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# TESTS OF REINFORCED BRICK COLUMNS

by Inge Lyse*

## 1. SYNOPSIS

This paper presents the data obtained in the first extensive investigation ever made on reinforced brick columns. The results were very gratifying insofar as they furnished a basis for the development of rational design formulas. The strengths of the columns were found to be made up of the effective strength of the masonry plus the yield-point strength of the longitudinal reinforcement. A study of the type of masonry mortars revealed that portland cement mortar containing 15 per cent ordinary brick clay by weight of the cement gave better results than did any of the other types used.

For completeness, a review of all known experiments on brick piers and columns is incorporated in the paper.

## 2. INTRODUCTION

Numerous tests have been made in the past on the strength of plain brick piers and columns, but until recently no data were available on the advantage of reinforcement in brick columns. The introduction of reinforced brick construction into the field of structural engineering made it imperative to secure reliable data on the structural behavior of these columns. During the early part of 1933 the Fritz Engineering Laboratory of Lehigh University, tested

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33 columns, the results of which are presented in this paper. All columns were about 12-1/2 by 12-1/2 in. in cross-section and 10 ft. in length. Five of the columns had no reinforcement, six had longitudinal steel only, nine had lateral reinforcement only, and thirteen had both longitudinal and lateral reinforcement. The bricks used were of three types, common solid stiff mud brick, de-aired solid brick, and de-aired perforated brick. All three types of brick were of good quality, the de-aired types being excellent. Five types of mortar were used; straight portland cement mortar, cement mortar containing 15 and 100 per cent lime by volume, and cement mortar containing 5 per cent celite or 15 per cent clay by weight of the cement.

3. EARLIER TESTS ON BRICK COLUMNS

Tests of brick piers at the Watertown Arsenal in 1882 are reported in Kidder's ARCHITECTS AND BUILDERS POCKET-BOOK. The cross-section was 8 by 12 in. and the nominal height varied from 20-1/2 to 23 in. "Common" lime mortar, 3 parts lime mortar and 1 part portland cement, 3 parts lime mortar and 1 part natural cement, 1:2 portland cement mortar, and 1:2 natural cement mortar were used. The compressive strength of the piers varied from 1562 to 3020 lb. per sq.in. or from 12.8 to 24.8 per cent of the compressive strength of the brick.

Other tests made at the Watertown Arsenal are reported in several of the annual reports of TESTS OF METALS. Tests of twelve brick piers for the City of Philadelphia in 1883 are reported in the 1884 volume. The piers or cubes were 13 by 13 by 13 in. Four kinds of bricks and two kinds of mortar, 1:4 lime mortar and 1:2 natural cement mortar were used. The compressive strength of the piers ranged from 10.7 to 26.3 per cent of that of the bricks. In the 1884 volume, results are also given for tests of 33 piers varying from 8 by 8 in. to 16 by 16 in. in cross-section and from 16 in. to 10 ft. in length, using portland cement mortar, natural cement mortar, and lime mortar. The compressive strength of these piers ranged from 6.1 to 27.2 per cent of the compressive strength of the brick used. In the 1886 volume the results are given for 53 piers ranging in sizes from 8 by 8 in. to 16 by 16 in. in cross-section and from 2 to 12-1/2 ft. in length, using a natural cement mortar. The strengths of the columns ranged from 6.4 to 18.2 per cent of the strength of the brick. The strength of the columns was found to be inversely proportional to the ratio between longitudinal and lateral dimension, for a ratio of 3 the column strength was 17 per cent of the brick strength, and for a ratio of 15 the column strength was only 13 per cent of the brick strength.

In the 1893 volume the results are given for six brick piers varying from 8 by 8 in. to 16 by 16 in. in cross-section and from 6 to 8 ft. in height. Lime mortar and neat portland cement paste were used in solid and hollow piers, with bricks on edge and flat. The compressive strength of the piers ranged from 601 to 4623 lb. per sq.in. In the 1904 volume of TESTS OF METALS tests of 26 brick columns, 12 by 12 in. and 8 ft. long, are reported. The mortars used were neat portland cement paste, 1:2 and 1:3 cement mortar, and 1:3 lime mortar. The columns having neat cement paste had an average strength equal to 30 per cent of the strength of the brick, for 1:3 portland cement mortar the average strength was 24 per cent and for 1:3 lime mortar the column strength was only 13 per cent of the strength of the brick. In the 1905 volume, a report is given of 13 columns having clay brick and one column having sand-lime brick. These columns were 12 by 12 in. by 8 ft. with solid or hollow cores in neat portland cement mortar, 1:2, 1:3 and 1:5 cement mortars, and 1:3 lime mortar. The columns having neat cement mortar gave strength from 1500 lb. per sq.in. for sand-lime brick to 4550 lb. per sq.in. for clay brick. Columns having 1:3 lime mortar gave strengths between 652 and 955 lb. per sq. in. The 1906 volume contains a report of tests of 15 brick piers 12 by 12 in. by 8 or 9 ft. Neat portland cement paste, 1:1, 1:3, 1:5, and 1:6 portland cement mortars, and 1:3 lime mortar and 1:1:1 and 1:1:3 cement-lime mortars were used. The strengths of the clay brick columns varied from 850 to 3440 lb. per sq.in., and that of the sand-lime brick columns from 450 to 1400 lb. per sq.in. In the 1907 volume of TESTS OF METALS results are given for 32 columns about 12 by 12 in. by 8 ft. long. The mortars were neat portland cement paste, 1:1, 1:2, and 1:3 portland cement mortar, and 1:3 lime mortar. The strength of the columns were found to be closely related to the strength of the mortar used. The strength increased considerably with the increase in age of the column, in one case varying from 2100 lb. per sq.in. at four hours to 4500 lb. per sq.in. at seven days for neat cement paste.

In the Transactions of the Association of Civil Engineers of Cornell University for 1897-98 and 1899-1900, results are given for tests of brick columns made at Cornell University. One group of tests consisted of 18 piers, 13 by 13 in. varying from 2-1/2 to 7-1/2 ft. in length, with 1:2 portland cement mortar. The strength of the piers varied between 635 and 1093 lb. per sq.in., or between 17 and 31 per cent of the brick strength. Another group consisted of 14 piers, 11 of which had horizontal reinforcement consisting either of iron straps, wire netting, or iron plates. The piers were 13 by 13 in. and 6-3/4 ft. long, with 1:2 portland cement mortar. The results showed that the average column strength in percentage of brick strength was 30 for the plain brick columns, 24 when iron straps were used in every fourth course, 22 in every sixth course, and 24 per cent in every eighth course. For wire netting the percentage was 46 for netting in every course, and 53 for netting in every second course. For iron plates in every fourth course the percentage was 28.

At the University of Toronto 17 brick piers were tested, a report of which is given in DIGEST OF PHYSICAL TESTS, Vol. 1, No.3, 1896. The piers were 9 by 9 in. in cross-section and varied in length from 16 to 72 in. The mortars used were 1:2 lime mortar and 1:3 portland cement mortar. The columns having lime mortar gave strength averaging 17 per cent of the brick strength and the columns having portland cement mortar averaging 42 per cent of the brick strength.

At Purdue University tests were made in 1906-07 on 32 short columns of clay and sand-lime bricks, and a report of the results is given in ENGINEERING NEWS, February 25, 1909. A 1:3-1/2 lime mortar was used for all piers which had a cross-sectional area of 12 by 12 in. and a height of 4 ft. The compressive strength of these piers ranged from 7.3 to 35.0 per cent of the strength of the brick.

Bulletin No. 27 of the University of Illinois (1908) contains a detailed report on tests of 16 brick columns and 16 terra cotta columns. The brick columns were 12-1/2 by 12-1/2 in. in cross section and 10 ft. in length. Two grades of brick were used, an excellent building brick and a soft grade brick. The best grade brick averaged 10,700 lb. per sq.in. in strength and the soft brick averaged only 3900 lb. per sq.in. Eleven of the brick columns had 1:3 portland cement mortar, two had 1:5 portland cement mortar, one had 1:3 natural cement mortar and two had 1:2 lime mortar. The percentage of the average strength of the column to that of the brick at an age of about two months was 31 for well laid 1:3 portland cement mortar, 27 for poorly laid 1:3 portland cement mortar, 21 for well laid 1:5 portland cement mortar, 16 for well laid natural cement mortar, and 14 for well laid 1:2 lime mortar, when first class brick was used. For soft brick columns the average percentage was 27 for well laid 1:3 portland cement mortar. The initial modulus of elasticity varied from about 4,000,000 to 5,500,000 lb. per sq.in. for first-class brick columns in well laid 1:3 portland cement mortar, between 3,000,000 and 3,500,000 lb. per sq.in. for well laid 1:5 portland cement mortar, was 800,000 lb. per sq.in. for 1:3 natural cement mortar and varied between 101,000 and 107,000 lb. per sq.in. for 1:2 lime mortar. For soft brick columns the initial modulus of elasticity was about 430,000 lb. per sq.in. for 1:3 portland cement mortar.

The ENGINEERING RECORD for March 22, 1913, reports tests of two large brick piers. The piers were 48 by 48 in. in cross section and 12 ft. in height. The mortars used were 1:1 portland cement and 1:1 lime. The pier having cement mortar gave compressive strength equal to 28.9 per cent and that having lime mortar 7.5 per cent of the strength of the brick.

At Columbia University tests were made in 1914-1915 on 69 brick piers. The piers were 8 by 8 in. in cross section by 7 ft. in height. The mortars used were 1:3 portland cement with no admixture, with 10, 15, 25, 50 and 75 per cent lime as admixture, and 1:3 lime mortar. The age at test varied from seven days to three months. Two types of brick were used, with compressive strengths of 10,500 and 3221 lb. per sq.in. With straight 1:3 cement mortar the strength of the piers increased slightly between the ages of 7 and 28 days, but showed no increase between 28 days and 3 months. When lime admixture or lime mortar was used the strength of the piers increased consistently up to the age of three months. The test results indicated that the highest strength was obtained by the use of cement mortar containing 25 per cent lime. The compressive strength of the piers ranged from 14.6 to 52.1 per cent of the strength of the bricks. A report on these tests is given in Bulletin J of the Hydrated Lime Bureau of the National Lime Association, June 1, 1916.

Tests of 50 brick piers at the Bureau of Standards Laboratory at Pittsbugh, Pennsylvania, are reported in TECHNOLOGIC PAPER No. 111 of the Bureau of Standards. The piers were 30 by 30 in. in cross section and either 5 or 10 ft. long. Different grades of brick were used with 1:3 portland cement mortar without admixture and with 15 per cent lime, and 1:3 and 1:6 lime mortars. One or the piers had wire mesh in every joint and another one had wire mesh in every fourth joint. The compressive strength of the plain brick columns ranged from 7.6 to 75.1 per cent of the strength of the brick. The wire mesh in every joint raised the percentage to 92.7.

Tests of 14 brick piers at the University of Toronto are reported in Proceedings of the Fifth Annual Meeting of the Building Officials Conference, 1919. The piers were 8 by 8 in. in cross section and varied from 1 to 9 ft. in height. The mortars were 1:3 portland cement mortar with 15 per cent lime and 1:3 lime mortar. The bricks had a strength of only 1000 lb. per sq.in. flat. The piers with cement mortar gave strength varying from 54 to 78 per cent of the brick strength, while the piers with lime mortar gave values between 30 and 55 per cent. The short piers gave higher strength than did the long piers.

ENGINEERING NEWS-RECORD for August 31, 1932, contains a report of tests of four brick piers cut from masonry of wrecked buildings, 16 years old. The piers were 12 by 16 in. in cross section and varied in height from 21-1/2 to 27 in. A 1:3 portland cement mortar was used in the piers. The compressive strength of the piers varied from 877 lb. per sq.in. for a pier with uneven bearing plate to 2095 lb. per sq.in.

At Columbia University tests were made of 131 brick piers, report of which is given in Bulletin 2, Department of Civil Engineering testing laboratories, Columbia University, 1923. The piers were 12 by 12 in. in cross section with a height of either 3-1/2 or 7 ft. with 1:3 portland cement mortar. Clay brick, sand-lime and concrete brick were used in the piers. The compressive strength of the piers ranged from 17.6 to 99.0 per cent of the strength of the brick.

Tests of 57 brick piers in England in 1895-1897 are reported in Royal Institute of British Architects, Report on Brickwork Tests, 1905. The piers varied in cross section from 13 by 13 in. to 18 by 28 in. and were 6 ft. in height. Different grades of bricks were used with 1:4 portland cement mortar and with 1:2 lime mortar. The compressive strength of the piers varied from 7.8 to 46.8 per cent of the strength of the bricks.

