U. S. AIR FORCE

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RESEARCH MEMORANDUM

THE STRENGTH OF ANCHOR BOLTS SET IN CONCRETE

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ABSTRACT

This memorandum reviews our present knowledge of the strength of anchor bolts set in concrete. Experimental data on the different types of loading (i.e., tension, shear, bond) on anchor bolts is adequate, but very little data on their ultimate strength is available. Many types of anchors have been designed by rule-of-thumb methods, without knowledge of their true behavior. Since the design of structures on the basis of ultimate strength (or plastic theory) is becoming more common, it has become essential to obtain accurate knowledge of the actual structural behavior of the anchorages. This knowledge can only be obtained by a comprehensive series of tests.

INTRODUCTION

Considering that the failure of anchor bolts is one of the most important factors in the response of structures to air blast loading, it is the object of this report to review some of the pertinent experimental data and methods of analysis used in determining the strength of these bolts.

Very little data is available on the ultimate strength of anchor bolts. There has been some research on anchor bolts subjected to direct tensile loads. The paucity of information is perhaps due to the fact that anchor bolts represent a very minor item in the cost of a structure and designers can easily afford to be generous so that failure under ordinary service conditions is unlikely. With the present interest in air blast loadings, (which induces very high lateral loads) failure of the anchorages becomes quite important and perhaps a primary mode of failure.

Today, design criteria and knowledge of the ultimate strength of anchor bolts are based mainly on the theories and results of pull-out bond tests on steel rods. This limits the applicability of these results to a few types of anchors.

SCOPE

This report will cover only anchor bolts with heads and straight or hooked bars. Some reference will be made to moment resistant column bases (with emphasis on the anchor bolts). Expansion bolts, "shot" bolts and other patented connectors will be omitted. The test results of anchor bolts set in holes packed with lead wool have only been included as being part of a series of tests.

The tests reported and the methods of analysis may be classified as follows:

1. Type of loading
2. Type of stress
3. Type of bolt

All of the tests referred to in this report, except one, were performed under one type of loading - static. The one exception is a series performed under dynamic loading conditions. There is no reference made to the effects of creep, sustained or fatigue loading.

The types of stress considered are:

1. Tension
2. Shear
3. Combined shear and tension

} in the bolt material

and,

1. Bond
2. Shear
3. Bearing

} in the foundation material

A great variety of types of anchor bolts are used in service, but only a few more common types will be considered here. These types are described in the next section.

TYPES OF ANCHOR BOLTS

(Refer to corresponding type numbers in Fig. 1.)

1. Straight bar, usually plain, threaded at projected end to receive nut.
2. Plain bar with semi-circular or ninety degree hook for added strength.
3. Bolt or bar with bearing plate. Bearing plate may be cut from flat plate, angle or channel.
4. Machine bolt with standard head.

More comprehensive descriptions and construction procedures may be found in references 1 and 2.

TESTS AND RESEARCH

There have been numerous tests performed on the physical properties of a steel used for anchor bolts. The most commonly specified steel for anchor bolts is designated as A.S.T.M.-A7. It has the following properties:

Tensile strength, p.s.i.	60,000 to 72,000
Yield point, min., p.s.i. but in no case less than	0.5 x tensile strength 33,000
Elongation in 8 in., min., per cent.	1,500,000 tensile strength
Elongation in 2 in., min., per cent.	22

A typical stress-strain diagram for this material is shown in Fig. 2.

The ultimate shearing strength of the bolt material is specified as three-quarters of the ultimate tensile strength. Anchor bolts are seldom

