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TESTS OF LARGE COLUMNS WITH H-SHAPED SECTION

BY

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Page
III. Coupons 7
1. Identification of test coupons 7
2. Tensile test specimens 8
3. Tensile tests 8
4. Chemical analysis 9
IV. Column tests 9
1. Testing machine 9
2. Calibration of testing machine 9
3. Adjustment of columns for test 11
4. Compressometers 12
5. Strain gauges 12
6. Lateral deflection gauges 12
7. Loading and observations 13
V. First series tests 14
1. Fabrication of columns and preparation for test 14
2. Coupon specimens 15
3. Test results and discussion 15
(a) Results from coupon specimens 15
(1) Test results 15
(2) Chemical analyses 20
(3) Yield point and tensile strength of individual specimens 20
(4) Average results of yield point and tensile strength 22
(b) Results from column tests 23
(1) Sample log sheets 23
(2) Stress-strain curves 30
(3) Lateral deflection 30
(4) Failure of column BSH12a 30
(5) Failure of column BSH24b 31
(6) Retests 31
(7) General summary tables and curves 32
4. Interpretation of the results 34
(a) Comparison of column strength with slenderness ratio 34
(b) Comparison of column strength with tensile tests on the material 34
(c) Area weighting 37
(d) Column efficiencies 40
(e) Supplementary tensile tests 40
(f) Correction for systematic difference 41
(g) Corrected efficiencies 43
(h) Comparison of curves 44
(i) Results of former tests 44
(j) Probable causes of discrepancies 44
(k) Secondary failure 45
VI. Second series tests 46
1. Fabrication of columns 46
2. Coupons 46
3. Test results and discussion 47
(a) Coupons 47
(1) Chemical analyses 47
(2) Area weighting of results of tensile tests 48
(3) Reliability of area weighting 49
(4) Weighted averages 49

VI. Second series tests—Continued.
3. Test results and discussion—Continued. Page
(b) Columns 50
(1) Sample log sheets 50
(2) Stress-strain curves 56
(3) "Pick-up" and "hang-on" of load 57
(4) Lateral deflection 62
(5) Secondary failure 67
(6) General summary tables and curves 68
4. Interpretation of results 71
VII. Comparison of the two series of tests 73
1. Scope 73
2. Column tests 73
3. Coupon tests 74
4. Summary table and curves 75
5. Probable causes of discrepancies 77
6. Selected results 80
7. Correlations and regression equation 81
8. Outstanding discrepancies 84
VIII. Yield point as a measure of column strength 85
IX. Effect of end constraint and slenderness ratio 85
X. Testing of yield points 86
XI. Suggestions for future tests 87
XII. Conclusions 87

I. INTRODUCTION

1. HISTORICAL

The results of tests of large structural steel columns, made at the Bureau of Standards, Washington, D. C., during the years 1915 to 1917 were published in the Proceedings of the American Society of Civil Engineers [1] and the Proceedings of the American Railway Engineering Association [2] and were later discussed by Basquin [3] from the standpoint of the tangent modulus theory. These reports showed that, as between light and heavy rolled sections, the light-rolled sections had relatively higher column strength for the same slenderness ratio. The differences between the light and heavy sections were too great to be accounted for by the differences in the results of the mill tests on coupons—either in yield point ("elastic limit") by drop of beam or ultimate strength. A correlation was, however, found between the "useful limit point" [4] of the columns tested and the "useful limit point" of corresponding coupons tested by the Bureau of Standards, which suggested that the customary mill tests on coupons failed to show differences in certain properties of the steel,

[1] (a) Final Report of the Special Committee on Steel Columns and Struts. Proceedings A. S. C. E., **43**, p. 2409; 1917. (b) Transactions, A. S. C. E., **83**, p. 1583; 1919–20.

[2] Column tests, Proc. A. R. E. A., **16**, p. 636; 1915; 18, p. 789; 1918.

[3] B. S. Tech. Paper No. 263, by O. H. Basquin, Tangent Modulus and the Strength of Steel Columns in Tests.

[4] See footnote 1.

properties which had a large influence on the strength of the columns. As the A. S. C. E. test program had not been planned with these points in view, further tests seemed desirable.

