1930

Tests of riveted and welded steel columns, 1930

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TESTS OF RIVETED AND WELDED STEEL COLUMNS

for McCLINTIC-MARSHALL COMPANY

by

W. A. Slater and M. O. Fuller

July 1, 1930

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1. The Columns. The program of tests here reported included the testing of eight built-up steel columns furnished for the tests by the McClintic-Marshall Company. Each column consisted of a core, formed by an "I" or an "H" section, and a cover plate attached to each flange of the core. Fig. 1 shows the details of the columns, including the methods of fastening the cover plates to the flanges. As noted, all of the columns were welded except columns 2 and 5, which were riveted. Fig.2 shows a view of a column in the testing machine. Fig. 3 and 4 show columns 1BB, 2, 3, 4, and 5 after they had been tested.

Upon receipt of the columns, it was discovered that column 1 was so much out of alignment that it was not believed to be comparable with the other columns, which were much straighter, especially since a comparison was desired with column 2, its riveted counterpart. A new column, 1BB, was furnished to take its place. However, column 1 was tested in order to study the effect of its lack of alignment on its behavior under load. Previous to testing each column, its departure from a straight line in the direction of each of two planes was measured, one plane parallel to, and the other at right angles to the plane of the cover plates. These departures are shown in Fig. 5. These columns were designed to be counterparts of columns of Types 6 and 6A, tested at the Bureau of Standards for the Special Committee of the American Society of Civil Engineers, on Steel Columns and Struts (see page 1598, TRANSACTIONS, Am.Soc.C.E.,Vol.83, 1919-20). The Special Committee provided three lengths in each type of column and the columns here reported were originally of the intermediate length. However, in this series of tests, in order to provide material for coupons, one foot was cut from the end of each column, making them one foot shorter than the corresponding columns tested for the Special Committee.

The columns were tested with "flat ends" as nearly as this condition could be approached. The top and bottom of each column had been milled for the purpose of giving true bearing surfaces for applying the loads. However, it was discovered that the milling did not give as nearly plane surfaces as might be desired. It is believed that lack of planeness of the ends affected somewhat, the location of the load line in the columns as the loads were applied.

2. Test Coupons. Coupons for the columns were tested in tension for yield point, ultimate strength, and a few for modulus of elasticity. To secure the test coupons, a piece one foot long was cut from each rolled section (plates, I-beams, and H-beams) before the columns were shipped from the McClintic-Marshall shops at Pottstown, Pennsylvania. This made the columns one foot shorter than the lengths originally designated. Four test coupons were taken from each cover plate. Six coupons were taken from each I-section, and eight from each H-section. Hence a total of 14 or 16 coupons were used in obtaining the average yield point and ultimate strength of the steel in each column.

Fig. 6 shows the location and numbering of the test coupons cut from the various sections. In any coupon number, the numeral at the beginning is the number of the column represented. The letter A, when present, indicates that the coupon was taken from the core, that is, from the I-section or the H-section. The letter P indicates that it was taken from one of the plates, while the letter B or C indicates which plate. The final numeral indicates the location in the section, as shown in Fig. 6. Thus 3BP1 was a coupon cut from Column 3, plate B, and location 1. The coupons were arranged with a view of determining whether there were systematic variations of yield point throughout the section.

The tests of the coupons were made in a 50,000-lb. Riehle Universal Testing Machine in the usual manner for tension tests. The yield-point load was determined by the "drop of beam" in the tests in which the modulus of elasticity was not determined. In the modulus tests, the yield point was chosen at the load for which the strain indicated by the gages showed a rapid increase with little increase in load. A Ewing extensometer with a gage length of two inches was used in the modulus of elasticity tests.

Considerable attention has been paid to the determination and weighting of yield point stresses, because the strength of the column is generally found to be more directly a function of the yield point than of the strength of the materials from which the column was made.

The yield point stresses for individual coupons have been plotted in Fig. 7. The horizontal distances between points are proportional to the distances center to center of coupons, so that a horizontal line on the diagram representing the average yield point for all the coupons for a given plate, will be weighted approximately according to the sectional areas represented by the several coupons. Fig. 7(a) shows a tendency for the higher yield points to occur at the edges of the flanges and at the center of the web, and a lower yield point at the roots and at intermediate points on the flanges. However, the average for all the curves does not show a marked difference in yield point for different positions. In Fig. 7 (b) the variation in yield point for different positions in the I-section is less regular than that in Fig. 7 (d) for the H-section. The average curve for Fig. 7 (b) shows almost equal yield points in all parts of the H-section. Fig. 7 (c) and 7 (d) for the plates, indicate that the yield point in most cases varied only slightly across the plate. However, the yield points for the plates were in general different from those for the corresponding cores. Because of the uniformity within any section it was concluded that a numerical average for yield points of that section, whether of I- or H-section of plate, was as good for practical uses as an average in which the coupons were weighted according to the areas which they represented. However, because of the difference between yield points for plates and cores of the same column, it was necessary, in determining yield-point stress for the column, to weight the yield points of the plates and the core in proportion to the areas of each. This has been done, and the results are given in Table 1.

The yield points for the three H-sections show little variation from each other, while the yield points for the I-sections showed a somewhat greater variation, due to the low yield point for the I-section in Column 3. Among the plates the variation of yield point was greatest of all. Columns 6 and 7 were furnished considerably later than the other columns, and the yield points of the plates in these columns were considerably greater than the average for all plates. With only one exception, the yield point of the plates was lower than that for the core section in the same column. The maximum variation of an individual weighted yield point from the average of all was about seven percent.

3. Testing. Column 4 was tested first (November 30 and December 1, 1928). The following description of the methods of testing applies to Column 4. The other columns were tested in the same manner except for minor changes and improvements, as follows:

(1) Two-inch strain-gage readings (section A-A, Fig. 8) were omitted from the other column tests.

(2) Four more gage lines in which slipping of the plates was measured, were added in the later tests at section DD.

(3) Gage lines 1, 3, 13, and 15 were added at sections BB and DD. Another difference was made in the testing of Column 1 which will be described later.

The location of the gage lines on the cross-section of the column are shown on Fig. 8, except as noted above. The gage length at section A-A was two inches. At section BB, CC, and DD it was ten inches. The gage holes were drilled with a No. 54 drill (.054 in. in diameter). Gage lines 5, 11, 17, and 23 in section BB, were on the edge of the I-beam forming the core of the column. Gage lines 5b, 11b, 17b, and 23b, employed the same upper holes as 5, 11, 17, and 23, but the lower hole for each of these gage lines instead of being in the I-beam, was in the cover plate close to the fillet weld. If the strain in gage line 5 should be the same as that of 5b, there could have been no slipping of the plate, but any difference in the strain between 5 and 5b indicates slipping of the plate relative to the I-beam, and so with the other three gage lines.

Before placing Column 4 in the testing machine, it was whitewashed with a mixture of white Portland Cement and water, in order to make more evident the flaking of the mill scale (herein termed strain lines) as the column came under stress.

After the column had been placed in the machine, and before any load had been applied, provision was made for measuring the shortening over the whole length of the column at its four corners, and for measuring the center deflection of the column relative to the ends. The instruments for measuring this shortening are here termed compressometers to distinguish them from the strain gage. Each compressometer consisted of a 3/8-in. steel pipe attached to the column one inch below the top, and of such length that its lower end bore against the plunger of an Ames gage fastened one inch above the bottom of the column. Thus the compressometers measured the total shortening of a column under load except that which occurred within the two inches outside the gage length. The compressometer pipe was held in line by guides at about the one-third points of the length of the column. The attachment of the Ames gages and the arrangement of the pipes are shown in Fig. 9 for the Northwest and Southwest corners of Column 4. The Ames gages read satisfactorily to thousandths of an inch. Each one-thousandth inch total shortening corresponds to an average strain* of $\frac{.001}{182}$ or .0000055 in. per in. for the 182-in. gage length, or to an average stress of 160 lb. per sq.in., using a modulus of elasticity of 29,000,000 lb. per sq.in.

For measuring the deflections, two fine wires were attached to the web of the column six inches below the top and six inches above the bottom, giving a span of 172 in. The arrangement is shown in Fig. 10. At the center of the column these wires passed in front of two mirrors placed at right angles to each other, each carrying a scale graduated to hundredths of an inch. By lining up the wire with its image in the mirror parallax in reading the scale was avoided. By using mirrors at right angles to each other, deflections in the direction of either axis of the column could be observed. Readings on each wire served as a check on those on the other wire.

* The expression "unit deformation", and the word "strain" are used to mean the change of length per unit of length, and the word "stress" to mean the intensity of the internal force per unit of sectional area. See PROCEEDINGS A.S.T.M., Vol. 25 (1925), Part I, p.879. The expression unit-deformation is applied to change of length due to any cause such as stress or expansion due to heat, while the word strain should be applied only to change of length caused by stress. However, it is not always possible to determine what is the principal cause of a change of length and there may be some confusion in the use of the two terms.

The column was tested in a two-screw Riehle testing machine of 800,000 lb. capacity. As placed in the testing machine, the web of the column was in the plane of the longitudinal center lines of the screws. See Fig. 9. The bottom of the column was placed upon a planed steel plate three inches thick which rested directly upon the bed of the machine.

This column was so placed that its top was accurately centered between the screws, letting the bottom of the column come where it would. Mounted on top of the columns was a three-inch plate, planed on both sides. On top of the plate, and directly under the head of the compression block, were three pairs of wedges, each resting on a spherical bearing block. These may be seen in Fig. 2, although the details are not very distinct. The three spherical bearing blocks as placed on the three-inch plates, outline an isosceles triangle, the apex block being centered over the web, 4-5/8 in. north of the center line of the column. The other two bearing blocks were 4-5/8 in. south of the center line of the column, eight inches apart, center to center.

The compression head of the testing machine was then brought down until the wedges were nearly in contact with it.

Then the wedges were driven up to an equal contact. A load of 15,000 lb. was then applied to the column, and the compressometer readings taken on all four edges of the column. This was followed by a load of 60,000 lb. after which the compressometers were again read. The proper subtraction of the readings gave the shortening of the column over a length of 182 in. If the shortening on the four edges of the column revealed an eccentric loading, the compression head was raised and the wedges readjusted. This procedure was repeated until the shortenings measured by the four compressometers were equal within .002 in. in the 182 in. gage length. The loading was then considered to be nearly enough axial to permit proceeding with the test.

The test was carried out with the increments of load shown in Fig. 26. Readings were taken on the compressometers and the deflection apparatus at more frequent intervals than the strain gages.

4. Slipping of Plates. It was mentioned in Section 3 that gage lines 5b, 11b, 17b, and 23b, were placed so that they measured the movement of a point on the cover-plate relative to a point on the I-section or H-section. These gage lines were placed only on section B at the top of Column 4, and on both sections B and D for Columns 1BB, 2, 3, and 5,

since it was believed that if slipping occurred at all, it would be near one end of the column. In figures 11 to 18 the movement in gage lines 5 and 5b, 11 and 11b, 17 and 17b, 23 and 23b, have been plotted in pairs, both gage lines of each pair being referred to the same origin. The dotted lines are the graphs for gage lines 5, 11, 17, and 23, and the solid lines are for gage lines 5b, 11b, 17b, and 23b. The numbers designating the gage lines are shown near the origin of the respective graphs. The capital letter B or D indicates whether the measurement was at section B or section D, and the Arabic numerals indicate the position of gage line in the section. See Fig. 8. If there were no slipping of the plates, and no error of observation, the solid lines and the dotted lines should coincide. Divergence of the solid and the dotted graphs indicated either error of observation or slipping of the plates, or both. Since there is certain to be some error of observation, there is bound to be some divergence of the lines. Error of observation, if it occurs in the zero reading, will cause the solid and dotted graphs to remain at a fixed horizontal distance apart; if it occurs in readings for loads above that for the zero reading it will cause an erratic divergence and convergence of the graphs. Slipping of the plate with reference to the structural shape should be expected to increase with increased load, and therefore should cause a progressive divergence of the graphs.

The curves (Fig. 11 to 18) show many erratic divergences and convergences of the lines, most of which are slight, indicating slight errors in the measurements. There are a few slight divergences which are progressive over a part of the test, such as that for gage line D17, D17b, for Column 1BB, and that for gage line D11, D11b, for Column 2, Fig. 12 and 13. These divergences, however, represent at most a slip of approximately one-thousandth in., and it cannot be stated positively that it represents a slip at all. On the whole, the practical coincidence of the solid and dotted graphs in these figures indicate that there was little if any slipping of the plates in either the welded or the riveted columns.

5. Strains and Strain Lines. Fig. 8 shows the positions of the gage lines. While the cross-sections of the different columns varied, the same scheme of gage numbering was used throughout the series. Strains for all gage readings on all columns have been tabulated and are presented in Tables 2 to 9 inclusive.

Although the bearings were adjusted in such a way that, at a load of approximately 60,000 lb. the strains at the four corners of the column were equal, bending strains developed quite early in the test. It was assumed that the over-all shortening, which was used in making the adjustments of the bearing, would detect bending strains in the columns due to eccentricity of the bearing. However, an examination of Column 4, (see Fig. 29) indicated bending moments at the middle and at the ends nearly equal in value and opposite in sign. This reversal of moment tended to equalize the over-all shortening measured on the four corners of the columns, and therefore reduced the sensitiveness of the compressometers as an adjusting agent. It is evident that if the over-all shortening at the four corners of the column were equal in spite of large bending moments in the column, the compressometer readings would be of no use in detecting eccentricity of load.

A diagram indicating the presence of bending strains is given in Fig. 19. The figure shows the strains for the cross-sections at BB, CC, and DD of Column 4. The method of determining the bending strains from these measured strains is given in Section 8. The load for Fig. 19 (approximately 21,500 lb. per sq.in.) was at a point of pronounced change of slope of the average stress-strain curve as shown in Fig. 20. The strain diagram (Fig. 19) is more or less typical of the strain distribution across the sections of the columns for loads near the critical load.

The average strains at the center section were approximately the same as the average over the full length of the column up to a certain load for each column, above which the average strain at the center was greater than the average for the full length of the column. This is shown by the divergence of the broken, from the solid lines, for the higher loads in Fig. 20.

Evidently there were two major influences which affected the number, location, and direction of the strain lines in the whitewash, namely, the weight of the section, and the method of fabrication. In the columns made of the lighter sections, the strain lines were much more general than with the heavier sections. With the 10-in. 25.4-lb. I-sections the strain lines in the web were closely spaced and prominent, but never extended into the fillets, either from the webs or from the flanges. With both the heavier cores, that is, the 10-in. 35-lb. I-sections and 8-in. 32-lb. H-sections, the flaking lines were less general, but they extended entirely across the web and out into the flanges. No case was found in which a strain line crossed a weld, and only a few in which they crossed the line of the weld on the outer face of the plate, that is, on the face opposite that of the weld. With the riveted columns, the strain lines extended to the edge of the flange and up close to the rivets.

The stress at which strain lines first appeared is given in Table 12, Column C. It ranged from 21,000 to 10,000 lb. per sq.in. except for Column 6 in which the first strain lines appeared at a stress of 5800 lb. per sq.in. The average stress for all was 15,000 lb. per sq.in. The stress at which strain lines appear is generally assumed to be approximately the yield point of the steel. For this to have been the case with these columns, required that there must have been an initial stress at the point where the strain lines started, averaging about 20,000 lb. per sq.in.

There are some reasons for thinking that compressive stresses were set up in the webs of the I-beams and H-beams by unequal cooling after rolling, but it is not possible to estimate their magnitude.

Though initial stresses of considerable magnitude due to the heat of rolling and of welding were undoubtedly present, this fact need not be alarming since the strengths of the columns were about what should be expected with the materials, shapes, and lengths used. The appearance of strain lines on the columns is recorded in some detail in the appendix. In the stitch-welded columns (6 and 7), the same general placement of the strain lines existed as in the columns with the continuous-welds, except that the strain lines, generally, were found in groups opposite the welds and practically never in the sections between the intermittent welds.

In a study of the strains due to welding, and their effect on the location of strain lines, a column five feet long was fabricated and tested. (See Fig. 21). Two 11 by 5/16-in. cover plates were stitch-welded to a core which consisted of a 10-in. 35-lb. I-beam. The welds at the top and bottom of the column were continuous for ten inches from the ends of the column. The intermediate welds were each two inches long and were eight inches apart, center to center. Previous to the welding of the plates to the I-section, numerous two-inch gage lines were established and read. The gage lines were again read after the welding was completed and the column had cooled down to normal temperature. Load was then applied up to a maximum of 398,000 lb., which caused an average stress in the column of 27,700 lb. per sq.in. After the strain readings had been obtained under this load, the load was removed and another set of readings was taken to measure any permanent set in the column.

Fig. 22 shows the location of intermittent welds in relation to the gage lines used to determine the distribution of the strains in a cross-section at the center of the column and along the edges of the cover plate for some distance above and below the center. The elevation of the gage lines is given by letters, and the position on the cross-section is given by numbers. For example, D-25 was located at mid-height of the column and on the fillet of the I-section.

In Fig. 22(e) the unit deformations in all gage lines cut by Section D at mid-height of the column have been plotted opposite the gage line in a direction at right angles with the surface in which the strain occurred. Distance away from the surface represents compressive strain. Evidently all the gage lines cut by the section shortened, though the stress cannot have been compression in all of them, since the total stress on the section was zero. At the time of making the weld, the metal surrounding it was heated to a high degree, causing a marked expansion and greatly reducing its resistance to forces causing deformation. Since the metal at some distance from the weld was not heated to so high a temperature, the restraint which it offered against elongation must have produced in the metal immediately surrounding the weld, a large plastic flow which was accompanied by very little stress. As the highly heated metal cooled, it would regain its resistance to stress and would be subjected to a high tensile stress, due to the resistance of the surrounding metal which had not suffered plastic flow. Correspondingly the metal at some distance from the weld would be subjected to compressive stress, since the total external force on the section was zero.

Without some knowledge of how much plastic flow there was, it is impossible to state how much of the resultant deformations shown in Fig. 22 (a) represent stress. However, the smaller the sectional area of the highly heated portion, the greater will be its plastic flow due to the heat, and the greater will be the tensile stress due to contracting with cooling. At points in the section so far removed from the weld that plastic flow due to the heat was unlikely, the strains indicate a compressive stress of about 15,000 lb. per sq.in., and it seems likely that at the weld the tensile stress was as great as the yield point of the metal in spite of the fact that the strain readings showed that it had shortened due to the welding.

The gage lines in the rows numbered 1, 2, and 3 in Fig. 22 (b) and (c) give the average strain at three corners of the column at several sections between and through the welds. The gage lines in rows 4 and 5 are so placed as to detect any local bending in the plate, but their average is directly comparable with the gage lines in rows 1, 2, and 3

Fig. 22 (b) shows that at all four corners of the column there was a marked shortening at the section through the welds and a marked elongation at the sections between welds. Sections B and F, midway between welds, were far enough from the weld that there probably was no plastic flow in them. The average tensile strain at the edges of the plates for these two sections were 600 and 250 millionths respectively. Using the average modulus of elasticity of 29,000,000 lb. per sq.in. the corresponding stresses are 17,400 and 7250 lb. per sq.in. Since the external force upon each of these sections is zero, there must have been compressive stresses upon other parts of the section to balance the tensile stresses.

Fig. 22 (d) shows that the strains on opposite faces of the cover plate were not equal, but that local bending strains varying somewhat regularly from weld to weld, took place. These bending strains were probably due to the fact that the heat was applied to only one side of the plate. The difference in strains corresponds to a difference of stress on opposite sides of the plate, amounting at Section B to approximately 27,000 lb., and at Section F to 19,500 lb. per sq.in.

The variations of strain along the edges of the plate, as shown in Fig. 22 (b), make evident why the strain lines on the welded columns appeared first opposite the welds. Evidently the heat of welding had set up compressive stresses at these points and tensile stresses at the edges of the cover plates between them so that when the load came upon the column, the yield point was reached first at points opposite the weld.

The phenomena pointed out in the foregoing paragraphs make it apparent that there is room for much further study of the effect of welding on stresses in structural members. It would be entirely feasible to cut out strips of the section at which the large deformations due to heat occurred, and determine what the total elastic strain is. Not all of this would be due to the welding, however, since strains due to the heat of rolling probably were already present.

Upon application of load to the column, the strains were read and have been plotted in Fig. 23. The slope of the graphs in Fig. 23 indicates that the strains increased at approximately the rate to be expected for steel under compression, but beginning in each case with the strain set up by the welding. As a result, the total strains at gage lines D1 to D21, Fig. 23, under the final stress of 27,700 lb. per sq.in., were very lange. As should be expected, strain lines formed in the white cement coat at the indicated points of high strain opposite to, and some distance from the welds, but none close to the welds. This is consistent with the fact that, as was previously pointed out, tensile stresses must have existed in the immediate vicinity of the welds. Fig. 24 and 25 show the strain lines at this place. The absence of strain lines in the welds may have a further explanation since auxiliary tests made on small angles showed no strain lines on the welds, although the load applied caused stresses far beyond the yield point of the steel.

6. Modulus of Elasticity. Table 10 gives the modulus of elasticity as determined for certain coupons and for the columns. The modulus of elasticity of the coupons for the core sections and the plates were weighted in proportion to the sectional areas of each, and the weighted average for the entire cross-sections of the columns determined. To determine the modulus of elasticity directly from the tests of the columns the strains in the gage lines at mid-height (section CC) were weighted in proportion to the approximate areas of the cross-sections which they represented, and weighted averaged strains for Section CC were determined from these weighted values. These strains were plotted in Fig. 20, and from these stress-strain diagrams the moduli of elasticity, given in the last column of Table 10, were determined.

Only the first five columns tested, 1BB, 2, 3, 4, and 5 were used for these determinations since in Columns 1, 6, and 7 some or all of the gage lines on Section CC were omitted. For the values of modulus of elasticity from the coupons tested in tension, the extreme range was about 10% of the average value. For the values from the column tests (compression tests) the range was about three percent.

The average modulus from the coupons was 29,300,000 and that from the columns was 28,650,000 lb. per sq.in. The agreement between the two values is reasonably good, and their average is very close to 29,000,000 lb. per sq.in., the value used in the computation of stresses from strains in this report.

The agreement between the weighted modulus for the column and the modulus for the coupons is of interest in view of the fact that tests of two independent structures in recent years reported by Professor Clyde T. Morris* and Professor A. H. Fuller** indicated (1) that the modulus of elasticity of the columns was only about 22,300,000 lb. per sq.in., (2) that the load was about 27% greater than that computed, or (3) that errors due to temperature deformations entered the data. Both tests appear to have been so carefully conducted, and the results were so consistent for a large number of columns, as to make it unlikely that appreciable error due to temperature changes or inaccuracy in determining loads was involved.

* DEAD LOAD STRESSES IN THE COLUMNS OF A TALL BUILDING, Engineering Experiment Station, Bulletin No. 40, Ohio State University.

** MEASUREMENT OF STRESSES IN FOUR STEEL COLUMNS OF THE EQUITABLE BUILDING, Bulletin No.72, Engineering Experiment Station, Iowa State College.

It was largely in an effort to find out whether uneven distribution of stress over the cross-section could explain the discrepancy in the tests by Morris and Fuller that the gage lines shown in Fig. 8 were so completely distributed over the cross-section of the column. However, the results of these tests offer no explanation of the unexpected phenomena observed by Morris and Fuller.

7. Deflections. The initial alignments of the columns as given by measurements on the cover plates, are shown in Fig. 5. The load deflections for the columns under load are given in Fig. 26, and the deflections at maximum load are given in Table 11. In both cases the deflection given occurred in the plane of least resistance.

The following discussion of deflections applies to Column 4 which was the first column tested. The behavior indicated here may be taken as more or less typical of all the columns. Column 4 was not entirely straight at the beginning of the test. (Fig. 5). Each cover-plate had a camber of .08 in. at the center, but the camber was in opposite directions for the two plates, so that for deflections of the column as a whole, the effect should be nearly the same as though the column had been straight. The camber in opposite directions might tend to introduce a twisting, but if any twist was present the deflection apparatus used was not sensitive enough to detect it.

Some deflection in the plane of least resistance was apparent almost from the beginning of the test (Fig. 26). At a load of 266,000 lb. this deflection was .02 in. and from then on the deflection increased rapidly, becoming .77 in. at the maximum load of 527,000 lb. Deflection in the plane of greatest resistance began at a load of about 266,000 lb. (the load at which the deflection in the plane of least resistance first began to increase rapidly). From then on it increased steadily to .03 in. at a load of 504,000 lb. at which time a rapid increase began. At the maximum load of 527,000 lb. this deflection was .06 in. Although the test was continued beyond the maximum load, the instruments had been removed and the deflection was not measured. The principal final deflection took place in the plane of least resistance when, with the testing machine still running, the load had fallen off to about 500,000 lb. That in the plane of greatest resistance was still not apparent to the eye. The other columns behaved in much the same manner as Column 4. Therefore detailed descriptions of the deflection of the other columns have not been given except in the case of Column 1, which was tested in a different manner and which is discussed in Section 9.

Columns 1, 1BB, and 2, all were counterparts of each other except that 1 and 1BB were welded with a continuous bead and 2 was riveted. Likewise, Columns 4 and 5 were counterparts of each other, but 4 was welded with a continuous bead, and 5 was riveted.

Inspection of Fig. 26 shows that in both instances, except at the maximum load, the deflections of the riveted columns were smaller than those of the corresponding columns welded with continuous beads. Fig. 5 indicates that the riveted columns were initially straighter than the continuously welded columns.

Similarly, comparisons may be made between columns welded with continuous and intermittent beads. Columns 3 and 4 were counterparts respectively of Columns 6 and 7 except that the former were welded with continuous, and the latter with intermittent beads. Likewise, Fig. 26 shows that the columns with intermittent beads deflected less under load than did the slightly less straight columns with continuous beads.

Still another comparison may be made. Columns 4, 5, and 7 were alike except that 5 was riveted, 7 was welded with an intermittent bead, and 4 with a continuous bead. The magnitudes of the initial departures from a straight line increased in the order given, that is, 5, 7, and 4, whereas the deflection under load was least for Column 7 (intermittent weld), next larger for Column 5 (riveted), and largest for Column 4 (continuous weld).

In all comparable cases the deflections were largest for the columns welded with the continuous bead. Only one comparison between a riveted column and a column with intermittent bead could be made, and the deflection was less for the intermittently welded than for the riveted column. The two comparisons available showed the deflection for the intermittently welded to be less than that for the continuously welded column.

The columns fabricated by riveting were straighter than those fabricated by either continuous or intermittent welding. The magnitude of deflection under load corresponded to the magnitude of the initial departures from straightness except that the riveted column (No. 5) gave greater deflection under load than the less straight column (No. 7), which was welded with intermittent beads.

In general, the differences in deflection were small and only one column of a kind was tested. Therefore, this summary of the deflections should not be taken as a conclusion that it represents in general, the relation between deflections of riveted and welded columns.

8. Bending Stresses. The average of the measured strains for gage lines 4 and 12, and for 16 and 24, were computed separately. The former represents the strain on the

West, and the latter the strain on the East edges of the cover plates. Half the sum of these average strains represents the average strain over the whole cross-section and half their difference represents the bending strain in the "extreme fibre", provided that (1) the strains were measured correctly, and (2) a plane section before bending remains plane after bending. These strains multiplied by 29,000,000 lb. per sq.in., the average modulus of elasticity for all columns, give the bending stress and the average stress, $\frac{P}{A}$, respectively.

A comparison of the average stress thus computed, with the total loads divided by the area of the columns, that is $\frac{P}{A}$, is given in Fig. 27 and 28. The two curves for average stress agree closely for the lower loads. This agreement should be expected up to a point where the maximum stress is near the yield point of the material, but a marked divergence takes place at a $\frac{P}{A}$ value of 21,000 lb. per sq.in. for Column 1BB, and at a value of 16,000 lb. per sq.in. for Column 8 (total loads 510,000 lb. and 336,000 lb. respectively), whereas the yield point stresses from the coupons occurred at a stress of about 35,000 lb. per sq.in. for each of these columns (Table 1).

Fig. 29 is a summary of the bending stresses for Columns 1 to 5 inclusive. The relation between bending stresses at the top, middle, and bottom for Column 1 is shown in some detail in Fig. 30. In all cases the bending stresses at the top and bottom Sections BB and DD are opposite in sign from those on the same side of the column at the mid-section CC, though all were plotted in the same direction for convenience. In Columns 3, 4, and 5, the bending stresses at the top, middle, and bottom were about equal as would be the case if the columns were fixed at the top and bottom. In Columns 1, 1RB, and 2 the bending stresses were greater at the top than at the middle, indicating some initial eccentricity of loading in the columns. There is nothing in Fig. 29 to indicate any marked advantage of either riveted or welded columns over the other, so far as freedom from bending moments is concerned.

