A STUDY OF ANCHORAGE BOND IN PRESTRESSED CONCRETE

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INVESTIGATION OF PRESTRESSED REINFORCED CONCRETE
FOR HIGHWAY BRIDGES

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THE ENGINEERING EXPERIMENT STATION
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and
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BUREAU OF PUBLIC ROADS

Project IHR-10

INVESTIGATION OF PRESTRESSED REINFORCED CONCRETE
FOR HIGHWAY BRIDGES

Urbana, Illinois
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1. INTRODUCTION

1.1 Object and Scope

The object of this study of the bond characteristics of prestressing reinforcement is to provide basic information for use in the determination of the anchorage length in pretensioned beams.

The types of reinforcement used were 1/4-in. 7-wire round strand and 0.192-in. diameter plain wire. The reinforcement was tested under both clean and rusted conditions. The other variables involved in this study were the concrete strength, the embedment length and the state of stress in the reinforcement.

The distribution of bond forces along the reinforcement was expected to be non-uniform. Hence, one of the goals of this study was to determine a bond versus slip relationship for an infinitesimal length along the strand. This cannot be done under practical conditions. The specimen in which the reinforcement is embedded must have a finite length. Therefore, specimens of varying length were tested in order to extrapolate the bond-slip characteristics for an infinitesimal length.

If the state of stress in the reinforcement of the pull-out specimen is different from that of an actual pretensioned beam, the pull-out test should not be used to determine the anchorage length. In the case of an actual pretensioned beam, the maximum slip and maximum diameter of the reinforcement occur at the point of zero stress, while the minimum slip and minimum diameter of the reinforcement occur at the point of maximum stress. In the pull-out test, these slip versus stress and reinforcement diameter versus slip relationships are reversed. Thus, the bond characteristics of the reinforcement should
be determined under conditions simulating the end block of a pretensioned beam where the reinforcement is "released into the concrete" rather than pulled out of it. To investigate the effect of prestressing, each test included one prestressed and one nonprestressed specimen.

1.2 Acknowledgments

This study was carried out as a part of the research under the Illinois Cooperative Highway Research Program Project IHR-10, "Investigation of Prestressed Reinforced Concrete for Highway Bridges." The work on the project was conducted by the Department of Civil Engineering of the University of Illinois in cooperation with the Division of Highways, State of Illinois, and the U. S. Department of Commerce, Bureau of Public Roads.

On the part of the University, the work covered by this report was carried out under the general administrative supervision of W. L. Everitt, Dean of the College of Engineering, Ross J. Martin, Director of the Engineering Experiment Station, N. M. Newmark, Head of the Department of Civil Engineering, and Ellis Danner, Director of the Illinois Cooperative Highway Research Program and Professor of Highway Engineering.

On the part of the Division of Highways of the State of Illinois, the work was under the administrative direction of R. R. Bartelsmeyer, Chief Highway Engineer, Theodore F. Morf, Engineer of Research and Planning, and W. E. Chastain, Sr., Engineer of Physical Research.

The program of investigation has been guided by a Project Advisory Committee consisting of the following:
Representing the Illinois Division of Highways

W. E. Chastain, Sr., Engineer of Physical Research, Illinois Division of Highways

W. J. Mackay, Bridge Section, Bureau of Design, Illinois Division of Highways

C. E. Thunman, Jr., Bridge Section, Bureau of Design, Illinois Division of Highways

Representing the Bureau of Public Roads

Harold Allen, Chief, Division of Physical Research, Bureau of Public Roads

E. L. Erickson, Chief, Bridge Division, Bureau of Public Roads

Representing the University of Illinois

C. E. Kesler, Professor of Theoretical and Applied Mechanics

Narbey Khachaturian, Professor of Civil Engineering

Fred Kellam, Bridge Engineer, Bureau of Public Roads and George S. Vincent, Chief, Bridge Research Branch, Bureau of Public Roads, also participated in the meetings of the Advisory Committee and contributed materially to the guidance of the program.

The investigation was directed by Dr. C. P. Siess, Professor of Civil Engineering, as Project Supervisor and as ex-officio chairman of the Project Advisory Committee. Immediate supervision of the investigation was provided by Dr. M. A. Sozen, Associate Professor of Civil Engineering, as Project Investigator.

Acknowledgment is due Mr. L. M. Sur, student in Civil Engineering, for his help in carrying out the tests and in presenting the data.
The prestressing reinforcement used in this investigation was donated by the American Steel and Wire Division of the United States Steel Corporation.

1.3 Test Specimens

Insofar as the specific objective of these tests is concerned, the ideal test specimen would be the end block of a pretensioned beam. By measuring the strain in the reinforcement or even in the concrete, if a reliable method of converting strain to stress is available, the rate of transfer of stress from the strand to the concrete could be determined which would indicate the bond characteristics of the strand under actual conditions. In fact, there would be no necessity to determine the bond characteristics, since the rate of transfer of stress is what is sought. However, the instrumentation required for this purpose would be either too elaborate to be practical or would result in severe disturbances which would make the results useless.

Insofar as laboratory practice is concerned, the ideal specimen would be the pull-out specimen. For reasons discussed before, this is not desirable before it is established beyond any doubt that the bond characteristics in the pull-out tests are comparable, or can at least be related consistently, to the bond characteristics developed when the strand is released.

After considering various schemes, it was decided that a test could be devised which could use the same specimen as in a pull-out test but under different conditions. The specimen and the test setup are shown in Fig. 1.1. A length of reinforcement is prestressed in a frame. A prism of
concrete (A)* is cast around the reinforcement (B). One end of the concrete prism rests against a steel plate (C). Traveling microscopes are mounted in place to measure the slip at both ends (Fig. 1.2), and the stress is released at a steady rate from the end opposite the plate on which the specimen rests.

Details of the test setup and procedure are described in Chapters 2 and 3.

1.4 Outline of Tests

A total of 82 specimens were tested in five series as indicated below:

<table>
<thead>
<tr>
<th>Series</th>
<th>No. of Specimens</th>
<th>Reinforcement</th>
<th>Nominal Concrete Strength psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36</td>
<td>Clean Strand (1/4-in.)</td>
<td>5000</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>Clean Wire (0.192-in. dia.)</td>
<td>5000</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>Rusted Wire (0.192-in. dia.)</td>
<td>5000</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
<td>Rusted Strand (1/4-in.)</td>
<td>5000</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>Clean Strand (1/4-in.)</td>
<td>3000</td>
</tr>
</tbody>
</table>

Series 1 and 4 comprise tests on specimens with embedment lengths of 1.5, 3, 6, and 9 in. In Series 2, 3, and 5, the 1.5-in. specimens were excluded. All specimens measured 4 by 4 in. in cross section. Each test included two specimens of the same length: A nonprestressed specimen (pull-out test) and a prestressed specimen.

In the table above "clean" refers to reinforcement which had no known history of rusting, which appeared "bright," and which was cleaned

* Letters in parentheses refer to corresponding letters in Fig. 1.1.
thoroughly with acetone. The term "rusted" refers to reinforcement which was rusted deliberately by wetting and salting (NaCl).

