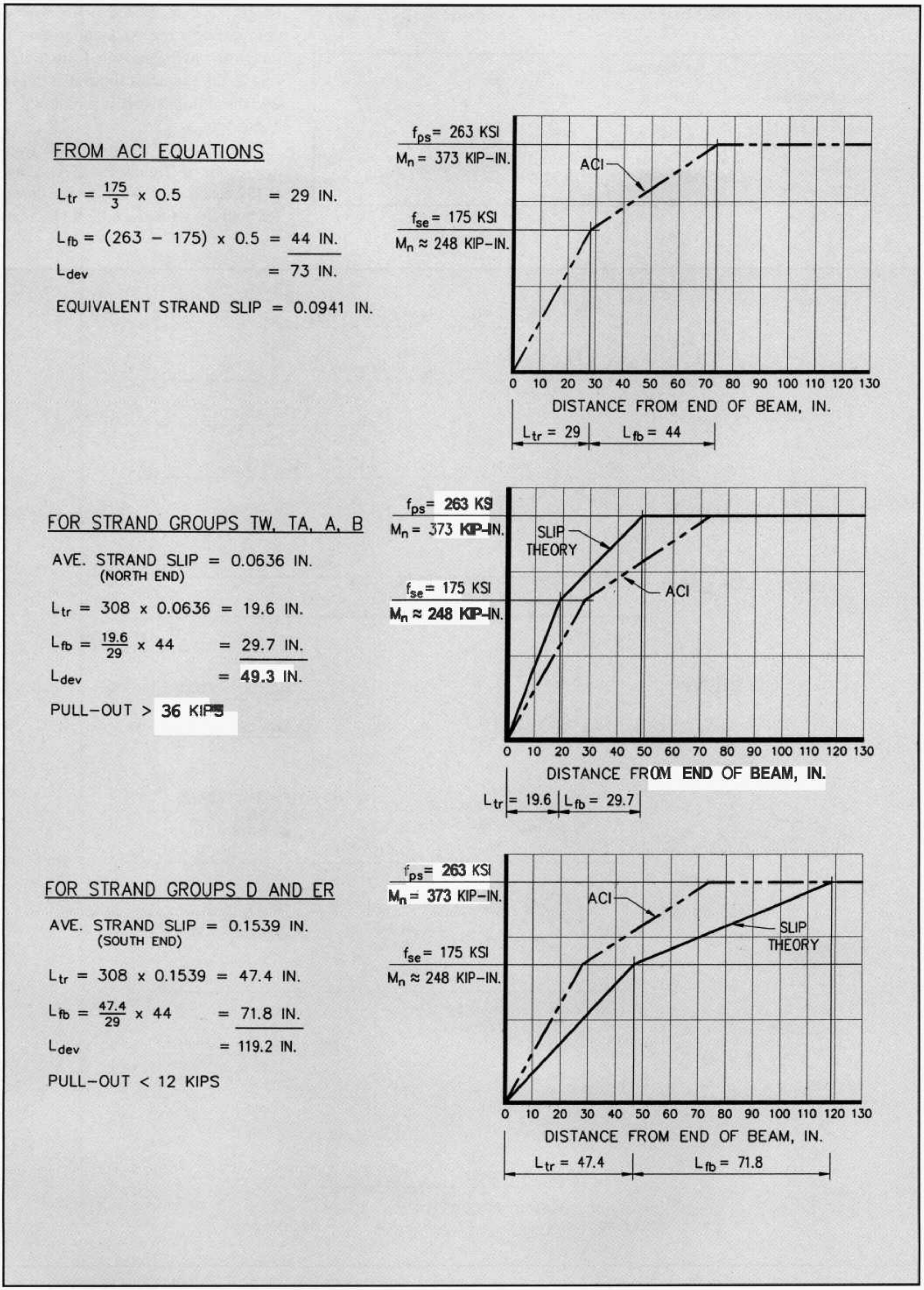


Fig. 29. Modified bilinear development curves based on Mast's strand slip theory.

Table 5. Comparison of transfer and flexural bond lengths of strand test results with ACI equation.

	End slip	L_{tr} +	L_{fb} =	L_{dev}
Per ACI equation	0.0941 in.	29 in.	44 in.	73 in.
Groups TW, TA, A, B (average, north end)	0.0363 in.	19.6 in.	29.7 in.	49.3 in.
Groups D, ER (average, south end)	0.1539 in.	47.4 in.	71.8 in.	119.2 in.

Note: 1 in. = 25.4 mm.

lengths are decreased or increased, compared to the ACI equations, in proportion to the measured slip. Referring to the examples illustrated in Fig. 29, the comparison is as shown in Table 5.

Figs. 30 and 31 compare the average results of Groups TW, TA, A, and B (32 tests) with Mast's slip theory for both the 6.08 and 4.83 ft (1.85 and

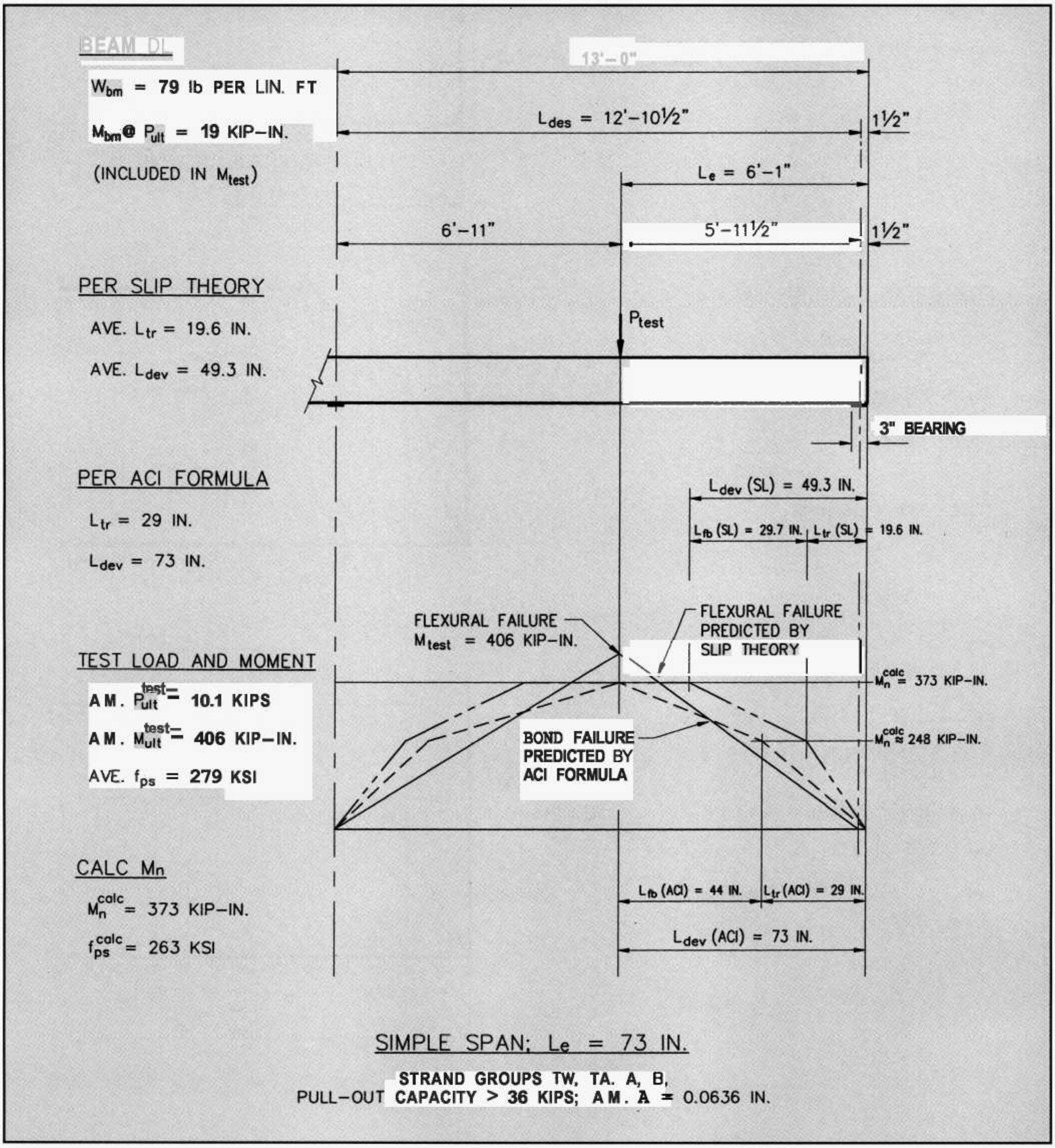


Fig. 30. Mast's strand slip theory. Simple span, L_e = 73 in. (1854 mm); Strand Groups TW, TA, H, B. Pull-out capacity greater than 36 kips (160 kN); average strand slip = 0.0636 in. (1.62 mm)

1.47 m) embedment cases in the simple beam tests. In both cases, the ACI equation predicted bond failure prior to reaching the final test load, whereas the slip theory correctly predicted the flexural failure mode at the final test load, which actually occurred in all 32 tests.

Figs. 32 and 33 compare the average results of Groups D and ER (16 tests) with Mast's slip theory for both the 6.08 and 4.83 ft (1.85 and 1.47 m) embedment cases in the simple beam tests. In neither case did the beams reach the failure loads predicted by the ACI equations, whereas the slip theory correctly predicted the premature bond failures which actually occurred in all 16 tests.

VISUAL INSPECTION, RESIDUE TEST, AND LAY MEASUREMENTS

Many observers have noted differences in appearance, color, noticeable residue, and lay measurement of strand from various manufacturers and have questioned whether those observed characteristics might be related

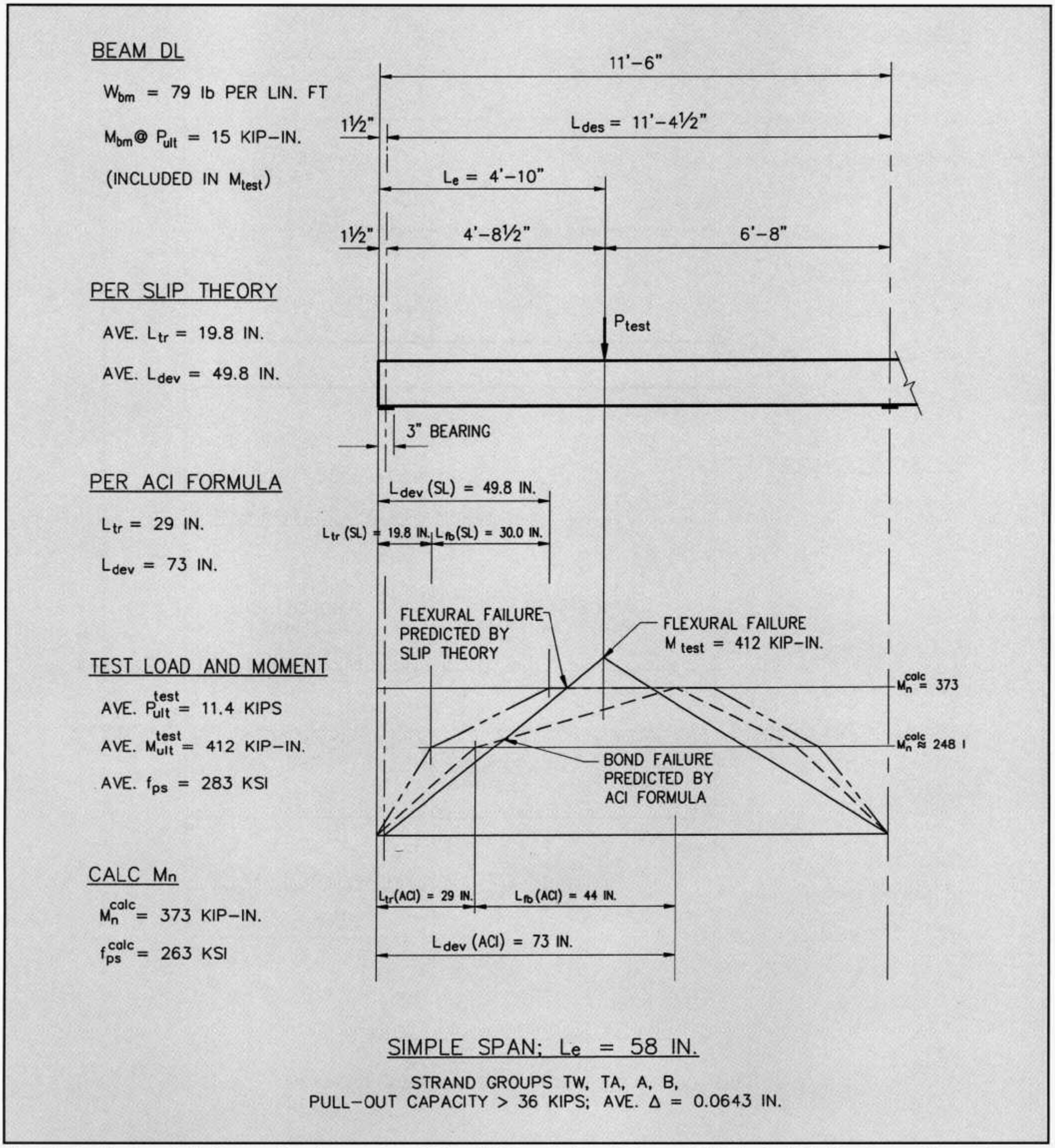


Fig. 31. Mast's strand slip theory. Simple span, $L_e = 58$ in. (1473 mm); Strand Groups TW, TA, A, B. Pull-out capacity greater than 36 kips (160 kN); average strand slip = 0.0643 in. (1.63 mm).