Strangely enough the bending stress seems to have had little effect on the maximum loads carried. This is shown in the fact that the ratio of the stress at maximum load, to the yield point stress of the material, (given in Table 12) was nearly constant for all the columns.

9. Bending Moments and Deflections in Column 1. In the test of Column 1, longitudinal strains were measured on the four corners of the column, that is, on the edges of the cover plates at sections approximately two feet apart, throughout the length of the column. At the same sections deflections were measured parallel to, and at right angles to the web of the column. The deflections due to a load of 528,000 lb. were added to the initial departures from a straight line and the resulting total departures (Fig. 30, curve 2) indicate the total curvature in this plane under a load of 528,000 lb.

It was desired to ascertain whether the deflections of this column under load were those which should be expected with a column with as much initial curvature as this column possessed. This question appears to be of the greater significance since Column 1 carried a maximum load (785,000 lb.) slightly in excess of that (784,000 lb.) carried by the much straighter column 1BB, which was substituted for it.

For the load of 528,000 lb. the bending moments about a gravity axis which was parallel to the web of the columns were computed from the measured strains for all sections at which strain gage measurements were taken. For these computations the usual formula $M = \frac{SI}{c}$ was used in which M is the moment of the internal stresses, S is the bending stress, I is the moment of inertia of the column section about the gravity axis to which the moment is referred, and c is the distance from the gravity axis to the extreme fibre, that is, one-half the width of the plate. The strain used in computing the stress, S, was one-half the average difference of the strains measured on the opposite edges of the cover plates. For the computations of the stress, S, a modulus of elasticity of 29,000,000 lb. per sq.in. was used.

The bending moments computed in this manner have been plotted in curve 3 of Fig. 30. It will be noted that there were two points of zero moment within the length of the column. Since the bending moment is equal to the product of the load times the distance of its line of action from the center of gravity of the section of the column, it follows that at the sections of zero bending moment, the line of action of the load on the column must pass through the center of gravity of the section. This fact was used to locate the line of action of the load. Projecting the two points of zero moment horizontally from curve 3, to intersect curve 2, two points on the line of action of the column were established. Passing a line through these points it is indicated that there was an eccentricity of the load equal to 0.36 in. at the top of the column and 0.09 in. at the bottom. Multiplying the load by the departures of its line of action from the center line of the deflected column (the horizontal distance from the curve of total deflection to the line of action) gives the moments at the various sections.* These have been plotted in curve 4 for comparison with those found from the strains.

While there are certain disagreements, the general agreement between these two moment curves 3 and 4 is good. From each moment curve (that is, that obtained directly from the strains, and that from the product of the load times the departures) the deflections have been determined by a double integration of the $\frac{M}{EI}$ curve for the column. The measured deflections and the two computed deflection curves have been plotted in curves 5, 6, and 7,** for comparison with each other. The agreement, which is very good, indicates that there was nothing mysterious in the behavior of the column so far as deflections are concerned. It is not clear, however, why Column 1 carried a slightly larger load than column 1BB in spite of the lack of alignment of Column 1. The explanation is not to be found in a difference of the yield points of the steel for the two columns, since the difference amounted to only 500 lb. per sq.in. The weighted average

* Strictly these moments should be multiplied by the angle of inclination of the line of action, but the angle was so small that the cosine was taken as unity.

** Since the deflection curve could have been determined directly from the measured strains instead of first using the strains to compute the moments, the deflection curve 6 has been designated as that computed from the measured strain. In determining the deflection given in curve 7 the moments computed as loads times departures were used.

yield point for Column 1 was 34,900 lb. per sq.in., and that for Column 1BB was 35,400 lb. per sq.in. In spite of its greater initial straightness, the maximum bending stress at the load of 528,000 lb. was greater in Column 1BB than in Column 1, and this may account for the fact that Column 1 carried slightly more load than 1BB. Possibly the lack of planeness of the ends of the columns had more to do with the development of bending stresses than did the lack of initial straightness.

It was unexpected to find an eccentricity of 0.36 in. for the resultant load at the top and to find eccentricity so much greater there than at the bottom. As indicated in Section 3, much care was used in centering the columns. However, as shown in Fig. 29, bending strains were found early in the tests. Although the column ends were milled, they were not plane enough to provide uniform contact with the bearing plate and this lack of planeness seems to be the most probable cause of the eccentricity.

10. Proportional Limit and Maximum Load. The proportional limit stresses for the columns were determined from Fig. 20 and are given in Table 12.

The stress at which any curve in Fig. 20 departed appreciably from a straight line was taken as the proportional limit for the column represented by the curve. The proportional limits for Columns 3, 6, and 7 are so low as to raise some doubt as to the validity of the values selected, but for Column 3 the points determined by the strain gage and those determined by the compressometer readings for the full length of the column coincide throughout the curve, giving confirmation of the correctness of the proportional limit. Also for Columns 1BB, 2, 4, and 5, the points determined by the strain gage coincide with those from the compressometer up to a high load. For Columns 1, 6, and 7 strain gage readings for plotting the average strains were not taken so no comparison between proportional limit by the two methods was available.

The stresses at the proportional limit as shown in Table 12, were higher than the stresses at the first appearance of strain lines, yet there is a general correspondence between the two sets of values which leaves the impression that there probably was a relation between them. It has been indicated quite clearly that the presence of initial compressive stresses at any position hastened the appearance of strain lines at that position. The general correspondence between stresses at the proportional limit and at the first appearance of strain lines, suggests that the presence of initial stresses also affects the limit of proportionality between applied stress and resulting strain.

A comparison of the stresses computed by the use of Rankine's formula

$$\frac{P}{A} = \frac{S}{1 + \frac{1}{25,000}\frac{l^2}{r^2}}$$

with the results of the tests, is given in Table 32. In this formula:

P = the maximum load

A = the sectional area

S = the yield-point stress from the coupon tests

$\frac{l}{r}$ = slenderness ratio, and

$\frac{1}{25,000}$ = an empirical constant for steel columns with fixed ends

Rankine's formula was used for comparison because it is a well-known and quite generally accepted formula.

The strength of different columns cannot be properly compared merely on the basis of the stresses developed at the maximum load. It has been found* that for columns of the same slenderness ratio, $\frac{l}{r}$, the stresses at maximum load were approximately proportional to the yield-point stress of the

*TECHNOLOGIC PAPER no. 328, p.85, of the Bureau of Standards steel from which they were made. The ratio of the average stress at maximum load on the column to the yield-point stress of the steel thus becomes a measure of the effectiveness with which the material in the column is used. This ratio, which is here termed the effectiveness ratio, has been computed and is given in the next to the last column of Table 12. The highest ratio given is 0.954, and lowest is 0.879, and the average of all is 0.913. The maximum variation from the average is 4.4%. The average effectiveness ratios for the riveted, continuously welded, and stitch-welded columns were 0.909, 0.921, and 0.900, respectively.

On the whole, it must be concluded that the maximum loads stated in terms of the yield-point stress of the material, that is, the effectiveness ratios, were so nearly equal regardless of the method of fabrication of the columns, that no reliable distinction can be made as to the effectiveness of the three methods represented.

The ratio of the $\frac{P}{A}$ computed by Rankine's formula to the average stress at maximum load is given in the last column in Table 12. These values represent a measure of the accuracy with which Rankine's formula may be used to predict the average stress at maximum load in these columns. The values of this ratio range from 84% to 92% and the average for all values is 88% of the maximum load.

11. Summary of Results. (1) The largest slipping of plates shown by the measurements, was about 0.001 in. Even this may have been merely a difference in compressive deformation within the gage length over which the measurements were taken. No weaknesses attributable to slipping of plates developed.

(2) Stitch-welding caused shortening of the metal at sections through the welds and elongation at the edges of the cover plates at sections midway between welds. In the stitch-welded columns, the strain lines appeared first on the sections through the welds but none appeared in the welds or in the metal very close to the welds. In general, they did not appear between the welds except in the webs of the columns, where their formation apparently was brought about by initial compressive stresses set up in the cooling of the section after rolling.

(3) The points of first appearance of strain lines corresponded to the points of highest initial stress due to heating of the metal so far as the stress due to heating could be determined.

(4) The average modulus of elasticity determined from the coupon tests was 29,300,000 lb. per sq.in. and that determined in the tests of the columns was 28,650,000 lb.per sq.in. The modulus used in computing stress from strain was 29,000,000 lb. per sq.in.

(5) In all comparable cases, the deflections were greatest for the continuously welded columns. There was little distinction as to deflection between the riveted and the stitch-welded columns. In general the magnitude of the deflection corresponded to the magnitude of the initial departures from straightness. However, only one column of a kind was tested and the differences in deflection are not large. Therefore conclusions as to deflection should be used with caution.

(6) In Columns 3, 4, and 5 the bending stresses, and therefore the bending moments, were about equal at top, middle, and bottom. In the other columns the position of maximum moment varied between top, middle, and bottom. Nothing in the tests indicated any marked advantage of either riveted or welded columns over the other so far as freedom from bending moments is concerned, although the continuously welded columns seemed to be more subject than the others to initial deflection.

(7) In spite of its large initial deflection, Column 1, which was continuously welded, carried slightly greater maximum load than its counterpart, Column 1BB. The bending moments in this column, computed as the product of the loads times the deflections relative to the line of action, agreed fairly well with the moments computed from the measured strains. The deflections computed from the bending moments also agreed very well with the measured deflections.

(8) The limit of proportionality between applied stress and resulting strain occurred at stresses well below the yield point but higher than the stresses at which strain lines first appeared. There was, however, a general correspondence between the stress at the limit of proportionality and that at which strain lines first appeared, and this suggests that both were influenced by the presence of initial stresses in the columns.

(9) The ratios of the stress at maximum load to the yield-point stress determined from the coupons were so nearly equal for all the columns tested, that no reliable distinction can be made as to the effectiveness of riveting columns or welding them, either with a continuous or an intermittent weld.

(10) Although the tests indicated the presence of initial stresses of considerable magnitude, set up in cooling after welding, and probably after rolling also, the maximum loads carried did not appear to be appreciably influenced thereby.

(11) The stress at maximum load averaged about 15% greater than the stress computed by Rankine's formula

$$\frac{P}{A} = \frac{S}{1 + \frac{1}{25,000}\frac{l^2}{r^2}}$$

12. Acknowledgment. This investigation was made in the Fritz Engineering Laboratory of Lehigh University. The writers wish to thank the following men of the Department of Civil Engineering: Professor R. J. Fogg for helpful suggestions; Professor C. D. Jensen for carrying out the test of the short column discussed in section 5, and for furnishing interpretations of this, and other parts of the investigation; and Mr. R. B. Morris for valuable assistance in the testing and working up of the data.

APPENDIX

Phenomena of Tests

A detailed description of behavior of a specimen forms tedious and generally unprofitable reading. However, for reference to specific features, a record of the phenomena of tests may be of value, and such a record is therefore included as an appendix to the report.

The flaking of the whitewash permits some judgment to be formed of the behavior of the columns independently of the readings of strains and deflections. The notes on "Phenomena of Tests" consist largely of the description of the flaking. Column 4 was the first column tested, and the general notes taken on it were somewhat fuller than those for the other columns. For this reason Column 4 is frequently made the basis for comparison with the phenomena of other columns.

In the following notes where the "inside" or "interior" face of the cover-plates is referred to, the face towards the center of the column is meant, that is, the face on which the welding was done. Similarly by "outside" or "exterior" face is meant the face away from the center of the column.

Flaking of the whitewash is taken as an indication of high strain at the place where the flaking occurs. The first flaking generally took the form of lines in the white-wash and they are here referred to as "strain lines".

Column 1 (Welded)

The first strain lines appeared at a load of 388,000 lb. (approximately 16,000 lb. per sq.in.) on the outside faces of the cover plates. These lines consisted of diagonal strain lines opposite sections at which strain gage readings were taken. At this load there were no strain lines visible on the web on flanges of the H-section. At a load of 528,000 lb. (approximately 22,000 lb. per sq.in.) the lines on the cover plates were extending and becoming more numerous. There were a few lines on the edges of the south cover plate (plate B) and a very few on the inside faces of the cover plates. On the web of the H-section some diagonal strain lines appeared near the junction of the web and the flanges.

At a load of 672,000 lb. the lines above noted and many new strain lines developed on the faces and edges of the plates. Short diagonal strain lines were quite generally distributed over the entire length of the column along the flanges of the H-section. At the maximum load of 785,000 lb. (approximately 32,000 lb. per sq.in.) both the north and south plates showed a large number of strain lines over the entire length of the column. (See Fig. 31). The strain lines were horizontal for the lower three feet of both plates and there were a few horizontal lines at other points along the plates. However, the majority of the lines were diagonal. In general, the lines on the exterior faces of the plates stopped before reaching the line of the weld. Those on the inside face of the cover plate started at the edges and extended inward but not as far as the weld. In the H-section, lines extended entirely across the web at very short intervals and on to the flanges, but not entirely to the edge. The general range of the lines was the same as for Column 1BB and a comparison similar to that made for Column 1BB could be made for this column.

<u>Column 1DB (Welded)</u>

The first strain lines appeared at a load of 334,000 lb. (approximately 16,000 lb. per sq.in.) on the edges and the outside face of the south cover plate (plate B), but none on the exposed portion of the inside face of this plate. At the same load strain lines also appeared on the flanges of the H-section, generally near mid-height of the column. There were none on the web of the H-section.

At a load of 528,000 lb. (approximately 22,000 lb. per sq.in.) the strain lines on the flanges of the H-section were more numerous than at the previous load. As in the case of Column 4, the strain lines on the flanges of the H-section started at the fillet and extended toward the edge of the flange but did not reach the weld. At this load there was no flaking on the web. The south face showed many lines which were horizontal near the bottom of the column and inclined near the top. The lines were very few on the north face.

At 672,000 lb. many of the lines above noted, and other new ones, extended to the web throughout the length of the column (Fig.32). The south face was very much cut up with strain lines. In the lower half of the north plate few lines showed on the face and few on the edge of the plate.

At the maximum load, 784,000 lb. (approximately 32,000 lb. per sq.in.) the south plate (plate B) showed a large number of strain lines (Fig. 33). In the central part of the length of the column the horizontal lines predominated but still there were many inclined lines. At both the top and bottom the diagonal lines predominated; in fact there were very few horizontal lines there. On the north plate there were probably almost as many strain lines as on the south plate, but they were so small that they gave the impression of much less strain. In general, the lines on the exterior faces of the plates stopped before reaching the line of the weld, much as in Column 4. There were short lines on the interior face of the north plate but none at all on the interior face of the south plate. Those on the north plate started at the edge and extended inward for a distance of about 2 in. stopping about 1 in. from the weld. In the H-section, lines extended entirely across the web at very short intervals and out into the flanges to within about 1-1/4 in. of the edge. In the web the lines were generally horizontal, but when they reached the flange they took a diagonal direction, some upward and some downward.

In general, the arrangement was the same as for Column 4 except that in the web the lines passed entirely across the web from flange to flange whereas in Column 4 there was a strip of the web next to each flange which no strain lines crossed.

Column 2 (Riveted)

The first strain lines were noted on this column also at a load of 384,000 lb. (approximately 16,000 lb. per sq.in.). This occurred at the northwest corner of the column on the outside face of plate B, extending from the edge of the plate approximately horizontally about 3 in. There were a few similar lines on the southwest corner of the column about five feet above the base.

At a load of 528,000 lb. (approximately 22,000 lb. per sq.in.) there were additional strain lines on the edges of the plates near the mid-height of the column, and new lines appeared at the bottom at the northeast and the southeast corners on the edges of plates B and C. These lines extended to the edge of the flange of the H-section. There were no strain lines on the webs or flanges of the H-section at this load.

At a load of 672,000 lb. the strain lines formerly noted, had extended in length. There were a few new lines on the plates and none on the webs.

At a load of 768,000 lb. (approximately 32,000 lb. per sq.in.) the old lines were extending around the rivets on the east side; there were horizontal lines in the web near the top and bottom of the column (~~Fig. 34~~). There were also diagonal lines in both plates near the bottom of the column.

At the maximum load of 790,000 lb. (approximately 32,500 lb. per sq.in.) the lines on the south plate (plate C) were generally diagonal in both directions (Fig. 35). There were some horizontal lines and many diagonal lines extending inward a short distance from the edges. Where diagonal lines appeared there was a tendency for them to continue across the lines of rivets towards the center of the plate. That is, there was not so distinct a break in the continuity of the lines at the line of rivets as appeared at the line of the welds in Column 4. The lines on plate C were most numerous at the region of maximum deflection. Plate B on the north side, was quite similar to plate C, except that the lines were less numerous. On the interior faces of the plates (Fig. 36) the lines were quite numerous throughout the length and extended all the way in to the edge of the flange of the H-section. In the H-section there were horizontal lines across the web spaced about five inches apart for a distance of about 30 in. in the region of maximum deflection. These were large and distinct markings in the interior portion of the web, but they faded to very fine lines as they approached the fillet. For a distance of about two feet at the top and also at the bottom, the horizontal lines on the web were much closer averaging, say, one inch apart (Fig. 36). Both at the center of the column and at the ends, the lines extended across the fillets into the flanges and generally stopped at the line of rivets. A few of the strain lines at mid-height of the column extended across the line of rivets to the edge of the flange.

Column 3 (Welded)

At 508,000 lb. (approximately 21,000 lb. per sq.in.) a few strain lines appeared on the east side of the column on the edges of the plates B and C. Those on plate C (the north plate) were distributed over the whole length of the column and extended around on the face of the plate. Most of these lines on the edges of the plates were inclined. Of those on the face of the plate, some were horizontal and some were inclined. The lines on plate B (the south plate) were very few. Similarly on the west side there were a few lines on the edge and on the face of plate C, but none were noted on plate B.

On the east side of the column at the north, there were a few strain lines at the fillet of the I-section. There were no such lines at any of the other three fillets and there were no lines on the web.

At 644,000 lb. (approximately 27,000 lb. per sq.in.) on the east side, the strain lines on the north plate were extending, and were so numerous three feet above the base as to indicate that at this place there was a high stress. On the west side of the column the lines on the south plate were extending. There were more lines than before at the northeast fillet, and they were appearing at the other three fillets.

There were some lines on the web on both the east and west sides about two and seven feet above the base of the column.

At the maximum load, 739,000 lb. (approximately 50,000 lb. per sq.in.) the column had comparatively few lines of flaking. They were most numerous on the outside faces of the plates at the top and bottom of the column and were mostly diagonal (Fig. 37). There were very few at the center of the column.

There also were very few lines on the interior faces of the plates on the east side of the column but somewhat more on the west side. Those which were present were at the top and bottom but there were none at the center of the column. In this column, as in Column 4, the strain lines did not cross the lines of welding.

In the web of the column at the top and bottom, the lines crossed from flange to flange and continued out into the flanges (Fig. 38). They were more numerous at the center and ends than at intermediate points. Here they were somewhat broken but extended across the fillet into the flange.

Column 4 (Welded)

Strain lines first appeared at a load of 266,000 lb. (approximately 19,000 lb. per sq.in.). These lines showed up as buckling of the mill scale on horizontal lines extending from the edges toward the centers of the plates for a distance of about two inches. None were appreciably longer than this. The first lines were observed near the top, but either they occurred simultaneously over the entire length of the column, or extended very rapidly over the entire length. They occurred in pairs, one appearing on the outside face of the cover-plate for each one on the inside face. The vertical distances between the strain lines on outside and inside faces was seldom more than 1/8 in. With the machine stopped at a load of 306,000 lb., the lines continued to appear but did not extend beyond two inches from the edge of the plate nor did any appear on the I-section. A few forked slightly near the ends of the lines.

Under a load of 303,000 lb. (approximately 22,000 lb. per sq.in.) additional strain lines appeared, extending from the fillets of the I-section outward toward the corners of the column (Fig. 39). These lines at first were about 3/8-in. long. As the load increased they extended slightly in length but never reached a length greater than 1-1/4 in. They did not extend into the web at all, but ended in the flange.

Some of these lines were inclined but most of them were horizontal. At the same load (308,900 lb.) there were some strain lines on the outside of the plates across the webs at the top within about three inches of the end of the column. As the loading continued, the lines extended, becoming more pronounced and showing more forking at the ends of those which had developed earlier in the test (Fig. 40). The column at mid-height, deflected markedly to the west at the higher loads. This deflection can be seen in Fig. 41 in the lack of parallelism between the edges of the column and the loading screw of the testing machine. The top portion of this figure shows approximately the mid-height section of the column.

The distribution of strain lines after the completion of the test is well shown in Fig. 39, 41, and 42. Fig. 41 indicates that the flaking of the whitewash merely accentuated the phenomenon of the separation of the mill scale from the steel. At places patches of mill scale of considerable size are seen to be curling off the metal. In Fig. 39 the shapes of the figures formed by the strain lines are shown for the web and the inner faces of the flange. The uniformity with which the strain lines in the web of the columns terminated in two vertical parallel lines about 2.5 in. on either side of the vertical center line of the column is notable, as well as the faithfulness with which the strain lines in the flanges began at the fillet and terminated at a vertical line about 1-1/2 in. from the fillet. Fig. 42 shows similarly the figures for the exterior of the cover-plates of the column. The lines on the cover-plates, which crossed the web, terminated at about the same distance from the web as did those on the interior of the flange of the I-beam. These photographs were taken after the completion of the test, and figures formed by the flaking show many more diagonal lines and much more forking than at the maximum load. Most of the lines were horizontal at the time of reaching the maximum load. The vertical line which appears in Fig. 40 at about the position of the web of the column is not due to strain in the plate, but to accidental abrasion of the whitewash. There were no strain lines at the junction of the plate with the I-section.

Column 5 (Riveted)

The first strain lines occurred at a load of 240,000 lb. (approximately 17,000 lb. per sq.in.) about six inches below the top of the column on the southeast corner. At this load there were only two strain lines and they occurred on both the outside and inside of the plate.

At 308,000 lb. (approximately 22,000 lb. per sq.in.) the scaling had increased at the plates where it was noted for the former load. On the east face there were strain lines on the cover-plate next to the flange of the I-section. On the south plate strain lines generally occurred opposite the rivets, but on the north plate midway between the rivets. There were two points of starting of strain lines, one at the edge of the plate and working in, the other at the edge of the I-section and working out. They showed on both the exterior and interior, but most plainly on the interior face.

At a load of 392,000 lb. (approximately 27,000 lb. per sq.in.) strain lines were more general on the cover-plates at the upper southeast and lower northeast corners than elsewhere. There were numerous diagonal lines between the two rows of rivets directly opposite the rivets (Fig. 43). On the outside of the rivets there were diagonal lines at various places. There were very few strain lines in the intermediate portion of the column. At a load of 448,000 lb. (approximately 31,000 lb. per sq.in.) there were no strain lines in the web of the column and extremely few in the fillets of the I-section.

At 504,000 lb. (approximately 35,000 lb. per sq.in.) there were no strain lines in the web, and a few more in the fillets than at the previous load.

At the maximum load of 510,000 lb. (approximately 36,000 lb. per sq.in.) there were horizontal strain lines in the web of the column similar to those in Column 4, but in this case they occurred only at the top and bottom and at mid-height of the column on both the East and West sides (Fig. 44). There was buckling of one cover-plate at mid-height on the southeast corner. It had been noticed at the beginning of the test, before any load was applied, that there was a slight curling of the plate at the bottom bearing at the southwest corner of the column. There was nothing to indicate that this had affected the behavior of the column.

Column 6 (Welded - Intermittent Bead)

The first strain lines appeared at a load of 138,000 lb. (approximately 5,800 lb. per sq.in.) in the form of three small lines on the east edge of plate C (the north plate). These became more noticeable at 230,000 lb. (approximately 9,600 lb. per sq.in.) and a few cracks appeared on the West edges of both cover plates. At 368,000 lb. (approximately 15,000 lb. per sq.in.) the lines started to form on the edges of the plates (both inside and outside faces) just opposite the welds. These lines became distinct as more load was applied (Fig. 45).

Up to 430,000 lb. (approximately 20,000 lb. per sq. in.) no strain lines had appeared on the I-section. At 430,000 lb. and above, lines appeared on the flanges of the I-beam opposite the welds. These lines along with the lines on the edges of the cover plates previously described, indicated that local stresses had been put into the plates and core by the welds. The maximum load carried indicated, however, that the local stresses did not decrease the strength of the column below that of a similar column fabricated by riveting or continuous welding.

At 500,000 lb. (approximately 24,000 lb. per sq.in.) the first strain line appeared in the web of the I-section. The lines, however, were very few until 590,000 lb. (approximately 28,000 lb. per sq.in.) was reached.

Meanwhile at 644,000 lb. diagonal lines appeared on the North plate near the bottom, extending practically across the plate.

At 700,000 lb. (approximately 33,000 lb. per sq.in.) the maximum load on the column, lines had appeared on both faces of the web, extending horizontally across it (Fig. 45) and running into the flanges. There also were a few diagonal lines on the web. It was noted that all lines, whether in plates or I-section, were in groups around the intermittent fillet welds.

Column 7 (Welded - Intermittent Bead)

The first strain lines in Column 7 appeared at a load of 140,000 lb. (approximately 10,000 lb. per sq.in.) along the edges of the cover plates opposite the welds.

At 224,000 lb. (approximately 16,000 lb. per sq.in.) small lines appeared on the flanges of the I-section opposite all welds. There were also a few diagonal lines on the outside face of the south cover plate. All of these lines were extending under increasing load, and at 308,000 lb. were quite numerous.

At 392,000 lb. (approximately 27,000 lb. per sq.in.) five horizontal strain lines appeared on the web near the bottom. Also, a line appeared on the web opposite the fourth weld up from the bottom. The cover plates at this load showed many diagonal lines on the outside faces as well as along the edges.

At a load of 490,000 lb. (approximately 34,000 lb.per sq.in.) the lines were well distributed around the welds and on the web of the I-section. The cover plates were not as badly lined as was the web of the I-section.

Upon applying 523,000 lb. (approximately 37,000 lb. per sq.in.) both cover plates buckled, at one point each, between welds. (Fig. 45). The north plate buckled ten inches below the middle of the column, while the south plate buckled 31 in. below the middle. In Fig. 46 the numerous strain lines which appeared in the web simultaneously with the buckling may be seen.

The buckling of the cover plates was not due to any observed defect of the welding but probably to too great spacing of the intermittent welds. The ten-inch center to center spacing of the welds proved too great for the 5/16-in. cover plates of Column 7, but was adequate for the 5/8-in. cover plates of Column 6.