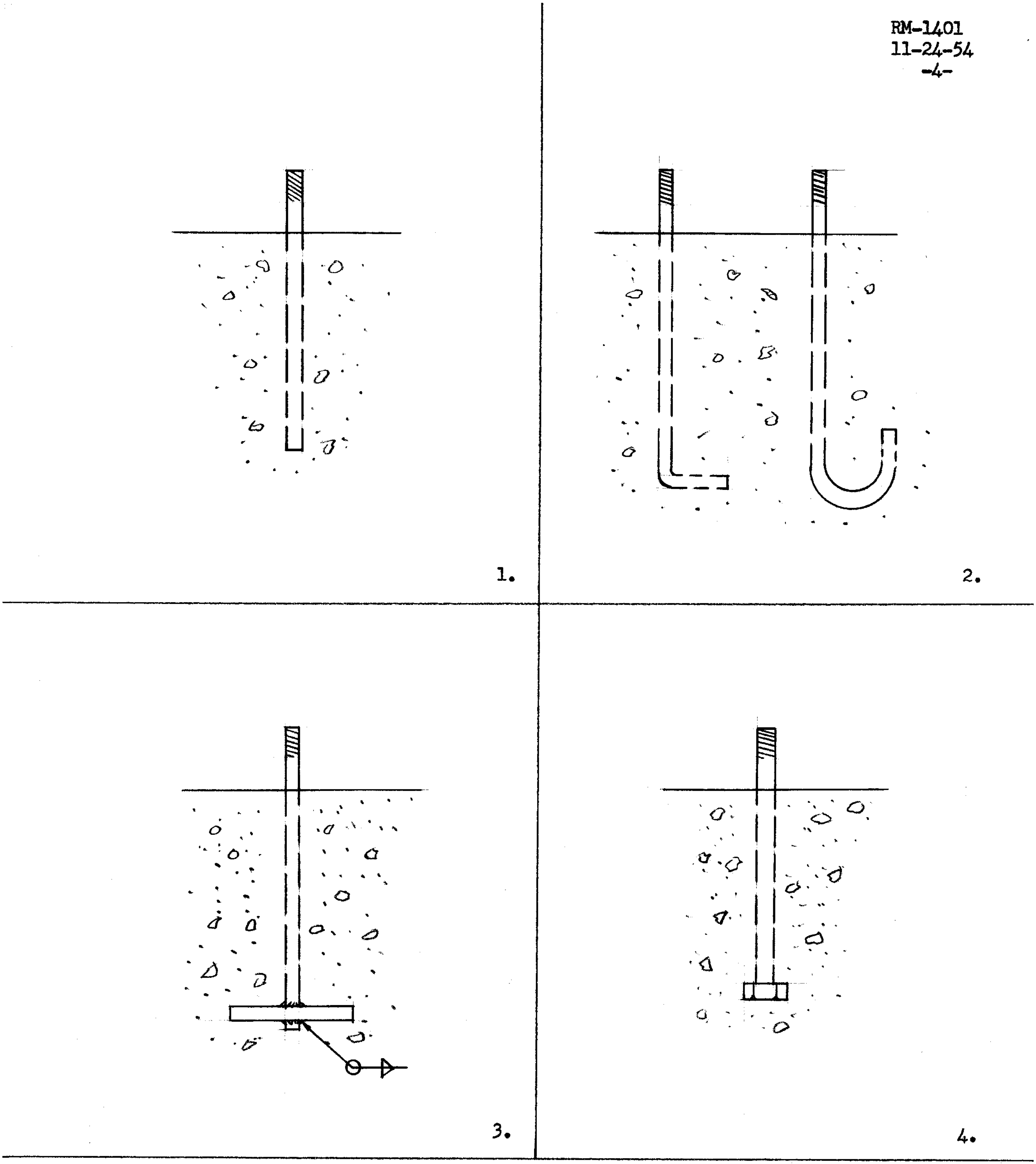


Fig. 1

Types of Anchor Bolts

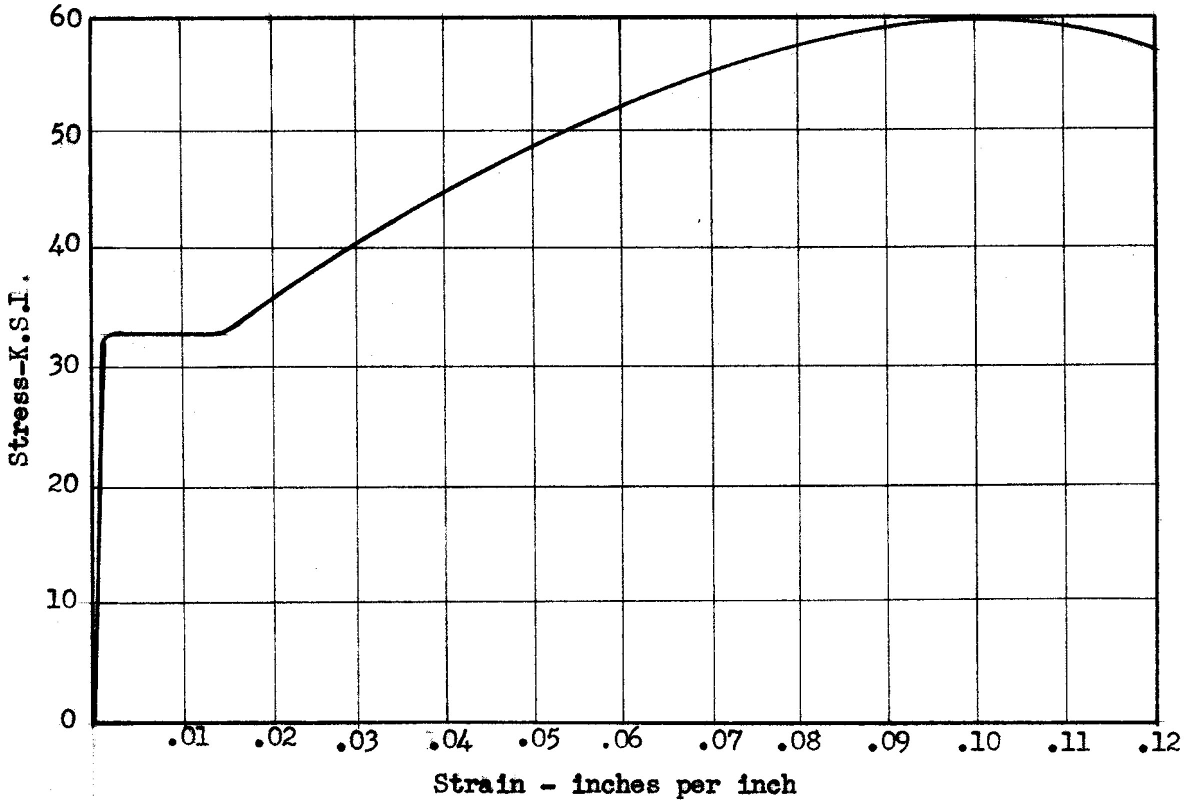


Fig. 2

Typical Stress-Strain Curve for

Anchor Bolt Material

subjected to pure shear or pure tension. The usual loading is combined shear and tension. Higgins and Munse[3] have reported the results of a series of tests on rivets subjected to this combined loading. Fig. 3 is adapted from the interaction curves given in their report.

The ultimate strength of steel anchors set in drilled holes in concrete has been determined by Graham[4] and Richard.[5] The results of their tests and the modes of failure are shown in Tables I and II.

Whittemore, Nusbaum and Seaquist made extensive tests on the impact and static tensile properties of bolts in 1938.[6]

The discussion so far has been concerned with the properties of the bolt material. The strength of concrete in bond, shear and bearing has been determined from tests primarily designed to fix allowable stress values for beams, columns and highway slabs. Abrams, in 1913, made the first comprehensive tests on bond.[7] In 1938, Gilkey, Chamberlin and Beal showed, in a series of tests, that bond stresses were not proportional to concrete stresses above certain limiting values.[8] Fig. 4 shows the relation of bond strength to concrete strength as determined in their tests. Fig. 5 shows the relation of length to diameter ratio and bond strength, also determined in the same series of tests.

Clark, in 1947-1951, performed tests at the Bureau of Standards on the bond strength of the new type of deformed bars.[9]

In 1928, Mylrea tested the carrying capacity of hooked bars.[10] In 1947 he developed a method of computing the carrying capacity of both straight and hooked bars.[11] Fishburn[29] has performed tests on this strength and slip of bent bar anchorages in haydite concrete.

