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ANCHORAGE CHARACTERISTICS OF STRAND IN PRETENSIONED PRESTRESSED CONCRETE

by

George A. Dinsmore

and

Peter L. Deutsch

Lehigh University
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This experimental study has been executed at

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FRITZ ENGINEERING LABORATORY
DEPARTMENT OF CIVIL ENGINEERING

Professor W. J. Eney
Director and Head

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LEHIGH UNIVERSITY

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INTRODUCTION

This experimental study of anchorage bond in pretensioned prestressed concrete was undertaken to determine, in so far as possible, the nature of the phenomenon. The evaluation of this information would then permit the formulation of recommendations for design practice which would prohibit anchorage bond failures in structural members. Considerable progress has been made toward the fulfillment of these objectives, and tentative recommendations are offered at the end of this report.

Anchorage Bond Failure

The principles involved in anchorage bond failure are easily seen if a pretensioned member is imagined which has the strand in its central portion encased in a frictionless tube (See Figure 1). This beam is, in effect, a post-tensioned member whose end anchorage is developed by the bond between strand and concrete over the embedment length $L$. When the prestress is released to the member, the prestressing force in the strand builds up to its effective level over a short length $L_t$ at the ends. This is the transfer or transmission length. Should the required transfer length be greater than the available embedment length, bond failure must occur at release of prestress. But, if the embedment length is great enough so that the beam
Figure 1  End Anchorage Concept
withstands the transfer of prestress and the beam is subsequently loaded, increasing the strand force at the unbonded interior of the beam, the tendency for the strand to slip and screw inward is likewise increased. If at a given load the embedment length is not sufficient to develop a total bond force equal to the strand tension, the strand must slip.

**Ultimate Anchorage Length**

For any particular beam there must theoretically exist a certain length of embedment which will provide just sufficient anchorage bond to resist the full tensile capacity of the strand. This embedment is the "ultimate anchorage length." If the embedment length in the hypothetical beam is made equal to the ultimate anchorage length and the beam is loaded, stretching the strand to its ultimate strength, the strand will rupture simultaneously with the occurrence of strand slip.

**The Slip Limit Envelope**

It seems evident that in a member having an available embedment less than the ultimate anchorage length, that the embedment present provides sufficient bond capacity to resist some particular strand tension. The bond capacities of various embedment lengths may then be thought of as defining a curve, shown in Figure 2 - The Slip Limit Envelope. Any combination of strand tension and embedment length falling
Figure 2 The Slip Limit Envelope
outside the slip limit envelope (that is, falling in Area 1) should produce a slip failure. A combination giving a point within the envelope (Area 2) would be expected to perform safely.

The determination of the ultimate anchorage length and the establishment of the slip limit envelope for 7/16 inch prestressed strands embedded in 6000 psi concrete were the immediate objectives of the testing program.

DESCRIPTION OF TESTS

The "pull-in" tests reported in this paper simulate the conditions in the anchorage regions of the hypothetical beam of Figure 1. They are also believed to faithfully reproduce the conditions existent in fully bonded members until the instant of first slipping. Thirty-four of the pull-in specimens were poured and tested in the Fritz Laboratory prestressing bed in eight series of tests. The specimens were of various lengths, all 4" x 4" in cross-section and were reinforced by a single centrally located 7/16 inch tensioned strand.

Testing Sequence

The testing setup and the sequence of operations is shown in Figure 3. The prestressing bed is seen to be essentially a rigid steel frame. Mechanical jacks bearing against the
7/16" Strand Tensioned to 18,900 Lbs.

Beam Cast With One End Cast Against Bulkhead

Strand Burned at Point X, Then Jack Forces Increased To Ultimate Load.

Figure 3 Diagrams Showing Sequence of Operations
frame push against a moveable beam. The strand is stretched between the floating beam and the far end of the 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 prestressed 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.

The prestressing bed was modified in the course of the test program by the addition of a second floating beam and a second set of jacks so that jacking could be performed at either end of the bed. This permitted the placing of specimens at both ends of the bed doubling the capacity. Prestress was released by burning the strand between the specimens and the testing was then performed at each end independently.

