REPORT OF COMMITTEE ON THE USE OF HIGH ELASTIC STEEL AS REINFORCEMENT FOR CONCRETE

H J. GILKEY, *Chairman*

FOREWORD

This report constitutes Chapter XII of a continuing project made up of a series of investigations of problems relating to the use of high elastic limit steel as reinforcement for concrete

The titles and authorship of the past and current chapters are as follows:

Chapter I. Questions and Their Status Vol. 14 (1934), p. 258–270. (Gilkey and Ernst.)
Chapter II. References and Brief Summaries. Vol 14 (1934), p 271–283. (Gilkey and Ernst)
Chapter III. Design Procedure and Possible Economies from the Use of Higher Design Stresses Vol 14 (1934), p 283–314 (Gilkey and Ernst)
Chapter IV. Sustained Loading Tests on Slender Concrete Beams Reinforced with High Elastic Limit Steel Vol. 15 (1935), p 81–111. (Gilkey and Ernst)
Chapter V Pull-out Tests for Bond Resistance of High Elastic Limit Steel Bars. (Reconnaissance Series of 1936) Vol. 16 (1936), p. 81–95 (Gilkey and Ernst)
Chapter VI. An Experimental Study of Bond Stress Vol. 16 (1936), p 96–99 (Dunagan and Ernst.)
Chapter VII Concrete Slabs Reinforced with High Yield Point Steel Bars Vol 16 (1936), p 100–114 (Mylrea)
Chapter VIII. Bond Resistance of High Elastic Limit Steel Bars, Series of 1937. Vol 17 (1937), p 150–186. (Gilkey, Chamberlin and Beal)
Chapter IX The Distribution of Strain in the Concrete of Pull-out Specimens, Series of 1937 Vol 18 (1938), p 114–129 (Gilkey, Chamberlin and Beal.)
Chapter X The Effects of Impact on Reinforced Concrete Beams. Vol. 18 (1938), p 130–139 (Mylrea.)
Chapter XI. Bond Tests on Rusted Bars Vol. 19 (1939), p 149–163. (Gilkey, Chamberlin and Beal)
Chapter XII. Distribution of Bond in Long Pull-out Specimens. Vol 20 (1940), p. 499 (Gilkey, Chamberlin and Beal.)

The work reported as Chapter XII was conducted at Iowa State College as a cooperative project between the Highway Research Board and the Iowa Engineering Experiment Station

These results were submitted by the project committee to the Department of Design which approved them for publication. The project committee as now constituted consists of:

G. C. Ernst, Assistant Professor of Civil Engineering, University of Maryland.
T D Mylrea, Professor and Head of Civil Engineering, University of Delaware.
F E Richart, Research Professor of Theoretical and Applied Mechanics, University of Illinois.
Searcy B Slack, Consulting Engineer, Decatur, Georgia
H J Gilkey, Professor and Head of Theoretical and Applied Mechanics, Iowa State College, Chairman

CHAPTER XII DISTRIBUTION OF BOND IN LONG PULL-OUT SPECIMENS

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SYNOPSIS

Three duplicate series of pull-out tests were conducted on special alloy steel plain bars (yield strength about 175,000 p s i) ¼-in and ½-in diameters for L/D ratios 12 to 96 (embedments from 3 to 48 in) In no case did stresses equal as much as one-half the yield strength of the steel These tests were to determine the actual distribution of bond for specimens with long embedments but for which yield point (or yield strength) stresses were not approached It was also desired to ascertain whether or not there might be some limiting length of plain bar beyond which added length of embedment gave no added bond resistance Surface strains were measured on the concrete for the specimens of one of the three series and slippages were measured at both the loaded and the unloaded ends of the bars in all cases Due to added residual drag with added length of embedment, there appears to be no length beyond which the total pull is not increased slightly with added length of embedment The results supplement and confirm trends and findings of the previous studies on related aspects of bond and supply additional basic information on the subject

INTRODUCTION

The reports presented as Chapters VIII and IX, based on the Bond Series of 1937, suggested the need for further information on (1) the relation between bond resistance and length-diameter (L/D) ratio in pull-out specimens when not complicated for the longer embedments by the proximity of yield point stress in the steel, and (2) a quantitative verification of the distribution of bond stress as determined from the measurement of strains on the surfaces of pull-out specimens The relatively long gage lengths (4 in) of the Martens mirror extensometers used to measure concrete strains necessitated very long embedments in order to secure strain data which would show clearly the differential behavior of bond action along the specimen Thus a satisfactory study of the effect of length of embedment and of bond stress distribution involves embedments of such lengths that yield point stresses are reached when commercial reinforcing steel is used In order to insure that the steel stresses remained within the elastic range, high-strength alloy steel bars (S A E 6145) were used Since the yield strength of this steel was approximately 175,000 p s i the tests are indeed somewhat academic and outside the realm of any conceivable reinforced concrete practice. Nevertheless the authors have found them an excellent medium for securing the basic information which they sought

OUTLINE OF THE TESTS

A graduated series of pull-out specimens using two sizes of bars was chosen, the only variables being length of embedment and diameter of bar The high-strength plain round ¼ and ½-in diameter bars were cast into 4 by 4-in pull-out specimens with embedments of 3, 6, 12, 18 and 24 in for the ¼-in bars and 3, 6, 12, 18, 24, 36 and 48 in for the ½-in bars These gave L/D ratios from 12 to 96 and from 6 to 96, respectively Figure 1 shows one complete set of specimens for each size of bar. As described later, the set of specimens shown in Figure 1 was twice duplicated by subsequent repeat castings.