to differences in pull-out capacity and/or transfer and development performance.

In response to these questions, visual inspection, towel wipe for residue, and lay measurements were conducted on each strand group. The results for each group are shown in Table B 1 of Appendix B.

Color

In this test series, the poorest performing strand groups, D and ER, appeared to be slightly brassy in color, compared to the black/blue color of the other groups, but that difference was too subtle to be a reliable bond quality guide.

Noticeable Residue

The poorest performing groups, D and ER, had heavy residue in the towel wipe test, but the residue on the best performing as-received strand group, TA, was also heavy, and there was no discernible difference that could serve as a reliable guide (see

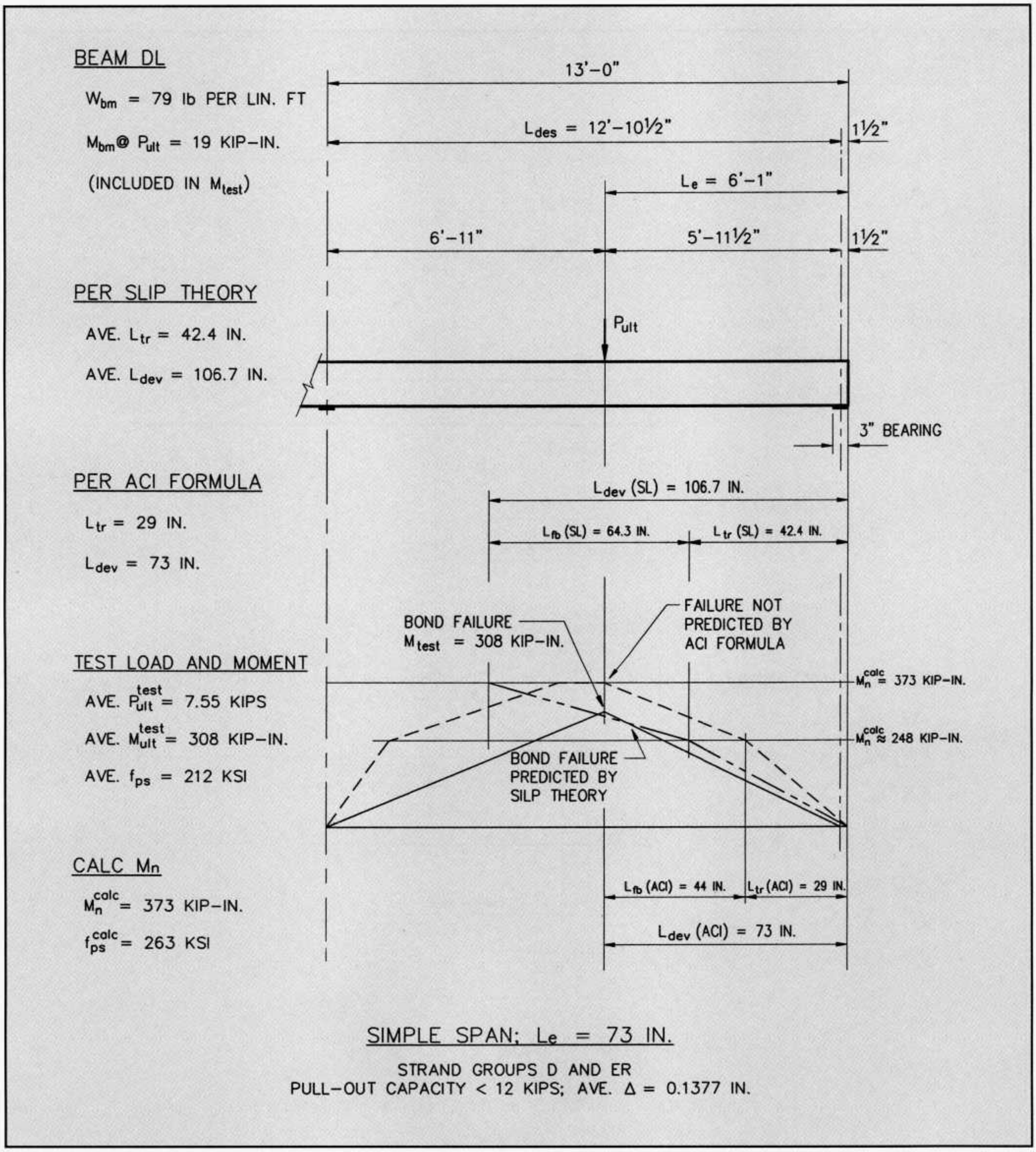


Fig. 32. Mast's strand slip theory. Simple span, L_e = 73 in. (1854 mm); Strand Groups D and ER. Pull-out capacity less than '2 kips (53 kN); average strand slip = 0.1377 in. (3.50 mm).

Fig. 34 through 36). The cleanest strand group, B, had the lowest pull-out capacity of the top four groups, but it was the second best performer in the transfer length test, and performed almost as well as the best group, TA, in the flexural beam tests. It is clear that a simple towel wipe test for a qualitative check of removable residue is not a reliable indicator of bond quality.

Rust

It has been claimed for years that a light coating of rust enhances the bond capacity of strand." In this series, the TA and TW groups represented strand from the same manufacturer and from the same shipment of strand to a concrete producer. The TA group had been protected from weathering, and the TW group had been put into service in that producer's yard and had developed obvious light rust throughout its length.

In preliminary pull-out tests, Group TA had a slightly higher pull-

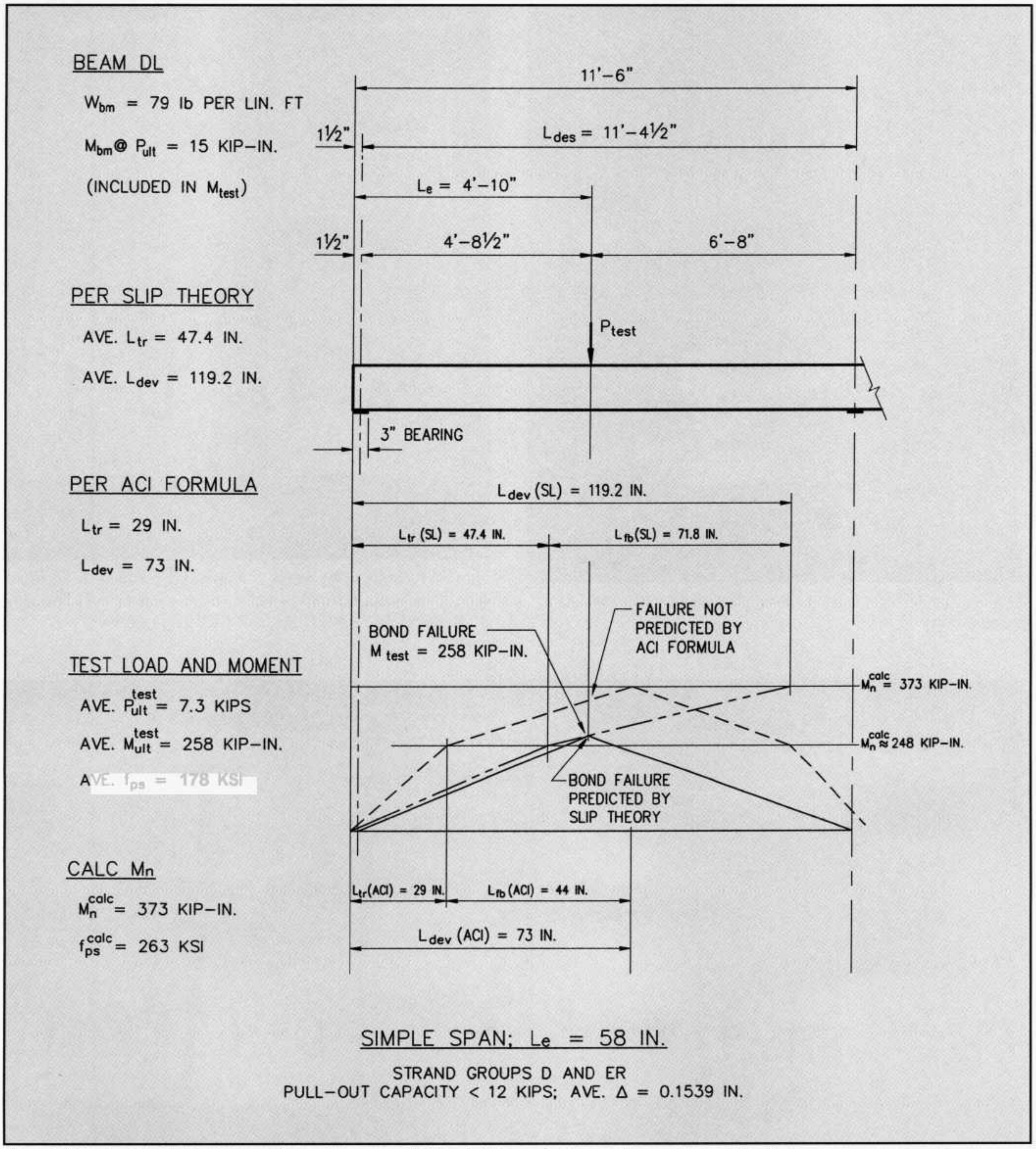


Fig. 33. Mast's strand slip theory. Simple span, L_e = 58 in. (1473 mm); Strand Groups D and ER. Pull-out capacity less than 12 kips (53 kN); average strand slip = 0.1539 in. (3.91 mm).

out capacity than Group TW. In the final pull-out tests, the ranking reversed, but both groups tested about **40** kips (178 kN). The TA group, as well as Group B, which had the cleanest, smoothest surface, performed better in end-slip tests (transfer length) than the weathered group, TW. All of the top three as-received strand groups performed as well as the weathered group, TW, in the flexural beam development length tests, except that TA out-performed all other groups by developing its full tensile strength with an embedment of only 29 in. (737 mm).

Thus, it can be concluded that strand purchased from certain manufacturers, used directly from freshly delivered coils, is at least **equal** to weathered strand in achieving outstanding bond quality.