The modification of the bed also made it possible to release specimens gradually. In this case they were cast at one end of the bed only. The jacks at the far end were later unloaded in stages to accomplish the gradual release.
Procedure and Instrumentation

The details of the procedure are best described with the help of photographs. Figure 4 shows the end of the prestressing bed with four strands under tension. The strands are gripped by patented chucks called "Strandvises." These proved capable of withstanding the ultimate strand tension. In only one case did a strand break in or near the grip and in that instance the load was well above the guaranteed ultimate for the strand. Between the strandvises and the floating beam are the pipe dynamometers used in the measurement of strand tension. They consist of four SR-4 electrical resistance strain gages mounted on an extra heavy pipe section in such a way as to be self-compensating for temperature changes.

The specimens are cast in the oiled steel forms after the strand has been thoroughly cleaned with acetone. At the bearing end of the specimen the strand passes through a bearing plate which also serves as the end of the form. In Series IV through VI 3/8 inch spacers were introduced between the bearing plate and the frame. When these spacers were removed after the specimen was cured, the bearing plate was firmly clamped to the frame and a Carbo-Vitrobond cap was poured between the end of the specimen and the bearing plate to assure positive contact and to compensate for any shrinkage which might have
Figure 4  Tensioning Arrangement

Figure 5  Curing Specimens
caused the specimen to draw away from the bearing surface. Figure 5 shows the specimens in the steel forms being cured under plastic (note the test cylinders also under plastic beside the bed). In Figure 6 the caps are shown as poured in place at the bearing ends of the specimens.

To avoid the superposition of bearing strains on those resulting from the prestress, an unbonded length is provided at the bearing ends of the specimens. The lengths of specimens discussed in this report are the bonded lengths in all cases. The bond is effectively destroyed in the unbonded portion by wrapping the strand with waxed paper smeared with heavy grease, the resulting hole is cylindrical and no restraint is imposed on the strand within the length.

At the release or transfer of prestress, the strand at the release end is drawn into the specimen by a small amount. This is called "release slip" as distinguished from "strand slip," the term describing bond failure. Figure 7 shows mounted on the strand the dials which are used to measure release slip in those cases where the release is gradual. To obtain accurate release slip data for sudden release, the set-up shown in Figure 8 was devised. Here, two dials supported from the specimen bear against a plate mounted on the strand. This set-up compensates for any movement of the strand during release and
Figure 6  Bearing End of Specimen

Figure 7  Gradual Release of Prestress
Figure 8 Slip Gages for Sudden Release

Figure 9 Aluminum Channels for Mounting SR-4 Gages
the average of the two dial readings gives a valid measurement of release slip.

Strain readings were taken along the entire length of several specimens at the surface of the concrete. Two different techniques were used to obtain these readings. The SR-4 gages, clearly visible in Figures 6 and 7, are mounted on the surface of small aluminum channels whose flanges have been deformed as shown in Figure 9. The aluminum strips were screwed to the steel forms before the concrete was poured. The deformed flanges provided complete bonding with the concrete and the aluminum offered a smooth dry surface on which the strain gages could be mounted without fear of moisture contamination. This technique proved to be entirely practical but mechanical difficulties in some of the laboratory switching boxes resulted in the loss of considerable data.

The second procedure for measuring concrete strains is illustrated in Figure 10. Instead of electrical gages a mechanical tensometer was used over a gage length of ten centimeters. Small holes in the probes of the gage slip over the minute steel spheres set into small aluminum plates which are, in turn, cemented to the sides of the specimen. The technique is slow and laborious but readings can be duplicated consistently. Corrections must be applied to the data for
Figure 10  Huggenberger Tensometer Measuring Concrete Strains

Figure 11  Slip Gaging at Test
temperature changes in both the specimen and the instrument. The final results appear to be in good agreement with those obtained with electrical gages.