1.5 Notation
(a) Designation of Test Specimens

Each specimen was designated by two letters and two numbers, e.g., P16a, except in the cases where two nonprestressed specimens were included in a single test. These nonprestressed specimens include an identifying numerical subscript. The first letter refers to the state of stress of the reinforcement. The letter P indicates the reinforcement was prestressed, whereas the letter N refers to a specimen in which the reinforcement was 'nonprestressed'. The first numeral refers to the series number. The second numeral indicates the length of the specimen in inches, except for the 1.5-in. specimens. The length of these specimens has been designated as 1. The lower case letter differentiates between tests which were otherwise identical. Subscripts were used to designate the two 3-in. nonprestressed specimens of tests 'a' and 'b' of Series 1.

(b) Symbols

The following symbols were used throughout this report:

\[ f'_c \] = Concrete compressive strength as determined from 6 by 12-in. control cylinders

\[ f_t \] = Concrete tensile strength as determined from splitting tests of 6 by 6-in. control cylinders

\[ P_m \] = Maximum load attained in test

\[ P_s \] = Sustained load for test

\[ g_m \] = Maximum unit bond (load per unit length)
\( g_s \) = Sustained unit bond (load per unit length)

\( P_{mp} \) = Maximum load for prestressed specimen

\( P_{mn} \) = Maximum load for nonprestressed specimen

\( P_{sp} \) = Sustained load for prestressed specimen

\( P_{sn} \) = Sustained load for nonprestressed specimen
2. MATERIALS, FABRICATION OF SPECIMENS, AND TEST SETUP

2.1 Materials

(a) Cement: Marquette brand Type III portland cement was used for all of the specimens.

(b) Aggregates: Wabash River sand and pea gravel were used for all of the specimens. The sand had a fineness modulus of approximately three. The maximum size of the gravel was 3/8 in.

(c) Concrete Mix: The concrete mix was designed by the trial batch method. The properties by weight of the mixes and the water/cement ratios are listed in Table 1.

(d) Reinforcement: The reinforcing strand used for the specimens was 1/4-in. "American Special High-Strength Stress Relieved Strand" manufactured by the American Steel and Wire Division of the United States Steel Company. According to the designation given by the University of Illinois, the strand used in these tests was cut from Lot B. Its stress-strain curve based on an eight-inch gage length is given in Fig. 2.1.

The reinforcing wire used for the specimens was 0.192-in. "Hard Drawn Stress Relieved Super-Tens Wire" manufactured by the American Steel and Wire Division of the United States Steel Company. Its stress-strain curve based on an eight-inch gage length is given in Fig. 2.2.

2.2 Test Setup

The special testing frame designed for the tests of the prestressed specimens is shown in Fig. 1.1. Basically, the frame consists of two rods
The two outside plates (E and F) represent the abutments for the stressing operation while the inside plate (C) provides a reaction for the prestressed specimen. The rods are 1 1/4 in. round and 42 in. long. They were threaded for a length of 18 in. on one end and 6 in. on the opposite end. Each plate measures 4 by 14 by 1 in. (Two-in. thick plates were used for the 9-in. strand specimens to minimize the deflections of the middle plate.) Ten nuts (G) were used to keep the plates in the desired positions.

The two end plates (E and F) have two 1 5/16-in. holes drilled on 10-in. centers and one 5/16-in. hole drilled at the center. The rods pass through the outside holes of the plates. The end plates are kept at the desired places by two nuts on each rod on each side of the plate. The middle plate (C) is identical to the end plates except that the diameter of the center hole is 1-5/16 in. rather than 5/16 in. This hole was made larger in order to allow easy access for instrumentation to measure slip. Nuts were placed on the rod only on one side of the plate.

Prior to prestressing, the strand is threaded through the middle holes of all three plates and the forms are placed around the strand on the side of the middle plate opposite the nut. Dynamometers (K and L) are placed on each end of the strand outside the end plates and washers (J) are placed between the dynamometer and the end plate. These dynamometers were made of hollow aluminum tubes 5/8-in. in outer diameter with a wall thickness of 0.175 in. and 2 in. long. They were instrumented with four strain gages to form a "four-arm" bridge. These dynamometers were used to measure the load in both the prestressing and the release operations.

* Letters in parentheses refer to corresponding letters in Fig. 1.1.
The prestressing was affected by the use of the nuts bearing on
the two end plates. First, one set of nuts was brought to a desired location
on the rod, making sure that the end plate when bearing on these nuts would
be perpendicular to the rods. Then, the prestressing was completed by
tightening the nuts bearing on the other end plate, making sure that this
tightening procedure was uniform for the two nuts. The wires were tensioned
one day before casting.

2.3 Casting and Curing

A companion pull-out specimen was cast with each prestressed speci
men. The pull-out specimen was cast without the use of a frame and therefore
with no tension in the reinforcement. All specimens were cast with the
reinforcement in a horizontal plane.

The forms were made of plywood and consisted of removable ends with
various lengths of inserts to allow for the variation in the length of the
specimens. The forms were oiled lightly before casting. Extreme care was
taken to assure that no oil came into contact with the strand which was
thoroughly cleaned with acetone before casting.

The concrete was mixed in batches of 200 lb in a pan type mixer
of 2 cu. ft. capacity. A total of four 6 by 12 and four 6 by 6-in. cylinders
were cast with each pair of test specimens. The 6 by 6-in. cylinders were
used in the "splitting tests" to obtain a measure of the tensile strength of
the concrete. The 6 by 12-in. cylinders were capped with neat cement about
four hours after casting.

The concrete in the test specimens was vibrated with internal
vibrators. Immediately after casting, the top surfaces of the specimens
were struck off and all test pieces were covered with polyethylene sheets. One day after casting, the forms of all test pieces were removed and they were allowed to dry in the laboratory air.
3. INSTRUMENTATION AND TEST PROCEDURE

3.1 Instrumentation

(a) Load Measurement: Two aluminum dynamometers (K and L)* were used to measure the load in the case of the prestressed specimens. In the case of the pull-out specimens, only one dynamometer (L) was used. The dynamometers had a calibration factor of approximately 10 lbs per dial division on the strain indicator which could be read consistently to about half a dial division.

In the tests of the prestressed specimens, both dynamometers were used in prestressing and also in releasing the prestress. In prestressing, the two dynamometers provided a check for each other. In releasing the stress, the difference in the loads indicated by the two dynamometers was the load transferred to the specimen. A certain amount of prestress was lost due to seating and deflection of the center plate (C). This results in a slight reduction in load on the dynamometer (L) opposite the release end (before slip occurs at this end). The "effective prestress" is thus defined as the stress in the reinforcement before testing, less the reduction due to deflection and seating of the center plate. Deflection and seating cause a reduction in prestress of possibly 100 lbs.

(b) Slip Measurement: The slip of the strand with respect to the concrete was measured with the use of two traveling microscopes, one placed at the attack and the other at the trail end of the specimen (Fig. 102). The attack end is defined as the end first to experience a relative movement between the concrete and reinforcement. Thus, in the case of a pull-out

* Letters in parentheses refer to corresponding letters in Fig. 1.1.
specimen it is the end at which load is applied. In the prestressed specimen it is the end at which load is released into the specimen. The trail end is the end opposite the attack end.

The slip was measured by determining the relative movement of scribe marks on 0.015 gage strips of metal, one of the strips glued to the concrete and the other to the steel with Eastman 910 adhesive.

At the end of the specimen where the strand slipped out of the concrete, one piece of sheet metal was glued to the strand over a very small area of contact immediate to the face of the concrete. The other piece of sheet metal was glued to the face of the steel plate immediately above the strand. Thus, it was possible to eliminate the deformation of the strand outside the concrete section from being recorded as a slip.

