INVESTIGATION OF BOND IN 3/8 INCH DIAMETER STRAND FOR PRETENSIONED CONCRETE MEMBERS

by

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Abstract

A direct method which was useful for repeated quick tests was presented to determine the bond anchorage length for 3/8 inch diameter strand and the distribution of bond forces within the anchorage length.

Seventy-four specimens were tested. Three different cross sections were tried, namely 4 in. x 4 in., 3 in. x 3 in. and 2 in. x 2 in. Two types of load conditions were tested, tensioned and untensioned.

From the experimental results it was observed that friction appears to be the major component determining the bond strength. The bond strength of strand does not appear to be significantly affected by the degree of initial steel stress in concrete. The anchorage length for 3/8 inch diameter rusted strand was found to be between 8 and 10 inches for a force of 13 to 14 kips.
Acknowledgement

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March, 1963

Vancouver, British Columbia.
# Table of Contents

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Functions of Bond</td>
<td>1</td>
</tr>
<tr>
<td>Factors Contributing to Bond</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Mechanics of Prestress transfer and discussion of previous work</td>
<td>3</td>
</tr>
<tr>
<td>Bonding action of smooth wires</td>
<td>3</td>
</tr>
<tr>
<td>Bonding action of strand</td>
<td>4</td>
</tr>
<tr>
<td>Discussion of Previous Work</td>
<td>6</td>
</tr>
<tr>
<td>Purpose of this investigation</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>Description of the Experimental method</td>
<td>13</td>
</tr>
<tr>
<td>Apparatus</td>
<td>13</td>
</tr>
<tr>
<td>Testing Sequence</td>
<td>14</td>
</tr>
<tr>
<td>Description of tests</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>21</td>
</tr>
<tr>
<td>Experimental results and conclusions</td>
<td>21</td>
</tr>
<tr>
<td>Table of Results and Graphs</td>
<td>21</td>
</tr>
<tr>
<td>Observation from Experimental results</td>
<td>21</td>
</tr>
<tr>
<td>Conclusions</td>
<td>39</td>
</tr>
<tr>
<td>Appendix</td>
<td>40</td>
</tr>
<tr>
<td>Specification of materials and apparatus used</td>
<td>40</td>
</tr>
<tr>
<td>Bibliography</td>
<td>45</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1.</td>
<td>Transfer zone deformations due to prestress</td>
</tr>
<tr>
<td>2.</td>
<td>Diagram showing the sequence of operation of the work of George A. Dinsmore, Peter L. Deutsch and Jose L. Montemayor.</td>
</tr>
<tr>
<td>3.</td>
<td>Details of test frame</td>
</tr>
<tr>
<td>4.</td>
<td>Details of vibration attachment</td>
</tr>
<tr>
<td>5.</td>
<td>Load transfer distribution for series I</td>
</tr>
<tr>
<td>6.</td>
<td>Load transfer distribution for series II</td>
</tr>
<tr>
<td>7.</td>
<td>Load transfer distribution for series III</td>
</tr>
<tr>
<td>8.</td>
<td>Load transfer distribution for series IV</td>
</tr>
<tr>
<td>9.</td>
<td>Load transfer distribution for series V</td>
</tr>
<tr>
<td>10.</td>
<td>Load transfer distribution for series VI</td>
</tr>
<tr>
<td>11.</td>
<td>Slip Versus Load anchored for 3 in. x 3 in. cross section specimens</td>
</tr>
<tr>
<td>12.</td>
<td>Slip versus anchored force for 6 in and 12 in. length specimens of 3 in. x 3 in. cross section</td>
</tr>
<tr>
<td>13.</td>
<td>Tensioned broken specimen</td>
</tr>
<tr>
<td>14.</td>
<td>Untensioned broken specimen</td>
</tr>
<tr>
<td>15.</td>
<td>Longitudinally cracked specimen of 2 in. x 2 in. cross section</td>
</tr>
<tr>
<td>16.</td>
<td>Load cells calibration curves</td>
</tr>
<tr>
<td>17.</td>
<td>Individual and combined aggregate gradings</td>
</tr>
<tr>
<td>18.</td>
<td>Relaxation curve for 3/8 inch diameter strand</td>
</tr>
</tbody>
</table>
Chapter I.
Introduction

Functions of bond

Bond between concrete and steel may serve three different functions.

First the pretension force in the steel is transferred from abutments or forms to the concrete member entirely by bond. Thus a prestress transfer bond is present from the ends of a prestressed member to the beginning of a region in which the steel tension is constant before the loads are applied.

Secondly, if a moment gradient is present in a loaded member, bond stresses will be induced by shear in a manner similar to that occurring in ordinary reinforced concrete.

Thirdly, when flexural cracks form in a highly loaded member high bond stresses are set up immediately adjacent to the cracks.

These two latter types of bond stresses, those due to shear and those occurring at cracks, will generally be superimposed on each other. These two will be called flexural bond stresses.