All specimens were cast vertically in steel forms with the same orientation as they have in Figure 1. The proportions of the concrete were 1:2.72:1.62 with a water-cement ratio of 0.55, all by weight. The slump was 6 in., plus or minus 1 in. Hawkeye cement and Des Moines River sand and gravel of $\frac{3}{4}$-in. maximum size were used. Forms were stripped at 24 hours and all specimens were cured under water for 27 additional days. All specimens were tested at 28 days and within a few hours after removal from the water.

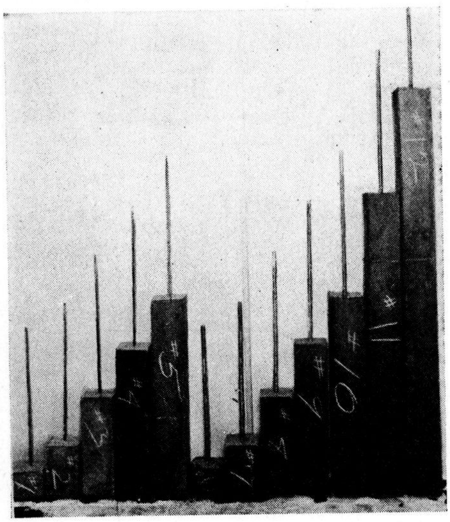

Fig. 1. One complete casting of the pull-out specimens made with high strength alloy bars.

The results from the first casting were not entirely consistent for the two sizes of bar and after the tests for that lot were completed, the concrete was broken away and the same bars were re-cast into a second lot of specimens. Later the bars were again re-used in a third lot of specimens. While the bars were very smooth as received, there were visible upon some of them slight spiral markings which had been introduced during the straightening operation which had followed the heat treatment. These mark-

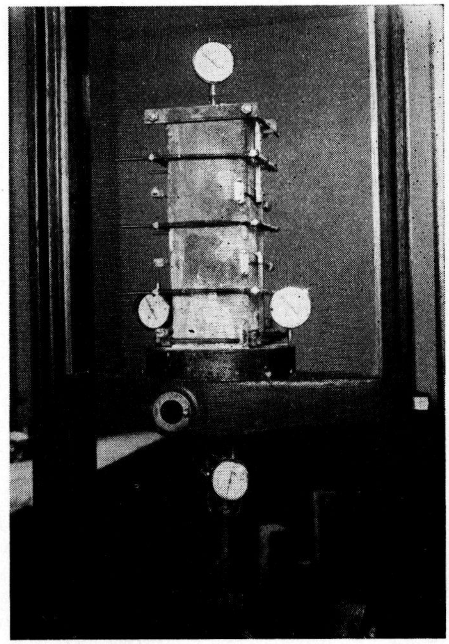

Fig. 2. Pull-out Specimen Ready for Test

Shows Martens mirror extensometers for measurements of surface strains in the concrete and Federal dial gages having a least count of 0.0001 in. for measurements of slip at both loaded and unloaded ends of bar.

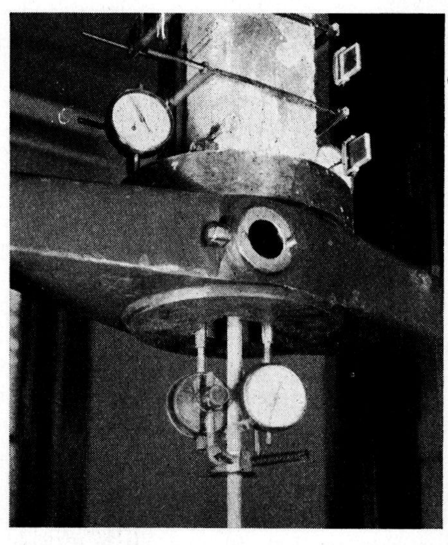

Fig. 3. Pull-out specimen showing detail of arrangement for measuring slip at the loaded end of the bar.