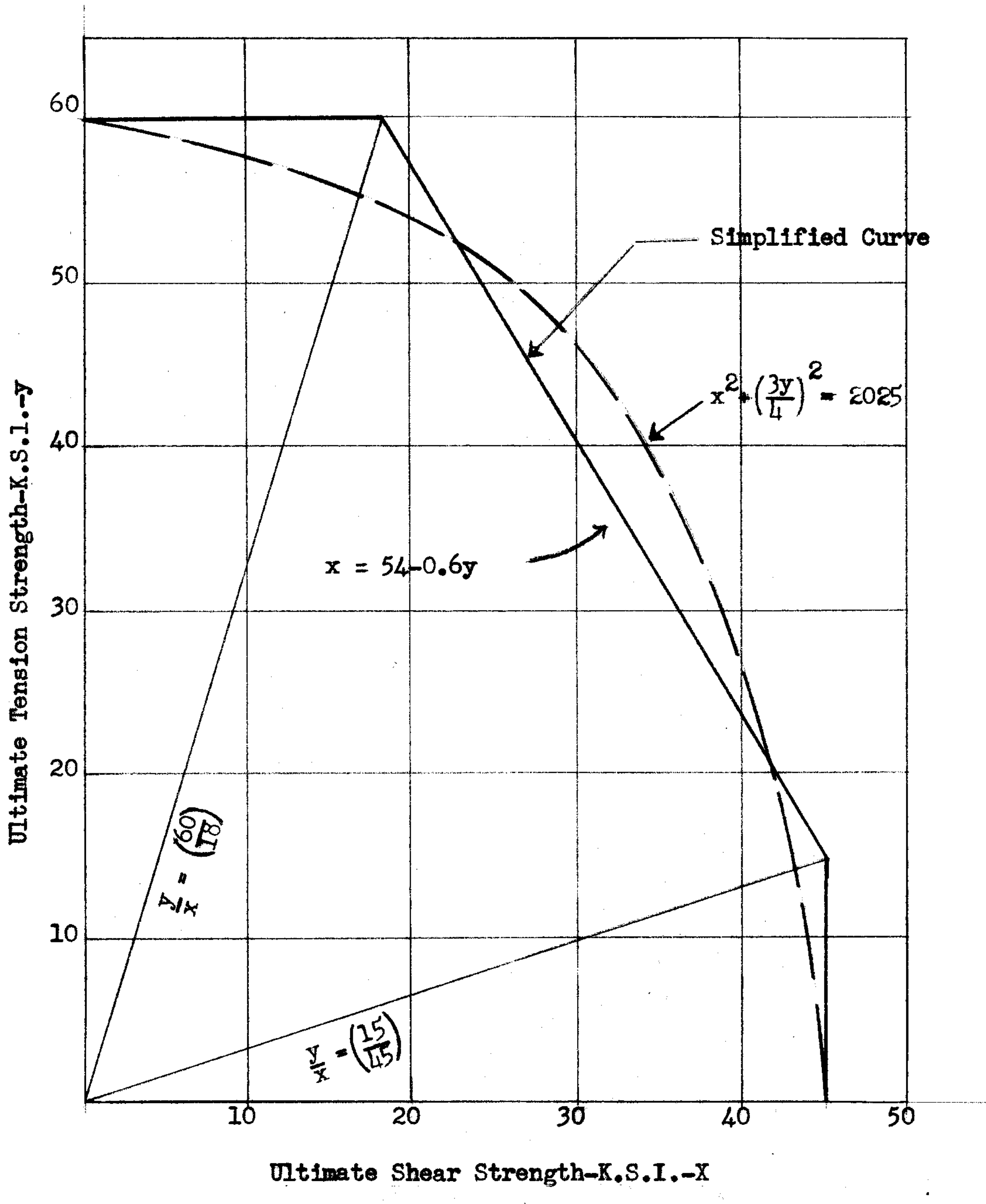


Fig. 3

Simplified Curve for Combined Rivet Stress

Adapted from "How Much Combined Stress Can a Rivet Take" Higgins and Munse, Engineering News-Record, December 4, 1952. Copyright 1952, McGraw-Hill Publishing Company. (All ordinates appearing in the Engineering News-Record curves have been multiplied by a factor of 3.)

TABLE I *

STEEL ANCHORS IN DRILLED HOLES IN CONCRETE
RESISTANCE OF BARS TO WITHDRAWAL
VALUES UNDER A DENOTE RESISTANCE IN KIPS PER TWO BAR UNIT AND
VALUES UNDER B ARE LOADS IN KIPS PER INCH OF BAR CIRCUMFERENCE

	$1\frac{1}{4}$ in. Plain Round Bars									$1\frac{1}{4}$ in. Square, Deformed Bars								
Embedment Inches	Test No.	Horiz. Bars 1:1 Grout		Test No.	Bent Bars 1:8 Slope 1:1 Grout		Test No.	Horiz. Bars Compacted Lead Wool		Test No.	Horiz. Bars 1:1 Grout		Test No.	Bent Bars 1:8 Slope 1:1 Grout		Test No.	Horiz. Bars Compacted Lead Wool	
		A	B		A	B		A	B		A	B		A	B		A	B
10		---	---		---	---	6	9.8	1.3		---	---		---	---	14	33.3	3.3
20		---	---	3	49.1	6.3	7	3.9	0.5	8	117.8	11.8	11	104.1	10.4	15	33.4	3.3
30	1	39.3	5.0	4	49.1	6.3		---	---	9	121.7	12.2	12	58.9	5.9		---	---
40	2	14.6	9.5	5	43.2	5.5		---	---	10	115.8	11.6	13	25.5	2.6		---	---

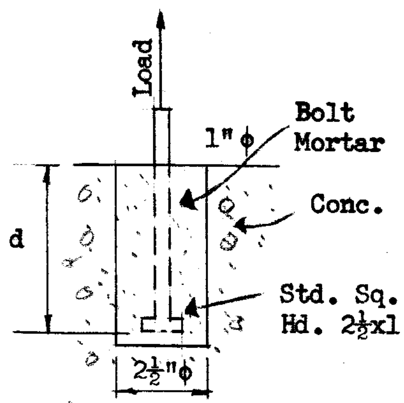
Mode of Failure:

Horiz. bars - held in bond, grout failed.
Sloping bars - initial failure of concrete, followed by grout failure.
Plain bars in comp. lead wool - bond failed.
Def. bars in comp. lead wool - lead failed.

TABLE II

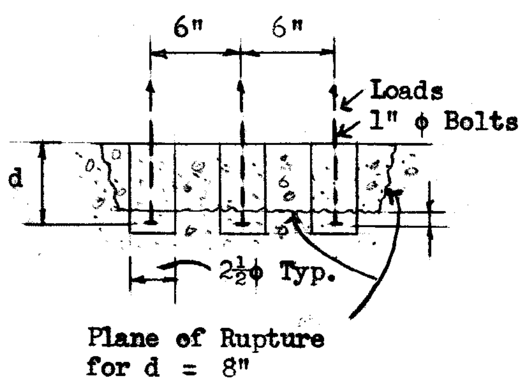
STRENGTH OF ANCHOR BOLTS SET IN DRILLED HOLES

DATA: Mortar, w/c = 1/2 Sand: Cem = 2:1
Conc., $f'_c \cong 2900$ p.s.i.
Bolt Steel, Ult. Load for 1"ø bolt = 18.9 T T = 2240#