Factors contributing to bond

There are three factors which will contribute to the bond: adhesion, friction and mechanical resistance.

Adhesion:- Adhesion can be present only before slip has taken place between concrete and steel. Near the ends of pretensioned members considerable slip takes place when the pretension is released and adhesion is, therefore, probably not present.

Frictional resistance:- This is due to very high contact pressures between steel and concrete in pretensioned members. This contact pressure is partly due to the shrinkage of the concrete during the curing process and partly due to the lateral expansion of the steel as the stress is reduced.
Mechanical resistance: Mechanical resistance contributes little to prestress transfer in the case of individual smooth wires, but it will be a factor of some significance in the case of strands.

The length of concrete section required to anchor the force in a strand, by means of some or all of the above factors is a function of many interrelated variables such as surface conditions, concrete strength, degree of vibration, etc. The variables studied in this investigation are initial steel pretension and level of stress in concrete. The following investigation is to determine the anchorage length and the distribution of bond forces in 3/8 inch diameter rusted strand within the anchorage length.
Chapter II.

Mechanics of prestress transfer and discussion of previous work.

Bonding action of smooth wires

To facilitate this discussion of bond developed at release of prestress, a simple case; that of a prism centrally prestressed by a single smooth wire, will be considered.

In Figure 1a equidistant cross sectional planes have been arbitrarily selected and labelled a a, b b, etc., starting from one end of the member.

The deformations resulting from the release of prestress are idealized in Figure 1b. The member as a whole is shortened by elastic compression of the concrete. It is assumed for clarity that the prestress transferred between the end of the member and the section under consideration is uniformly distributed over the section except for a local warping or dishing effect in the intermediate vicinity of the prestressing tendons.

The original sections a a, b b, c c, etc. after release of prestress are displaced to A A, B B, C C respectively. At the interface between the concrete and steel the concrete has shifted further to positions A', B', C' etc. The steel has moved to A", B", C" etc. as a result of relative movement of the steel with respect to the concrete.

In the region where the adhesive bond has not been destroyed the displacement of steel and concrete are necessarily the same, i.e. C' and C" coincide. This region has been termed the elastic zone. In this region the bond capacity varies as the stress strain characteristics in bond of the concrete rather than with a friction coefficient.

The region in which adhesion is destroyed giving rise to relative movement between the steel and concrete is termed the friction zone. Bond transfer in this portion is dependent upon the frictional coefficient of the two materials, the radial pressure at the interface and mechanical
resistance to slip. The portion of the prestress transferred in the elastic zone is primarily dependent upon the adhesive bond capacity.

**Bonding action of strands**

The familiar seven wire strand is inherently favorable to effective bonding because the strand cross section is not a true circle, there are ridges of concrete which fill the valleys between the exterior wires. And since the strand is wound in a helical pattern, these ridges will also follow the exact helical pattern of the wires in their displaced positions due to initial prestress. Upon release, there is relative displacement between steel and concrete. But, while a single smooth wire slips straight in without any rotation, a strand must rotate or screw in, as a threaded bolt, following the predetermined grooves in the concrete. Also as the stress in the steel is decreased from its initial value before release, the strand not only expands radially due to Poisson's ratio, but also decreases in length, longitudinally. This decrease in length is represented by a decrease in pitch of the original helical pattern of the strand. Since, in the friction zone, the decrease in steel strain is greater than the increase in concrete strain, at the interface, the amount that the steel pitch decreases will be limited by the amount that the pitch of the concrete ridges decreases. This effect results in a mechanical resistance to movement of the steel relative to the concrete.

The mechanical resistance adds to the pure friction, to make the force transferred in the friction zone of a strand greater than that of a straight cable having the same cross section and perimeter. The total length of the friction zone for strand will therefore be less than that of the similar single rod. Thus, a strand transfers force in the friction zone not by friction alone but a combination of friction and the resistance of the concrete
FIGURE 1: TRANSFER ZONE DEFORMATIONS DUE TO PRESTRESS
ridges to mechanical shearing.

Discussion of previous work:

Previous work on prestress transfer bond by Evans and Robinson\(^1\), Marshall\(^2\), Janney\(^3\), George A. Dinsmore\(^4\), Peter L. Deutsch and Jose L. Montemayor are discussed here. Evans and Robinson\(^1\) devised a radiographic technique for measuring strains in wire. "The radiographic strain measuring technique involves placing small lead markers in slots formed in the reinforcement."\(^1\) Concrete is cast around them. "The positions of markers are recorded on an x-ray photograph which is measured by a travelling microscope."\(^1\)

"The steel strain and slips were obtained by measuring x-ray films showing the displacement of markers. Bond stress distribution curves were prepared from steel strain curves by a process of graphical differentiation."\(^1\) This does not seem to be accurate because it is difficult to find the gradient of the steel strain curves accurately at a point.

They suggested an equation for transmission length.

\[
L = \frac{3.6 \Delta_1}{(S_1 - S_0)}
\]

where

- \(L\) = transmission length
- \(S_1\) = strain in steel before release
- \(S_0\) = strain in steel beyond the transmission length
- \(\Delta_1\) = slip at end of specimen.