At the end of the specimen where the strand slipped into the concrete, it was not possible to glue the piece of sheet metal on the steel as close to the face of the concrete. In that case, the piece of sheet metal was glued to the steel about 0.15 in. away from the face of the concrete. This limited the extent of measurement to a slip of about 0.15 in.

One of the traveling microscopes could be used to read slip to 1/6400 in. and the other to 1/10,000 in.

3.2 Test Procedure

(a) Prestressed Specimens: The prestressing force was released by loosening the nuts supporting the end plate at the attack end of the specimen (See plate F in Fig. 1.1). The rate at which the load was released into the specimens varied for the specimens reinforced with strand. In the
case of the 1.5, 3 and 6-in. specimens approximately 5200 lbs were released in 1 hr. 15 min. This was a release rate of about 70 lbs per min. In the case of the 9-in. specimens approximately 6000 lbs were released in 1 hr. 15 min. This was a release rate of approximately 80 lbs per min. In the case of the specimens reinforced with plain wire the load was released at a rate of 4000 lbs per 1 hr. 5 min., or 60 lbs per min.

The procedure used in releasing the load and recording slip measurements was as follows:

(1) An increment of load resulting from loosening each nut 1/6 turn was released into the specimen. (2) A time interval of approximately one minute was allowed to elapse. (3) Slip measurements were taken with the traveling microscope situated at the attack end. (4) Slip measurements were taken with the traveling microscope situated at the trail end.

The above procedure was repeated until the entire prestress force was released. If at the release of the entire prestress force a slip of at least 0.15 in. had not been recorded at the trail end, additional load was applied at the trail end until a slip of this magnitude was recorded.

(b) Nonprestressed Specimens: The nonprestressed or pull-out specimens were tested in the same way as the prestressed specimens except that the load was measured only at the end at which the force was applied (See dynamometer L in Fig. 1.1). The rate of loading of the nonprestressed specimens corresponded to the rate of release of the force into the prestressed specimens.

(c) Control Specimens: Two 6 by 12-in. and two 6 by 6-in. cylinders were cast with each specimen. In most cases this resulted in four 6 by 12-in.
and four 6 by 6-in. cylinders being cast for each test. The exceptions to this were tests 'a' and 'b' of the 3-in. specimens of Series 1. For these two tests, six 6 by 12-in. and six 6 by 6-in. specimens were cast. The values of concrete compressive strength and concrete tensile strength recorded in Tables 1 and 2 are either averages of two or four cylinders. Whenever a compressive and tensile strength is recorded for each specimen of a test, these values are averages of two cylinders. A single value recorded for each test is an average of four cylinders.
4. PRESENTATION AND DISCUSSION OF TEST RESULTS

4.1 Introductory Remarks

The test results are tabulated in Table 2. Two values of load are reported for each specimen. The first, \( P_m \), is the maximum load attained. The second, \( P_s \), called the "sustained load," is defined as the minimum load recorded after the maximum load had been reached and before a trail end slip of 0.1 in. had been developed.

The term "bond" is usually used to describe the means by which slip between concrete and reinforcement is prevented or minimized. In the past bond has been referred to as a stress, that is, a force per unit area of bar surface. This is reasonable for plain bars since they have a definite area which can be determined. With the development of deformed bars the term stress remained even though it had lost its meaning. The term "bond stress" applied to strand also has no significance since it is difficult to calculate the area of contact of the strand with the concrete. Throughout this report the quantity "unit bond" rather than bond stress will be used. Unit bond represents the average rate of shear flow and is designated by the letter "g." It is given in units of load per unit length, or more specifically in kip per in.

Section 4.2 of this chapter presents all of the measured load-slip curves, Section 4.3 condenses these curves into a representative curve where applicable, and Section 4.4 discusses the general characteristics of each series. Sections 4.5 through 4.8 discuss the effects of prestressing, embedment length, concrete strength, and anchorage length of the reinforcement.
4.2 Measured Load-Slip Curves

Figures 4.1 through 4.34 present all of the measured load-slip curves for the attack and trail ends of the specimens. Any characteristic which is general to all the embedment lengths of a particular series will be discussed in Section 4.4. Any characteristic which is unique to a particular test or to a particular embedment length will be discussed in this section.

(a) Series 1

The measured load-slip curves of Series 1 are presented in Fig. 4.1 through 4.8. Clean, 1/4-in., 7-wire round strand was used in all tests of Series 1. The nominal concrete strength was 5000 psi.

Figures 4.1 and 4.2 present the load-slip curves for the attack and the trail ends of the 1.5-in. specimens. Because N1la was damaged before testing no curves are shown for this specimen. A comparison of Fig. 4.1 and 4.2 indicate no discernible difference between the curves for the attack and trail ends. Several of the 1.5-in. specimens exhibited a minimum load immediately beyond the maximum load, with a subsequent increase in load at larger slips. This was more pronounced in the prestressed specimens.

The curves for the attack and trail ends of the 3-in. specimens are presented in Fig. 4.3 and 4.4, respectively. The results of these 3-in. specimens were very inconsistent. Although there is a fairly wide range of concrete strengths it will be shown later in this chapter that this is not responsible for the scatter. Tests 'a' and 'b' each had two pull-out or nonprestressed specimens. This accounts for the numerical subscripts on these nonprestressed specimens. Test 'b' and 'c' were conducted in the summer during periods of high humidity. It is quite possible that the strands
for P13b and P13c, which developed high loads, were slightly rusted before casting. However, because the strands for the companion pull-out specimens (NL3b1, NL3b2, and NL3c) were subjected to the same atmosphere, it seems unlikely that only two of these strands rusted. It should be noted that if the strand for P13b and P13c were rusted, it was invisible to the naked eye.

Tests 'a', 'b' and 'c' were not timed. Since the exact rate of loading is not known for these tests, it is possible that the increase in load of P13b at large slips is caused by a slightly increased rate of loading.

The attack end curve for NL3d and the trail end curve for P13b are not shown. They were not measured because of malfunctions in the test apparatus.

Figures 4.5 and 4.6 present the curves for the attack and trail end of the 6-in. specimens. A very distinct difference between the curve for the attack end and the curve for the trail end of a given specimen can be noticed in the curves for these longer specimens.

A comparison of the maximum loads and the concrete compressive strength of the 6-in. specimens would seem to indicate that a correction for the compressive strength of test 'b', which has both a low maximum load and a low compressive strength, would place it in line with tests 'a' and 'c'. Such a correction, however, does not apply for other tests in the series.

Tests 'a' and 'b' were not timed. The increase in load on specimens Pl6a, N16a, and Pl6b could be caused by a slightly increased rate of loading. However, many of the specimens in this series that were paced at a predetermined rate of loading also indicated a slight increase in load at large slips.
The load-slip curves for the 9-in. specimens are presented in Fig. 4.7a, 4.7b, and 4.8.

No slip was recorded at the trail end of the 9-in. specimens during the release of the entire prestress force. Initial slip at the trail end was obtained either by immediately applying additional load to the strand at the trail end, or by allowing the specimen to remain under the effective prestress for a time period. By applying additional load to the trail end of the specimen, the state of stress at that end has essentially been changed from the "trail" condition of a prestressed specimen to the "attack" condition of a pull-out specimen.

Figure 4.7a presents the curves for the attack end of the prestressed specimen only to the point where the entire prestress force was released. Figure 4.7b presents the entire curves for the prestressed specimens. The portion of these curves recorded after the application of additional load at the "trail" end is indicated with a broken line. This broken line is used to indicate a change in the state of stress at the ends of the specimens.