Tests on Single Bolts:

d(in.)	Ult. Load	Mode of Failure	No. of tests
8	20 T	Tens. Failure of shank	4
7	19 T	" " " "	1
6	13 T	Pull-out Mortar & some concr.	1
5	10 1/2 T	" " " "	1



Tests on Cluster of 3 Bolts 6" c/c

d(in.)	Ult. Load	Mode of Failure	No. of tests
8	42	Tear out cone of	1
8	57 1/2	concr. (dotted line)	1
13	54 1/2	Tens. Fail. of Bolt Shank	1
13	57 1/2	" " " " "	1

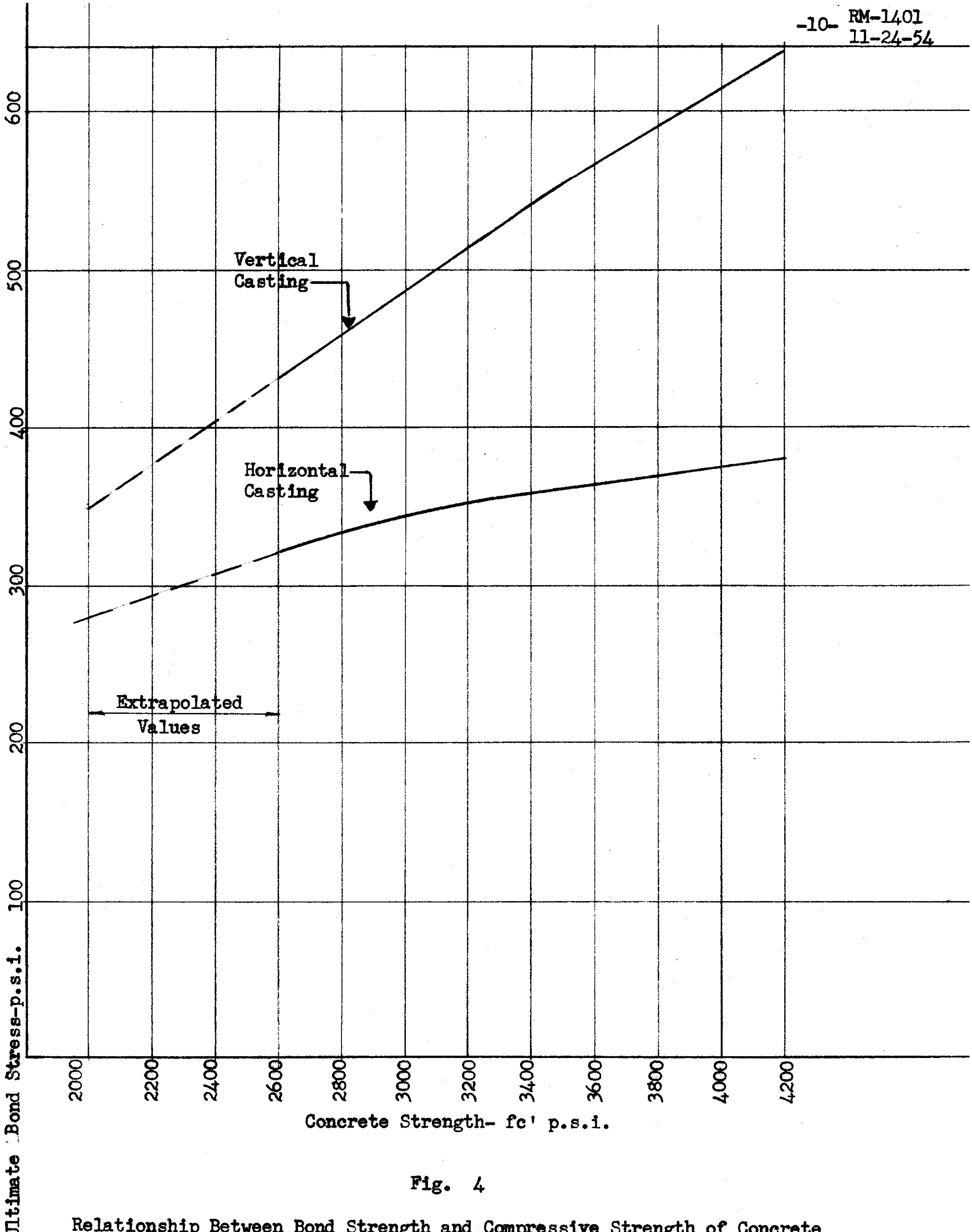


Fig. 4

Relationship Between Bond Strength and Compressive Strength of Concrete
(Plain Bars) L/D = 12.8

Reference: Series VI Tests pg 105 "Bond Between Concrete and Steel"
Gilkey et al., Iowa Engr. Exp. Sta. Bull. 147, Dec. 1940

