CHAPTER IX. THE DISTRIBUTION OF STRAIN IN THE CONCRETE OF PULLOUT SPECIMENS

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SYNOPSIS

This report presents the evidence secured on pullout strains, for two strengths of concrete (nominally 3000 and 5000 lb. per sq. in.), and for three diameters of plain and deformed rail-steel bars (⅜, ⅝, and ¾ in. round). For the plain bar pullout specimens, lengths of embedment varied from 3 to 24 in. For the deformed bar pullout specimens there were three minimum depths of concrete cover. In most respects the plotted data are strikingly consistent. Because strains were measured only at concrete surfaces it is impossible to show quantitatively just what was happening near the adjacent surfaces of steel and concrete, and the tests, at best, leave some questions yet to be answered relative to the specific distribution of bond stresses along an embedded bar. The evidence does demonstrate and emphasize the progressive nature of bond resistance and also the similarity of action for plain and deformed bars during the earlier stages of loading.

In the Series of 1937, surface strains in the concrete were measured with Martens' mirrors mounted on slightly overlapping 4-in. gage lengths on all of the beams and pullout specimens and a few of these data appear in reference (1)[1] p. 177–179, and especially Figures 34–39, inclusive. The strain data were so voluminous that it seemed best to defer attempts at detailed analysis for separate chapters. This chapter includes the data and discussion which relate to the pullout bond tests.

The outline of Figure 1 is repeated from Chapter VIII (1) but in all other respects access to and familiarity with the preceding paper (1) is assumed.

While with the Martens' mirrors unit deformations were measured to 0.0000114, corresponding to stresses of about 46 and 56 lb. per sq. in., respectively, in the two strengths of concrete or 350 lb. per sq. in. in steel (1, p. 158 and Fig. 19) one must realize that these strains were all measured at external surfaces of the concrete and the data secured bear only indirectly upon the situation existing at the contact surfaces of concrete and steel. In this respect these results differ from limited data secured by Glanville (2, p. 9) in which his pullout bars were hollow rods along the inside surface of which strains were measured.

In these tests the stresses applied directly to the steel are transmitted by bond to the concrete and by shear through the concrete to the outside surface of the specimens where the compressive strains were measured. The mirrors were mounted on two opposite faces of the specimen. The concrete of the entire cross section of a pullout specimen was in more or less uniform compression except for some of the deformed bar specimens in which the bar was placed off center in order to vary the depth of cover. For these non-symmetrical specimens there was variable stress in the concrete, the variations depending upon the amount of eccentricity of the bar.

Even for the symmetrical pullout specimens, there was bound to be shearing deformation between bar and surface of a member which would produce a coning effect or strain lag between where the concrete picked up its load and the surface where the strain was measured. There was a similar but unsymmetrical coning effect present in the specimens with variable cover.

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[1] Numbers in parentheses refer to list of references at end.

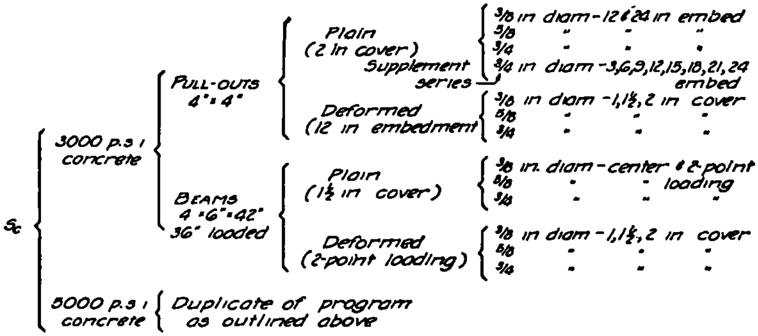
It is the purpose in this chapter to scrutinize the measurements of surface pullout strains, to determine, if possible, how these were influenced by the recognized variables such as strength of concrete, length of embedment, depth of cover, and type and size of bar

PULLOUT STRAINS

In considering and comparing the pullout strains measured at the surfaces of the concrete, the following simplifying assumptions are made

(a) The compressive stress in the concrete is within the proportional limit and the unit stress is therefore the product of Young's modulus and the measured unit strain

(b) For all specimens in which the bar is concentric with the specimen, the compressive stress is distributed uniformly over each cross section and the total stress in the concrete at a cross section is the product of the net cross-sectional area of the concrete, Young's modulus, and the observed unit strain This implies among other things, that the "coning effect" previously mentioned is disregarded [2]



Note - Also 1-full-length beam for each strength of concrete, 4×6×78 (overall), clear span 72" and 2-4"×4×8" prisms and 3-3×6" cylinders, compressive controls for each batch

Figure 1. Outline of Program for Entire 1937 Series of Bond Tests, Indicating Types of Specimens and Variables Studied

The plotted strains represent only the average for the 4-in. gage lengths over which they were measured. The average unit strain in the concrete at the bottom of the specimen (the face of the concrete at the loaded end) while not measurable directly, must be that corresponding to the total load on the bar and was computed in accordance with the preceding assumptions.

Figure 2 is an illustrative diagram similar to those shown by Dunagan and Ernst (3, p. 99, Fig 6) and shows the progressive action of bond distribution at successive stages of a test. The ordinates of (a) and (c), Figure 2 (at right angles to the axis of the specimen) may be thought of as unit strains, or stresses, or as total loads on the bar at corresponding cross sections In viewing curves such as (a) and (c), Figure 2 one should recognize and keep in mind that

(a) The bond stress at any point is represented by the inclination of the curve (with the axis of the specimen) at that point. The steeper the curve the higher is the bond stress

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[2] The effect of coning is to produce nonuniform strain (and stress) over the cross section The total stress over the cross section must still equal the total pull on the bar at that cross section, however

(b) Regions of constant slope are regions of uniform bond stress

(c) There are no bond stresses where the curves are parallel to the axis of the specimen (zero slope)

The truth of these statements is recognized when one realizes that bond stress can be present only over a region of changing stress in the steel or the concrete. Bond is what makes stress-transfer possible

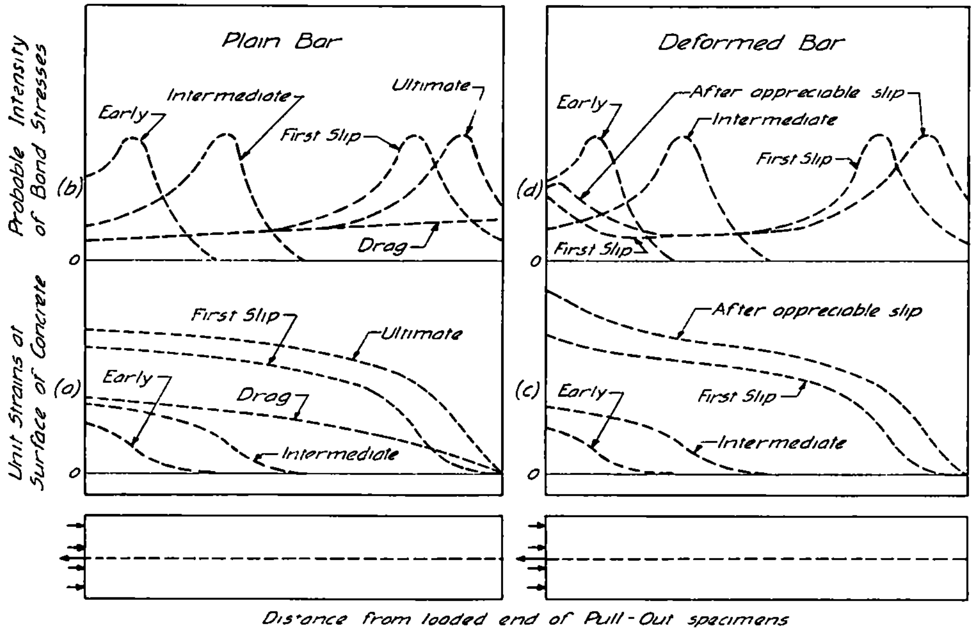

Figure 2. Qualitative Portrayal of What Presumably Happens during a Pull-Out Test for Bond. (a) and (c)—Compressive unit strains at the surfaces of the concrete at successive points along the specimen. (The same curves are representative of concrete stress and of the total compression in the concrete or tension in the steel at a given cross-section) (b) and (d)—Intensities of bond stress between the concrete and the steel at successive points along the bar

