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G. R. Wernisch

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Head of the Department
of Civil Engineering

Date ______________

BOND STUDIES OF DIFFERENT TYPES OF REINFORCING BARS

by George Robert Wernisch

Lehigh University

1937

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The author wishes to thank Professor Inge Lyse, in charge of the Fritz Engineering Laboratory, for helpful supervision and valuable suggestions, and Mr. W. S. Thomson, Secretary of the Concrete Reinforcing Steel Institute, for his continued interest, suggestions, and aid in obtaining steel reinforcement.

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I - SYNOPSIS

The results of bond tests on one hundred and eighty-eight 6 by 6-in. cylindrical pullout specimens and forty-eight 6 by 12 by 36-in. beams (nominal effective depth 9 in.) containing fourteen types of 1/2, 3/4, and 1-in. diameter reinforcing bars are reported in this paper.

It was found to be difficult to correlate the results of the aforesaid pullout and beam tests. The pullout test seems to be a very poor measure of the bond resistance of reinforcing bars placed in beams of the aforesaid dimensions, both in initial and ultimate end slip. It was found that the type of bar has a marked effect on the resistance of bars subjected to a pullout test, whereas, with the exception of screw thread and smooth bars, the type of bar has only a slight influence on the bond resistance of the bars embedded in beams; that increasing the strength of the concrete does not result in a very large increase in the bond resistance of both beams and pullouts; that the initial slip in the beams occurs at a much greater calculated bond stress than the initial slip in pullout tests; that the pullout test may give erroneous comparative results in some instances; that most commercial bars are barely one-quarter stronger than plain bars in bond resistance as determined by beam tests; that twisting two bars

together does not increase their strength in bond resistance whatsoever;

II - REVIEW OF PREVIOUS INVESTIGATIONS

In 1909 Withey(1)* published results of some bond studies and stated "the method of making a bond test by pulling a rod from a cylinder of concrete in such a manner that the concrete around the rod is compressed gives results which are neither quantitative nor qualitative" and that "the beam tests give results which appear to approach actual conditions to which the bar and the surrounding concrete are most often subjected in beams and slabs". Withey also found that the static bond between concrete and corrugated bars is about twice as great as that which can be developed with plain round bars.

Abrams(2) in his monumental work states: "The pullout tests and beam tests gave nearly identical bond stresses for similar amounts of end slips in many groups of tests ··· it is believed that the properly designed pullout test does give the correct value of bond resistance" and "a properly made pullout test on a specimen of correct design is a valuable aid in determining the bond resistance of reinforcing steel in concrete, if due consideration is given to the load slip relation. An embedment of eight diameters is recommended".

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* Numbers in parenthesis refer to bibliography

Abrams also stated that "in a deformed bar of good design the projection should present bearing faces as nearly as possible at right angles to the axis of the bar ····· a closer spacing of the projections than is used in commercial deformed bars would be of advantage" and that "the use of deformed bars of proper design may be expected to guard against local deficiencies in bond resistance due to poor workmanship and their presence may properly be considered as an additional safeguard against ultimate failure by bond. However, it does not seem wise to place the working bond stress for deformed bars higher than that used for plain bars".

Again, in 1925, Abrams(3) states: "Bond responds to changes in the water-ratio of the concrete much the same way as compressive strength."

In 1936, Withey(4) found that "the bond from pullout tests on cylinders averages 2-1/4 to 2-3/4 times the bond calculated from strain measurements in beams."

Gilkey and Ernst(5) found that the bond resistance was increased by increasing the strength of the concrete and that the removal of mill scale by overstressing of the steel seemed to have no injurious influence upon the bond resistance.

Steinman(6) in 1936 stated that beams reinforced with special reinforcement "possess an extra reserve of resistance and capacity at ultimate loads" and that this type of reinforcement has a bond resistance 71 to 137 per cent higher than plain and deformed bars.

Posey(7) has made an anchorage investigation in which he also compared a commercial deformed bar with bars deformed by nicking and threading. He concluded that nicked bars were vastly superior to commercial deformed bars. These conclusions were based entirely on pullout tests. Only one type of commercial bar was used.

Glanville(8) has made a theoretical analysis of the distribution of bond stresses. The theory is in agreement with Abrams' pullout test results. The theory applies only to the distribution of bond in pullout specimens in which the steel is subjected to either tension or compression, the concrete being in compression in both instances (cases (b) and (c), Fig. 1, page 5). The theory has not been developed, it seems, for cases (a) and (d) in which the concrete is in tension.

III - INTRODUCTION

In reinforced concrete construction, the bond between the concrete and steel is of prime importance, for without it the interaction of concrete and steel cannot be obtained. Despite its importance, there appears to be a tendency to treat the problem with indifference. It is surprising, for instance, that definite available bond data are lacking on various types of commercial reinforcing bars.

A deformed bar is vaguely understood to be one which has a bond resistance twenty-five per cent in excess of that of a plain bar. The Progress Report of the Committee on Standard Specifications for Concrete and Reinforced Concrete, January 1937, recommends that deformed bars, to be acceptable, should develop an increase of twenty-five per cent in bond over a plain bar at an end slip of 0.01-in. in pullout tests. Obviously, this may lead to difficulties, depending upon the type of plain bar with which comparison is made. A slightly rusted or roughened plain bar, for example, should offer a greater bond resistance than a smooth bar; also, modern manufacturing methods tend to impart a smoother finish to plain bars, so that present tests may not be comparable to older tests. Consequently, the variation of bond resistance may be considerable, depending upon slight surface irregularities and method of manufacture. Therefore it seems that the recommendation of the aforementioned committee is inadequate.

Present code specifications base the permissible bond working stresses of reinforcing bars on the ultimate compressive strength of the concrete in which they are embedded; the permissible working stress of plain bars is four per cent whereas the permissible working stress for deformed bars is five per cent of the ultimate compressive strength of the concrete.

It seems desirable, therefore, to investigate whether test data of present day reinforcing bars justify present specifications wherein the permissible working stresses for deformed bars are twenty-five per cent in excess of the working stresses for plain bars.

The matter of increasing the permissible bond working stresses is becoming increasingly important. With the introduction of higher steel working stresses, it is essential that the bond stresses be increased proportionately (providing it is safe to do so, of course) in order to make the use of higher steel working stresses economical. Obviously, a higher tensile working stress causes a reduction in steel area and, for a constant bar size, a reduction in the perimeter, which must be offset by increasing the permissible working stresses, or increasing the number of bars. Some engineers advocate the use of stronger concretes to increase the permissible bond working stresses, the general belief being that a stronger concrete should offer proportionately higher bond resistance. This belief has not as yet been fully substantiated by experimental data.

The type of deformation on reinforcing bars probably is also very important. The question whether bars with longitudinal, transverse, diagonal or twisted deformations are superior to plain bars should be studied, and it should also be determined whether there is a great discrepancy in the bond resistance of various types of deformed bars.

This investigation was undertaken to study the following questions:

1. Does the type of deformation affect the bond resistance of reinforcing bars?
2. Is there an essential difference between the bond resistance of various types of commercial bars?
3. How does the strength of concrete affect the bond resistance of reinforcing bars, especially at small end slips?
4. Do pullout tests give a fair indication of the bond resistance of bars at small end slipe? (that is, is there a similarity between the bond-slip curves of pullout and beam tests?)
5. Are present bond specifications justified?

IV - OUTLINE OF TEST PROGRAM

The test program comprised two series which overlapped considerably.

In one series the effect of the strength of the concrete on the bond resistance of the reinforcing bars was studied by means of pullout and beam tests. Five concrete strengths, varying from approximately 3000 p.s.i. to 7000 p.s.i. were used.

In the second series the bond-slip pullout and beam curves of nine types of bars used.(3/4 and 1-in. in diameter) were compared to determine whether the bond resistance offered by various types of bars was uniform, or whether there was a great discrepancy in the bond resistance. The transverse, diagonal, longitudinal and twisted types of deformations were investigated.

The outline of the test program is given in Table I.

V - MATERIALS, METHOD OF MANUFACTURE, AND TESTING

All the materials used in this investigation, except the sand and gravel, were donated; the steel bars by the Carnegie-Illinois Steel Corporation, Republic Steel Corporation, Bethlehem Steel Company, The Franklin Steel Works, and Jones and Laughlin Steel Corporation, and the cement by the Lehigh Portland Cement Company.

The coarse and fine aggregates used in the concrete were Portland gravel and Portland sand, respectively, from Portland, Pennsylvania. The coarse aggregate was so combined as to contain fifty per cent, by weight, No.4 to 3/8-in. and fifty per cent 3/8 to 3/4-in. The fine and coarse aggregates were combined in the ratio 2:3. In designing the concrete, which was mixed in a two cubic feet Lancaster Counter Current Mixer, the cement-water method of proportioning was adopted; the water content per cubic foot of concrete was kept constant The concrete data is given herewith.

Concrete Strength lb. per sq in.	c/w ratio	Proportions c:s:gr.
3000	1.57	1: 2.8 : 5.07*
4000	1.86	1: 2.36 : 3.58
5000	2.15	1: 2.0 : 3.10
6000	2.45	1: 1.66 : 2.50
7000	2.75	1: 1.35 : 2.06

* 1 per cent of weight of aggregates added for absorption.

Fig. 1 indicates the straight line relation between the strength of concrete and cement-water ratio for the cement used in the investigation.

Fourteen kinds of bars were used in this investigation. Bars A, B, and C were manufactured with transverse deformations. The sharp, large deformation of bar A was carried across the face of the bar into a longitudinal deformation running continuously along the entire length of the bar. The transverse and longitudinal deformations were of constant height throughout. The deformations on bars B and C did not run across the entire face of the bar, and gradually decreased in thickness until they merged into the average diameter of the bars. The deformation of bar B was somewhat wide, and low, and had its corners rounded. The deformation of bar C was narrower, higher and sharper and was spaced at slightly greater intervals.

Bar D contained a double diagonal deformation, placed at about 45 and 135 degrees to the longitudinal axis of the bar. The somewhat wide and low deformations intersected at approximately 90 degrees. The deformation on bar E was considerably larger than that on bar D, probably because only one diagonal, running zig-zag down the face of the bar, was employed. Both bars D and E contained two symmetrically placed continuous longitudinal deformations.

Bars F and G contained longitudinal deformations, staggered and overlapped so that almost any section cut transversely through the bar contained several deformations. The deformations of bar F were considerably larger and were spaced at greater intervals than those of bar G. However, bar D contained four continuous longitudinal deformations spaced symmetrically about the circumference of the bar.

Two kinds of plain bars (H) were used, one bar having a somewhat smooth surface whereas the other bar had the ordinary mill scale surface.

Bar I consisted of two 1/2-in. plain bars twisted in the torsion machine of the Fritz Laboratory so as to induce one complete twist every twelve and one-half diameters of the bar.

Bar J consisted of two 1/2-in. plain bars, placed adjacent to each other. Bar K contained two deformed bars (similar to bar E) placed adjacent to each other.

Bar L was manufactured with a square thread, four to the inch, 1/8-in. deep and 3/32-in. wide.

Bar M made also was a threaded bar, nine v-threads to the inch. In one type, the threads were cut only 1/16-in.deep while in the other type the threads were cut 1/8-in. deep.

It should be noted that all threaded bars had a diameter of 3/4-in. at the root of the threads.

Fig. 2 indicates the types of bars investigated.

As shown in Fig. 3, four 6 by 6-in. cylindrical pullout specimens and three 3 by 6-in. control cylinders were made for each type of bar and each concrete strength used in the study. One hundred and eighty-eight pullout specimens were made with the steel held in a vertical position. The concrete was placed in the mould in three layers similar to the method used in making compressive control specimens. The 3/4-in. bars had an embedment of eight diameters, as recommended by Abrams, whereas the 1-in. bars had an embedment of six diameters.

Two or three 6 by 12 by 36-in. concrete beams (refer to test program) each containing one 3/4-in. bar or two 1/2-in. bars and eight stirrups (refer to Fig.4), and six 3 by 6 in. control cylinders were made for each type of bar and concrete strength investigated. Forty-eight beams were manufactured. The bars in the beams were held in a horizontal position, 2-5/8 in. from the bottom of the form (making the distance from the center of reinforcement to the surface of the beam 3 in.) and the concrete was placed continuously.

All pullout and beam specimens, and control cylinders were permitted to remain in the forms for one day, whereafter they were stored in the moist room (having a constant temperature of 70 degrees Fahrenheit, and a humidity of 100 per cent) until the age of twenty-eight days, at which time they were tested. Fig. 5 shows pullout specimens in the moist room.

The beams were loaded with two equal loads, placed nine inches from each support, and the end slip was measured at both ends of the embedded bar. The beams were tested in a 300,000-lb. Olsen screw machine, the load being applied in increments of 3000 lb. at the rate of 0.10-in. per minute for the first 12,000 lb. and thereafter at the rate of 0.05-in. per minute, Fig 6 shows a beam about to be tested.