A report on tests of 57 brick piers at the Swedish Technical Institute is published in TONINDUSTRIE ZEITUNG, September 9 and 21, 1916. The piers varied in cross section from 8 by 8 in. to 11 by 11 in. and in height from 5 in. to 9 ft. The mortar used was either 1:3 lime mortar or a mixture of cement and lime in the following proportions: 1 cement, 2 lime, 9 sand; 1 cement, 1 lime, 6 sand; 2 cement, 1 lime, 9 sand; 1 cement, 2 lime, 7 sand; and a 1:3 portland cement mortar. Some of the piers were eccentrically loaded. The results showed that the shorter the pier the greater was the strength. They also showed that the eccentricity of loading decreased the strength materially. The 1:3 cement mortar gave higher strength than did any of the other mortars. The compressive strength of the piers ranged from a minimum of 10.2 per cent for piers loaded at the quarter point to a maximum of 71.8 per cent for concentrically loaded piers.

A summary of the tests of brick piers is presented in Table I.

## 4. ACKNOWLEDGMENT

The investigation of reinforced brick columns was undertaken at the initiative of Judson Vogdes, representative of the National Brick Manufacturers Research Foundation. The Lehigh Brick Works of Allentown, Pennsylvania, through Robert K. Mosser, supplied all materials and built

the columns. The testing of the columns was done as part of the research experiments of the Fritz Engineering Laboratory of Lehigh University.

## 5. MATERIALS

The bricks used in this investigation were of three types, solid brick made by the stiff-mud process, solid de-aired brick, and perforated de-aired brick. The bricks were manufactured by the Lehigh Brick Works at Allentown, Pennsylvania. The de-aired brick gave excellent strength results, the average strength for solid brick for one group being 13,760, 10,070, and 10,680 lb. per sq.in. for flat, on end, and on edge respectively; and for another group 11,000 lb. per sq.in. flat. One group of perforated brick had strength of 12,190, 6760 and 7720 lb. per sq.in., and another group 7520, 4840 and 5080 lb. per sq.in. for flat, on end, and on edge respectively. The bricks of the old stiff-mud type gave an average compressive strength of 8000 lb. per sq.in. flat, 3780 lb. per sq.in. on end, and 7670 lb. per sq.in. on edge. The rate of absorption for the three types of brick used is shown in Fig. 1. The perforated brick showed absorption about twice that of the solid brick for less than ten minutes of submersion. The solid stiff-mud brick showed a higher absorption than did the solid de-aired brick. The difference in structure of the de-aired brick and the stiff-mud brick is shown in Fig.2

for bricks sawed into sections. It is noted that the stiff-mud brick had laminations and small shrinkage cracks, while the de-aired brick showed a very dense and uniform structure.

The average weight of the solid stiff-mud brick was 2116 grams per brick, the solid de-aired brick 2264 grams, and the perforated de-aired brick 2000 grams.

The cement used for the mortar in the investigation was standard portland cement manufactured by the Lehigh Portland Cement Company.

The mortar sand was a New Jersey lake sand having a sieve analysis as follows:

| Per Cent Retained on Sieve No. | | | | | |
|---|---|---|---|---|---|
| 100 | 48 | 28 | 14 | 8 | Fineness Modulus |
| 85.3 | 55.3 | 30.1 | 12.6 | 3.4 | 1.87 |

This sand proved to be very satisfactory and was used throughout the investigation.

Three different admixtures were used in the mortar. In one group of columns hydrated lime in amounts equal to 15 and 100 per cent by volumn of the cement was used. The mortar which contained 100 per cent lime had six parts sand to one part cement. All other mortars had three parts sand to one part cement by loose volume, except the mortar for the last five columns which had two parts sand by weight to one part cement. One sack of cement (1 cu.ft.) was taken as weighing 94 lb., and one sack (1 cu.ft.) hydrated lime as 50 lb. In another group of columns 5 per cent celite by weight was used as an admixture to the cement mortar in order to provide for the necessary plasticity. A third group had 15 per cent by weight of ordinary brick clay added to the mortar. The sieve analysis of the brick clay was as follows.

| Per Cent Retained on Sieve No. | | | | | |
|---|---|---|---|---|---|
| 200 | 100 | 48 | 28 | 14 | 8 |
| 84.6 | 77.0 | 66.4 | 50.4 | 27.7 | 5.3 |

The 1:3 cement mortar which contained no admixture lacked plasticity and was considered unpractical for ordinary masonry. The addition of 15 per cent hydrated lime improved the plasticity somewhat, but did not produce the necessary workability. The 5 per cent celite improved the workability of the mortar but did not produce the plasticity obtained by 100 per cent hydrated lime or 15 per cent clay. Every indication pointed towards the mortar containing 15 per cent clay as the more desirable one. It had the plasticity of the 100 per cent hydrated lime mortar and had strength nearly equal to that of the straight portland cement mortar. The results of the compressive strength at 28 days of 3 by 6-in. mortar specimens made from different batches of mortar gave average values of 2790, 1420, 2290 and 2370 lb. per sq.in. for

straight cement mortar, mortar containing 100 per cent lime, 5 per cent celite and 15 per cent clay, respectively.

The longitudinal reinforcement consisted of four bars with milled ends bearing directly against the end plates of the columns. The physical properties of the longitudinal reinforcement were as follows:

| | | Tensile Strength lb. per sq.in. | | Elongation in 10 in. |
|---|---|---|---|---|
| | | Y.P. | Ult. | per cent |
| 1 in. diam. | intermediate | 43,600 | 83,000 | 20.5 |
| 1/8 in. square | high strength | 60,000 | 92,500 | 22.2 |
| 1/2 in. square | high strength | 94,500 | 132,500 | 6.0 |

The lateral reinforcement consisted of soft steel tied of either 3/8 or 1/4 in. diameter, placed in different mortar joints. The ties were bent into 8-in. square sections with at least 5-in. laps. One column had wall strips for lateral reinforcement. Table II gives the information for the columns used in this investigation.

## 6. CONSTRUCTION AND STORAGE OF COLUMNS

The reinforced brick columns were constructed by brick masons in the employ of a contractor in Allentown. Generally, a column was completed in one day. Occasionally, however, a column was one-half completed on one day and finished on the next day. The lateral ties were pressed into the mortar in the joints where they were used. The thickness of the mortar joints was approximately 1/2 inch. The longitudinal reinforcement was lined up on the base plate before the construction of the column began, the brick followed the alignment of the steel, and the last layer of brick was slightly below the top of the steel. After the columns were completed they were capped by a 1:1 cement mortar. The capping plate was pressed down so as to bear against the milled ends of the longitudinal reinforcing steel.

The columns were stored on the main floor of the laboratory. During the first seven days the columns were sprinkled with water once in the morning and once in the afternoon. The last five columns, however, were sprinkled with water only at the age of one day.

## 7. METHODS OF TESTING

A few of the columns were tested at the age of 7 days while the majority were tested at the age of 28 days. The columns were placed in the testing machine with both base and top plates attached to the columns. The base of the column rested directly on the table of the testing machine, and on the top of the column the load was transferred from the moveable head of the machine to the column by means of a spherical bearing block. The load was applied in increments of either 25,000, 50,000, or 100,000 lb. A complete set of deformation observations was taken after each increment of loading. The deformation instruments were removed when the columns had been loaded to approximately two-thirds of their strength, and further load was applied gradually until the ultimate strength was reached.

## 8. DEFORMATIONS

The longitudinal deformations were observed at each increment of loading by means of 1/1000-in. Ames dials working on a gage line of about nine feet. The dials were clamped to a collar which was attached to the column about 6 in. from the bottom. Steel bars (1/2-in. square) were clamped to a collar which was attached to the column at about 6 in. from the top of the column. These bars bore against the plunger of the dials which were attached to the collar near the base of the column. The total movement of the two collars was registered by the dials. Lateral deformation measurements were taken on some of the columns by means of 1/10,000-in. Ames dials. These dials were so attached to steel frames as to give the deformation in a gage length of about 11 in. Lateral deflection measurements were taken on the first group of columns, but due to the smallness of the deflection these measurements were abandoned. Two of the columns had Huggenberger tensometers attached to the bricks and also across the mortar joint. These instruments gave the relative deformation of the brick and the joint, and also furnished data from which to compute the modulus of elasticity of the brick. The stress-strain curve for the brick and for the joint is shown in Fig. 3. It is noted that the initial modulus of elasticity of the brick was about 5,000,000 lb. per sq.in.

## 9. TYPES OF FAILURE

Three distinct types of failure occurred. The columns which had no reinforcement collapsed completely upon reaching the maximum load. The columns with longitudinal, but no lateral reinforcement showed vertical splitting. When the load approached the maximum, sounds of cracking were heard and vertical cracks were seen to follow the vertical mortar joints and straight through the brick between these joints. Thus, long vertical cracks occurred and at maximum load the column failed in sections as is indicated in the photograph shown in Fig. 4. The columns which had both longitudinal and lateral reinforcement showed local failure without collapsing. For small amounts of lateral reinforcement the cracks followed the vertical joints as for columns without lateral ties. Fig. 5 shows a typical failure of a column with both longitudinal and lateral ties. With large amounts of lateral reinforcement, however, the splitting action took place at the layer of the ties and the bricks spalled off outside the ties, causing failure by buckling, as shown in Fig. 6.

## 10. TYPE OF MORTAR

The type of mortar used for reinforced brick columns had a marked effect upon their strength. Columns 18, 19 and 20 were identical except for the type of mortar used. The masons were strongly in favor of the mortar containing 15 per cent clay. This mortar stuck to the trowel and could be worked better than any of the other mortars included in the investigation. From a workability standpoint the mortar containing 100 per cent lime was the second choice of the masons. However, the high lime content reduced the strength of the mortar to such an extent as to eliminate this type where high strength was required. The 5 per cent celite gave a fairly plastic mortar, but could not compete with the 15 per cent clay and the 100 per cent lime mortar. Mortar containing 15 per cent lime was difficult to handle and so was the straight cement mortar to a still greater extent. The strength of the column containing mortar with 15 per cent clay was greater than for a straight cement mortar and for a mortar containing 5 per cent celite. No doubt the better workability gave a more compact joint and therefore contributed to the strength. In general the stronger the mortar used, the stronger was the column. For these columns the cement mortar containing 15 per cent ordinary clay was by far the most satisfactory mortar. The stress-strain diagram for columns having straight cement mortar, 15 per cent clay admixture and 5 per cent celite admixture, is given in Fig. 7. Perforated de-aired brick was used in these columns. The combined effect of the type of mortar and type of brick on the modulus of elasticity of the column is shown in Fig.8. The results of tests on the 33 columns included in this investigation are given in Table II.

## 11. EFFECT OF TYPE OF BRICK

Three types of bricks were used, old type solid stiff-mud brick, de-aired solid brick, and de-aired perforated brick. For mortar containing 100 per cent lime the columns with solid de-aired bricks were about 1000 lb. per sq.in. stronger than similar columns with perforated bricks. For straight cement mortar the difference in strength was less. The de-aired perforated bricks, however, gave strength of columns in excess of those with ordinary solid stiff-mud bricks. Column 22 had an inferior type of an under-burned solid de-aired brick. The strength of this column was therefore correspondingly lower than that of other columns having solid de-aired bricks. For given conditions it may be considered that the strength of the column is in proportion to the strength of the brick used.

### 12. EFFECT OF WORKMANSHIP

The workmanship of the masons affected the strength of the columns. While this workmanship varied considerably, a variation in strength as great as 100,000 lb. (or 600-700 lb. per sq.in.) may be attributed to this cause. The variation was naturally different for the different types of mortar used, but in general the mason who built the stronger columns with one type of mortar would also do so with another type of mortar.

### 13. EFFECT OF REINFORCEMENT

The longitudinal reinforcement contributed both to the rigidity and the strength of the columns. In general, the larger reinforcing bars did not contribute their full yield-point strength nor did they contribute their full elastic rigidity as seen from Fig. 9. This is probably due to the difficulty of producing as good a center portion of the column with the large bars in place as with smaller or no bars. The small bars (1/2-in. square) contributed their full elastic rigidity and also added their full yield-point value to the strength of the column. Fig. 10 shows a load-deformation diagram for a column with small vertical bars. In the design of reinforced brick columns account may therefore be taken of the full yield-point value of the longitudinal reinforcement, provided the bars are small and sufficient lateral reinforcement is used.

While the lateral ties did not seem to contribute directly to the strength of the columns, they influenced the type of failure materially. Fig. 4 and 5 show the type of failures of reinforced brick columns with and without lateral ties. For columns with no lateral ties the vertical fracture completely disrupted the column, while for the columns with sufficient lateral ties the failure was localized and the main part of the column remained unbroken. The amount of lateral ties did not seem to affect the type of break until too large diameter ties were used. For 3/8-in. diameter ties in every or every other joint, the type of failure was of the nature illustrated in Fig. 6. Instead of cracking along the vertical joints and straight across the bricks in line with the joints, these columns cracked in line with the location of the ties. The bricks broke off in line with the ties and the columns failed in a typical buckling fashion. The increase in thickness of the joints with the heavier ties probably tended to decrease the strength of the columns.

The test results indicated that 1/4-in. diameter ties in every fourth joint would be sufficient as lateral reinforcement for the 12-1/2 in. square columns used in this investigation. The diameter of the lateral reinforcement should be 1/2 or less of the thickness of the mortar joint. Welded ties did not give as high a strength as lapped ties. The excess thickness of the ties due to the welding, probably caused local failures before the full strength of the column was reached. Ordinary wall strips used as lateral reinforcement did not have any effect upon the behavior of the column.