The indications of (a) and (c), Figure 2 are plotted in (b) and (d), Figure 2 as bond stresses in accordance with the three statements above In order properly to interpret the data which are to follow, it is essential that one master the relationship of curves (b) and (d) to curves 2(a) and 2(c) and be able to recognize the trends of the former when viewing the latter.

A study of these figures makes it apparent that for a plain bar pullout specimen

(a) Bond resistance is first developed near the loaded end only and no stress is transmitted to the portion of the bar further along the specimen

(b) 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 a more or less uniform frictional or drag resistance of greatly reduced intensity

(c) 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[3]

[3] When the maximum total pull on the bar exceeds that at the "first slip" it indicates that

(d) After appreciable slippage, the primary bond resistance is gone and the bar offers throughout its entire length a more or less uniform frictional or drag resistance amounting altogether to perhaps half the maximum load carried

For a deformed bar pullout specimen of moderate length the sequence will be the same as for the plain-bar specimen until after "first slip" has occurred, since there must be an appreciable slippage before lug action starts After "first slip" has occurred the lugs near the loaded end are finally brought into bearing and high ultimate bond resistances are developed providing the encasing block of concrete is not first split by the wedging action of the lugs

For longer embedments the sequence may be expected to be that shown in (c) and (d), Figure 2 Lugs near the loaded end may become effective before "first slip" occurs at the unloaded end and the total resistance even at, or prior to, initial slip may be made up of lug action near the loaded end, friction or drag resistance in the intermediate region where the slippage has been insufficient to bring the lugs into bearing, and of more or less pure[4] bond resistance in the vicinity of the unloaded end of the specimen

All of the deformed bar pullout specimens of these tests were 12 in long and that length was evidently insufficient to develop enough lug action to show up clearly in the strain observations although the load at "first slip" was considerably above that for the plain-bar specimens The relatively long gage lengths (4 in) for the 12-in length of specimens mitigated against securing strain data which would show clearly the differential behavior along the specimens

An effort was made to express the strain data in terms of bond stresses but slight variations in the slopes of the strain curves were so greatly magnified when translated into bond stresses that it was decided that the strain diagrams would provide the better basis for comparisons

EFFECT OF STRENGTH OF CONCRETE ON PULLOUT STRAIN DIAGRAMS

Figures 3 and 4 compare strain diagrams for 12- and 24-in plain bar pullout specimens of the three bar sizes and the two strengths of mixture Figure 5 supplies similar comparisons for 12-in deformed bar pullout specimens

Companion specimens for the two concrete mixtures show that the 5000 lb per sq in mixture behaves as does the 3000 lb per sq in mixture but that a given tension in the bar is developed in a shorter length of embedment which is in agreement with the fact that the stronger mixtures do develop somewhat greater bond resistances (even though this increase is not proportional to the increase in compressive strength) The stronger concrete also shows its added stiffness (larger value for Young's modulus) by the lower unit strain corresponding to the load on a given size of bar

At the bottom of Figures 3 and 4 are appended duplicate 12-in and 24-in specimens from the "length of embedment" series There are differences in the loads at "first slip" and at ultimate but almost perfect agreement at all of the earlier increments of load

EFFECT OF SIZE OF BAR ON PULLOUT STRAIN DIAGRAMS[5]

There is great similarity between the strain curves for the bars of different

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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

[4] Whatever this may be, see later discussion on nature of bond

[5] Glanville (2, p 14) contends that the average unit bond resistance depends upon length of embedment and is not influenced by diameter of bar Thus according to Glanville it is the length of embedment rather than the

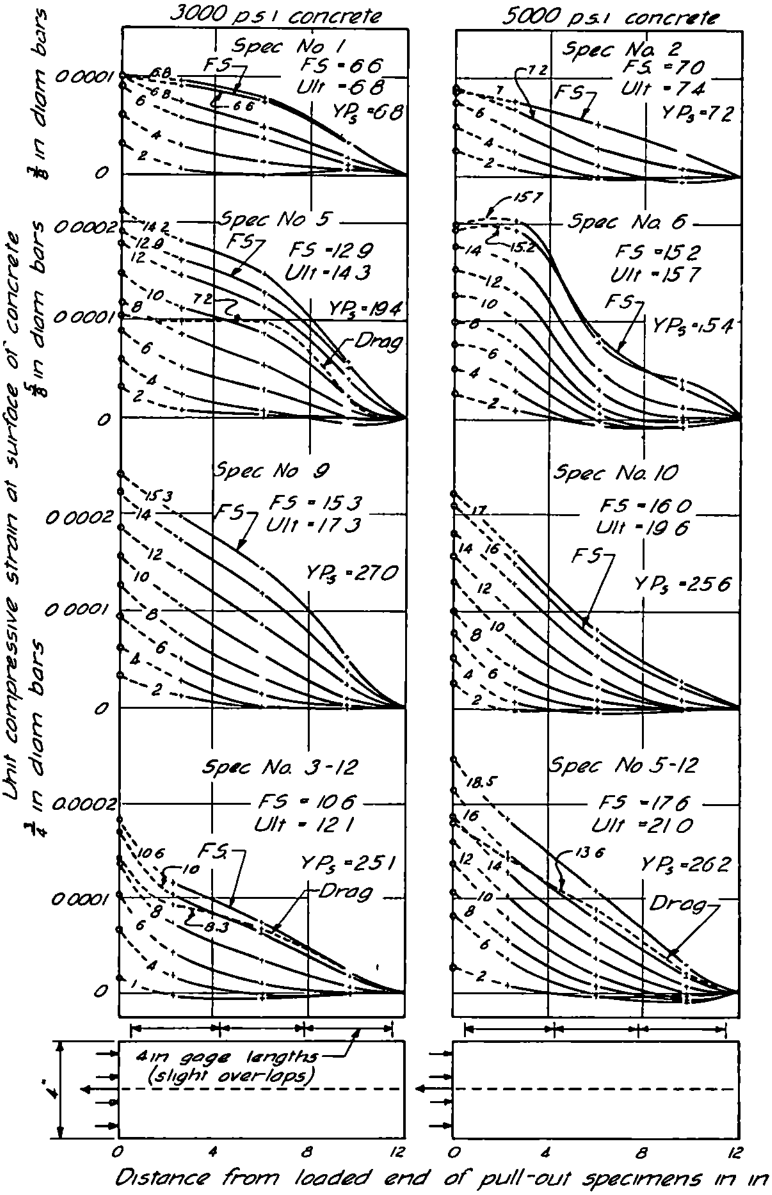

Figure 3. Plain-Bar 12-in. Pull-Out Specimens. Center of bar at center of 4- by 4-in. specimen in every case. Figures on or near curves are total loads on bar in kips. F.S = First Slip. Ult. = Ultimate Load. Y P$_s$ = Load required to produce yield point stress in the steel. Drag = Load after about 0 08 in total slip at unloaded end of bar.