The pullout specimens were tested in a 50,000-lb. Riehle screw machine at the rate of 0.05-in. per minute as shown in Fig. 7. All specimens were placed on a spherical bearing block through which a 1-1/8 in. hole had been drilled to insure proper bearing. Load readings were taken at end slips of 0.00005, 0.0001, 0.0003, 0.0005, 0.001, etc.

The deformation in the concrete (and hence the deformation in the steel, assuming no slip between the concrete and steel - a logical assumption when the bond stress between the concrete and steel is zero for live load) was measured along two gage lines ten inches in length located three inches from the bottom surface, one on each side of the beam.

The end slip in the bars of both pullout and beam specimens, and the concrete deformations were measured by means of Ames dials reading to the ten-thousandths of an inch.

VI - EFFECT OF THE TYPE OF DEFORMATION ON BARS

a. Pullout Tests - Fig. 8 to 14 inclusive, and Table II, indicate that there is a considerable variation in the bond resistance of various types of reinforcing bars. Except as otherwise noted, the following discussion refers to 3/4-in. bars embedded in 3000 p.s.i. concrete (Fig.8). Excluding twisted, smooth and threaded bars, and considering only ordinary deformed and plain bars (B to H, inclusive) the data indicate that some deformed bars (D and E) offer approximately two times as much resistance as an ordinary plain bar at ultimate loads. If the comparison includes the somewhat smooth bar, some of the deformed bars are more than seven times as strong as the smooth bar. Some of the deformed bars slip initially at a stress approximately three times that of the ordinary plain bar. Comparing the ordinary plain with the smooth plain bar, it is observed that although the ordinary plain bar is more than three times as strong, the initial slip of the ordinary bar is only slightly greater.

When considering twisted bars, due allowance must be made for the greater perimeter obtained for equal steel areas (two small bars having a larger perimeter than one large one) in order to make a fair comparison. Thus a twisted bar may have less resistance per square inch but more TOTAL resistance, due to the greater perimeter. When this allowance has been made (refer to Fig.8) it is apparent that two bars twisted do not offer any greater bond resistance than an ordinary bar, despite the fact that in the case under consideration the twisted bar had one-third more surface area, probably because the twisting removes the mill scale on the bar and increases the smoothness of the finish, and possibly because the concrete cannot be placed as efficiently and intimately around the twisted bar. Consequently, any possible increased resistance due to twisting is approximately offset by the decreased resistance due to smoothness and difficult placing.

The effect of twisting is indicated in Fig. 15 wherein the bond-slip curves for two twisted bars and two bars placed adjacent to each other are plotted. The bond-slip curves of the two bars placed adjacent (both plain and deformed) are approximately identical to the bond slip curves of the twisted bars.

Comparing the twisted bars with the ordinary deformed bars, it is noted that the ultimate loads of the pullout tests on deformed bars are two to three times those of the twisted bars. For initial slip the deformed bars are approximately ten to seventy per cent stronger than the twisted bars. All twisted bar comparisons given in this paragraph are based on the adjusted values for twisted bars; i.e., all calculated unit stresses were multiplied by 1.33 because the surface of the twisted bars was approximately one-third greater than the surface of the 3/4-in. bars.

Considering only the ordinary commercial deformed bars (B to G inclusive) there is a variation of approximately 35 per cent in the initial slip stresses and about 65 per cent in ultimate pullout stresses. The variations are not quite so pronounced in the specimens made of the higher strength concrete.

The following table illustrated some of these variations in 3/4-in. bars.

Type of Bar	Concrete Strength p.s.i.	Initial Slip p.s.i.	Ultimate Stress p.s.i.
B	2830	340	960
C	3350	290	1035
D	3245	330	1160
E	3100	380	990
F	2870	300	705
G	3250	280	863
B	6000	540	1276
C	6120	500	1485
D	6230	580	1480
E	6340	520	1490
F	7100	390	933
G	5810	510	1210

Generally, the data indicate that the diagonal types of deformations (bars D and E) are strongest in resisting slip, whereas the longitudinal types of deformations (bars F and G) offer the least resistance.

It was observed that the bond resistance of bars with transverse deformations is dependent upon the number, height and shape of the deformations. Bar C, for example, is manufactured with a high, sharp deformation, whereas bar B is manufactured with a flat, wide and somewhat rounded deformation which permits the concrete to flow around it, thus causing an earlier bond failure. It was also noted that for the same type of bar the specimens with the greater number of deformations embedded in the concrete usually offered the greater bond resistance.

Most of the pullout specimens made with the stronger concretes failed by bursting due to the development of tension in the concrete, which probably prevented the concrete from being utilized to its maximum value in compression. In this connection it was observed that the twisted bar had the action of a cork-screw upon being pulled out of the concrete cylinder. The spherical bearing block thus permitted the concrete cylinder to rotate. In the 3000 p.s.i. concrete tests the specimens cracked upon being held firmly in place, indicating that the twisted bars may induce considerable diagonal tension in the concrete.

b. Beam Tests - With one or two exceptions which will be noted herein, there was little pronounced difference in most of the bars tested. As would be expected, the smooth plain bar offered the least bond resistance. Fig. 16 indicates that the ordinary plain bar developed approximately 70 to 85 per cent of the bond resistance developed in the commercial deformed bars, whereas the smooth plain bar developed approximately 50 per cent of the strength of the deformed bars.

Although Bar G developed considerably more stress for initial slip than the other commercial bars, the ultimate bond stresses of all six commercial deformed bars were approximately the same. It can be noted by referring to Fig. 17 that the maximun difference between any two bars is approximately fifteen per cent.

Again referring to Fig. 15, it can be seen that the twisting of two bars does not materially affect the bond resistance of the bars. The beams containing two bars placed adjacent to each other (both plain and deformed) developed slightly greater initial slip and ultimate stresses than the beam containing the twisted bars.

Using the adjusted value for the twisted bars, the data indicate that the twisted bar is approximately as strong as the weakest deformed bar. However, five of the commercial bars are stronger to a maximum of fifteen per cent.

Fig. 18 gives a comparison of the bond-slip curves of several reinforcing bars embedded in high strength concrete. Although the curves are not quite as similar as in the case of the lower concrete strength, the ultimate strengths of the five commercial bars did not vary more than twenty per cent. The twisted bars seemed to offer the least resistance to slip, the beams containing the deformed bars being eight to thirty per cent stronger.

The various types of threaded bars embedded in 3000 p.s.i. concrete exhibited considerably more bond resistance than any of the commercial bars, bar L for example, being approximately fifty per cent stronger than the strongest deformed bar. The data indicate that the number of threads per inch affect the strength of the bars, which can be observed by comparing curves for bars L and M. The greater number of threads per inch appear to give better results. It should also be noted that the depth of the thread has an effect upon the bond resistance of the bars, the deeper threads offering more bond resistance than the shallow threads. Increasing the depth of thread from 1/16 to 1/8-in. increased the ultimate bond resistance approximately nine per cent; for initial slip the deeper thread developed twenty-five per cent more bond stress.

VII - EFFECT OF STRENGTH OF CONCRETE

a. Pullout Tests - Fig. 19 indicates a typical relation between the strength of the concrete and the bond resistance of the bars. In all cases the stronger concretes offered greater bond resistance. In the case of the smooth bar, the bond resistance was doubled when the concrete strength was doubled (3000 to 6000 p.s.i.). In the case of the twisted bar the bond resistance was increased about 55 per cent when the concrete strength was increased from 3000 p.s.i. to 7000 p.s.i.

All the stronger concrete specimens burst at end slips ranging from 0.0035-in. to 0.01-in.

Referring to Fig. 20 and considering only the commercial bars, it should be noted that the bond resistance was increased 23 to 63 per cent when the concrete strength was increased 133 per cent (3000 to 7000 p.s.i.). The initial slip stress was increased from 30 to 75 per cent when the concrete strength was increased from 3000 p.s.i. to 6000 p.s.i. Bar E appeared to be most sensitive to change in concrete strength, the ultimate bond strength increasing 63 per cent when the concrete strength was increased as aforesaid. In initial slip bar D increased its bond resistance 75 per cent for a 133 per cent increase in concrete strength. Bar D appeared to be the strongest bar in both low and high strength concretes, although bars C and E were approximately as strong in the high strength concrete tests.

It is apparent that in pullout tests the bond resistance of the bars does not increase proportionately with the concrete strength increase, and that the bond resistance can be increased to a greater extent by substituting a strong bond resistant bar for a weak one than by increasing the concrete strength several times.

b. Beam Tests - Fig. 20 and 21 indicate the effect of the strength of concrete on the bond resistance of the bars embedded in beams. Generally, the rate of bond resistance increase is approximately the same as that for pullouts, as can be noted by referring to Fig. 21. In the commercial bars investigated, the beam strength was increased 25 to 70 per cent when the concrete strength was increased from 3000 p.s.i. to 7000 p.s.i.

The strength of the twisted bar was increased approximately fifty per cent when the concrete strength was increased from 3000 p.s.i. to 7000 p.s.i.

For initial slip the concrete strength increases the bond stresses in approximately the same ratios as in the ultimate stresses.

The data indicate that generally the bond resistance cannot be increased to a very great extent by increasing the strength of the concrete. A threaded bar embedded in 3000 p.s.i. concrete is nearly as strong as the strongest deformed bar embedded in 7000 p.s.i. concrete.

VIII - COMPARISON OF PULLOUT AND BEAM TESTS

Fig. 22 indicates a typical relation between the bond-slip curves of pullout and beam. A comparison of the results also can be obtained by referring to Fig. 20.

Usually the comparison data are erratic. In some cases the pullout tests give lower values than the beam tests in the ultimate bond stresses, although in most instances the pullout tests give higher values. The beam tests usually give higher initial slip stresses than the pullout tests.

The pullout tests usually gave an erroneous concept of the bond strength of the reinforcing bars, especially relative to the smooth, ordinary and twisted bars. The pullout test data indicate, for example, that some deformed bars were about seven times as strong as the smooth bars. The beam tests, on the other hand, indicated that the ratio of strength of the deformed bars to the smooth bars varied from 2.00 to 1.27, which is entirely different from the large ratios obtained in the pullout tests. The pullout test data also indicated that the twisted bar was much weaker than the deformed bars. Actually, in the pullout test, the ratio of the strength of the deformed bars to the strength of the twisted bars was about 2.5 - 1.2 to 1.0, whereas in the beam tests the ratio was about 1.15 - 1.0 to 1.0.

Bar F, when embedded in 3000 p.s.i. concrete, developed the lowest pullout resistance of the six commercial bars; however, in the beam tests it developed the second highest strength. In the high strength concrete Bar B developed an ultimate pullout stress of 850 p.s.i. whereas it developed 1180 p.s.i. in the beam tests. There are other such inconsistencies, as can be noted by observing Fig. 17.

IX - DISCUSSION OF RESULTS

As stated heretofore, the author attempted to correlate the results of the pullout and beam tests, and for this reason embedded the reinforcement in the beams a distance of three inches from the surface of the beam to its center, which is the amount of cover of the reinforcement in the pullout specimens.

The author is fully cognizant of the fact that in the region between loads, where theoretically the bond stress is equal to zero and the greatest longitudinal stress exists, a phenomenon very similar to bond will exist in an appreciable extent. However, this phenomenon was disregarded in an effort to ascertain whether the end slips of pullout and beam tests followed similar laws.

The results were so at variance that it is doubtful whether any correlation can be obtained, considering especially the favorable conditions under which the beams were manufactured and tested. The three-inch embedment and the favorable loading conditions would never be realized in actual construction.

It is significant that notwithstanding all these favorable conditions, the bond stresses developed by most of the reinforcing bars were relatively low. For the beams of 3000 p.s.i. concrete, considering only the commercial bars, the ultimate bond stress, calculated by the usual formula ($u = V/\Sigma o\ jd$) ranged from 550 p.s.i. to 845 p.s.i. giving a factor of safety of 3.67 to 5.60 if we assume a working bond stress of 0.05f'c. Although these factors of safety may appear high, we must remember that the three-inch embedment of the bars may have increased the initial slip stress over the two-inch embedment as much as one-third, and that the nearness of the load to the reaction may have also increased the ultimate load stresses to a considerable extent, although it should not have affected the initial slip stresses.

Although strain gage readings were taken in some of the earlier tests, they were discontinued after it was found that the bond stresses, by strain, were very low until near ultimate loads. It is doubtful whether this method of calculating bond stresses is of much practical value, inasmuch as it would be rather difficult to compute stresses in this manner.

It was noted that when the bars in the beams began slipping they had developed at least fifty per cent of their ultimate bond strength; in pullout specimens generally the initial slip stress was considerably lower than this value.