Application of additional load at the "trail" end does not necessarily mean an immediate occurrence of additional slip at the "attack" end. The vertical portions of the broken curves (Fig. 4.7b) indicate that load was applied but no slip recorded at the "attack" end. The occurrence of additional slip at the "attack" end indicated slip had occurred over the entire length of specimen. At large slips the broken line probably approaches the curve which would have resulted had there been sufficient prestressing force to develop the maximum load of the specimen.
The curve for P19e (Fig. 4.7b) was obtained by allowing a 1 hr. 7 min. time interval to occur following the release of the entire prestress force. This resulted in an additional slip of 0.018 in. at the "attack" end and a loss of load equal to 0.6 kip.

The curve for the attack end of N19c is missing due to damage of the metal strip shortly after testing was begun.

Figure 4.8 presents the trail end curves for all the 9-in. specimens in this series. Again the curves for the prestressed specimens are represented with broken lines to indicate that the slip measurements were recorded during the subsequent "pull-out" test.

(b) Series 2

The load-slip curves for Series 2 are given in Fig. 4.9 through 4.14. Clean 0.192-in. diameter wire was used in this series. The nominal concrete strength was 5000 psi.

Figures 4.9 and 4.10 present the load-slip curves for the 3-in. specimens.

The load-slip curves for the attack and the trail end of the 6-in. specimens are presented in Figs. 4.11 and 4.12, respectively. The curve for specimen P26b exhibits an increasing load at large slips which cannot be attributed to an increased rate of loading since this test was timed. It should be pointed out that the curves are designated correctly in Fig. 4.11 and 4.12 although the relation of the P and N specimens of tests 'a' and 'b' seem to indicate a typographical error.

Figures 4.13 and 4.14 present the load-slip curves for the 9-in. specimens. Specimen P29a did not slip at the trail end during the release of the entire prestress force. Immediately after release of the entire
prestress force, additional load was applied at the "trail" end. As can be seen in Fig. 4.13 this caused no increase in slip at the "attack" end until the maximum load was reached. Figure 4.14 indicates the amount of slip occurring at the "trail" end following the release of the prestress force and before the maximum load was reached.

Specimen P29b slipped at the trail end during the release of the entire prestress. Hence, this curve is represented as a solid line.

(c) Series 3

The load-slip curves for Series 3 are given in Figs. 4.15 through 4.20. Rusted 0.192-in. diameter wire was used in this series. The nominal concrete strength was 5000 psi.

Figures 4.15 and 4.16 present the data from the 3-in. specimens and Figs. 4.17 and 4.18 the data from the 6-in. specimens. The load-slip curves for the 9-in. specimens are given in Figs. 4.19 and 4.20.

The entire effective prestress was developed by P39a without trail end slip. Additional load was applied to the trail end until a total load of 5,15 kip was obtained. At this point slip occurred with such violence that the metal strips were vibrated loose from both ends. Hence, no measurements were recorded beyond the maximum load.

(d) Series 4

Figures 4.21 through 4.28 present the load-slip curves for Series 4. Rusted, 1/4-in. diameter, 7-wire round strand was used in this series. The nominal concrete strength was 5000 psi.

Figures 4.21 through 4.26 present the curves for the 1.5-in., 3-in., and 6-in. specimens of this series. Test 'a' of the 6-in. specimens (Fig. 4.25 and 4.26) appears to record a load unusually high for the pull-out specimen (N46a) and unusually low for the prestressed specimen (P46a).
Of the two tests on the 9-in. specimens (Figs. 4.27 and 4.28), one of the prestressed specimens recorded a slip at the trail end during the release of the prestress force and one did not. Specimen P49b, which did not record a trail end slip during the release of the prestress, was allowed to creep under the effective prestress. After a time lag of two hours (Fig. 4.27) the specimen still had not slipped at the trail end. The attack end recorded an additional slip at 0.0040 in., however. Additional load was then applied to the "trail" end which resulted in a slight increase in load and then a fairly rapid drop. Figure 4.27 indicates a slight increase in slip during the application of load at the trail end and before the maximum load was reached. This is probably an additional slip resulting from the disturbance of applying the load at the "trail" end.

(e) **Series 5**

Figures 4.29 through 4.34 present the load-slip curves for the specimens of Series 5. Clean, 1/4-in. diameter, 7-wire round strand was used in this series. The nominal concrete strength was 3000 psi.

The load-slip curves for the 3-in. and 6-in. specimens of Series 5 are presented in Figs. 4.29 through 4.32.

Figures 4.33 and 4.34 present the load-slip curves for the 9-in. specimen. The prestressed specimen, P59a (Fig. 4.34), did not slip at the trail end during the release of the prestress force. After a time lag of 1 hr. 19 min., slip had occurred at the trail end and the load dropped to 4.8 kip. Tightening the nuts at the trail end resulted in a slight increase in load with relatively large slips.
4.3 **Average Load-Slip Curves**

It is desirable for an over-all discussion to represent the phenomena at each end of a given length of specimen by an average or representative load-slip curve. Certain requirements must be met by the individual curves, however, before they can be averaged. The individual curves should be reasonably comparable to one another. To keep the averages compatible at the attack and trail ends of a given length specimen, the individual specimens must contribute a curve for each end. Also, it is desirable that the concrete strengths be reasonably consistent. In this section, the preparation of the average load-slip curves is explained in detail. The implications of these curves are discussed in Section 4.4.

Average load-slip curves were drawn for each end of the specimens of only Series 1 and 4. The individual load-slip curves of Series 2 and 3 were not consistent enough to justify averaging. The curves of Series 5 were not averaged because of the insufficient number of tests conducted.

The average curves were obtained by averaging the loads of the individual curves at a given slip. No corrections were made for concrete strengths on any of the individual curves before averaging. Because the maximum load does not necessarily occur at the same slip for each specimen, this results in an average curve with a maximum load less than the average of the individual maximum loads.

The average curves for Series 1 are presented in Fig. 4.35 through 4.38. Figure 4.35 presents the average load-slip curves for the 1.5-in. specimens. Because specimen N11a was damaged before testing, only tests 'b' and 'c' were included in the averages of the nonprestressed specimens. Curves from all three specimens were averaged for the prestressed specimens.
Test 'b' was omitted from the averages of the 3-in. prestressed specimens (Fig. 4.36) because the curve was missing for the trail end (N13b). For the same reason, test 'd' was omitted from the averages of the nonprestressed specimens.

Two average curves are presented for each end of both the prestressed and nonprestressed 6-in. specimens of Series 1 (Fig. 4.37). Test 'b' is included in one and omitted in the other. Because of the low maximum loads attained by both specimens of test 'b', along with the low concrete strength, it was felt that an average of test 'a' and 'c' might be more representative.

The average load-slip curves for the 9-in. specimens are presented in Fig. 4.38. Test 'c' was omitted from the average of nonprestressed specimens because of the absence of the curve for the attack end. The average curve for the attack end of the prestressed specimens is broken beyond the point where the entire effective prestress was released (Fig. 4.38a). A slip of 0.02 in. was taken as representing the slip at the release of the entire prestress (See Fig. 4.7a). The broken portion of the curve between a slip of 0.06 in. and 0.12 in. was obtained by averaging the curves for the individual specimens. The portion between slips of 0.02 and 0.06 in. was sketched to approximate the shape of the curves for the prestressed specimens of shorter lengths. No average curve was drawn for the trail end of the prestressed specimens. Examination of the individual curves for the trail end of the prestressed specimens (Fig. 4.8) indicates the impossibility of obtaining an average curve compatible with the average curve for the attack end (Fig. 4.38a).