Marshall\(^2\) has conducted some experiments on two sets of ten columns, each of 4 in. x 4 in. cross section one being prestressed by 52 wires of 0.08 in. diameter and the other by 12 wires of 0.2 in. diameter. "The full initial prestress in each set of columns was about 3000 P.S.I."\(^2\) He varied the length of the columns from 4 inches to 72 inches. "The distance between the
gauge pins which were set in the concrete along the length of the column were measured by a travelling microscope reading to \( \frac{1}{4,000} \text{m.m.} \)².

He derived an equation to measure the steel strain at any point \( x \).

\[
f_s = f_{\text{max}} \left[ 1 - e^{-\frac{a}{d} x} \right]
\]

where

- \( f_s \) = true steel strain
- \( f_{\text{max}} \) = maximum retained steel strain
- \( a \) = a constant for the particular wire
- \( x \) = distance from the end
- \( d \) = wire diameter.

From his observations he concluded time has some effect on transmission length. He has found that the transmission length for 0.08 inch diameter wire varies from 60 diameters one day after release to 90 diameters one year after release. He also observed that compaction of concrete has a great deal of effect on transmission length.

The experimental procedure adopted by Janney was more convenient than that of Evans and Marshall. Before pretensioning the wire or strand, each wire was fitted with two SR-4 electric strain gauges and each strand was fitted with four gauges. In each case one waterproofed gauge was placed at the midpoint of the prism. All steel reinforcement was tensioned to 120,000 PSI as determined from several gauges and checked with a calibrated pressure gauge on the hydraulic system used to tension the wire.

Twenty-six SR-4 gauges were placed along the sides of the prism after moist curing was complete. Just before the pretension was released, readings were taken on all gauges on the concrete surface and on the steel. The tension on the steel was released and again all gauges were read. This data established the pretension in the steel just prior to release, the
tension retained in the steel at the centre of the specimen, and the distribution of prestress."

"The steel stress distributions were derived from distribution of prestress as determined from strain measurements on the concrete surface, on the basis that the stress in the concrete is uniform over the entire section."

Janney noted that of the three important factors influencing bond, friction, adhesion and mechanical resistance, friction between concrete and steel is largely responsible for the transfer of the stress to the concrete.

On this basis Janney made an elastic analysis of the prestress transfer. "As the tension is released and a wire starts to slip, the diameter of wire increases in proportion to the reduction in tension, and a radial pressure is exerted on the surrounding concrete; thus the frictional force restraining slippage of the wire is increased. This force is dependent upon the radial pressure developed and the coefficient of friction between the steel and the cement paste in intimate contact with the steel. The coefficient of friction will vary with the surface characteristics of the wire and possibly with the character of the cement paste."

Using thick walled cylinder theory he suggested an equation for relationship between the wire tension and length from free end.

\[
\log \frac{f_{se}}{f_s} = \frac{2 \phi u_s L}{r \left[1 + (1 + u_c) \frac{E_s}{E_c}\right]}
\]

where

- \( r \) = radius of wire
- \( f_s \) = tensile stress in the wire at any point
- \( f_{se} \) = Pretension stress in wire
Janney concluded that the ability of pretensioned wire to transfer stress to the concrete through bond does not vary a great deal with wire size in the range of 0.100 to 0.276 in diameter. The length of embedment necessary to transmit stress fully to the concrete prisms is moderately greater as the wire diameter increases. He tested three surface conditions namely rusted, clean and lubricated and concluded that the rusted wire develops the full transfer of prestress at a more rapid rate and in a shorter distance from free end.

The experimental method adopted by George A. Dinsmore, Peter L. Deutsch and Jose L. Montemayor was different and more convenient than that of Evans and Janney. The testing set up and sequence of operation is outlined in Figure 2. The prestressing bed is a rigid steel frame. Mechanical jacks bearing against the frame push against a movable beam. The strand is tensioned between the floating beam and far end of frame as the jacks are loaded. The specimen is then poured around the tensioned strand with one end bearing firmly against the jacking end of the frame. After the specimen is cured, the strand at the free end is burned and the specimen is then equivalent to the end portion of a beam. The pull in test is accomplished by additional jacking at the bearing end, which produces increased strand forces simulating those arising from applied moment in a beam. The jacking is continued until the strand slips or ruptures.
10. HYDRAULIC STRAND BURNED AT POINT X, THEN JACK FORCES INCREASED TO ULTIMATE LOAD.

FIGURE 2: DIAGRAM SHOWING THE WORK OF PETER L. DEUTSCH, GEORGE A. DINSMORE AND JOSE L. MONTEMAYOR
They have performed experiments on 7/16 in. diameter strands and only one surface condition, namely clean. The cross section of the specimens were 4 in. x 4 in., 2 1/2 in. x 2 1/2 in. and 6 in. x 6 in. All strands were tensioned to 18,900 lbs.