TABLE I - RESULTS OF COUPON TESTS OF COLUMN MATERIAL

Column No.	Sectional Area sq.in. I Section	H Section	Plates	Yield Point Stresses lb. per sq.in. Core Section I or H	Plates	Weighted Average	Ultimate Stresses lb.per sq.in. Core Section I or H	Plates	Weighted Average
1		9.3	15.0	38,800'	32,500'	34,900	62,200'	58,700'	60,100
1BB		9.3	15.0	38,800'	33,800'	35,400	60,200'	58,600'	59,200
2		9.3	15.0	40,800'	32,800'	35,900	61,700'	57,500'	59,100
3	10.22		13.75	35,300*	34,100'	34,600	56,800*	58,600'	57,700
4	7.38		6.88	38,900*	38,500'	38,700	59,200*	59,400'	59,300
5	7.38		6.88	40,300*	38,100/	39,200	59,800*	59,800/	59,800
6	10.22		13.75	40,500*	36,000'	37,900	66,400*	65,000'	65,600
7	7.38		6.88	39,200*	40,400'	39,800	62,100*	57,200'	59,700
Average				39,000	35,800	37,100	61,050	59,350	60,060

* Average of 6 test coupons

' Average of 8 test coupons

/ Average of 12 test coupons

Load	Section	Strain at gage line No (Millionths)																											
		4	12	16	24	Av.	5	5b	11	11b	17	17b	23	23b	Av.	2	14	Av.	7	8	9	Av.	1	3	13	15	Av.	6	10
72,000	B-B	60	40	60	-30	32	50	30	20	40	50	50	10	10	32	40	60	50					0	40	40	60	35		
	C-C	10	20	20	10	15	30		20		20		10		20	-20	0	-10	0	10	20	10	10	50	20	30	28	-10	-30
	D-D	40	-10	40	-10	15	40	60	50	0	20	30	80	40	40	40	0	20					20	60	00	20	25		
144,000	B-B	210	150	160	30	138	180	150	120	150	170	160	100	90	140	140	170	155					50	160	140	160	128		
	C-C	160	170	180	150	165	130		120		160		150		140	100	140	120	120	150	200	157	140	140	120	190	148	140	120
	D-D	170	70	150	80	118	160	150	90	60	150	170	170	130	135	150	110	130					110	160	80	130	120		
240,000	B-B	400	320	300	150	292	360	340	280	290	320	310	220	190	289	270	330	300					120	320	290	300	258		
	C-C	260	290	350	290	298	230		260		300		260		262	220	300	260	280	280	280	280	260	250	160	260	232	220	230
	D-D	340	220	320	230	278	330	320	260	210	280	320	330	280	291	300	260	280					270	330	230	280	278		
384,000	B-B	620	490	420	240	442	560	530	460	480	450	430	340	300	444	430	490	460					320	520	480	460	445		
	C-C	470	470	560	510	502	380		450		560		550		485	440	450	445	510	530	490	510	550	480	270	430	432	380	420
	D-D	500	400	470	370	435	500	500	440	380	460	470	500	430	460	480	400	440					450	530	390	450	455		
528,000	B-B	940	730	620	410	675	810	780	730	730	650	640	530	500	671	660	760	710					540	790	760	680	692		
	C-C	650	730	870	930	795	660		710		860		910		785	760	760	760	760	830	780	790	860	680	550	740	708	630	670
	D-D	780	640	700	610	682	820	820	660	610	690	720	680	680	710	860	630	745					710	870	630	680	722		
672,000	B-B	1610	1320	860	710	1125	1460	1400	1260	1300	1020	990	860	830	1140	1180	1300	1240					950	1370	1300	1100	1180		
	C-C	880	1150	1520	1450	1250	970		1120		1440		1410		1235	1120	1300	1210	1170	1240	1260	1223	1290	960	1220	1310	1195	1020	1050
	D-D	1400	1140	980	920	1110	1420	1440	1230	1090	990	1000	1100	1060	1166	1460	990	1225					1160	1570	1090	980	1200		
768,000	B-B	2750	2640	850	800	1760	2410	2430	2390	2420	1290	1220	1180	1090	1804	1770	2200	1985					1290	2080	2570	1510	1862		
	C-C	970	1270	2600	2530	1842	1210		1410		2380		2350		1838	1600	1920	1760	1620	1710	1780	1703	2030	1240	1620	2140	1758	1340	1460
	D-D	2770	2190	970	940	1718	2590	2630	1990	2020	1170	1200	1350	1280	1779	2240	1620	1930					1540	2670	2000	1300	1878		
785,000	C-C	770	1200	3380	3130	2120																							

Initial load = 48,000

Strains for all gage lines Col. No. 1 Table 2

Load	Section	Strain at gage line No. (Millionths)																												
		4	12	16	24	Av.	5	5b	11	11b	17	17b	23	23b	Av.	2	14	Av.	7	8	9	Av.	1	3	13	15	Av.	6	10
72,000	B-B	-20	0	90	10	20	50	40	20	20	50	-20	10	20	24	50	10	30					10	30	00	10	12		
	C-C	20	40	40	20	30	40		40		60		20		40	20	60	40	10	20	0	10	30	40	20	10	25	50	30
	D-D	40	0	40	60	35	40	20	20	10	10	10	10	10	16	40	20	30					40	40	20	10	28		
144,000	B-B	110	70	170	110	115	150	150	110	120	180	60	110	110	124	140	140	140					110	120	100	160	122		
	C-C	120	150	140	120	132	130		140		160		120		138	130	150	140	120	130	100	117	130	170	110	100	128	120	150
	D-D	160	130	140	190	155	190	130	150	150	150	190	100	120	148	130	130	130					130	130	110	250	155		
240,000	B-B	240	170	330	250	248	280	270	220	240	320	230	240	260	258	270	260	265					230	230	180	290	232		
	C-C	240	260	280	280	265	250		280		320		280		282	280	290	285	250	260	220	243	290	290	230	230	260	240	250
	D-D	300	280	260	320	290	310	280	270	260	270	290	230	240	269	270	260	265					260	270	260	270	265		
384,000	B-B	390	310	780	430	478	430	400	390	390	550	530	410	430	441	460	470	465					440	400	370	530	435		
	C-C	460	440	520	490	478	510		520		480		480		498	560	530	545	500	450	410	453	510	500	430	430	468	420	430
	D-D	490	420	440	440	448	500	490	460	440	420	390	400	410	439	440	450	445					430	450	430	450	440		
528,000	B-B	550	460	1030	660	675	640	600	540	550	910	920	640	650	681	670	690	680					660	570	520	780	632		
	C-C	680	690	750	700	705	710		760		700		700		718	840	760	800	710	620	620	650	740	800	720	710	742	650	650
	D-D	760	640	640	650	672	750	750	680	680	670	620	580	580	664	640	660	650					620	660	640	660	645		
672,000	B-B	880	720	1530	980	1028	1000	970	820	840	1400	1280	940	980	1029	1010	1020	1015					1030	930	860	1200	1005		
	C-C	1000	1130	1300	1360	1198	1070		1180		1240		1260		1188	1360	1230	1295	1190	1200	1160	1183	1260	1290	1200	1190	1235	1150	1040
	D-D	1270	1230	1000	1020	1130	1250	1230	1180	1160	1110	960	1010	990	1111	1180	1060	1120					1080	1180	1100	1020	1095		
768000	B-B	1650	1580	1900	1180	1578	1740	1720	1610	1680	1810	1780	1310	1280	1616	1580	1740	1660					1420	1560	1670	1670	1580		
	C-C	1560	1440	2060	2350	1852	1710		1690		1960		2140		1875	2240	1870	2055	1850	1700	1630	1727	2110	1980	1750	1950	1948	1820	1540
	D-D	2020	2070	1640	1450	1795	2010	1960	1970	1970	1710	1640	1530	1460	1781	1880	1820	1850					1600	1860	1880	1670	1752		
784,000	B-B	1970	2090	1840	1080	1745	2030	2010	2010	2110	1850	1810	1310	1250	1798	1710	2010	1860					1420	1750	2050	1750	1742		
	C-C	1610	1380	2370	2810	2042	1800		1690		2180		2500		2042	2480	1980	2230	2000	1860	1760	1873	2450	2140	1760	2140	2122	1970	1590
	D-D	2330	2510	1710	1380	1982	2250	2220	2300	2330	1820	1820	1570	1540	1981	2010	2110	2060					1650	2050	2270	1890	1965		

Initial load = 48,000

Strains for all gage lines   Col. No 1BB   Table 3

Load	Section	Strain at gage line No. (Millionths)																											
		4	12	16	24	Av.	5	5b	11	11b	17	17b	23	23b	Av.	2	14	Av.	7	8	9	Av.	1	3	13	15	Av.	6	10
72,000	B-B	40	20	50	30	35	60	00	50	40	70	60	-10	40	39	20	30	25					40	50	30	40	40		
	C-C	20	50	50	20	35	30		50		20		40		35	20	20	20	40	30	30	33	20	20	20	40	25	30	40
	D-D	-10	40	20	10	15	40	50	20	40	00	30	20	30	29	20	60	40					50	40	20	30	35		
144,000	B-B	130	120	150	130	132	170	140	160	150	160	160	120	140	150	120	130	125					150	140	120	140	138		
	C-C	120	160	130	110	130	120		150		150		160		145	120	120	120	130	130	140	133	140	130	100	160	132	120	140
	D-D	100	140	100	100	110	120	140	140	150	110	80	140	100	122	120	140	130					130	140	120	120	128		
240,000	B-B	240	250	310	270	268	320	270	330	280	320	320	260	270	296	240	270	255					280	270	240	280	268		
	C-C	260	280	260	220	255	240		260		270		280		262	240	230	235	300	260	260	273	240	270	220	300	258	250	260
	D-D	230	290	230	270	255	260	300	280	280	240	260	240	240	262	240	300	270					250	250	260	230	248		
384,000	B-B	440	450	550	490	482	500	470	520	480	530	530	470	500	500	460	480	470					500	440	450	510	475		
	C-C	500	470	440	400	452	400		450		450		440		435	430	420	425	520	520	430	490	420	450	440	480	448	500	480
	D-D	450	550	420	420	460	500	540	490	520	440	460	480	500	491	440	520	480					440	500	490	440	468		
528,000	B-B	680	650	920	760	752	740	700	690	680	830	840	720	760	745	700	750	725					760	710	680	820	742		
	C-C	780	770	740	700	748	650		690		670		650		665	720	720	720	740	750	660	717	620	650	680	690	660	720	750
	D-D	660	950	740	730	770	760	790	780	860	680	700	740	760	759	780	760	770					670	750	770	720	728		
672,000	B-B	1080	990	1370	1110	1138	1080	1080	950	970	1240	1320	1120	1170	1116	1040	1110	1075					1120	1040	1040	1220	1105		
	C-C	1140	1120	1120	1050	1108	960		1000		970		980		978	1000	1000	1000	1020	1010	1000	1010	920	950	910	960	935	980	980
	D-D	1050	1370	980	1050	1112	1140	1150	1180	1250	1010	1060	1080	1070	1118	1060	1140	1100					1010	1100	1150	1050	1078		
768,000	B-B	1790	1790	1570	1180	1582	1650	1700	1710	1670	1490	1580	1320	1340	1558	1370	1670	1520					1330	1550	1660	1900	1610		
	C-C	1340	1150	1670	1650	1452	1120		1100		1340		1400		1240	1280	1220	1250	1390	1320	1250	1320	1270	1180	1040	1300	1198	1180	1140
	D-D	1620	2140	1330	1260	1588	1700	1700	1960	2020	1470	1490	1380	1390	1639	1400	1820	1610					1310	1580	1890	1600	1595		
790,000	B-B	2690	2910	1350	850	1950	2390	2470	2650	2570	1480	1560	1210	1240	1946	1680	2070	1875					1320	2070	2360	1740	1872		
	C-C	1070	800	2320	2400	1648	1070		970		1790		1980		1452	1540	1360	1450	1560	1520	1390	1490	1750	1170	970	1660	1388	1180	1090
	D-D	2530	3300	1050	1000	1970	2400	2390	2920	2980	1460	1450	1320	1300	2028	1660	2320	1990					1340	2140	2690	1730	1975		

Initial load = 48,000 lbs.

Load	Section	Strain at gage line (Millionths)																									
		4	12	16	24	Av.	5	5b	11	11b	17	17b	23	23b	Av.	2	14	Av.	7	8	9	Av.	1	3	13	15	Av.
69,000	B-B	20	20	20	30	22	20	00	40	20	-20	80	20	20	22	20	30	25					20	10	30	20	20
	C-C	20	10	40	30	25	40		20		30		20		28	10	40	25	40	30	40	37	20	20	40	30	28
	D-D	30	20	40	30	30	70	50	30	10	30	30	50	20	36	20	20	20					20	20	10	20	18
138,000	B-B	160	120	110	120	128	100	120	140	110	70	190	120	120	121	110	140	125					120	100	180	120	130
	C-C	140	110	140	140	132	130		110		110		100		112	80	140	110	120	140	110	123	100	90	170	130	122
	D-D	170	140	140	120	142	230	160	130	90	120	110	140	130	139	130	140	135					120	120	120	120	120
230,000	B-B	300	260	230	240	258	230	230	340	240	200	330	220	230	252	230	250	240					240	230	220	180	218
	C-C	260	240	310	300	278	230		290		230		220		242	190	280	235	240	280	210	243	200	200	280	290	242
	D-D	310	280	230	250	268	360	380	280	240	240	230	270	260	282	280	310	295					240	270	290	260	265
368,000	B-B	550	540	380	410	470	440	440	530	450	390	510	400	380	442	410	480	445					420	420	610	450	475
	C-C	410	420	590	560	495	390		480		460		460		448	370	510	440	440	480	400	440	440	340	480	530	448
	D-D	550	520	340	450	465	610	570	510	470	360	370	470	440	475	470	520	495					440	500	470	400	452
506,000	B-B	880	820	530	560	698	720	710	800	730	600	710	610	600	685	650	740	695					600	700	780	640	680
	C-C	500	620	910	940	742	630		690		810		790		730	670	740	705	750	700	640	697	810	490	690	790	695
	D-D	900	910	460	680	738	920	870	800	770	550	550	700	710	734	760	750	755					680	830	790	580	720
644,000	B-B	1400	1440	630	620	1022	1090	1080	1300	1230	840	930	790	760	1002	910	1100	1005					800	1080	1320	890	1022
	C-C	570	750	1570	1680	1142	870		920		1210		1300		1075	1050	1080	1065	1040	1100	1010	1050	1330	730	940	1270	1068
	D-D	1670	1630	380	840	1130	1540	1470	1340	1310	720	710	1050	1030	1146	1260	1190	1225					1020	1450	1340	780	1148
736,000	B-B	2910	3920	110	150		2090	2120	3080	*	1240	1270	940	880		1410	2100						820	2060	3280	1210	
	C-C	-30	250	3500	4470		1150		1100		2520		3030			2000	1700		1940	1970	1780		3090	1050	1000	1410	
	D-D	*	*	-160	350		3370	3350	3110	3120	1070	1030	1490	1400		2460	2040						1400	3380	3070	1060	

Initial load = 46,000

*Out of range

Strains for all gage lines Col. No. 3 Table 5

Load	Section	Strain at gage line No. (Millionths)																										
		4	12	16	24	Av	5	5b	11	11b	17	17b	23	23b	Av	2	14	Av	7	8	9	20	Av.	1	3	13	15	Av.
42,000	A-A	00	00	00	15	4	30		46				110			15	00	7		-15		46	15	15	30	30	00	19
	B-B	20	20	10	-10	10	40	20	40	120	10	00	20	20	34	50	–											
	C-C	40	00	0	10	12	70		-10		30		20		27	40	30	35	-120	10	0		-37	20	40	0	10	7.7
	D-D	20	20	-10	0	8	30		10		-120		30		-12	30	30	30										
140,000	A-A	460	290	210	150	277	290		310				240			260	230	245		276		260	268	168	290	280	350	272
	B-B	190	280	230	140	210	240	260	160	280	350	20	230	230	221	200	–	^										
	C-C	210	190	250	230	220	250		240		220		240		237	250	220	235	70	210	230		170	260	240	220	210	232
	D-D	260	210	290	270	257	230		230		120		240		205	310	200	255										
224,000	A-A	760	530	500	230	505	540		500				380			470	460	465		430		520	475	370	490	530	550	485
	B-B	400	490	360	400	412	420	430	470	480	410	400	410	400	427	460												
	C-C	340	380	500	460	420	450		440		430		440		440	430	440	435	250	410	460		373	480	420	430	460	447
	D-D	520	500	450	350	455	430		640		260		450		445	500	380	440										
308,000	A-A	860	630	580	200	567	720		690				580			550	950	750		640		630	635	470	640	760	730	650
	B-B	770	880	560	560	692	670	680	770	830	660	660	620	620	689	710												
	C-C	530	570	820	760	670	680		710		730		730		712	670	720	695	530	670	700		633	640	660	710	730	685
	D-D	870	880	650	660	765	790		680		460		680		652	660	670	665										
392,000	A-A	1070	1080	550	260	740	920		1130				730			640	1710	1175		820		780	800	730	920	1140	990	945
	B-B	1270	1380	810	800	1065	1130	1100	1200	1290	1030	1010	820	900	1060	1030												
	C-C	790	810	1280	1090	992	980		1010		1150		1120		1065	1120	1090	1105	900	1060	1040		1000	1080	990	1040	1130	1060
	D-D	1360	1270	820	940	1097	1230		950		770		1060		1002	1060	980	1020										
448,000	A-A	1620	*	630	270	1035	1280		1600				880			1110	2020	1565		1080		930	1005	850	1220	1500	1160	1182
	B-B	1790	1860	1020	920	1397	1520	1510	1560	1600	1300	1260	1120	1090	1370	1410												
	C-C	990	930	1880	1680	1370	1260		1300		1600		1600		1440	1430	1480	1455	1250	1400	1460		1370	1550	1250	1280	1670	1437
	D-D	1830	1660	950	1080	1380	1620		1310		980		1270		1295	1300	1260	1280										
504,000	A-A	3120	*	610	240	1772	1870		2410				1130			1750	2270	2010		1200		1050	1125	1048	1860	2200	1390	1622
	B-B	2660	2900	1020	910	1872	2230	2210	2340	2460	1650	1580	1430	1390	1911	1890												
	C-C	940	930	2820	2790	1870	1510		1660		2340		2250		1940	1390	2080	1735	1790	1860	1960		1870	2260	1510	1600	2510	1970
	D-D	2940	2500	970	1030	1860	2360		1990		1250		1590		1797	1820	1680											
527,000	A-A	*	*	3710	3410		3300		3890				1240			*	2560			1130		1200		1040	3200	*	1360	
	B-B	4620	4790	410	330		3560	2610	3600	2810	1820	1730	1680	1560		2650												
	C-C	350	240	4930	4540		1590		1840		3850		3240			2480	2950		2290	2480	2360			3320	1430	1680	4020	
	D-D	*	4140	360	360		3930		2960		1400		1830			2660	2220											

Initial load = 28,000 lbs.

Col. No. 4

*Out of range, averaged as if equal to corresponding strain line.

Table 6
Strains for all gage lines

Load	Section	Strain at gage line No. (Millionths)																									
		4	12	16	24	Av.	5	5b	11	11b	17	17b	23	23b	Av.	2	14	Av.	7	8	9	Av.	1	3	13	15	Av.
42,000	B-B	00	70	-10	40	25	30	20	30	40	60	10	10	20	28	10	200	105									
	C-C	30	30	30	40	32	20		20		30		40		28	30	20	25	10	20	40	23	30	40	90	20	45
	D-D	30	00	10	10	12	60	-20	20	40	10	10	20	00	18	10	-40	-15									
140,000	B-B	280	290	220	270	265	230	220	280	290	280	230	250	190	246	220	240	230									
	C-C	300	290	220	280	272	260		250		270		280		265	230	210	220	220	290	240	250	200	270	240	220	232
	D-D	240	210	270	260	245	250	230	220	230	240	220	260	250	238	220	160	190									
240,000	B-B	480	580	470	550	520	470	460	540	560	490	490	510	500	502	480	540	510									
	C-C	540	590	430	520	520	530		530		560		510		532	460	440	450	430	520	470	473	370	550	520	520	490
	D-D	520	470	560	540	522	500	490	480	480	500	490	520	500	495	470	430	450									
308,000	B-B	610	740	630	770	688	600	610	620	730	680	660	590	700	649	630	700	665									
	C-C	690	740	580	660	668	690		730		700		650		692	640	600	620	600	660	630	630	600	700	690	670	665
	D-D	660	620	680	720	670	680	660	660	660	680	670	720	670	675	650	580	615									
392,000	B-B	730	910	1010	1250	975	820	820	950	960	1020	970	1060	1100	962	910	990	950									
	C-C	980	980	850	830	910	950		950		900		850		912	900	880	890	880	890	910	893	840	1010	920	850	905
	D-D	800	890	940	1060	922	900	880	900	900	980	970	1000	990	940	930	880	905									
448,000	B-B	750	970	1590	1760	1268	1050	1030	1080	1160	1440	1410	1430	1490	1261	1120	1310	1215									
	C-C	1390	1370	900	880	1135	1230		1210		1030		1010		1120	1110	1070	1090	1090	1130	1100	1107	980	1270	1180	970	1100
	D-D	830	900	1470	1440	1160	1080	1070	1110	1130	1340	1320	1390	1400	1230	1200	1160	1180									
504,000	B-B	200	440	3250	3240	1782	1080	1060	1220	1220	2410	2440	2330	2430	1774	1670	1900	1785									
	C-C	3330	2820	350	230	1682	2440		1990		1110		1080		1655	1780	1520	1650	1700	1700	1590	1663	1050	2900	2010	960	1730
	D-D	260	410	2790	3050	1628	1180	1130	1190	1200	2230	2200	2330	2360	1728	1780	1630	1705									
510,000	B-B	-380	-110	4270	4320		1030	980	1230	1220	*	*	3010	2120		1950	2340										
	C-C	9650	4580	-400	-1230		6490		2940		1180		1780			4350	1970		3920	3460	2630		1760	7790	3000	-170	
	D-D	-440	-120	*	*		1130	1060	1200	1190	3940	2910	3060	3100		1960	2000										

Initial load = 28,000 lbs.

*Out of range

Strains for all gage lines Col. No 5 Table 7

Load	Section	Strain at gage line (Millionths)								
		5	5b	11	11b	17	17b	23	23b	Average
69,000	B-B	30	40	50	50	20	10	20	40	33
	D-D	60	50	40	40	50	80	40	70	54
138,000	B-B	130	130	150	170	90	90	130	130	128
	D-D	140	150	110	90	150	160	110	130	130
230,000	B-B	260	270	300	320	190	200	290	280	264
	D-D	290	310	240	220	320	340	250	280	281
368,000	B-B	490	490	540	580	390	400	530	530	494
	D-D	510	530	430	410	550	580	430	470	489
506,000	B-B	780	790	810	870	590	600	780	800	753
	D-D	670	700	640	620	820	870	630	710	708
644,000	B-B	1080	1100	1060	1130	850	860	1060	1070	1026
	D-D	920	940	960	940	1260	1270	970	1070	1041
690,000	B-B	1210	1230	1190	1250	1000	1020	1220	1220	1168
	D-D	1010	1030	1090	1070	1460	1530	1110	1210	1189
747,500	B-B	1480	1480	1420	1480	1340	1360	1570	1580	1476
	D-D	1190	1170	1380	1310	1950	2040	1480	1570	1511
799,000	B-B	1630	1540	1650	1590	2470	2540	2680	2750	2106
	D-D	1340	1270	1690	1490	3730	3920	2730	2910	2385

Initial Load 23,000

Strains for all gage lines   Col. No. 6 Table 8

Load	Section	Strain at gage line (Millionths)								
		5	5b	11	11b	17	17b	23	23b	Average
42,000	B-B	10	10	60	60	70	70	120	130	66
	D-D	20	20	10	70	10	40	30	20	28
84,000	B-B	230	230	140	130	140	140	240	230	185
	D-D	100	120	130	200	90	60	100	90	111
140,000	B-B	380	380	240	240	270	260	390	360	315
	D-D	210	220	250	350	210	190	220	220	234
224,000	B-B	580	560	400	380	440	430	560	560	488
	D-D	410	450	490	580	430	400	420	440	452
308,000	B-B	850	840	630	610	680	660	830	830	735
	D-D	630	660	690	800	640	640	600	650	663
392,000	B-B	1170	1190	950	940	980	960	1130	1130	1056
	D-D	970	1000	990	1110	970	960	930	970	987
420,000	B-B	1310	1330	1110	1070	1130	1120	1260	1270	1200
	D-D	1110	1130	1120	1240	1120	1110	1080	1110	1127
490,000	B-B	1790	1810	1570	1550	1580	1560	1690	1690	1655
	D-D	1590	1620	1610	1710	1600	1570	1510	1540	1594
523,000	B-B	2090	2210	2230	3280	1590	1500	1320	1230	1931
	D-D	1910	1950	1960	2080	1360	1290	1410	1410	1671

Initial Load 14,000

Strains for all gage lines Col. No. 7 Table 9

TABLE 10 - MODULUS OF ELASTICITY

Column No.	Core Section	Plates	Weighted Average	From Column Tests
1	29,600,000+	30,000,000+	29,800,000	28,000,000
1EB	28,400,000+	30,100,000+	29,500,000	28,400,000
2	31,000,000+	30,400,000+	30,600,000	28,800,000
3	31,300,000+	28,900,000+	29,900,000	29,200,000
4	28,000,000+	27,400,000+	27,700,000	28,400,000
5	27,500,000+	29,100,000*	28,300,000	29,100,000
Average	29,300,000	29,300,000	29,300,000	28,650,000

All figures represent lb. per sq.in.

\+ Average of 2 test coupons

* Average of 4 test coupons

TABLE 11 - RESULTS OF COLUMN TESTS

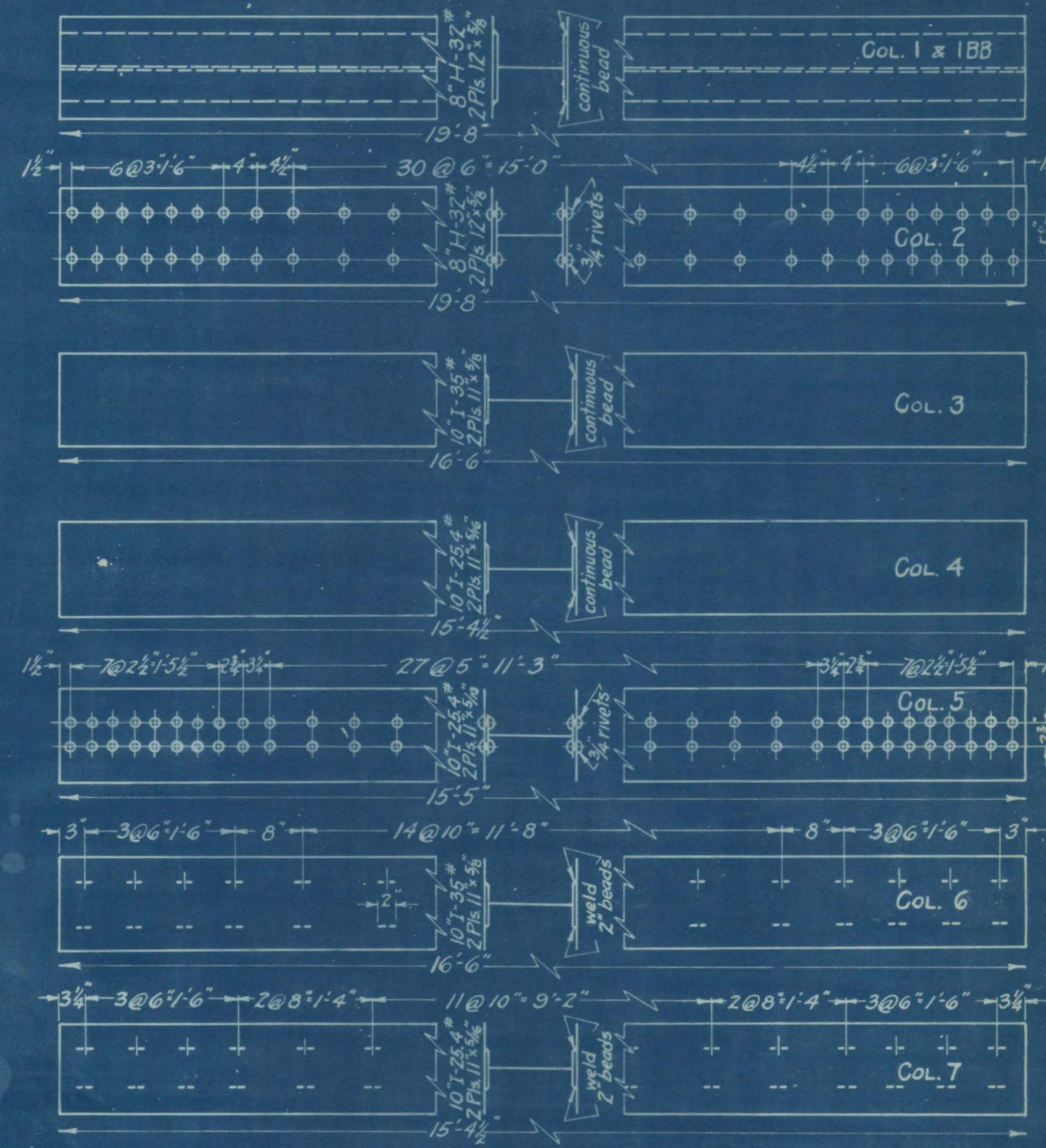
Column No.	Area Sq. In.	$\frac{l}{r}$	Maximum Load Total Lb.	Maximum Load Unit Lb. per Sq. In.	Deflection of Maximum Load - In.	Modulus of Elasticity Lb. per sq. in.
1	24.30	80.8	785,000	32,300	0.68	28,000,000
1BB	24.30	80.8	784,000	32,300	0.53	28,400,000
2	24.30	80.0	790,000	32,500	0.50	28,800,000
3	23.97	77.9	739,000	30,800	0.75	29,200,000
4	14.26	78.7	527,000	36,900	0.77	28,400,000
5	14.26	78.7	510,000	35,800	0.87	29,100,000
6	23.97	77.9	799,000	33,300	0.62	26,000,000
7	14.26	78.7	523,000	36,700	0.38	27,500,000
Average	-	--	----	33,800	0.61	28,155,000

TABLE 12 - COMPARISON OF COMPUTED STRESSES FOR MAXIMUM LOAD ON COLUMN

WITH YIELD POINT STRESSES FROM COUPONS AND STRESSES COMPUTED

BY RANKINE'S FORMULA

Column No.	Yield Point of Coupons Lb.per sq.in.	Stress at First Strain Line Lb.per sq.in.	Stress at Proportional Limit of Column	Stress at Maximum Load From Test	Stress at Maximum Load Computed	Ratio of Stress at Maximum Load to Yield Point of Coupons	Computed $\frac{P}{A}$ to Stress at Maximum Load
A	B	C	D	E	F	$G = (\frac{E}{B})$	$H = (\frac{F}{E})$
1	34,900	16,000	21,800	32,300	27,700	.925	.858
1BB	35,400	16,000	21,800	32,300	28,100	.912	.870
2	35,900	16,000	21,800	32,500	28,500	.905	.877
3	34,600	21,000	15,300	30,800	27,800	.892	.903
4	38,700	19,000	21,400	36,900	31,000	.954	.840
5	39,200	17,000	21,400	35,800	31,400	.913	.877
6	37,900	5,800	15,400	33,300	30,500	.879	.916
7	39,800	10,000	15,400	36,700	31,900	.922	.869



NOTE-

All ends milled

In Columns 1, 1BB, 3, and 4, Reinforcing Plates were welded to I-Beam with a continuous bead.