## 4. DESIGN OF REINFORCED BRICK COLUMNS

While this investigation did not cover all the features involved in the structural behavior of reinforced brick columns, it furnished information on which to base preliminary design formulas.

For proper workmanship under rigid inspection the strength of the reinforced brick column having sufficient lateral reinforcement, may be estimated as made up of the effective strength of the brick, plus the yield-point strength of the longitudinal reinforcement. The effective strength of the brick is a function of the strength of the brick, the strength and workability of the mortar, the proportions of the column, the workmanship of the masons, the thickness of the mortar joint, and the curing of the masonry. The strength formula may therefore be expressed as:

$$S = A_b \cdot f'_b \cdot k + A_s f_s \qquad (1)$$

or, since $A_b$ is nearly equal to A:

$$S = A(k \cdot f'_b + p \cdot f_s) \qquad (2)$$

where:

- $S$ = total strength of column
- $A$ = total area of column
- $A_b$ = area of brick masonry
- $A_s$ = area of longitudinal steel
- $f_b''$ = ultimate strength of brick
- $f_s$ = yield-point stress of longitudinal steel
- $p$ = ratio between area of longitudinal steel and of column
- $k$ = effectiveness ratio of brick masonry, that is, ratio between the strength of masonry and the strength of the brick used.

The permissible working load may be considered equal to 1/4 of the ultimate load, or the factor of safety equal to 4. Thus the design working load would be equal to:

$$P_b = A.f_b = \frac{S}{4} = \frac{k}{4}A_b.f_b'' + \frac{f_s}{4}.A_s = \frac{A}{4}(k.f_b'' + p.f_s) \quad (3)$$

or the working stress:

$$f_b = \frac{1}{4}(k.f_b'' + p.f_s) \quad (4)$$

A factor of safety of 4 is considered ample, especially so in view of the fact that the factor of safety on ultimate strength for reinforced concrete columns proposed by the column committee of the American Concrete Institute is as low as 2-1/2 for fast loading and 2.0 for sustained load.

The value of k should be determined from experiments. A convenient method for determining k would be to make tests on small plain brick columns containing the proper type of brick and mortar, and the same workmanship and other conditions as that to be used in the structure. With k equal to 0.30, brick of 12,000 lb. per sq.in. compressive strength, 1 per cent longitudinal steel of 60,000 lb. per sq.in. yield-point stress, the working stress would be:

$$f_b = \frac{1}{4}(0.30 \times 12{,}000 + 0.01 \times 60{,}000)$$

$$= \frac{1}{4}(3600 + 600) = 1050 \text{ lb. per sq. in.}$$

## 15. SUMMARY

The most important results obtained in this investigation may be summarized as follows:

1. Portland cement mortar containing 15 per cent common brick clay as an admixture, gave better results than any other mortar used in this investigation.

2. Both the plasticity and the strength of the mortar affected the strength of the column.

3. The strength of the brick had a marked effect upon the strength of the column.

4. Columns with no lateral reinforcement collapsed completely upon reaching the maximum load.

5. The lateral reinforcement had little if any direct effect upon the strength of the column, but generally determined the type of failure.

6. Lateral ties 1/4 in. diameter in every fourth joint gave sufficient lateral reinforcement for developing the yield-point strength of the longitudinal reinforcement.

7. With sufficient lateral ties, small longitudinal reinforcing bars added their full yield-point strength to the strength of the column. Large reinforcing bars added only a portion of their yield-point strength.

8. The workmanship of the mason had a marked effect upon the strength of the column.

9. Reinforced brick columns having sufficient lateral reinforcement gave ample warning of impending failure.

10. The strength of a properly reinforced brick column may be computed from the formula:

$$S = A(k.f_b' + p.f_s)$$

11. The safe working stress for properly reinforced brick columns may be computed from the formula:

$$f_b = \frac{1}{F}(k.f_b' + p.f_s)$$

or for a factor of safety of 4:

$$f_b = \frac{1}{4}(k.f_b' + p.f_s)$$

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TABLE I - SUMMARY OF TESTS ON BRICK PIERS AND COLUMNS

| Column Reference No. | Year | No. of Columns | Nominal Height from (in.) | Nominal Height to (in.) | Nominal Lateral Dimensions from (in.) | Nominal Lateral Dimensions to (in.) | Mortar | Strength of Masonry from (lb./sq. in.) | Strength of Masonry to (lb./sq. in.) | Strength Ratio Masonry to Brick from (per cent) | Strength Ratio Masonry to Brick to (per cent) | Approximate Age (months) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1882 | 8 | 20½ | 23 | 8x12 | — | Various | 1562 | 3020 | 12.8 | 24.8 | 5 |
| 2 | 1883 | 6 | 16 | — | 12x12 | — | 1 N.C.-2S | 1021 | 2021 | Not | Given | 22 |
| 3 | 1883 | 12 | 13 | — | 13x13 | — | Various | 699 | 2685 | 10.7 | 26.3 | 15 |
| 4 | 1884 | 33 | 16 | 120 | 8x 8 | 16 x16 | Various | 773 | 3776 | 6.1 | 27.2 | 15 -24 |
| 5 | (1886 & (1891 | 53 | 24 | 150 | 8x 8 | 16 x16 | ( mostly (1 N.C.-2S | 964 | 2798 | 6.4 | 18.2 | 21 |
| 6 | 1893 | 6 | 72 | 96 | 8x 8 | 16 x16 | Various | 601 | 4623 | Not | Given | 2½ |
| 7 | 1895-96 | 17 | 16 | 72 | 9x 9 | — | Various | 296 | 2408 | 10.7 | 60.9 | 2½ |
| 8 | 1895-97 | 57 | 72 | — | 13x13 | 18 x28 | Various | 145 | 1940 | 7.8 | 46.8 | 3 -11 |
| 9 | 1897-98 | 18 | 30 | 78 | 13x13 | — | 1 P.C.-2S | 635 | 1093 | 16.9 | 31.1 | 3½-15 |
| 10 | 1898-99 | 14 | 80 | — | 13x13 | — | 1 P.C.-2S | 780 | 1692 | 22.2 | 48.0 | 7 |
| 11 | 1904 | 26 | 96 | — | 12x12 | — | Various | 465 | 4700 | 8.8 | 41.5 | 1 - 6 |
| 12 | 1905 | 14 | 96 | — | 12x12 | 12½x12½ | Various | 652 | 4552 | 7.4 | 50.0 | 2½- 6 |
| 13 | 1906 | 15 | 96 | — | 12x12 | 12½x12½ | Various | 450 | 3437 | 11.2 | 40.3 | 3½- 8½ |
| 14 | 1906-07 | 32 | 48 | — | 12x12 | — | 1 L - 3½S | 178 | 594 | 7.3 | 35.0 | 1½-15½ |
| 15 | 1907 | 32 | 96 | — | 12x12 | — | Various | 730 | 5608 | Not | Given | 24 |
| 16 | 1907 | 16 | 120 | — | 12x12 | — | Various | 1030 | 4110 | 12.7 | 38.4 | 2 - 6 |
| 17 | 1913 | 2 | 144 | — | 48x48 | — | Various | 757 | 2917 | 7.5 | 28.9 | 1 |
| 18 | 1914-15 | 69 | 84 | — | 8x 8 | — | Various | 1032 | 4435 | 14.6 | 52.1 | ¼- 3 |
| 19 | 1915 | 50 | 60 | 120 | 30x30 | — | Various | 126 | 3800 | 7.6 | 75.1 | 1 - 4 |
| 20 | 1915 | 57 | 5 | 79 | 9x 9 | 11 x11 | Various | 371 | 2340 | 10.2 | 71.8 | 1 |
| 21 | 1918 | 14 | 12 | 108 | 8x 8 | — | Various | 300 | 780 | 30.0 | 78.0 | 3½ |
| 22 | 1919 | 4 | 22 | 27 | 12x16 | — | 1 P.C.-3S | 877 | 2093 | Not | Given | 192 |
| 23 | 1920-21 | 131 | 42 | 84 | 12x12 | — | 1 P.C.-3S | 495 | 2656 | 17.6 | 99.0 | 1 - 3 |

NOTE: Column Reference No. 1, 2, 3, 4, 5, 6, 11, 12, 13, and 15, tested at Watertown Arsenal
No. 7, 20, tested at the University of Toronto
No. 8, tested in England
No.16, tested at the University of Illinois
No.18, 22, 23, tested at Columbia University
No. 9, 10, tested at Cornell University
No.14, tested at Purdue University
No.17, 19, tested at Bureau of Standards
No.20, tested at Swedish Technical Inst.

TABLE II - RESULTS OF BRICK COLUMN TESTS

| Mortar Mix | Admixture in Mortar | Reinforcement per cent | | Maximum Load lb. | Maximum Strength lb/sq.in. | Type of Brick De-Aired |
|---|---|---|---|---|---|---|
| | | Long. | Lateral | | | |
| 1:3 | 15% Lime | 0 | 0 | 738,000* | 4730* | Solid |
| 1:3 | 15% Lime | 0 | 0 | 800 000 | 5130 | Solid |
| 1:6 | 100% Lime | 0 | 0 | 410 500 | 2630 | Perf. |
| 1:3 | 15% Lime | 2.0 | 0 | 800 000* | 5130* | Solid |
| 1:3 | 15% Lime | 2.0 | 0 | 810 000 | 5200 | Solid |
| 1:3 | 15% Lime | 2.0 | 0 | 708 700 | 4540 | Perf. |
| 1:6 | 100% Lime | 2.0 | 0 | 628 200 | 4020 | Solid |
| 1:6 | 100% Lime | 2.0 | 0 | 473 500 | 3030 | Perf. |
| 1:3 | 15% Lime | 2.0 | 1/4"Ties[c] | 800 000* | 5130* | Solid |
| 1:3 | 15% Lime | 2.0 | 1/4"Ties[c] | 752 000 | 4820 | Solid |
| 1:3 | 15% Lime | 2.0 | 1/4"Ties[c] | 732 500 | 4700 | Perf. |
| 1:6 | 100% Lime | 2.0 | 1/4"Ties[c] | 483 400* | 3100* | Solid |
| 1:6 | 100% Lime | 2.0 | 1/4"Ties[c] | 584 200* | 3740* | Solid |
| 1:6 | 100% Lime | 2.0 | 1/4"Ties[c] | 671 000 | 4300 | Solid |
| 1:6 | 100% Lime | 2.0 | 1/4"Ties[c] | 527 700 | 3380 | Perf. |
| 1:3 | 0 | 0.67 | 3/8"Ties[a] | 530 000 | 3400 | Perf. |
| 1:3 | 0 | 0.67 | 3/8"Ties[b] | 452 800 | 2900 | Perf. |
| 1:3 | 0 | 0 | 1/4"Ties[b] | 479 300 | 3070 | Perf. |
| 1:3 | 15% Clay | 0 | 1/4"Ties[b] | 594 300 | 3800 | Perf. |
| 1:3 | 5% Celite | 0 | 1/4"Ties[b] | 531 000 | 3400 | Perf. |
| 1:3 | 5% Celite | 0 | 1/4"Ties[b] | 705 000 | 4520 | Perf. |
| 1:3 | 5% Celite | 0 | 1/4"Ties[b] | 562 000 | 3600 | Solid° |
| 1:3 | 5% Celite | 0 | 1/4"Ties[b] | 640 500 | 4100 | ** |
| 1:3 | 15% Clay | 0 | 0 | 657 800 | 4220 | Perf. |
| 1:3 | 15% Clay | 0.67 H.Y. | 1/4"Ties[b] | 800 000 | 5130 | Perf. |
| 1:3 | 15% Clay | 0 | 1/4"Ties[b] | 489 200 | 3140 | Perf. |
| 1:3 | 15% Clay | 0 | 1/4"Ties[d] | 598 600 | 3830 | Perf. |
| 1:3 | 15% Clay | 0 | 1/4"Ties[a] | 609 200 | 3900 | Perf. |
| 1:2 | 15% Clay | 0 | 0 | 636 000* | 4080* | Solid |
| 1:2 | 15% Clay | 0.67 H.Y. | 0 | 690 000* | 4420* | Solid |
| 1:2 | 15% Clay | 0.67 H.Y. | 1/4"Ties[c] | 800 000* | 5130* | Solid |
| 1:2 | 15% Clay | 0.67 H.Y. | Flats [c] | 659 000* | 4220* | Solid |
| 1:2 | 15% Clay | 0.67 | 1/4"Ties[c] | 715 000* | 4580* | Solid |

* Tested at the age of 7 days, all others tested at 28 days.

° Underburned, low strength brick.

** Solid stiff mud brick.

a, b, c, d, reinforcement in every 1st, 2nd, 3rd and 4th joint, respectively.