Figures 4.39 through 4.42 present the average load-slip curves for Series 4. The curves for the 1.5-in. specimens are presented in Fig. 4.39.
The curves presented in Fig. 4.39 are not actually "average" curves since only one test was conducted on the 1.5-in. specimens.

Figure 4.40 presents the average curves for the 3-in. specimens. Note that the average curves for the nonprestressed specimens exhibits a higher maximum load than the curves for the prestressed specimens.

The average curves for the 6-in. specimens are presented in Fig. 4.41. Because of the unusually low maximum load attained on the prestressed specimen and the unusually high value attained on the pull-out specimen (Fig. 4.25), test 'a' was omitted from the averages.

Figure 4.42 presents the average curves for the 9-in. nonprestressed specimens. The two prestressed specimens were considered to be too inconsistent to average (See Fig. 4.27).

4.4 General Characteristics

Certain characteristics of the load-slip curves are unique to one or more of the series regardless of the embedment length. This section will discuss the general characteristics of each series. The average load-slip curves in Fig. 4.35 through 4.42 will be referred to when discussing the characteristics of Series 1 and 4.

(a) Series 1

The clean strand of Series 1 indicated an appreciable increase in load after slip had occurred at the trail end. (See the average load-slip curves for the trail end, Fig. 4.35 through 4.38.) The load on the specimen increased after slip had occurred over the entire embedment length. Hence, general slip of the clean strand did not constitute failure.

The load-slip curves for this series exhibited a nearly elasto-plastic condition by leveling off at a load not greatly below the maximum load. The sustained load averaged about 85 percent of the maximum with a minimum of 75 percent.
A comparison of the curves for the attack ends of Fig. 4.35 through 4.38 indicates that the load at which slip initiated at this end was independent of the embedment length.

(b) **Series 2**

The tests on clean wire resulted in large variations for ostensibly identical specimens. (Fig. 4.9 through 4.14). Hence, no average curves were presented for this series.

The specimens for Series 2 recorded no or very little increase in load after slip occurred at the trail end (Fig. 4.10, 4.12 and 4.14). It is possible that the maximum load recorded was slightly less than the true maximum load of the specimen. The test procedure involved the application of successive increments of small deformations. The load was read after the application of the deformation. Therefore, if the maximum load was attained during the application of the deformation, it would not have been recorded.

(c) **Series 3**

The tests conducted on the rusted wire exhibited much less variation than did the tests on the clean wire (Fig. 4.15 through 4.20). The load-slip curves for this series were much closer to an elasto-plastic shape than were those of Series 2. Most of the specimens exhibited an increase in load after slip had occurred at the trail end (Fig. 4.16, 4.18, and 4.20). Specimens P36b and P36a were exceptions to this (Fig. 4.18).

(d) **Series 4**

Although the maximum load attained by the rusted strand was higher than that of the clean strand, the sustained load was about the same for clean and rusted strand. This is indicated by a comparison of the appropriate average load-slip curves of Series 1 and 4 (Fig. 4.35 through 4.42).
Rusting the strand increased the initial slope of the load-slip curve.

(e) Series 5

The shape of the curves for clean strand embedded in the lower strength concrete was much the same as those for the higher strength concrete. The only apparent difference was that all the tests with the low strength concrete yielded load-slip curves with a negative, though small, slope at large slips.

4.5 Comparison of the Bond Characteristics of Prestressed and Nonprestressed Specimens

One of the principal objectives of this study was to determine the effect prestressing has on bond. It has been a matter of interest for some time to determine the effect that the expansion of the reinforcement has on bond. The prestressed and the comparison nonprestressed specimens of each test provided a means to determine this effect. Both specimens were cast from the same batch of concrete, both were subject to the same curing conditions, and in most cases both were tested on the same day.

Figures 4.43 through 4.45 show the ratios of the maximum loads for prestressed and nonprestressed specimens. The ratios are plotted against the embedment length. A ratio greater than one indicates a larger maximum load on the prestressed specimen. Figure 4.43 indicates that all tests except one had ratios greater than unity for Series 1 and 5. In plotting this figure, the maximum load for the nonprestressed specimens of tests 'a' and 'b' of the 3-in. specimens of Series 1 was determined by averaging the maximum loads of both specimens. The maximum load used for the 9-inch prestressed specimens
was always the maximum load recorded for that particular specimen whether slip occurred at the trail end during the release of the prestress or whether it was necessary to apply additional load at the trail end.

Figure 4.44 compares the ratios of maximum load against embedment length for the tests of Series 2 and 3 on wire. Series 2 shows a much larger scatter than does Series 3. Two of the six tests of Series 2 exhibit a ratio less than one.

Figure 4.45 compares the ratios of maximum load against embedment lengths for the tests of Series 4 on rusted strand. Three of the nine tests exhibit ratios less than one.

Figures 4.46 through 4.48 present the comparison of the ratios of sustained load with embedment length. Figure 4.46 presents the comparison for Series 1 and 5, Fig. 4.47 the comparison for Series 2 and 3, and Fig. 4.48 the comparison for Series 4.

The scatter of the data in Fig. 4.47 makes it unreasonable to draw any conclusions from the figure other than repetition of the fact that bond on plain wire is quite unpredictable. The data for strand plotted in Fig. 4.46 and 4.48 indicate no significant effect of the expansion of the reinforcement.

In general, prestressing increased the maximum unit bond of clean strand (Fig. 4.43). This effect was not so obvious when the strand was rusted (Fig. 4.45). In the case of rusted wire, prestressing appeared to improve the maximum unit bond. The data were inconsistent for clean wire (Fig. 4.44). Figures 4.46 and 4.48 indicate prestressing to be less effective in increasing the sustained unit bond for strand.

A comparison of the initial slopes of the curves for the attack ends of the average load-slip curves (Fig. 4.35 through 4.42) indicate the
prestressed specimen to have the steeper slope. Examination of the individual curves for the attack ends of Series 2 and 3 (The odd numbered figures of Fig. 4.9 through 4.20) substantiates this for the plain wires. The curves presented in Fig. 4.29, 4.31 and 4.33 indicate this to be true for Series 5 too.

4.6 Effect of Embedment Length

A comparison of the maximum unit bond with the embedment length is presented in Fig. 4.49 through Fig. 4.53 for all tests. The data for the prestressed and the nonprestressed specimens are plotted using different symbols. The maximum unit bonds for the 9-in. prestressed specimens were computed by dividing the maximum load recorded on the particular specimen by the embedment length. Figures 4.54 through 4.58 present the comparison of the sustained unit bond with the embedment length.

The comparison of maximum unit bond and sustained unit bond with embedment length in Fig. 4.49 through 4.58 were made with no correction for concrete strengths. Current practice implies that bond should be dependent on the square root of the concrete compressive strength ($\sqrt{f'_c}$) or directly dependent on the concrete tensile strength. With this in mind the maximum unit bonds were arbitrarily corrected to a compressive strength of 4900 psi (Fig. 4.59 through 4.63). This correction was made directly according to the square root of the compressive strength. The effect of concrete strength will be discussed in Section 4.7. Figures 4.64 through 4.68 correct arbitrarily the values of maximum unit bond to a tensile strength of 400 psi. This is a direct linear correction, based on the tensile strength obtained from the splitting tests of 6 by 6-in. cylinders.
The maximum unit bond for clean strand is shown in Fig. 4.49 and 4.53. There is no definite trend with embedment length. This is also true for sustained unit bond (Fig. 4.54 and 4.58).