L/D (length-diameter) ratio which is important For bars of equal diameters the two criteria are identical Glanville's analysis is based on the condition which exists after a "general slippage" has occurred From the standpoint of the designer, conditions after the so-called "first slip" (general slippage) are not those of primary importance sizes until the yield point of the steel is reached

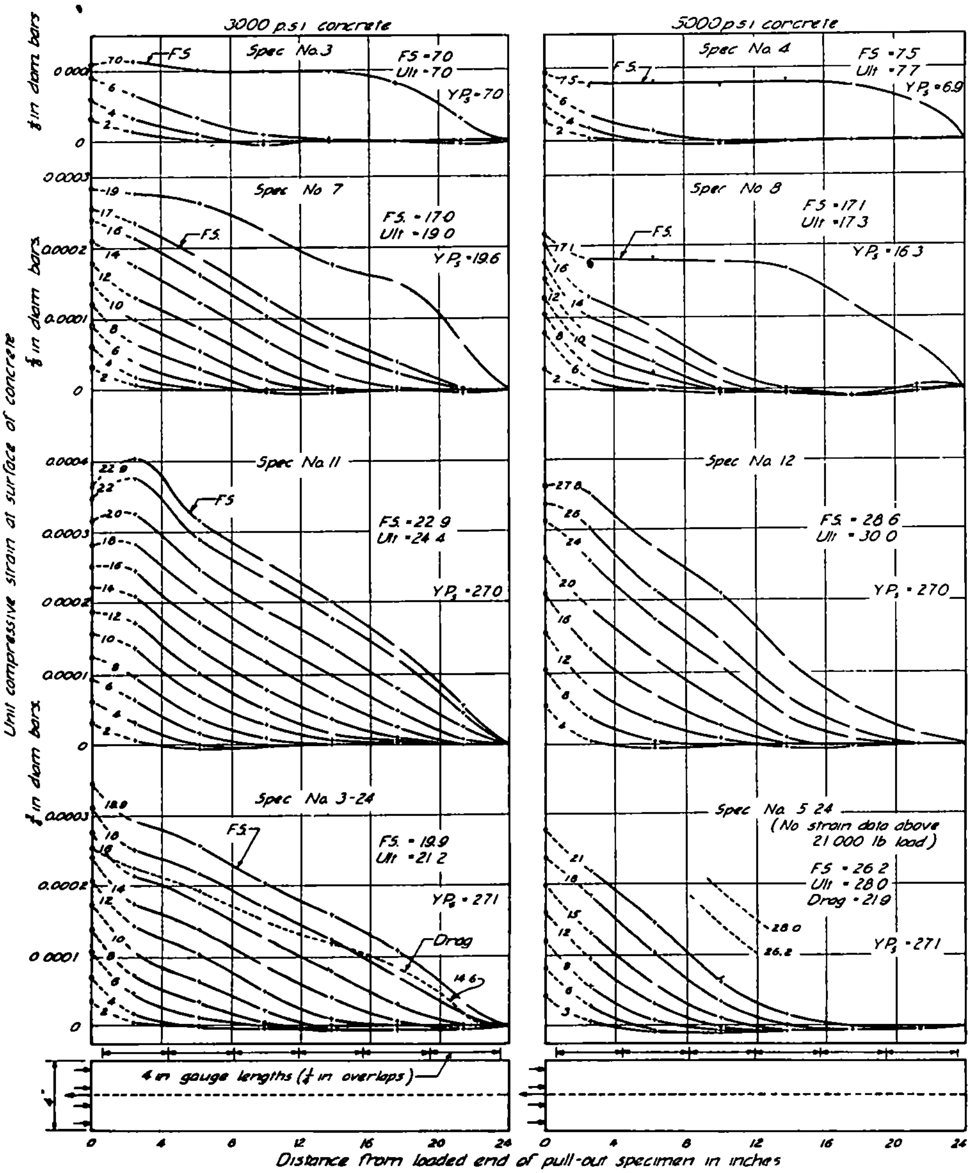

Figure 4. Plain-Bar 24-in. Pull-Out Specimens. Center of bar at center of 4- by 4-in. specimen in every case Figures on or near curves are total loads on bar in kips. F S = First Slip Ult. = Ultimate Load Y.P $_s$ = Load required to produce yield point stress in the steel Drag = Load after about 0.08-in total slip at unloaded end of bar.

For the 12-in embedment the yield point of the steel was reached prior to "first slip" for all the ⅜-in bars and for the ⅝-in plain bar embedded in the stronger concrete For the 24-in embedments (plain bars only) "first slip" occurred at or near the yield point of the steel for the stronger concrete for all three sizes of bar but was well below the yield point for both the ⅝- and ¾-in bars embedded in the 3000 lb per sq in concrete For the deformed bars (12-in embedment only) the "first slip" occurred for stresses below the yield point for all except the ⅝-in bars mentioned before and shown on Figure 5.

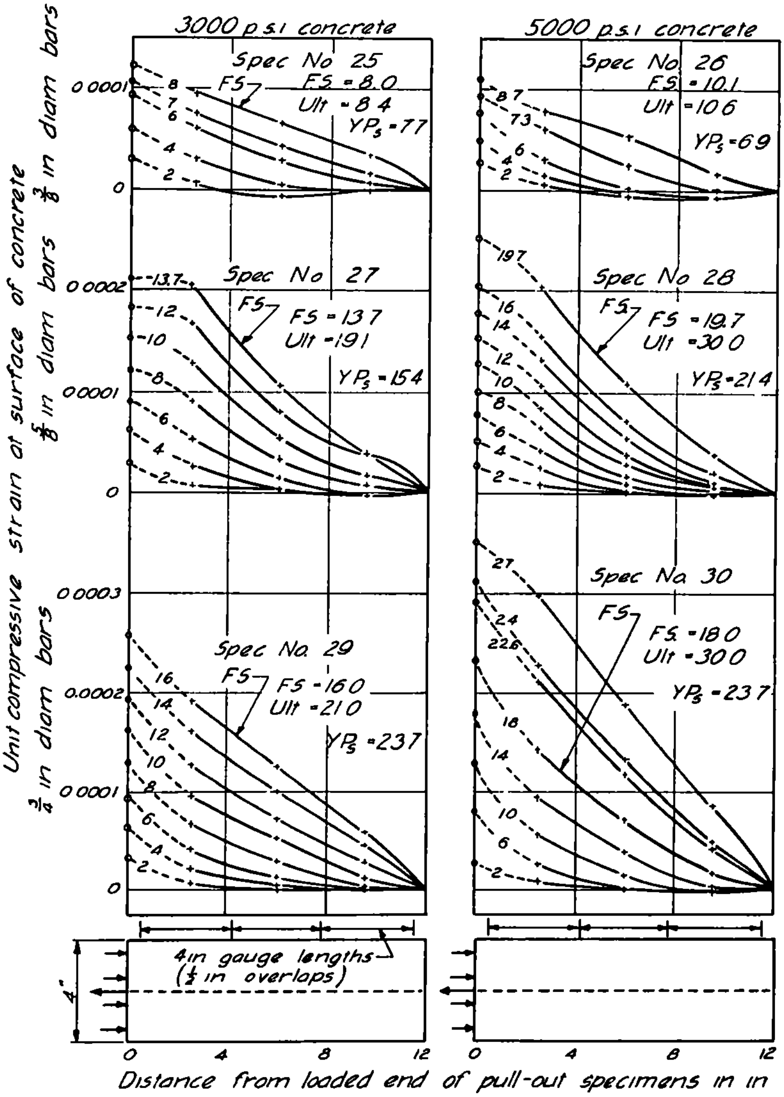

Figure 5. Deformed-Bar 12-in. Pull-Out Specimens Center of bar at center of 4- by 4-in. specimen in every case. Figures on or near curves are total loads on bar in kips. F.S. = First Slip. Ult. = Ultimate Load. Y P $_s$ = Load required to produce yield point stress in the steel