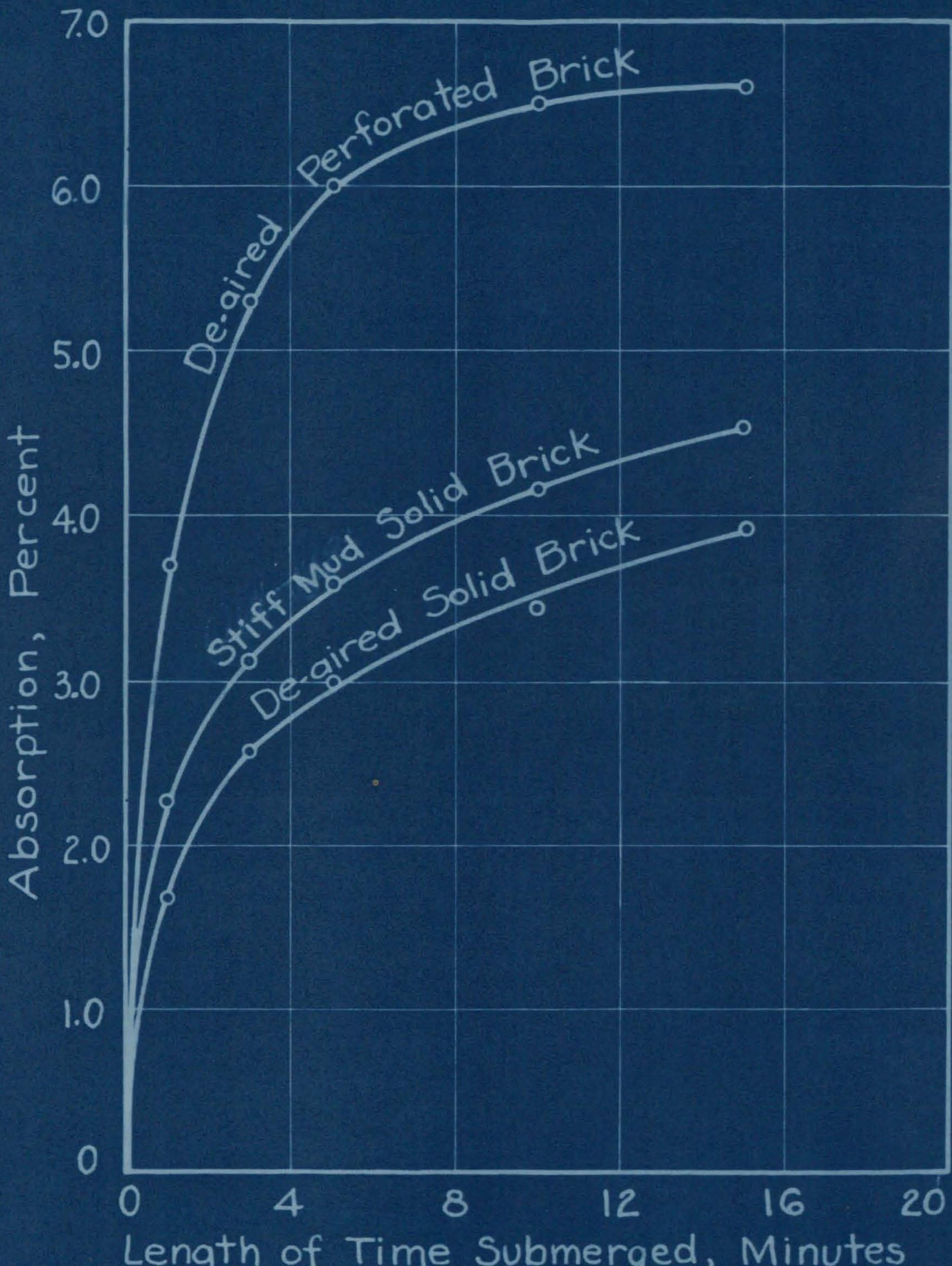


Fig 1-Rate of Absorption for Brick

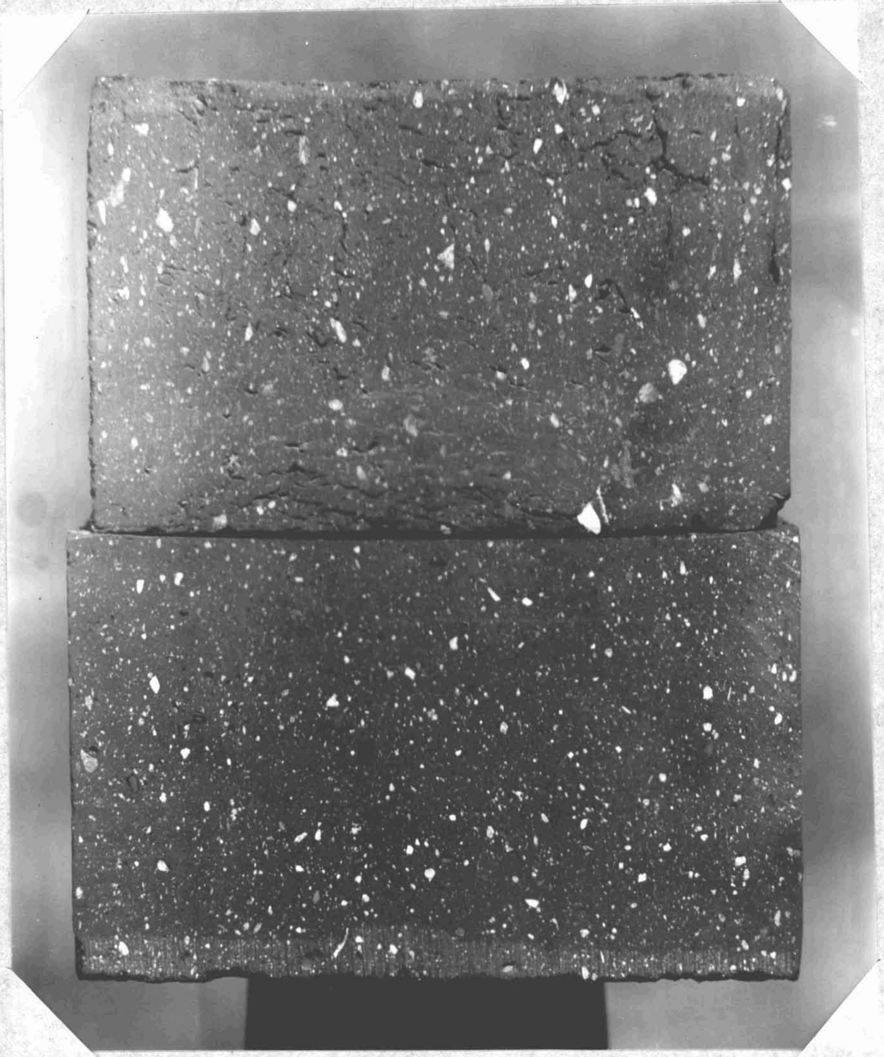

Fig. 2 - Structure of Brick

Top, Stiff-Mud Brick
Bottom, De-Aired Brick

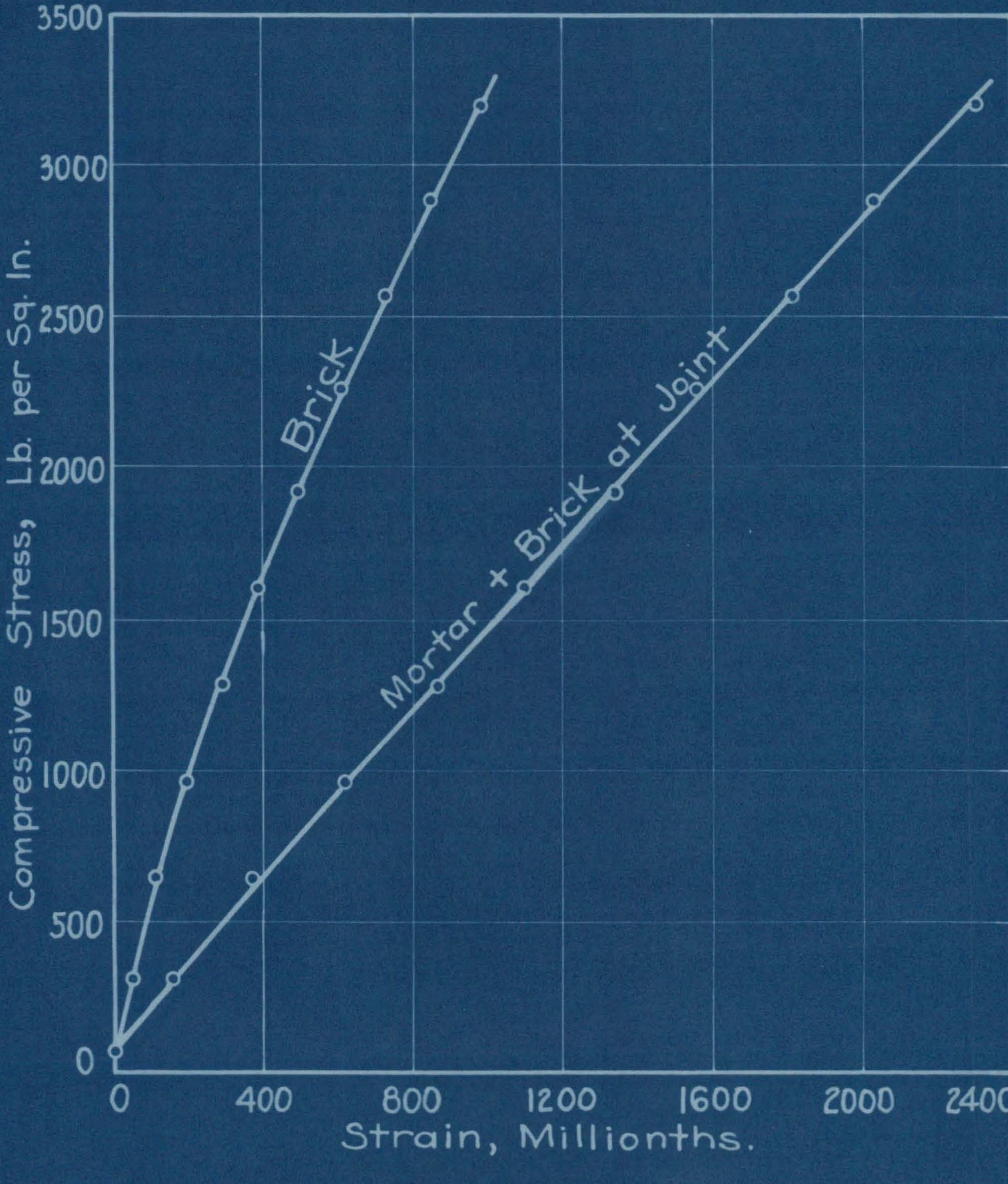


Fig 3 – Deformation Diagram for Brick and for Mortar Joint.

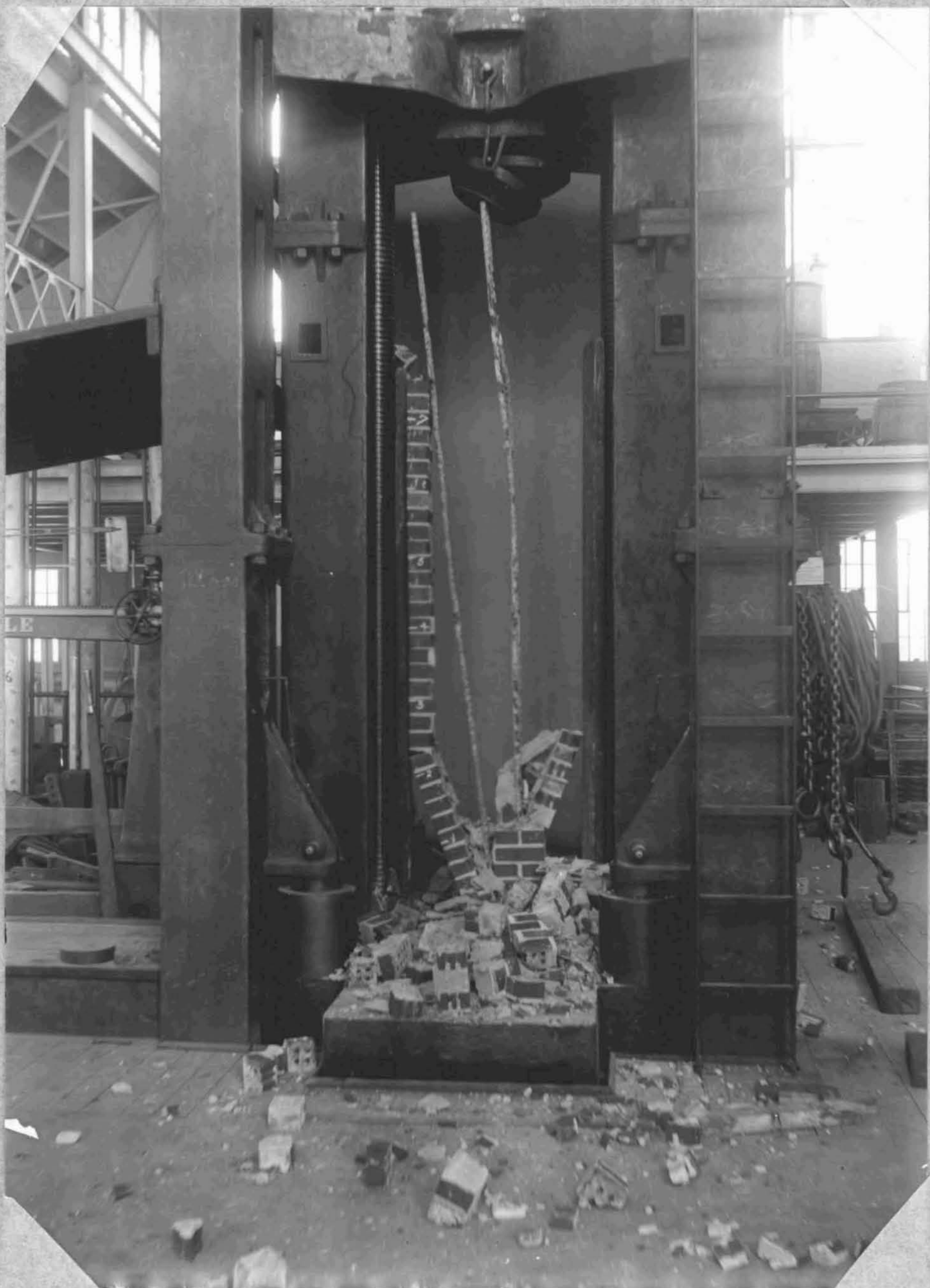

Fig. 4 - Failure of Columns Having
No Lateral Reinforcement.