The low increases in bond resistance with large increases in the strength of the concrete would indicate that the bond resistance cannot be increased to any great extent by the use of stronger concretes. The data also indicated that it is incorrect to assume that bond stresses may be calculated as a constant fraction of the ultimate concrete compressive strength. In the 3000 p.s.i. concrete the factors of safety ranged from 3.7 to 5.6 on the assumption that the permissible bond working stress was 0.05f'c. In the 7600 p.s.i. concrete, the same bars gave a range of factors of 2.75 to 3.3, which is considerably lower than those for the lower strength concretes.

Considering the favorable loading and placing conditions and the low calculated bond values obtained, it is questionable whether permissible bond working stresses are too conservative. If it were not for the facts that in actual construction twenty-five to fifty per cent of the reinforcement is carried through to the columns and past points of inflection (thus giving greater anchorage) that there are irregularities and bends in the reinforcement, and that we are confronted with the embarrassing fact that we have had few, if any, actual bond failures in buildings constructed heretofore, the author would be of the opinion that permissible bond working stresses are too high.

X - SUMMARY

It should be understood that the conclusions given herein apply only to the beams and pulloutsinvestigated.

1. It was found impossible to correlate the results of pullout and beam tests.

2. With one or two exceptions, the pullout tests gave higher bond stresses than the beam tests.

3. Any correlation between the pullout and beam tests is purely accidental. There seems to be no reason why the results of a pullout test in which the concrete

surrounding the bar is in compression should be identical with those of a beam test wherein the concrete surrounding the bar is in tension.

4. Pullout test results are neither qualitative nor quantitative and should be discontinued.

5. Although the difference in pullout strength of some commercial deformed bars was sixty per cent, the difference in beam strength was only fifteen to twenty per cent.

6. Twisting two bars together does not increase their bond strength appreciably.

7. Increasing the concrete strength 133 per cent (3000 to 7000 p.s.i.) does not increase the bond strength of the commercial bars more than twenty-five to seventy per cent.

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LIST OF TABLES AND FIGURES

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TABLE I - OUTLINE OF TEST PROGRAM

Type of Bar in.	Concrete Strength p.s.i.	Type of Test
A - 1	2830	Pullout
1	5340	Pullout
B - 3/4	2830	Pullout and Beam
3/4	3940	Pullout
3/4	5120	Pullout
3/4	6000	Pullout
3/4	7150	Beam
C - 3/4	3350	Pullout and Beam
1	2970	Pullout
3/4	4150	Pullout
3/4	4900	Pullout
1	4880	Pullout
3/4	6120	Pullout
D - 3/4	3245	Pullout and Beams
1	2970	Pullout
3/4	3910	Pullout
3/4	4650	Pullout and Beam
1	5320	Pullout
3/4	6230	Pullout
3/4	7340	Pullout and Beam
E - 3/4	3100	Pullout and Beam
1	2940	Pullout
3/4	3990	Pullout
3/4	5090	Pullout Beam
1	4800	Pullout
3/4	6340	Pullout
3/4	7650	Pullout and Beam
F - 3/4	2870	Pullout and Beam
3/4	7100	Pullout and Beam
G - 3/4	3250	Pullout and Beam
3/4	3850	Pullout
3/4	4830	Pullout
3/4	5810	Pullout
3/4	7190	Pullout and Beam

TABLE I - Outline of Test Program, Cont'd.

Type of Bar	Concrete Strength	Type of Test
H - 3/4	3240	Pullout
1	3240	Pullout
3/4	3180	Beam (somewhat smooth finish on bar)
3/4	2780	Beam (rough finish on bar)
3/4	4050	Pullout
1	4960	Pullout
3/4	5910	Pullout
3/4	7230	Pullout
I - two 1/2 twisted	2960	Pullout and Beam
two 1/2 twisted	3990	Pullout
two 1/2 twisted	5160	Pullout
two 1/2 twisted	5910	Pullout
two 1/2 twisted	7450	Beam
J - two 1/2 plain	3340	Beam and Pullout
K - two 1/2 deformed	3500	Beam and Pullout
L - 1-in. bar, 4 square threads to inch, each thread 3/32-in. wide, 1/8-in. deep	3160	Beam
M - 1-in. bar, 9 V-threads to inch, threads 1/8 in. deep	3380	Beam
7/8-in. bar, 9 V-threads to inch, threads 1/16 inch deep	3390	Beam

TABLE I - Outline of Test Program, Concl'd.

Note: All beams contained one 3/4-in. bar. Pullout specimens made in quadruplicate. Beam tests of bars B, D, E, and G made in triplicate; other beams made in duplicate. One hundred and eighty-eight pullout specimens and 48 beam specimens made. All loads placed 9 in. from supports except for bar E where loads were placed 6 in. from supports, in 3100 p.s.i. concrete beams.

TABLE II - SUMMARY OF RESULTS

PULLOUT TESTS

Type of Bar in.	Concrete Strength p.s.i.	Average Load lb.	Bond Stress p.s.i.
A - 1	2830	16,800	890
1	5340	22,300	1180
B - 3/4	2830	13,600	960
3/4	3940	14,850	1050
3/4	5120	16,450	1165
3/4	6000	18,050	1276
C - 3/4	3350	14,650	1035
1	2970	12,650	670
3/4	4150	16,850	1190
3/4	4900	18,200	1290
1	4880	17,250	915
3/4	6120	21,000	1485
D - 3/4	3345	16,400	1160
1	2970	14,900	790
3/4	3910	16,000	1130
3/4	4650	20,400	1445
1	5320	19,700	1045
3/4	6230	20,900	1480
3/4	7340	20,300	1435
E - 3/4	3100	14,000	990
1	2940	14,250	755
3/4	3940	17,000	1200
3/4	5090	17,550	1240
1	4800	19,100	1010
3/4	6340	21,100	1490
3/4	7650	22,700	1610
F - 3/4	2870	9,990	705
3/4	7100	13,200	933
G - 3/4	3250	12,200	863
3/4	3850	11,800	835
3/4	4830	15,900	1125
3/4	5810	17,150	1210
3/4	7190	17,500	1235

TABLE II - Summary of Results, Cont'd.

Type of Bar	Concrete Strength	Average Load	Bond Stress
H - 3/4	3240	2,190	155
1	3240	4,200	223
3/4	4050	3,150	235
1	4960	7,550	400
3/4	5910	4,390	310
3/4	7230	4,670	330
I - two 1/2	2960	6,530	350
Twisted	3990	7,350	390
	5160	9,250	490
	5910	10,400	555
J - two plain adjacent	3340	6,900	367
K - two deformed adjacent	3500	11,400	605
	BEAM TESTS		
B	3310	36,500	955
B	7150	49,100	1285
C	3350	28,670	750
D	3245	26,830	700
E	3100	30,400	795
E	5090	43,200	1130
E	7650	41,200	1075*
F	2870	29,630	775
F	7100	43,825	1145
G	3250	32,170	845
G	7190	39,800	1040
H (smooth)	3180	16,000	420
H (ordinary)	2780	21,000	550
I (2 twisted)	2960	26,550	520
I (2 twisted)	7450	37,250	732
J (2 pl.adj.)	3340	35,920	705
K (2 def.adj.)	3500	28,525	560
L	3160	35,110	920
M (1/16" ht. thread)	3380	42,900	1120
M (1/8" ht. thread)	3390	45,750	1195

* diagonal tension failure

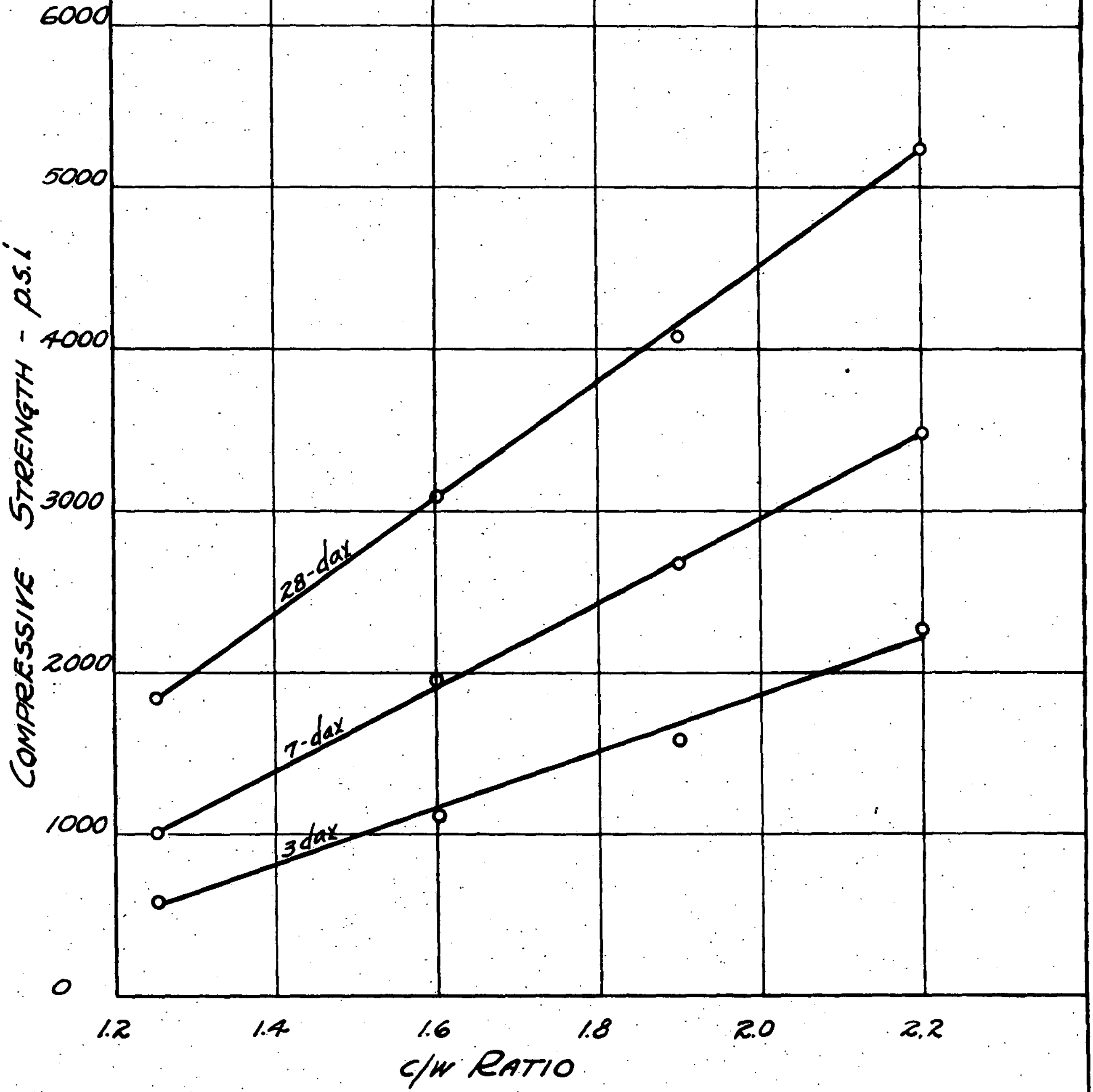

Fig. 1. Relation Between Compressive Strength of Concrete and c/w Ratio.