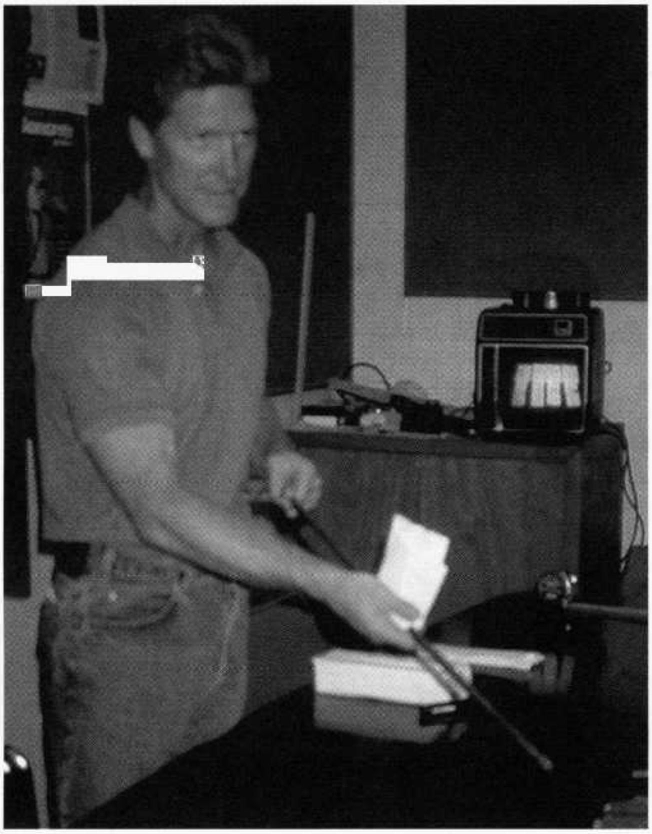


Fig. 34. Towel-wipe test for removable residue from strand sample (May 17, 1996).

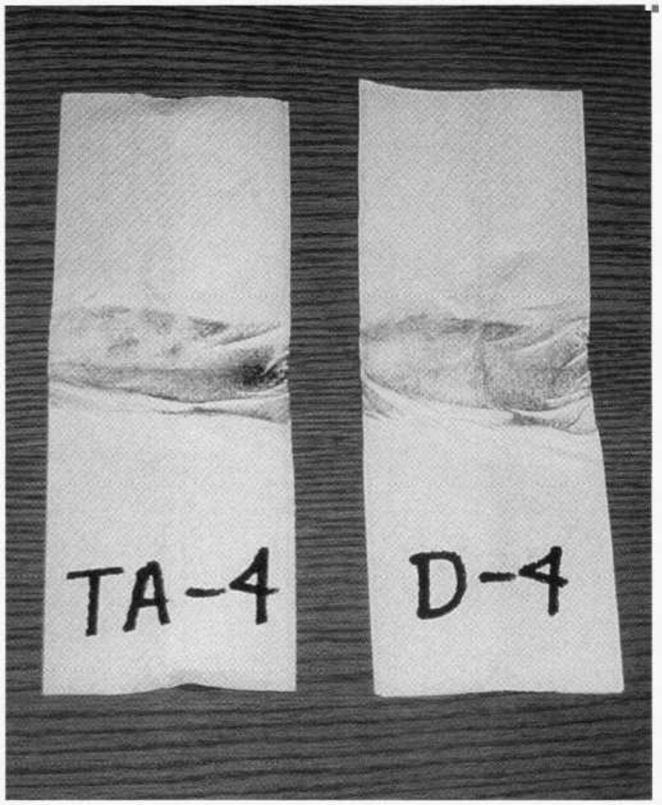


Fig. 36. Residue from Strand Samples TA-4 and D-4. Residue difference is not distinguishable. Pull-out capacities: TA(avg) = 40.0 kips (177.7 kN); D(avg) = 11.2 kips (49.8 kN).

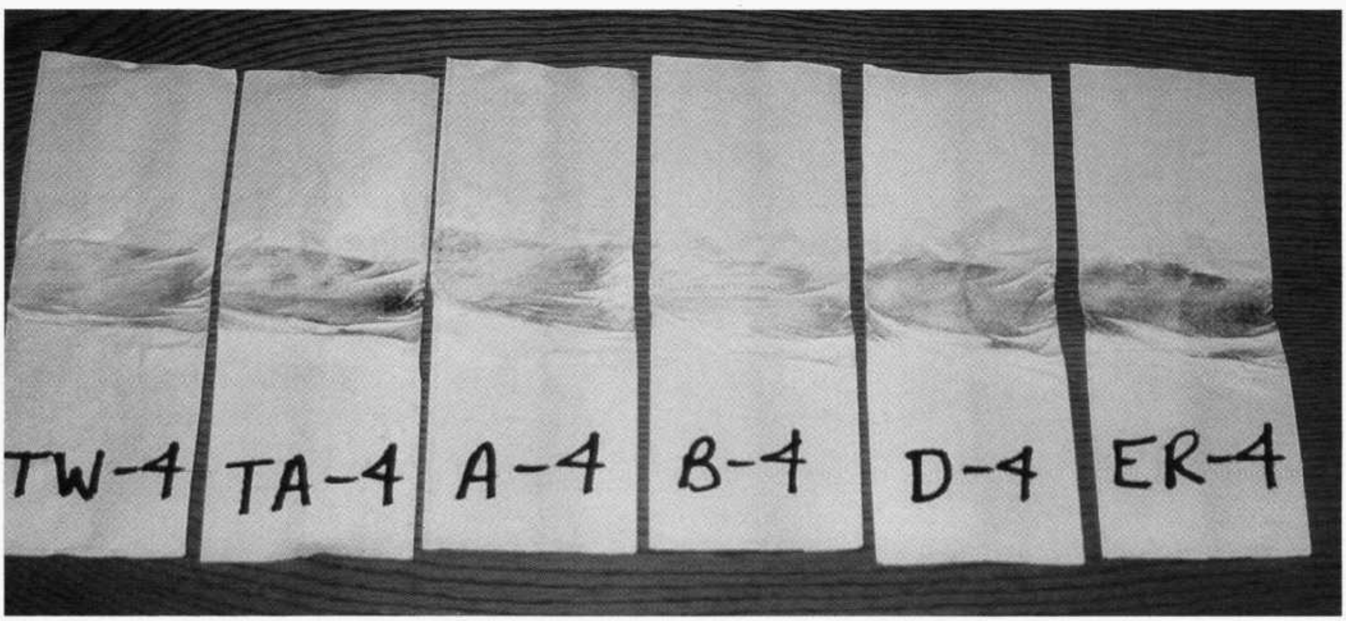


Fig. 35. Residue remaining on towels from strand specimens (all six strand groups). Rust from weathered sample, TW-4, partially shown at left (May 17, 1996).

Lay (or Pitch) of Outer Wires of Strand

The lay of the strand is the distance for an outside wire to make one complete revolution around the straight center wire. Several observers have postulated that a shorter lay would increase the bond capability of such strand. In this series, the 6.5 in. (165 mm) lay of one of the best performing as-received groups, TA, was indeed 1.25 in. (32 mm) shorter than the 7.75 in. (191 mm) lay of one of the poor performers, Group D. However, the lay of Group D was nearly the same as the 7.5 in. (191 mm) lay of the other two top as-received groups, A and B. Thus, differences in lay do not appear to be of any significance.

CONCLUSIONS

Based on the results of this investigation, the following conclusions can be drawn:

1. There is a significant difference in the transfer/development performance in pretensioned concrete beams among strands produced by different strand manufacturers. In this test series:

(a) The high bond quality strands performed much better than predicted by the ACI equations for both transfer and development lengths.

(b) The poor bond quality strands experienced a substantial increase in transfer length (end slip) in just 21 days. All beam specimens failed prematurely in bond with the test load applied at the calculated ACI development length, without noticeable warning deflection.

2. The simple pull-out test (Moustafa method) of untensioned 0.5 in. (13 mm) diameter strand embedded 18 in. (457 mm) into concrete test blocks provided an immediate, reliable prediction of the differences in flexural beam behavior experienced by the different strand groups.

(a) With strands having an average pull-out capacity exceeding 36 kips (160 kN), the transfer lengths averaged 15 in. (381 mm) at release of prestress and stabilized, in 21 days, at an average of 20 in. (58 mm), compared to the calculated ACI transfer length of 29 in. (737 mm) for the test parameters. The beams failed in flexure (mostly in tensile failure of the strand) at embedment lengths of 73 in. (1854 mm) (ACI development length), and 58 in. (1473 mm) (80 percent of the ACI development length), in 36 tests. There was ample warning deflection prior to failure.

(b) With the strands having an average pull-out capacity less than 12 kips (53.3 kN), the average transfer length at release of prestress was equal to the 29 in. (737 mm) predicted by the ACI equation. However, the transfer lengths increased to an average of 45 in. (1143 mm) in only 21 days. The beams failed in bond in all 10 tests at the calculated 73 in. (1854 mm) ACI development length, and at all tests at the shorter embedment lengths. Generally, the beams abruptly failed at or shortly after the formation of the first crack directly under the applied load, without noticeable warning deflection.

3. The following tests and observations did not reliably predict the transfer and development behavior of the strand in pretensioned concrete applications.

(a) The end slip ***immediately upon release*** of prestress did not initially detect the poor bond characteristics of Strand Groups D and ER, as indicated above. After 21 days, the end slip did increase substantially to the extent that it then provided the warning of potential deficiencies in development length performance.

(b) There was no distinguishing color of the strand that gave a reliable clue to potential deficiencies in bond performance.

(c) Surprisingly, the amount of surface residue that came off during the wipe test provided no indication of subsequent bond performance. There was relatively heavy residue on the best performing strand and the worst performing strand, and the visible difference in their residue was indistinguishable.

(d) The lay (or pitch) of the outside wires of two of the best performing groups of strand was nearly identical to one of the worst groups and, thus, minor differences in the lay of strands had no effect on their bond performance in the beam tests.

4. Light rust on strand is not required to attain outstanding bond performance. The light rust on Group TW did not increase the bond performance of the T series strands. The as-received samples of this strand, TA, actually out-performed the weathered samples in both transfer length and development length. Also, the cleanest, smoothest strand group, B, out-performed TW in transfer length and equaled TW's outstanding performance in the development length tests. Thus, it can be concluded that strand purchased from certain manufacturers, used directly from freshly delivered coils, can reliably perform better than predicted by the ACI equations without requiring surface rust or other evidence of weathering.

5. Mast's strand slip theory, which utilizes measured end slip due to transfer of prestress to modify the ACI equations for transfer and development lengths, appears to closely predict the bond capacity of the strands tested in this series.

6. Because the flexural bond performance of 0.5 in. (13 mm) strand with pull-out capacity greater than 36 kips (160 kN) significantly exceeded the requirements of the ACI equations, it is anticipated that the limit for pull-out capacity can be reduced. Strand from at least six manufacturers have tested greater than 36 kips (160 kN) in the past, but additional testing needs to be performed to determine whether that limit can be attained on a consistent basis. Flexural beam tests (as well as 21-day strand slip measurements) are more direct measures of flexural bond performance, and can be conducted on strand that does not meet the 36 kip (160 kN) limit to determine its suitability for use in pretensioned applications.

7. Tentatively, unless a direct flexural test is performed and until further testing can generate a lower threshold for pull-out capacity, it is suggested that all 0.5 in. (13 mm) diameter strand used in pretensioned applications be required to have a minimum average pull-out capacity of 36 kips (160 kN), with a standard deviation of 10 percent for a six sample group.

8. Once the pull-out limits have been better defined, future strand and development length research should be restricted to strand having such minimum pull-out capacity. Although much has been learned about general bond behavior over the years, the specific results of any past research are only applicable to the strand source actually tested.

RECOMMENDATIONS FOR FUTURE RESEARCH

This test series has opened the opportunity for further research that can benefit from a preliminary test to eliminate the variable of bond quality of strand in future transfer and development length testing. Also, additional questions were raised during these tests that were beyond the scope of this investigation and that need to be addressed. The following are some of the areas recommended for future testing:

1. In order to enlarge the scope and verify reliability of the recommended pull-out test, samples from the same reel of strand, carefully maintained in its as-received condition, should be subjected to the following tests:

(a) The pull-out test (Moustafa procedure) should be performed by several different laboratory technicians in different locations in order to determine its consistency and sensitivity to minor variations in procedure.