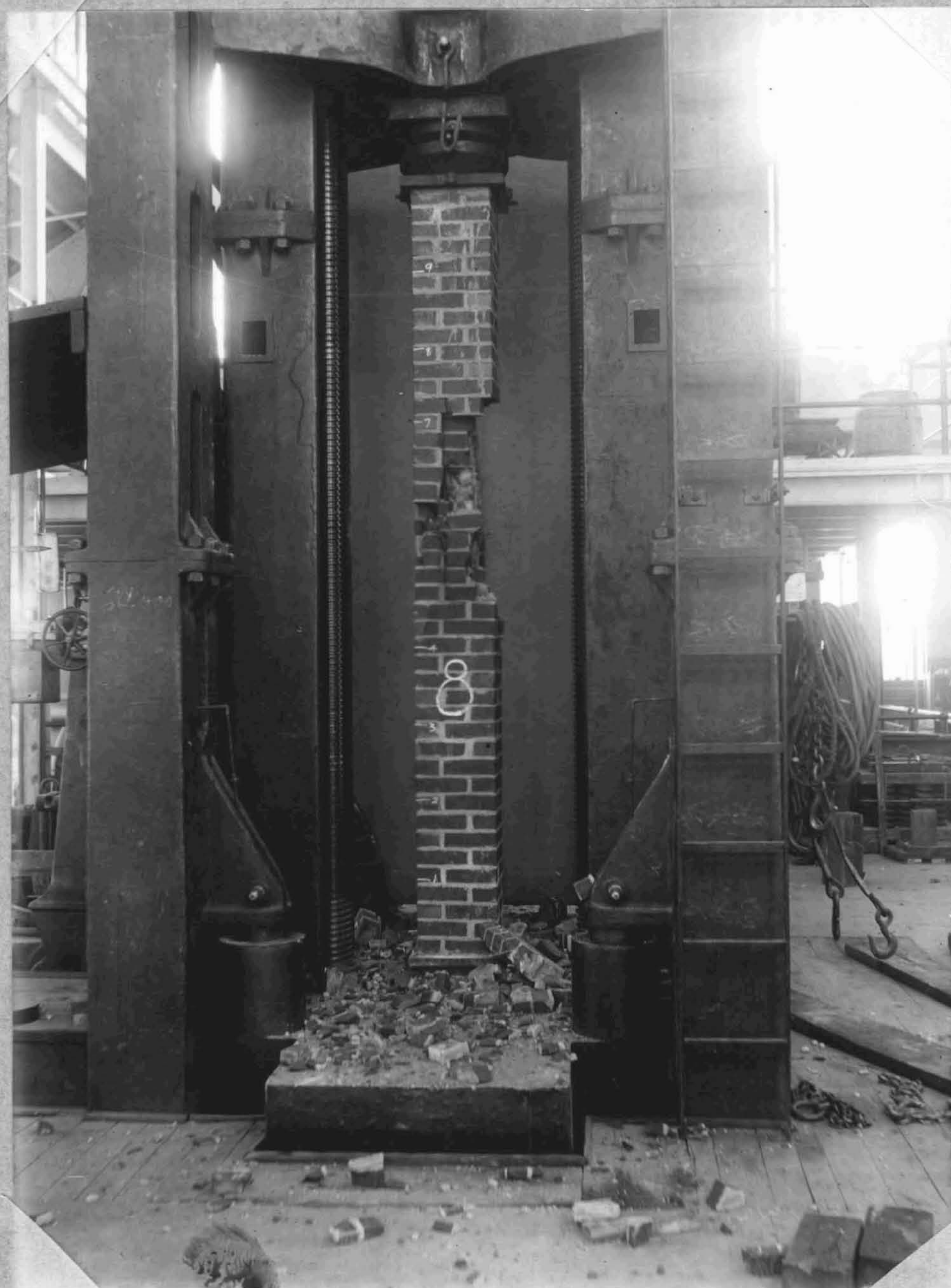

Fig. 5 - Failure of Columns Having

1/4-in. Diameter Lateral Ties

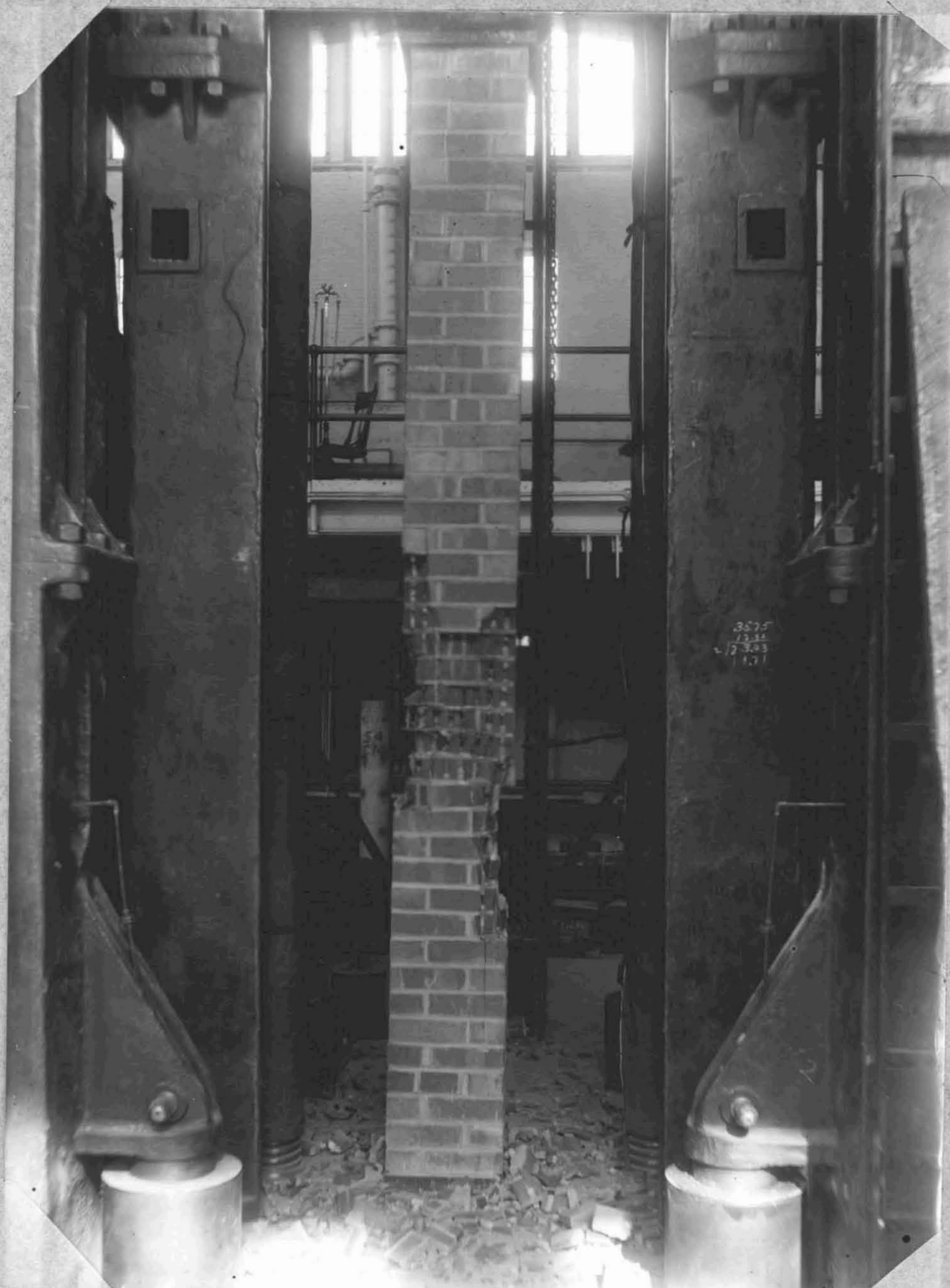

Fig. 6 - Failure of Columns Having
3/8-in. Diameter Lateral Ties

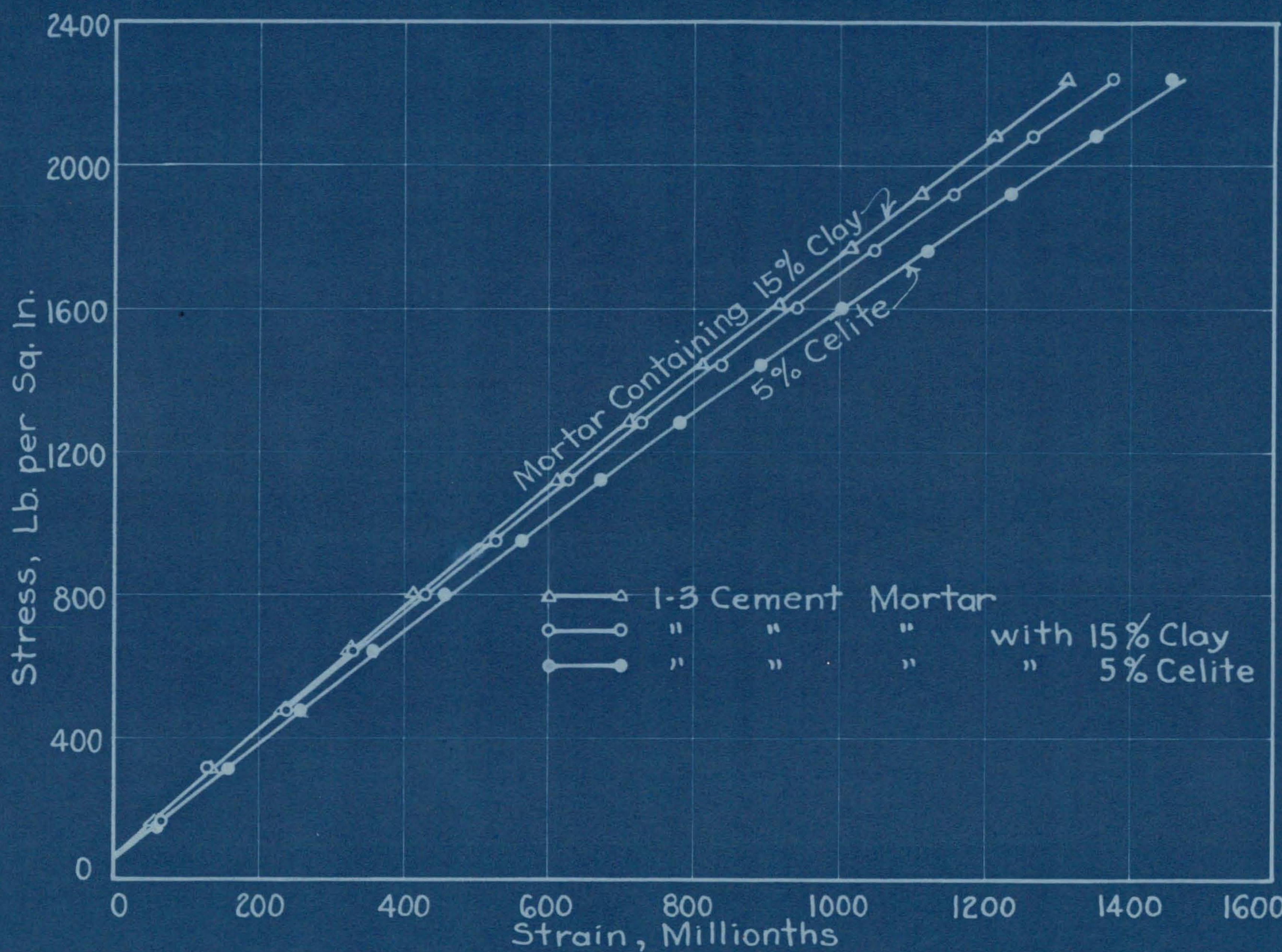


Fig 7 Effect of Type of Mortar on Elastic Properties of Perforated Brick Columns

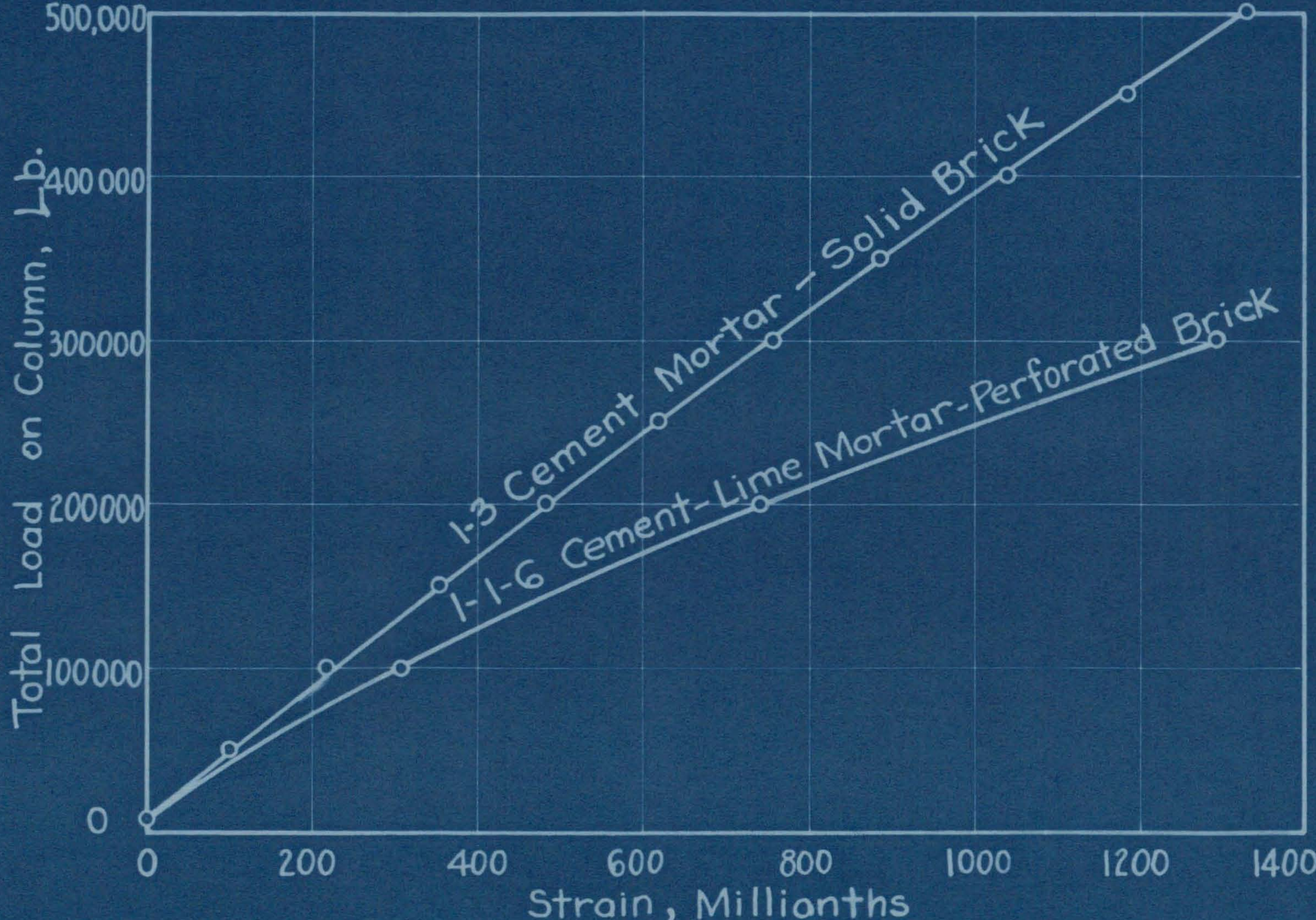


Fig 8 - Deformation of Plain Brick Columns.

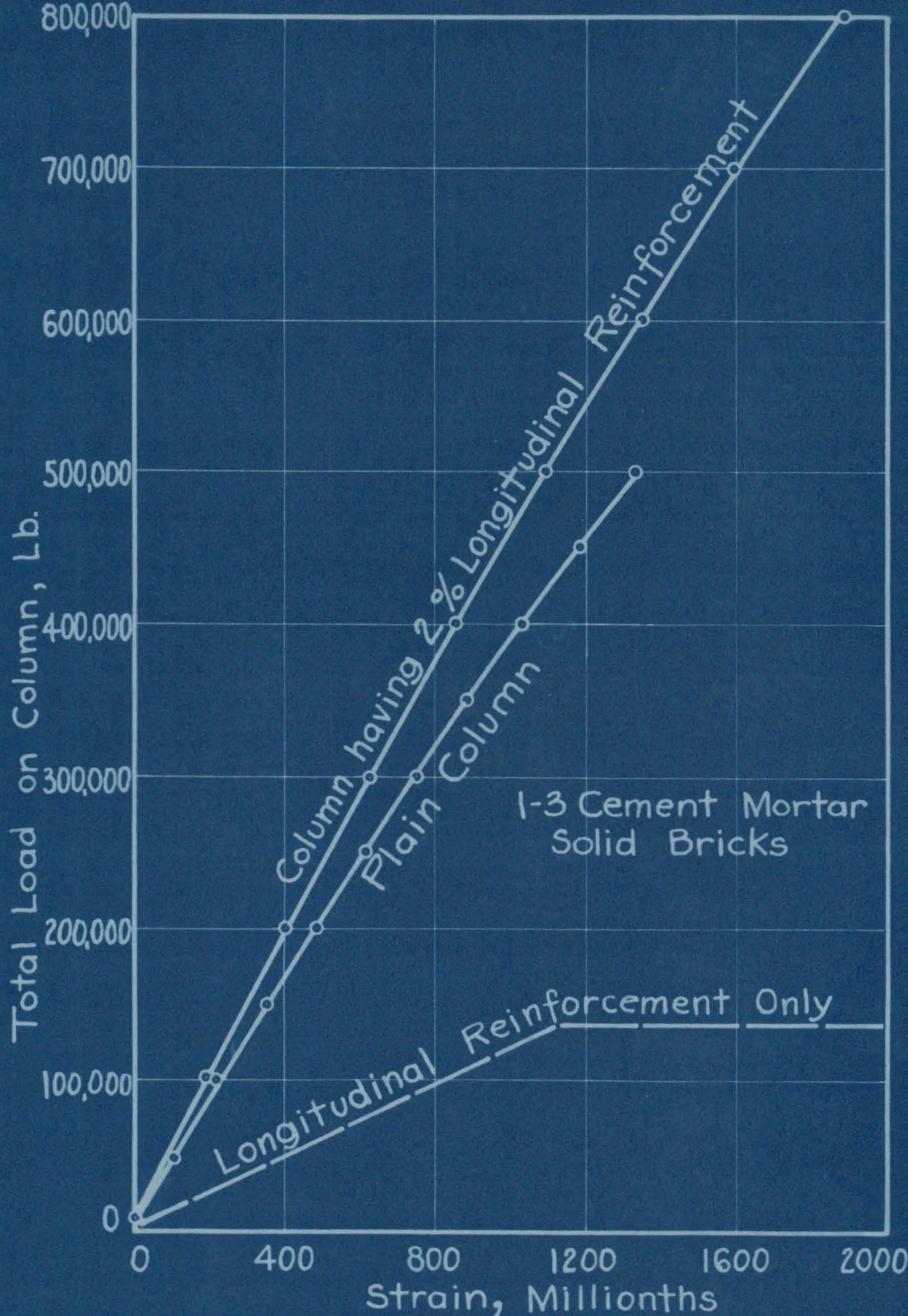


Fig. 9 - Effect of Longitudinal Reinforcement on Deformation of Column.

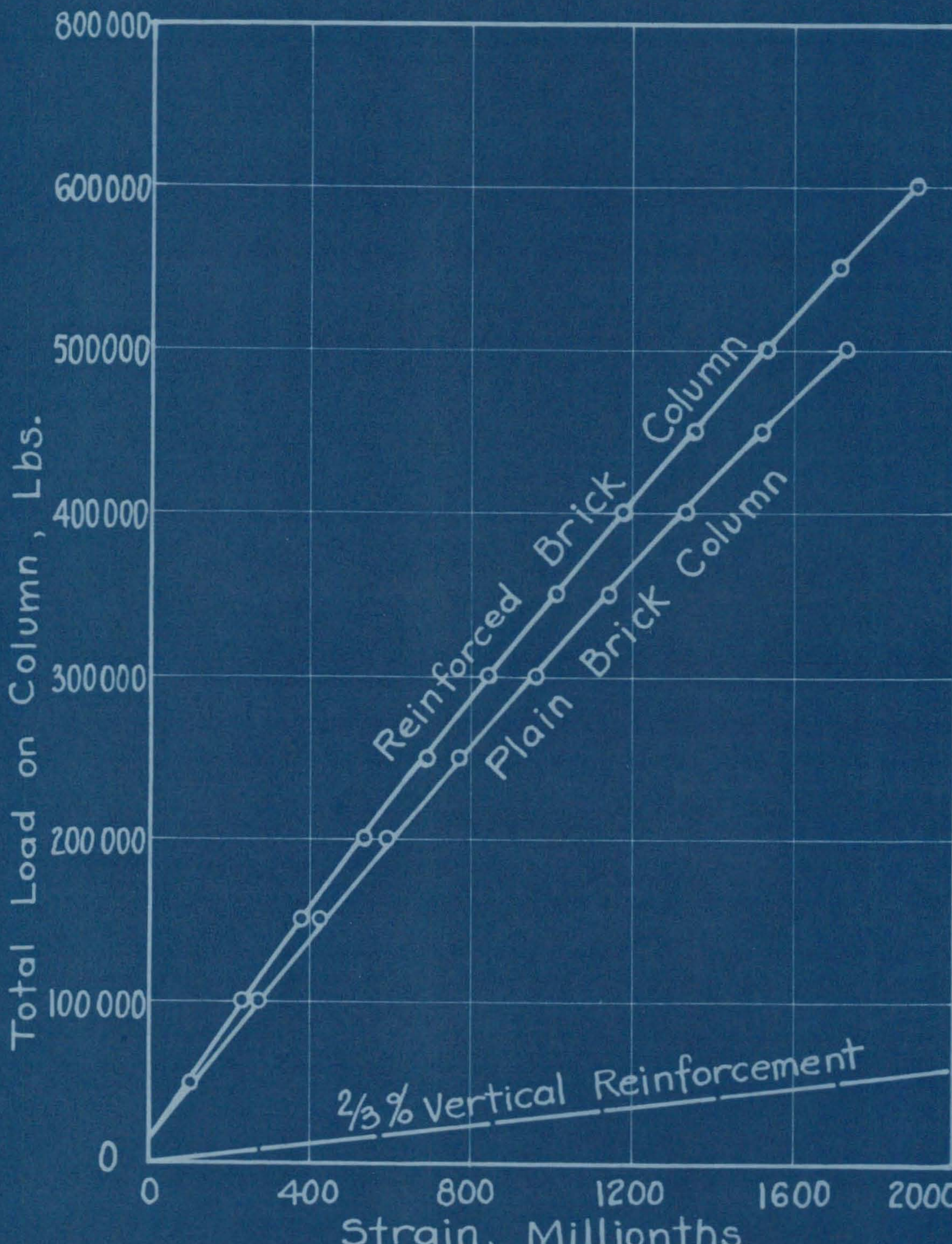


Fig 10- Load Deformation Diagram for
Plain and Reinforced Brick Columns.

# BOND TESTS OF DIFFERENT TYPES OF REINFORCING BARS

by Inge Lyse*

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## I. INTRODUCTION

At the request of representatives of the Kalman Steel Company, a subsidiary of Bethlehem Steel Company, Bethlehem, Pennsylvania, the Fritz Engineering Laboratory of Lehigh University conducted an investigation of the bond between steel and concrete for different types of reinforcing bars. The Kalman Steel Company has recently brought out a new design of reinforcing bar, called the Bethlehem Bar, and it was the purpose of this investigation to study the merits of this new bar on the basis of its bond properties. The difference between the Corrugated bar and the Bethlehem bar is that the Corrugated bar has transverse ribs while the Bethlehem bar has continuous diagonal deformation ribs. In order to make this investigation at the least possible expense, pull-out tests were used for the determination of the bond properties. A total of four different types of 7/8-in. diameter reinforcing bars were used in two different grades of concrete. Furthermore, tests were made on the bonding properties of square bars and of round bars having equal cross-sectional area.