Dial gages set up to measure strand slip during the testing phase of the operation were either mounted in the manner of Figure 8 or of Figure 11, the methods being equally convenient. In Figure 11 a protractor can be seen with a pointer mounted on the strand to give a crude indication of the rotation of the strand.

Figure 12 gives an overview of the test set-up for Series V in which three of the four specimens were fully instrumented with SR-4 gages. Temperature compensating gages were mounted on aluminum channels cast into the cylinder shown in the foreground of the picture.

The twelve specimens of Series VIII are shown in the prestressing bed in Figure 13. The four specimens at the center of the frame are short beams cast around well-oiled strands. They are discussed in detail later.

Materials

Type IA cement was used for all specimens except those of Series 1 and 2 for which type I plus an admixture was used. The particulars of the mix for each series are given in Table I. The coarse aggregate was crushed limestone of a
Figure 12 Test V During Gradual Release

Figure 13 Test VIII Overview of Set-up
3/4 inch maximum size. The mixes were designed to yield a 6000 psi concrete at twenty-eight days. The actual cylinder strengths at the time of release, at test, and at twenty-eight days are recorded in Table II. In this table values are given for the modulus of elasticity of the concrete. As indicated, two methods were used in the determination of these values. In the flexure procedure one of the regular test specimens was loaded as a beam, its deflections measured and the tangent modulus at no load computed from the load-deflection curve. In those cases where the value was found by cylinder test, the load-deflection curve was obtained from the data given by SR-4 gages mounted opposite to one another at the mid-depth of the cylinder. Again the tangent modulus is recorded.

The entrained air in all mixes was approximately three percent.

The strand was 7/16 inch nominal diameter seven-wire uncoated strand. The manufacturer gives the approximate area as 0.1089 square inches, the ultimate strength as 27 kips, the average modulus of elasticity as $27 \times 10^6$ psi, and recommends a design load of 15,120 pounds and a tensioning load of 18,900 pounds.

In the initial tensioning of strands for the specimens the 18.9 kip load was approached as nearly as possible. With four strands involved at a time, all could not be brought
### TABLE I  Concrete Mixes

<table>
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<tr>
<th>Series</th>
<th>Cement Factor</th>
<th>W/C Ratio</th>
<th>Mix Quantities in Lb/cu yd</th>
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<tr>
<td></td>
<td>Sks/yd</td>
<td>Gal/sk</td>
<td>Water</td>
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<tr>
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<td>320</td>
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### TABLE II  Concrete Strengths

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<th>Age in Days</th>
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<td>At Test</td>
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<td>VII</td>
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<td>17</td>
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<tr>
<td>VIII</td>
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<td>39</td>
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(f) $E_c$ Determined by Flexure Test.

(c) $E_c$ Determined by Cylinder Test.
exactly to this figure. Certain losses reduced this load to the effective prestressing forces shown in Tables III and IV. The values are in the practical range. Losses prior to the release of prestress include some inelastic deformation of the frame in the cases where four and five strands were tensioned, and some relaxation of the strand, an unknown portion of which was reflected in the dynamometer readings. After release elastic and creep losses for the unbonded portion and for the Carbo-Vitrobond caps are present along with whatever losses develop from the deflection of the end beam of the rigid frame.

RESULTS OF THE TESTS

The requisite data for the determination of the ultimate anchorage and the establishment of the slip limit envelope is arranged in order of lengths of the specimens in Table III and graphical form in Figure 14.

The thirty-four specimens tested ranged in length from one to twelve feet. No specimen having a bonded length of more than four feet slipped either at release of prestress or under applied load. Two of the four specimens four feet long slipped, but none of the six specimens between four and five feet did. So five to six feet would appear to be a safe conservative value for the ultimate anchorage length.
<table>
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<th>Specimen Number</th>
<th>Bonded Length Feet</th>
<th>Type Release</th>
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<th>Strand Slip</th>
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* Maximum load attained. Strand not broken.
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<th>Specimen Number</th>
<th>Bonded Length Feet</th>
<th>Type Release</th>
<th>Ultimate Strand Kips</th>
<th>Strand Slip</th>
<th>Effective Prestress Kips</th>
<th>Slip at Release In.</th>
<th>$f'_c$ at Test Psi</th>
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<td>.028</td>
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* Maximum load attained. Strand not broken.