(b) The test should be performed with different concrete mix ingredients to determine if there are any differences related to variations in sand, coarse aggregate, and brands of cement and additives.

(c) So far, high range water reducers (HRWR) have not been used in the pull-out tests conducted at Stresscon or Concrete Technology Corporation. Identical strand samples should be tested in otherwise identical mixes, with and without HRWR, to determine if there is any effect on pull-out capacity.

(d) Some concrete producers prefer to perform the pull-out test with the jack in the horizontal position. Tests that are otherwise identical need to be conducted in both positions to determine if there is any effect on pull-out capacity,

(e) In tests conducted at Stresscon and CTC since 1990, it has been observed that variations in concrete strength between 3500 and 5900 psi (24 and 40.7 MPa) have not appeared to affect the pull-out capacity of strand. However, more extensive testing should be conducted to verify or modify this observation.

2. Strand samples of 0.5 in. (13 mm) diameter with pull-out capacities ranging from 15 to 30 kips (67 to 133 kN) need to be collected and subjected to transfer and development length tests in order to determine the minimum pull-out capacity that still enables such strand to meet the requirements of the ACI transfer and development length equations.

3. Pull-out tests on 0.6 in. (15 mm) diameter strand have already been conducted at the Universities of Texas[2] and Colorado using an 18 in. (457 mm) embedment and some correlation testing with transfer and development length has been done. This program needs to be extended to establish a recommended pull-out capacity for 0.6 in. (15 mm) strand, as well as other strand diameters in use in the pretensioned concrete industry.

4. With strand that meets the minimum requirement for pull-out capacity, many tests can proceed with confidence that strand bond capacity will no longer be an important variable. Some suggested areas that need attention are as follows:

(a) Examine the transfer and development performance of strand located at varying heights above the bottom of a pretensioned member in its casting position.

(b) Determine the effects of zero slump concrete and various extrusion processes on the bond behavior of strand.

(c) Evaluate the effects of lightweight concrete over a wide

Advisory group and observers participating in various phases of testing program.

Advisory group	Concept and planning	Casting specimens	Pull-out test	End slip at release	End slip 21 days	Beam tests	Review meeting	Report review
Roger Becker	✓				✓	✓	✓	✓
Robert Mast	✓						✓	✓
Saad Moustafa	✓		✓	✓			✓	✓
Donald Logan	✓	✓	✓	✓	✓	✓	✓	✓
Donald Pellow	✓				✓	✓	✓	✓
Bruce Russell	✓	✓	✓	✓	✓	✓	by fax	✓
Norman Scott	✓				✓	✓	✓	✓
Observers Simon Harton		✓	✓	✓	✓	✓	✓	
Mark Brooks						✓		
Wes Hall							✓	
Francis Jacques							✓	✓

Fig. 37. Advisory group members and observers at development length tests (June 8, 1996). Left to right: Roger Becker, Simon Harton, Mark Brooks, Don Pellow, Norman Scott, Donald Logan, Bruce Russell.

range of densities on the bond behavior of strand.

(d) Examine the bond behavior of strand in concrete produced with fly ash, microsilicas, and other additives.

5. Subject strand made of materials other than steel to the pull-out test and correlate to transfer and development testing.

6. Conduct chemical analyses of surface residue on different strands to determine if there is a correlation between composition of such residue with pull-out capacity and flexural bond performance of the corresponding strands.

7. Strand manufacturers can use the pull-out test to evaluate the effects on bond quality of proposed modifications in their manufacturing procedures, wire drawing lubricants, processing temperatures, cleaning agents, and other variables.

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In addition, the author acknowledges the valuable input, time and effort of Stresscon personnel Craig Cason and Robert Taylor, who were closely involved in all phases of the tests, and to Dennis Cates and Rob Kolinski who conceived and executed certain production and testing procedures that enabled this extensive test program to be performed so quickly and efficiently.

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REFERENCES

1. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-95) and Commentary (ACI 318R-95)," American Concrete Institute, Farmington Hills, MI, 1995.
2. Burns, Ned H., "Texas Development Length and Pull-Out Results — 0.6 in. Diameter Strand," Interim Committee Report, University of Texas at Austin, Austin, TX, October 19,1996.
3. Janney, Jack R., "Report on Stress Transfer Length Studies on 270K Prestressing Strand," PCI JOURNAL, V. 8, No. 1, February 1963, pp. 41-45.
4. Hanson, Norman W., and Karr, Paul H., "Flexural Bond Tests of Pretensioned Prestressed Beams," *ACZ Journal*, V. *55*, No. 7, January 1959, pp. 783-802.
5. Martin, Leslie D., and Scott, Norman L., "Development of Prestressing Strand in Pretensioned Members," *ACI Journal*, V. 73, No. 8, August 1976, pp. 453-456.
6. Mostafa, Talat, and Zia, Paul, "Development Length of Prestressing Strands," PCI JOURNAL, V. 22, No. 5, September-October 1977, pp. 54-65.
7. Logan, Donald R., Discussion of "A Review of Strand Development Length for Pretensioned Concrete Members," PCI JOURNAL, V. 41, No. 2, March-April 1996, pp. 112-116.
8. Cousins, Thomas E., Johnston, David W., and Zia, Paul, "Transfer and Development Length of Epoxy-Coated and Uncoated Prestressing Strand," PCI JOURNAL, V. 35, No. 4, July-August 1990, pp. 92-103.
9. Buckner, C. Dale, "A Review of Strand Development Length for Pretensioned Concrete Members," PCI JOURNAL, V. 40, No. 2, March-April 1995, pp. 84-105.
10. Anderson, A. R., and Anderson, R. G., "An Assurance Criterion for Flexural Bond in Pretensioned Hollow-Core Units," *ACI Journal*, V. 73, No. 8, August 1976, pp. 457-464.
11. Brooks, Mark D., Gerstle, Kurt H., and Logan, Donald R., "Effect of Initial Strand Slip on the Strength of Hollow-Core Slabs," PCI JOURNAL, V. 33, No. 1, January-February 1988, pp. 90-111.
12. Moustafa, Saad, "Pull-Out Strength of Strand and Lifting Loops," Concrete Technology Associates Technical Bulletin, 74-B5, May 1974.
13. Russell, B. W., and Rose, D. R., "Investigation of Standardized Tests to Measure the Bond Performance of Prestressing Strand," Research Report, Fears Structural Engineering Laboratory, University of Oklahoma, Norman, OK, July 1996,212 pp.
14. Burns, N. W., and Russell, B. W., "Measured Transfer Lengths of 0.5 and 0.6 in. Strands in Pretensioned Concrete," PCI JOURNAL, V. 41, No. 5, September-October 1996, pp. 44-65.
15. Devalapura, Ravi K., and Tadros, Maher K., "Critical Assessment of ACI 318 Eq. (18-3) for Prestressing Steel Stress at Ultimate Flexure," *ACZ* Structural *Journal*, V. 89, No. *5*, September-October 1992, pp. 538-546.

APPENDIX A — STRAIN COMPATIBILITY ANALYSIS

To carry out the strain compatibility analysis for a typical prestressed concrete **beam** with a rectangular cross section, use the Tadros stress-strain curve.[15]

Assume that $\varepsilon_c = 0.003$, $f_c' = 5000$ psi (34.5 MPa), $f_{pu} = 270$ ksi (1862 MPa).

Given: Rectangular prestressed concrete beam (see Fig. A1) with a single prestressing strand, with the following properties:

$b = 6.5$ in. (165 mm)

$h = 12.0$ in. (305 mm)

$A = 78$ sq in. (50322 mm^2)

$S_b = 156$ in.^{3} (2556382 mm^3)

$y_{ps} = 2$ in. (51 mm)

$d_{ps} = h - y_{ps} = 12 - 2 = 10$ in. (254 mm)

Assume 0.5 in. (13 mm) diameter, 270K strand.

$\beta_1 = 0.85 - [0.05(f_c' - 4000)/1000]$

$= 0.85 - [0.05(5000 - 4000)/1000]$

$= 0.800$

$E_{ps} = 28{,}500$ ksi (196508 MPa)

$A_{ps} = 0.153$ sq in. (98.71 mm^2)

$f_{psj} = 190$ ksi (1310 MPa)

Assume prestress losses are 8 percent.

$f_{se} = (1 - \text{Losses})f_{psj}$

$= (1 - 0.08)190$

$= 175$ ksi (1207 MPa)

Compute strain:

$\varepsilon_{se} = f_{se}/E_{ps}$

$= 175/28{,}500$

$= 0.00614$

Try $c = 1.8205$ in. (46.2 mm)

$a = \beta_1 c = 0.800 \times 1.8205 = 1.456$

$C_c = 0.85 a f_c' b$

$= 0.85 \times 1.456 \times 5 \times 6.5$

$= 40.23$ kips

$\varepsilon_p = 0.003[(d_{p1} - c)/c]$

$= 0.003[(10 - 1.8205)/1.8205]$

$= 0.01348$

$\varepsilon_{ps} = \varepsilon_p + \varepsilon_{se} = 0.01348 + 0.00613$

$= 0.01961$

For $\varepsilon_{ps} = 0.01961$, Tadros' curve" gives $f_{ps} = 263$ ksi (1813 MPa)

$T_{ps} = A_{ps} f_{ps}$

$= 0.153 \times 263$

$= 40.23$ kips (179 kN)

$C_c = 40.23$ kips (179 kN)

$M_n = C_c(d_{ps} - a/2)$

$= 40.23\,(10 - 1.456/2)$

$= 373.0$ kip-in. (42.1 kN-m)

Using Tadros' stress-strain curve:

$f_{ps} = \varepsilon_{ps}[887 + 27613/\{1 + (112.4\varepsilon_{ps})^{7.36}\}^{1/7.36}]$

$= 262.96$ ksi (1813 MPa)

Use $f_{ps} = 263$ ksi (1813 MPa).

If $\varepsilon_{ps} > 0.0280$, then $f_{ps} = 270$ ksi (not applicable)

Check $0.85a/d_{p1} < 0.36\beta_1 = 0.124 < 0.36 \times 0.8 = 0.288$ (ok)

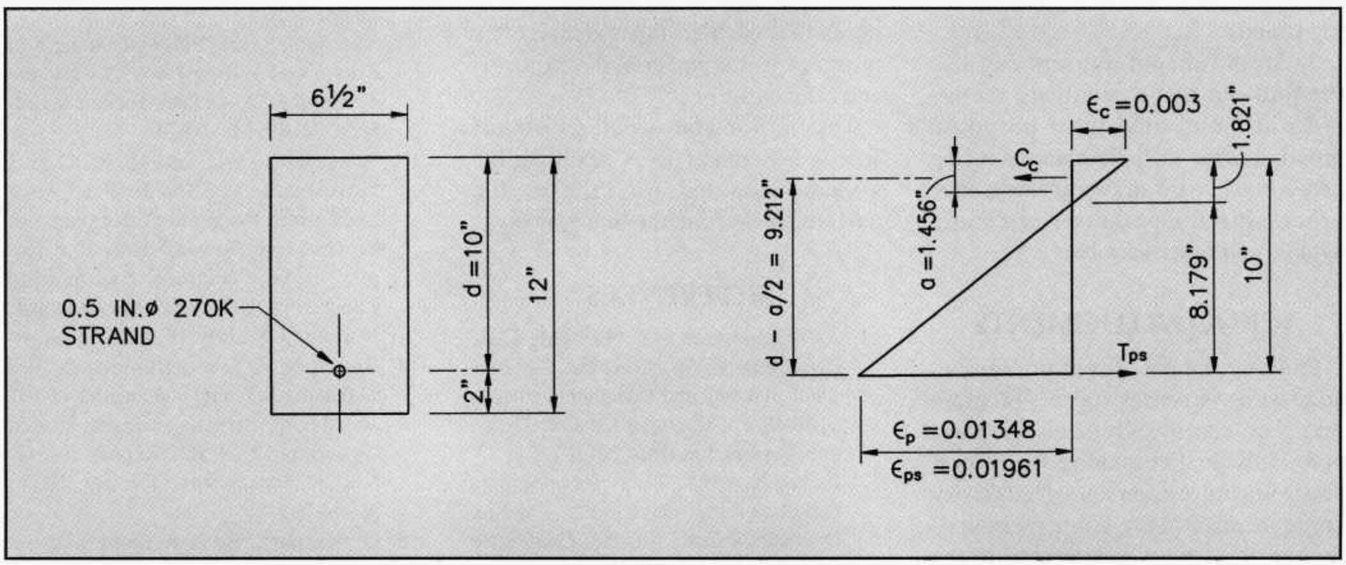


Fig. A1. Derivation of ultimate capacity of 6.5 x 12 in. (165 x 2845 mm) cross section using strain compatibility analysis.