They have come to the following conclusions:

1. Friction is the major component determining ultimate bond strength.
2. Concrete strength does not appear to be the principal variable affecting the bond strength.
3. The degree of vibration and resultant compaction of the wet concrete appear to be the most significant variables affecting the bond strength of high strength, low slump concrete.
4. Transfer strength was not observed to increase with time.
5. The bond strength does not appear to be significantly affected by the degree of initial pretension.

Purpose of this investigation

From the preceding discussion it can be seen that previous workers have reached substantial agreement on the nature of bond. They have also reached some agreement on the transmission lengths. However, the extensive instrumentation used by them, namely the radiographic technique by Evans and strain gauge measurement by Janney, has prevented them carrying out the broader testing programme necessary to confirm and utilize their findings.

The purpose of this investigation is to put forward a direct method for the determination of anchorage length of 3/8 inch diameter rusted strand, similar in some respects to the technique used by George A. Dinsmore, Peter L. Deutsch, and Jose L. Montemayor. An attempt was made to determine by direct measurement the variation of steel stress along the anchorage length.
The anchorage length of a strand depends upon many variables such as surface condition, concrete strength and degree of initial vibration. Variables studied in this investigation are initial steel pretension and level of stress in concrete.
Chapter III
Description of the Experimental Method

Apparatus

The apparatus consisted of a steel frame of two longitudinal channels 7 in. x 2 in., two end, and a central bulkhead of 7 in. x $3\frac{1}{2}$ in. welded to it. The end of the specimen against the central bulkhead is referred to as the "tight end", and the opposite end is referred to as the "free end". The distance between the longitudinal channels is 10 inches. The three bulkheads incorporate welded stiffners inside the web at the third points. There is a ½ inch hole at the centre of the bulkheads to pass the strand. A plywood base was bolted to the bottom of the frame to carry the wooden forms and wooden skids were attached to ease movement of the apparatus where and when necessary.

A screw jack system was used for tensioning the strands. A ½ inch jack base plate with 3 inch recess was bolted to the bulkheads to fix the screw jack rotor. Yokes were bolted on the ends of the longitudinal channels to prevent rotation of upper part of jack and strand. The distance between the jack base plate and the end of the yoke is 6 inches. These yokes consist of 1 in. x 2 in. steel bars with a rectangular hole at the centre to pass the screw jack. The jack was turned by a wrench about four feet long. Complete details of screw jack system is shown in Figure 3.

To measure the tension in the strand "load cells" made by the Baldwin Lima Hamilton Company were used. They consist of a steel rod carrying strain gauges. This rod, the dummy gauge and necessary circuitry are sealed inside a cylindrical steel case. Facilities are provided for loading in tension or compression. The load cells were calibrated on Baldwin Hydraulic testing machine. Complete details of calibration of load cells are given in the Appendix.
A load cell was installed at each end of the strand, to obtain the net force in the strand, as the prestress force was transferred from the frame to the concrete specimen. The load cells were connected to the strand by commercial strand grips, housed in screw couplings. 7/16 inch diameter strand was used to connect the other end of the load cells to the loading screw jack.

"The load cells had to be read in quick succession on a single strain indicator. A switching device was used for this purpose. The switching device was constructed by mounting four two-way mercury switches in a watertight plexiglass box. The results obtained with the switching device showed no variation due to contact resistance."

To measure the slip on both ends of the specimen, that is, free end and tight end, two dial gauges were used. The dial gauges used were "Federal" measuring with an accuracy of 0.001 inch. The dial gauges were attached to the frame by means of magnets and clamps, and were in contact with aluminum gauge stops attached to the strand.

**Testing sequence**

The concrete mix was designed for 6000 PSI after forty-eight hours. Type III Portland cement was used. After testing a number of 6 inch diameter and 4 inch diameter cylinders it was found difficult to obtain a constant high strength mix using the small drum mixer available. Several mixes were tried. Finally a mix which produced 4500 PSI after forty-eight hours was used. Complete details of mix design is given in the Appendix. Two tensioned specimens, one untensioned specimen of the same length, and two 4 in. x 8 in. cylinders were cast from each batch.

The strands used in the tests were 7 wire 3/8 inch diameter rusted
strands of Japanese manufacture. The aluminum gauge stops and end forms were installed and then the strand was tensioned. Creep was minimized in the test series by applying a seven percent overstress for about three minutes during prestressing. The strands were left four to five hours to permit primary creep to take place. The weighing and batching of concrete were started three hours after tensioning the strand. The forms were then placed in position.

In order to get the constant vibration of the specimens and cylinders, the procedure was standardized. A \( \frac{3}{4} \) inch machined steel plate with spacers and studs were fixed to the sides of the wooden forms and the vibrator head attached through a steel yoke and cross head. A similar arrangement was used for vibrating the cylinders. Complete details of vibrator attachment are shown in Figure 4.

The specimens and cylinders were vibrated in two layers for twenty seconds each, in the following order: first the two tensioned specimens, then the untensioned specimen and the cylinders. This procedure was adopted throughout the series.