TABLE IV - Tabulated Results of Pull-In Tests
The performance of specimens of four feet and less in length is seen to be highly erratic and nothing even suggesting the theoretical slip limit envelope is indicated. Two of the specimens shorter than four feet developed the ultimate strength of the strand. Six such specimens withstood the release of prestress successfully but failed in slip during the application of jacking load (The shortest of these was 1 1/2 feet long). Five specimens failed at release of prestress. The one foot specimen and the two foot specimen were released suddenly. The three, three and one-half, and four foot specimens slipped during a gradual transfer of prestress. For these specimens the transfer length was evidently in excess of the length of the specimen. The performance of these three specimens is obviously exceptional, but no satisfactory explanation has yet been discovered.

The performance of the four untensioned specimens is remarkably similar to the performance of those which were prestressed. The three specimens longer than four feet developed the ultimate strength of the strand, whereas the one shorter than four feet slipped at a load in excess of the usual prestress level. It is apparent that the level of prestress has little if any effect on the bonding capacities.
No specimen in any of the tests showed any cracking, spalling or any other indication of distress in the concrete. Only in Series VIII were any sounds heard from the specimens. There were sharp reports which accompanied abrupt slipping of strand. This unique effect is discussed in detail later.

Many of the specimens tested were later smashed and the grooves in the concrete surrounding the strands studied. In all cases in which slip occurred the grooves were highly polished, but not in any way destroyed. A polished groove then indicates that a relative movement between the strand and the concrete has taken place. All of the specimens which did not fail in slip showed the same polished appearance in the transfer region and also at the jacking end. In that portion of these specimens between the transfer region and the region affected by the jacking, the grooves showed a dull, rather chalky appearance. Unfortunately the contrast was not sufficiently great to permit the measurement of the various lengths by these observations.

The data presented in Table III is rearranged in order of series in Table IV to facilitate the following discussion of each series.

Series I and II

These were preliminary tests designed to establish the order of magnitude of the ultimate anchorage length. The
specimens had lengths of six, eight, ten, and twelve feet with an additional six inches of unbonded length at the bearing end. The strand was quite badly rusted, having been drawn from old laboratory stock. The release was sudden. The measurement of release slip was crude; a single dial was attached to the strand prior to the burning of the strand. Slips on the order of .01 to .05 inches were observed by this method.

Series III

The two beams of Series III were five and seven feet in length with again an additional six inches of unbonded length at the bearing end. Clean new strand was used for this and all subsequent tests. The five foot specimen had SR-4 gages mounted on aluminum strips on the sides of the specimen. Zero readings on these gages were taken just prior to the sudden release. The strain history of the specimen is recorded on Figure 15. Immediately after release a strain of 180 micro-inches over the greater length of the specimen was observed. Dividing the effective prestress by the area of the specimen and this strain of 180 micro-inches per inch, the modulus of elasticity is found to be 5.3 million, a figure which checks very nicely with that determined from the load-deflection curve obtained from the specimen under flexural load.
The transfer length is seen to be on the order of ten inches for the specimen.

The zero readings prior to the jacking test were taken twenty-three hours after release. It is seen that creep resulted in a fairly uniform increase in strain.

Examination of Figure 15 shows the influence of the jacking forces penetrating two and one-half feet into the bonded length of the specimen before the strand finally ruptured at a load of 28.3 kips. The same data is shown in Figure 16 with the pre-test strains taken as a base. The effect is to smooth the curves and reveal a quite linear characteristic. The slight increase in strain between the one and two foot marks is probably only further development of creep under the prestress developed in the transfer length since the testing required several hours for completion.