APPENDIX B — VISUAL OBSERVATIONS AND PULL-OUT TEST RESULTS

Table B1. Strand Groups TW, TA and A.

Strand sample mark number	Strand surface condition*	Maximum pull-out load, kips	Description of failure†
TW-1	Light/moderate residue Light powdery rust full length	41.5	Strand break, seven wires broke at chuck
TW-2	Light/moderate residue Light powdery rust full length	42.5	Strand break, seven wires broke at chuck
TW-3	Light/moderate residue Light powdery rust full length	40.5	Abrupt bond failure, no broken wires
TW-4	Light/moderate residue Light powdery rust full length	43.0	Abrupt bond failure, one broken wire
TW-5	Light/moderate residue Light powdery rust full length	43.0	Abrupt bond failure, one broken wire
TW-6	Light/moderate residue Light powdery rust full length	38.9	Abrupt bond failure, no broken wires
TA-1	Moderate/heavy residue No rust	40.0	Abrupt bond failure, no broken wires
TA-2	Moderate/heavy residue A few light rust spots	41.9	Abrupt bond failure, no broken wires
TA-3	Moderate/heavy residue A few light rust spots	42.0	Abrupt bond failure, no broken wires
TA-4	Moderate/heavy residue A few light rust spots	34.6	Abrupt bond failure, no broken wires
TA-5	Moderate/heavy residue No rust	40.7	Abrupt bond failure, no broken wires
TA-6	Moderate residue No rust	40.7	Abrupt bond failure, one broken wire
A-1	Moderate residue No rust — occasional white scale	40.8	Abrupt bond failure, no broken wires
A-2	Moderate residue No rust — occasional white scale	33.2	Gradual then abrupt bond failure, no broken wires
A-3	Moderate residue No rust — occasional white scale	37.2	Gradual then abrupt bond failure, no broken wires
A-4	Moderate residue No rust — occasional white scale	40.8	Abrupt bond failure, no broken wires
A-5	Moderate residue No rust — occasional white scale	41.7	Abrupt bond failure, no broken wires
A-6	Moderate residue No rust — occasional white scale	32.5	Abrupt bond failure, no broken wires

Note: 1 kip = 4.448 kN.

* Visual inspection and towel-wipe inspection: May 16, 1996.

† Pull-out test date: May 18, 1996; concrete strength at test: 4226 psi (29 MPa).

Table B1 (cont.). **Strand Groups B, D and ER.**

Strand sample mark number	Strand surface condition*	Maximum pull-out load, kips	Description of failure†
B-1	Light residue No rust	39.3	Gradual then abrupt bond failure, no broken wires
B-2	Light residue No rust	30.5	Gradual then "chatter" to full load, no broken wires
B-3	Very light residue No rust	40.2	Gradual then abrupt bond failure, no broken wires
B-4	Very light residue No rust	38.9	Abrupt bond failure, no broken wires
B-5	Light residue No rust	32.0	Gradual then abrupt failure, no broken wires
B-6	Light residue No rust	40.0	Abrupt bond failure, no broken wires
D-1	Moderate/heavy residue A few light rust spots	11.6	Gradual, no impact, little resistance pull-out more than 6 in.
D-2	Moderate/heavy residue No rust	10.5	Gradual, no impact, little resistance pull-out more than 6 in.
D-3	Moderate/heavy residue A few light rust spots	12.2	Gradual, no impact, little resistance pull-out more than 6 in.
D-4	Moderate/heavy residue No rust	10.8	Gradual, no impact, little resistance pull-out more than 6 in.
D-5	Moderate/heavy residue A few light rust spots	12.1	Gradual, no impact, little resistance pull-out more than 6 in.
D-6	Moderate/heavy residue A few light rust spots	9.8	Gradual, no impact, little resistance pull-out more than 6 in.
ER-1	Heavy residue No rust	10.8	Gradual, no impact, little resistance pull-out more than 6 in.
ER-2	Heavy residue No rust	10.9	Gradual, no impact, little resistance pull-out more than 6 in.
ER-3	Heavy residue No rust	11.3	Gradual, no impact, little resistance pull-out more than 6 in.
ER-4	Heavy residue No rust	10.0	Gradual, no impact, little resistance pull-out more than 6 in.
ER-5	Heavy residue No rust	10.3	Gradual, no impact, little resistance pull-out more than 6 in.
ER-6	Heavy residue No rust	11.1	Gradual, no impact, little resistance pull-out more than 6 in.

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

* Visual inspection and towel-wipe inspection: May 16, 1996.

† Pull-out test date: May 18, 1996; concrete strength at test: 4226 psi (2Y MPa).

Note:

APPENDIX C — RESULTS OF STRAND DEVELOPMENT LENGTH TEST SERIES

Tables C1 through C6 — ▶ ▶ ▶ ▶ ▶

1 in. = 25.4 mm; 1 in? = 0.09290 m^2; 1 in.^{3} = 0.00001639 m^3; 1 in.^{4} = 416,231 mm^4; 1 kip = 4.448 kN; 1 ksi = 6.895 MPa; 1 psi = 6.895 kPa.

Section: 6.5 x 12 in. with one 0.5 in. diameter strand 270 ksi, low relaxation.

d = 10 in.; A = 78.0 in.^{2}; I = 936 in.^{4}; S = 156 in.^{3}; b_w = 6.5 in.; f'_c = 5300 psi; A_{ps} = 0.153 in.^{2}; approximate f_{se} = 175 ksi; eccentricity e = 4.0 in.

Pressure gauge correction = 0.915.

APPENDIX C — RESULTS OF STRAND DEVELOPMENT LENGTH TEST SERIES

Table C1. Strand Group TW (weathered); pull-out capacity = 41.6 kips.

Type of test	Beam number (end)	Span ft	L_e ft	Load at first crack kips	Apparent cracking stress psi	Load at first slip kips	Load at failure kips	Slip at failure in.	Moment at failure kip-in.	Apparent f_{ps} ksi	Apparent L_{tr} in.	Failure mode remarks
ACI L_{dev} Simple span	TW-5(N)	12.87	6.08	7.0	-714	No slip	10.4	None	420	289	20.9	Flexure-strand break
ACI L_{dev} Simple span	TW-3(N)	12.87	6.08	6.4	-556	No slip	10.1	None	405	279	20.0	Flexure-strand break
ACI L_{dev} Simple span	TW-2(N)	12.87	6.08	6.1	-489	No slip	9.7	None	391	269	18.5	Flexure-cracks opening
ACI L_{dev} Simple span	TW-1(N)	12.87	6.08	6.2	-511	No slip	10.2	None	409	281	22.2	Flexure-strand break
ACI L_{dev} Simple span	Average	12.87	6.08	6.5	-568	No slip	10.1	None	406	280	20.4	Flexure-strand strain > 2 percent
ACI L_{dev} Cantilever	TW-4(N)	—	6.08	3.3	-642	No slip	5.8	None	416	286	16.9	Flexure-strand break
ACI L_{tr} Cantilever	TW-4(S)	—	2.42	10.3	-792	12.2	14.5	?	363	250	24.6	Longitudinal concrete split/bond
80% ACI L_{dev} Simple span	TW-5(S)	11.37	4.83	7.2	-513	0.0	12.0	None	412	283	15.1	Flexure-cracks opening
80% ACI L_{dev} Simple span	TW-3(S)	11.37	4.83	6.8	-416	0.0	12.0	None	412	283	16.0	Flexure-strand break
80% ACI L_{dev} Simple span	TW-2(S)	11.37	4.83	7.1	-493	12.0	12.0	Small	412	283	22.2	Flexure-strand break
80% ACI L_{dev} Simple span	TW-1(S)	11.37	4.83	7.6	-590	0.0	12.2	None	418	288	20.9	Flexure-strand break
80% ACI L_{dev} Simple span	Average	11.37	4.83	7.2	-503	0.0	12.0	Negligible	413	284	18.6	Flexure-strand strain > 2 percent

Table C2. Strand Group TA (as received); pull-out capacity = 40.0 kips.

Type of test	Beam number (end)	Span ft	L_e ft	Load at first crack kips	Apparent cracking stress psi	Load at first slip kips	Load at failure kips	Slip at failure in.	Moment at failure kip-in.	Apparent f_{ps} ksi	Apparent L_{tr} in.	Failure mode remarks
ACI L_{dev} Simple span	TA-5(N)	12.87	6.08	7.0	-714	No slip	10.7	None	430	296	16.6	Flexure-cracks opening
ACI L_{dev} Simple span	TA-3(N)	12.87	6.08	6.4	-556	No slip	10.1	None	405	279	15.7	Flexure-strand break
ACI L_{dev} Simple span	TA-2(N)	12.87	6.08	6.4	-556	No slip	10.2	None	413	284	19.1	Flexure-strand break
ACI L_{dev} Simple span	TA-1(N)	12.87	6.08	6.4	-556	No slip	9.8	None	395	272	15.4	Flexure-strand break
ACI L_{dev} Simple span	Average	12.87	6.08	6.6	-596	No slip	10.2	None	411	283	16.7	Flexure-strand strain > 2 percent
ACI L_{dev} Cantilever	TA-4(N)	—	6.08	3.5	-734	No slip	5.8	None	416	286	15.1	Flexure-cracks opening
ACI L_{tr} Cantilever	TA-4(S)	—	2.42	10.6	-845	14.5	16.1	Small	404	278	19.1	Flexure-strand break
80% ACI L_{dev} Simple span	TA-5(S)	11.37	4.83	7.7	-610	0.0	12.2	None	418	288	15.7	Flexure-cracks opening
80% ACI L_{dev} Simple span	TA-3(S)	11.37	4.83	6.2	-299	0.0	12.3	None	421	290	20.3	Flexure-strand break
80% ACI L_{dev} Simple span	TA-2(S)	11.37	4.83	6.2	-299	0.0	12.1	None	415	285	19.1	Flexure-strand break
80% ACI L_{dev} Simple span	TA-1(S)	11.37	4.83	7.3	-532	0.0	11.6	None	400	275	19.4	Flexure-strand break
80% ACI L_{dev} Simple span	Average	11.37	4.83	6.9	-435	0.0	12.0	None	413	284	18.6	Flexure-strand strain > 2 percent