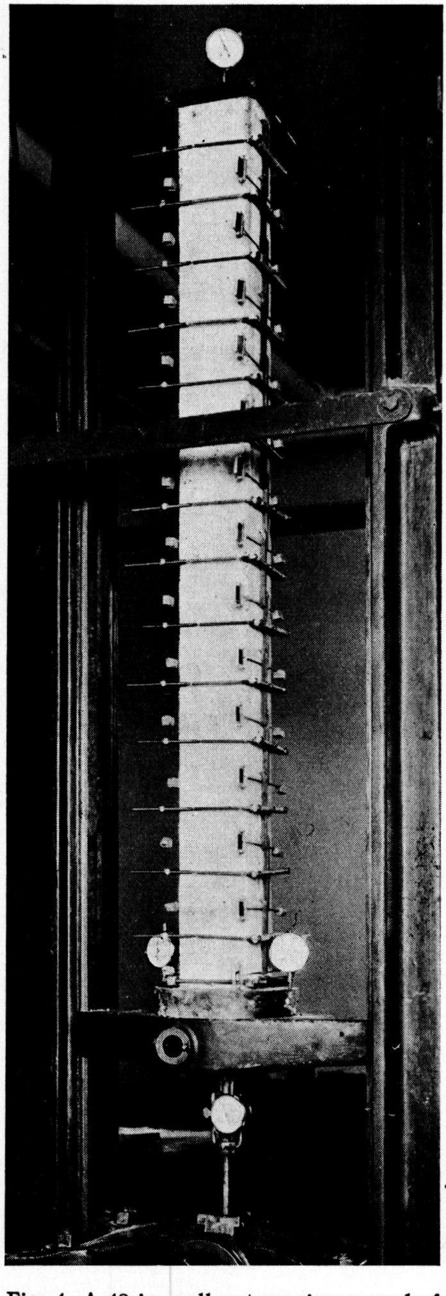

Fig. 4. A 48-in. pull-out specimen ready for test showing 28 Martens mirror extensometers in place on 14 slightly over-lapping 4-in gage lengths on each of two opposite sides of the specimen.

ings were almost imperceptible to the touch but on the suspicion that they might in some way have influenced the bond, the surfaces of both sizes of bars were polished with fine emery cloth, all markings being thus removed prior to the two re-castings.

The strains at the surface of the concrete of the pull-out specimens of the initial casting were measured with Martens mirror extensometers according to the method described in detail in Chapter VIII. In order to provide time to secure the strain data when the specimens were tested, the first complete set of specimens (on which the strains were measured) was broken up into five batches which were cast on different days within a one-week period. Strains were not measured on the second and third lots and all of the specimens in each of the sets were cast from a single batch of concrete.

The pull-outs were tested in a 20,000-lb. hand-operated Olsen testing machine. Five Federal dials (0.0001-in.) were arranged as shown in Figures 2 and 3 (See Fig. 11, Chapter XI for details) to secure data on the first slips both at the loaded and unloaded ends of the bar. A 48-in. specimen ready for test is shown in Figure 4.

RESULTS

The results for all three sets of specimens are shown in Table 1. Specimens a, b and c represent respectively the first, second and third castings with the same bars. Whenever the term "first slip" is used it is to be taken as the load at a movement of two dial divisions (0.0002 in.) at the unloaded end of the bar. For all lengths of embedment the loads at "first slip" and ultimate were identical. For the smooth surfaces of these bars the "let go" is sudden and complete, and there is an immediate falling off of the load at "first slip"

TABLE 1

TEST RESULTS FOR HIGH-STRENGTH ALLOY STEEL BARS

Yield Strength of Steel Approximately 175,000 p s i.

Specimen No	Date cast	Length of embedment, (in)	L/D ratio	Ultimate compressive strength of concrete, (p s i)	At "first slip" (ultimate at same load)			Residual drag at slip of 0 08 in at free end			Slip at loaded end at "first slip," (in)
					Pull on bar, (lb)	Bond stress, (p s i)	Bond as per cent of ult compressive strength	Pull on bar, (lb)	Bond stress, (p s i)	Bond as per cent of ult compressive strength	
Col	a	b	c	d	e	f	g	h	i	j	k
Diameter of bar ¼ in.											
1—a[1]	6- 5-39	3 3	13 0	3980	1190	468	11 8	722	283	7 1	0 0018
—b[1]	7-18-39	3 6	14 4	4280	1700	601	14 0	482	171	4 0	0 0018
—c[1]	5-18-40	3 0	12 0	2830	1000	424	15 0	360	153	5 4	0 0020
2—a	6- 5-39	6 4	25 5	3980	2000	399	10 0	1170	233	5 9	0 0038
—b	7-18-39	6 5	26 0	4280	1900	372	8 7	720	141	3 3	0 0055
—c	5-18-40	6 2	24 8	2830	1760	361	12 8	1000	205	7 3	0 0050
3—a	6- 5-39	12 4	49 5	3980	2140	220	5 5	1290	133	3 3	0 0095
—b	7-18-39	12 2	48 8	4280	2320	242	5 7	1260	131	3 1	0 0140
—c	5-18-40	11 9	47 6	2830	1910	204	7 2	1385	148	5 2	0 0115
4—a	6- 7-39	18 5	74 0	3940	2970	204	5 2	2930	201	5 1	0 0246
—b	7-18-39	18 5	74 0	4280	2880	198	4 6	2100	144	3 4	0 0250
—c	5-18-40	18 0	72 0	2830	2620	185	6 5	2250	159	5 6	0 0200
5—a	6- 7-39	24 5	98 0	3940	3240	168	4 3	2790	145	3 7	0 0348
—b	7-18-39	24 4	97 6	4280	3140	164	3 8	2340	122	2 8	0 0380
—c	5-18-40	24 1	96 4	2830	2550	135	4 8	1910	101	3 6	0 0295
Diameter of bar ½ in											
6—a	6- 8-39	3 5	7 0	4070	2860	520	12 8	1200	218	5 4	0 0028
—b	7-18-39	3 5	7 0	4280	2220	404	9 4	610	111	2 6	0 0008
—c	5-18-40	3 3	6 6	2830	1320	255	9 0	310	60	2 1	0 0020
7—a	6- 8-39	6 6	13 2	4070	2700	260	6 4	1390	134	3 3	0 0016
—b	7-18-39	6 8	13 6	4280	3740	350	8 2	1280	120	2 8	0 0035
—c	5-18-40	6 0	12 0	2830	1880	199	7 0	960	102	3 6	0 0022
8—a	6- 8-39	12 3	24 5	4070	6350	330	8 1	3320	173	4 2	0 0104
—b	7-18-39	12 3	24 6	4280	3700	191	4 5	1250	65	1 5	0 0060
—c	5-18-40	11 9	23 8	2830	2740	146	5 2	1540	82	2 9	0 0035