2. FIRST SERIES OF TESTS

The Bureau of Standards, in cooperation with the American Bridge Co. undertook, therefore, a study of a limited number (39) of larger columns, here called the "first series," designed to compare the behaviors of light and heavy columns of similar cross section. It was further desired to compare the strengths of riveted columns fabricated in the ordinary manner of plates and angles with similar solid rolled sections of the same section area, radius of gyration, length, and of similar material. As the previous tests had indicated that the properties of the steel influenced in a large degree the behavior of the columns, a series of 85 tensile test coupons were cut from the material of the columns and tested for yield point (by drop of beam), tensile strength and elongation, and chemical analyses were made from each coupon. Later 42 supplementary coupons were cut from some of the material and tested.

The results of these tests seemed to indicate that the properties of the material which determine the yield point (by drop of beam) in a tensile test were closely correlated with the strength of the columns. However, certain unexplained discrepancies in the results, in particular the wider scatter of the results in the neighborhood of the slenderness ratio $\frac{L}{r}=40$, the apparently lower efficiency of the heavy solid rolled sections, and more especially the apparently anomalous behavior of one of the columns (BSH12a, see p. 30) made still further tests seem desirable.

3. SECOND SERIES OF TESTS

Thirty more columns, here called the "second series," were therefore tested in cooperation with the Bethlehem Steel Co. In this second series an effort was made to secure material suited to show any relation which existed between the results of tensile tests and the behavior of the columns. For this reason a large number of coupons (over 900) were tested, half at the Bureau of Standards and half at the Bethlehem Steel Co.'s works at Bethlehem, Pa. On the bases of these coupon tests the material for the final column tests was selected. The material was rolled and selected to border on the low limit of tensile strength (55,000 lbs./in.^{2}) of A. S. T. M. specifications for the fabricated columns and part of the solid rolled columns, and to border on the high limit of manufacturers specifications class B (70,000 lbs./in.^{2}) for the rest of the solid rolled sections. No fabricated columns of high tensile strength material were tested

B. of S. Tech. Paper 328

Please correct text as follows:

Page 17, Line 10. Tensile strength of "A-FSL24a3-S" should read "61 700".

Page 34, Table 8, Line 1. Ratio, column strength to tensile yield point, should read "0.886".

Page 50, Next to last line. should read "FSH12f and BSH12d".

Figure 26, Facing page 72. Legends should be transposed to read

"BSH12f	BSH12e	BSH12d
87.2	91.2	89.3
FSH12f	FSH12e	FSH12d
92.4	90.8	94.0 ".

because in the first series of tests the steel in the fabricated columns had bordered on the high limits (65,000 lbs./in.^{2}) of A. S. T. M. specifications. The material of the columns actually tested was represented by 332 coupon tests, so that the ordinary tensile properties of the material entering into these columns were probably much better known than in any comparable series of tests.

4. TEST CONDITIONS

As in the original A. S. C. E. and A. R. E. A. tests,[5] all the columns were tested with "flat" ends. It was attempted to keep the test conditions in the two series as nearly comparable as possible, but the somewhat different purposes of the two series necessitated small changes in the test procedure.

5. MODE OF PRESENTATION

It has, therefore, seemed desirable to present and discuss the test results of the two series separately and finally to discuss the combined results. This semihistorical method of presentation necessarily involves some duplication, but it is hoped that it will bring out more clearly the conclusions to be drawn from the tests.

6. ACKNOWLEDGMENTS

In the first series the test procedure was decided on by John H. Griffith, of the Bureau of Standards, and James H. Edwards, of the American Bridge Co., a member of the A. S. C. E. committee on columns and struts during the previous investigation. The material for this series was furnished by the American Bridge Co. Their engineers, under the direction of H. E. Cameron, assisted the personnel of the Bureau of Standards in making the tests.

In the second series the test procedure was determined by H. L. Whittemore and L. B. Tuckerman, of the Bureau of Standards, and H. T. Morris and R. M. Bird, of the Bethlehem Steel Co. The material for this series was furnished by the Bethlehem Steel Co. Their engineers, under the direction of R. M. Bird, assisted the personnel of the Bureau of Standards in making the tests.