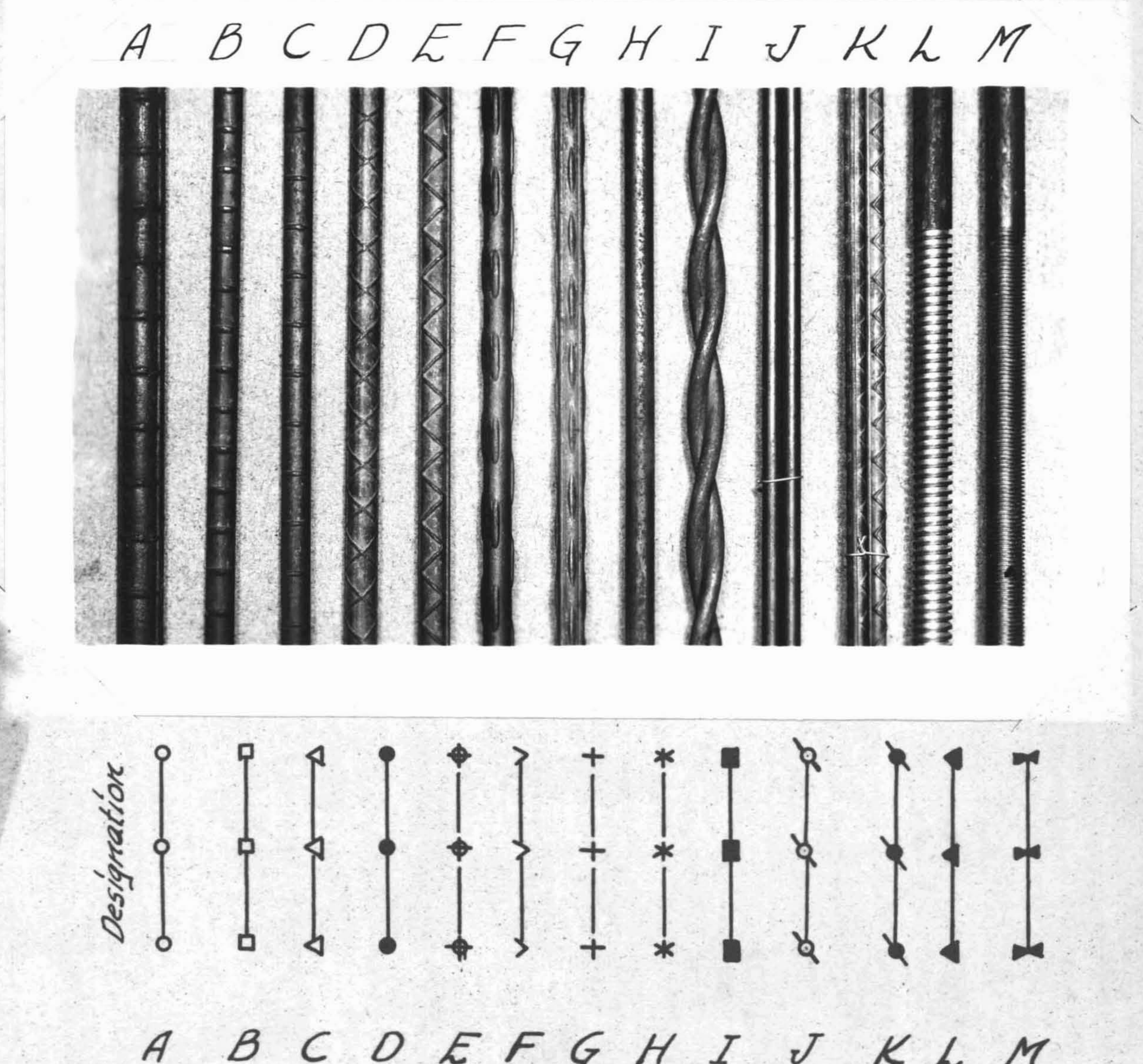

FIG. 2. TYPES OF BARS INVESTIGATED.

Fig. 3 - Pullout Specimens after Pouring

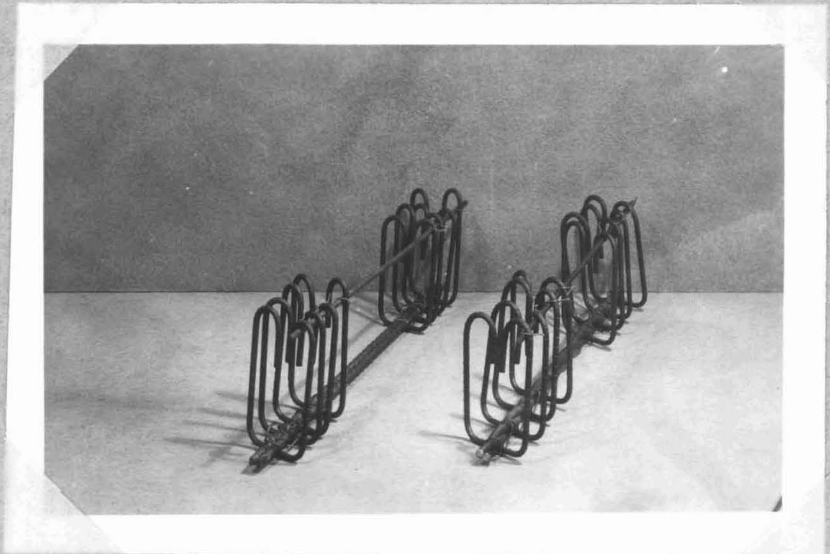

Fig. 4 - Beam Reinforcement

Fig. 5 - Pullout Specimens in Moist Closet

Fig. 6 - Beam in Testing Machine

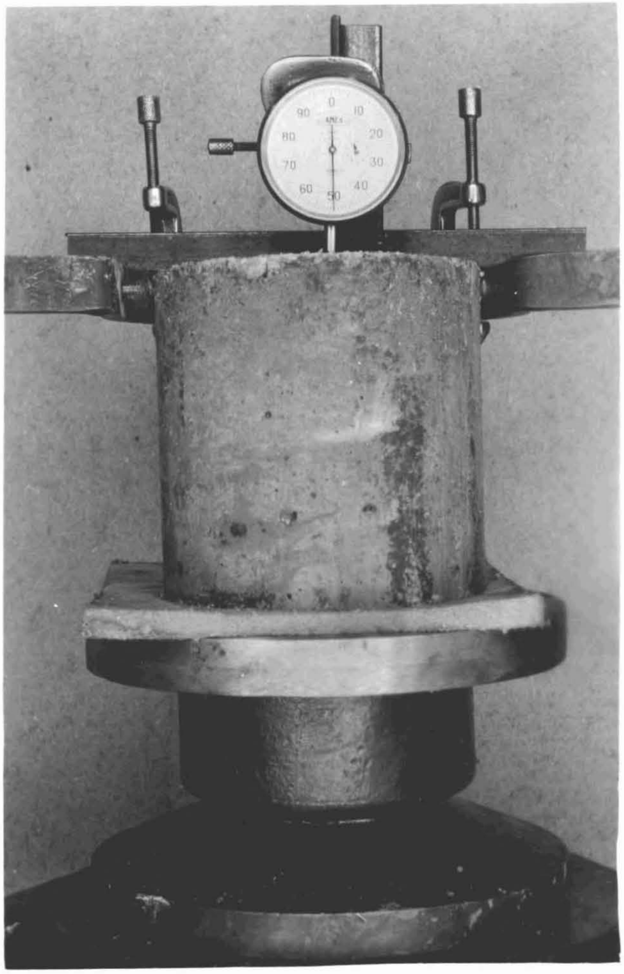

Fig. 7 - Pullout Specimen in
Testing Machine

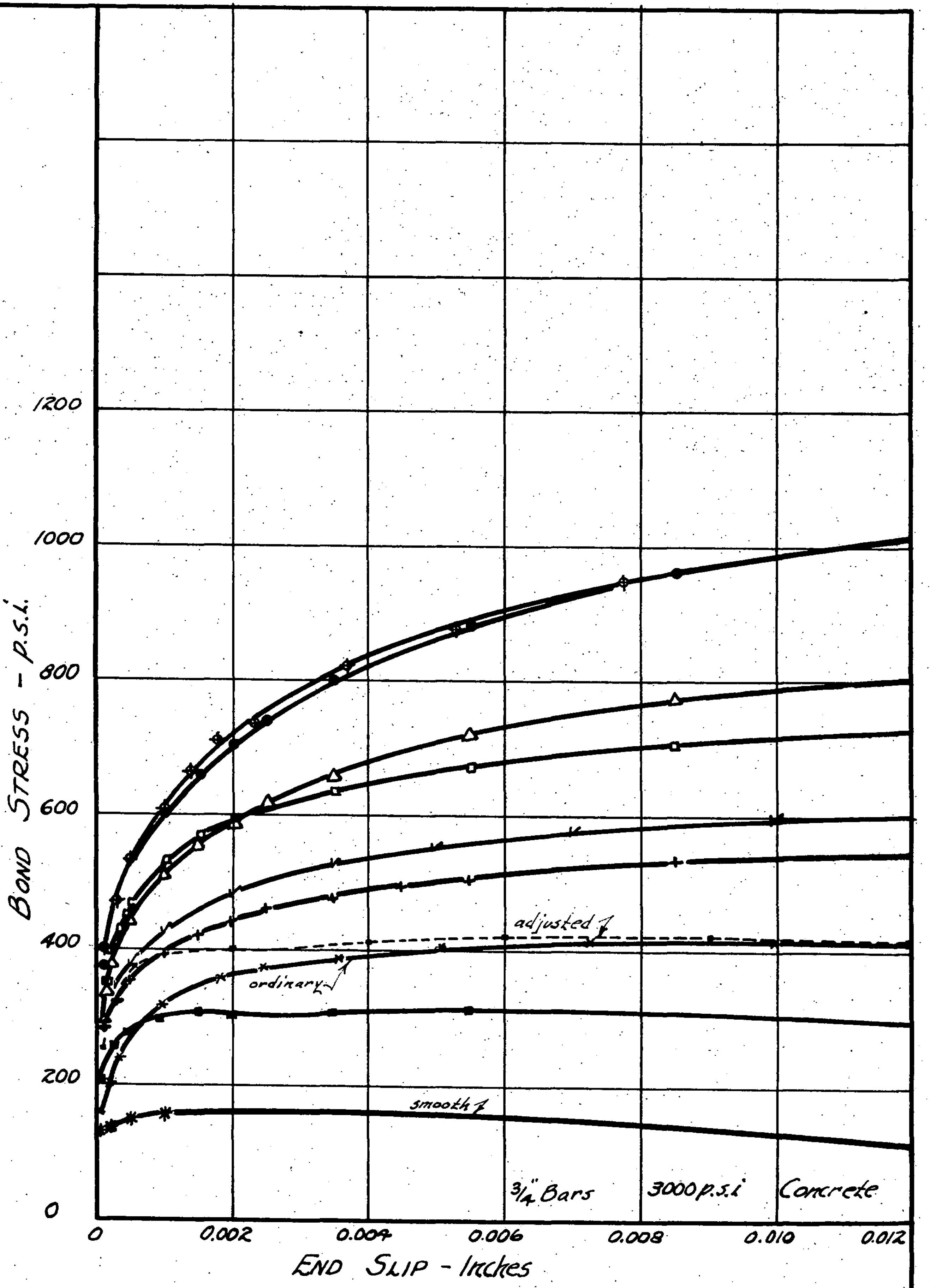

FIG. 8. BOND-SLIP CURVES OF PULLOUT SPECIMENS.

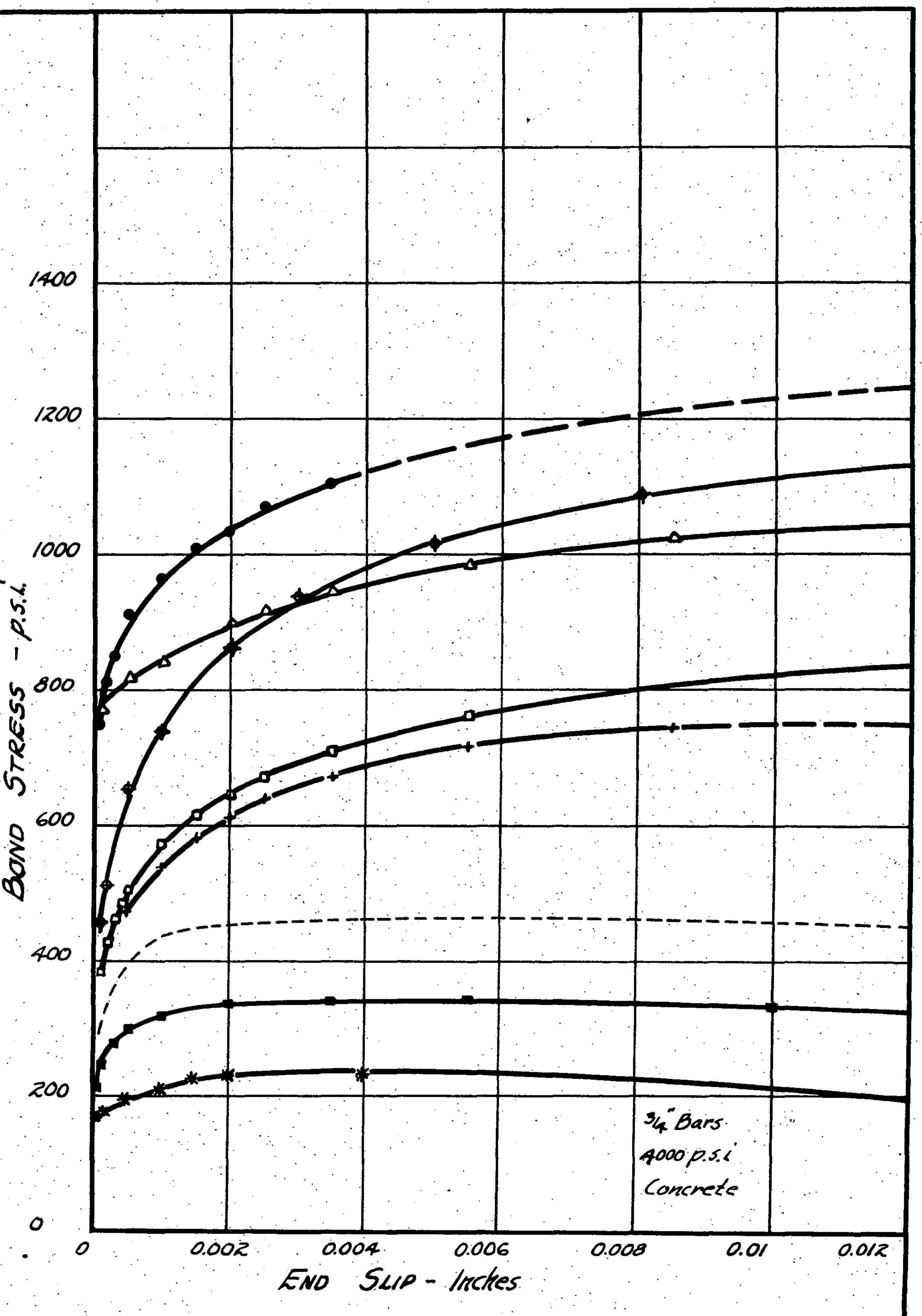

FIG. 9. BOND-SLIP CURVES OF PULLOUTS.