The near uniformity of the distribution of bond forces along the length of the clean strand was further substantiated by the fact that in almost all tests the measured difference in slip between finite slips measured at the trail and attack ends could be calculated by assuming a linear distribution of strain.

If it is assumed that the two results for the 1.5-in. specimens are in error, it can be claimed that there is a reduction in maximum unit bond with increase in embedment length for rusted strand (Fig. 4.52). Such a conclusion would be consistent with the ratio of maximum to sustained unit bond for rusted strand (See Table 2). Figure 4.57 indicates that the sustained unit bond is insensitive to embedment length. This is also consistent with the observed shape of the load-slip curve for these specimens (Fig. 4.39 through 4.42). After some slip at the trail end, the unit bond should be almost uniform throughout the specimen.

Figures 4.50, 4.51, 4.55, and 4.56 also show no definite trends for unit bond with embedment length for plain wire.

The data corrected for concrete strength in Fig. 4.59 through 4.68 provide no additional insight into the problem.

The influence of embedment length on the ratio of maximum to sustained load is studied in Fig. 4.69. This ratio was greater than unity in all cases except one. It is seen that it was definitely independent of the embedment length for the clean strand of Series 1. The average ratio $P_m/P_s$ for Series 1 is 1.18 with a standard deviation of 0.11. The results of Series 5 are comparable to those of Series 1.
As would be expected from the shape of the load-slip curves for the rusted strand of Series 4, the ratio $P_m/P_s$ has a tendency to decrease with increasing embedment length. The ratio $P_m/P_s$ is greater for the rusted strand than that for clean strand.

For the data from the clean and rusted wire, the scatter is large. However, it can be said that the ratio $P_m/P_s$ was greater for the wire than for the strand.

4.7 Effect of Concrete Strength

The testing program included tests on specimen with concrete strengths ranging from 2160 to 6260 psi. Measured values of maximum and sustained unit bond are plotted against the concrete compressive strength in Fig. 4.70 through 4.75 and the values of maximum unit bond are plotted against the tensile strength of the concrete based on splitting tests of 6 by 6-in. cylinders in Fig. 4.76 through 4.78. Data from only Series 1 and 5 are considered. Both series involved tests on clean strand. In Fig. 4.70 through 4.75 a curve is plotted representing the equation $g = 0.007 \sqrt{f_c}$ solely to show the shape of a quadratic curve against the plotted data.

On the basis of Fig. 4.70 through 4.78, it appears that unit bond was independent of the concrete strength. If there was a trend, it was no larger than the experimental scatter. This conclusion is also reflected in Fig. 4.59 through 4.68. The corrections made in the data to account for variations in the concrete strength did not reduce the scatter in the data.
4.8 Anchorage Length

(a) Strand

It follows from the data presented in the preceding sections that it is quite reasonable to assume an elasto-plastic or even a rigid-plastic shape for the unit bond versus unit slip relationship for clean seven-wire round strand. Although all reported results relate to 1/4-in. diameter strand, no evidence is known which would indicate that the shape of this relationship would change drastically with diameter. For rusted strand, this assumption can also be made if the maximum value is limited to the sustained unit bond. This is not a very conservative procedure since the maximum unit bond approaches the sustained value as the embedment length increases and since there is some evidence indicating that time may have the same effect.

The data from specimens with different concrete strengths indicate that the unit bond can be assumed to be independent of the concrete strength.

The over-all average for the sustained unit bond measured in tests with clean strand was 0.46 k/in. This value was 0.41 for the rusted strand. In determining anchorage length, the data from the longer specimens should have greater weight. An arbitrary value of 0.4 k/in. represents a reasonable lower bound to the values of sustained unit bond measured for the 9-in. specimens. Thus, a safe estimate of the anchorage length for 1/4-in. strand would be given by the expression

\[ L_a = 2.5F \]  \hspace{1cm} (4.1)

where \( L_a \) = anchorage length

\( F \) = force to be anchored in kips
Equation 4.1 indicates a length of 22.5 in. or 90 diameters to develop 9000 lbs, the strength of the strand. An effective prestressing force of 5000 lbs (approximately 140,000 psi) would require 12.5 in. or 50 diameters.

The anchorage length may be affected by the depth of concrete below the strand, a variable not yet investigated in this program. However, it is quite unlikely that Eq. 4.1 would give unsafe results for greater depths of concrete below the strand, provided the concrete was of the quality that should be used in prestressed concrete.

Equation 4.1 applies only to 1/4-in. round strand. Whether it can be projected to apply to different sizes of strand is yet to be investigated.

(b) Wire

The data from the specimens with wire was extremely erratic. On the basis of the available data, the only justifiable conclusion that can be made is that plain and even rusted wire should not be relied upon to develop anchorage by bond alone, except under conditions of excellent control.
5. SUMMARY

The primary object of this investigation was to obtain a better understanding of the bond characteristics of strand and plain wire reinforcement. Forty short-time tests are described in this report. Each test consisted of a prestressed and a companion nonprestressed specimen. Thirty of these tests were conducted on 1/4-in. round seven-wire strand. The remaining 10 tests were conducted on 0.192-in. plain wire. Both rusted and clean reinforcement were tested. The concrete compressive strength varied from 2160 to 6260 psi. The tensile strength varied from 200 to 450 psi. Embedment lengths of 1.5, 3, 6 and 9 in. were included. All specimens had a cross section of 4 by 4 inches. The reinforcement was at the center of the concrete prism which was cast horizontally.

Slip at both ends of the specimens was recorded for all stages of loading.

The load-slip curves for clean strand were practically elastoplastic. (See Fig. 4.35 through 4.38.) They did not exhibit the reduction in load beyond the point where the maximum load is reached, a phenomenon associated with plain reinforcement. For rusted strand, there was a reduction in resistance as slip increased beyond the slip corresponding to maximum load. (See Fig. 4.39 through 4.42.) Nevertheless, for practical purposes, the effect of embedment length on the average unit bond of both clean and rusted strand could be ignored. The ratio of the load developed at a slip of 0.01 in. to the length of embedment was nearly constant (Fig. 4.54, 4.57, and 4.58.)

The load-slip curves for wire were very erratic. Although the shape of the load-slip curves indicated that there should be a change in the average
unit bond with embedment length, this effect was lost in the scatter of
the data (Fig. 4.50 and 4.51).

Prestressing did improve the bond characteristics of the rein­
forcement. However, this increase was not so large as to eliminate the
significance of pull-out tests on nonprestressed reinforcement (Fig. 4.43
through 4.48).

No significant effect of the concrete strength was observed in
the range (2160 - 6260 psi) of the tests.

On the basis of the tests reported, it appears that a prestress
of 140,000 psi can be anchored safely through bond in 50 diameters of the
1/4-in. round strand. Anchorage by bond of the plain wire should not be
relied upon unless extremely good control is exercised.
TABLE 1

PROPERTIES OF CONCRETE MIXES

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<th>Water/Cem by weight</th>
<th>Slump in.</th>
<th>Comp. Strength $f'_c$ psi</th>
<th>Tensile Strength $f'_b$ psi</th>
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* Based on splitting tests of 6 by 6-in. cylinders.
** See Section 1.6 for definition.
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* Based on splitting tests of 6 by 6-in. cylinders.