II. COLUMNS

1. MATERIAL

The material for the first series was commercial structural steel, purchased in the open market under A. S. T. M. specifications A–7–16 (tensile strength 55,000 to 65,000 lbs/in.^{2}, yield point not less than one-half the tensile strength), the plates, angles, and channels

[5] See footnotes 1 and 2, p. 3.

for the fabricated columns from the Carnegie Steel Co., and the solid rolled sections from the Bethlehem Steel Co. The tests showed that the material complied with the specifications.

For the second series two types of material were rolled by the Bethlehem Steel Co., the first to border on the lower tensile strength limit of A. S. T. M. specifications A–7–16, and the second, for the purpose of obtaining a higher yield point, to border on the upper tensile strength limit of manufacturers standard specifications class B (tensile strength 55,000 to 70,000 lbs/in.^{2}), and only the material which showed from coupon tests the desired range of values was tested in the form of columns. Each piece bore an identification mark and a record was kept of its history from the ingot to its final place in the finished column. This record included the position of each portion of a rolled shape in the finished column, the location of each coupon in the cross section and along the length of the rolled shape, the portion of the slab or bloom from which it was rolled, the portion of the ingot which furnished the slab or bloom, and the ingot number and heat number. It was thus possible to relate each piece in a column closely to the coupon tests which were used to determine the tensile properties of the material.

2. SECTIONS

All the columns were of H section (fig. 1), and included two solid Bethlehem sections H–14–122½ (light) and H–14–287½ (heavy) and two corresponding plate and angle sections designed, so far as possible, using commercial sizes, to have the same area, radius of gyration, and section modulus as the corresponding solid Bethlehem sections. In the first series, three additional special columns fabricated from channels alone were also tested.

3. LENGTH OF COLUMNS

In the first series columns 12, 18, and 24 feet long were tested, covering a range of slenderness from about $\frac{L}{r}=38$ to $\frac{L}{r}=92$. As the test results of the first series showed that with these ("flat") end conditions and within this range of slenderness the variations in column strength due to variations in length were small compared to those due to other causes, the 18-foot lengths were omitted from the second series.

Although the testing machine can handle columns 24 feet 6 inches long, it was found that special rigging was necessary to place these large 24-foot columns in the machine. For this reason the nine "24-foot" columns last tested were made only 23 feet 6 inches long. This made it possible to handle them with the jockey crane on the head of the testing machine, materially reducing the time of setting up for test.