STRAIN DIAGRAMS FOR PLAIN VS THOSE FOR DEFORMED BARS

Comparisons of bars of corresponding sizes and of concrete strengths can be made between Figure 3 and Figure 5 for equal (12-in) embedments These show that for load increments below "first slip," the plain and deformed bars

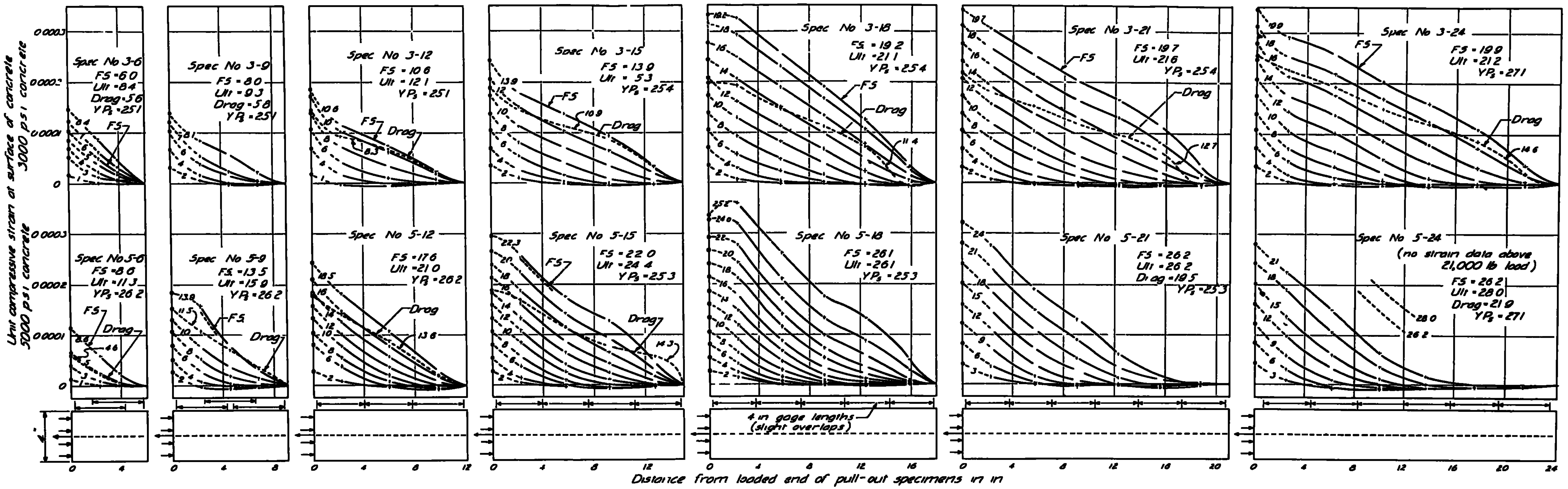

Figure 6 Plain Bar Pull-Out Specimens, Variable, Length of Embedment, All Bars ¾ in Diam Center of bar at center of 4- by 4-in specimens in every case Figures on or near curves are total loads on bar in kips F S = First Slip Ult = Ultimate Load. Y P$_s$ = Load required to produce yield point stress in the steel. Drag = Load after about 0 08-in total slip at unloaded end of bar.

function alike It is noticeable, however, that "first slip" occurs at a higher load for the deformed bar in every case This would seem to indicate that in a 12-in pullout specimen the deformation lugs of the deformed bar begin to function near the loaded end prior to "first slip" at the unloaded end[6] Longer embedments would be useful for checking up further on this point, but unfortunately no deformed bar specimens were cast with other than 12-in embedments.

The effect of lug action is pronounced in many of the deformed bar curves toward the latter stages of the test, shortly before splitting occurred at the highest load reached, as it did in most instances In several instances the deformed bar strains were not secured for loads very far above those at "first slip" for if any jerking occurred during the test it was likely to have disarranged some of the Martens' mirrors sufficiently to make the readings unreliable[7]

PULLOUT STRAIN CURVES FOR VARIABLE LENGTHS OF EMBEDMENT OF PLAIN BARS

Figure 6 shows the strain diagrams for both strengths of concrete for plain bar embedments varying from 6 to 24 in at intervals of 3 in No strains were secured for the 3-in embedments but the data on these are recorded in Table 2

The uniformity of these data are striking Up to the vicinity of first slip or yield point the curves for corresponding load increments of a mixture can virtually be superimposed, one on another Such indications would seem to establish the uniformity of the progressive action and the repeatability of strain measurements

The $\frac{3}{8}$-in plain bars with 24-in. embedment having an L/D ratio of 64 slipped initially at the yield point of the steel at virtually the same load (half the bond stress) as did the same size of bar at 12-in embedment First slip, ultimate load and yield point were at virtually identical loads The specimens were No 1 and No 2 for 12-in embedment (Fig 3), and No 3 and No 4 for 24-in embedment (Fig 4)

Reference to Figure 4 shows that stress had been developed at the surface of the concrete over only about half the length of the 24-in specimens at the last increment of load applied prior to first slip After first slip (and yield point) it is apparent that failure would probably have traveled progressively over almost any length of embedment The question not answered by Figure 4 is whether or not a yield point stress is prerequisite to such a continuing progressive slippage

Pullout specimen No 7 ($\frac{5}{8}$-in plain bar at 24-in embedment, see Fig 4) supplies evidence that a yield point stress is not prerequisite to continuing progressive slippage For specimen No 7 first slip occurred at a load of 17,000 lb and the ultimate load was 19,000 lb which are both slightly below the yield point of the steel (as determined by test of a tensile specimen from the same bar) The authors are planning to conduct additional tests upon some very high yield point steel to check more fully on this point

In no case were yield point stresses approached in the $\frac{3}{4}$-in embedded in 3000 lb concrete bars although the evidence shows that there was no gain in total resistance developed for embedments over 18 in (an L/D of 24 or less). This was shown clearly in (1, Fig 28, p. 171), and also in (4, Fig. 2, p. 5)

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[6] The differences in load at first slip could, of course, be due to differences in surface texture of the deformed bar rather than to lug action The lug action seems to the authors to be the more likely explanation, and is given tentative acceptance, with further study pending

[7] Jarring was not restricted to the deformed bar specimens, for it was also not possible to secure complete data for some of the plain bar specimens