** See Section 1.6 for definition.
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* Based on splitting tests of 6 by 6-in. cylinders.
** See Section 1.6 for definition.
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<td>( f_{b} ) psi</td>
<td>( P_{m} ) kip</td>
<td>( P_{s} ) kip</td>
<td>( g_{m} ) kip/in.</td>
<td>( g_{s} ) kip/in.</td>
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<td>4030</td>
<td>240</td>
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<td>1.82</td>
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<td>200</td>
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<td>P59a</td>
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<td>300</td>
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<td>4.40</td>
<td>0.56</td>
<td>0.49</td>
<td>1.06</td>
<td>1.01</td>
<td>1.15</td>
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<td>4.35</td>
<td>0.53</td>
<td>0.48</td>
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* Based on splitting tests of 6 by 6-in. cylinders.

** See Section 1.6 for definition.
FIG. 1.1 TESTING FRAME
FIG. 1.2 INSTRUMENTATION OF TEST SPECIMEN
FIG. 2.1 STRESS-STRAIN CURVE FOR 1/4-INCH 7-WIRE ROUND STRAND

\[ E_S = 27.4 \times 10^3 \text{ ksi} \]
FIG. 2.2 STRESS-STRAIN CURVE FOR PLAIN WIRE

\[ E_s = 30 \times 10^3 \text{ ksi} \]
FIG. 9.1 MEASURED LOAD-SLIP CURVES FOR 1.5-INCH SPECIMENS OF SERIES 1
ATTACK END
FIG. 4.2 MEASURED LOAD-SLIP CURVES FOR 1.5-INCH SPECIMENS OF SERIES 1 TRAIL END
FIG. 4.3 MEASURED LOAD-SLIP CURVES FOR 3-INCH SPECIMENS OF SERIES 1
ATTACK END
FIG. 4.4 MEASURED LOAD-SLIP CURVES FOR 3-INCH SPECIMENS OF SERIES 1
TRAIL END
FIG. 4.5 MEASURED LOAD-SLIP CURVES FOR 6-INCH SPECIMENS OF SERIES 1
ATTACK END
FIG. 4.6 MEASURED LOAD-SLIP CURVES FOR 6-INCH SPECIMENS OF SERIES 1 TRAIL END
FIG. 4.7a. MEASURED LOAD-SLIP CURVES FOR 9-INCH SPECIMENS OF SERIES 1
ATTACK END
FIG. 4.7b MEASURED LOAD-SLIP CURVES FOR 9-INCH PRESTRESSED SPECIMENS OF SERIES 1
ATTACK END
FIG. 4.8 MEASURED LOAD-SLIP CURVES FOR 9-INCH SPECIMENS OF SERIES 1
ATTACK END
FIG. 4.9 MEASURED LOAD-SLIP CURVES FOR 3-INCH SPECIMENS OF SERIES 2
ATTACK END
FIG. 4.10 MEASURED LOAD-SLIP CURVES FOR 3-INCH SPECIMENS OF SERIES 2
TRAIL END
FIG. 4.11. MEASURED LOAD-SLIP CURVES FOR 6-INCH SPECIMENS OF SERIES 2
ATTACK END
FIG. 4.12 MEASURED LOAD-SLIP CURVES FOR 6-INCH SPECIMENS OF SERIES 2 TRAIL END

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<tr>
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<td>4070</td>
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<td>N26a</td>
<td>4650</td>
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Load - kip

Slip in inches x 10$^{-2}$

- P26b
- N26a
- P26a
- N26b
FIG. 4.13 MEASURED LOAD-SLIP CURVES FOR 9-INCH SPECIMENS OF SERIES 2 ATTACK END

MARK CONCRETE STRENGTHS
Compressive S Tensile
$f'_c$ psi $f_b$ psi
P29a 5250 385
M29a  
P29b 4220 310
M29b  

Slip in inches $\times 10^{-2}$
FIG. 4.14  MEASURED LOAD-SLIP CURVES FOR 9-INCH SPECIMENS OF SERIES 2  
TRAIL END
FIG. 4.15 MEASURED LOAD-SLIP CURVES FOR 3-INCH SPECIMENS OF SERIES 3
ATTACK END
FIG. 4.16 MEASURED LOAD-SLIP CURVES FOR 3-INCH SPECIMENS OF SERIES 3
TRAIL END

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<td>4650</td>
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FIG. 4.17 MEASURED LOAD-SLIP CURVES FOR 6-INCH SPECIMENS OF SERIES 3
ATTACK END
FIG. 4.18 MEASURED LOAD-SLIP CURVES FOR 6-INCH SPECIMENS OF SERIES 3 TRAIL END
FIG. 4.19 MEASURED LOAD-SLIP CURVES FOR 9-INCH SPECIMENS OF SERIES 3 ATTACK END
FIG. 4.20 MEASURED LOAD-SLIP CURVES FOR 9-INCH SPECIMENS OF SERIES 3
TRAIL END
FIG. 4.21 MEASURED LOAD-SLIP CURVES FOR 1.5-INCH SPECIMENS OF SERIES 4
ATTACK END
FIG. 4.22 MEASURED LOAD-SLIP CURVES FOR 1.5-INCH SPECIMENS OF SERIES 4 TRAIL END
FIG. 4.23 MEASURED LOAD-SLIP CURVES FOR 3-INCH SPECIMENS OF SERIES 4
ATTACK END
FIG. 4.24 MEASURED LOAD-SLIP CURVES FOR 3-INCH SPECIMENS OF SERIES 4
TRAIL END
FIG. 4.25 MEASURED LOAD-SLIP CURVES FOR 6-INCH SPECIMENS OF SERIES 4
ATTACK END
FIG. 4.27 MEASURED LOAD-SLIP CURVES FOR 9-INCH SPECIMENS OF SERIES 4
ATTACK END

MARK CONCRETE STRENGTHS
Compressive Tensile
$f'_{c}$ psi $f'_{b}$ psi

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<th>$f'_{c}$ psi</th>
<th>$f'_{b}$ psi</th>
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<tr>
<td>P49a</td>
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<td>260</td>
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<tr>
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<td>395</td>
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2 hr. Time Lag

Load - kip

Slip in inches x 10^-2
FIG. 4.28 MEASURED LOAD-SLIP CURVES FOR 9-INCH SPECIMENS OF SERIES 4
TRAIL END
FIG. 4.29 MEASURED LOAD-SLIP CURVES FOR 3-INCH SPECIMENS OF SERIES 5
ATTACK END
FIG. 4.30 MEASURED LOAD-SLIP CURVES FOR 3-INCH SPECIMENS OF SERIES 5
TRAIL END
FIG. 4.31 MEASURED LOAD-SLIP CURVES FOR 6-INCH SPECIMENS OF SERIES 5
ATTACK END