[1] a, b, and c represent successive castings with the same bars

Note: Proportions of all batches were identical—1.2 72.1 62, with a water-cement ratio of 0 55, all by weight First casting (batches "a") surfaces of bars were as received except for cleaning with carbon tetrachloride Second and third castings (batches "b" and "c") bars were worked over with fine emery cloth to remove dimly visible spiral markings produced by the straightening process applied after heat treating Batches "c" were all cast from Hawkeye cement which had been in storage for 4 years in closed galvanized iron cans Differences in strength of batch "c" from "a" and "b" probably represent differences in strength of cement used due possibly to deterioration during storage. The pull corresponding to the yield strengths of the bars was about 8600 lb for the ¼-in bars and about 34,400 lb. for the ½-in. bars.

TABLE 1—*Concluded*

Specimen No	Date cast	Length of embedment, (in)	L/D ratio	Ultimate compressive strength of concrete, (p s i)	At "first slip" (ultimate at same load)			Residual drag at slip of 0 08 in at free end			Slip at loaded end at "first slip," (in)
					Pull on bar, (lb)	Bond stress, (p s i)	Bond as per cent of ult compressive strength	Pull on bar, (lb)	Bond stress, (p s i)	Bond as percent of ult compressive strength	
Col	a	b	c	d	e	f	g	h	i	j	k
Diameter of bar ½ in											
9—a	6- 9-39	18 5	37 0	4360	7320	252	5 8	4320	149	3 4	0 0181
—b	7-18-39	18 5	37 0	4280	5040	173	4 0	3180	109	2 5	0 0105
—c	5-18-40	18 0	36 0	2830	4370	155	5 5	2790	102	3 6	0 0080
10—a	6- 9-39	24 3	48 5	4360	10990	288	6 6	6810	179	4 1	0 0304
—b	7-18-39	24 2	48 4	4280	5630	148	3 5	3660	96	2 3	0 0135
—c	5-18-40	24 0	48 0	2830	4380	116	4 1	3370	89	3 2	0 0125
11—a	6-10-39	36 5	73 0	4430	9790	171	3 9	7500	131	3 0	0 0460
—b	7-18-39	36 8	73 6	4280	6750	117	2 7	5460	95	2 2	0 0280
—c	5-18-40	36 0	72 0	2830	5160	91	3 2	4020	71	2 5	0 0205
12—a	6-10-39	48 8	97 5	4430	13960	182	4 1	11680	152	3 4	0 0933
—b	7-18-39	48 7	97 4	4280	7000	92	2 2	6380	84	2 0	0 0400
—c	5-18-40	48 0	96 0	2830	6360	84	3 0	5680	75	2 7	0 0360

even though the elastic stress in the steel is low As can be seen from Col (e) of Table 1 no bar was stressed to as much as one-half its yield strength The pull to produce yield strength stress would have been about 8600 lb for the ¼-in. bars and 34,400 lb for the ½-in bars

Length of embedment

On Figure 5 the pull on the bar, the unit bond stress, and the bond as percentage of the ultimate compressive strength of the concrete, all at "first slip", are plotted for the full range of L/D ratios for both bar sizes The corresponding curves for the length-of-embedment series of 1937 using rail-steel bars (Fig. 28, Chapter VIII) indicated that:

1. The total bond resistance offered increases with added length of embedment up to about 24 bar diameters, after which there appears to be but little added resistance with added length of embedment. If this indication is significant it means that plain bars will give added resistance as length of embedment increases up to a limiting amount beyond which extra length of embedment will contribute only the moderate added resistance that results from the drag resistance offered by the added length of bar

2. The increase in total bond resistance with added embedment is not proportional to the amount of added embedment, and the unit bond resistance reduces steadily from that for very short embedments to that for long embedments

Study of Figure 5 shows excellent agreement with the foregoing indications except as regards the limiting L/D of about 24. This difference may, of course, be due to the difference in the surfaces of the bars, those of the Series of 1937 being the hot rolled commercial product of a rolling mill. The high-strength alloy bars of Figure 5 were unusually smooth besides being a different grade of material. Figure 5 seems to establish withstand by bond and that long embedments are relatively ineffective per unit length of bar or per unit area of contact surface.