The pronounced dip in the strain distribution curves of Figure 15 at the bearing end suggested the desirability of capping the specimens against their bearing plates after curing was completed to minimize the losses at release which undoubtedly accounted for the dip. This dip was not characteristic of later tests, so the remedy was evidently appropriate.

After the failure of the strand the specimen was in reality a prestressed beam, but one having an exceptionally
long transfer length at the jacking end. In Figure 15 it is seen that, over the entire length disturbed by jacking, the strand force builds up linearly, suggesting that the bond is entirely frictional. Considerable residual strain is noted at the jacking end.

It should be noted that the manipulations at the jacking end have left completely unaffected the transfer portion of the original curve. Presumably if the jacking action had produced strains encroaching on this portion of the curve, the strand would have slipped. It seems reasonable to conclude, therefore, that the ultimate anchorage length for this specimen is approximately three and one-half feet, the sum of the transfer length and the length influenced by the jacking. If either of these were increased, the ultimate anchorage length would be increased. Both of these lengths will be seen to be variable as the remaining tests are reviewed.

The second specimen of the series also developed the full strength of the strand.

Series IV

The eight specimens of Series IV were graduated in bonded length from one to four and one-half feet in six inch increments. The specimens were capped in place and an
additional six inches of unbonded length was provided at the jacking end. Prior to this series the prestressing bed had been modified by the addition of the second floating beam which permitted jacking from either end. The release of the specimens was sudden. No attempt was made to obtain release slip data since no reliable procedure had been devised.

Table IV provides an adequate summary of the basic data. It was in this series that strand slip was first encountered. The one foot and the two foot specimens slipped at release but retained an effective prestress of 10.1 and 14 kips respectively. The one and one-half foot specimen withstood the release of prestress showing an effective prestress of 16.8 kips but began to slip as the jacking load was increased beyond 18 kips. The two and one-half foot specimen slipped at a load exceeding 19 kips, and the four foot specimen at a load in excess of 22.5 kips. The three foot, the three and one-half foot, and the four and one-half foot specimens did not slip.

Dials were affixed to the specimens to measure slip during the loading by the method of Figure 11. The strands had been burned off close to the specimen and as the jacking was continued the button on the strand formed by this burning was drawn into the specimen. Slip is plotted against jacking
force in Figure 31 for these specimens. It is seen that the load carrying capacity of the specimen continues to increase as the slip progresses and that the rate of increase is greatest with specimens slipping at high loads and a minimum with specimens slipping at release. Since the button was drawn in on all of these specimens it evidently is not the determining factor. Three curves for specimens of Series V which slipped at release are plotted on this graph. It is striking that they have exactly the same slope as do the Series IV specimens which failed in the same manner since the strands in Series V were burned several inches from the end of the specimens and no buttons were present to influence the results.

It must be pointed out again that the "free" slip observed in these specimens is not possible in a beam and that the slip curves are of academic interest only.

**Series V**

Three of the four specimens in this series were instrumented with SR-4 gages over their entire lengths. Their lengths were three, three and one-half and four feet. A fourth specimen without any special instrumentation was another at three and one-half feet. This had been indicated as the ultimate anchorage length in Test III.
The specimens were released gradually. Slip was measured by the method of Figure 7. The three specimens carrying the heavy instrumentation all showed abnormal slipping when only thirty percent of the prestress had been transferred. All three slipped in excess of 0.3 inches. The slip is plotted against percent of prestress released for these specimens in Figure 29. The curve for the fourth specimen is compared with those for other "normal" specimens in Figure 32.