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<td>N56a</td>
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<td>P56b</td>
<td>2160</td>
</tr>
<tr>
<td>N56b</td>
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</table>
FIG. 4.32 MEASURED LOAD-SLIP CURVES FOR 6-INCH SPECIMENS OF SERIES 5 TRAIL END
FIG. 4.33 MEASURED LOAD-SLIP CURVES FOR 9-INCH SPECIMENS OF SERIES 5
ATTACK END
FIG. 4.34 MEASURED LOAD-SLIP CURVES FOR 9-INCH SPECIMENS OF SERIES 5
TRAIL END
FIG. 4.35 AVERAGE LOAD-SLIP CURVES FOR 1.5-INCH SPECIMENS OF SERIES 1
FIG. 4.36 AVERAGE LOAD-SLIP CURVES FOR 3-INCH SPECIMENS OF SERIES 1
FIG. 4.37 AVERAGE LOAD-SLIP CURVES FOR 6-INCH SPECIMENS OF SERIES 1
FIG. 4.38 AVERAGE LOAD-SLIP CURVES FOR 9-INCH SPECIMENS OF SERIES 1
Fig. 4.39 Average Load-Slip Curves for 1.5-Inch Specimens of Series 4
FIG. 4.40 AVERAGE LOAD-SLIP CURVES FOR 3-INCH SPECIMENS OF SERIES 4
FIG. 4.41 AVERAGE LOAD-SLIP CURVES FOR 6-INCH SPECIMENS OF SERIES 4
FIG. 4.42 AVERAGE LOAD-SLIP CURVES FOR 9-INCH SPECIMENS OF SERIES 4
FIG. 4.43 COMPARISON OF THE RATIO $\frac{P_{mp}}{P_{mn}}$ WITH EMBEDMENT LENGTH
SERIES 1 AND 5
FIG. 4.44 COMPARISON OF THE RATIO $P_{mp}/P_{mn}$ WITH EMBEDMENT LENGTH
SERIES 2 AND 3
FIG. 4.45 COMPARISON OF RATIO $\frac{P_{mp}}{P_{mn}}$ WITH EMBEDMENT LENGTH

SERIES 4
FIG. 4.46 COMPARISON OF THE RATIO \( \frac{P_{sp}}{P_{sn}} \) WITH EMBEDMENT LENGTH
SERIES 1 AND 5
FIG. 4.47 COMPARISON OF THE RATIO $P_{ap}/P_{sn}$ WITH EMBEDMENT LENGTH
SERIES 2 AND 3
FIG. 4.49 EFFECT OF EMBEDMENT LENGTH ON MAXIMUM UNIT BOND
SERIES 1
FIG. 4.50 EFFECT OF EMBEDMENT LENGTH ON MAXIMUM UNIT BOND
SERIES 2
FIG. 4.51  EFFECT OF EMBEDMENT LENGTH ON MAXIMUM UNIT BOND
SERIES 3
FIG. 4.52 EFFECT OF EMBEDMENT LENGTH ON MAXIMUM UNIT BOND
SERIES 4
FIG. 4.53 EFFECT OF EMBEDMENT LENGTH ON MAXIMUM UNIT BOND
SERIES 5
FIG. 4.54 EFFECT OF EMBEDMENT LENGTH ON SUSTAINED UNIT BOND
SERIES 1
FIG. 4.55 EFFECT OF EMBEDMENT LENGTH ON SUSTAINED UNIT BOND
SERIES 2
FIG. 4.56 EFFECT OF EMBEDMENT LENGTH ON SUSTAINED UNIT BOND
SERIES 3
FIG. 4.57 EFFECT OF EMBEDMENT LENGTH ON SUSTAINED UNIT BOND
SERIES 4
FIG. 4.58 EFFECT OF EMBEDMENT LENGTH ON SUSTAINED UNIT BOND
SERIES 5
FIG. 4.59  EFFECT OF EMBEDMENT LENGTH ON MAXIMUM UNIT BOND; SERIES 1
Values of Unit Bond Corrected Arbitrarily for Concrete Compressive Strength
FIG. 4.60 EFFECT OF EMBEDMENT LENGTH ON MAXIMUM UNIT BOND; SERIES 2
Values of Unit Bond Corrected Arbitrarily for Concrete Compressive Strength
FIG. 4.61  EFFECT OF EMBEDMENT LENGTH ON MAXIMUM UNIT BOND; SERIES 3
Values of Unit Bond Corrected Arbitrarily for Concrete Compressive Strength
FIG. 4.62 EFFECT OF EMBEDMENT LENGTH ON MAXIMUM UNIT BOND; SERIES 4
Values of Unit Bond Corrected Arbitrarily for Concrete Compressive Strength
FIG. 4.63 EFFECT OF EMBEDMENT LENGTH ON MAXIMUM UNIT BOND; SERIES 5
Values of Unit Bond Corrected Arbitrarily for Concrete Compressive Strength
FIG. 4.64 EFFECT OF EMBEDMENT LENGTH ON MAXIMUM UNIT BOND; SERIES 1
Values of Unit Bond Corrected Arbitrarily for Concrete Tensile Strength
FIG. 4.65 EFFECT OF EMBEDMENT LENGTH ON MAXIMUM UNIT BOND; SERIES 2
Values of Unit Bond Corrected Arbitrarily for Concrete Tensile Strength
FIG. 4.66 EFFECT OF EMBEDMENT LENGTH ON MAXIMUM UNIT BOND; SERIES 3
Values of Unit Bond Corrected Arbitrarily for Concrete Tensile Strength
FIG. 4.67 EFFECT OF EMBEDMENT LENGTH ON MAXIMUM UNIT BOND; SERIES 4
Values of Unit Bond Corrected Arbitrarily for Concrete Tensile Strength
FIG. 4.68 EFFECT OF EMBEDMENT LENGTH ON MAXIMUM UNIT BOND; SERIES 5
Values of Unit Bond Corrected Arbitrarily for Concrete Tensile Strength
FIG. 4.69 EFFECT OF EMBEDMENT LENGTH ON RATIO $P_m/P_s$
FIG. 4.70 EFFECT OF CONCRETE COMPRESSIVE STRENGTH ON MAXIMUM UNIT BOND; SERIES 1 AND 5; 3-INCH SPECIMENS
FIG. 4.71 EFFECT OF CONCRETE COMPRESSIVE STRENGTH ON MAXIMUM UNIT BOND; SERIES 1 AND 5; 6-INCH SPECIMENS
FIG. 4.72 EFFECT OF CONCRETE COMPRESSIVE STRENGTH ON MAXIMUM UNIT BOND; SERIES 1 AND 5; 9-INCH NONPRESTRESSED SPECIMENS

\[ g = 0.007 \sqrt{f_c'} \]
FIG. 4.73  EFFECT OF CONCRETE COMPRESSIVE STRENGTH ON SUSTAINED UNIT BOND; SERIES 1 AND 5; 3-INCH SPECIMENS
FIG. 4.74 EFFECT OF CONCRETE COMPRESSIVE STRENGTH ON SUSTAINED UNIT BOND; SERIES 1 AND 5; 6-INCH SPECIMENS
FIG. 4.75 EFFECT OF CONCRETE COMPRESSIVE STRENGTH ON SUSTAINED UNIT BOND; SERIES 1 AND 5; 9-INCH SPECIMENS
FIG. 4.76 EFFECT OF CONCRETE TENSILE STRENGTH ON MAXIMUM UNIT BOND; SERIES 1 AND 5; 3-INCH SPECIMENS
FIG. 4.77 EFFECT OF CONCRETE TENSIILE STRENGTH ON MAXIMUM UNIT BOND; SERIES 1 AND 5; 6-INCH SPECIMENS
FIG. 4.78 EFFECT OF CONCRETE TENSILE STRENGTH ON MAXIMUM UNIT BOND; SERIES 1 AND 5; 9-INCH NONPRESTRESSED SPECIMENS