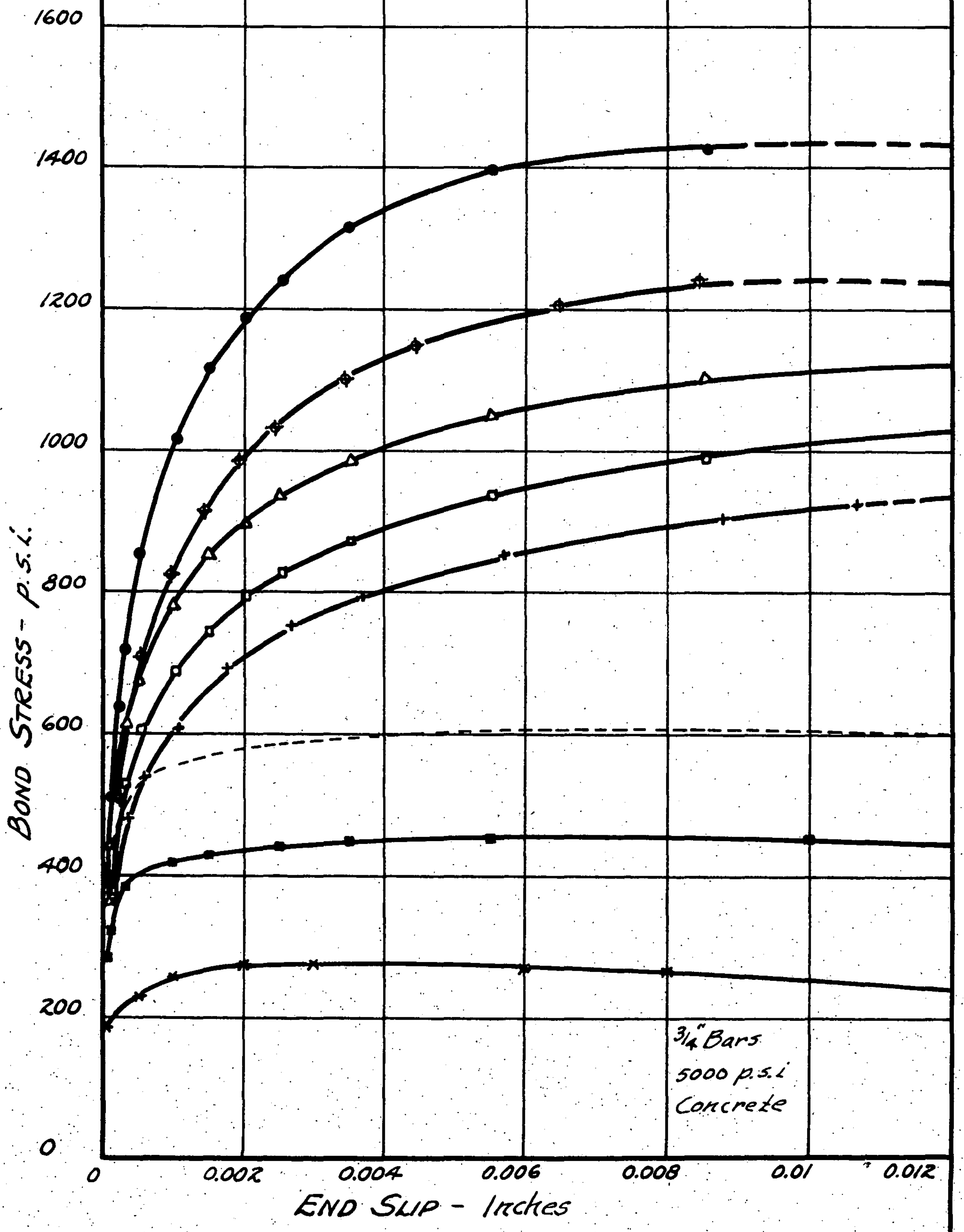

FIG.10. BOND-SLIP CURVES OF PULLOUTS.

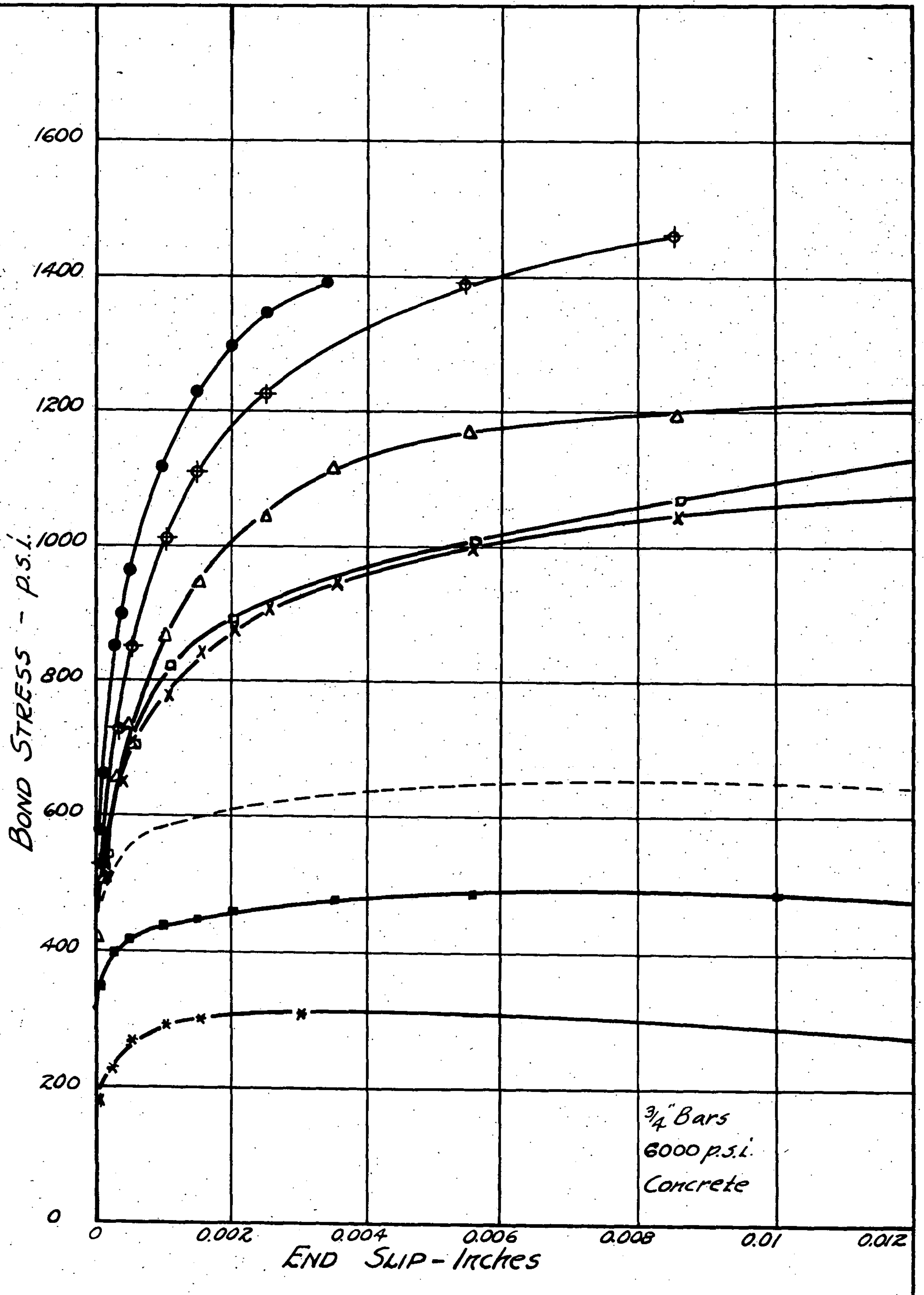

Fig. 11. Bond-Slip Curves of Pullouts.

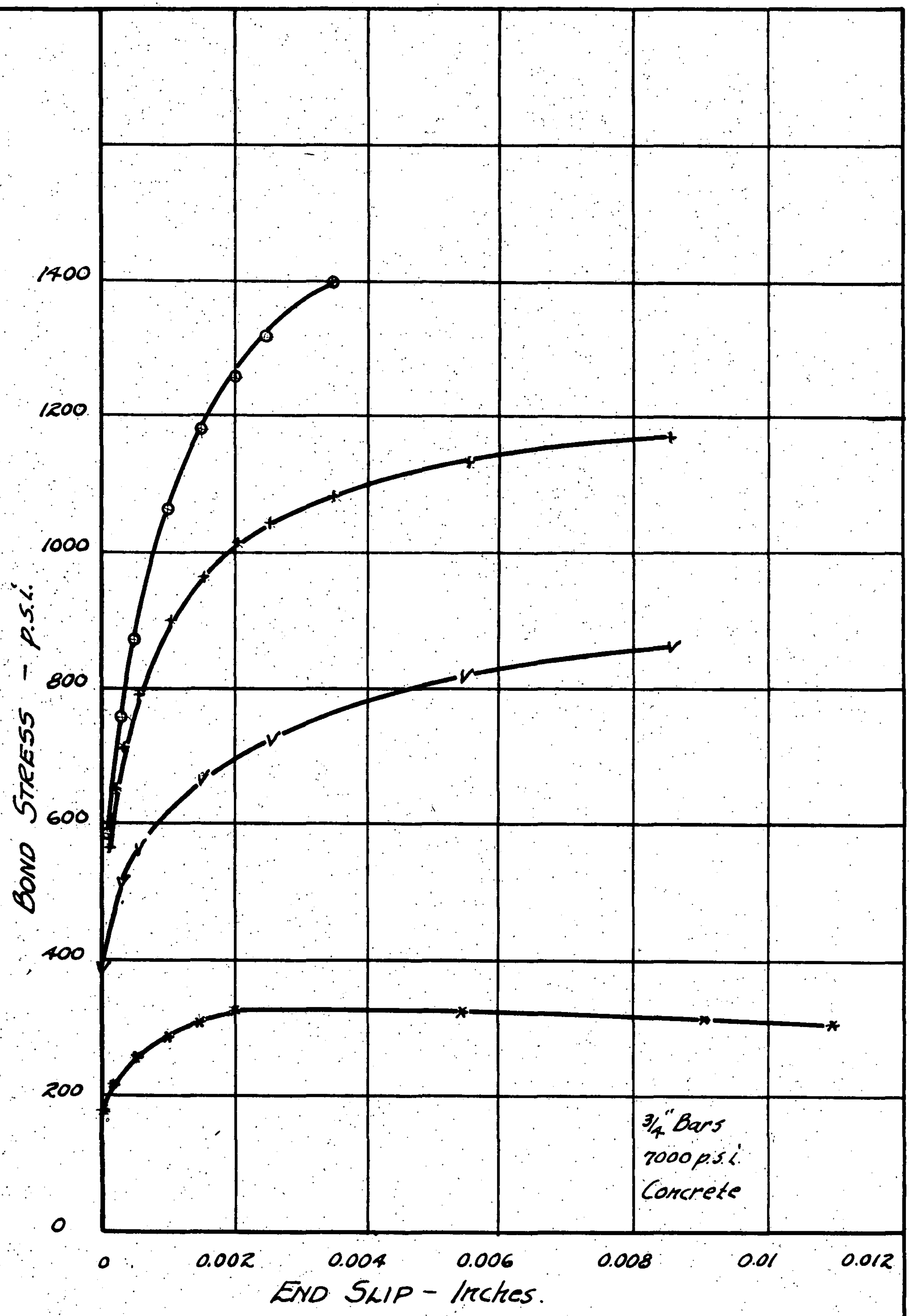

FIG. 12. BOND SLIP CURVES OF PULLOUTS.