In Columns 6 and 7, Plates were welded to I-Beam with an intermittent bead.

In Columns 2 and 5, Plates were riveted to I-Beam.

DETAILS
— OF —
COLUMNS TESTED

Fig. 1

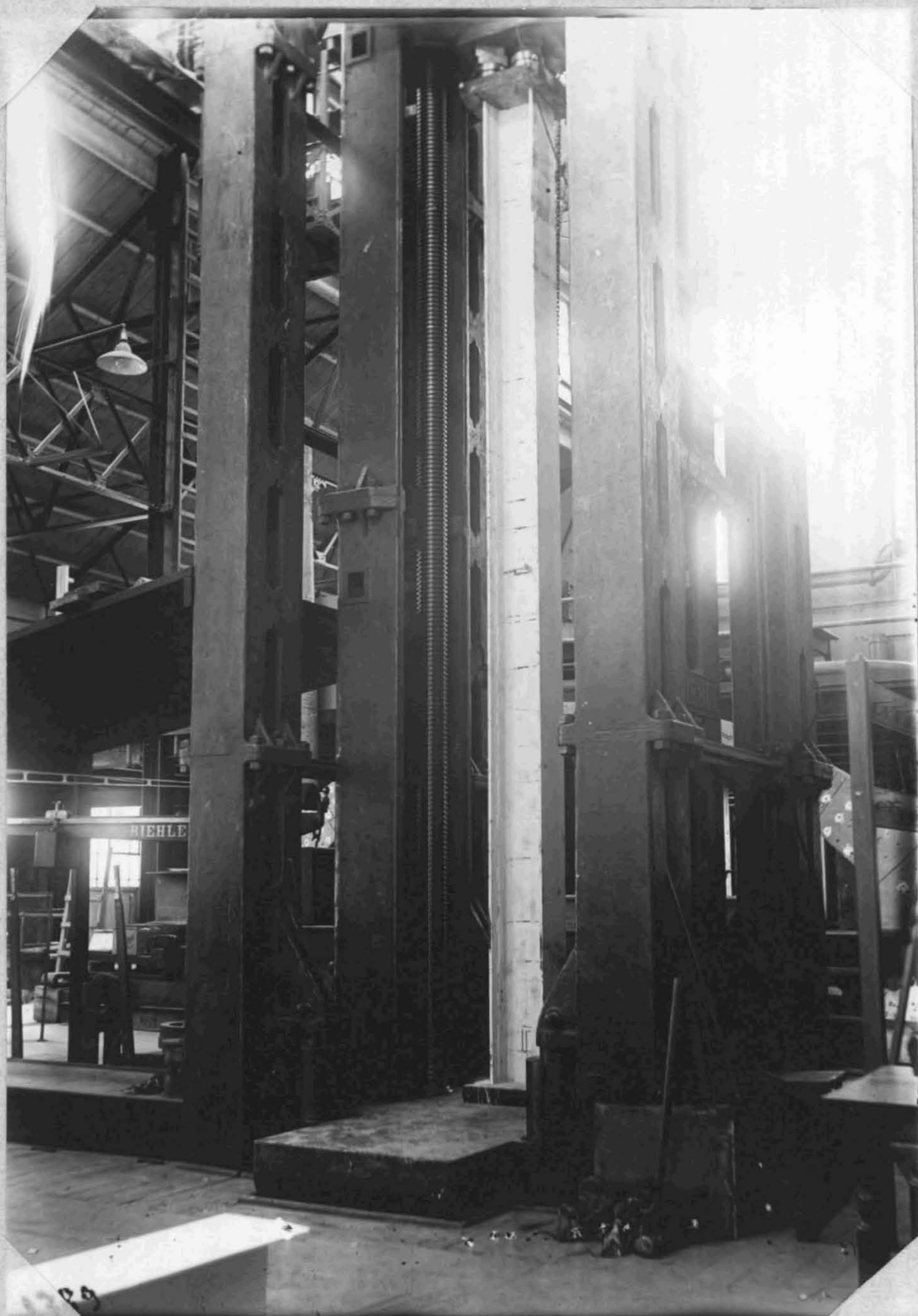


Fig. 2 - View of Column in Testing Machine

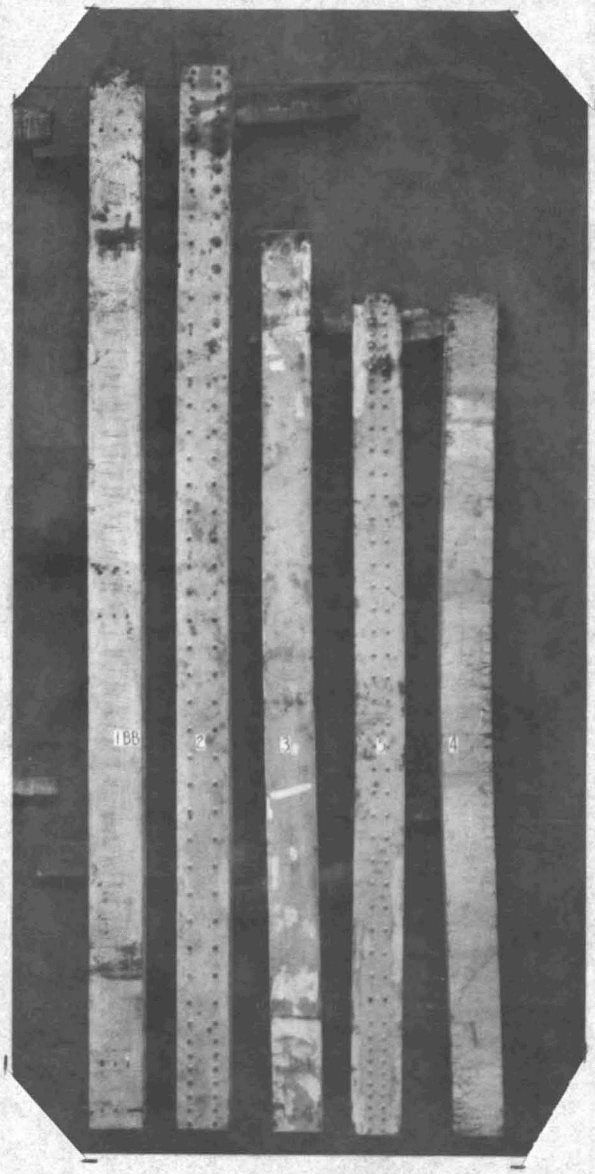


Fig. 3 - Columns 1BB, 2, 3, 4, and 5
After Testing

NOTE: Location of Column Numbers indicate the portion of the columns shown in Fig.33, 35, 37, 42, and 43

Fig. 4 - Columns 1BB, 2, 3, 4, and 5
After Testing

NOTE: Location of Column Numbers indicate the portion of the columns shown in Fig. 32, 34, 35, 38, and 44.

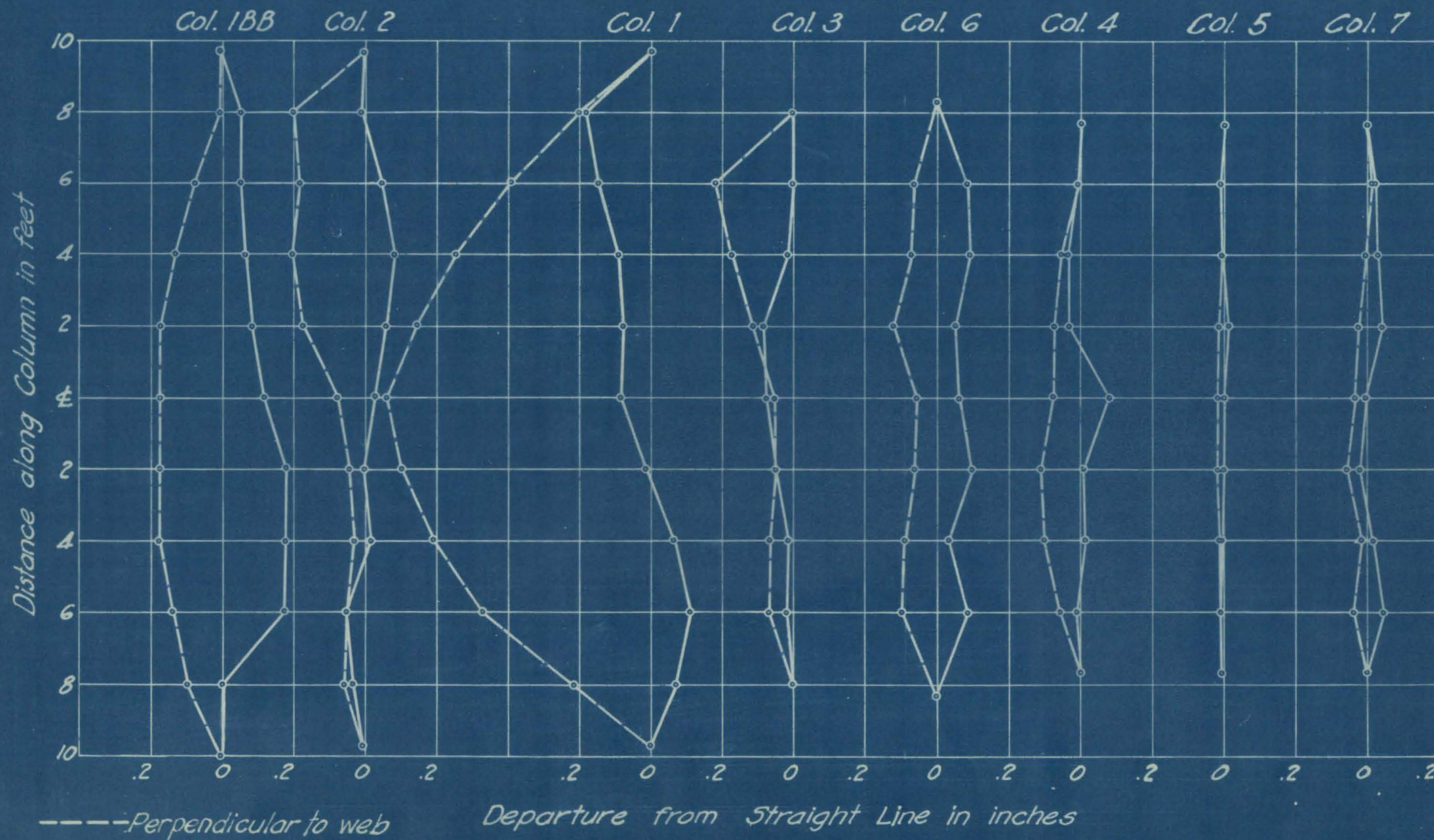
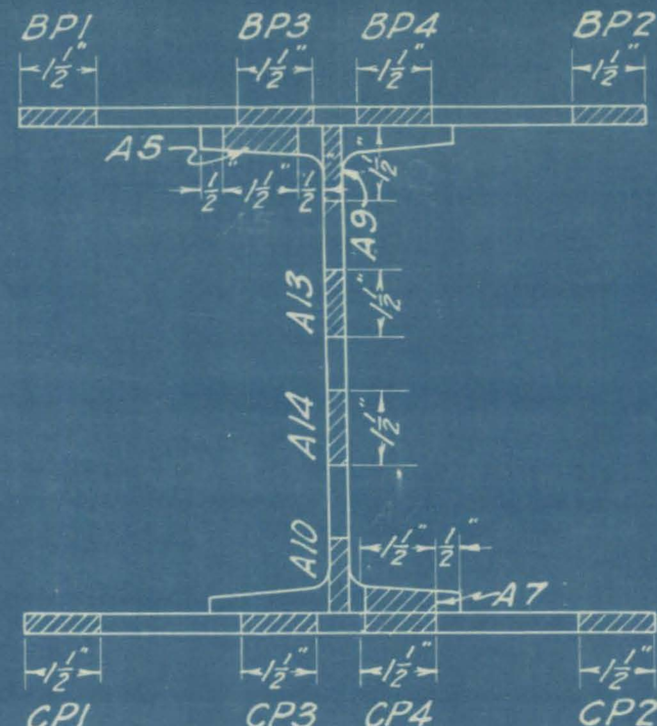
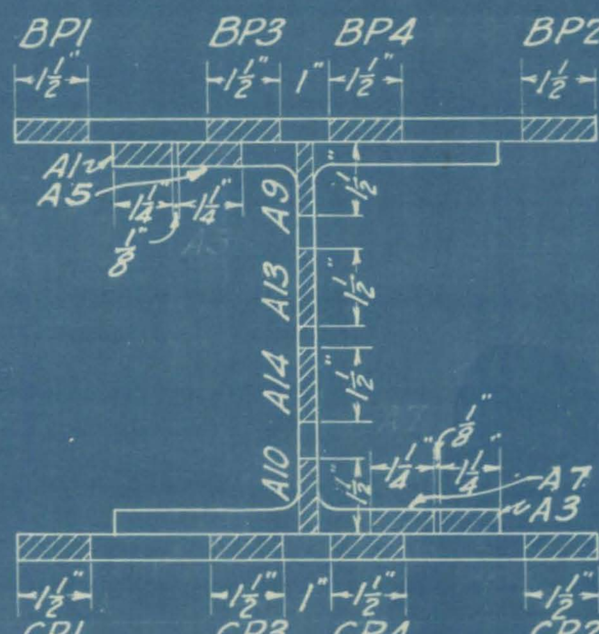


Fig. 5 - INITIAL ALIGNMENT OF COLUMNS



General Section of Columns 3, 4, 5, 6, and 7



General Section of Columns 1, 1BB, and 2

NOTE: Shaded Sections show location of Coupons

Fig. 6

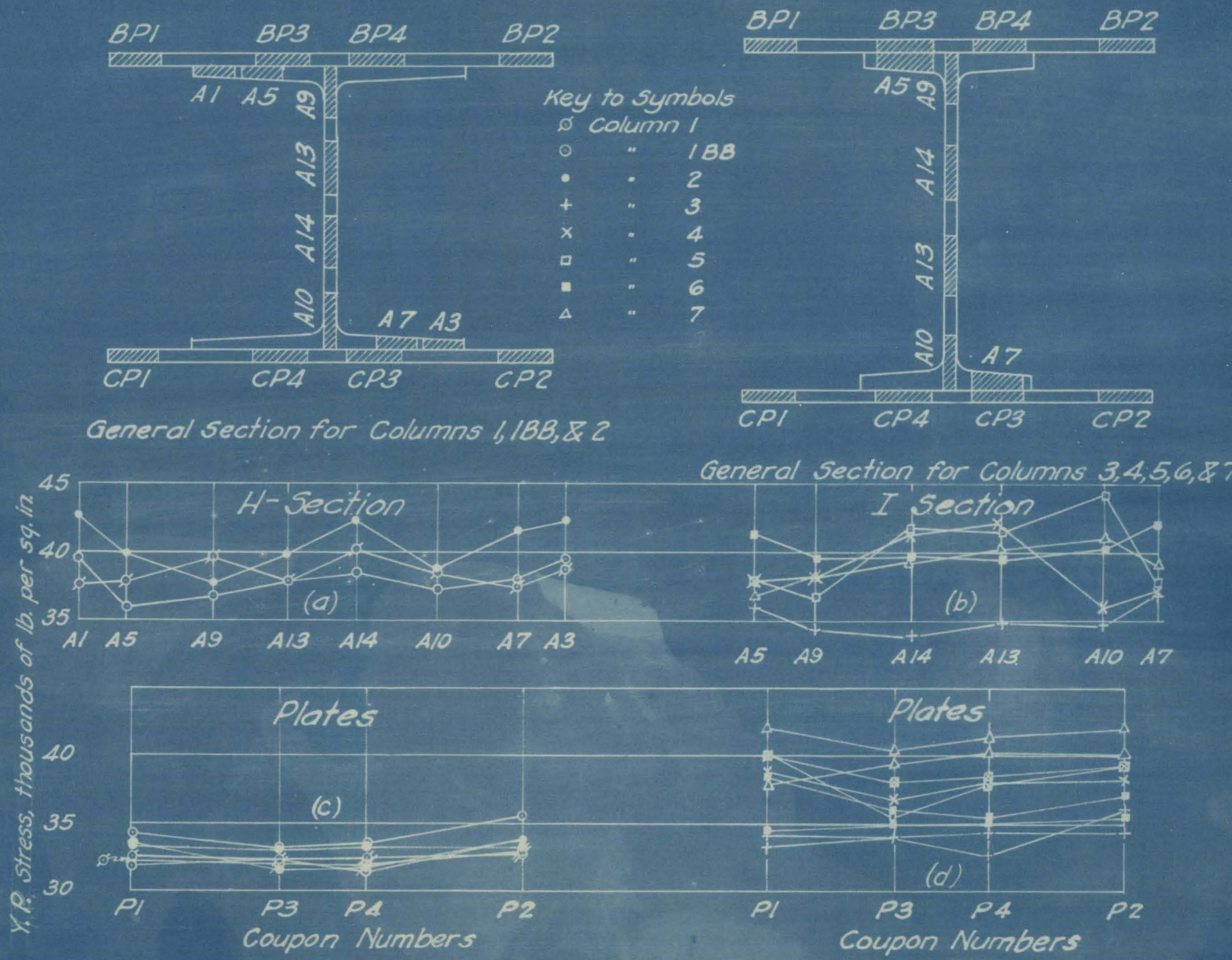


Fig. 7 - Yield Point Stresses Determined for Coupons

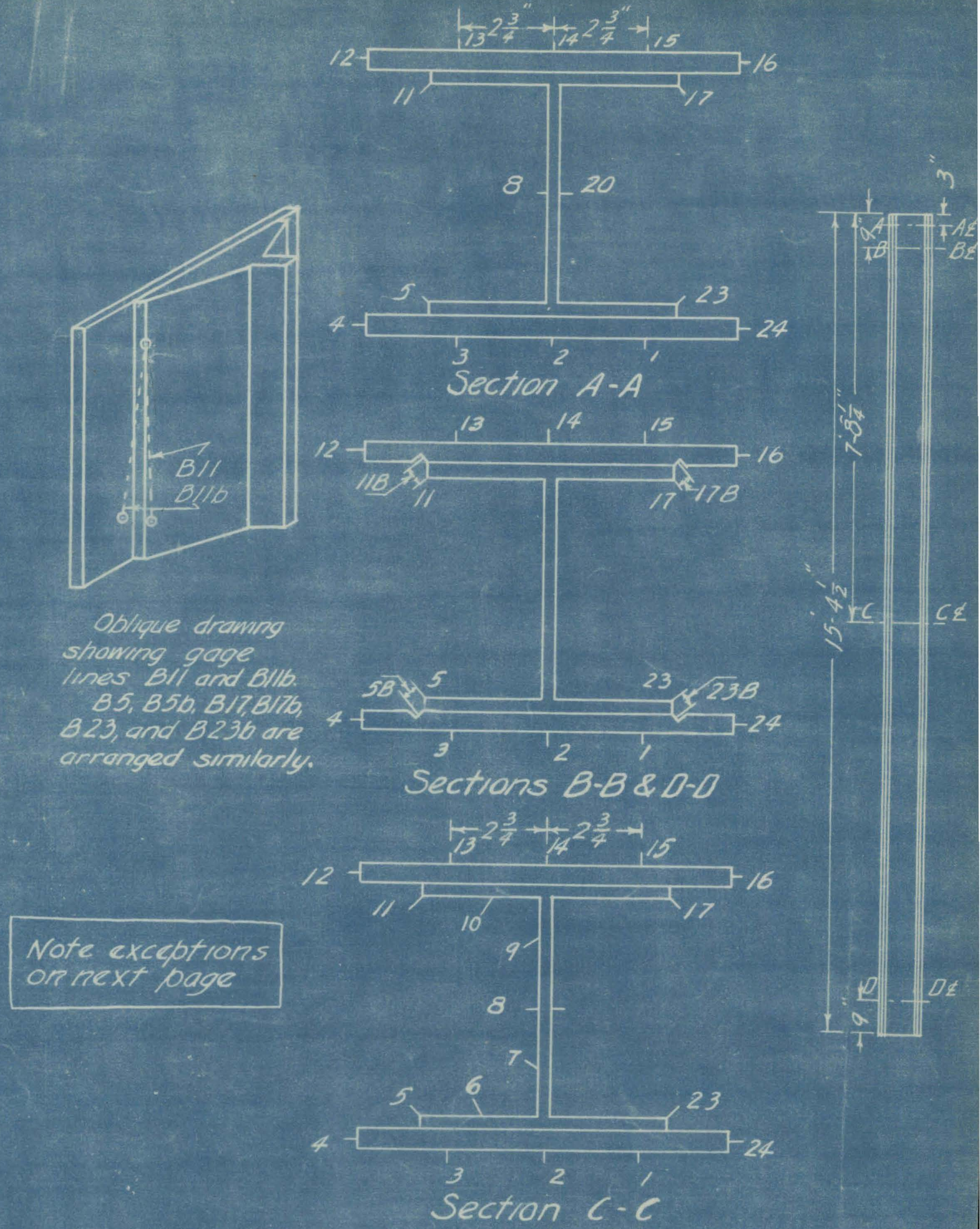


FIG. 8-LOCATION OF GAGE LINES

OMISSIONS AND EXCEPTIONS IN PLACING GAGE LINES

(See Preceding Figure)

Column 1	Section A-A omitted
Column 1BB	Section A-A omitted
Column 2	Section A-A omitted
Column 3	Section A-A omitted. No. 6 and 10 on Section C-C omitted
Column 4	No. 17 on Section A-A, and 5b, 11b, 17b, and 23b omitted on Section D-D. No. 6 and 10 omitted on Section C-C and No. 14 on B-B. Also No. 1, 5, 18, and 15 on Sections B-B and D-D were omitted.
Column 5	Section A-A omitted. No. 6 and 10 on Section C-C omitted
Column 6	All readings omitted except 5, 5b, 11, 11b, 17, 17b, 23, and 23b on Sections B-B and D-D
Column 7	Same as for Column 6