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## II. MATERIALS AND TEST SPECIMENS

Pull-out tests were made by applying tension to one end of the bar which was embedded axially in a 6 by 12-in. concrete cylinder. The concretes used for the 7/8-in. diameter bars were designed to have compressive strengths of 2000 and 3500 lb. per sq.in. Concretes of design strength of 2000 lb.per sq.in. were used in the study of square and round bars. The compressive strength of the concrete was determined on 3 by 6-in. cylinders made simultaneously with the bond specimens. A total of 33 bond tests and 21 compression tests were made.

The design of the concrete mixes is shown in Table 1. Nazco cement was used in order to produce sufficient strength of the concrete at the age of test, which was seven days. The specimens were made in accordance with standard practice. They remained in the molds for 24 hours and were cured in the moist room for six days.

In one group of tests the reinforcing bars consisted of nominal 7/8-in. diameter bars of Corrugated, Bethlehem, Havemeyer and Plain designs. Another group consisted of 1-in. and 1-1/4 in. square corrugated bars and round Bethlehem bars having cross-sectional area equal to that of the square bars. The types of bars used are illustrated in Fig. 1.

The pull-out tests were made in accordance with ordinary methods. Fig. 2 shows the testing arrangement. Plaster of Paris was used for securing uniform bearing of the concrete on the plate which was on the top of the testing machine. The bearing plate had a 1-1/8 in. diameter hole for the 7/8-in. bars and a 1-7/8 in. hole for the 1-in. and the 1-1/4 in. square bars. The slip of the bars during loading, was measured by means of a 0.0001-in. Ames dial supported by a frame-work carried by the concrete specimen, with the moving plunger of the dial in contact with the free end of the test bar.

The original data of all the bond tests are presented in sheets 1 to 14.

## III. DISCUSSION OF TESTS

The bond between steel and concrete may be recognized at two distinct stages, the adhesion bond and the friction bond. The adhesion bond determines the bond at initial slip of the bar and the friction bond determines the amount of resistance offered after the initial slip has occurred. Table 2 gives the results of all the tests. It is noted that the average compressive strengths of the two concrete mixes used for the 7/8-in. diameter bars were 2090 and 3450 lb. per sq.in. Table 2 also gives the individual and average loads at initial and final slip. Initial slip was taken at the load at which the total slip of the end of the embedded bar was as much as 0.00005-in. The 7/8-in. diameter bars gave very uniform results for both initial and final slip. The 1-1/4 in. bars gave more irregular results, especially for final slip. It is of interest to note that for the 3450 lb. per sq.in. concrete the Corrugated and the Bethlehem bars of 7/8-in. diameter passed the yield-point stress of the bars before final slip occurred. The yielding of the bars took place at a load between 26,000 and 27,000 lb. corresponding to a yield-point stress in the bars between 43,000 and 45,000 lb. per sq. in.

Table 3 gives the average bond stress at initial and final slip for the different types of bars used. In order to make the results more illustrative, the stresses at first slip have been plotted in Fig. 3. The stresses at final slip have been plotted in Fig. 4. It is evident from these figures that for the 7/8-in. diameter bar the Corrugated and the Bethlehem bars gave nearly the same results, the Corrugated being slightly higher, both with respect to initial and final slip. The difference between Corrugated and Bethlehem bars, however, is so small that it is within the limit of the experimental errors of this investigation. These bars were found to develop bond stresses far in excess of those for the Havemeyer and Plain bars. The Corrugated and the Bethlehem bars have bond stress at initial slip approximately 100 per cent in excess of the bond stress of the plain bars for both grades of concrete. The bond stresses for the Havemeyer bars at initial slip are only about 41 per cent for the 2090 lb.per sq.in. concrete and 13 per cent for the 3450 lb. per sq.in. concrete in excess of the bond stress of the plain bars. For final slip the Corrugated and the Bethlehem bars have more than 200 per cent greater bond stress than have the plain bars for the 2090 lb. per sq.in. concrete, and more than 150 per cent greater than the plain bars for 3450 lb. per sq.in. concrete. The corresponding values for the Havemeyer bars are approximately 140 per cent and 85 per cent for the two grades of concrete.

The 1-in. and the 1-1/4 in. square Corrugated bars gave considerably greater total bond strength, both at initial and final slip, than did the Bethlehem round bars of equivalent cross-sectional area. Since the square bars have about 11 per cent greater area than the round bars, the bond strength was correspondingly higher. However, the bond stress per unit of area was very nearly the same for the two types of bars. Moreover, the 1-in. and the 1-1/4 in. bars gave a considerably lower bond stress both at initial and at final slip than did the 7/8-in. bars of the same designs.

This is due to the difference in numbers of ribs embedded in the concrete. The 7/8-in. bars had 14 ribs in the 12-in. embedment while the 1-in. bars had 11 ribs and the 1-1/4 in. bars had 8 ribs embedded.

## IV. SUMMARY

The following indications are brought out by this investigation.

1. The 7/8-in. diameter bars of Corrugated and Bethlehem design had approximately the same bond stress both at initial and at final slip.

2. The Havemeyer bars had bond stress considerably below the bond stress for the Corrugated and the Bethlehem bars, but in excess of plain bars.

3. For the Corrugated, the Bethlehem, and the Havemeyer bars the bond stress at final slip was more than twice that at initial slip.

4. The bond stress was nearly equal for the square Corrugated bars and the round Bethlehem bars of equivalent cross-sectional area.

5. The number of embedded deformation ribs affected the bond stress materially.

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TABLE 1 - CONCRETE MIXES

2000 lb. per sq.in. concrete - c/w = 1.30 - slump, 4-6 in.

3500 lb. per sq.in. concrete - c/w = 1.90 - slump, 4-6 in.

Age at test - 7 days

Net water content = 38 gallons per cubic yard

Absorption allowance = one per cent by weight of aggregates

Two batches of concrete of each mix

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Materials per batch for 2000 lb. per sq.in. concrete

| | | |
|---|---|---|
| Nazco Cement = | 13,850 grams | |
| Water = | 11,730 grams | |
| Sand = | 95.0 lb. | |
| No.4 - 3/8 in. = | 152.0 lb. | Accumulated |
| 3/8 - 3/4 in. = | 237.0 lb. | Accumulated |

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Materials per batch for 3500 lb. per sq.in. concrete

| | | |
|---|---|---|
| Nazco Cement = | 20,250 grams | |
| Water = | 11,650 grams | |
| Sand = | 90.0 lb. | |
| No.4 - 3/8 in. = | 144.0 lb. | Accumulated |
| 3/8 - 3/4 in. = | 225.5 lb. | Accumulated |

Make eighteen bond specimens (6 by 12-in. cylinders) and six control specimens (3 by 6-in. cylinders) from the both batches of each grade of concrete.

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TABLE 2 - RESULTS OF BOND TESTS

| Strength of Concrete lb./sq.in. | Type of Bars | Size of Bars in. | Load at Initial Slip** Specimen 1 | 2 | 3 | Av. | Load at Final Slip Specimen 1 | 2 | 3 | Av. |
|---|---|---|---|---|---|---|---|---|---|---|
| 2090 | Corrugated | 7/8 dia. | 14,000 | 13,000 | 13,000 | 13,300 | 28,420 | 27,080 | 27,230 | 27,580 |
| 2090 | Bethlehem | 7/8 dia. | 14,000 | 13,000 | 11,000 | 12,700 | 26,940 | 27,250 | 26,950 | 27,050 |
| 2090 | Havemeyer | 7/8 dia. | 10,000 | 8,000 | 10,000 | 9,300 | 21,520 | 18,220 | 22,010 | 20,580 |
| 2090 | Plain | 7/8 dia. | 6,000 | 7,000 | 7,000 | 6,700 | ---- | 8,600 | 8,460 | 8,530 |
| 2040 | Corrugated | 1-1/4 sq. | 18,000 | 18,000 | 19,000 | 18,300 | 34,160 | 34,300 | 35,220 | 34,560 |
| 2040 | Bethlehem | 1-1/4 Eq.* | 17,000 | 17,000 | 16,000 | 16,700 | 32,850 | 28,810 | 31,560 | 31,070 |
| 2350 | Corrugated | 1 sq. | 15,000 | 16,000 | 18,000 | 16,300 | 38,410 | 30,010 | 29,450 | 32,620 |
| 2350 | Bethlehem | 1 Eq.* | 14,000 | 16,000 | 15,000 | 15,000 | 30,310 | 30,460 | 28,940 | 29,900 |
| 3450 | Corrugated | 7/8 dia. | 19,000 | 16,000 | ---- | 17,500 | 35,780 | 37,420 | ---- | 36,600 |
| 3450 | Bethlehem | 7/8 dia. | 15,000 | 16,000 | 15,000 | 15,300 | 36,430 | 36,000 | 36,290 | 36,240 |
| 3450 | Havemeyer | 7/8 dia. | 9,000 | 10,000 | ---- | 9,500 | 25,540 | 25,700 | ---- | 25,620 |
| 3450 | Plain | 7/8 dia. | 9,000 | 7,000 | ---- | 8,000 | 15,000 | 12,920 | ---- | 13,960 |

* Round bar of cross-sectional area equal to that of the square bar.

** Initial slip taken at a total movement of 0.00005-in.

TABLE 3 - BOND STRESS AT INITIAL AND FINAL SLIP

| Strength of Concrete | Type of Bars | Size of Bar (Nominal) | Average Bond Stress At Initial Slip | Average Bond Stress At Final Slip |
|---|---|---|---|---|
| lb./sq.in. | | in. | lb. per sq.in. | |
| 2090 | Corrugated | 7/8 dia. | 404 | 836 |
| 2090 | Bethlehem | 7/8 dia. | 386 | 820 |
| 2090 | Havemeyer | 7/8 dia. | 282 | 624 |
| 2090 | Plain | 7/8 dia. | 203 | 258 |
| 2040 | Corrugated | 1-1/4 sq. | 305 | 575 |
| 2040 | Bethlehem | 1-1/4 Eq.* | 315 | 585 |
| 2350 | Corrugated | 1 sq. | 340 | 680 |
| 2350 | Bethlehem | 1 Eq.* | 352 | 702 |
| 3450 | Corrugated | 7/8 dia. | 530 | 1110 |
| 3450 | Bethlehem | 7/8 dia. | 464 | 1100 |
| 3450 | Havemeyer | 7/8 dia. | 288 | 777 |
| 3450 | Plain | 7/8 dia. | 242 | 423 |

* Round bar of cross-sectional area equal to that of the square bar.