The curves of Figure 29 show that once the slipping has fully developed it becomes directly proportional to the prestress released. In Figure 30 the percent of prestress lost at the load end is plotted with slip and again the three curves are parallel and straight one slip has developed throughout the length of the specimens. This seems to establish that the bond has become entirely frictional. Again it should be noted that in an actual beam the physical restraints imposed by the concrete place definite limits on the loss of prestress which can occur. The friction was sufficient for the specimens to develop some effective prestress: 4.1 kips in the three foot, 4.2 kips in the three and one-half foot, and 7.6 kips in the four foot specimen.
The strain gages along the lengths of the specimens should have provided an excellent picture of what was happening, but the failure of several contacts in the laboratory switch boxes resulted in the loss of the zero reference and the interpretation of the data was made very difficult. The picture which finally emerged from the confusion is indicated in Figure 33. Curve 1 represents the release of a small percent of the prestress, for example 10%. It shows a normal development of transfer length. The release of additional prestress exceeds the capacity of the transfer length for some unknown reason and Curve 2 results. The curve develops a slope showing a frictional bond at work. A second transfer length develops in the interior of the specimen, but the release of additional prestress exceeds its capacity, the strand slips through the full length of the specimen and the strains collapse to the level of Curve 3, the bond becoming entirely frictional.

These three remarkable specimens had shown that the transfer length could be greater than four feet, suggesting an ultimate anchorage length in excess of six feet. Perhaps even more remarkable was the existence of the fourth specimen, in every way similar except in instrumentation, which not only declined to slip at release, but when tested broke the strand at 27.9 kips.
Before the jacking forces were applied, Huggenberger tensometer gage points were applied along the length of the fourth specimen. Under load the curves of Figure 17 were obtained. They are quite similar to those obtained in Series III except that the influence of the jacking penetrates a somewhat shorter distance, about a foot and one-half. This then requires the transfer length to be less than two feet in this specimen.

The slip vs. load curves developed by the specimens which slipped and shown in Figure 31 have been previously discussed.

**Series VI**

The four specimens of this series were intended to clarify the unexpected results of Series V, and to reproduce them if possible. Two factors in particular were to be checked. It was felt that the gradual release of the pre-stress might have had an effect and secondly there was the possibility that three of the specimens had been over-vibrated. When the specimens had been broken open a multitude of pock marks, almost microscopic, were observed. These had not been present in other specimens in such numbers. It was felt that a foam may have collected on the strand as the result of over-vibration of the air entrained concrete.
A four foot specimen and a three and one-half foot specimen were slated for gradual release. A three and one-half and an eight foot specimen were to be released suddenly. The eight foot specimen was to be very severely over-vibrated. All of the specimens were to have a two foot unbonded length to permit a full leveling of strains at the bearing end. They were all to be capped in position and all were to be adorned with tensometer gage points over their entire lengths.

None of the specimens slipped at release.

None of the specimens slipped under test. In each case the strand attained the guaranteed ultimate load.

The release slip for the specimens gradually released are shown in Figure 32. The build-up of the concrete strains during the gradual release is shown in Figures 18 and 25. The transfer lengths are a little more than a foot. The curves are very similar to those shown for beams by Debly in Progress Report 13. Figures 19, 26, and 27 show the development of the strains under test. A wire in the strand of the four foot specimen broke (probably at a weld) at 24.6 kips. Only one set of readings was obtained after the start of the test. The effect of the jacking was evidently felt for only a few inches into the bonded length. The curves
for the three and one-half foot specimen show the effect of
the jacking to be penetrating only about a foot into the
specimen. The curve resulting after strand failure would
show a transfer length of about one foot at the jacking end.
This is quite a contrast to the curve of Series III, but in
each case the curve resulting after strand failure is a good
mirror image of the jacking curve immediately preceding the
failure.

The three and one-half foot specimen which was
suddenly released had a transfer length of about ten inches.
The influence of the jacking forces penetrated little more
than a foot. The ultimate anchorage length indicated by
this specimen is about two feet. The strains are shown in
Figures 20 and 21. The curves continue to rise in an inex-
PLICABLE manner in the unbonded length.

The strain distribution curves for the eight foot
specimen are extremely irregular: Figures 22, 23, and 24.
The data was taken simultaneously with that for the other
specimens and must be accepted as reliable. The influence
of the jacking forces again penetrated only about a foot and
there is no evidence that the over-vibration of the mix had
any adverse effect on the bonding.
Series VII

The four specimens of this series were made with untensioned strands, but had a two foot unbonded length and caps cast in place and were treated in the customary manner. The specimens were seven, five and one-half, four and one-quarter, and two and three-quarters feet in length. The shortest specimen slipped under a load of almost 20 kips. The slip curve appears in Figure 34. The other specimens developed the full strength of the strand.