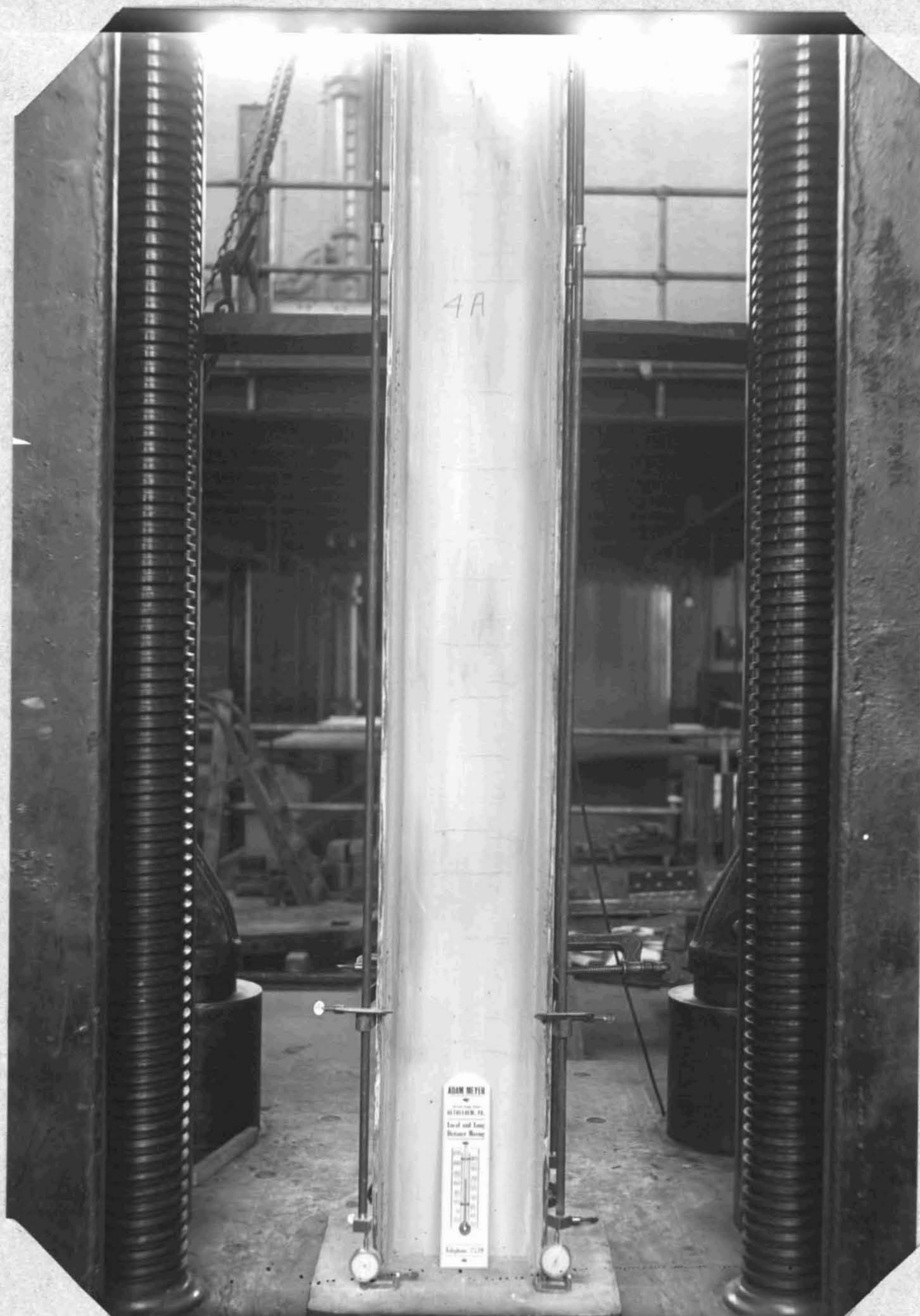


Fig. 9 - Base of Column 4
Showing Compressometers

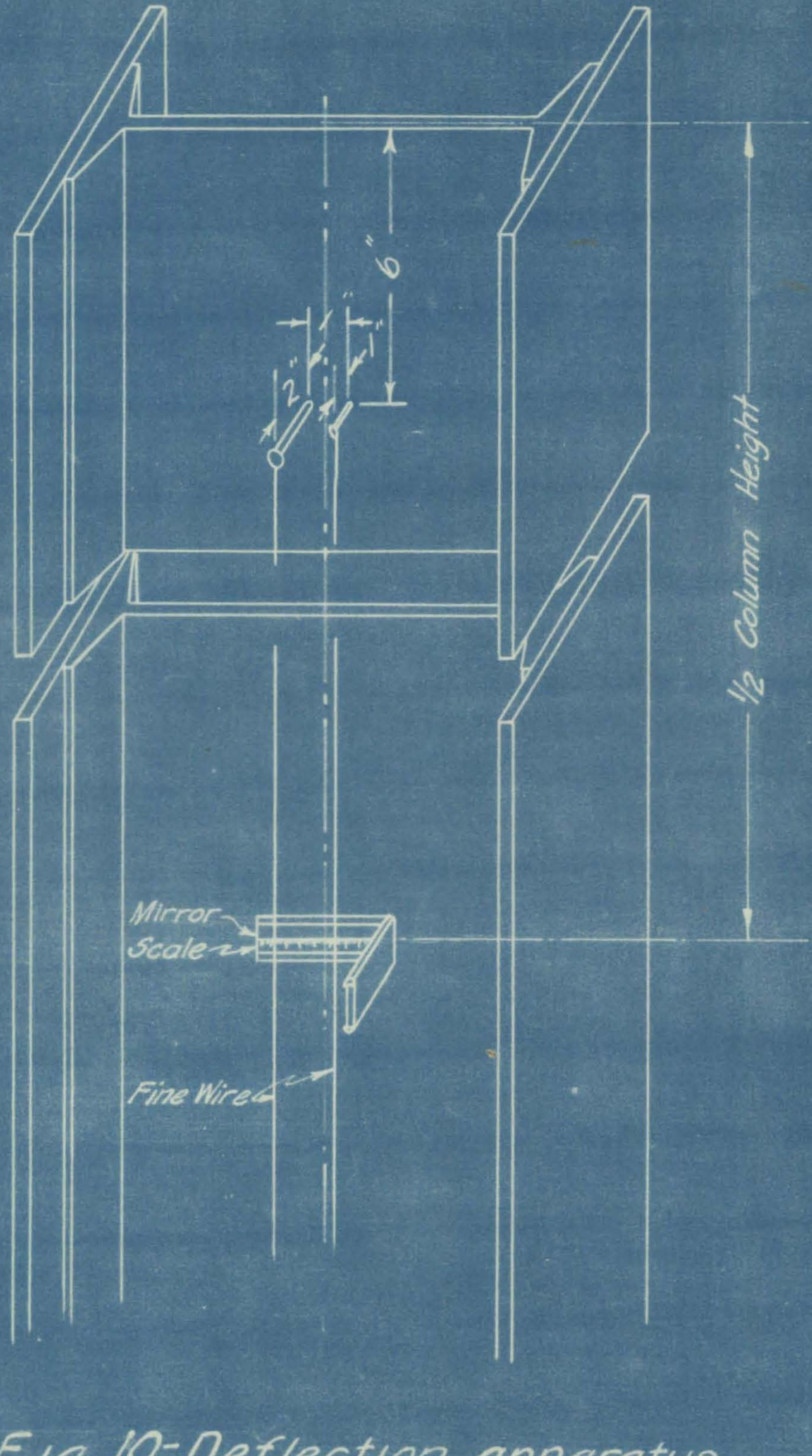


Fig. 10-Deflection apparatus

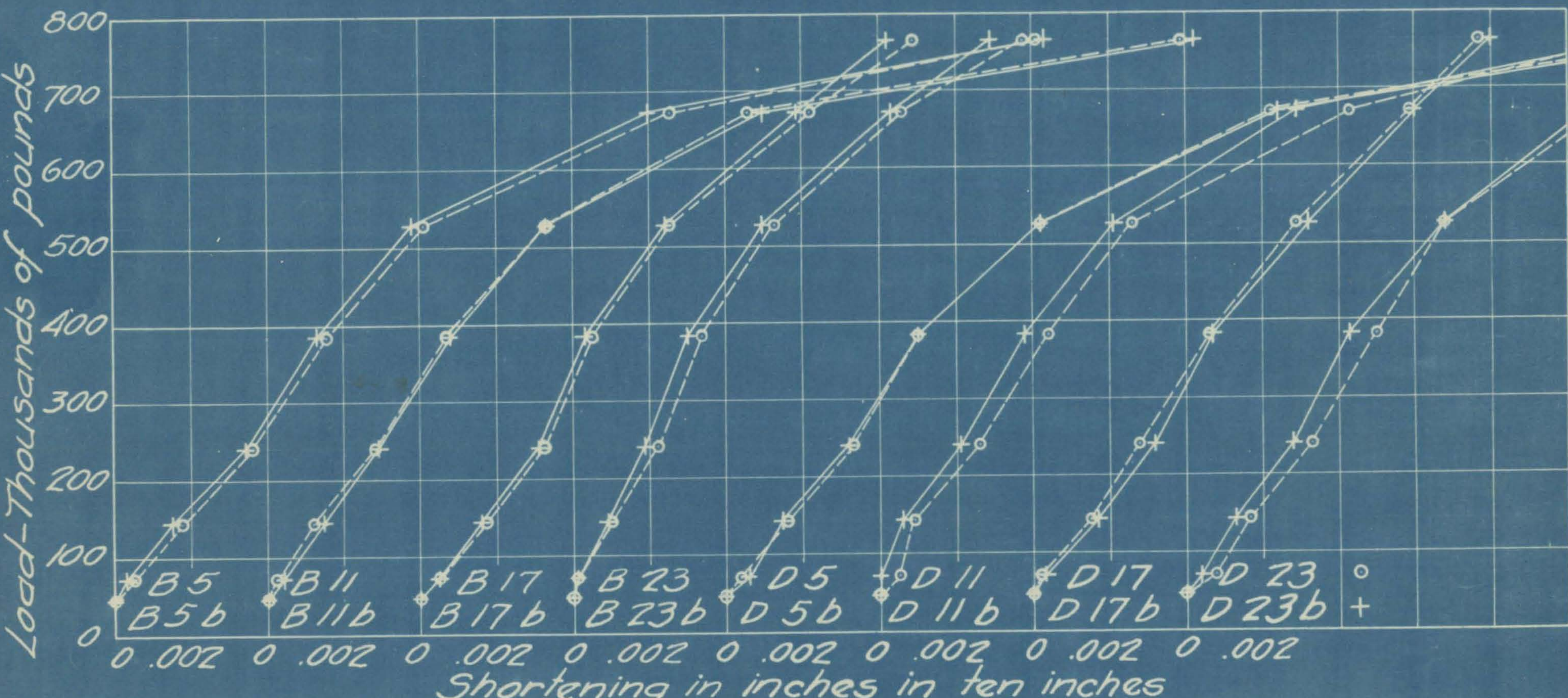


Fig. 11 - Slip of plates for column 1

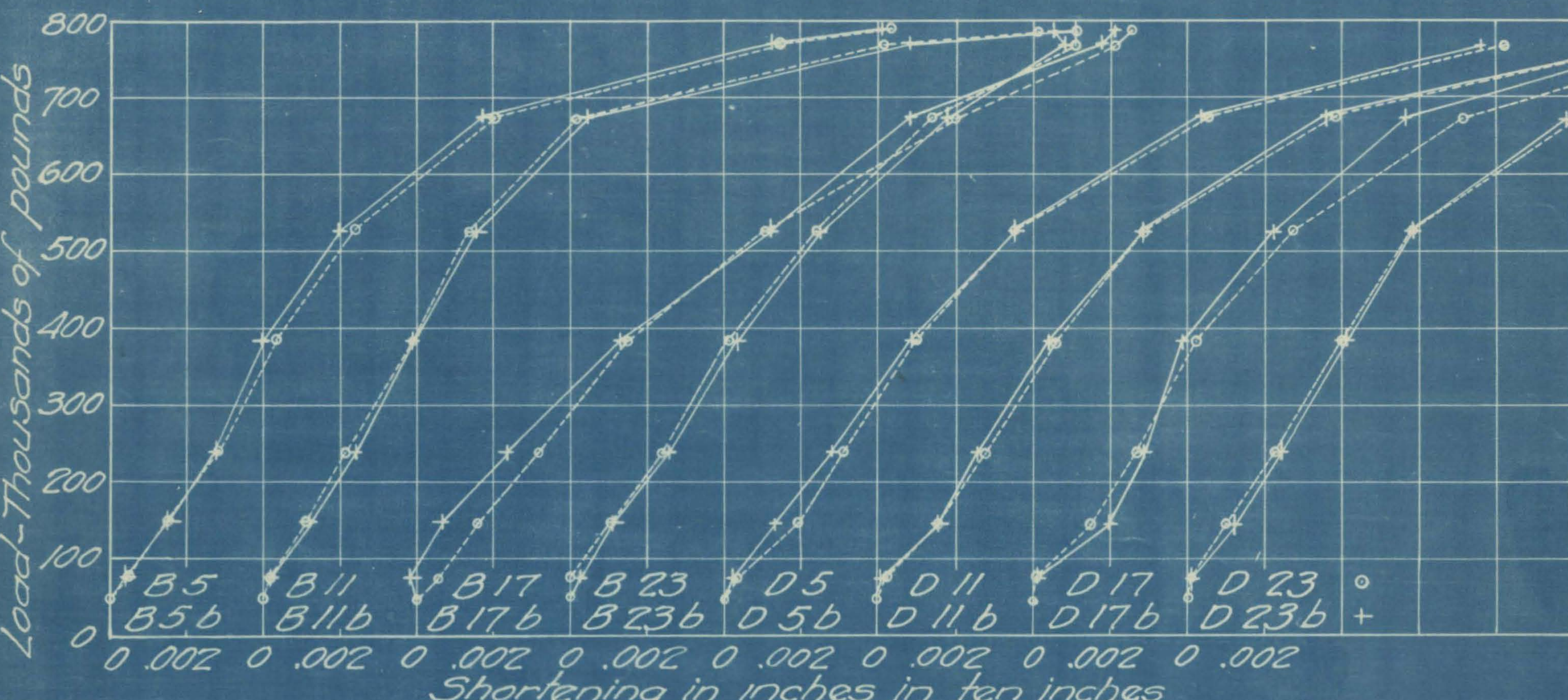


Fig 12 - Slip of plates for column 1BB

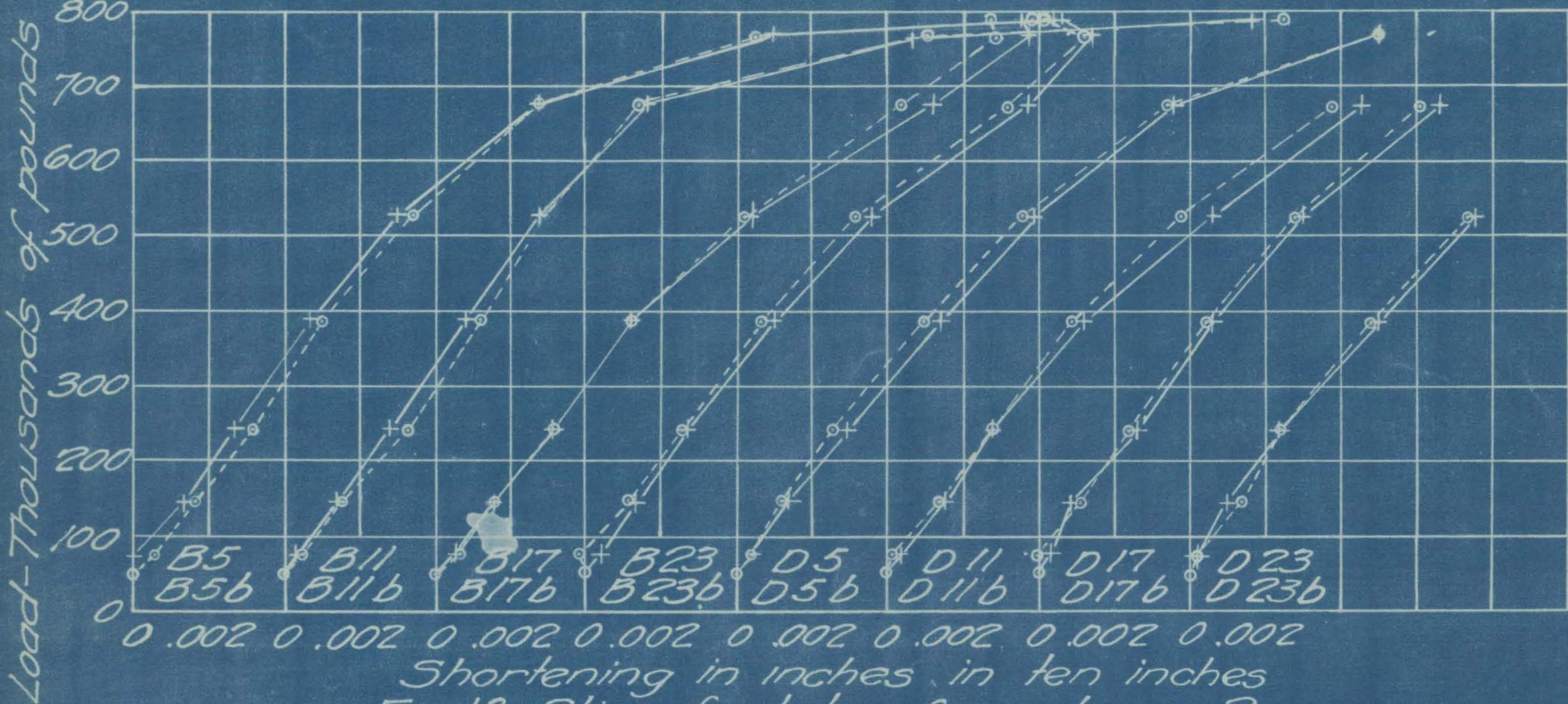


Fig 13 - Slip of plates for column 2.

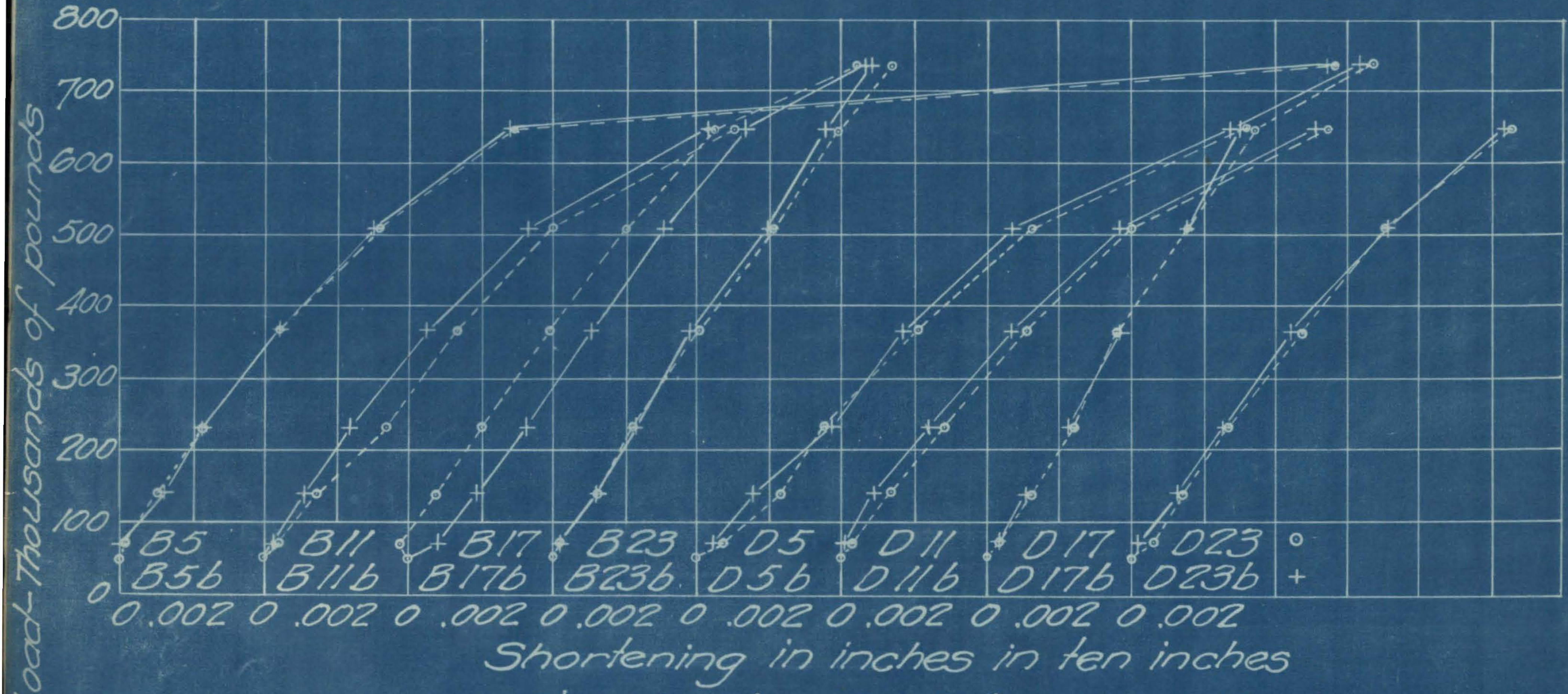


Fig 14 - Slip of plates for column 3

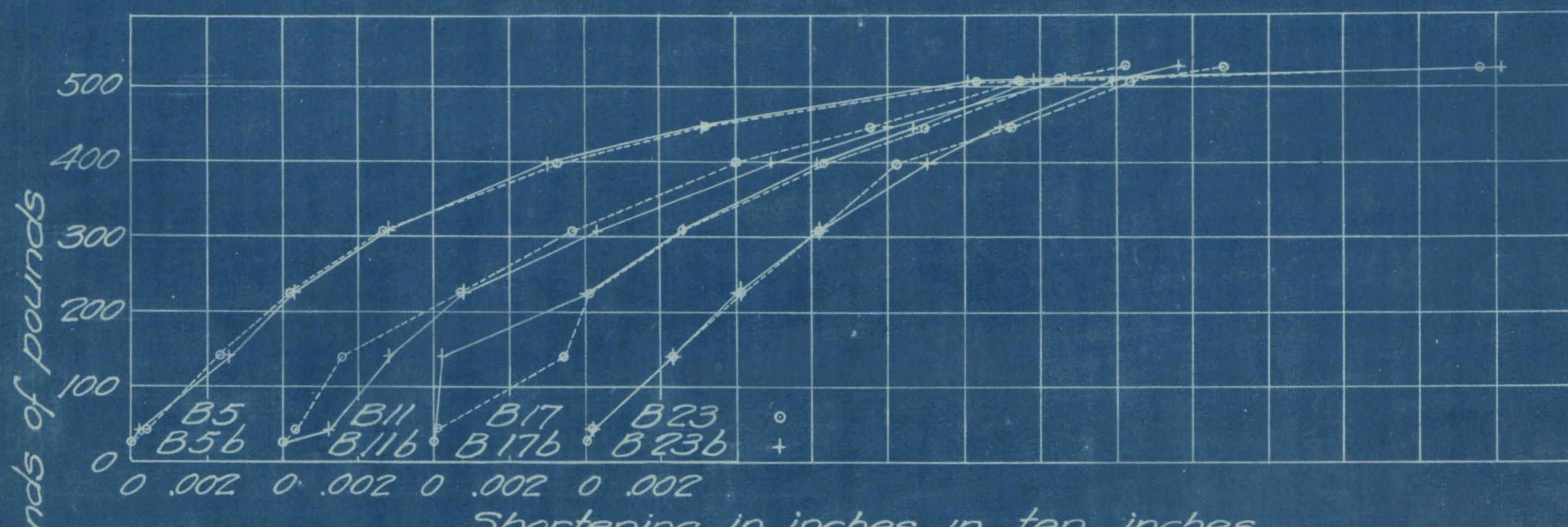


Fig. 15 Slip of plates for column 4

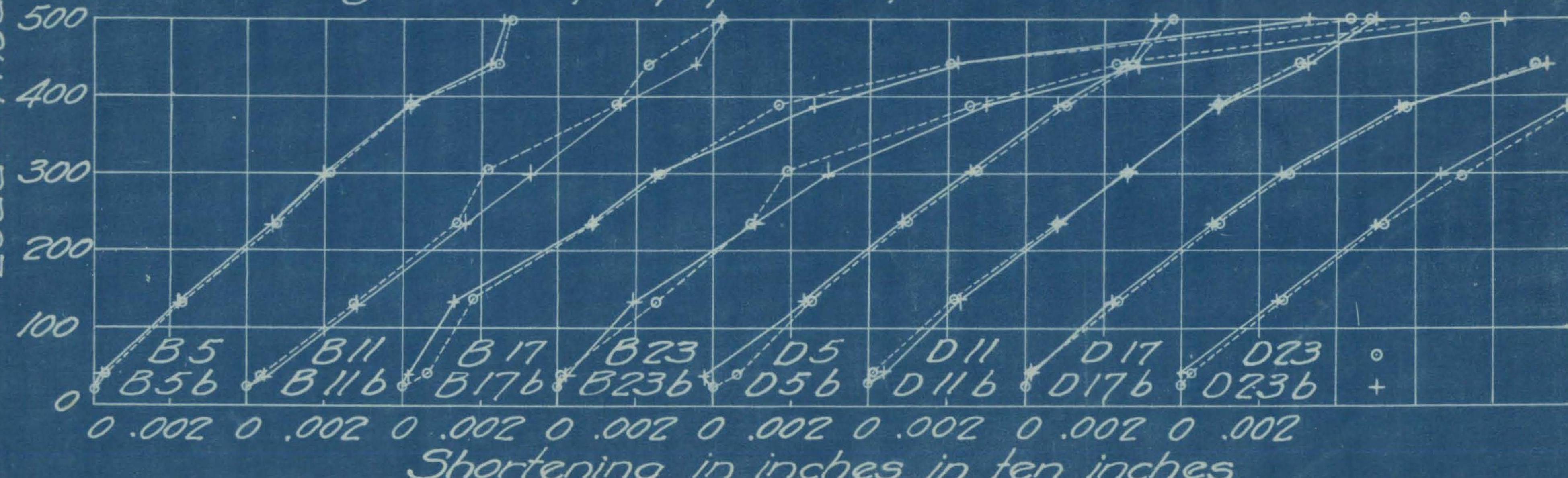


Fig. 16 - Slip of plates for column 5

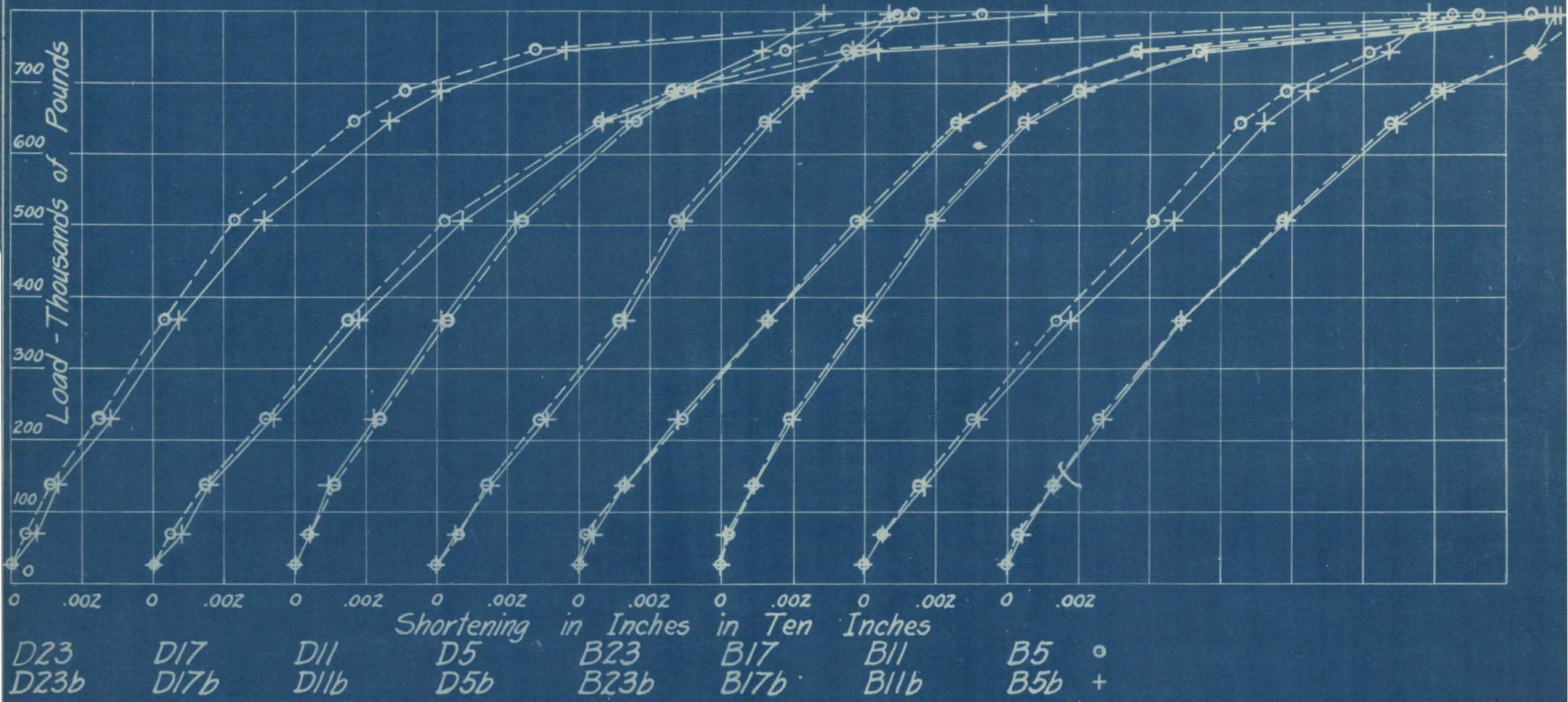


Fig. 17-Slip of Plates for Column 6

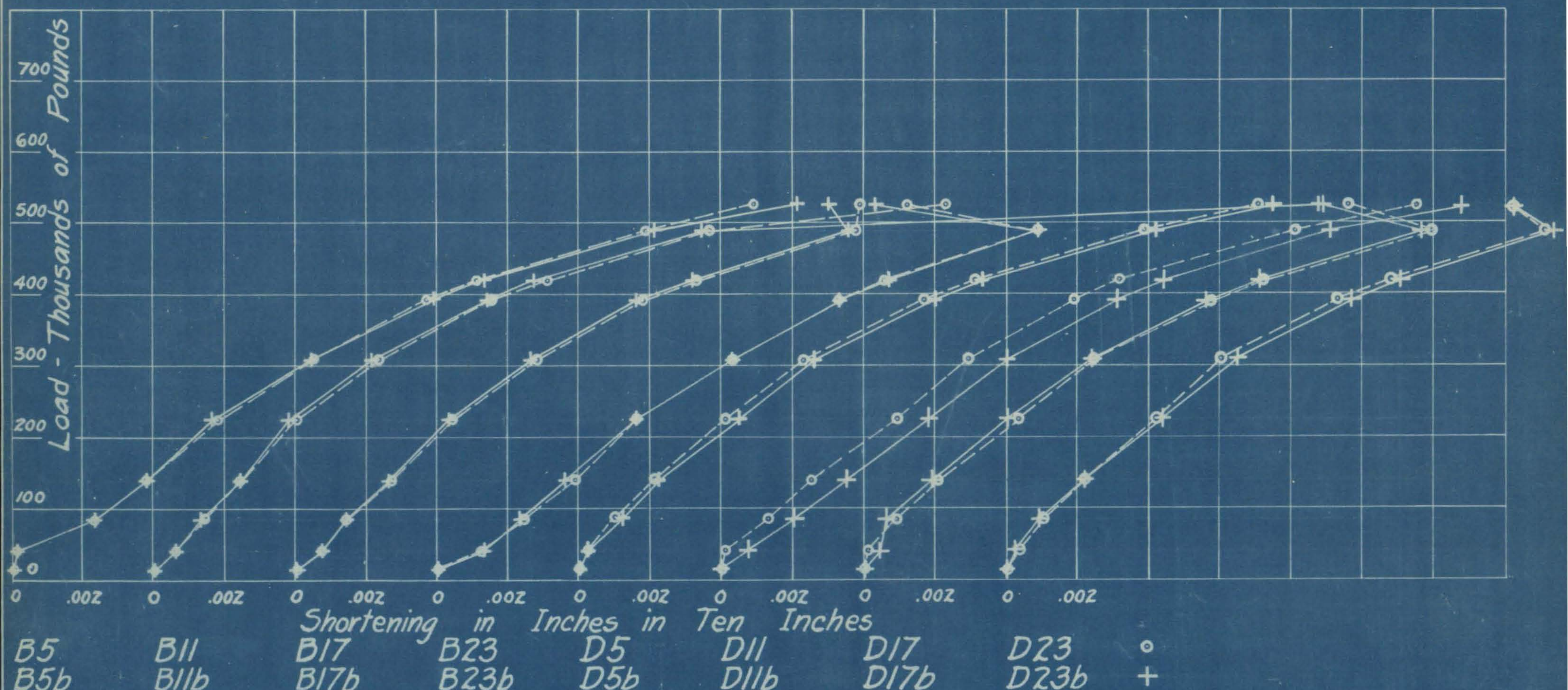


Fig. 18 - Slip of Plates for Column 7

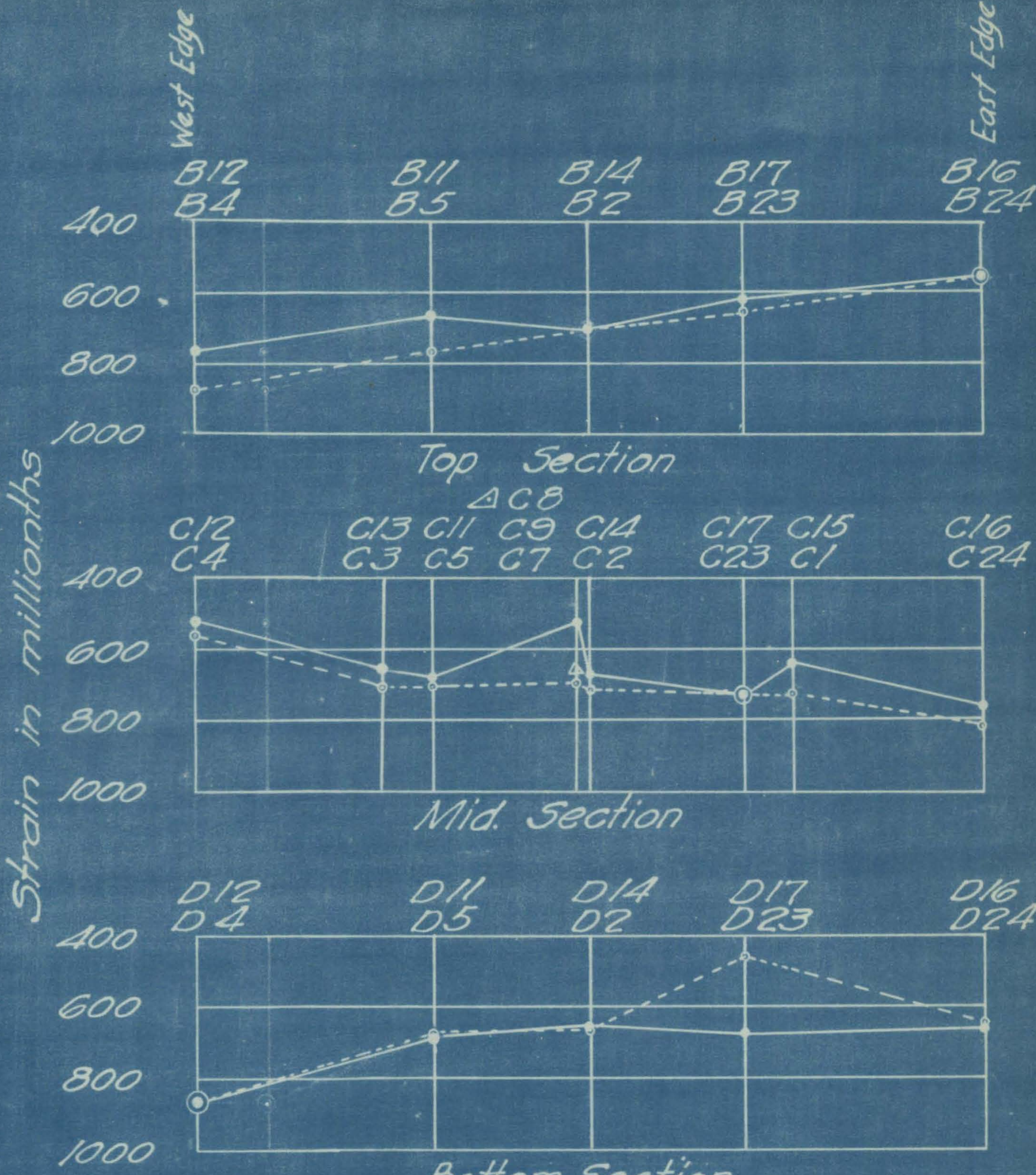


Fig. 19 - Distribution of strains at sections of column 4 for load of 308,000 pounds.