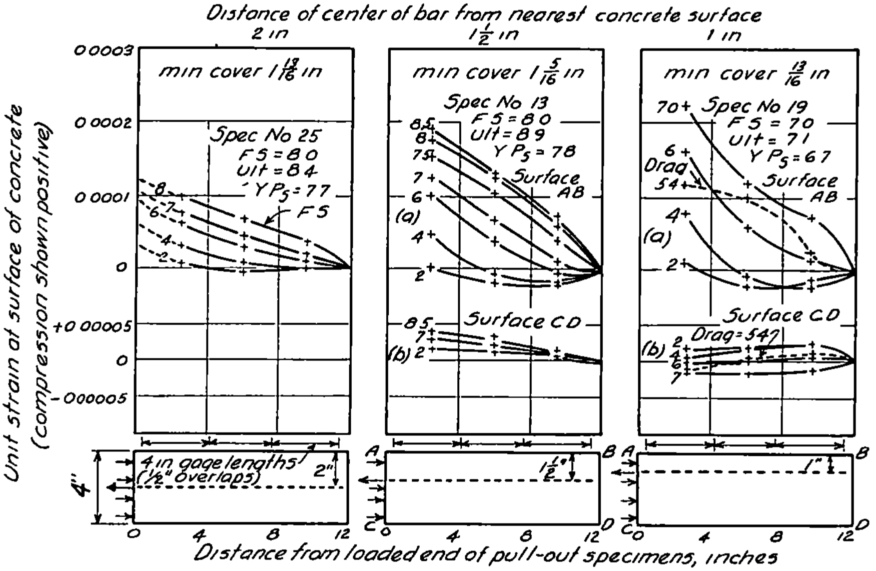

Figure 7 (a). Effect of Depth of Concrete Cover over ⅜-in Deformed Bars. 3000 lb. per sq. in. concrete. (Cover varied by placing bar eccentrically in the 4- by 4-in. concrete block) Figures on or near curves are total loads on bar in kips. F S = First Slip. Ult. = Ultimate Load. $Y.P._s$ = Load required to produce yield point stress in the steel. Drag = Load after about 0 08-in. total slip at unloaded end of bar.

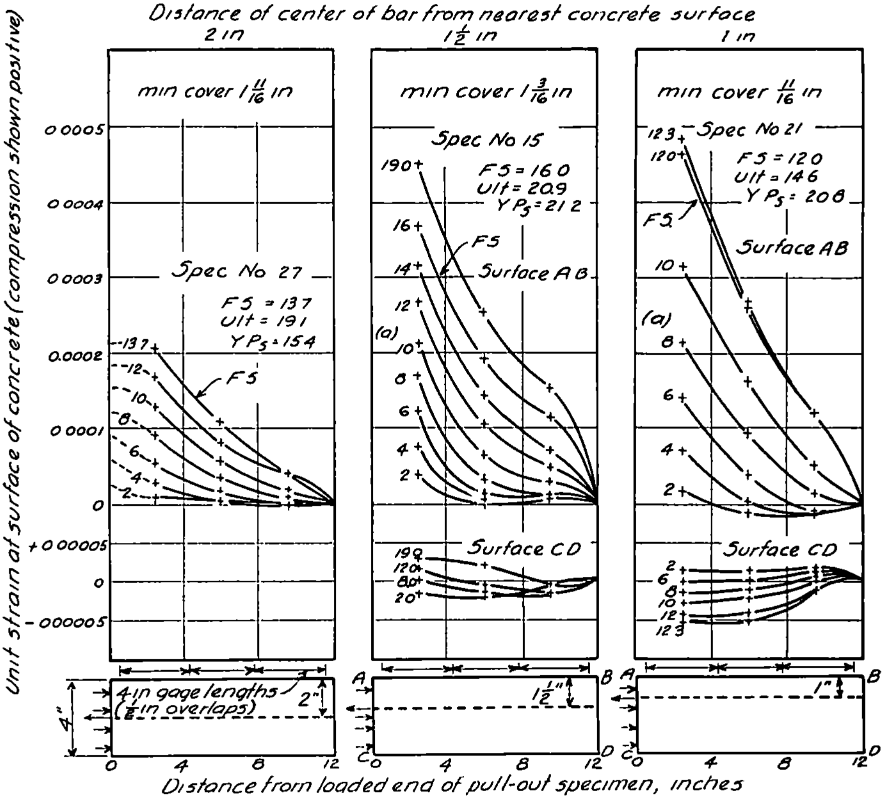

Figure 7 (b). Effect of Depth of Concrete Cover over ⅝-in Deformed Bars. 3000 lb. per sq. in. concrete. (Cover varied by placing bar eccentrically in the 4- by 4-in concrete block) Figures on or near curves are total loads on bar in kips. F.S. = First Slip. Ult. = Ultimate Load. $Y.P._s$ = Load required to produce yield point stress in the steel. Drag = Load after about 0.08 in. total slip at unloaded end of bar.

DEPTH OF CONCRETE COVER OVER DEFORMED BARS IN PULLOUT SPECIMENS

Figures 7a-b-c and 8a-b-c show the depth of cover vs strain curves for the 3000 and 5000 lb per sq in mixtures, respectively

The purpose in conducting these tests was to secure some indication of the relative effectiveness of added depth of concrete cover in preventing or delaying the splitting or spalling that usually occurs when a deformed bar specimen finally fails at a load well below what it would have developed if splitting had not occurred

As shown by Figures 7 and 8 and also by (1, Fig 33, p 176), added depth of cover does materially aid against splitting especially for the stronger concrete, but it would rarely be an economical or practicable device for use in reinforced concrete members

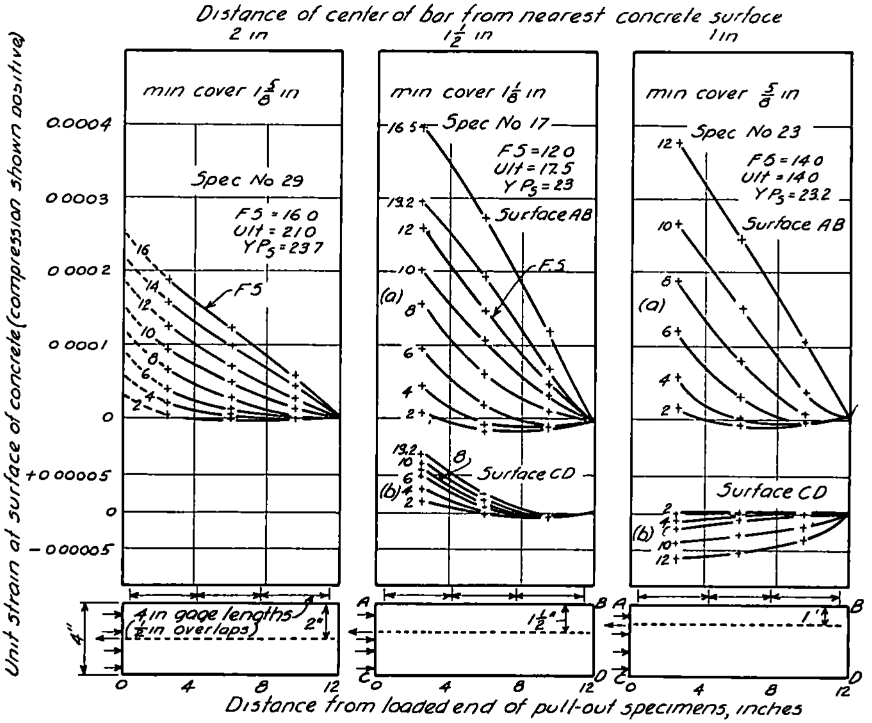

Figure 7 (c). Effect of Depth of Concrete Cover over $\frac{3}{4}$-in. Deformed Bars. 3000 lb per sq in. concrete (Cover varied by placing bar eccentrically in the 4- by 4-in concrete block.) Figures on or near curves are total loads on bar in kips F.S = First slip Ult. = Ultimate Load. Y P.$_s$ = Load required to produce yield point stress in the steel. Drag = Load after about 0.08-in. total slip at unloaded end of bar.