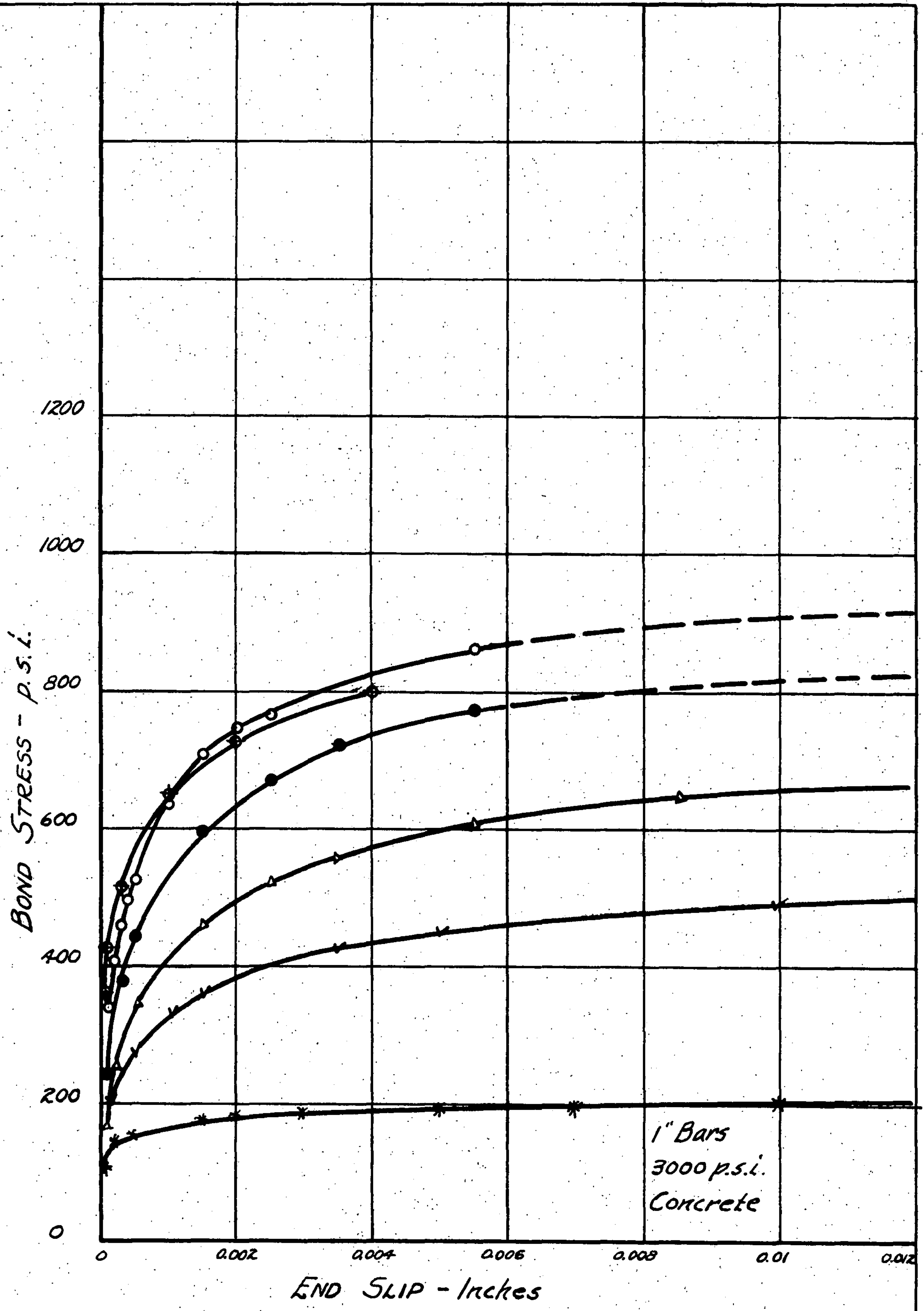

Fig. 13. Bond-Slip Curves of Pullouts.

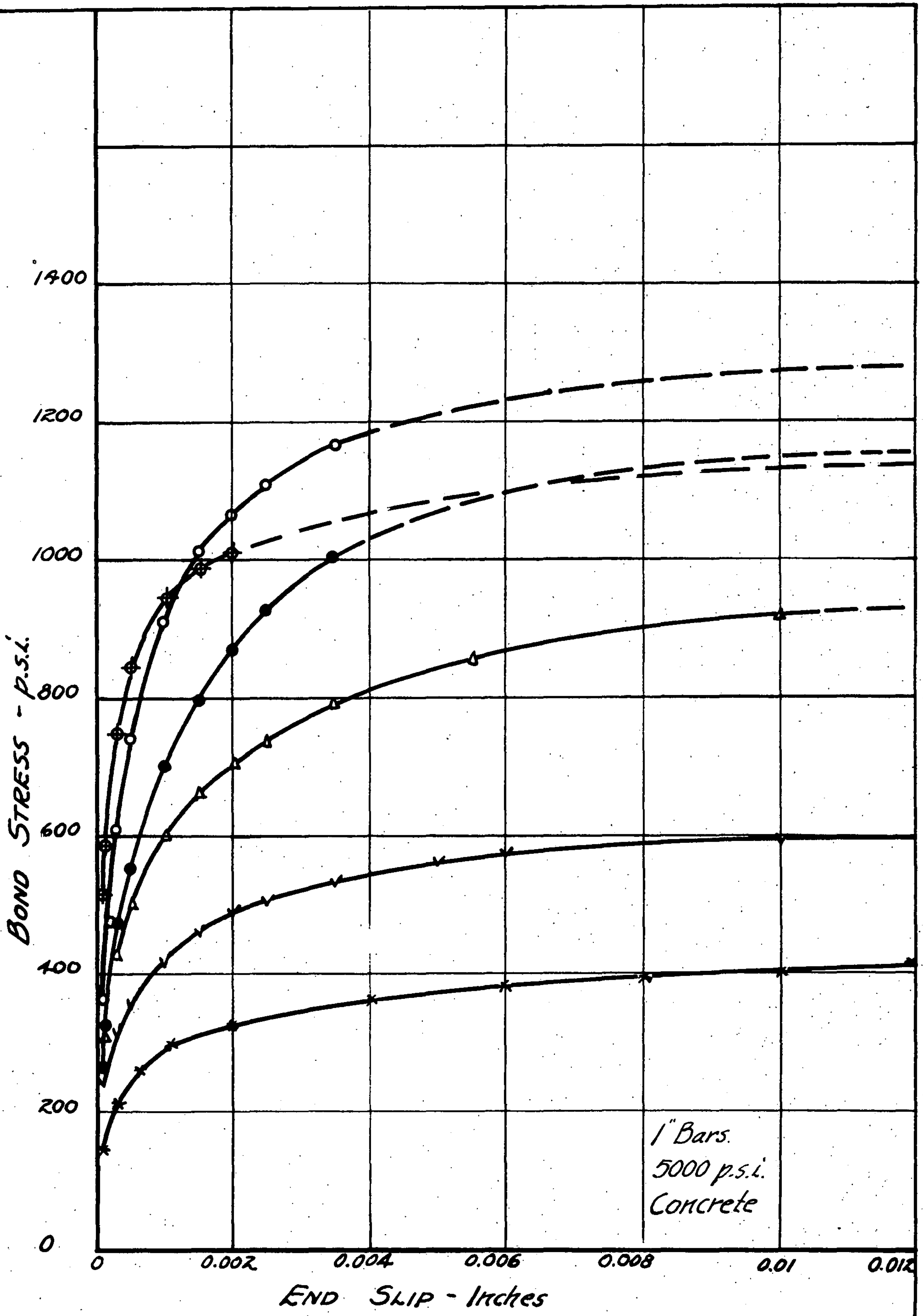

FIG. 14 BOND-SLIP CURVES OF PULLOUTS.

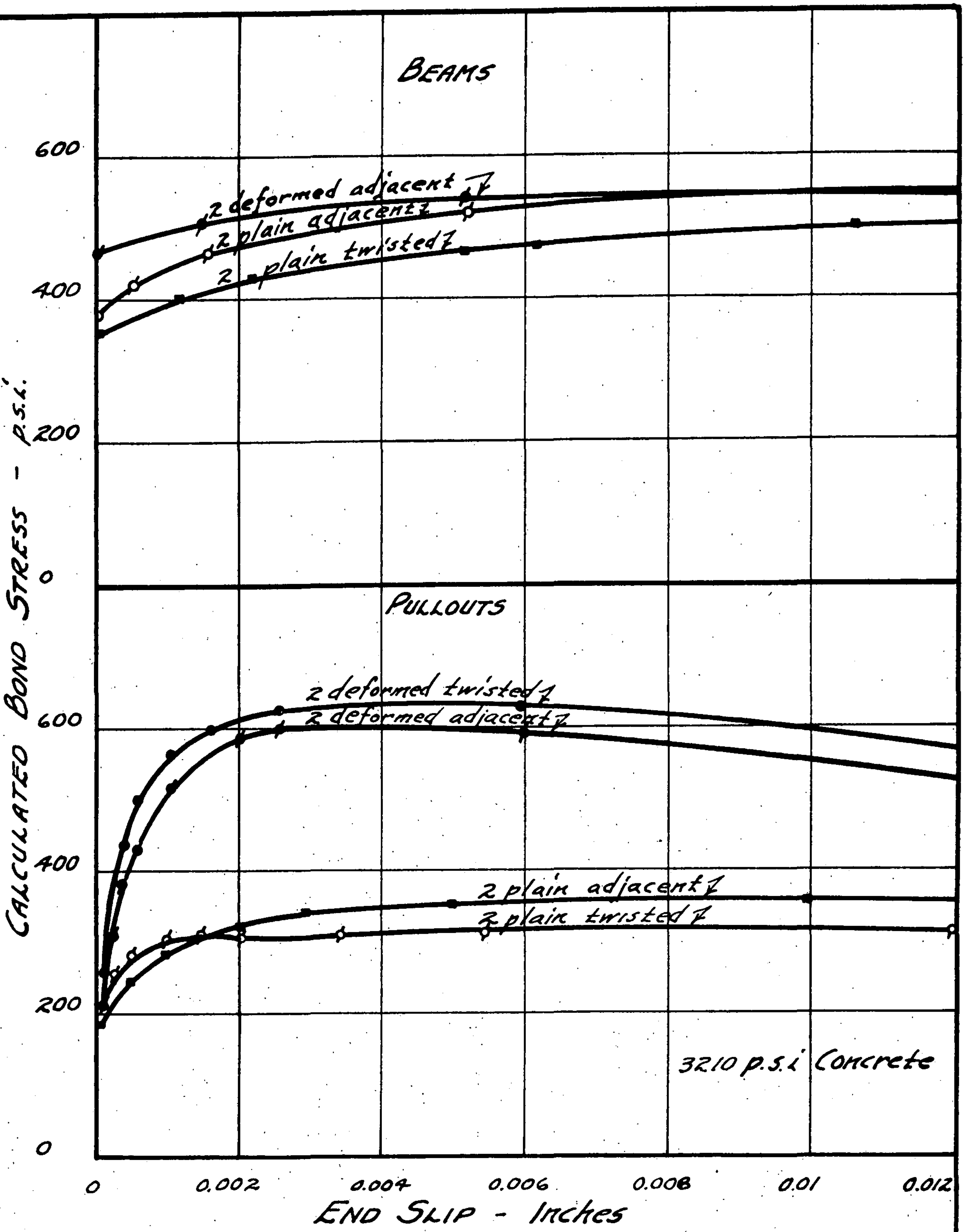

FIG. 15. EFFECT OF TWISTING OF TWO BARS ON PULLOUT AND BEAM RESISTANCE.