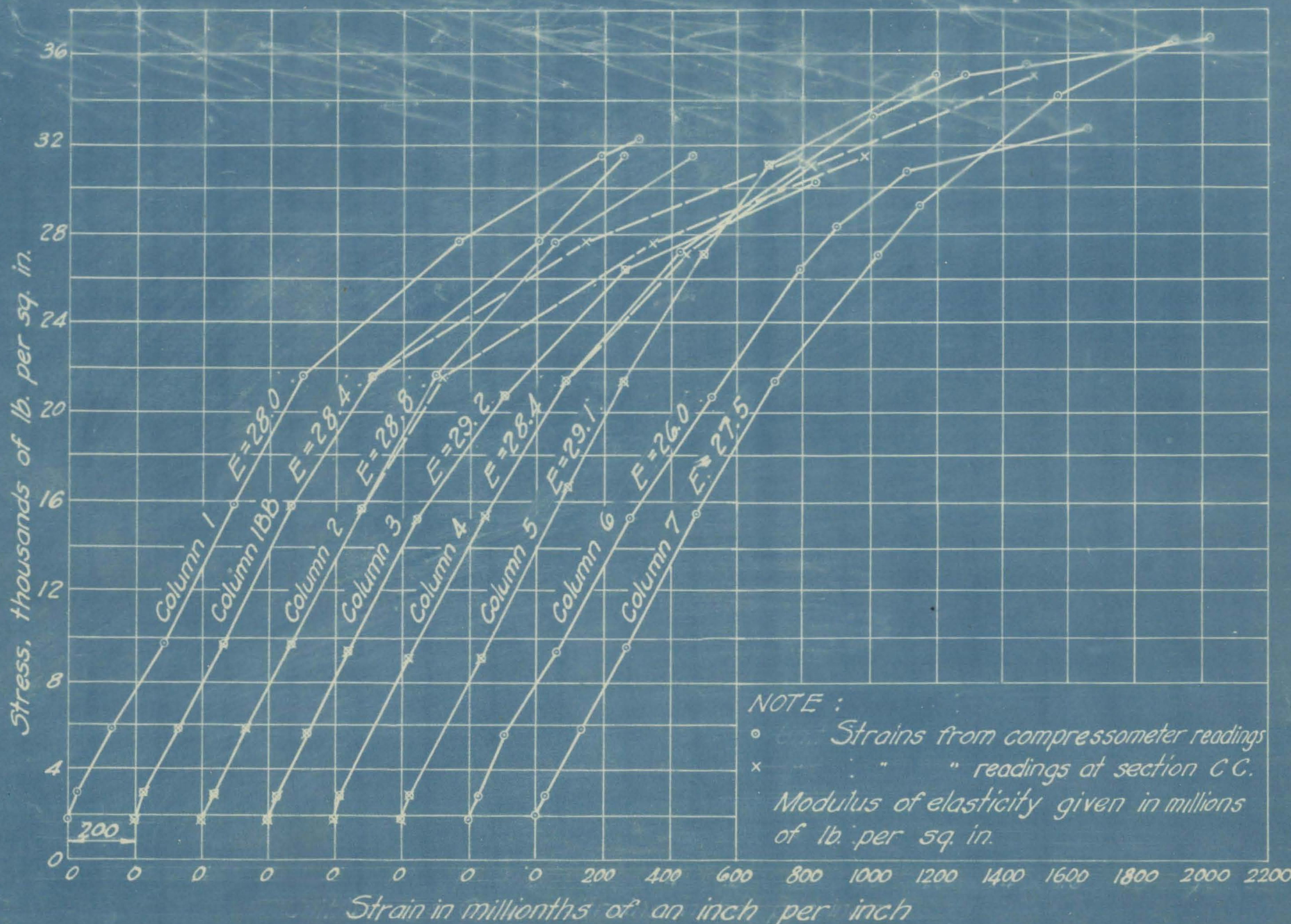


FIG. 20 - STRESS STRAIN CURVES.

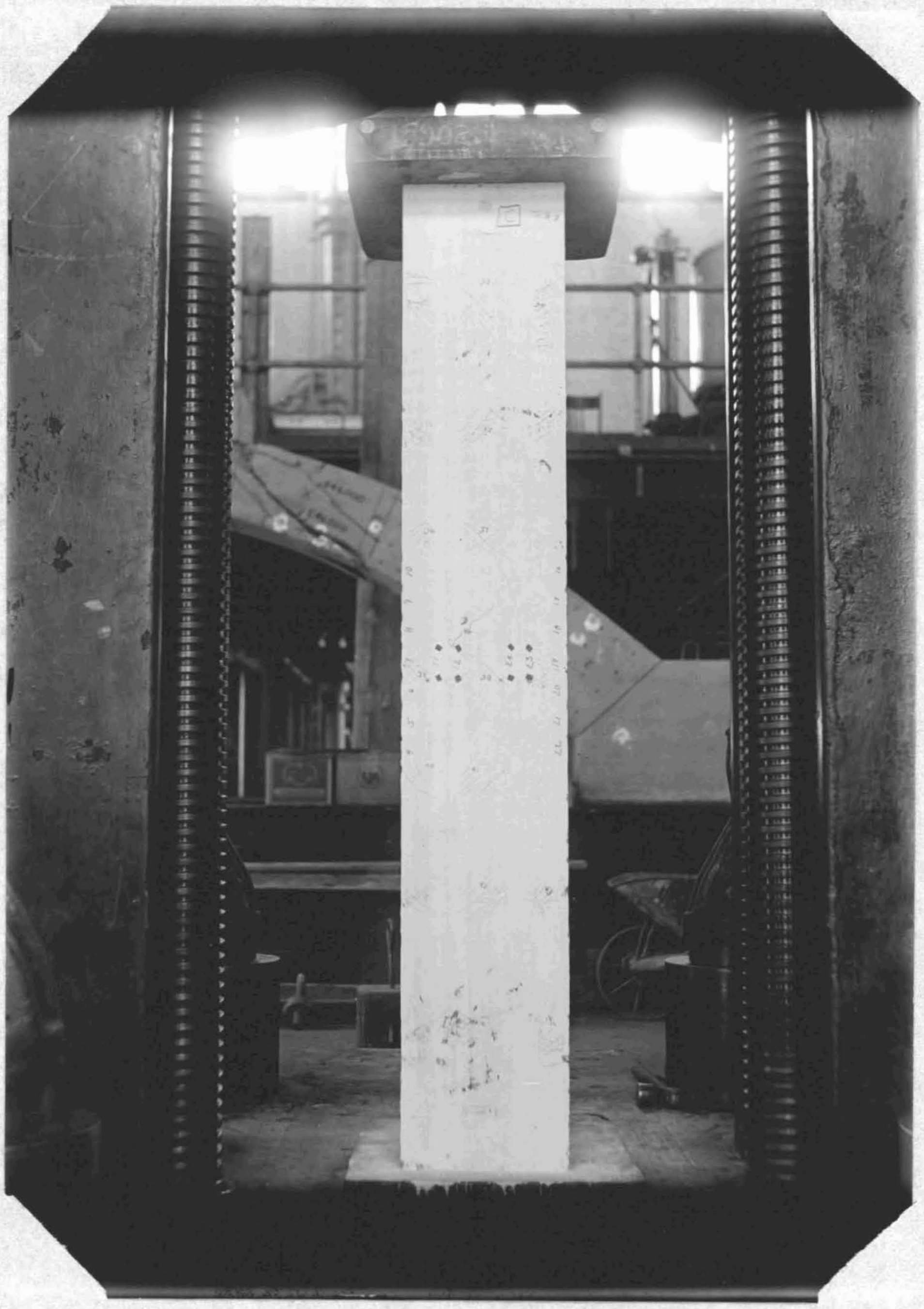


Fig. 21 - Photograph of Short Column

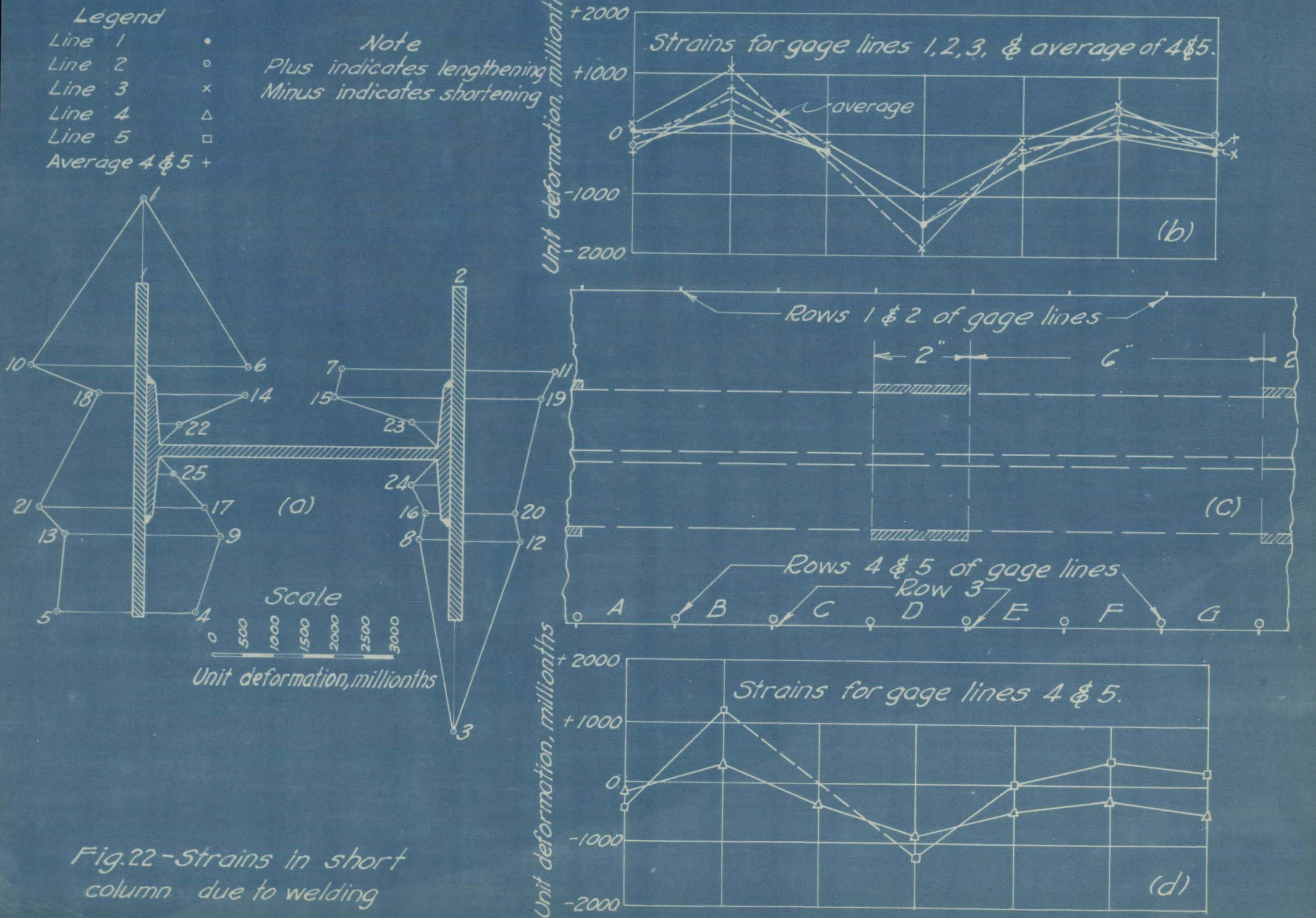


Fig. 22 - Strains in short column due to welding

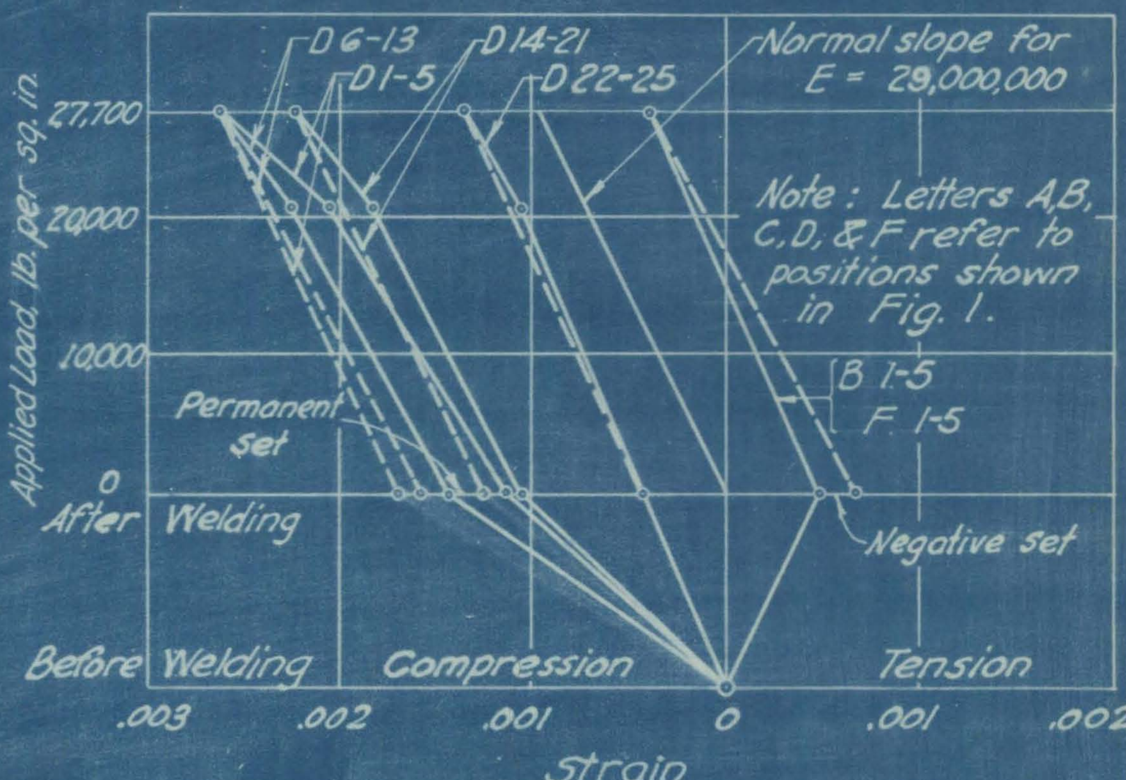


Fig. 23-Local Strains in Columns based on Readings taken before Fabrication.

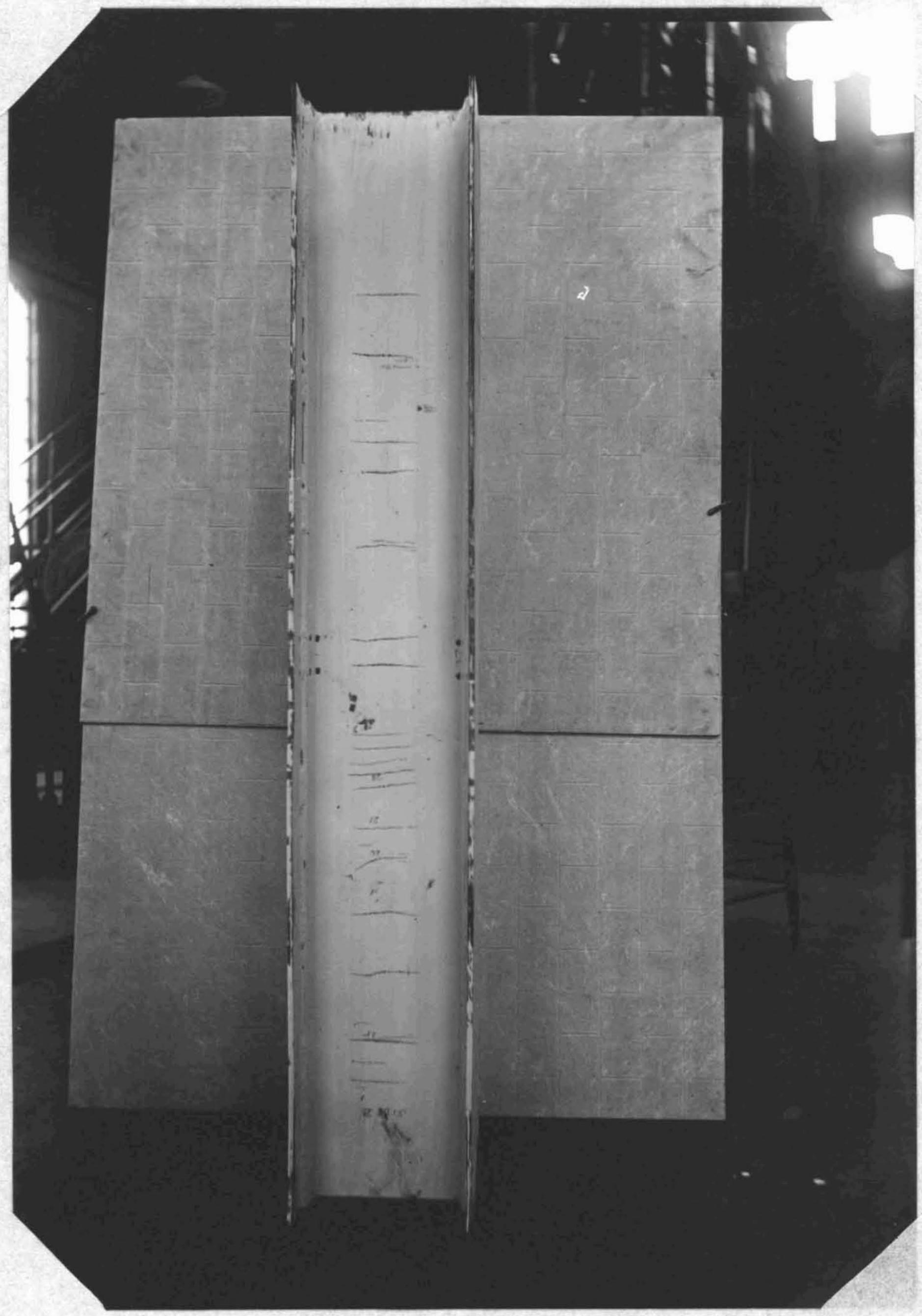


Fig. 24 - Strain Lines in Short Column

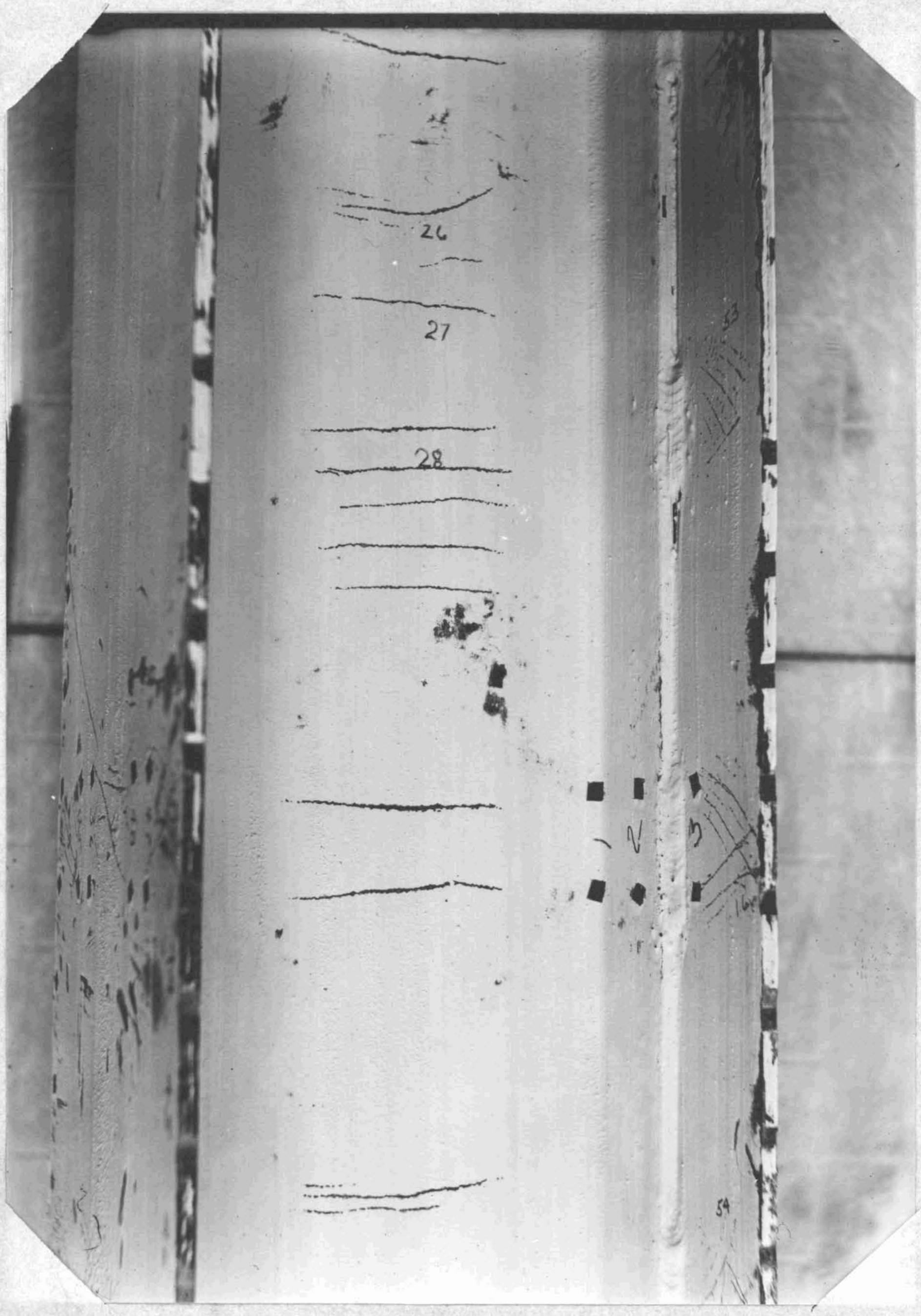


Fig. 25 - Strain Lines in Short Column

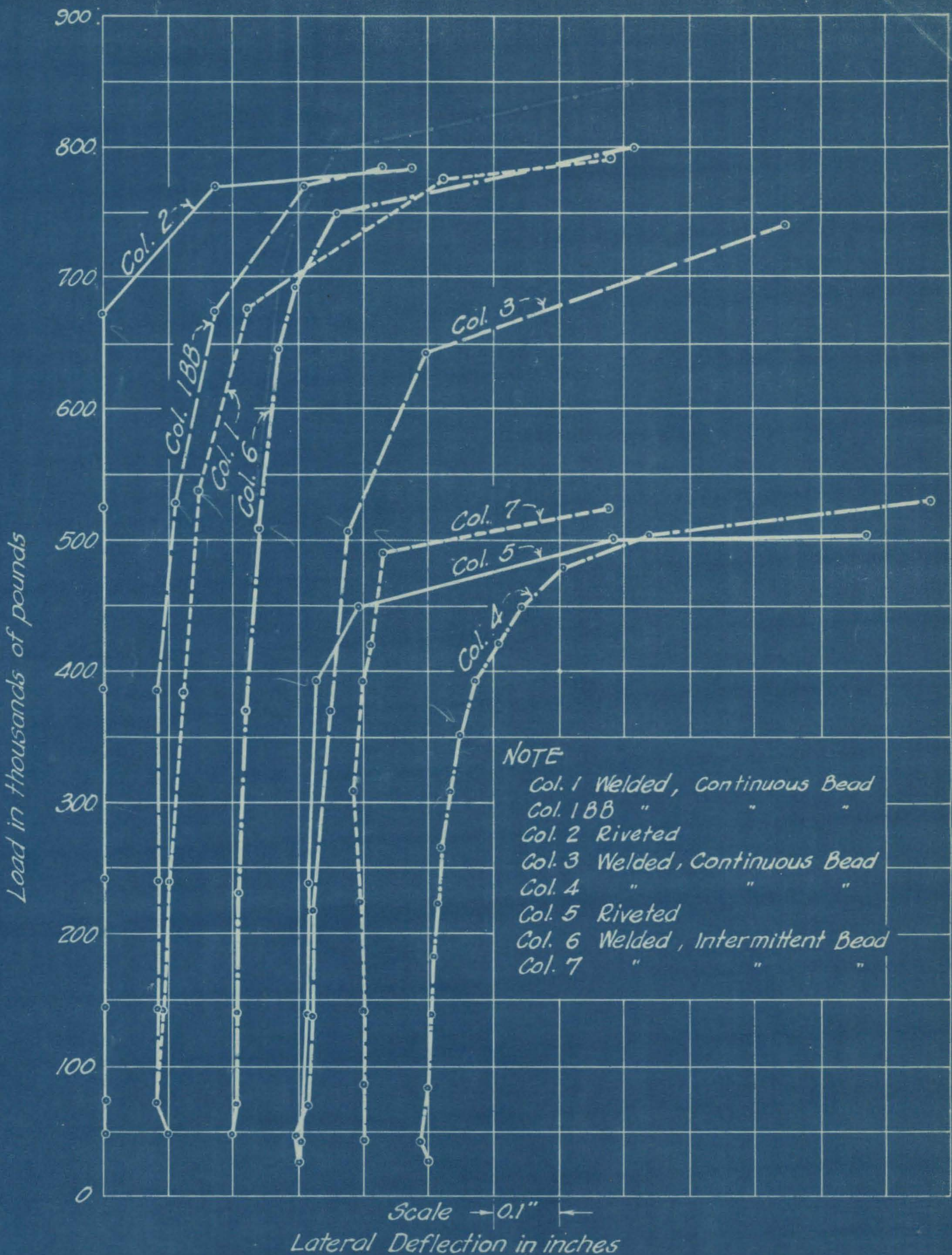
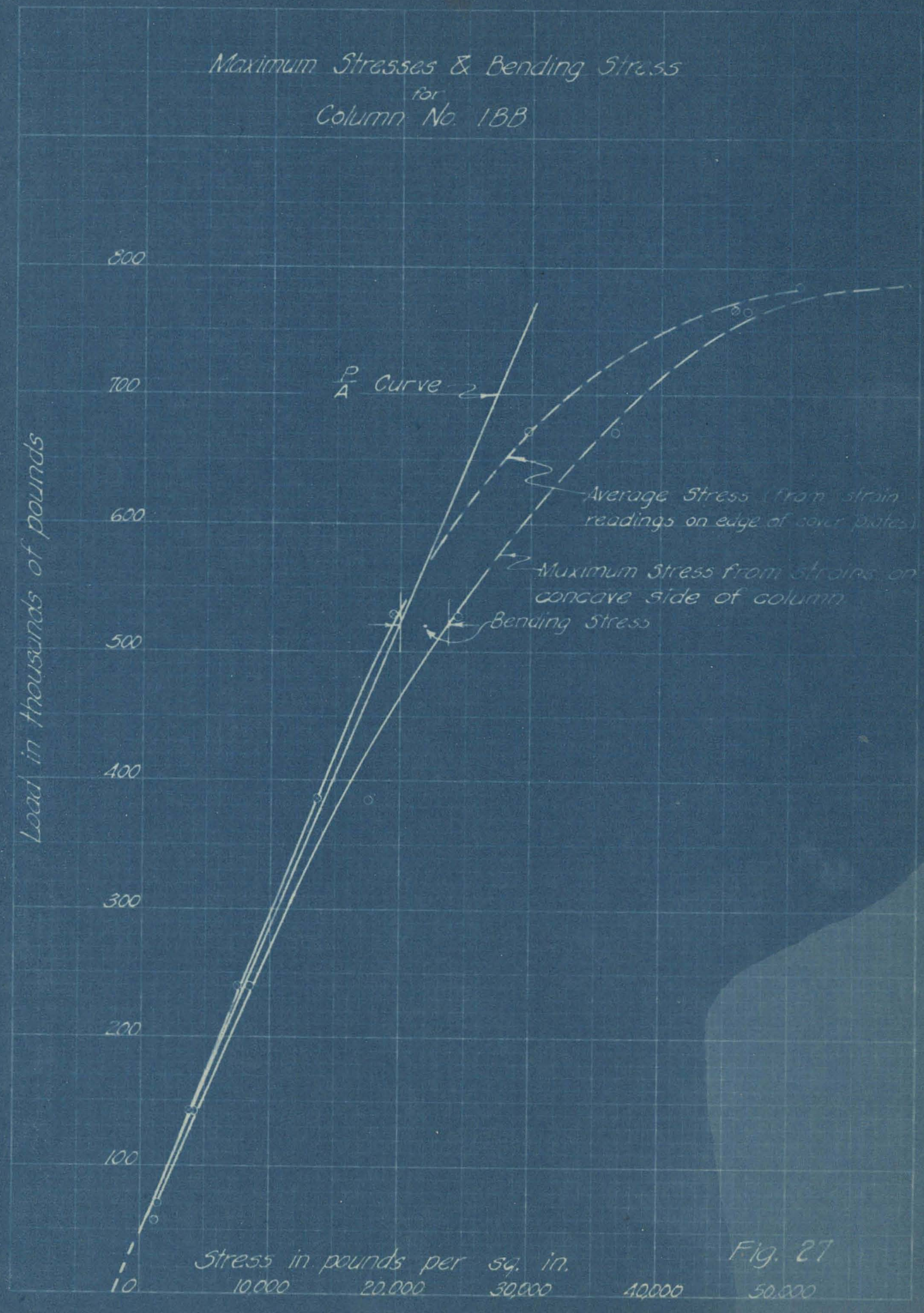