All pullout specimens were 4 in by 4 in square in cross section The simplest way to vary the depth of cover was to set the bars closer to one face of the specimen The distances from centers of bars to nearest faces of specimens and also the net cover on that face are tabulated above the diagrams Obviously the minimum nominal covers of $1\frac{1}{2}$ in and 1 in were accompanied by nominal covers of $2\frac{1}{2}$ and 3 in from the opposite face This off-center placement of the bars for $1\frac{1}{2}$-in and 1-in covers produced eccentricity of loading and the strain

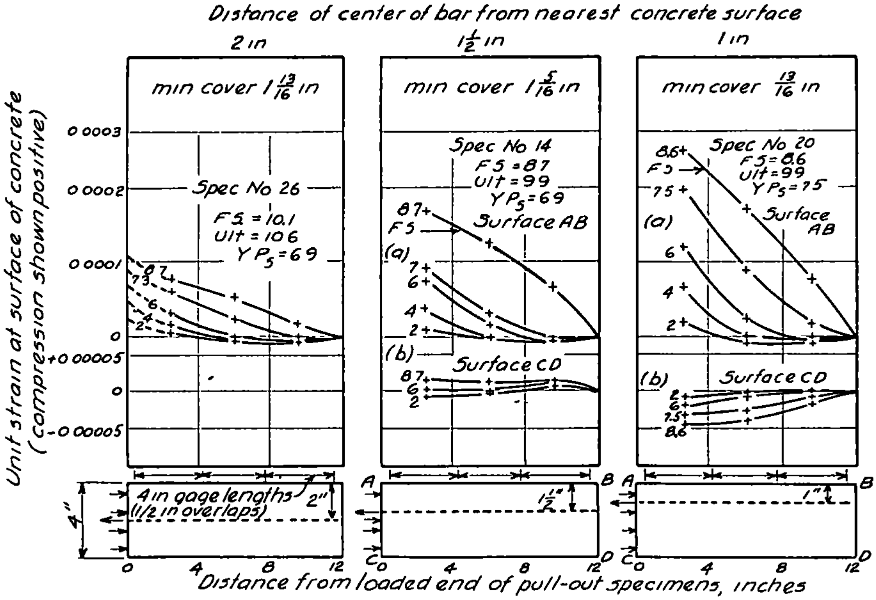

Figure 8 (a). **Effect of Depth of Concrete Cover over ⅜-in. Deformed Bars. 5000 lb. per sq. in. concrete. (Cover varied by placing bar eccentrically in the 4- by 4-in. concrete block.) Figures on or near curves are total loads on bar in kips F.S. = First Slip. Ult. = Ultimate Load. Y.P.$_s$ = Load required to produce yield point stress in the steel.**

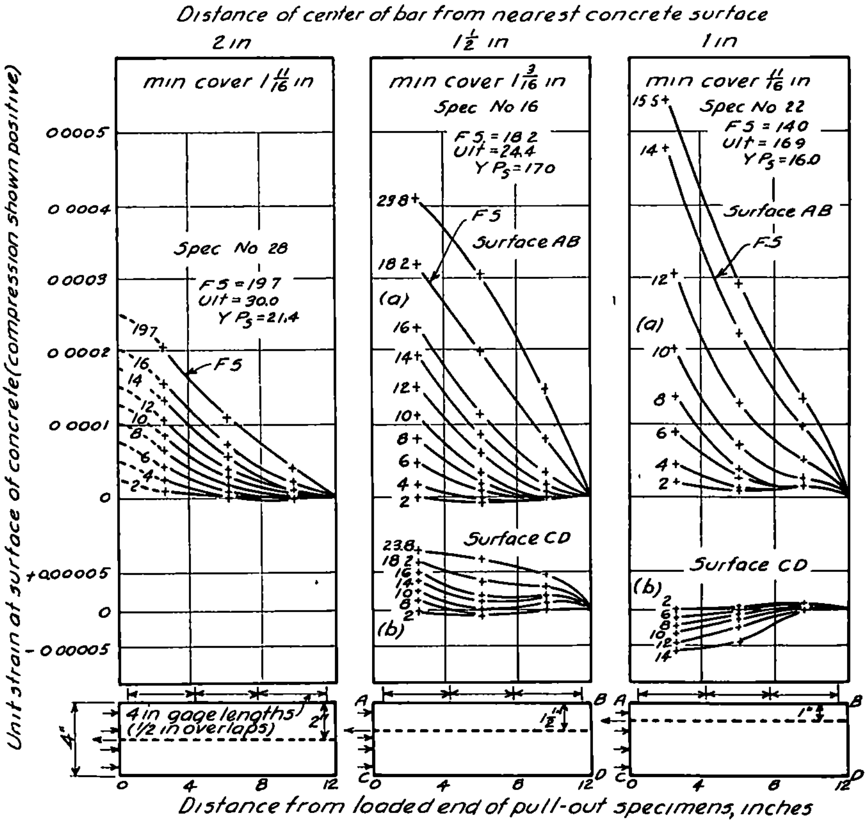

Figure 8 (b). **Effect of Depth of Concrete Cover over ⅝-in. Deformed Bars. 5000 lb. per sq. in. concrete. (Cover varied by placing bar eccentrically in the 4- by 4-in. concrete block.) Figures on or near curves are total loads on bar in kips. F.S. = First Slip. Ult. = Ultimate Load. Y.P.$_s$ = Load required to produce yield point stress in the steel.**

curves show the strains observed on both faces. For the greater eccentricities the diagrams show tension on the farther face from the bar, as would be expected after a simple calculation.

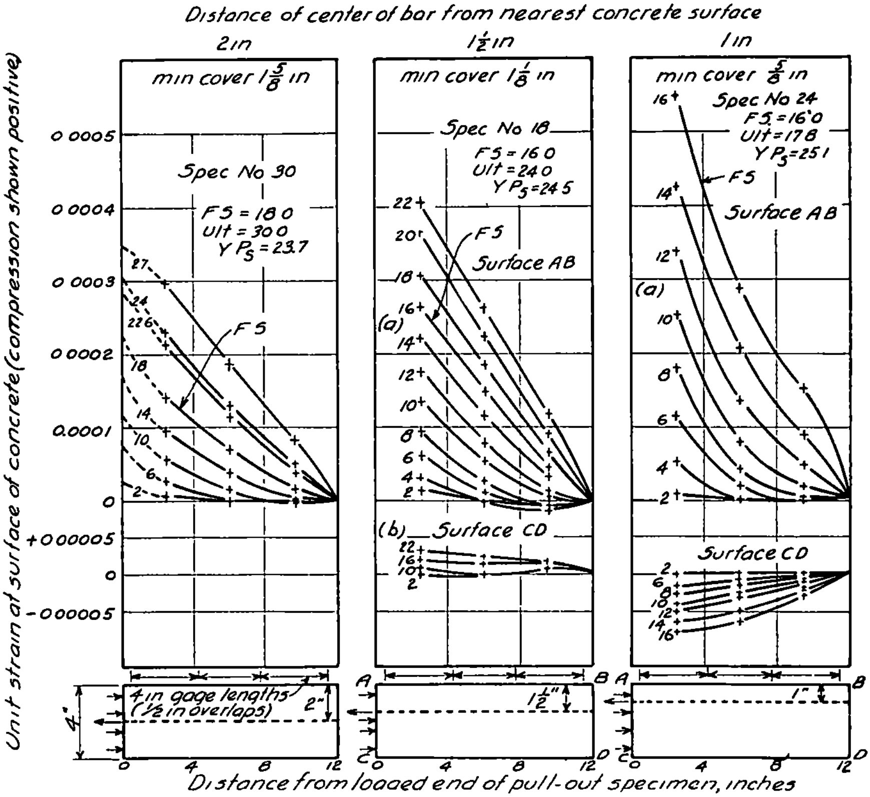

Figure 8 (c). Effect of Depth of Concrete Cover over ¾-in. Deformed Bars. 5000 lb. per sq. in. concrete. (Cover varied by placing bar eccentrically in the 4- by 4-in. concrete block.) Figures on or near curves are total loads on bar in kips. F.S. = First Slip Ult. = Ultimate Load. Y P $_s$ = Load required to produce yield point stress in the steel.