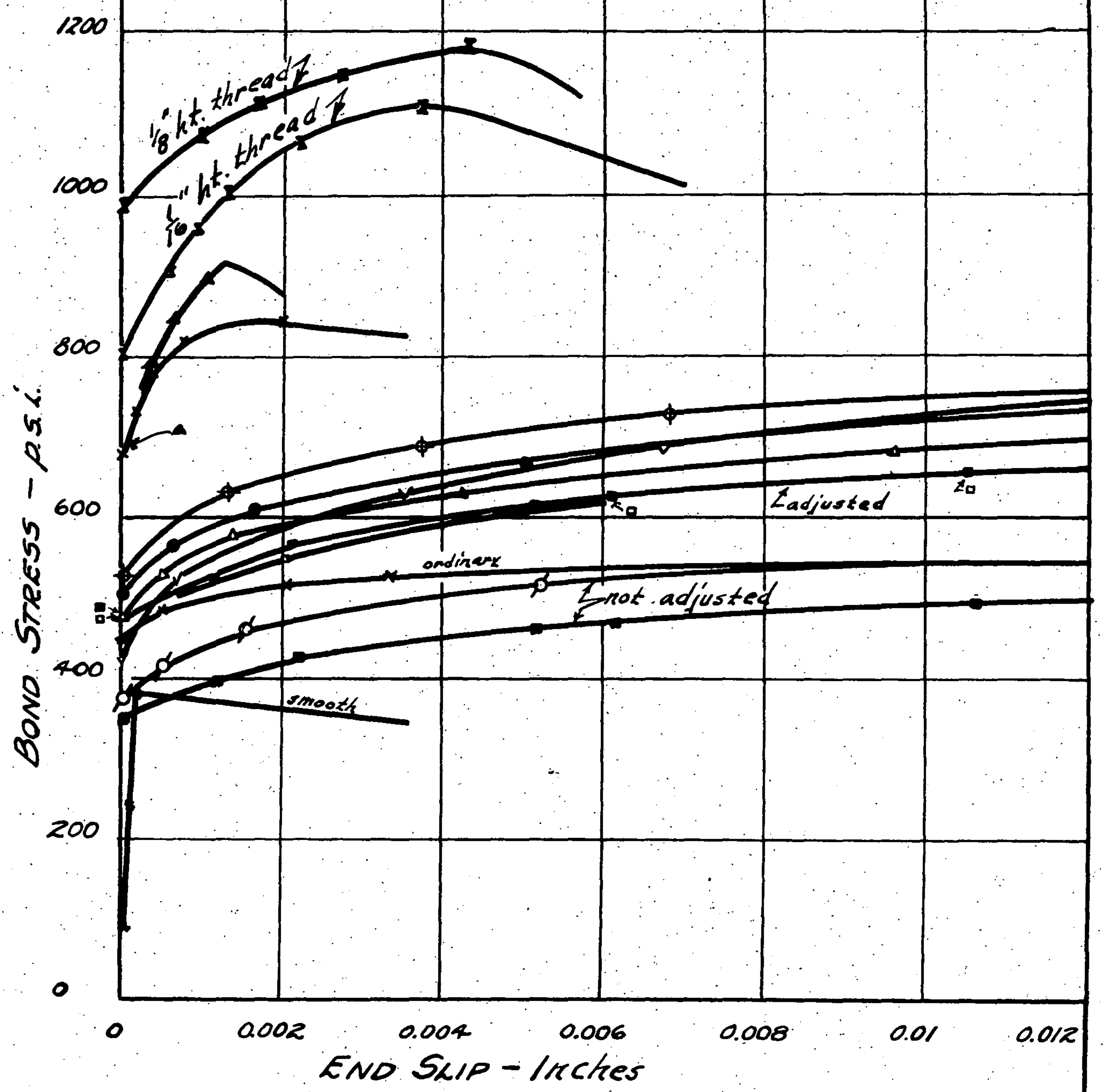

Fig. 16. Effect of Type of Deformation on Bond Resistance of Bars in Beams

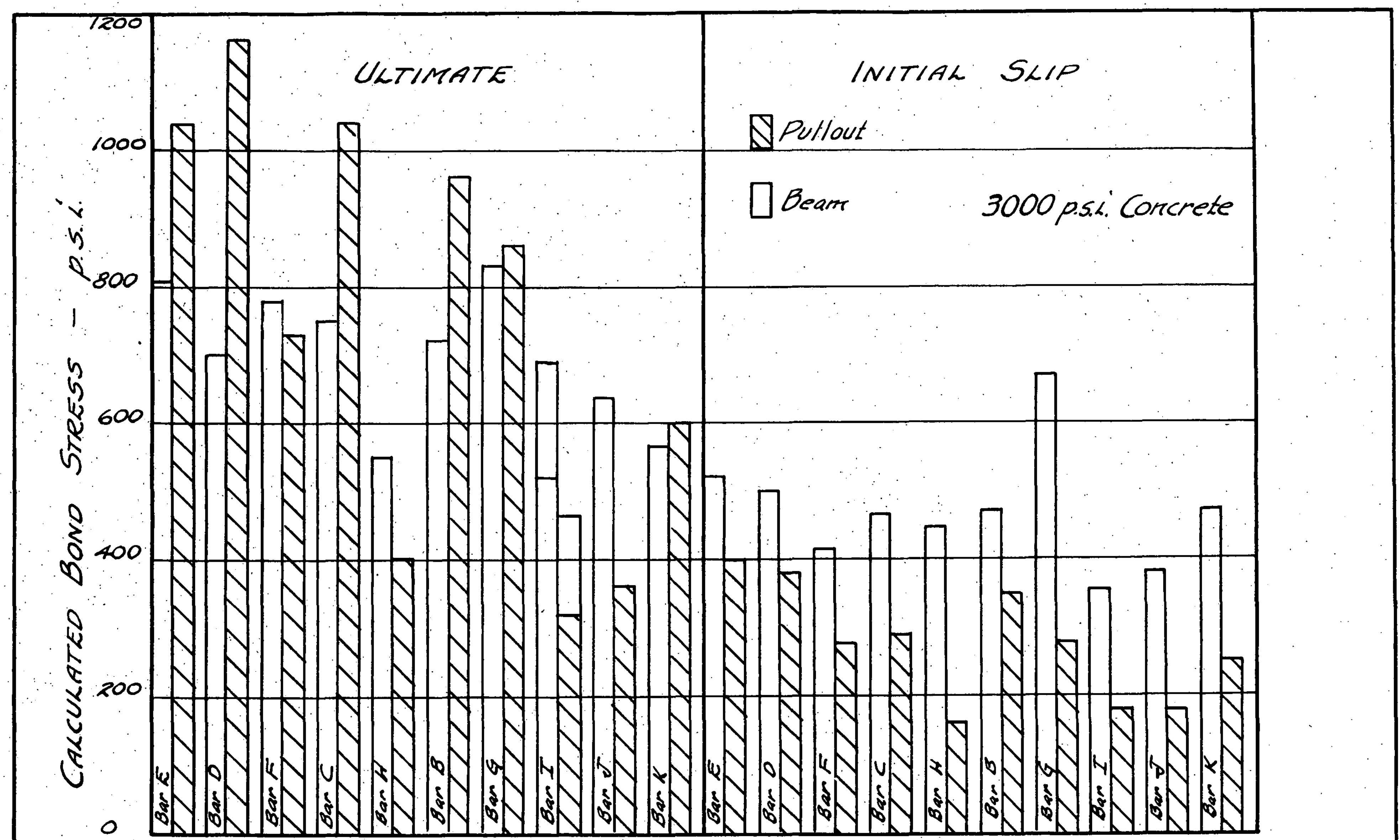

FIG. 17. INITIAL SLIP AND ULTIMATE BOND STRESSES OF BEAMS AND PULLOUTS.

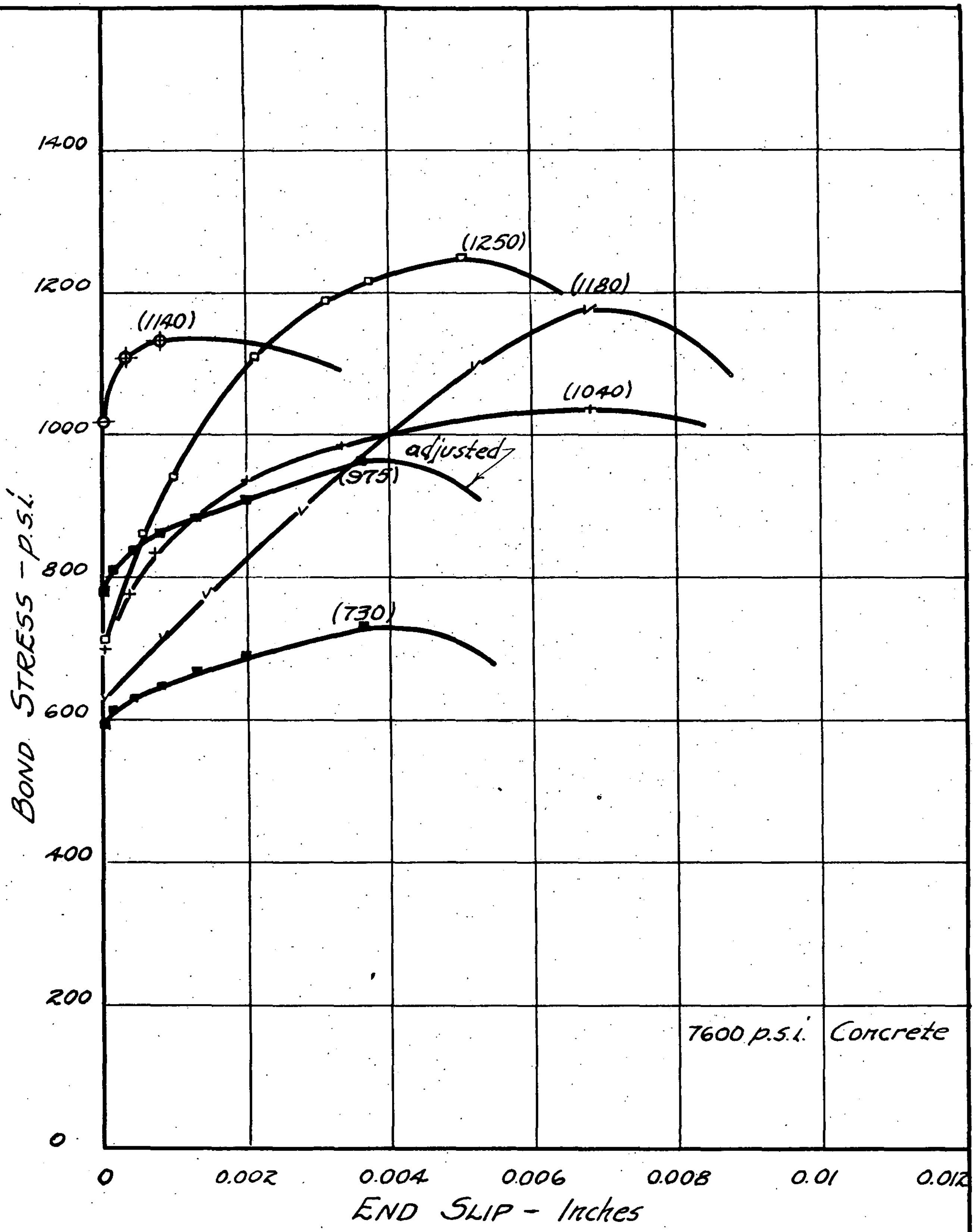

FIG. 18. BOND SLIP CURVES OF BARS IN HIGH CONCRETE STRENGTH BEAMS

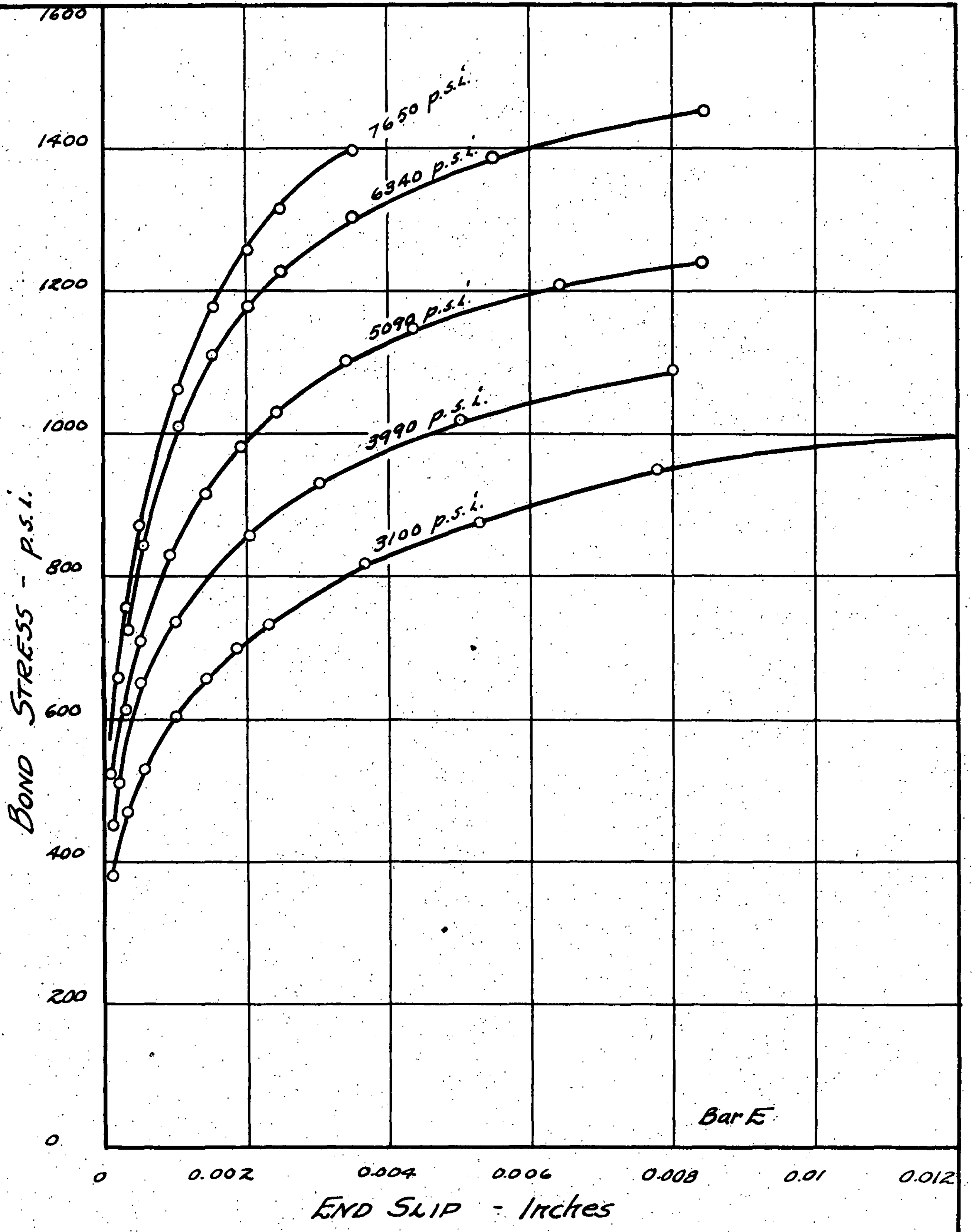

FIG. 19. TYPICAL EFFECT OF CONCRETE STRENGTH ON BOND PULLOUT RESISTANCE.