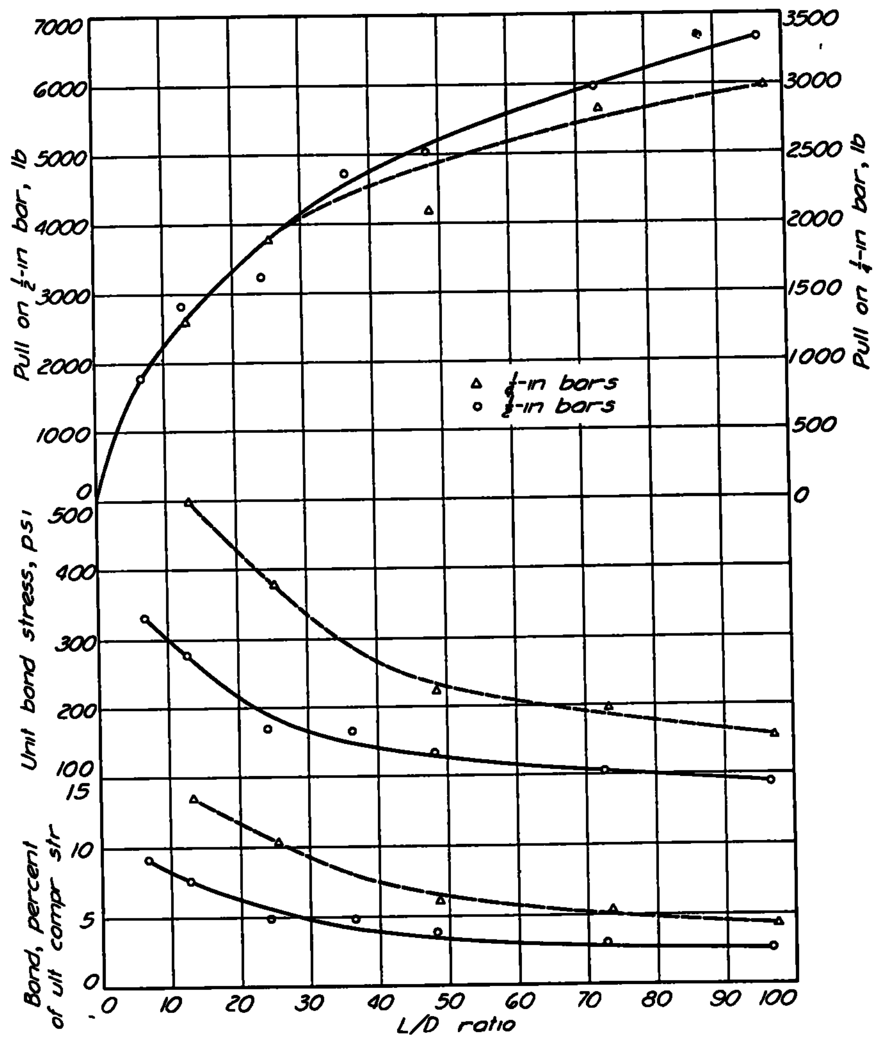

Fig. 5. Effect of Length of Embedment

Loads, stresses and bond ratios at "first slip." Each point is average for three specimens for ½-in. bars and average for two specimens for ¼-in. bars. For these bars "first slip" coincided with the ultimate.

beyond reasonable doubt that even within the range of elastic behavior, doubling the length of embedment of a plain bar will not double the pull it can

Figure 6 is similar to Figure 5 except that the curves are for the residual drag after a slip at the unloaded end of 0.08 in. These curves support and supplement the evidence of the residual drag curves for rail-steel bars with maximum L/D ratios of 32 from the Series of 1937 (Fig. 29, Chapter VIII), that.

3. The drag behavior is consistent and similar to the action at "first slip" except that there is no apparent flattening out of the total load curves. It seems apparent

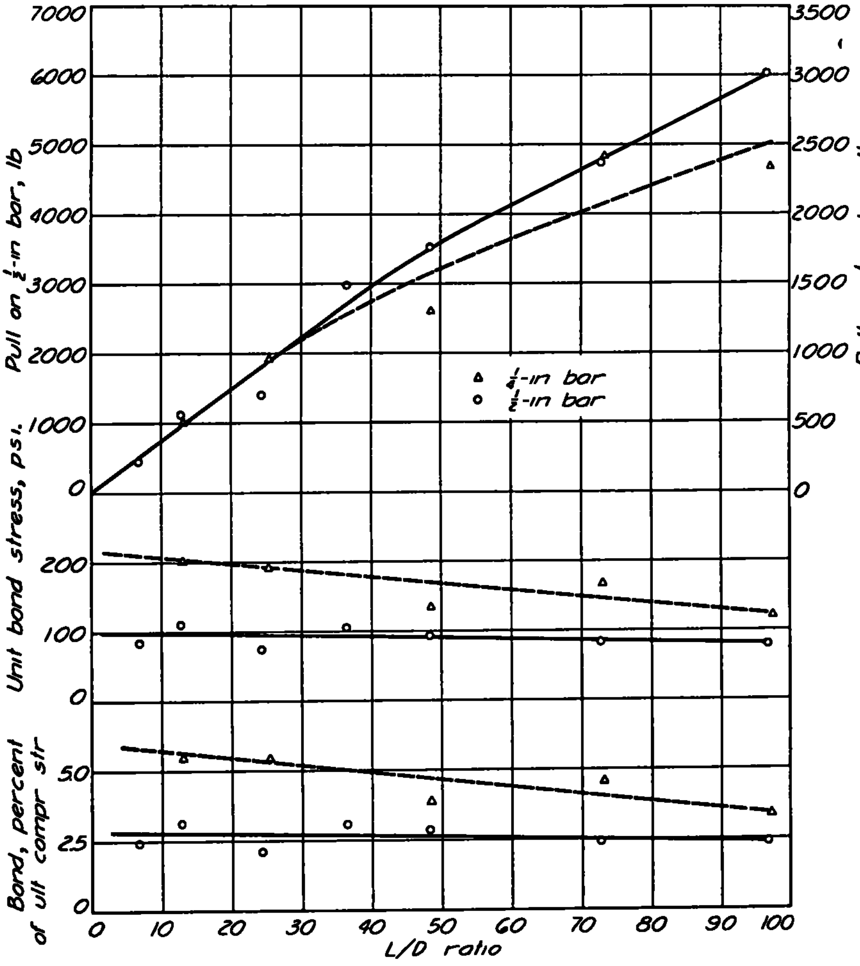

Fig. 6. Residual Drag

Loads, stresses and bond ratios after slip at unloaded end of 0.08 in. Each point is average for three specimens for ½-in. bars and average for two specimens for ¼-in. bars.