Table C3. Strand Group **A** (as received); pull-out capacity = 37.7 **kips.**

Type of test	Beam number (end)	Span ft	L_e ft	Load at first crack kips	Apparent cracking stress psi	Load at first slip kips	Load at failure kips	Slip at failure in.	Moment at failure kip-in.	Apparent f_{ps} ksi	Apparent L_{tr} in.	Failure mode remarks
ACI L_{dev} Simple span	A-5(N)	12.87	6.08	6.8	-646	No slip	10.2	None	413	284	21.3	Flexure-cracks opening
ACI L_{dev} Simple span	A-3(N)	12.87	6.08	6.4	-556	No slip	10.1	None	405	279	23.4	Flexure-strand break
ACI L_{dev} Simple span	A-2(N)	12.87	6.08	6.1	-489	No slip	9.9	None	398	274	18.8	Flexure-strand break
ACI L_{dev} Simple span	A-1(N)	12.87	6.08	6.2	-511	No slip	10.0	None	402	277	28.3	Flexure-strand break
ACI L_{dev} Simple span	Average	12.87	6.08	6.4	-551	No slip	10.0	None	405	278	22.9	Flexure-strand strain > 2 percent
ACI L_{dev} Cantilever	A-4(N)	—	6.08	3.3	-642	No slip	5.7	None	409	282	25.6	Flexure-cracks opening
ACI L_{tr} Cantilever	A-4(S)	—	2.42	8.2	-392	9.4	12.9	0.06	324	223	31.7	Flexure-concrete crushing
80% ACI L_{dev} Simple span	A-5(S)	11.37	4.83	7.7	-610	9.7	11.8	0.05	406	279	19.4	Flexure-concrete crushing
80% ACI L_{dev} Simple span	A-3(S)	11.37	4.83	8.1	-707	9.7	12.6	0.07	433	298	21.9	Flexure-strand break
80% ACI L_{dev} Simple span	A-2(S)	11.37	4.83	5.9	-241	9.7	11.9	0.02	409	281	32.0	Flexure-strand break
80% ACI L_{dev} Simple span	A-1(S)	11.37	4.83	7.3	-532	10.8	12.1	0.02	415	285	19.4	Flexure-strand break
80% ACI L_{dev} Simple span	Average	11.37	4.83	7.2	-522	10.0	12.1	0.04	416	286	23.2	Flexure-strand strain > 2 percent

Table C4. **Strand Group B (as** received); pull-out capacity = 36.8 **kips.**

Type of test	Beam number (end)	Span ft	L_e ft	Load at first crack kips	Apparent cracking stress psi	Load at first slip kips	Load at failure kips	Slip at failure in.	Moment at failure kip-in.	Apparent f_{ps} ksi	Apparent L_{tr} in.	Failure mode remarks
ACI L_{dev} Simple span	B-5(N)	12.87	6.08	6.8	-646	No slip	10.2	None	409	281	19.7	Flexure-cracks opening
ACI L_{dev} Simple span	B-3(N)	12.87	6.08	6.7	-624	No slip	9.9	None	398	274	15.4	Flexure-cracks opening
ACI L_{dev} Simple span	B-2(N)	12.87	6.08	6.3	-534	No slip	9.8	None	395	272	19.4	Flexure-strand break
ACI L_{dev} Simple span	B-1(N)	12.87	6.08	6.4	-556	No slip	10.2	None	409	281	19.1	Flexure-strand break
ACI L_{dev} Simple span	Average	12.87	6.08	6.5	-590	No slip	10.0	None	403	277	18.4	Flexure-strand strain > 2 percent
ACI L_{dev} Cantilever	B-4(N)	—	6.08	3.6	-780	No slip	5.7	None	409	282	17.6	Flexure-cracks opening
ACI L_{tr} Cantilever	B-4(S)	—	2.42	10.1	-740	12.9	15.2	> 1.0	381	262	20.9	Flexure/bond
80% ACI L_{dev} Simple span	B-5(S)	11.37	4.83	7.7	-610	No slip	11.5	None	397	273	19.7	Flexure-cracks opening
80% ACI L_{dev} Simple span	B-3(S)	11.37	4.83	8.1	-687	No slip	11.8	None	406	279	18.2	Flexure-strand break
80% ACI L_{dev} Simple span	B-2(S)	11.37	4.83	6.9	-435	No slip	11.9	None	409	281	17.6	Flexure-strand break
80% ACI L_{dev} Simple span	B-1(S)	11.37	4.83	6.9	-435	No slip	11.8	None	406	279	19.4	Flexure-strand break
80% ACI L_{dev} Simple span	Average	11.37	4.83	7.4	-542	No slip	11.8	None	404	278	18.7	Flexure-strand strain > 2 percent

Table C5. Strand Group D (as received); pull-out capacity = 11.2 kips.

Type of test	Beam number (end)	Span ft	L_e ft	Load at first crack kips	Apparent cracking stress psi	Load at first slip kips	Load at failure kips	Slip at failure in.	Moment at failure kip-in.	Apparent f_{ps} ksi	Apparent L_{tr} in.	Failure mode remarks
ACI L_{dev} Simple span	D-5(N)	12.87	6.08	6.4	-556	7.5	7.5	> 1.0	307	211	48.0	Bond-continuous slip
ACI L_{dev} Simple span	D-3(N)	12.87	6.08	5.9	-444	8.1	8.1	> 1.0	328	226	34.8	Bond-continuous slip
ACI L_{dev} Simple span	D-2(N)	12.87	6.08	6.2	-511	8.1	8.1	> 1.0	328	226	35.4	Bond-continuous slip
ACI L_{dev} Simple span	D-1(N)	12.87	6.08	5.8	-399	7.7	7.7	> 1.0	314	216	45.3	Bond-continuous slip
ACI L_{dev} Simple span	Average	12.87	6.08	6.1	-477	7.8	7.8	> 1.0	319	220	40.9	Bond-continuous slip
ACI L_{dev} Cantilever	D-4(N)	—	6.08	3.5	-734	4.6	4.6	> 1.0	334	230	24.9	Bond-continuous slip
ACI L_{tr} Cantilever	D-4(S)	—	2.42	6.1	9	6.1	6.1	> 1.0	155	107	42.5	Bond failed at first crack
80% ACI L_{dev} Simple span	D-5(S)	11.37	4.83	7.2	-513	7.2	7.2	> 1.0	254	175	41.0	Bond failed at first crack
80% ACI L_{dev} Simple span	D-3(S)	11.37	4.83	6.7	-396	6.7	6.7	> 1.0	236	162	37.0	Bond failed at first crack
80% ACI L_{dev} Simple span	D-2(S)	11.37	4.83	7.6	-590	7.6	7.6	> 1.0	266	183	51.1	Bond failed at first crack
80% ACI L_{dev} Simple span	D-1(S)	11.37	4.83	7.6	-590	8.1	8.1	> 1.0	282	194	48.0	Bond failed at second crack
80% ACI L_{dev} Simple span	Average	11.37	4.83	7.3	-522	7.4	7.4	> 1.0	260	179	44.3	Bond failed at first crack

Table C6. Strand Group ER (as received); pull-out capacity = 10.7 kips.

Type of test	Beam number (end)	Span ft	L_e ft	Load at first crack kips	Apparent cracking stress psi	Load at first slip kips	Load at failure kips	Slip at failure in.	Moment at failure kip-in.	Apparent f_{ps} ksi	Apparent L_{tr} in.	Failure mode remarks
ACI L_{dev} Simple span	ER-5(N)	12.87	6.08	6.4	-556	7.3	7.3	> 1.0	300	206	33.6	Bond-continuous slip
ACI L_{dev} Simple span	ER-3(N)	12.87	6.08	5.6	-354	7.1	7.1	> 1.0	293	202	52.7	Bond-continuous slip
ACI L_{dev} Simple span	ER-2(N)	12.87	6.08	6.2	-511	6.9	6.9	> 1.0	283	194	51.4	Bond-continuous slip
ACI L_{dev} Simple span	ER-1(N)	12.87	6.08	6.2	-511	7.7	7.7	> 1.0	314	216	37.9	Bond-continuous slip
ACI L_{dev} Simple span	Average	12.87	6.08	6.2	-483	7.3	7.3	> 1.0	297	205	43.9	Bond-continuous slip
ACI L_{dev} Cantilever	ER-4(N)	—	6.08	3.3	-642	4.1	4.1	> 1.0	302	208	48.7	Bond-continuous slip
ACI L_{tr} Cantilever	ER-4(S)	—	2.42	5.5	131	5.5	5.5	> 1.0	139	96	53.0	Bond failed at first crack
80% ACI L_{dev} Simple span	ER-5(S)	11.37	4.83	7.2	-513	7.2	7.2	> 1.0	254	175	44.0	Bond failed at first crack
80% ACI L_{dev} Simple span	ER-3(S)	11.37	4.83	6.7	-396	6.7	6.7	> 1.0	236	162	53.9	Bond failed at first crack
80% ACI L_{dev} Simple span	ER-2(S)	11.37	4.83	7.6	-590	7.8	7.8	> 1.0	272	187	45.9	Bond-shortly after first crack
80% ACI L_{dev} Simple span	ER-1(S)	11.37	4.83	7.6	-590	7.6	7.6	> 1.0	266	183	57.9	Bond failed at first crack
80% ACI L_{dev} Simple span	Average	11.37	4.83	7.3	-522	7.3	7.3	> 1.0	257	177	50.4	Bond failed at first crack

APPENDIX D — GRAPHICAL INTERPRETATION OF FLEXURAL BEAM TEST RESULTS

Advisory Group Member: Norman Scott

Fig. D1 shows the beam test results with the steel stress in the strand at failure plotted against the strand's embedment length from the end of the beam. As described in the test report, concentrated loads were applied to the beams at 29, 58, and 73 in. (737, 1473, and 1854 mm) from the beam ends. The test results, therefore, plot on each of the three vertical lines.

As shown on the legend below Fig. D1, the middle tri-linear curve represents the expectation from the ACI 318-95 Section R12.9 equation. At the transfer length [29 in. (737 mm)], the expected flexural bond stress at failure load should equal f_{se}, or 175 ksi (1207 MPa) in this case. At the calculated development length [73 in. (1854 mm)], the strand stress at failure should be equal to f_{ps}, but because&, and f_{pu}, guaranteed ultimate strength, are almost the same for these beams, this figure assumes that the strand would reach the full strength, f_{pu}, which was actually achieved or exceeded in all cases for the good bonding strand.

Only one set of tests was conducted at the ACI 318-95 calculated transfer length, which was a cantilever beam case. Four beams tested far above expectations and two had results far below.

Twenty-four beams were tested with concentrated loads on simple spans with the load applied 58 in. (1473 mm) from the beam end. Those test results are plotted on the middle vertical line. Again, the good bonding strand had stresses reaching the guaranteed ultimate strength, but the eight beams with poor bonding strand tested well below expectation.

For tests at the predicted ACI development length, 24 beams were tested on simple spans and six were loaded as a cantilever. The results were very similar for the two beam conditions. The good bonding strand tested at or above 270 ksi (1862 MPa), but the poor bonding strand only attained an average stress of 210 ksi (1448 MPa) at the ACI 318-95 calculated development length.

In Fig. D1, tri-linear curves are plotted above and below the ACI 318-95 curve. The top curve assumes that f_{se} of 175 ksi (1207 MPa) would be attained at 20 in. (508 mm) from the end based on measured end slip, and the second branch of the curve would be proportionately foreshortened. The lower curve is based on f_{se} becoming effective at 45 in. (1143 mm), which is the calculated transfer length based on average slip at the time of testing. The second linear branch of the curve is proportionately lengthened in the figure.