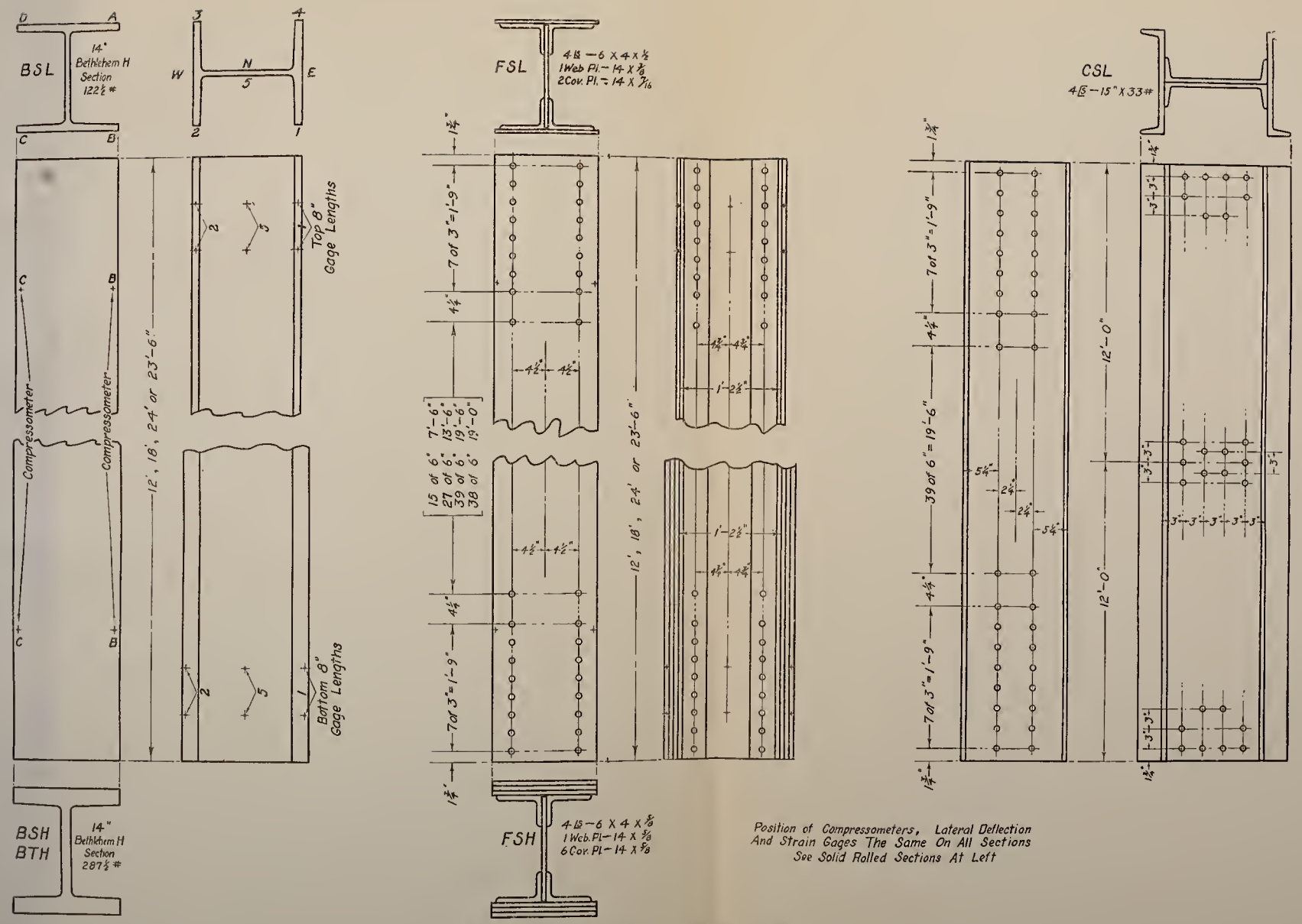

FIG. 1.—*Details of columns and location of gauge lines*

4. IDENTIFICATION SYMBOLS

The following symbols, in the order given, are used to identify the columns (fig. 1):

Fabrication:
- B=14-inch Bethlehem H section.
- F=14-inch H section fabricated from plates and angles.
- C=14-inch H section fabricated from channels, weight approximately 132 pounds per foot.

Material [6]:
- S=material complying with A. S. T. M. specifications A–7–16, and manufacturers standard specifications, Class A.
- T=material complying with manufacturers standard specifications, class B.

Sectional area:
- L=Light columns, area, approximately, 36 square inches; weight approximately, 122½ pounds per linear foot.
- H=Heavy columns, area, approximately, 85 square inches; weight approximately, 287½ pounds per linear foot.

Length:
- 12 feet.
- 18 feet.
- 24 feet.

The letters a, b, or c indicate individual columns supplied by the American Bridge Co. (first series). Thus the column, FSH12a, is one of a group of three fabricated plate and angle columns of heavy H section, 12 feet long, meeting A. S. T. M. specifications A–7–16, which were tested in cooperation with the American Bridge Co. Similarly, the letters d, e, or f indicate individual columns supplied by the Bethlehem Steel Co. (second series). Thus BTH24f is one of a group of three solid rolled Bethlehem heavy H sections (287½ pounds per foot), 24 feet long, meeting M. S. specifications class B, which were tested in cooperation with the Bethlehem Steel Co.

III. COUPONS

1. IDENTIFICATION OF TEST COUPONS

The test coupons are identified by the symbol of the column from which they were cut, followed by identifying letters and numbers to indicate their location in the section. These identifying letters and numbers are shown in Figure 2.