1. The total residual drag for plain bars continues to increase with added embedment

2. The increase in drag is not proportional to the increased area of contact from added embedment and the unit bond stress resistance decreases slightly but steadily.

that the entire length of plain bar functions against drag, whereas the resistance to initial slippage cannot be distributed effectively along the bar.

In Fig. 7 the total pull is plotted against the slip of the bar at the loaded end for the full range of embedments for each size of bar. These curves give added evidence of the progressive nature of bond action in specimens with relatively long embedments. The curves seem to indicate, well within the range of experimental error, as does also Figure 8, that there is a common load-slip curve for the various lengths of embedment up to loads just below the individual ul-

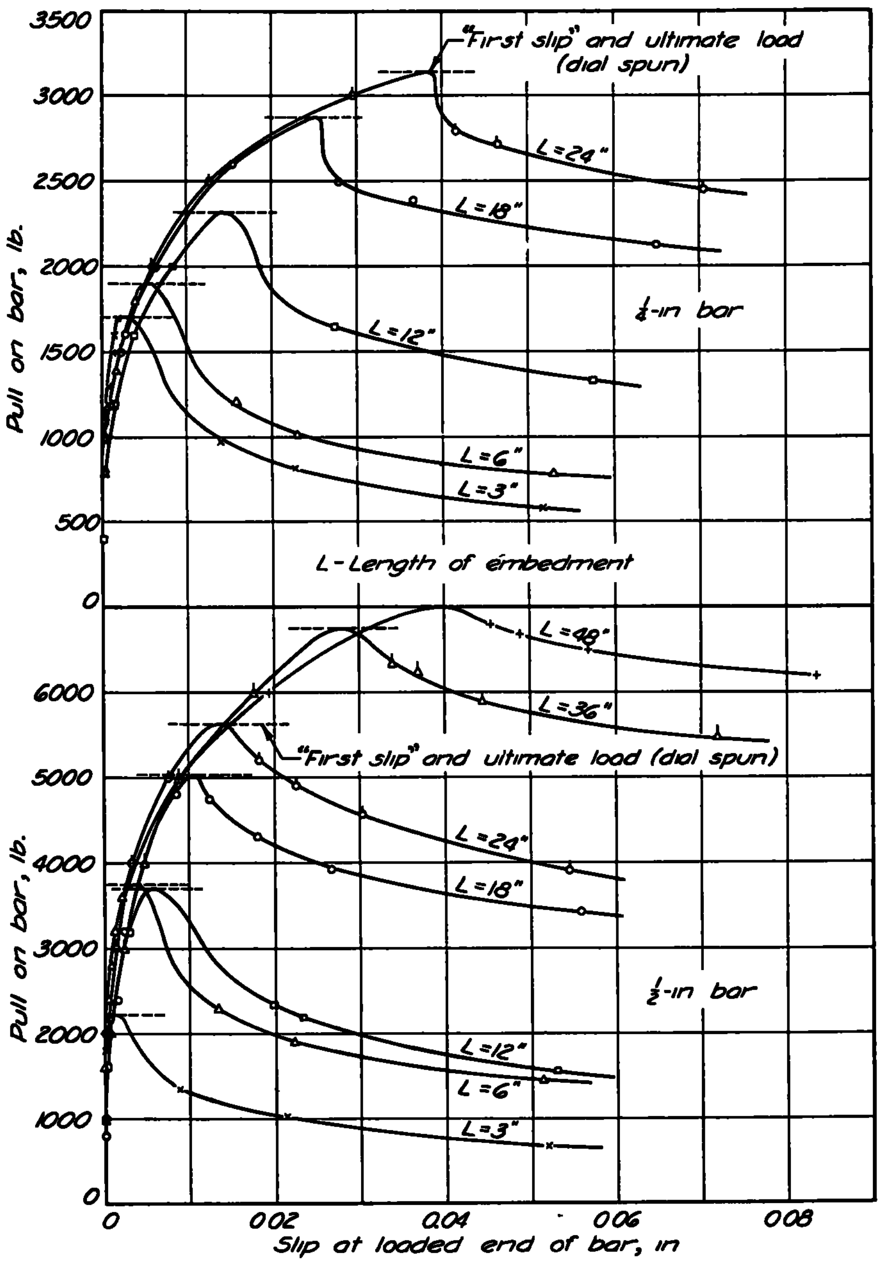

Fig. 7. Pull on bar vs. slip at loaded end of bar. ¼-in. and ½-in. diameter bars. Second casting

timates. In other words, the bond resistance developed for a given slip at the loaded end of the bar is the same for any length of embedment, providing the load is below the ultimate, and the added embedment in the longer specimens does not become effective until after considerable slip has occurred at the loaded end of the bar These indications are in accord with the analysis of bond behavior as based on the concrete surface strains measured with the Martens mirror extensometers