GENERAL DISCUSSION AND RESUME OF BOND ACTION IN A PULLOUT SPECIMEN

For a plain bar subjected to increasing pull, the sequence of events is about as follows.

Slipping starts at the loaded end at the first increment of applied load. Resistance to slippage (bond stress) develops along the bar for as far as is necessary to produce equilibrium. Within this length the intensity of bond resistance is not uniform but builds up to a maximum a short distance within the specimen and beyond this the stress gradually reduces to zero. At the point where the loaded bar enters the concrete, the bond stress was early built up to its maximum intensity and soon passed it.

As additional load is applied progressive slippage occurs and the location of maximum bond stress intensity moves progressively along toward the unloaded end of the bar. The total resistance continues to increase primarily because the portion of the bar which has passed its maximum resistance, does not let go entirely but continues to offer a residual or drag resistance which acts concurrently with the "true bond" resistance in the region of maximum bond stress intensity

With increasing load, bond stress finally is transmitted to the unloaded end of the bar and it is then that slippage has become general and "first slip" occurs At this stage the maximum intensity is still some distance away from the unloaded end and the ultimate resistance developed may be appreciably above that at "first slip"[8]

For an embedded deformed bar, the action is exactly the same until there has been sufficient slippage near the loaded end of the bar to bring some of the lugs into bearing At this stage the lugs offer appreciable and increasing resistance up to the point of splitting the concrete (if the bar does not fail first)

For short embedments such as the 8 in. used by Abrams (5, Fig 3, p 18) it is to be expected that "first slip" will occur before the lugs come into bearing and this expectation is in accord with Abrams' evidence that "first slip" occurred for deformed bars at the same load as for plain bars of equal size For the longer embedments, of these tests, there was evidently enough lug action to increase the resistance of the deformed bars at "first slip" A number of other investigators mentioned in references (1) and (4) have noted similar indications

After "first slip" the lug effect becomes increasingly important as is shown by the strain diagrams for deformed bars It is unfortunate that the lugs of deformed bars do not come into good bearing until after most reinforced concrete members have suffered serious damage

THE NATURE OF THE SLIDING RESISTANCE KNOWN AS BOND

Bond is mainly a manifestation of frictional resistance and, when the nature of friction is fully understood, the explanation can probably be carried over in a large measure to bond Abrams' tests with polished bars, both straight and with wedging and nonwedging tapers (5, p 50) and tests, by one of the authors, with drawn wire and greased bars (6, Table 1, p 90) indicate that most of the useful resistance developed is from the mechanical drag of the small surface irregularities along the bar The adhesive resistance probably reaches rather a high instantaneous value but it lets go so completely that it must function without much aid from other contact areas

Abrams (5, Fig 5, p 29 and Fig 18, p 52) estimates that the ordinary rolled plain bar develops its maximum resistance after a movement of about 0 01 in whereas the resistance for a polished bar falls off rapidly after a movement of 0 001 in or less The gradual building up and gradual decrease of resistance is important because it is during that entire phase that other contact surfaces can contribute their quotas to the total resistance offered

That the significant part of bond is essentially frictional rather than adhesive seems to be indicated by Glanville's pullout tests with aluminous cement (2, Fig 17, p 26) for which the bond resistance does not decrease with increased slippage as it does for portland cement This difference is explained as probably due to the relatively high shrinkage of the alumina cement which causes it to grip the bar firmly with a high normal pressure that maintains the frictional grip in spite of the drawing away from

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[8] As was shown in (1, Fig 30, p 174) and in (4, Fig 5, p 8) the increment of resistance between "first slip" and ultimate is dependent primarily upon the intensity of the stress in the steel Since for short lengths of embedment the steel stress intensity will be low at "first slip," the increment of load between the "first slip" and the ultimate will decrease, in general, as the length of embedment of a given bar increases

TABLE 1

Test Results for Pull-outs of Main Series

3000 lb per sq in concrete								5000 lb. per sq in. concrete							
Spec No	Bar Size and Type	Properties of Concrete and Steel		Cover * Nom and Min, in	Length Embedment, in	First Slip Ultimate		Spec. No	Bar Size and Type	Properties of Concrete and Steel		Cover * Nom and Min, in	Length Embedment, in.	First Slip Ultimate	
		Yield Point of Bar, lb and lb per sq in	Compr Str of Conc.—Mod Elast × 10⁻⁶, lb per sq in			Pull on Bar, lb	Bond Stress, lb per sq in			Yield Point of Bar, lb and lb per sq in	Compr Str of Conc — Mod Elast × 10⁻⁶, lb per sq in			Pull on Bar, lb.	Bond Stress, lb per sq in
Col	a	b	c	d	e	f	g	Col	a	b	c	d	e	f	g
1	⅜ Plain	6800 61500	3235 4 09	2 1 81	12	6660 6810	471 481	2	⅜ Plain	7230 65400	5450 4 96	2 1 81	12	7000 7410	495 524
3	⅜ Plain	6960 62900	3235 4 09	2 1 81	24	7035 7035	249 249	4	⅜ Plain	6920 62600	5450 4 96	2 1 81	24	7540 7705	267 273
5	⅝ Plain	19400 63200	3360 4 22	2 1 69	12	12910 14330	548 608	6	⅝ Plain	15410 50200	5020 4 90	2 1 69	12	15200 15700	645 665
7	⅝ Plain	19560 63700	3360 4 22	2 1 69	24	17000 19000	361 402	8	⅝ Plain	16330 53200	5020 4 90	2 1 69	24	17100 17300	363 367
9	¾ Plain	27000 61100	3170 4 05	2 1 63	12	15300 17270	541 610	10	¾ Plain	25630 57900	5100 4 87	2 1 63	12	16000 19630	566 695
11	¾ Plain	27000 61100	3170 4 05	2 1 63	24	22920 24420	405 432	12	¾ Plain	27000 61100	5100 4 87	2 1 63	24	28640 30000	507 530
19	⅜ Def	6720 60800	3130 3 95	1 0 81	12	7040 7100	498 502	20	⅜ Def	7540 68200	4892 4 67	1 0 81	12	8550 9925	604 702
13	⅜ Def	7810 70600	3350 4 20	1½ 1 31	12	8000 8915	566 630	14	⅜ Def	6940 62800	5435 4 79	1½ 1 31	12	8740 9905	618 701
25	⅜ Def	7660 69300	3180 4 10	2 1 81	12	8000 8430	566 595	26	⅜ Def	6930 62700	5332 4 92	2 1 81	12	10130 10630	717 753
21	⅝ Def	20780 67700	3085 3 88	1 0 69	12	12000 14570	509 617	22	⅝ Def	15960 52000	4960 4 86	1 0 69	12	14000 16880	594 715
15	⅝ Def	21170 68900	3350 4 20	1½ 1 19	12	16000 20900	679 885	16	⅝ Def	16950 55200	5435 4 79	1½ 1 19	12	18160 24380	770 1032
27	⅝ Def	15350 50000	3180 4 10	2 1 69	12	13660 19100	580 809	28	⅝ Def	21370 69600	5332 4 92	2 1 69	12	19740 30000	838 1270
23	¾ Def	23190 52400	3085 3 88	1 0 63	12	14000 14000	495 495	24	¾ Def	25110 56800	4960 4 86	1 0 63	12	16000 17780	566 628
17	¾ Def	23000 52100	3130 3 95	1½ 1 13	12	12000 17480	424 618	18	¾ Def	24450 55300	4892 4 67	1½ 1 13	12	16000 24000	566 849
29	¾ Def	23660 53600	3040 3 99	2 1 63	12	16000 21000	566 742	30	¾ Def	23660 53600	5438 4 93	2 1 63	12	18000 30000	636 1060