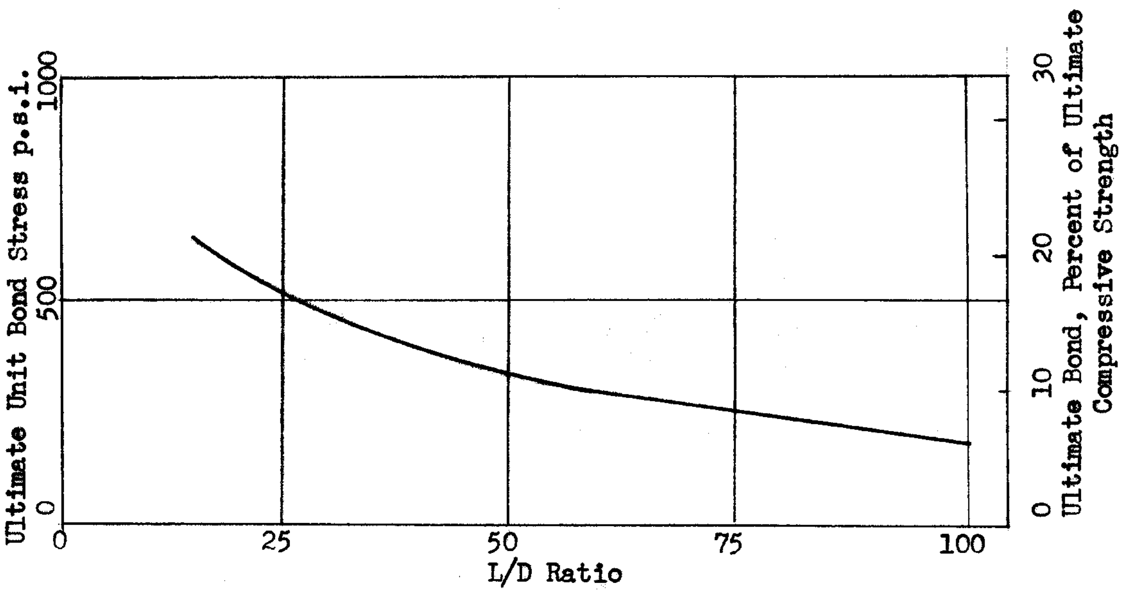


Fig. 5

Relationship of L/D Ratio and Ultimate Bond Stress for 3,000 psi Concrete
(Vertical Casting)

Reference: Pg 76 "Bond Between Concrete and Steel"
Gilkey, et. al., Iowa Engr. Exp. Sta. Bull. 147, Dec. 1940

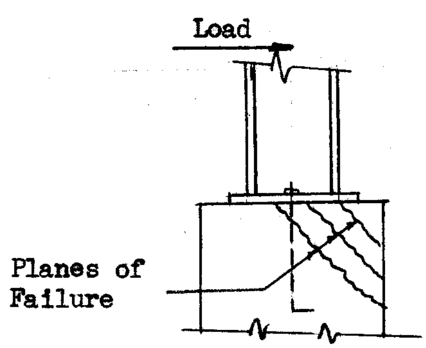


Fig. 6

Diagonal Tension Failure

The use of steel dowels in transverse pavement joints has prompted research on their load carrying capacity. Westergaard,[12] Friberg,[13] Kushing and Fremont[14] and others have tested and discussed dowels. Friberg found that the stresses in the concrete around the dowel at the face of the joint were extremely high. He reports a bearing pressure of 14,050 p.s.i. for a 3/4 in. diameter dowel subjected to a lateral load of 5000 lbs. Marcus discusses these results and develops a formula for computing the ultimate load carrying capacity for dowels.[15] From the data of these tests it appears that the strength of dowels carrying lateral loads is much greater than allowed in the building codes.[16,17,18]

Most of the above investigations were not directly concerned with anchor bolts but the results may be adapted to them. The Engineering Research Institute of the University of Michigan has outlined a research program that would add to the knowledge of the strength of concrete anchors.[19] This program would include:

1. Tests on the bond strength for various types of anchors.
2. Tests on the effects of compressive, flexural and shear loading.
3. Tests on various column-base details, i.e., resistance to moment, frictional resistance, amount of rotation.

METHODS OF DESIGN AND ANALYSIS

There is little information on the design of anchor bolts. For example, the AISC Manual[20] merely specifies that anchor bolts shall extend into the masonry not less than 2 ft.-6 in., and farther when necessary. The AREA manual of railways[21] says that anchor bolts shall be embedded a distance sufficient to resist 1.2 times the uplift forces. Even the building codes are little more explicit. Several Southern California codes state only the above and give allowable shear values in concrete and brick masonry.[16,17,18]

In large, heavy building structures the design of anchor bolts is almost unnecessary. The large dead loads and relatively small lateral loads reduce the uplift, and there is sufficient frictional resistance in the bearing plates to carry the shear loads.