It will be seen that the coupons in the second series were so located as to include specimens as nearly comparable to those in the first series as was compatible with the larger number desired. The locations of the comparable specimens were identical except in the webs of the solid rolled sections and the center of the plates. Here it was

[6] It should be noted that this designation of the material does not accuretaly characterize the differences in the material. Some of the material tested in the first series bordered on the upper limit of tensile strength of the A. S. T. M. specifications A–7–16, while all of the S material of the second series bordered on the lower tensile strength limit of the same specifications.

necessary in order to secure two symmetrical specimens to cut the specimens either side of the center instead of at the center (compare *W* with *11*, and *12*, or *13* and *14*, and *P–C* with *P–3* and *P–4*, fig. 2).

2. TENSILE TEST SPECIMENS

The tensile test specimens (fig. 2) conformed with A. S. T. M. specification A–7–16 (gauge length 8 inches by 1½ inches by thickness of material) with the following exceptions:

In the first series the reduced section of the specimen was machined to a uniform thickness of 1/2 inch, except in the case of material whose nominal thickness was 1/2 inch or under. These latter were machined to 1/8 inch under their nominal thickness.

In the second series the specimens 1, 2, 3, 4, 9, 10, 11, and 12 from the Bethlehem H sections (fig. 2) were machined to a thickness of 1/2 inch (to conform more nearly to the first series) instead of 3/4 inch as provided by the specifications.

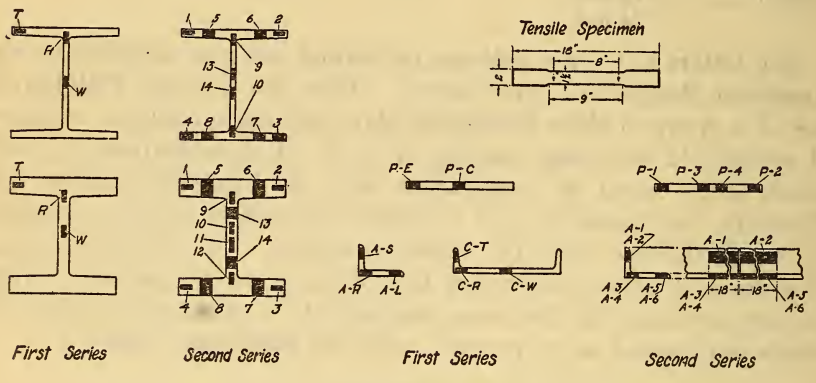

Fig. 2.—*Location and identification symbols of test coupons*

A, denotes angles; *C*, channel; and *P*, plate

3. TENSILE TESTS

In the first series the tensile tests were made in the 100,000-pound lever testing machine in the Bureau of Standards laboratory at Pittsburgh. The original tests were run at a speed of 0.37 inch per minute and the supplementary tests at a speed of 0.012 inch per minute (machine running idle).

In the second series, the Bureau of Standards tests were made in a 300,000-pound lever testing machine in the Bureau of Standards laboratory at Washington and the comparison tests at Bethlehem in a 300,000-pound hydraulic machine, both at the same speed, viz, 0.37 inch per minute (machine running idle). In all cases the yield point was determined by the drop of the beam.

The effect of difference in speed of pulling and difference in type of machine upon the test results will be discussed in detail later.