Tensometer gage points were provided only on the seven foot specimen. The resulting curves are given in Figure 28. The influence of the jacking forces has in this case penetrated about three feet into the specimen. While this is longer than the corresponding distances measured in the prestressed specimens, one four foot specimen of Series 4 failed under load and was probably similarly influenced. The series would certainly seem to indicate that the degree of prestress is relatively unimportant and that the ultimate anchorage length for untensioned specimens is on the same order as for those tensioned to recommended values.

Series VIII

The eight specimens of this series ranged in bonded length from two to four and one-half feet. One foot of
unbonded length was provided. The specimens were not capped. This group of tests was intended primarily to provide additional points for Figure 14 in the critical range of lengths.

The two foot specimen carried an effective prestress of 16.7 kips and slipped under the action of the first small increment of jacking load. Evidently the transfer length was almost two feet for this specimen. The two and one-half foot specimen managed a load of 23.7 kips before slipping. The slip curves for both of these specimens are given in Figure 34. They are completely unlike anything seen before. At the first slip there is a sharp drop in load. The load then builds up again without any slip and the process is repeated. Each sudden slip was accompanied by a sharp report. The jacking was discontinued for two days. No slip occurred during the rest, but upon resumption of jacking the performance was repeated.

The other two specimens at the same end of the frame were both three feet long. Both indicated a very slight slip as plotted in Figure 35, but were loaded beyond the guaranteed strand ultimate. They were then permitted to stand under load for two days. At the end of that time both strands had slipped. Additional jacking broke one of the strands after some additional slipping and resulted in a slip curve for the second specimen.
In comparing the various slip curves, the slip magnitudes must be kept in mind. The full scale in Figure 35 is .035 inches; in Figure 34, .160 inches; and in Figure 31, .500 inches. Very clearly different phenomena are represented.

The remaining four specimens developed the full strength of the strand and showed no slip.

**Special Short Beams**

Some of the extra space available in the forms for Series VI and VIII was utilized to pour five short beam specimens. Two of these were three feet long, one was three and one-half feet, one was four and one-half feet, and the last was five feet long. The beams were exactly the same section as the pull-in specimens. Prior to the pouring of the beams, the strand was impregnated with oil to destroy all bond. All of these beams were released suddenly. Slip data was not successfully obtained.

Figures 36 through 40 show the strain distribution at the time of release and several days thereafter. It is evident that some readjustment took place during the interval in several of the specimens since the indicated creep is obviously not proportional to the original strains.
Each of the curves shows a more or less linear increase in the strain at release to a maximum value at the interior of the beam. There is nothing like the customary transfer length. This is evidently a purely frictional effect which is forced by the impossibility of the strand pulling into the interior of the beam and there is nowhere for it to go. When the strand is released it attempts to shorten, which in turn tends to reduce the pitch. The grooves in the concrete prohibit a significant change in pitch, so normal forces are built up along the length of the spiral. This is why strand has such superior bonding qualities in comparison to plain wire.

The self-locking action observed in these beams must also be present even in a fully bonded cracked beam under load. Imagine a crack formed near the end of a beam. The strand begins to pull into the crack. As the strand slips it has to spiral out of the concrete. It is unable to do this without reversing the twist of the strand around the crack and destroying the grooves in the adjacent concrete or by twisting the uncracked portion of the beam in torsion.

The maximum strains attained in these specimens should all be of the same order — about two hundred millionths depending on the values taken for modulus of elasticity and
effective prestress. They are actually seen to be: for the three foot beams 270 and 130; for the three and one-half foot member, 160; for the four and one-half foot beam, 145; and for the five foot specimen, 220.
SUMMATION AND CONCLUSIONS

1. The great majority of the tests indicate an ultimate anchorage length of four feet, but certain exceptions show that this can be exceeded under some conditions as yet unknown.