Fig. 26 CENTER DEFLECTION IN PLANE OF COVER PLATES



Maximum Stresses & Bending Stress
for
Column No. 18B
800
700
600
500
400
300
200
100
Load in thousands of pounds
P/A Curve
Average Stress (from strain readings on edge of cover plates)
Maximum Stress from strains on concave side of column
Bending Stress
Stress in pounds per sq. in.
10
10,000
20,000
30,000
40,000
50,000

Fig. 27

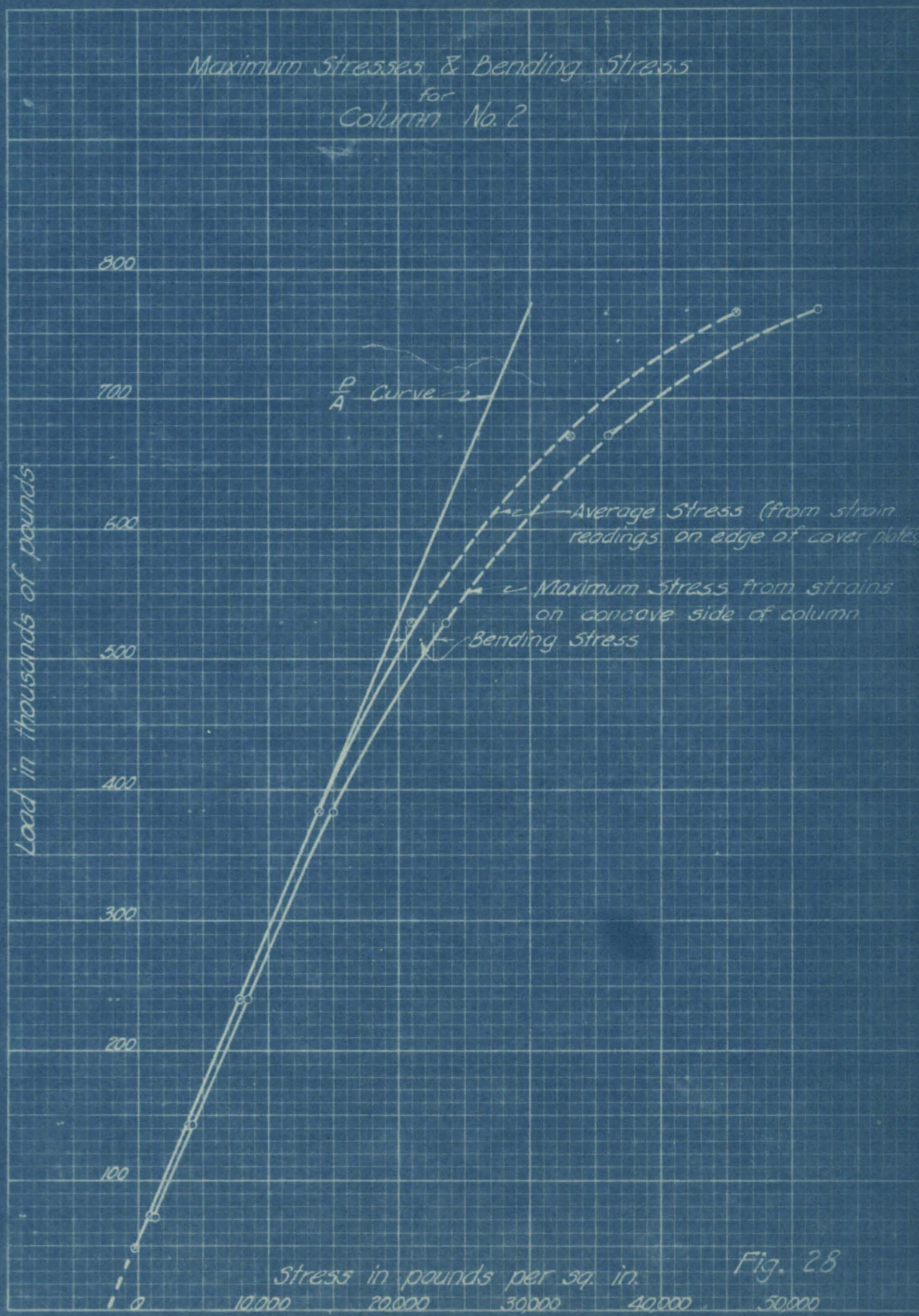


Fig. 28

EUGENE DIETZGEN CO. Chicago and New York
EDCO Efficiency 10 X 10
No. 340-10

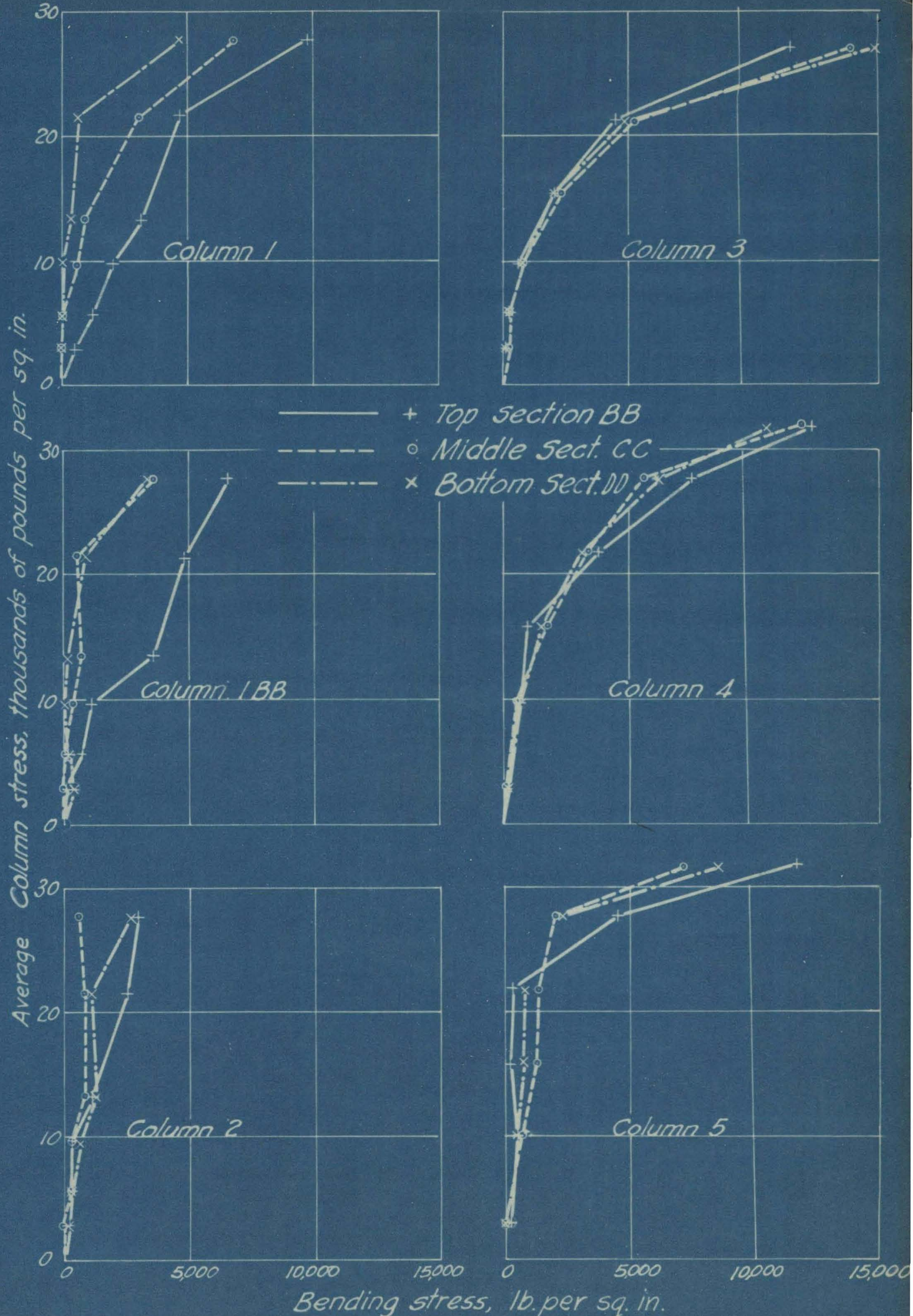
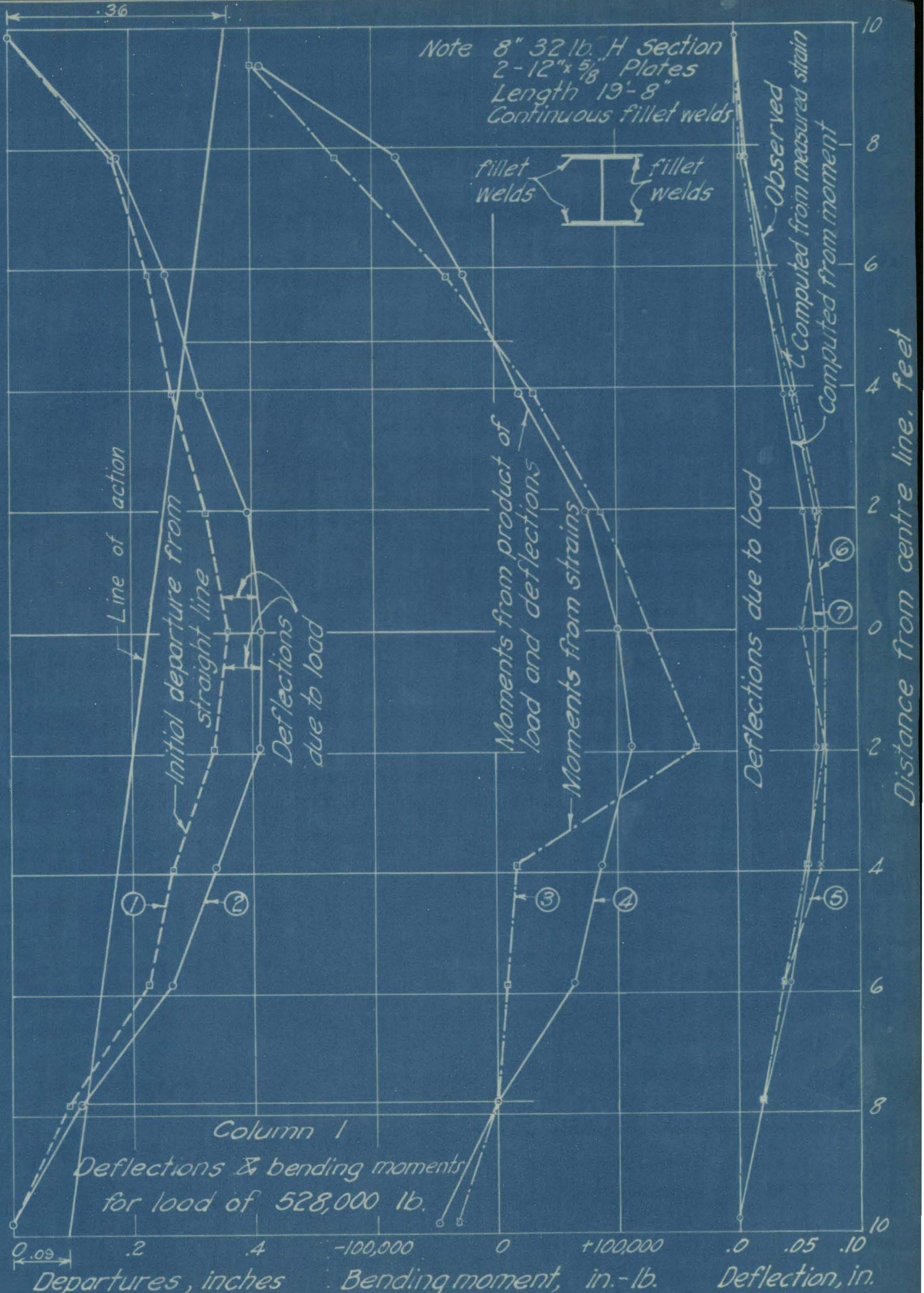


Fig. 29 - Bending stresses in columns



.36
Note 8" 32 lb. H Section
2-12"x 5/8" Plates
Length 19'-8"
Continuous fillet welds
fillet welds
fillet welds
Observed
Computed from measured strain
Computed from moment
Line of action
Initial departure from straight line
Deflections due to load
Moments from product of load and deflections
Moments from strains
Deflections due to load
Distance from centre line, feet
10
8
6
4
2
0
2
4
6
8
10
Column 1
Deflections & bending moments for load of 528,000 lb.
0.09
0
.2
.4
-100,000
0
+100,000
.0
.05
.10
Departures, inches
Bending moment, in.-lb.
Deflection, in.