* Nominal. Center of bar to nearest surface of concrete
Minimum. Surface of bar to nearest surface of concrete

TABLE 2

Test Results for Supplementary Pull-out Series

All bars in centers of 4 in x 4 in specimens
All bars plain, ¾ in diameter

Spec No	Length of Embedment, in	Load on Bar in Lb (above) % of Y P Load (below)				Bond Stress in lb per sq in (above) % First Slip (below)			Slip at Max Load, in
		Yield Point	First Slip	Ult	Drag @ 0 08 in Slip	First Slip	Ult	Drag @ 0 08 in Slip	
Col	a	b	c	d	e	f	g	h	i
Ultimate Compressive Strength of Concrete 3025 lb per sq in									
3-3	2 88	25100	3305 13 2	4185 16 7	2865 11 5	488	618 126 5	423 86 5	0 0100
3-6	6 25	25100	6040 24 0	8420 33 5	5645 22 5	411	572 139 2	383 93 2	0 0064
3-9	9 13	25100	8000 31 8	9280 36 9	5790 23 1	372	431 115 7	264 71 0	0 0035
3-12	11 75	25100	10555 42 1	12065 48 0	8300 33 1	381	436 114 4	300 78 8	0 0058
3-15	15 25	25350	13940 55 1	15315 60 6	10885 43 0	388	427 110 0	303 78 1	0 0058
3-18	18 25	25350	19200 75 8	21115 83 5	11400 45 1	447	491 109 8	265 59 3	0 0058
3-21	21 25	25350	19725 78 0	21585 85 2	12700 50 2	394	431 109 2	254 64 5	0 0059
3-24	24 25	27100	19940 73 6	21180 78 1	14620 54 0	349	371 106 2	256 73 4	0 0045
Ultimate Compressive Strength of Concrete 5830 lb per sq in									
5-3	3 00	26200	4550 17 4	5715 21 8	4180 16 0	644	808 125 2	591 91 6	0 0076
5-6	6 13	26200	8565 32 7	11330 43 3	4605 17 6	593	785 132 6	319 53 9	0 0049
5-9	9 25	26200	13520 51 7	15865 60 5	11520 44 0	621	728 117 1	529 85 2	0 0067
5-12	12 00	26200	17615 67 3	20985 80 1	13620 52 1	624	743 119 0	482 77 2	0 0091
5-15	15 25	25300	22000 87 0	24420 96 6	14300 56 5	613	680 111 0	398 64 9	0 0052
5-18	18 13	25300	26110 103 1	26110 103 1		610	610 100 0		0 0002
5-21	21 00	25300	26200 103 5	26200 103 5	19450 76 9	530	530 100 0	393 74 1	0 0002
5-24	24 00	27100	26200 96 8	28000 103 3	21850 80 6	463	493 106 4	387 83 6	0 0099

the concrete due to the "Poisson-ratio-effect"

That the "Poisson-ratio-effect" is, for portland cement, a significant factor, is indicated by the authors' tests (1, Fig 30, p. 174) and (4, Fig 5, p. 8) as well as by Glanville's results It is demonstrated further by the fact that the bond resistance offered by a pushout specimen increases with added load and is likely to split the block of concrete when the yield point of the steel is reached On the other hand a plain bar pullout specimen never develops a bond resistance exceeding the yield point of the bar, for slipping will then occur progressively over almost any length of embedment.

One important question yet to be conclusively answered is whether or not there is some limiting length of embedment for any high-strength, plain bar pullout specimen, beyond which added length of embedment of almost any amount will contribute but little added bond resistance, even though the bar has not reached its yield point. Some of the authors' tests seem to indicate that this is the case (1, Fig 28, p 171) and (4, Fig. 2, p 5).

CONCLUDING REMARKS

These data, along with the results secured by others of the more recent investigators, several of whom are listed in (4, p. 19–20), contribute much to a fuller understanding of the bond phenomenon. The evidence would be more complete and conclusive had the authors been able to have used much shorter gage lengths and to have measured strains close to the junction of steel and concrete instead of at the outside concrete surfaces Slippage measurements at the point where the loaded bar entered the concrete would also have bridged some gaps Qualitatively the overall aspects of the bond phenomenon seem now to be quite well catalogued but a considerable amount of quantitative evidence is still needed before such sketches as those of Fig 2 can be drawn to scale

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REFERENCES

1 Gilkey, Chamberlin and Beal "Bond Resistance of High Elastic Limit Steel Bars, Series of 1937" *Proceedings* Highway Research Board, Vol 17 (1937), p 149–186 (Chapter VIII of High Elastic Limit Steel Studies)

2 Glanville, W H "Studies in Reinforced Concrete, 1 Bond Resistance" Building Research Technical Paper No 10 Department of Scientific and Industrial Research (London, 1930)

3 Dunagan, W. M and Ernst, Geo C "An Experimental Study of Bond Stress" *Proceedings* Highway Research Board, Vol 16 (1936), p 96–99 (Chapter VI of High Elastic Limit Steel Studies)

4 Gilkey, Chamberlin and Beal "The Bond Between Concrete and Steel" *Journal* American Concrete Institute, Vol 10, No 1 (Sept, 1938), p 1–20 (*Proceedings*, Vol 35, 1939, p 1–20)

5 Abrams, D A "Tests of Bond Between Concrete and Steel" Bulletin 71, University of Illinois Engineering Experiment Station (1913)

6 Gilkey and Ernst "Pullout Tests for Bond Resistance of High Elastic Limit Steel Bars" Reconnaissance Series of 1936 *Proceedings* Highway Research Board, Vol 16 (1936), p 81–95, (Chapter V of High Elastic Limit Steel Studies)

7 Wernisch, Geo R "Bond Studies of Different Types of Reinforcing Bars" *Journal* American Concrete Institute, Vol 9, No 2, p 145–164 (Nov -Dec, 1937) Discussion in Vol 9, No 4 (Mar -Apr, 1938), p 164-1 to 164-15) Also *Proceedings* Vol 34 (1938) p 145–164 and discussions, p 164-1 to 164-15.

8 Davis, R E, Brown, Elwood H, and Kelly, J W "Some Factors Influencing the Bond Between Concrete and Reinforcing Steel" *Proceedings* A S T M, Vol 38 (1938), pt II