2. The Slip Limit Envelope has been shown to exist in theory only.

3. The length in which the transfer of prestress is accomplished is shown to vary inexplicably from ten inches to a length exceeding four feet in rare instances in specimens produced in identical circumstances.

4. The distance into a specimen which is influenced by the jacking forces may vary from one to perhaps as much as three feet.

5. No advantage is observed for either sudden or gradual release.

6. Over-vibration is found to have no effect on bonding.

7. Untensioned or partly tensioned strands require essentially the same anchorage length as prestressed strands.

8. There is evidently more than one type of slip. One type progresses smoothly and the load carrying capacity improves as the slip increases. In the second case the slip is
sudden and gives a sharp report. The force builds up without slipping until another sudden slip occurs. Both of these mechanisms would be restrained to a limited activity in a beam.

9. No absolutely foolproof design recommendation can be made at this stage of the investigation because of the unexplained exceptions, but it would seem reasonable to anticipate that any design which prohibits the formation of a crack at a distance of less than six feet from the end of a member will be secure against bond failure.
Figure 14 Strand Tension at Failure vs Embedment Length

7/16 strands
6000 #/" concrete
Figure 15 Development of Concrete Strain Over Length of Specimen III-1
Figure 16 Development of Concrete Strain Over Length of Specimen III-1
Figure 17 Development of Concrete Strain Over Length of Specimen V-4 During Test
Figure 18 Development of Concrete Strain Over Length of Specimen VI-1 During Gradual Release

Unit Longitudinal Concrete Strain in Millionths

% Release

100%

74%

49%

23%

24" Unbonded

Position Along Length of Specimen in Feet

Release End

Jacking End

0

1

2

3

4

5

6

Figure 18 Development of Concrete Strain Over Length of Specimen VI-1 During Gradual Release
Figure 19 Development of Concrete Strains Over Length of Specimen VI-1 During Test
Development of Concrete Strain Over Length of Specimen VI-2
Figure 21 Development of Concrete Strain Over Length of Specimen VI-2 at Test
Figure 22 Development of Concrete Strain Over Length of Specimen VI-3
Figure 23 Change in Concrete Strains at Strand Failure for Specimen VI-3
Figure 24 Development of Concrete Strains Over Length of Specimen VI-3 During Test
Figure 25 Development of Concrete Strain Over Length of Specimen VI-4 During Gradual Release
Figure 26 Development of Concrete Strain Over Length of Specimen VI-4 During Test
Figure 27 Development of Concrete Strain Over Length of Specimen VI-4 During Test
**Figure 28 Development of Concrete Strain Over Length of Specimen VII-1 At Test**
Figure 29 Strand Slip vs Prestress Released for Series V Specimens Failing During Gradual Release
Figure 30 Strand Slip vs Prestress Lost To Strand Slip During Release of Series V Specimens
Figure 31  Slip of Specimens of Series IV and V Under Applied Load
Figure 32 Progression of Release Slip During Gradual Release
Figure 33 Slip Failure at Release - Series V
Figure 34 Slip of Specimens VII-3, VIII-1 and VIII-2 Under Applied Load

Spec VII-3 (Untensioned - 2.75')
Spec VIII-2 (2.5' Long)
Spec VIII-1 (2.0' Long)

• Jacking Suspended for 42 hrs
Figure 35 Slip of Specimens VIII-3 and VIII-4 While Under Sustained High Load
Figure 36 Development of Concrete Strain Over Length of Specimen VI-5, Beam With Oiled Strand
Figure 37  Concrete Strain Distribution Over Length of Beam VIII - 9
Figure 38 Concrete Strain Distribution Over Length of Beam VIII - 10
Figure 39 Concrete Strain Distribution Over Length of Beam VIII - 11.

Figure 40 Concrete Strain Distribution Over Length of Beam VIII - 12.