Fig. 30

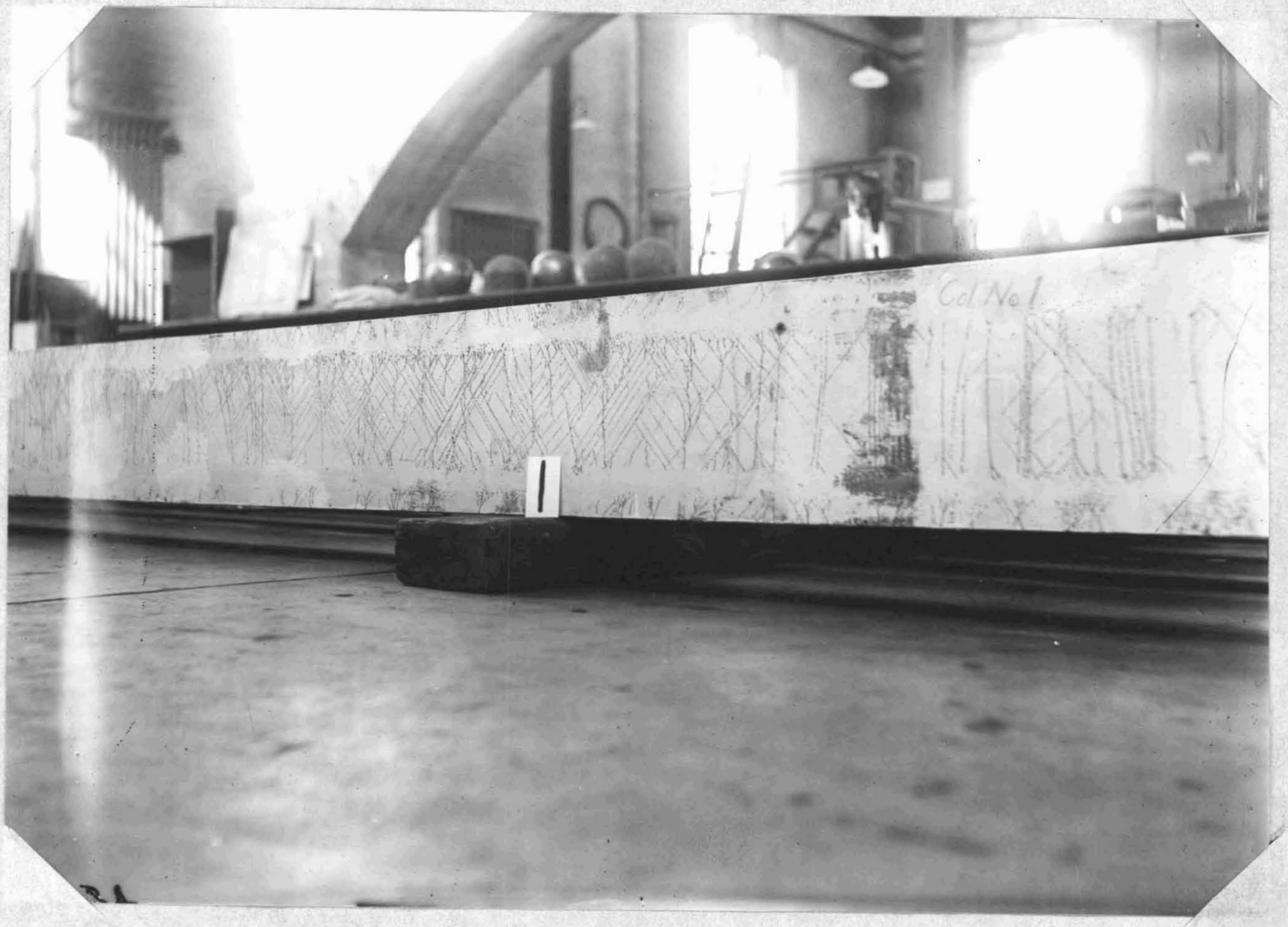


Fig. 31 - Strain Lines on Exterior Face of Column 1 at Maximum Load

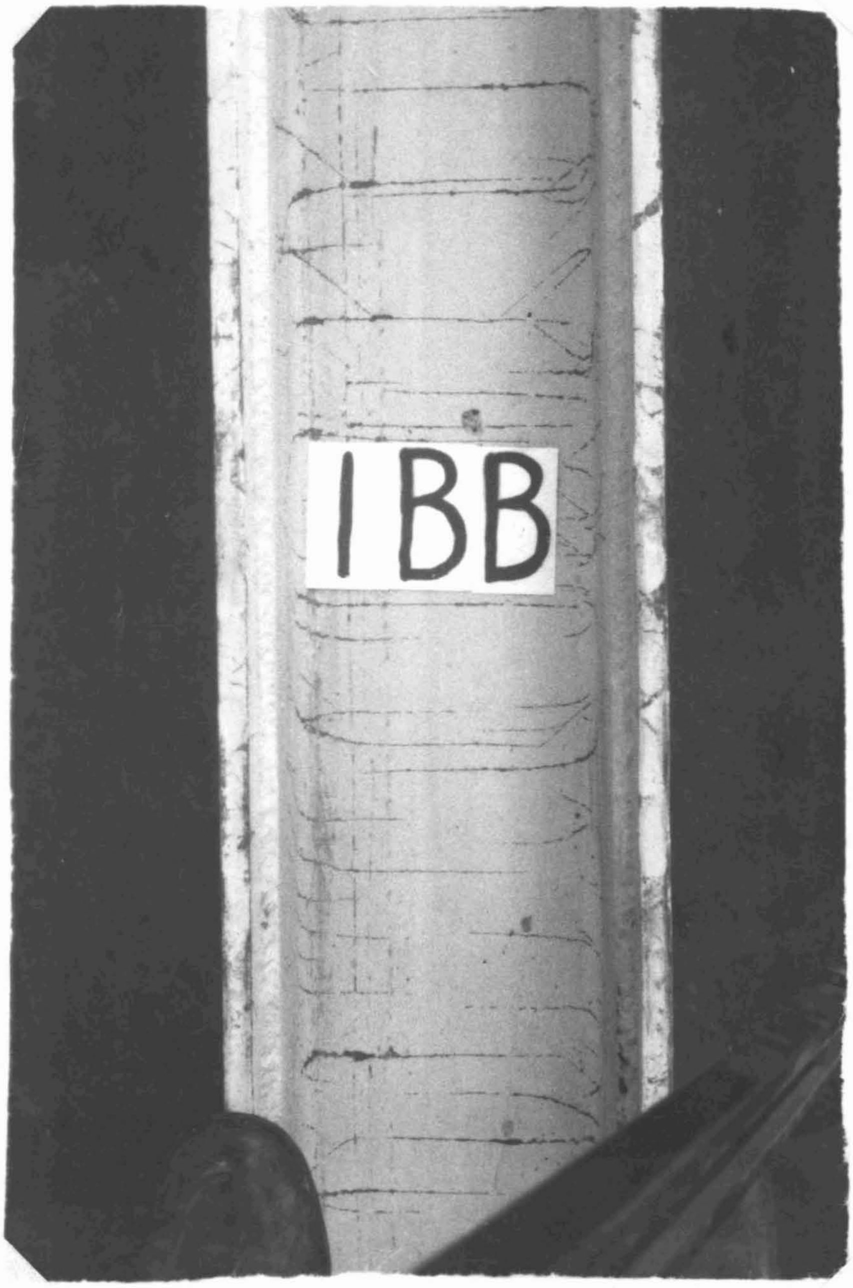


Fig. 32 - Strain Lines on Web of
Column 1BB

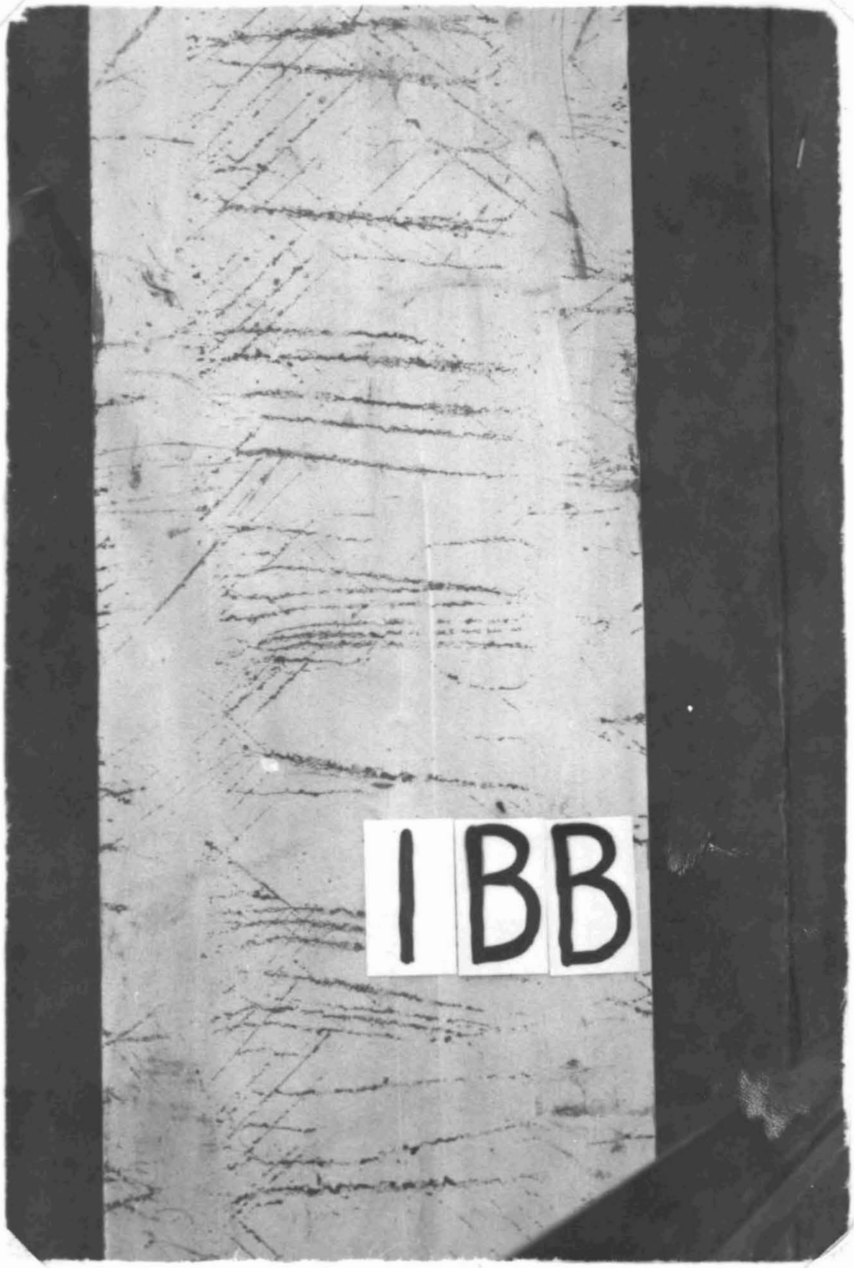


Fig. 33 - Strain Lines on the
Exterior Face of
Cover Plate of Column 1BB

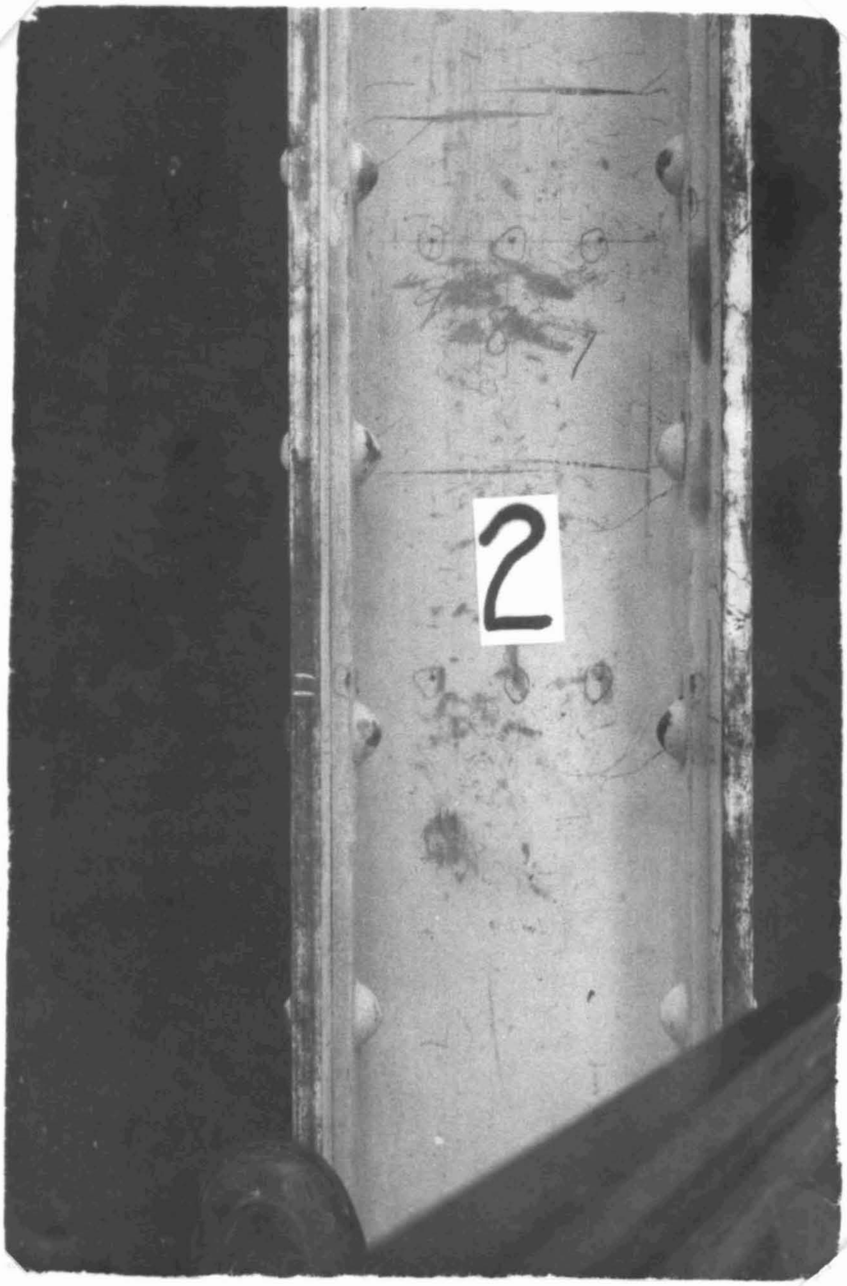


Fig. 34 - Strain Lines on Web of Column 2

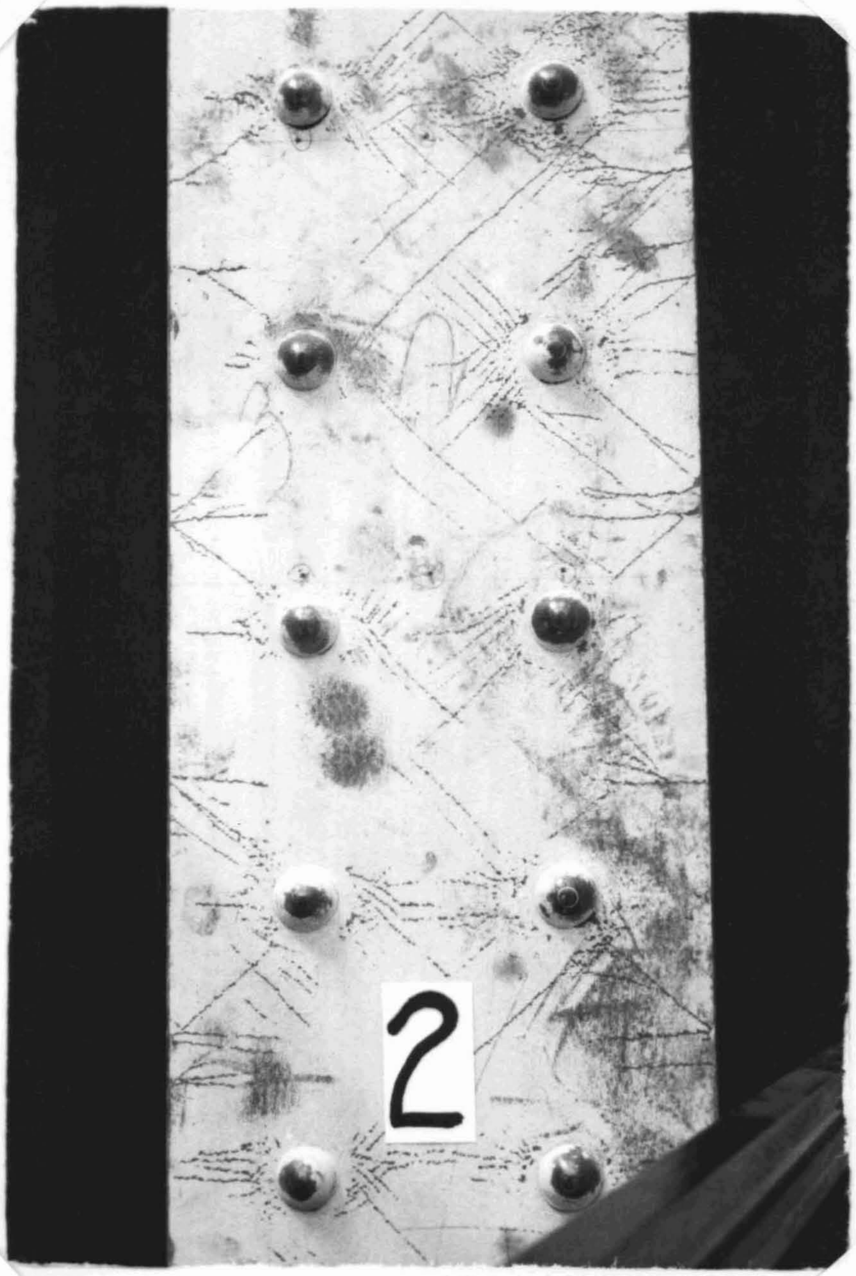


Fig. 35 - Strain Lines on Exterior Face of
Cover Plate of Column 2

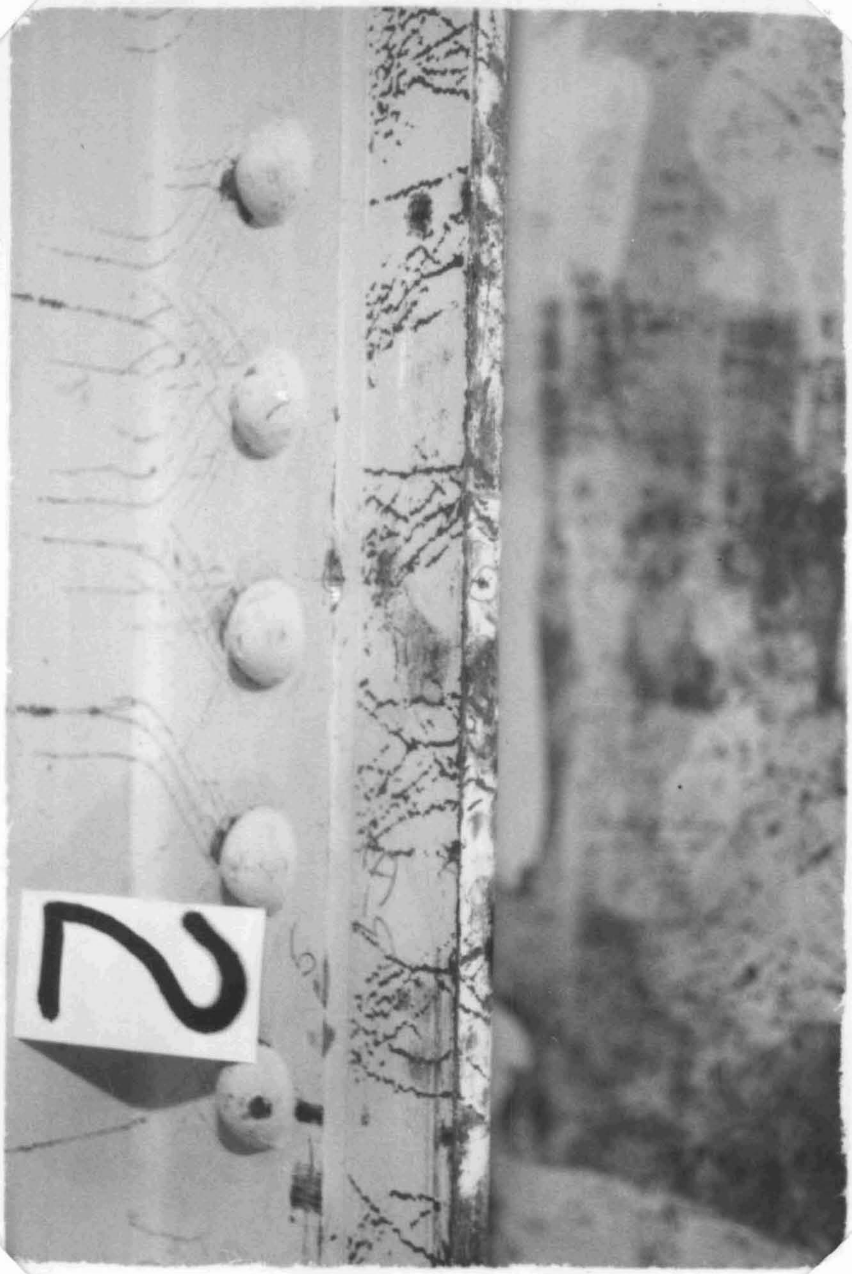


Fig. 36 - Strain Lines on Interior Face of Cover Plate of Column 2

Fig. 37 - Strain Lines on Exterior Face of
Cover Plate of Column 3

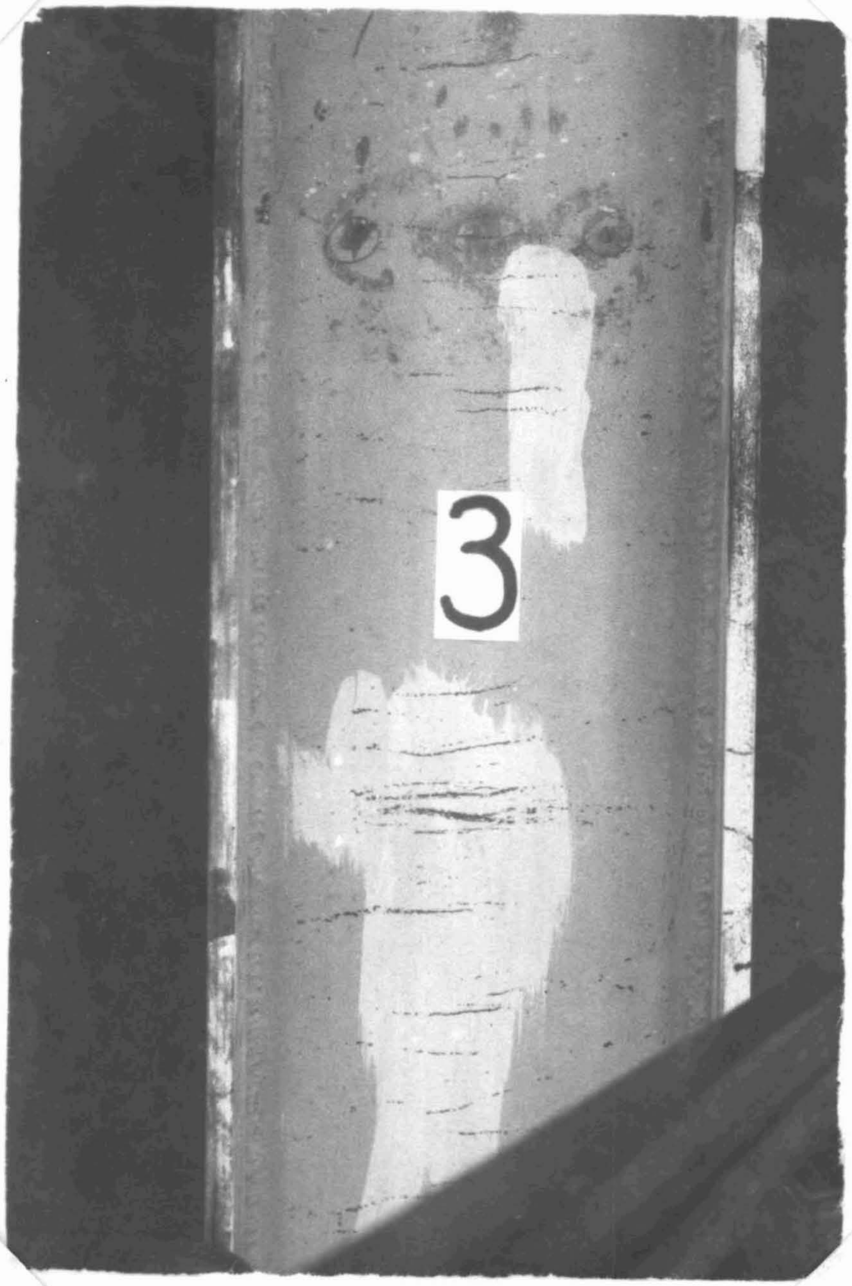


Fig. 38 - Strain Lines on Web of Column 3

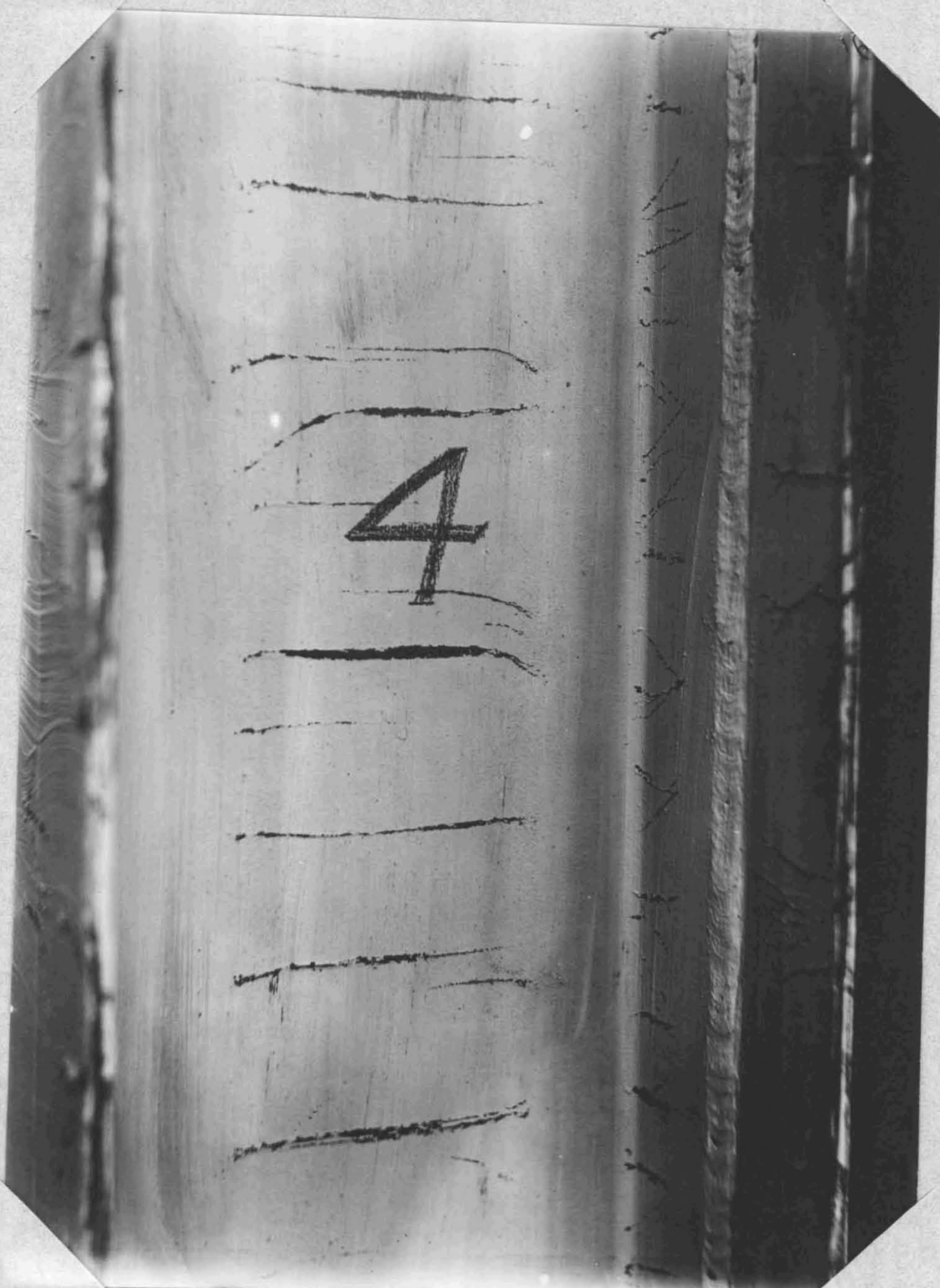


Fig. 59 - Strain Lines on Web of Column 4

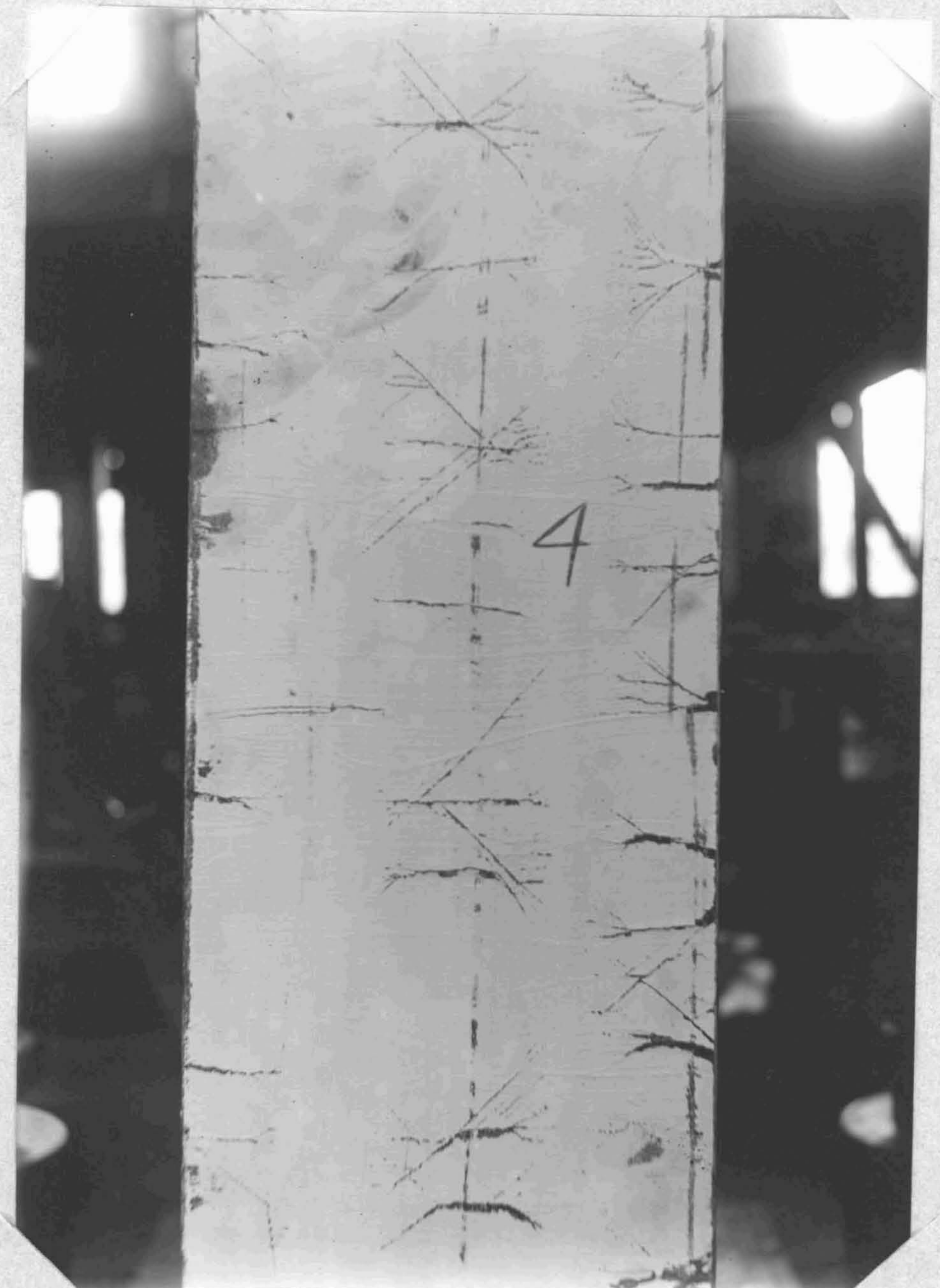


Fig. 40 - Strain Lines on Exterior Face of
Cover Plate of Column 4

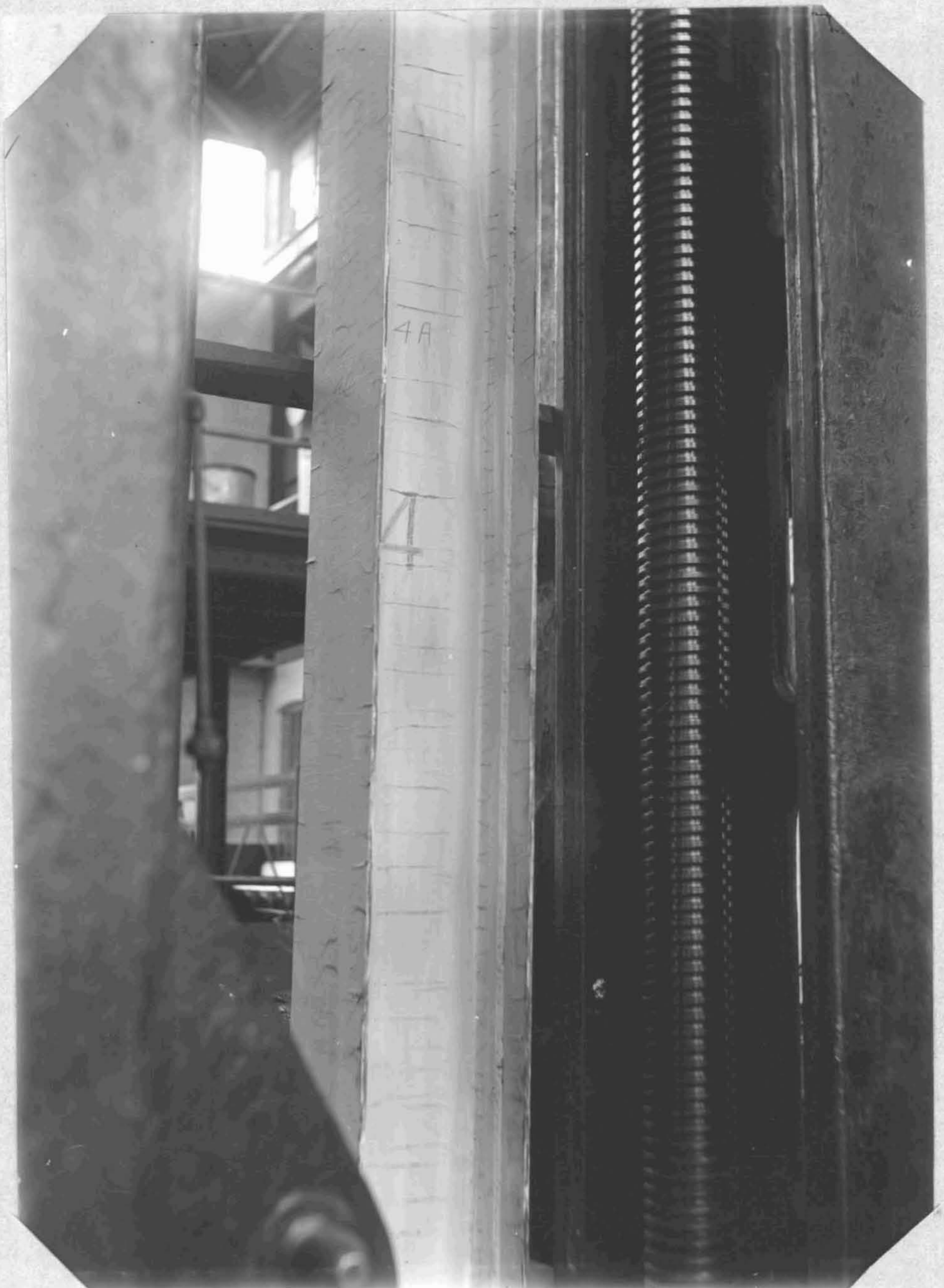


Fig. 41 - Strain Lines on Column 4

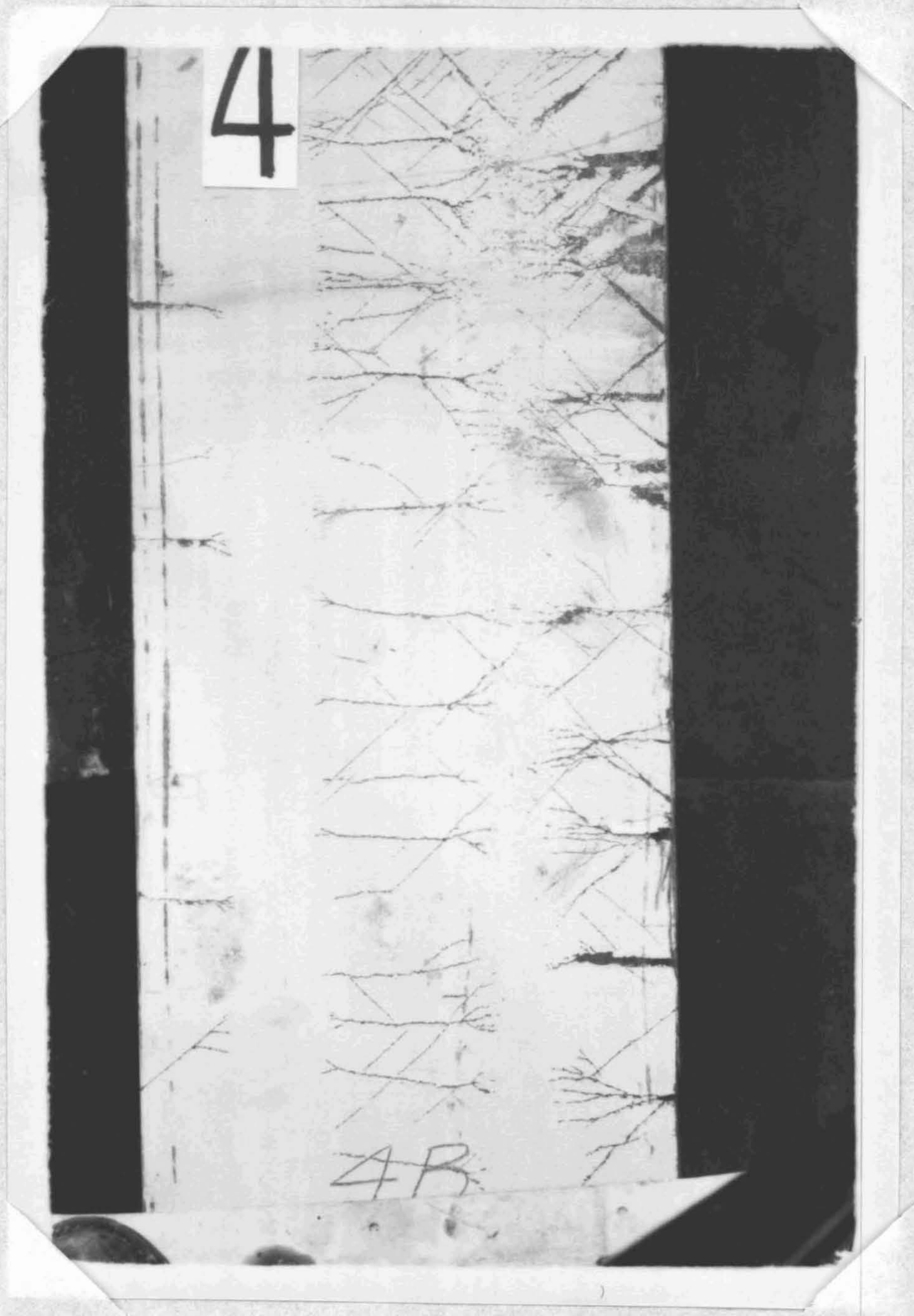


Fig. 42 - Strain Lines on Exterior Face of Cover Plate of Column 4

Fig. 43 - Strain Lines on Exterior Face of
Cover Plate of Column 5

Fig. 44 - Strain Lines on Web of Column 5

Fig. 45 - Strain Lines on Web of Column 6

Fig. 46 - Strain Lines on Web of Column 7