In the case of buildings with fixed column bases (crane columns, for example), machinery bases, chimneys, stacks, vertical tanks and blast furnace stories the anchorages must be designed to be moment resistant. Design methods for moment-resistant column bases are presented in various text books as steel design.[22,23,24,25,26,27] The Engineering Research Institute has outlined a method to determine the ultimate moment capacity and the rotation of fixed bases.[28]

Most of the resistance to overturning loads in stacks, towers and tanks must be provided by the anchor bolts since the dead load resisting moment is usually fairly small. The methods of design are semi-empirical (in some cases rule-of-thumb).[30,31] The dynamic nature of the lateral loads (wind or earthquake), the effects of repeated or reversed loads and sustained loading are taken into account by specifying low design stresses (usually 12,000 to 15,000 p.s.i.) without the usual one-third increase. This value is used to proportion the anchor bolts.

The length of embedment in the concrete, according to most design standards, is such that the allowable tensile value of the anchor bolt may be developed in bond. If sufficient length to develop this value is not available, the bar may be hooked or plates or structural shapes may be welded to the lower end of the bolt to develop the required strength in bearing instead of bond.

Failure in anchorages may be due to:

1. Failure of anchor bolts
2. Failure of concrete

This may be subdivided further. Anchor bolts may fail in tension, shear or combined tension and shear. The ultimate load in tension is given by the expression:

$$P_t = A_n S_{ult} \quad ,$$

where,

A_n = Net area (at root of threads) of anchor bolt cross section, in^2.

S_{ult} = Ultimate tensile strength of bolt material, p.s.i.

The strain at this point may be taken from a stress-strain diagram of the material (Fig. 2).+

The ultimate load in shear is given by the expression:

$$P_s = A_g S_s$$

where,

A_g = Gross area of anchor bolt cross section, in^2.

S_s = Ultimate shear strength of bolt material, p.s.i.

S_s is usually taken as three-fourths of the ultimate value in tension.

The combined failure load may be computed from the interaction curve of

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+ The effective length in tension must be used in determining strain. See reference 19.

Fig. 3. The simplified straight-line diagram may be used. The tensile load will govern when the shear stress is less than 18 K.S.I. and the shear may be neglected as far as the bolt material is concerned.

Failure of the concrete may occur in several ways. The most probable being a pull-out failure.

The ultimate strength of a straight bar in bond is given by the expression:

$$P_B = U_{ult}\ C\ L$$

where,

U_{ult} = Ultimate bond strength of concrete, p.s.i.

C = Circumference of anchor bolt at gross cross section, in.

L = Length of embedment of bar, in.

It has been shown by Gilkey et al that the maximum effective length in bond (L) is about 24 diameters.[8]

The strength of a hooked bar is due to a combination of embedment and hooking. Mylrea[11] has stated that a load which stresses a hooked bar to 20,000 p.s.i. represents the carrying capacity of a hook. Accordingly, the ultimate strength would be given by the expression:

$$P_h = U_{ult}\ C\ L' + 20{,}000\ A_g$$

where,

L' = the length of embedment from the face of the concrete to the point of tangency of the hook.

Values of U may be taken from Fig. 4 or the results of other tests. Mylrea has presented a method of computing the bond strength which takes into account the diminishing of the bond strength as the length of embedment increases.(11)

Failure of the concrete pier in diagonal tension (Fig. 6) is quite possible where shear loads are high and the pier is narrow. A method of analyzing this case has been developed by the Engineering Research Institute.(28)

Marcus,(15) as a result of his tests, has developed a formula for computing the crushing load of a steel dowel subjected to a lateral load, as follows:

$$P_c = \frac{3}{2} \frac{d(h-d)}{1 + \frac{e}{\ell}} \cdot f_t$$

where,

d = Diameter of anchor bolt, in.

h = Distance from center line of bar to edge of concrete, in.

e = Distance between the point of application of the load and the face of the joint, in.

ℓ = Length of embedment of bar, in.

$f_t = \sqrt{10 f'_c}$, the tensile strength of the concrete, p.s.i.

f'_c = The compressive strength of the concrete, p.s.i.

This formula was obtained for unreinforced concrete (no stirrups or ties).

Where short anchor bolts with a great deal of holding power are used, failure may occur by tearing out a piece of concrete. This type of failure has been reported by Graham and Richard (see Tables I and II). More experimental data on this type of anchorage are required.

Another possible mode of failure is the rupture of an unreinforced concrete pier due to tension. This is a foundation failure and is not considered here.

The effect of dynamic loads on the failure of anchor bolts has not been considered. Tests and experiments might uncover a "dynamic correction factor" that could easily be used in analysis.

In the overturning analysis of steel stacks subjected to air blast loads there are two conditions which determine the upper and lower boundaries of structural response. The upper boundary is determined under the condition that the anchor bolts in tension will stretch like "spaghetti" and offer considerable resistance to overturning. The lower boundary is fixed by the condition that the anchor bolts break before the structure has moved appreciably and offer little resistance to overturning.