The specimens and the cylinders were cured by covering with sacks which were kept moist by water spray.

Curing was stopped one and a half hours before testing. The sacks and side wooden forms were taken off and the specimens and cylinders were allowed to dry.

After one hour of drying the cylinders were capped with high strength, model CT-59 sulphur compound. The cylinders were tested in Baldwin testing machine with a speed of 0.05 inch/minute. The dial gauges were fixed close to the ends of the specimen to record the slip. Then the two tensioned
FIGURE 4  DETAILS OF VIBRATOR ATTACHMENT.
specimens were tested and the untensioned specimen was tested in one of the steel frames.

Initial readings were taken of the dial gauges and load in the strand on each end of the specimen. The force in the strand on the free end of the specimen was reduced in increments, both dial gauges and both cells being read at each increment. If the specimen were of sufficient length to anchor the whole prestress then the force in the free end could be reduced to zero without substantially reducing the force in the other end. The dial gauges and load cells were read when the load on the free end was zero. The load in the tensioned end of the specimen was increased until the strand slipped through the specimen. The dial gauges were noted just before the slip and after. Three or more readings were taken after the slip. If the length of the specimen was not sufficient to anchor the whole force the strand would slip while detensioning the strand. The dial gauges and load cells were noted just before and after slip. Readings were taken until the free end was completely unstressed. The untensioned specimen was placed in one of the steel frames and force was increased until the strand slipped. The dial gauges and load cells were read just before and after slip. Two or three more readings were taken after the slip.

Experiments were carried out on 3/8 inch diameter strands under two loading conditions and only one surface condition. Three different cross sections were tried, namely 4 in. x 4 in., 3 in. x 3 in. and 2 in. x 2 in. In all series with the exception of series VII strand tension was the same, so that concrete stress varied inversely with the size of cross section.

Slip

Two types of slip occurred. First was that which took place while releasing the pretension at the free end and it was called "release slip".
Second one is that which took place while tensioning the strand at the tight end after complete detensioning at the free end, and it was called strand slip.

Description of tests

Series I. 4 in. x 4 in. cross section prestressed specimens.
Twenty-one specimens were tested in this series ranging in length from 6 inches to 48 inches. The primary purpose of this series was to find the anchorage length. All the specimens were cast with small drum mixer available, and were tested after forty-eight hours. Two or three wires of the strand were broken when the lengths of the specimens were 24 inches and more, after the second slip. The break was at the end of the grip at the tight end. The force in the strand at the time of break was usually 1 to 1.5 kips less than the force at first slip. Specimens 10 inches and longer anchored the whole force. Specimens eight inches and shorter slipped while releasing the prestress.

Series II. 4 in. x 4 in. cross section untensioned specimens.
The primary purpose of this series was to find the difference in anchored force between the tensioned and untensioned specimens. These specimens were cast from the same batch as those of series I with small drum mixer and were tested after forty-eight hours. Seven specimens were tested in this series ranging in length from 6 inches to 18 inches.

Series III. 3 in. x 3 in. cross section prestressed specimens.
The primary purpose of this series was to find the effect of level of stress in concrete on the anchorage length. The specimens were cast with "Linear Cumflow" mixer and were tested after forty-two hours. The concrete strength of this series was slightly higher than that of the series I and II. Thirteen specimens were tested in this series ranging in length from 6 inches to 18
inches. Specimens ten inches and longer anchored the whole prestress. Specimens 8 inches and shorter slipped while detensioning the prestress. The strand was broken after the first slip at the end of the grip at the load of 19.100 kips in one of the 16 inch long specimens only.

Series IV. Untensioned 3 in. x 3 in. cross section specimens. The primary purpose of this series is the same as that of the series II. The casting of the specimens was similar to that of the series III and they were tested after forty-two hours. Eleven specimens were tested in this series ranging in length from 4 inches to 18 inches. Specimens 18 inches, 16 inches and one of the 14 inches were able to anchor the force of 14 kips.

Series V. 2 in. x 2 in. cross section prestressed specimens. The main purpose of this series is the same as that of the series III. Twelve specimens were tested in this series ranging in length from 4 inches to 20 inches. The performance of these specimens is very erratic. There was no clear indication of anchorage length for the 14 kips prestress. Some of the specimens exhibited a longitudinal crack which is undoubtedly due to radial stresses.

Series VI. Untensioned 2 in. x 2 in. cross section specimens. The purpose of this series was the same as that of the series II. There was a longitudinal crack in the 14 inch and 4 inch specimens.