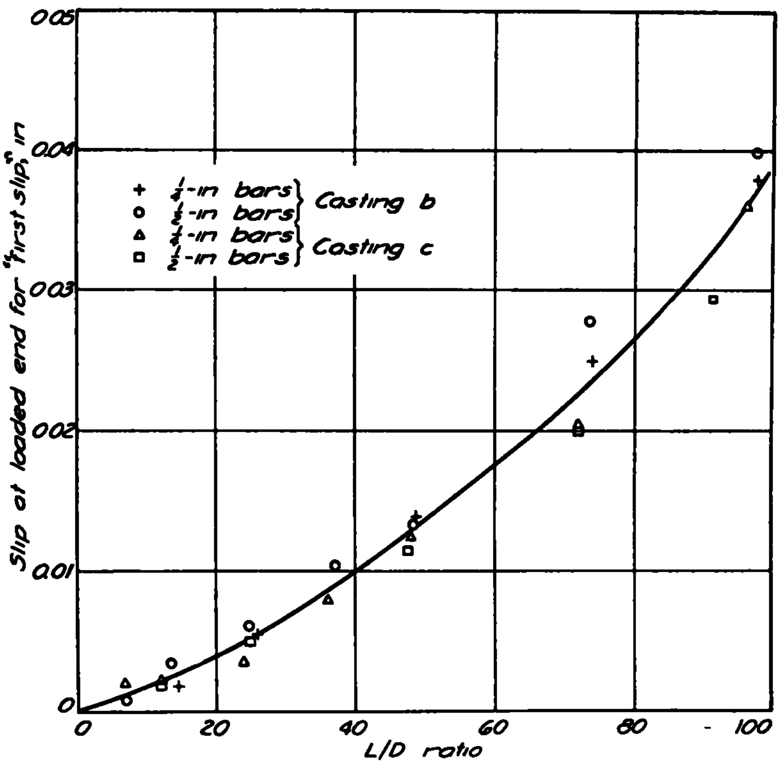

Fig. 8. Slippage at loaded end of bars at "first slip" of unloaded end for different lengths of specimens

Distribution of Bond Stress

Bond stresses as determined from strain measurements made at the concrete surfaces of a 48-in pull-out specimen are shown in Figure 9 The steps followed in determining the bond stresses were

1 The observed unit compressive strains along the specimen were plotted for each increment of load as the bottom curves of Figure 9

2. Each of the strain curves of this group was moved horizontally to the right until its point of maximum slope fell on the line representing the maximum slope of curve C The resulting composite curve is shown as curve C of the middle group. Curves B and A of the middle group were obtained in similar manner, using only the strain curves to the left in each case

3 The upper curves represent the slopes of the corresponding curves of the middle group The slopes of the curves of the middle group do not represent bond stresses directly but are proportional to them The derivation of the proportionality constant is indicated on the figure

A bond stress curve could have been obtained from the strain curve for each increment of load. By using the composite strain curves, however, the experimental irregularities of the individual curves were minimized. The apparent accuracy of the results may be demonstrated by a simple check on the equilibrium of the embedded bar. Curve C of the upper group represents the bond