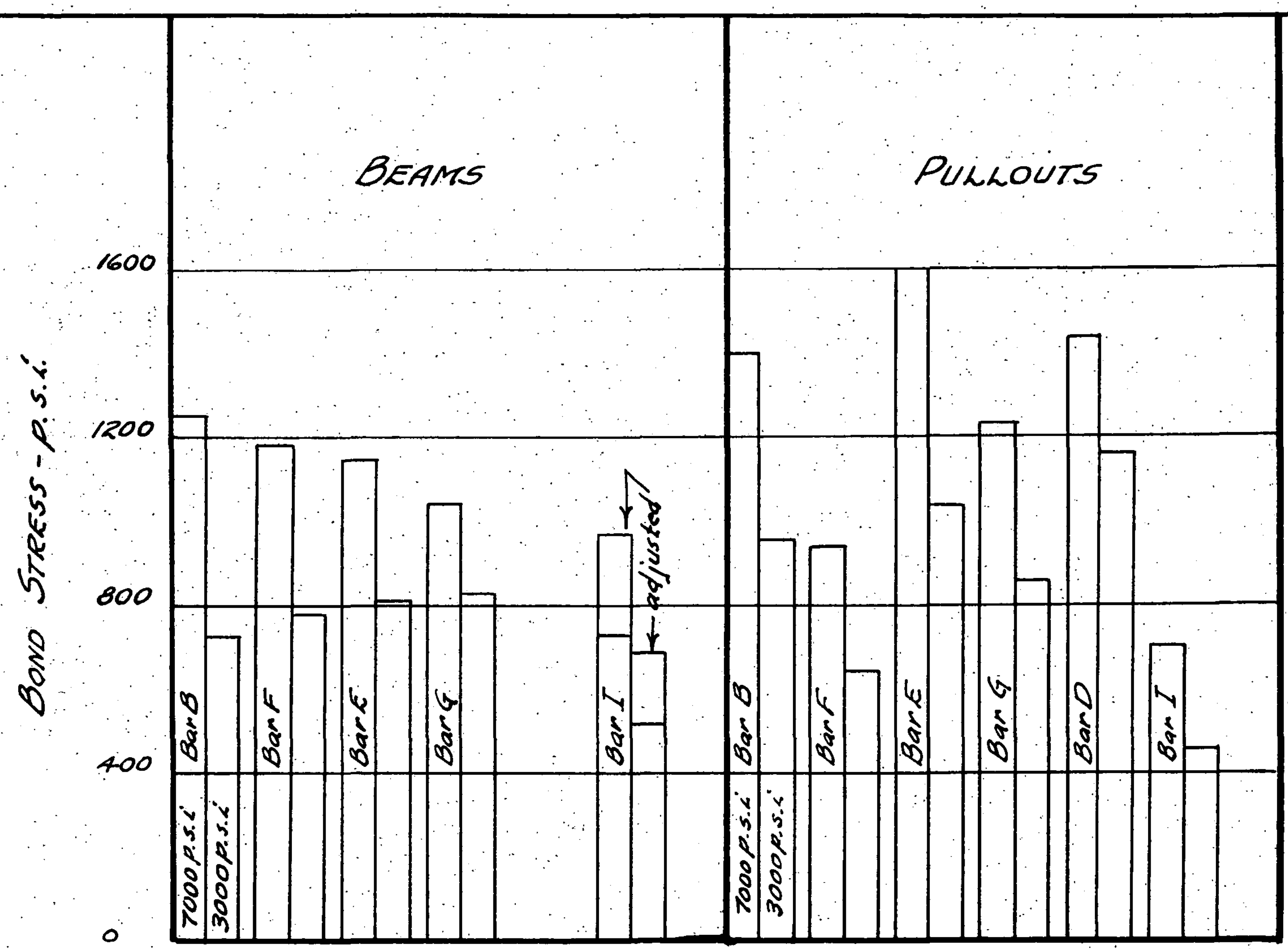

FIG. 20. EFFECT OF STRENGTH OF CONCRETE ON PULLOUT AND BEAM BOND RESISTANCE.

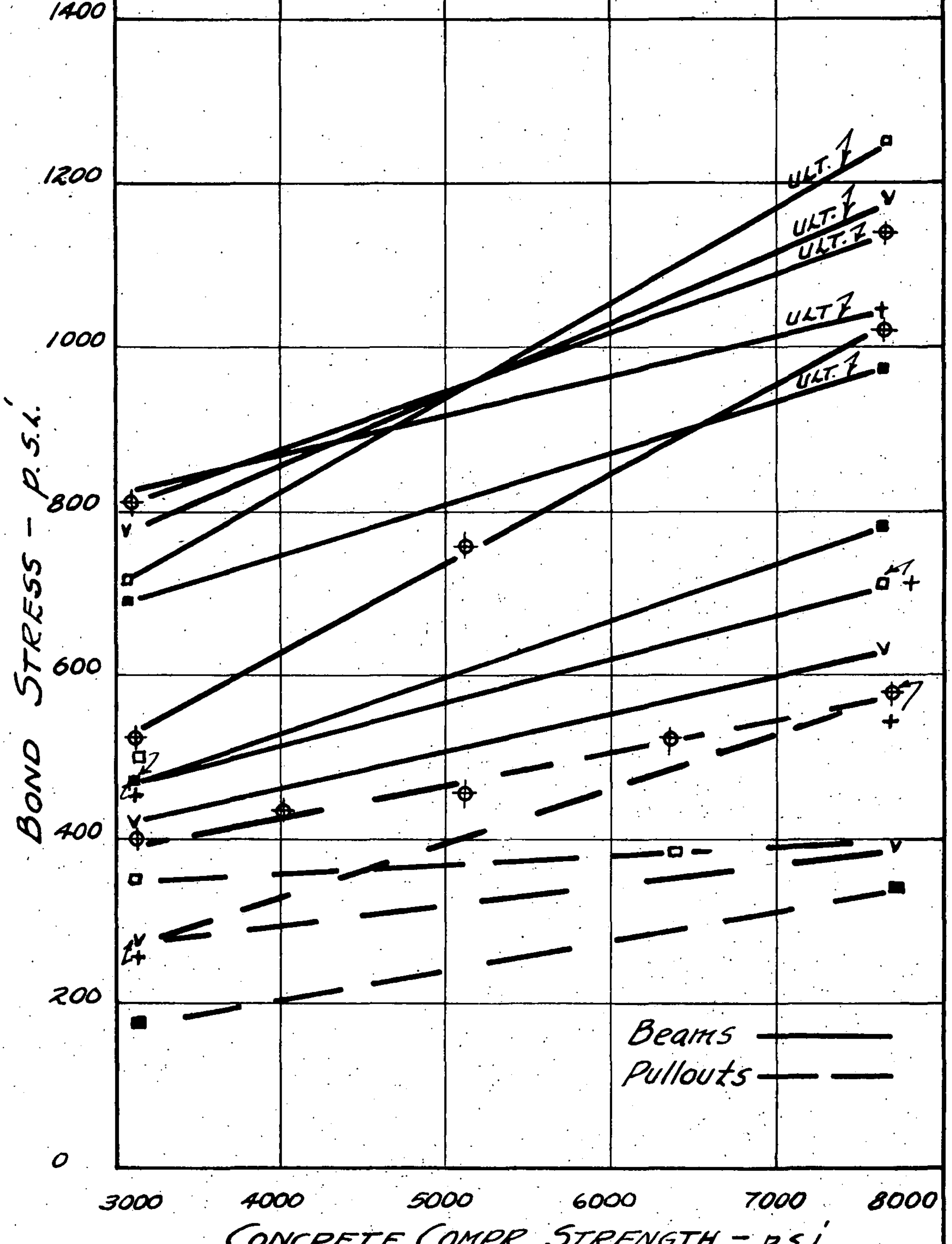

Fig. 21. Effect of Concrete Strength on Initial Slip and Ultimate Bond Stresses.

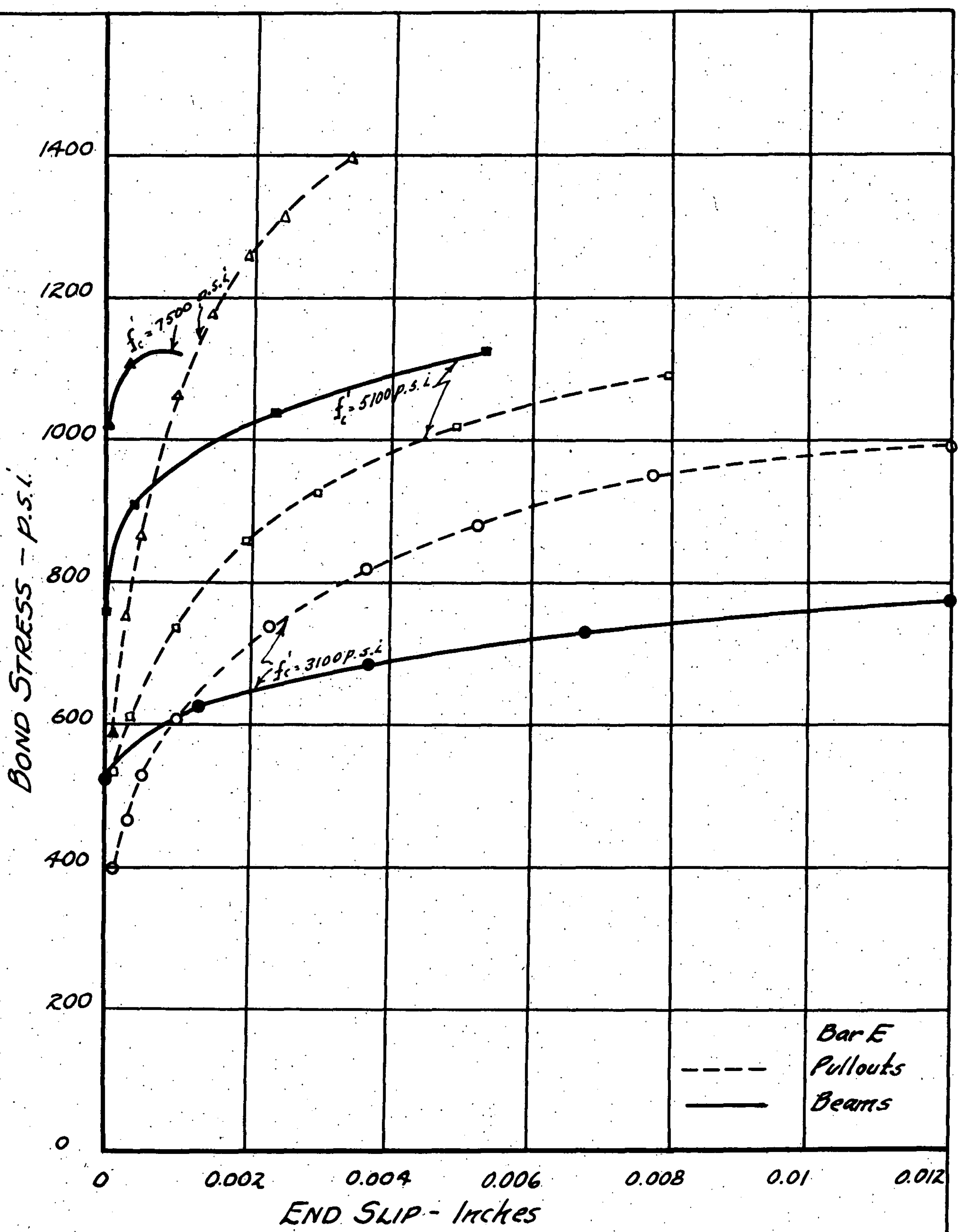

FIG. 22. COMPARISON OF BOND-SLIP CURVES OF BEAMS AND PULLOUTS.