Series VII. 4 in. x 4 in. cross section tensioned specimens. The primary purpose of this series was to find the effect of initial steel pretension. Three specimens were cast of length 10 inches, 12 inches and 14 inches. The strands were tensioned to 17 kips and reduced to 16 kips after three minutes to minimize the creep. 10 inch specimen slipped while releasing the prestress and 12 inch, 14 inch specimens anchored the whole prestress.
Chapter IV
Experimental Results and Conclusions

Table of Results and Graphs

The results of experiments were tabulated in Tables I to VII. Column 2 is the bonded length of the specimens in inches. Column 3 is the maximum force anchored in kips. Column 4 is the type of slip as defined in Chapter III. Column 5 is the strand movement at the free end just before the first slip. Column 6 is the strand movement at tight end just before the first slip. Column 7 is the strand movement at the free end recorded on the dial gauge after the first slip. Column 8 is the strand movement at the tight end after the first slip. Column 9 is the load remaining in the strand on the tight end of the specimen, when the load in the strand in the free end has been reduced to zero. Column 10 is the crushing strength of the two cylinders.

The results are shown graphically in Figures 5, 6, 7, 8, 9 and 10, which are curves of load anchored, versus length from the free end. Where slip took place before the load in the strand at the free end has been reduced to zero, the maximum difference anchored was plotted. In the absence of slip the load anchored after the tension at the "free end" has been reduced to zero was plotted. Figure 11 is the force anchored versus slip of specimens 3 in. x 3 in. cross section. Figure 12 is the force anchored versus slip of 6 inches x 12 inches length specimens of 3 in. x 3 in. cross section.

Observation from experimental results

The results as a whole show some scatter when plotted. The results are inconsistent because bond is basically a local phenomenon, and dependent upon the behaviour of a relatively small concrete area, namely the
| Serial No. | Bonded length in inches | Maximum load anchored in kips | Type of slip | Pull in at free end before slip at tight | Pull out at tight | Pull in at free end | Pull out at tight | Load at detention in kips | Cylinder strength
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Table 1. Series 1.

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<th>Maximum load anchored in kips</th>
<th>Type of slip</th>
<th>Pull in at free end before slip</th>
<th>Pull out at tight end before slip</th>
<th>Pull in at free end after slip</th>
<th>Pull out at tight end after slip</th>
<th>Load at detention in kips</th>
<th>Cylinder strength P.S.I.</th>
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</table>

Cross section of all specimens 4 in. x 4 in.

Prestress for all specimens initial 15 kips and effective 14 kips.

*Two or three wires of the strands were broken at the end of the grip after second slip.
Table II. Series II.

<table>
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<th>Serial No.</th>
<th>Bonded length in inches</th>
<th>Maximum load anchored in kips</th>
<th>Maximum strength of cylinder in P.S.I.</th>
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Cross section of all the specimens 4 in. x 4 in.

Untensioned specimens.
### Table III. Series III.

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<th>Bonded length in inches</th>
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<th>Type of slip</th>
<th>Pull in at free end before slip ( \times 10^{-3} )</th>
<th>Pull out at tight end after slip ( \times 10^{-3} )</th>
<th>Pull in at free end after slip ( \times 10^{-3} )</th>
<th>Pull out at tight end after slip ( \times 10^{-3} )</th>
<th>Load at detention in kips</th>
<th>Cylinder strength P.S.I.</th>
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<td>-</td>
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<td>4500 4550</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>15.300</td>
<td>&quot;</td>
<td>53</td>
<td>19</td>
<td>103</td>
<td>45</td>
<td>13.050</td>
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<td>&quot;</td>
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<td>-</td>
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Cross section of all specimens 3 in. x 3 in.
Prestress for all specimens initial 15 kips and effective 14 kips.

* Three wires of the strand were broken at the end of the grip at the force of 19.1 kips.
<table>
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<th>Serial No.</th>
<th>Bonded length in inches</th>
<th>Maximum load anchored in kips</th>
<th>Type of slip</th>
<th>Pull in at free end before slip inches x 10^-3</th>
<th>Pull out at tight end before slip inches x 10^-3</th>
<th>Pull in at free end after slip inches x 10^-3</th>
<th>Pull out at tight end after slip inches x 10^-3</th>
<th>Load at detention in kips</th>
<th>Cylinder strength P.S.I.</th>
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<td>105</td>
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Cross section of all specimens 3 in. x 3 in.

Untensioned specimens.
### Table V. Series V.

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<th>Bonded length in inches</th>
<th>Maximum load anchored in kips</th>
<th>Type of slip</th>
<th>Pull in at free end before slip in inches x 10^-3</th>
<th>Pull out at tight end before slip in inches x 10^-3</th>
<th>Pull in at free end after slip in inches x 10^-3</th>
<th>Pull out at tight end after slip in inches x 10^-3</th>
<th>Load at detention in kips</th>
<th>Cylinder strength P.S.I.</th>
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Cross section of all specimens 2 in. x 2 in.

Prestress for all specimens - initial 15 kips and effective 14 kips.

* Longitudinally cracked specimens.
Table VI: Series VI.