It may be seen from the above that accurate knowledge of the actual structural behavior of anchorages is lacking. Since the design of structures on the basis of ultimate strength (or plastic theory) is becoming more common, the design of anchor bolts on this basis is most desirable. A comprehensive series of tests for the purpose of obtaining this knowledge appears a necessity.

References

1. Dunham, C. W., "Foundations of Structures," McGraw-Hill Book Co. Inc., New York, 1950, pp. 203-13.

2. Structural Bureau, "Fastening and Bedding Column and Machine Bases," Portland Cement Association, Chicago, December 1949, ST 61.

3. Higgins, T. R., Munse, W. H., "How Much Combined Stress can a Rivet Take?" Engr. News Record 149(23):40-42, 1952.

4. Graham, H. E., "Strength of Steel Anchors in Concrete," Engr. News Record, Vol. 130, 1943, pp. 560-1.

5. Richard, E. L., "Anchor Bolts Set in Drilled Holes," Jour. ACI, Vol. 19, No. 1, Sept. 1947, pp. 81-3.

6. Whittemore, H., Nusbaum, G. W., Seaquist, E. O., "Impact and Static Tensile Properties of Bolts," National Bureau of Standards Journal of Research, Vol. 14, 1938.

7. Abrams, D. A., "Tests of Bond Between Concrete and Steel," University of Illinois Engineering Experiment Station Bull. No. 71, 1913.

8. Gilkey, H. J., Chamberlin, S. J., and Beal, R. W., "Bond Between Concrete and Steel," Iowa Engr. Exp. Sta., Bull. 147, Iowa State College, Ames, Iowa, 1940.

9. Clark, A. P., "Bond of Concrete Reinforcing Bars," Journal of Research of the National Bureau of Standards, Vol. 43, No. 6, Dec. 1949, pp.565-79.

10. Mylrea, T. D., "The Carrying Capacity of Semi-Circular Hooks," ACI Proc. Vol. 24, pp. 240-272, 1928.

11. Mylrea, T. D., "Bond and Anchorage," Jour. ACI, Vol. 19, No. 7, Mar. 1948.

12. Westergaard, H. M., "Spacing of Dowels," Proceedings, Highway Research Board, 1928.

13. Friberg, B. F., "Design of Dowels in Transverse Joints of Concrete Pavements," Laclede Steel Co., St. Louis.

14. Kushing, J. W. and Fremont, W. O., "Design of Load Transfer Joints in Concrete Pavements," Proceedings, Highway Research Board, 1940.

15. Marcus, H., "Load Carrying Capacity of Dowels at Transverse Pavement Joints," Jour. ACI, Vol. 23, No. 2, Oct. 1951, pp. 169-84.

16. "Los Angeles County Building Laws," Colling Publishing Co., 1949, pp. 126, 193.

17. "Uniform Building Code," Pacific Coast Building Officials Conference, 1949, pp. 92, 159.

18. Los Angeles City Building Code," Building Code Publishing Co., 1953, pp. 126.

19. Hu, L. S., Byce, R. C., Johnston, B. G., "Steel Beams, Connections, Columns and Frames," Dept. of Civil Engr., Univ. of Mich., March 1952.

20. AISC, "Steel Construction," Amer. Inst. of Steel Construction, New York, 1950.

21. AREA, "Manual for Railway Engineering," American Railway Engineering Association, Chicago, 1952, Vol. 2, pp. 15-22.

22. Lothers, J. E., "Design in Structural Steel," Prentice-Hall, Inc., New York, 1953.

23. Urquhart, L. C., "Civil Engineering Handbook," McGraw-Hill Book Co., Inc., New York, 1950, pp. 573-5.

24. Hook. G. A., Kinne, W. S., "Structural Members and Connections," McGraw-Hill Book Co., Inc., New York, 1942, pp. 313-18.

25. Hool, G. A., Kinne, W. S., "Steel and Timber Structures," McGraw-Hill Book Co., Inc., New York, 1942, pp. 53-4, 416-17, 479-82.

26. Grinter, L. E., "Theory of Modern Steel Structures," The Macmillan Co., New York, 1949, Vol. 1., pp. 112-13.

27. Shedd, T. C., "Structural Design in Steel," John Wiley and Sons, Inc., New York, 1950, pp. 407, 418.

28. Schenker, L., Salmon, C. G., Johnston, B. G., "Structural Steel Connections," Dept. of Civil Engr., Univ. of Mich., June, 1954.

29. Fishburn, C. C., "Strength and Slip Under Load of Bent Bar Anchorages and Straight Embedments in Haydite Concrete," ACI Jour., Vol. 19, No. 4, pp. 289-305, December 1947.

30. Merriman, T., Wiggin, T. H., "American Civil Engineers' Handbook," John Wiley and Sons, Inc., New York, 1942, 5th Ed, pp. 1287-9.

31. Fleming, R., "Anchor-Bolt Tension: Six Different Results from Six Books," Engineering News, April 1914, pp. 956-58, 1089.