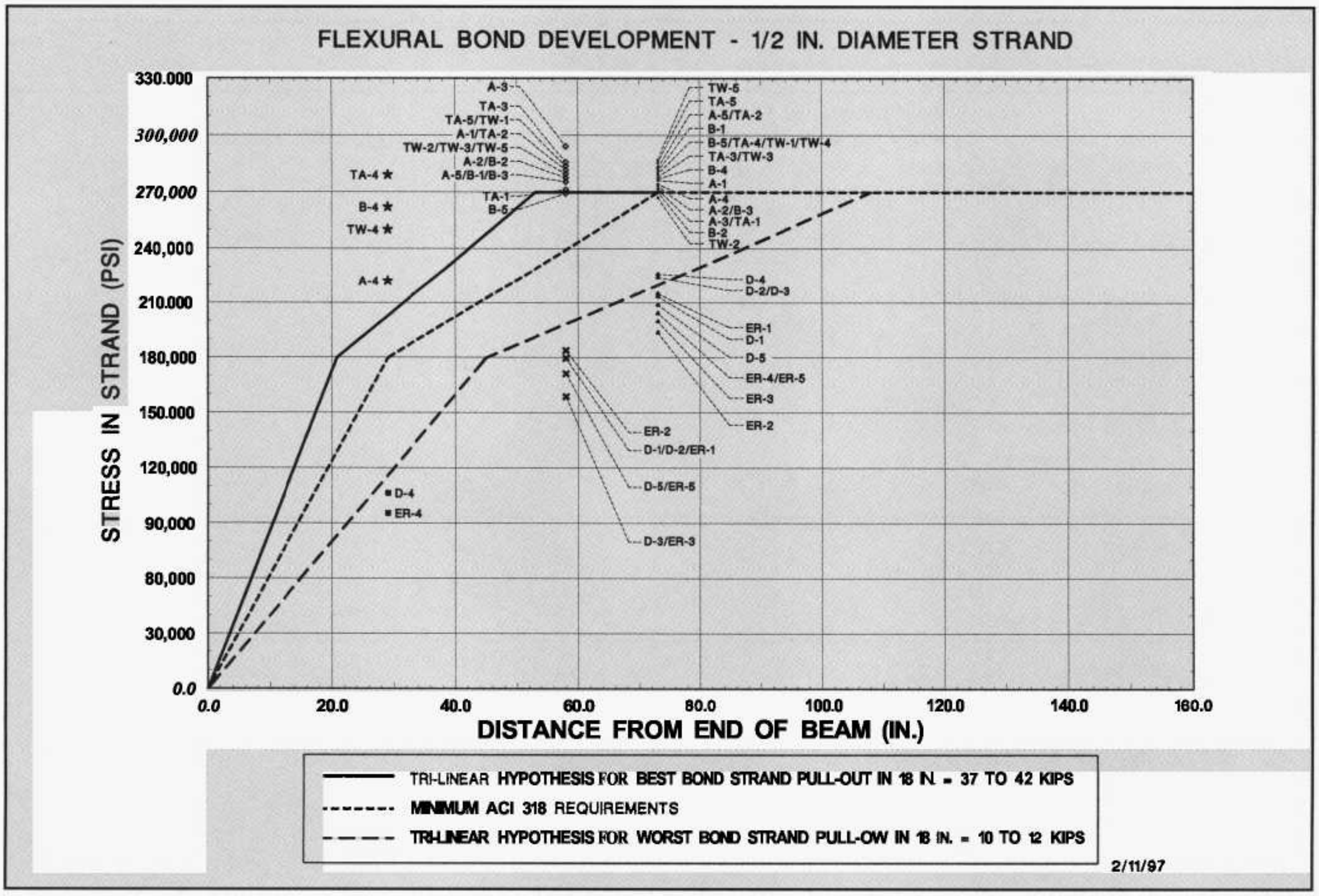


Fig. D1. Tri-linear curves showing beam test results with steel stress in strand plotted against strand's embedment length from end of beam.

APPENDIX E — PULL-OUT TEST PROCEDURE (MOUSTAFA METHOD)

OBJECTIVE

Determine the pull-out capacity of as-received strand samples (protected from weathering) and compare that pull-out capacity with the most recent benchmark established in Stresscon Corporation's bond test conducted in May-June 1996 (see Fig. E1). Four strand groups attained transfer and development lengths considerably shorter than the lengths computed by the ACI equations. The average pull-out capacities of each of these four groups ranged from 36.8 to 41.6 kips (164 to 185 kN), respectively.

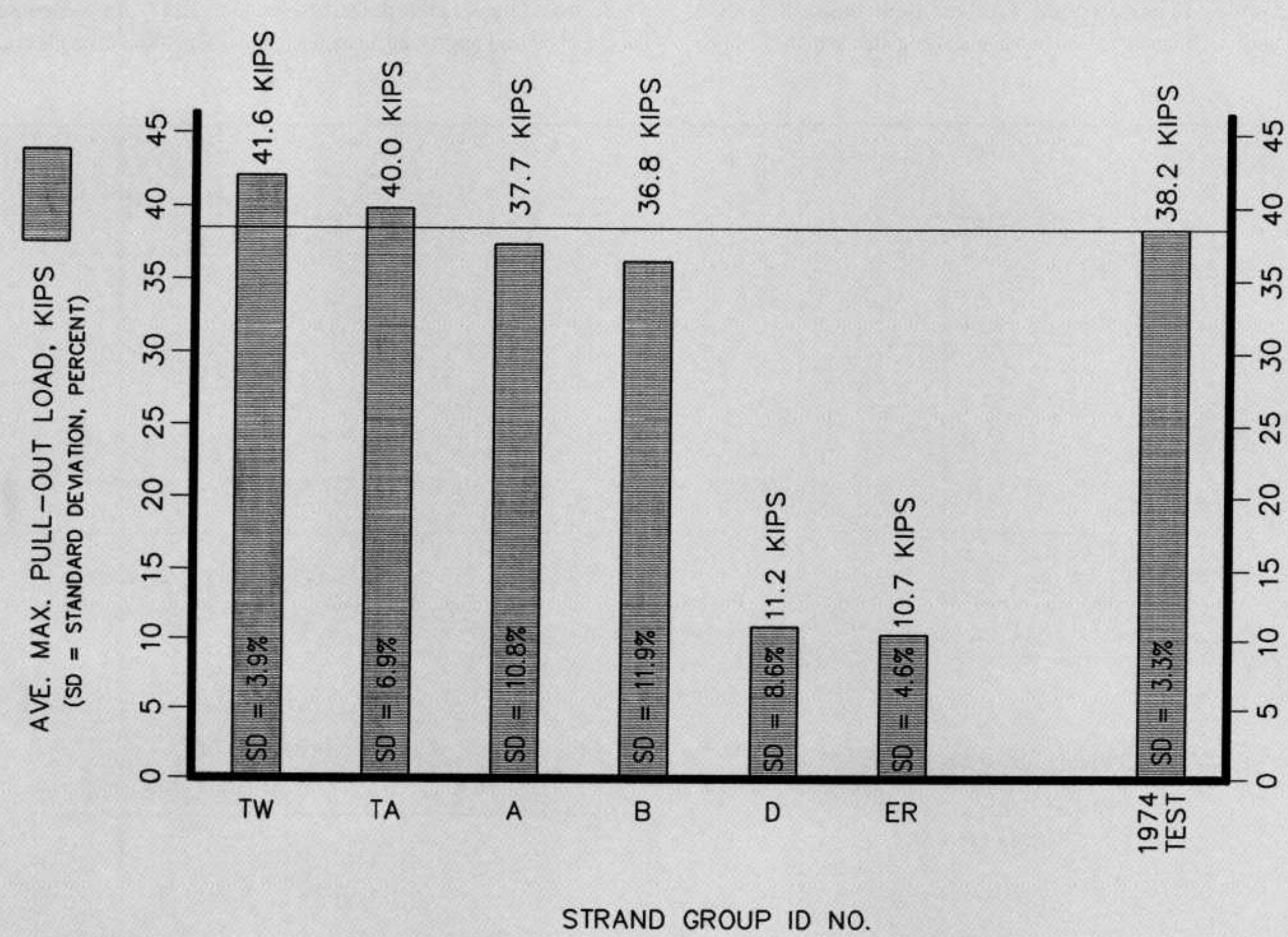
Based on the excellent transfer/development length performance of all of these top four strand groups, the following benchmark is recommended as the minimum acceptable pull-out capacity:

Average pull-out load = 36 kips (160 kN)
(set of six samples)
Maximum standard deviation = 10 percent

Note that this capacity is only applicable to 0.5 in. (13 mm) diameter, 270 ksi (1862 MPa) strand with an 18 in. (457 mm) embedment, cast in normal weight, well vibrated concrete having a concrete strength at the time of the pull-out test between 3500 and 5900 psi (24.1 and 40.7 MPa).

GENERAL PROCEDURAL COMMENT

To attain results consistent with a long series of tests extending back to 1974, it is of primary importance to closely follow the procedure used in the 1974 and 1992 tests conducted at Concrete Technology Corporation, Tacoma, Washington, and an extensive series of tests subsequently conducted at Stresscon Corporation, Colorado Springs, Colorado, since 1992. This procedure was first developed by Saad Moustafa in 1974 and was modified by Donald Logan, who introduced the 2 in. (51 mm) sleeve at the top concrete surface to eliminate the effects of surface spalling, and es-



Notes:

(1) The above results are from the strand bond tests conducted at Stresscon Corporation and supervised by Saad Moustafa in May 1996 (six specimens per test).

(2) Strand specimens were embedded 18 in. (457 mm) into well vibrated concrete test blocks. Concrete was Stresscon's standard production mix. All strand was 0.5 in. (13 mm) in diameter.

(3) All strand specimens, except TW, were in their as received condition and were protected from weathering.

Fig. E1. Pull-out capacity vs. strand group.

tablished the 20 kips per minute (89 kN/minute) load application rate, which is close to the average rate observed in earlier tests.

STRAND PREPARATION PROCEDURE

1. Six strand samples shall be taken from a fresh, unopened pack of unweathered strand (as-received from the manufacturer and not modified in any way by the manufacturer). Samples are to be saw-cut to 34 in. (864 mm) lengths, any projections from the saw-cutting will be removed, and the samples will be straightened by hand if they are bowed more than $^3/_8$ in. (9.5 mm) in their 34 in. (864 mm) length.

2. The strand samples shall be visually examined to verify that they are not rusted. They shall be wiped with a clean paper towel to clean off any loose dirt or incidental rust and to observe the residue on the strand as received from the strand manufacturer. The samples shall not be cleaned with acid or any other solvent.

3. If more than one shipment of strand (or more than one manufacturer's strand) is being tested for comparative performance, duct-tape tags shall be attached to the top end of all samples in accordance with an identification system. Each tag shall be marked with indelible ink with its appropriate symbol, and taped securely in a location where they will be visible after casting of the test block.

4. The taped samples shall be tied securely in each test block at the locations indicated in the test block layout drawing. If more than one group is being tested, it is important to have each test block contain an equal number of strand samples from each group distributed alternately throughout that block. This will ensure that each group receives equal concrete quality and equal placement and vibration of the concrete. Refer to Fig. E2 for an example of a test using three different strand groups.

CASTING PROCEDURE

1. Test block forms shall be set up, reinforcing cages installed and securely positioned before any strand samples are tied in place.

2. After the forms and reinforcement have been checked, the tagged strand samples shall be tied securely in place in accordance with the layout shown in the test block layout drawing. The time that the strands are exposed to the weather shall be minimized.

3. Immediately after the strand location and tying procedure is checked and approved, concrete placement shall take place.