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<th>Serial No.</th>
<th>Bonded length in inches</th>
<th>Maximum load anchored in kips</th>
<th>Type of slip</th>
<th>Pull in at free end before slip in kips \times 10^{-3}</th>
<th>Pull out at tight end before slip in kips \times 10^{-3}</th>
<th>Pull in at free end after slip in kips \times 10^{-3}</th>
<th>Pull out at tight end after slip in kips \times 10^{-3}</th>
<th>Load at detention in kips</th>
<th>Cylinder strength P.S.I.</th>
</tr>
</thead>
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<tr>
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<td>38</td>
<td>43</td>
<td>111</td>
<td>116</td>
<td>-</td>
<td>4850 4950</td>
</tr>
<tr>
<td>7</td>
<td>4*</td>
<td>3.950</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4900 4900</td>
</tr>
</tbody>
</table>

Cross section of all specimens 2 in. x 2 in.

*Longitudinally cracked specimens.

Untensioned specimens.
Table VII. Series VII.

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Bonded length in inches</th>
<th>Maximum load anchored in kips</th>
<th>Type of slip</th>
<th>Pull in at free end before slip in inches x 10⁻³</th>
<th>Pull out at tight end before slip in inches x 10⁻³</th>
<th>Pull in at free end after slip in inches x 10⁻³</th>
<th>Pull out at tight end after slip in inches x 10⁻³</th>
<th>Load at detention in kips</th>
<th>Cylinder strength P.S.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>10</td>
<td>13.250</td>
<td>Release slip</td>
<td>60</td>
<td>7</td>
<td>90</td>
<td>40</td>
<td>8.260</td>
<td>4500 4600</td>
</tr>
<tr>
<td>2.</td>
<td>12</td>
<td>16.650</td>
<td>Strand slip</td>
<td>58</td>
<td>9</td>
<td>185</td>
<td>115</td>
<td>14.750</td>
<td>4500 4750</td>
</tr>
<tr>
<td>3.</td>
<td>14</td>
<td>18.150</td>
<td>&quot;</td>
<td>-</td>
<td>13</td>
<td>-</td>
<td>125</td>
<td>14.750</td>
<td>4500 4500</td>
</tr>
</tbody>
</table>

Cross section of all specimens 4 in. x 4 in.

Prestress of all specimens - initial 17 kips and effective 16 kips.
FIGURE 5: LOAD TRANSFER DISTRIBUTION FOR SERIES I 4 IN. x 4 IN. TENSIONED SPECIMENS.

FIGURE 6: LOAD TRANSFER DISTRIBUTION FOR SERIES II 6 IN. x 4 IN. UNTENSIONED SPECIMENS.
Figure 1: Load transfer distribution for Series III
3 in x 3 in tensioned specimens

Distance from free end: inches

Figure 2: Load transfer distribution for Series IV
3 in x 3 in untensioned specimens

Distance from free end: inches
FIGURE 9: LOAD TRANSFER DISTRIBUTION FOR SERIES V
2-IN. X 2-IN. TENSIONED SPECIMENS

FIGURE 10: LOAD TRANSFER DISTRIBUTION FOR SERIES VI
2-IN. X 2-IN. UINTENSIONED SPECIMENS

DISTANCE FROM FREE END: INCHES

LOAD IN STRANDS: KIPS

0 5 10 15 20
0 5 10 15 20
Figure 11: Slip versus load on anchored for 5 in. x 5 in. cross section tensioned specimen.
Figure 12: Slip versus load anchored for 6 in and 12 in. length tensioned specimens of 3/8 x 3/8 in. cross section.
Fig. 13. Tensioned broken specimen.
Fig. 14. Untensioned broken specimen.
Fig. 15. Longitudinally cracked specimen of 2 in. x 2 in. cross section.
circumferential perimeter along the embedded length of the steel. The scatter was anticipated and every effort was made to keep conditions perfectly constant.

Comparison of figures 5 and 6, and 7 and 8 show that a rusted tensioned strand anchors force faster than an identical untensioned strand. The difference is particularly marked in the specimens 4 in. x 4 in. cross section, and 8 in. long. The pretensioned specimen anchors a maximum load of 8,350 lbs. while the untensioned specimen anchors only 5,125 lbs.

The force anchored versus length plot for rusty untensioned strand is substantially linear.

A modification was made in the dial gauge stops after series I and II. Aluminum dial gauge stops were used. With aluminum dial gauge stops we were able to note the readings of slip fairly accurately enough. With screw jack system it was difficult to tension the strands more than 17 kips. A hydraulic system would be more convenient and easier in that respect.

From the results it was observed that there was not much difference in anchorage length between 4 in. x 4 in. and 3 in. x 3 in. cross section specimens. There was a great deal of difference between 3 in. x 3 in. and 2 in. x 2 in. Many of the 2 in. x 2 in. specimens were cracked because the concrete cover is not sufficient to take the tension due to radial stresses.