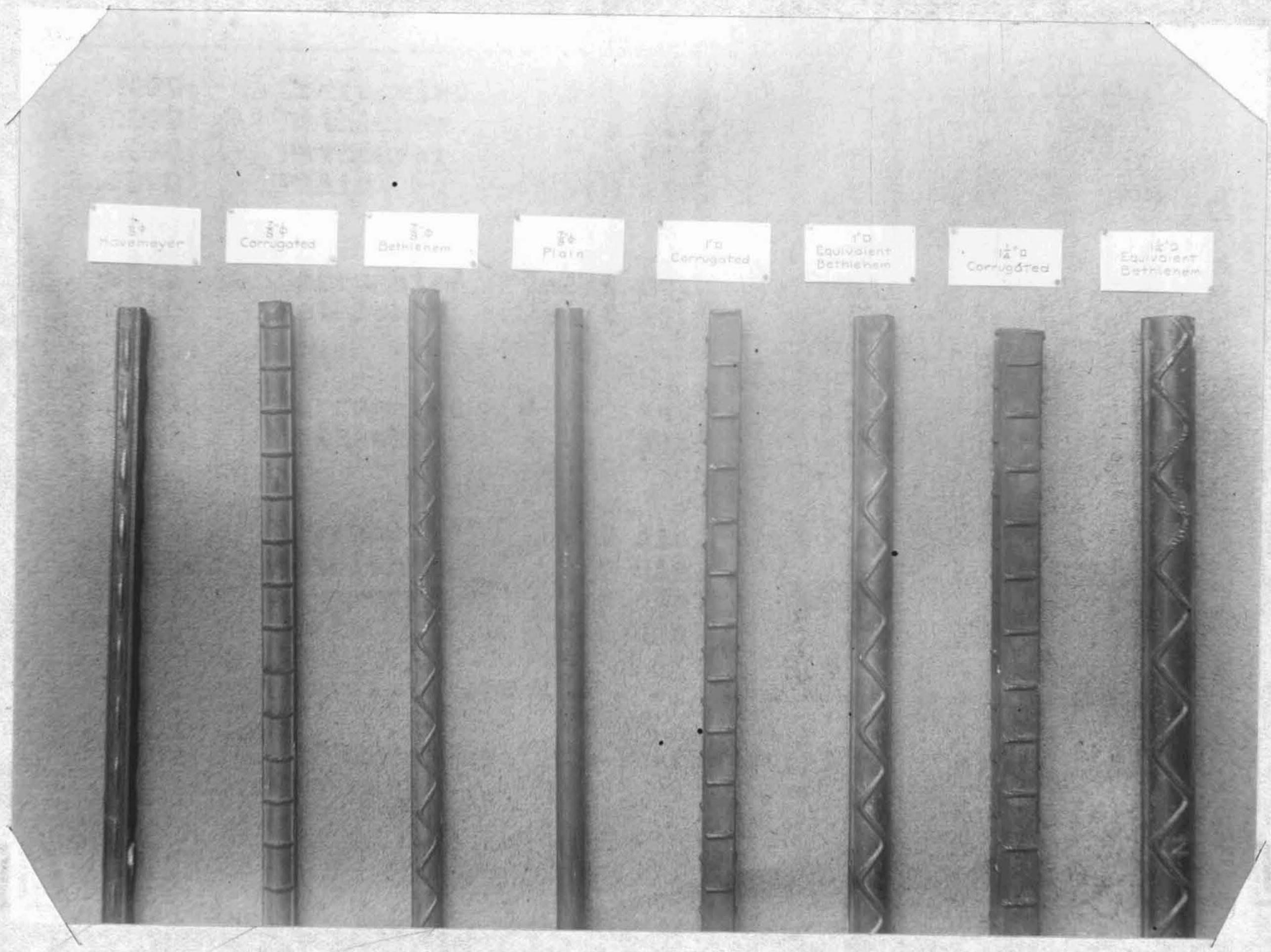


Fig. 1 - Types of Bars

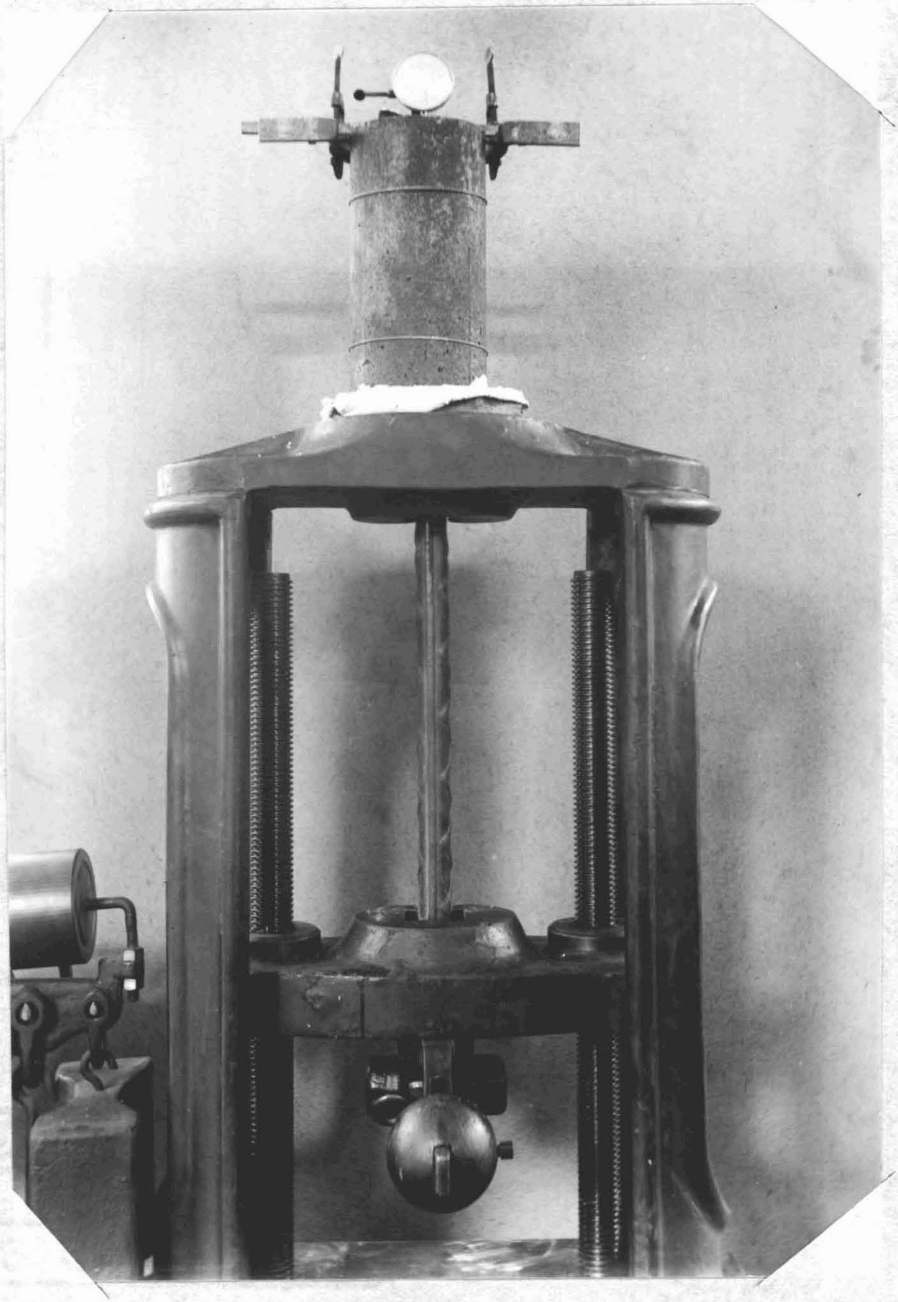

Fig. 2 - Testing Arrangement

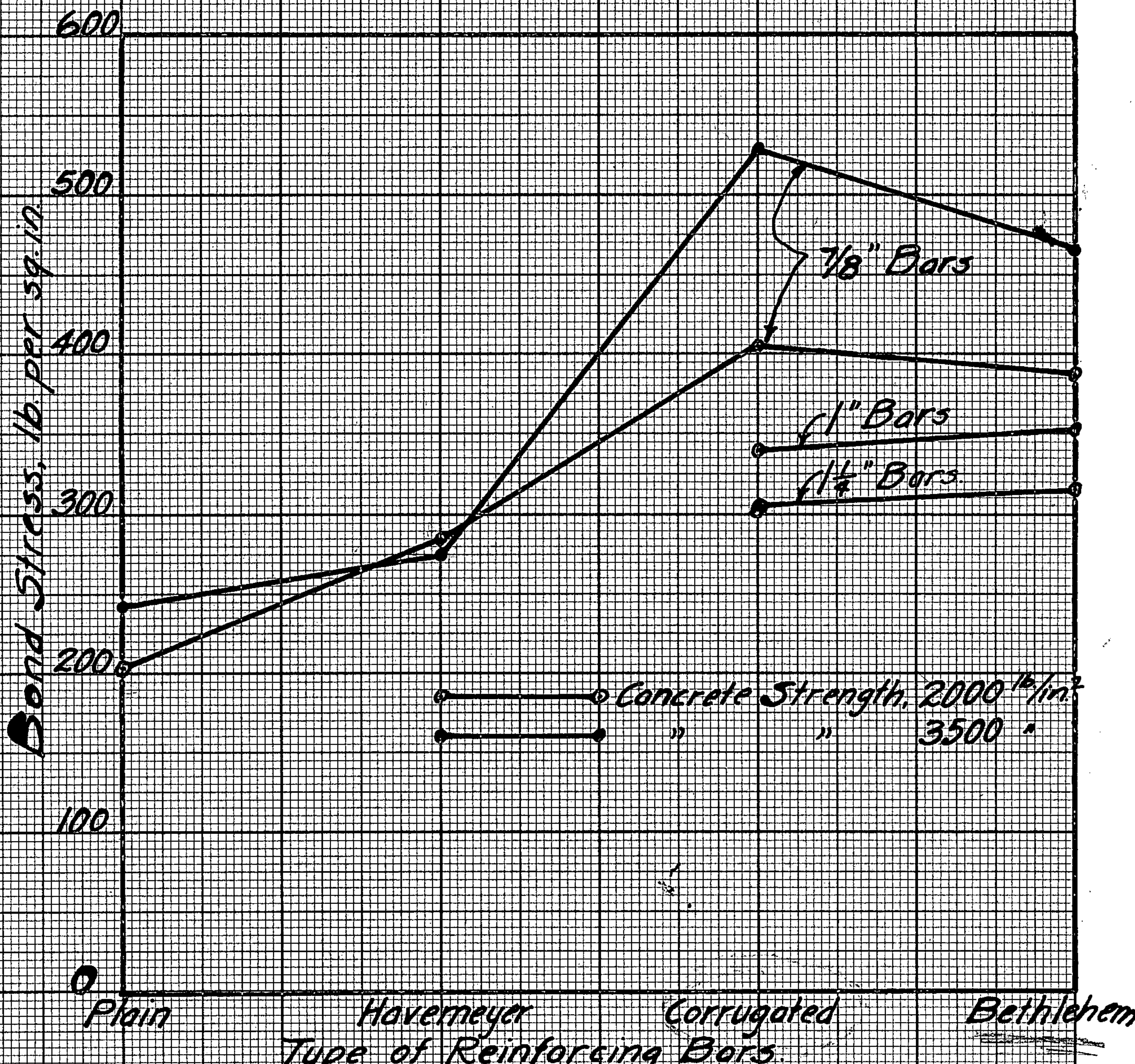


Fig. 3 - Initial Slip of Bars in Pull-Out Tests.

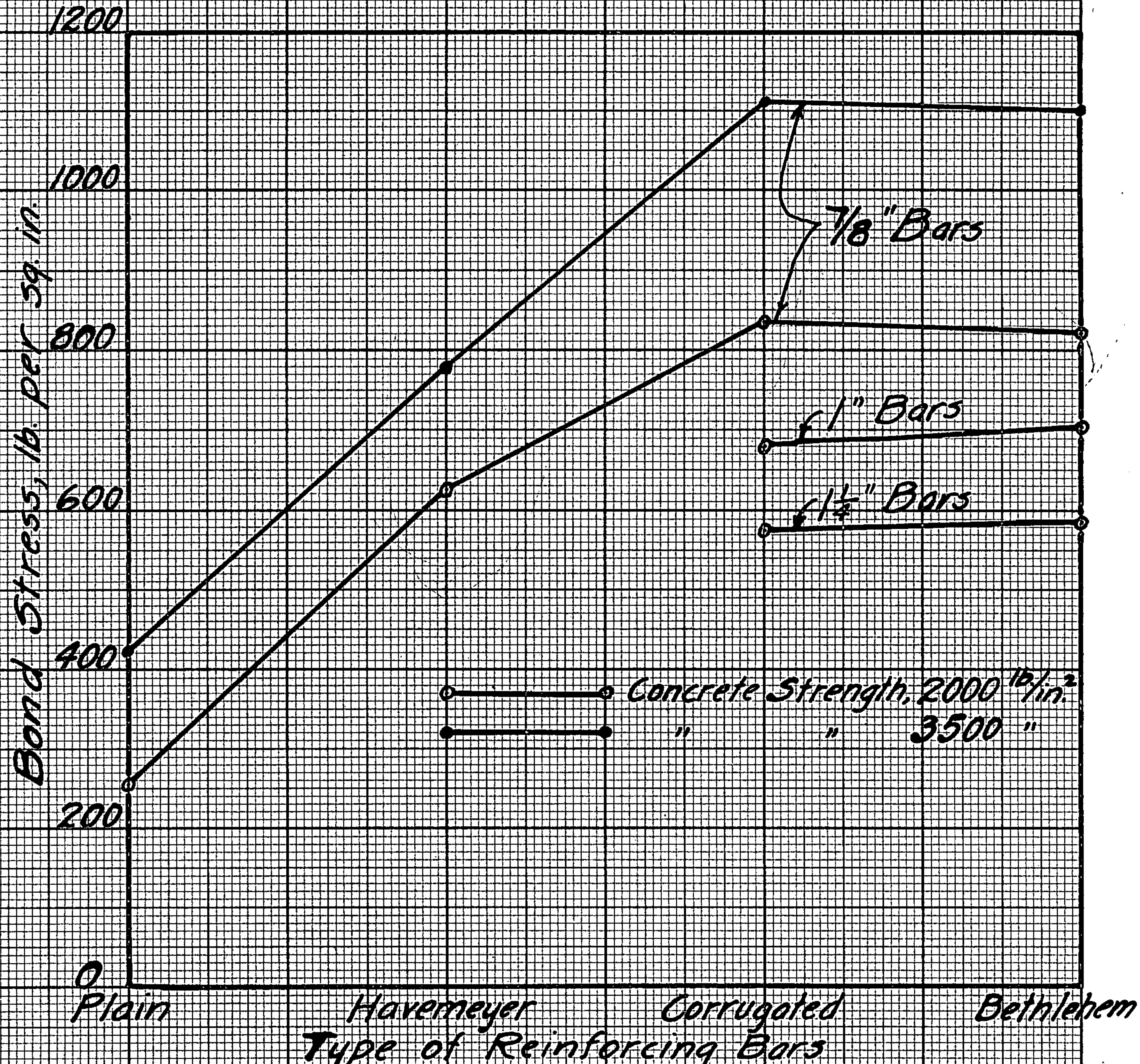


Fig. 4 - Final Slip of Bars in Pull-Out Tests.