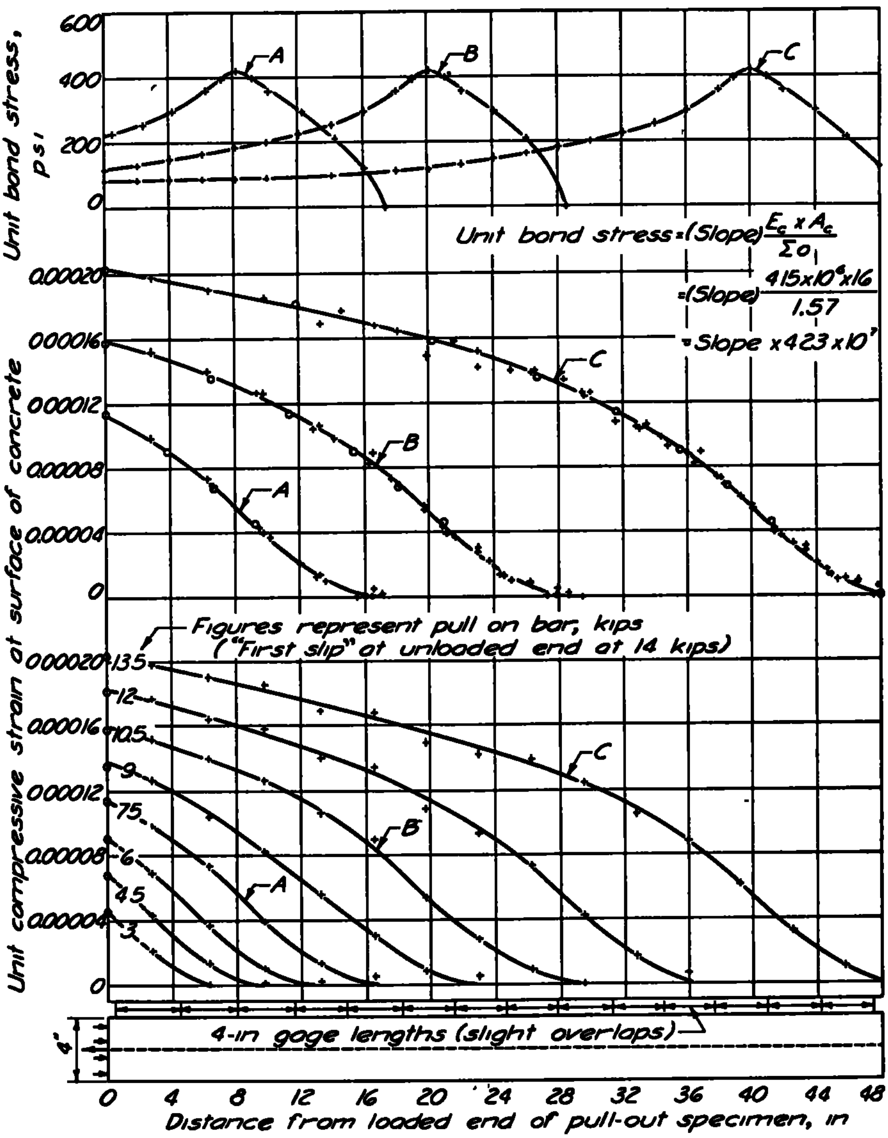

Fig. 9. Actual compressive strain and bond stress distribution for plain-bar 48-in. pull-out specimen

½-in. bar at center of 4- by 4-in. specimen. A_c = cross-sectional area of specimen; E_c = modulus of elasticity of the concrete; Σo = perimeter of bar (superficial area of a unit length).

stress distribution for a pull on the bar of 13,500 lb. If the area under curve C is multiplied by the surface area of a unit length of bar (Σo) the resulting total bond resistance is found to check the 13,500-lb load within less than 100 lb. The areas under curves B and A check their corresponding loads equally well It should be understood that the actual bond distribution (upper curves) would probably be different for different bar surfaces, different strengths of concrete, and other variables affecting bond resistance. Presumably the smoother the bar surface the sharper would be the humps and the lower would be the values of drag resistance.

Figure 9 affords an opportunity for a comparison of the "average unit bond stress" with the "instantaneous" bond stress at the point of maximum intensity. For this specimen at a load of 13,500 lb. the average unit bond stress is approximately 180 p s i while the maximum intensity is seen from the bond stress curve to have been approximately 420 p s i

The curves of Figure 9 indicate that for a plain-bar pull-out specimen

1. Bond resistance is first developed near the loaded end of the bar and only as slight slippages occur are tensions and bond stresses transmitted progressively to portions further from the loaded end

2 The region of maximum intensity of bond stress moves inward from the loaded end as the pull increases Between the loaded end and the region of high bond stress there is more or less uniform frictional or drag resistance of greatly reduced intensity

3 The so-called "first slip" occurs only after the maximum intensity of bond resistance has traveled nearly the full length of the specimen and has approached the unloaded end of the bar. When the maximum total pull on the bar exceeds that at the "first slip" it indicates that there must be a portion of the bar which still offers quite a high resistance to slipping for a time after a slight movement has occurred.

CONCLUSIONS

The results of these tests are offered in support of, and as supplements to, certain indications from previous investigations

1. Contrary to design assumptions long current the bond developed by added length of embedment of bar is not proportional to the added length of the embedment. The shorter the embedment the greater is the average unit bond stress that can be developed by a plain bar.

2. The longer the embedment, the more nearly does the average bond stress along the bar approach the average frictional drag as its limiting value

3. Slippage at the loaded end of a pull-out specimen starts virtually with the first application of load and continues as load is added The amount of slippage at the loaded end accompanying "first slip" at the unloaded end is about proportional to the length of the embedment. After "first slip" occurs, movements of the two ends of the bar are about equal

4 For smooth surfaced or polished bars such as cold drawn wire, or cold rolled material, the ultimate bond stress coincides with that at "first slip".

5 The development of bond resistance is progressive along the bar, a maximum intensity being attained and passed for each section successively as increments of load on the bar increase

6. For a short embedment, the total resistance or pull developed prior to "first slip" is largely a function of the value of the peak or maximum intensity that can be developed.

7. After any point along an embedded plain bar has attained and passed its maximum intensity of resistance, this resistance is reduced more or less gradu-

ally to a nearly constant intensity approaching that of the residual drag.

ACKNOWLEDGMENTS

The authors are indebted to the Carnegie-Illinois Steel Corporation (Mr G A. Price and Mr P M Guba, Managers of Sales) for the heat treated alloy steel bars which were necessary for the investigation Mr W A Jennings of the Economy Form Corporation of Des Moines supplied the steel forms which were used for the specimens

The work reported herein has been conducted as one phase of a joint cooperative program between the Highway Research Board, R. W Crum, Director, and the Iowa Engineering Experiment Station, Dean T. R. Agg, Director.

REFERENCES

In this chapter reference is made to Chapters VIII, IX and XI all of which are listed in the FOREWORD These chapters all contain references to other published literature on the subject Bulletin No. 147 Iowa Engineering Experiment Station, "Bond Between Concrete and Steel" by the authors of this paper contains an appendix consisting of a selected bibliography of most of the important work on bond which has been published up to this time That appendix probably constitutes the most complete listing of the literature which is now available