One tensioned and one untensioned specimens were broken open after testing and the grooves surrounding the strands were studied. Figure 13 is the tensioned broken specimen. In these two cases the grooves were polished but not in any way destroyed. A polished groove indicates that relative movement between the strand and concrete has taken place. Figure 15 is the longitudinally cracked specimen of 2 in. x 2 in. cross section. The longitudinal crack is due to radial stresses. In the case of release slip the cracks are due to the insufficient concrete cover to take the tension due to radial stresses on account of the swelling of the strand.
at detensioning. In the case of strand slip the radial stresses are caused by pulling the strand which assumes the shape of a cylindrical wedge on account of difference in force at each section of the strand.

The load in the wire retained after release of pretension is shown in Column 9. It was observed that this load only attains about eighty-five to ninety percent of the initial prestress of 14 kips even when the prestress is apparently fully anchored. The reduction is partly due to relaxation of steel and partly due to elastic flexure of the bulkhead under the compressive prestress load in the concrete. The relaxation of steel at 48 hours is observed to be 300 lbs. It was observed that this reduction in load is always higher in lighter frame than the heavier frame.

Conclusions From experimental results the following conclusions can be made:

1) The anchorage length of 3/8 inch diameter rusted strand is between 8 and 10 inches for a force of 13 to 14 kips.

2) Friction appears to be the major component determining the bond strength.

3) The bond strength of strand does not appear to be significantly affected by the degree of initial stress in concrete.

4) It appears that for an anchored force of 12 to 12.5 kips the slip of the strand at the free end is on the order of 0.028 to 0.040 in.
Appendix 1.

Specification of materials and apparatus used.

Load cells. Load cells were calibrated with a "K" type strain indicator and in Baldwin hydraulic testing machine. A graph is drawn between the load and indicator reading and is shown in Figure 16. From the graph it was found that one division in strain indicator is equal to five pounds of load.

Strand. The strand supplied by the manufacturers was specified as 7 wires 3/8 inch diameter of Japanese manufacture.

Tensile test was carried out on one strand in Baldwin hydraulic testing machine. The measured specifications were as follows:

- Breaking load: 21,250 kips.
- Tensile strength: 266 K.S.I.
- Yield: 18.50 kips.
- Yield stress: 232 K.S.I.

Relaxation of steel. Relaxation characteristics of 3/8 inch diameter strand is shown in Figure 18. The strands were overtensioned by 7 percent for 3 minutes to reduce creep losses commencing the observations.

Aggregate. The results of sieve analysis of the aggregate is shown below.

<table>
<thead>
<tr>
<th>Sieve No.</th>
<th>1'' Aggregate</th>
<th>3/8'' Aggregate</th>
<th>Sand</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 in.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3/4 in.</td>
<td>27.3</td>
<td>96.8</td>
<td>0</td>
<td>9.6</td>
</tr>
<tr>
<td>3/8 in.</td>
<td>96.8</td>
<td>0</td>
<td>0</td>
<td>34.0</td>
</tr>
<tr>
<td>No. 4</td>
<td>100</td>
<td>96.2</td>
<td>0</td>
<td>57.2</td>
</tr>
<tr>
<td>No. 8</td>
<td>100</td>
<td>11.75</td>
<td>0</td>
<td>63.00</td>
</tr>
<tr>
<td>No. 14</td>
<td></td>
<td>28.98</td>
<td>70.60</td>
<td></td>
</tr>
<tr>
<td>No. 30</td>
<td></td>
<td>57.52</td>
<td>82.20</td>
<td></td>
</tr>
<tr>
<td>Sieve No.</td>
<td>1&quot; Aggregate</td>
<td>3/8&quot; Aggregate</td>
<td>Sand</td>
<td>Combined</td>
</tr>
<tr>
<td>----------</td>
<td>--------------</td>
<td>----------------</td>
<td>--------</td>
<td>----------</td>
</tr>
<tr>
<td>No. 50</td>
<td></td>
<td>83.57</td>
<td>93.20</td>
<td></td>
</tr>
<tr>
<td>No. 100</td>
<td></td>
<td>97.35</td>
<td>99.00</td>
<td></td>
</tr>
<tr>
<td>No. 200</td>
<td></td>
<td>99.00</td>
<td>99.70</td>
<td></td>
</tr>
</tbody>
</table>

The gradings are plotted in Figure 17, the combined aggregate being shown as dotted. The aggregate cement ratio used in the mix was 3.2 and the water cement ratio was 0.396. Type III cement was used throughout the tests.

Capping of the cylinders. First it was thought to cap the cylinders with cement and sand. In fact several 6" diameter cylinders were tested with cement and sand caps. Finally a capping apparatus to cap 4" diameter cylinders was used for balance of tests. Minor modifications were made on the apparatus to get good caps. Cylinders were capped on both ends with high strength, model CT-59 sulphur capping compound. The thickness of the caps are between 1/8 in. to 1/4 in. Cylinders were tested in Baldwin hydraulic testing machine fifteen minutes after capping at the speed of 0.050 inch/minute. This procedure was adopted throughout the tests.
FIGURE 16: CALIBRATION CURVES OF LOAD CELLS NO 3 AND NO 4
Figure 18: Relaxation curve for 3/8 in. diameter strand.
Bibliography