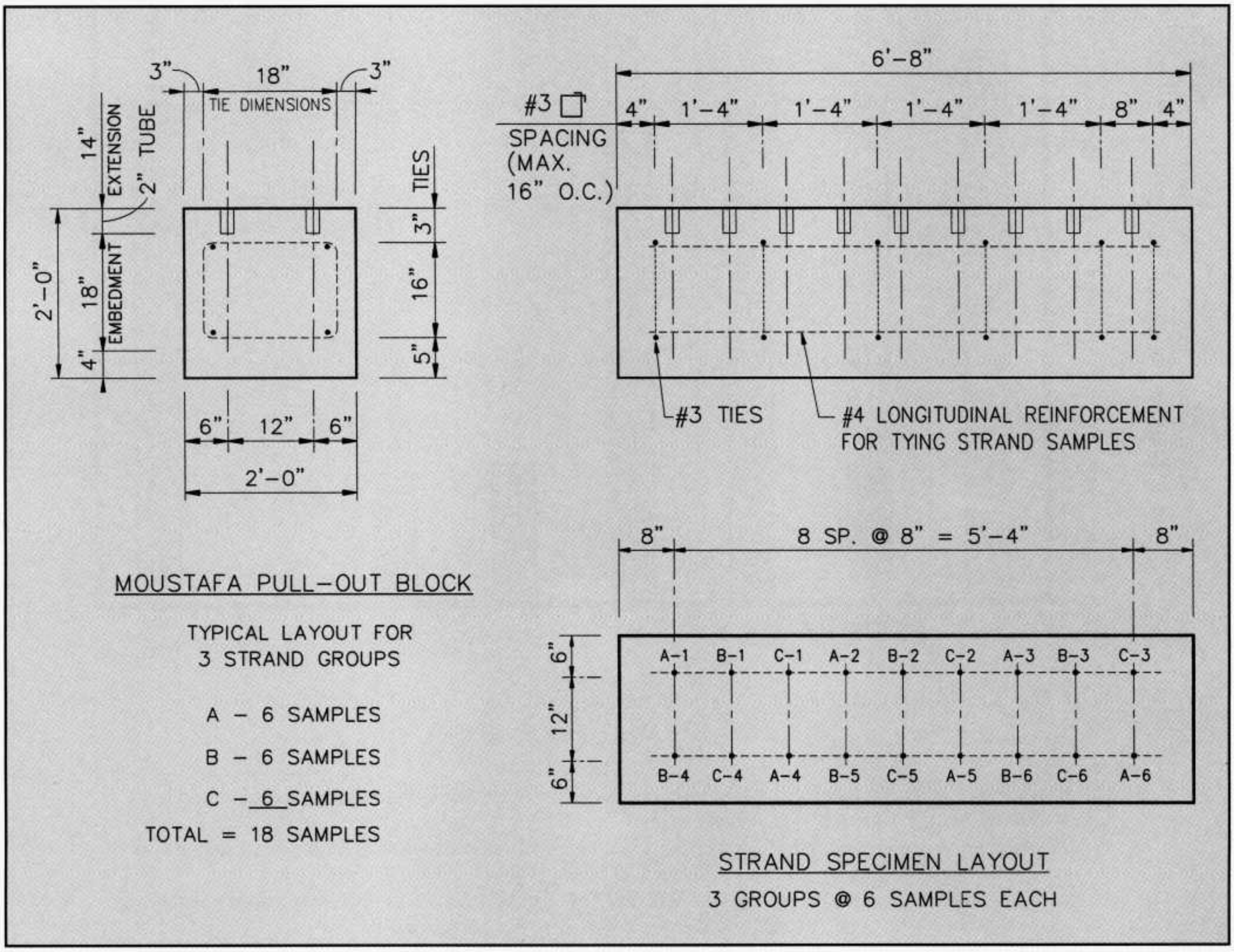


Fig. E2. Details of pull-out **test** block **(Moustafa method).**

Table E1. Suggested concrete mix design.

Materials	Quantity per cubic yard*
Cement (Type III)	660 lbs (299 kg)
Concrete sand	1100 lbs (499 kg) (SSD)
Crushed gravel [$^3/_4$ in. (19 mm)]	1900 lbs (862 kg)
Normal range water reducer	26 oz. (737 g)
Air-entraining agent	0 oz.
High range water reducer	0 oz.
Water	35 gal. (132 l)

* 1 cubic yard = 0.7646 m³.

4. The concrete will be produced from one batch of hard-rock structural concrete mix (without any high range water reducers) that is expected to attain between 3800 and 5000 psi (26.2 and 34.5 MPa) with overnight heat curing (or 2 days of ambient cure). Four cylinders shall be cast from that batch and cured with the test blocks to determine the concrete strength at the time of the test (three cylinders) and one cylinder saved for a 28-day test. A suggested concrete mix design is shown in Table E1.

5. The concrete shall be well-vibrated using internal vibrators, with the concrete at approximately 3 in. (76 mm) slump. The intent of the vibration is to duplicate good, production quality consolidation around the strand samples.

6. The top surface shall be smoothed using a one-pass trowel finish in order to attain flat concrete surfaces adjacent to the strand samples to uniformly support the jack bridging assembly. Special care needs to be taken to avoid moving any strand sample after the vibration is complete. [Do *not* re-adjust the height of any strand sample if it is not exactly at the proper height after vibration. A $^1/_4$ to $^1/_2$ in. (6.3 to 13 mm) extra embedment is not significant.]

7. Support racks shall be placed over the test blocks to keep the curing covers from coming in contact with the tops of the strand samples. Curing compound shall be sprayed on the tops of the blocks to prevent shrinkage cracks from occurring in the top surface.

TESTING PROCEDURE

1. The hydraulic jack shall be a pull-jack with a center hole assembly at the end of the ram (similar to those normally used for single-strand stressing). It shall be tested and calibrated to permit loading to 50 kips (222 kN), and shall have a travel of at least 12 in. (305 mm).

2. The bridging device shall be as shown in Fig. E3.

3. On the day after casting the test blocks (with heat curing), the cylinders shall be tested and the concrete strength recorded. Based on results of past testing, the concrete strength can range from 3500 to 5900 psi (24.1 to 40.7 MPa) without affecting the pull-out strength results.

4. The bridge is slipped over each strand to be tested and placed against the concrete surface. The strand chucks are slipped over the strand to the top of the bridge and light pressure is applied to the jack to seat the jaws of the chuck into the strand.

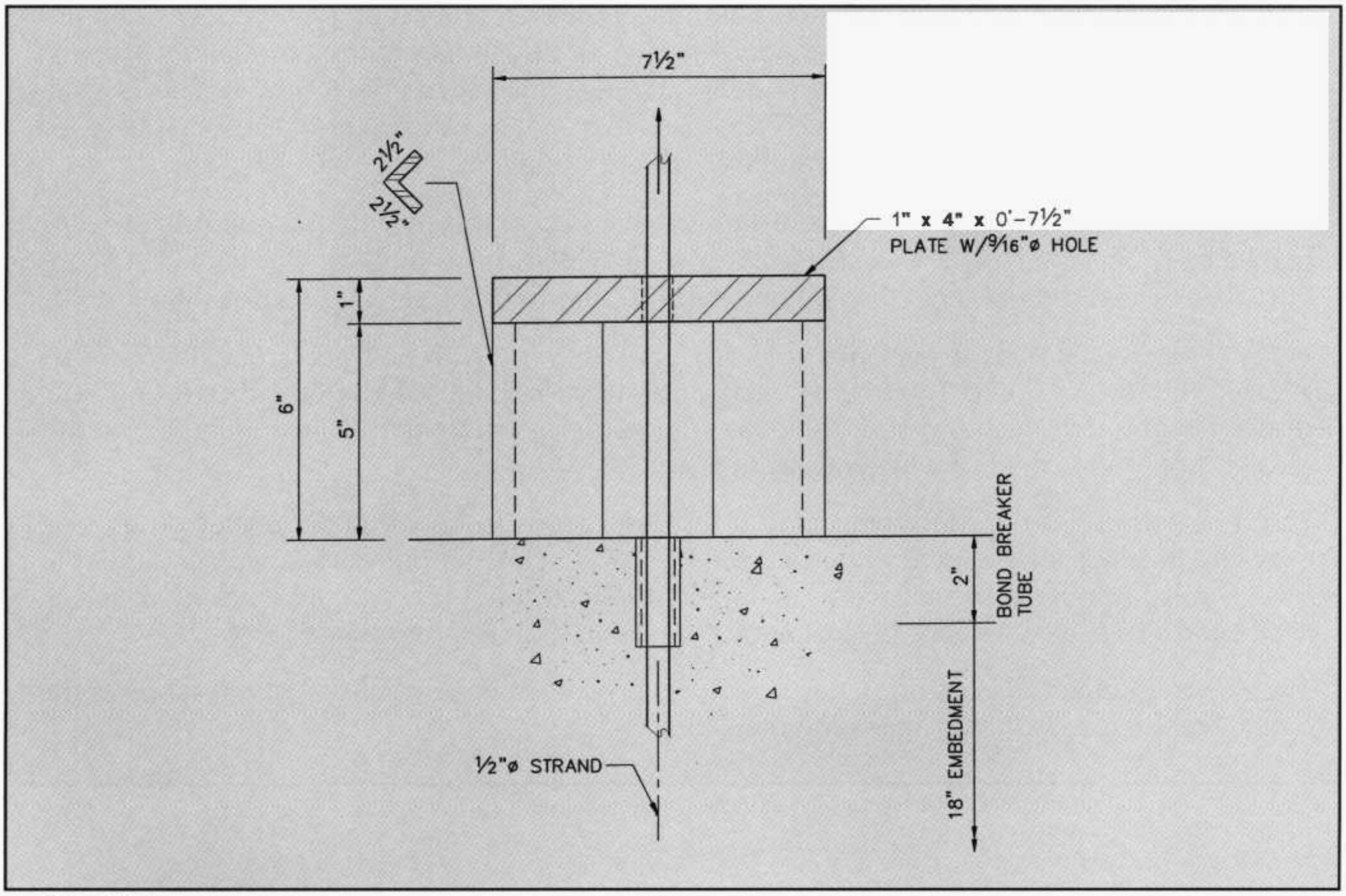


Fig. E3. Bridging device.

5. The jacking load shall be applied in a single increasing application of load at the rate of approximately 20 kips per minute (89 kN per minute) until maximum load is reached and the load gauge indicator can no longer sustain maximum load. Do not stop the test at the first sign of movement of the strand sample or for any other reason. The strand samples can pull out as much as 8 to 10 in. (203 to 254 mm) before maximum load is reached with poor bonding strand, and 1 to 2 in. (25.5 to 51 mm) with good bonding strand.

6. The pull-out capacity of the strand sample shall be recorded as the maximum load attained by the strand sample before the load drops off on the gauge and cannot be further increased.

7. The following data shall be recorded for each strand sample:

(a) Maximum capacity (as defined above).

(b) Approximate load at first noticeable movement.

(c) Approximate distance the strand pulls out at maximum load (for general reference, accuracy is not critical).

(d) General description of failure. Typical examples:

(i) Abrupt slip, loud noise. Strand started moving at 35 kips (156 kN). Two wires broke at failure load of 41.2 kips (183 kN).

(ii) Gradual slip, no noise. Strand started moving at approximately 6 kips (26.7 kN).

(iii) Initial movement at approximately 30 kips (133 kN), then abrupt slip at 36.3 kips (161 kN). Loud noise. No broken wires.

(iv) Strand break. All seven wires broke at the chuck.

8. Record data and compute average failure load and standard deviation for each strand group tested. Compare results with minimum requirements for acceptance for pretensioning applications.

PCI STATEMENT

PCI would like to thank Mr. Logan for his commitment to the important issue of strand bond. Our industry has been working towards developing a standard bond test for many years. As the research was independent and not sponsored by PCI, the PCI is not in a position to endorse the performance criteria at this time without the proper review by the engineering profession and industry. Mr. Logan's contribution, however, will be of great benefit as an important step towards developing a standard test. With this research, the correlation between the untensioned pull-out test and the pretensioned flexural test has been shown. This is a significant step and should help achieve consensus that the Moustafa pull-out test can be used to measure the bond capability of strand prior to tensioning.

The research also shows the excellent performance of strand that had a pull-out capacity higher than 36 kips (160 kN) and that the strand which has a pull-out capacity of 12 kips (53.3 kN) or less did not meet the ACI and AASHTO transfer and development length criteria.

What is not yet clear is the performance capability of strand with pull-out capacities between 12 and 36 kips (53.5 and 160 kN). PCI has not established any minimum values for pull-out results for any size of strand and, therefore, the reader is cautioned against judgment in this area without the benefit of a flexural beam test.

The repeatability of the Moustafa pull-out test also needs to be verified. Several prestressed concrete producers have performed pull-out tests and achieved pull-out capacities similar to Mr. Logan's; others, however, were unable to duplicate the pull-out capacities achieved in Mr. Logan's research, perhaps because of variations in their test procedures.

The PCI encourages discussion of this report. Comments must be confined to the scope of the report and be received at PCI Headquarters by July 1, 1997.