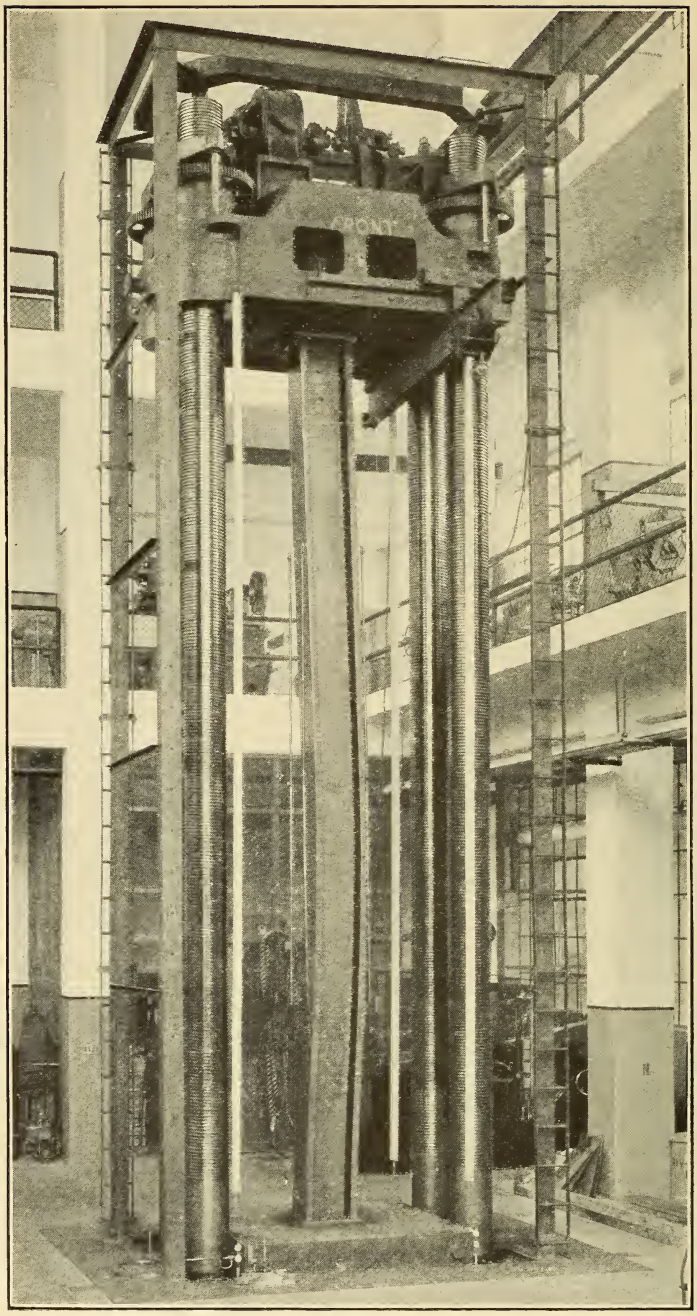

Fig. 3.—*Column BSH24e in testing machine*

4. CHEMICAL ANALYSIS

The samples for chemical analysis were taken from broken tensile test specimens, and the analyses were made by the chemical laboratory of the Bureau of Standards.

IV. COLUMN TESTS

1. TESTING MACHINE

The columns were tested in the 10,000,000-pound hydraulic compression machine of the Bureau of Standards. A description of this machine has been given by J. H. Griffith and J. G. Bragg.[7]

Figure 3 shows a column in place in the testing machine.

2. CALIBRATION OF TESTING MACHINE

In the first series of tests no direct calibration of the testing machines was made. However, the average modulus of elasticity obtained from the 270 short strain-gauge lines (30,170,000 lbs./in.^{2}) and the 72 long gauge lengths (30,290,000 lbs./in.^{2}) was compared with the average determined from the 42 supplementary coupon tests (29,900,000 lbs./in.^{2}). The agreement (discrepancy about 1 per cent) was considered satisfactory and no further calibration was made.

When the tests on the first column of the second series were started, the diaphragm in the weighing mechanism of the machine burst. The diaphragm removed from the machine was of thin sheet rubber known as "dental dam." Attempts, at the time, to replace it with a similar diaphragm failed because all of the rubber sheets which were tried tore when the load reached a few hundred thousand pounds. Finally a combination rubber and leather diaphragm was installed which held up to the maximum load used (3,840,000 lbs.).

At the close of the tests the machine was compared with the 2,000,000-pound Emery testing machine at Washington, using first a calibration bar up to 1,000,000 pounds and then extending the calibration to 1,500,000 pounds by means of a 7-foot Bethlehem H column (H14, 287½ pounds). Beyond 1,500,000 pounds the H column ceased to show proportionality between stress and strain so that the calibration could not be carried further with the means available.

As installed at Pittsburgh, the valves and piping were not arranged so that the load could be held sufficiently constant to enable the four compressometers on the H section to give wholly stable readings.

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[7] J. H. Griffith and J. G. Bragg, Tests of Large Bridge Columns. B. S. Tech. Paper No. 101; 1918.

Finally, readings concordant to about one-half per cent over the whole range were obtained by running the pump continuously reading the compressometers in sequence at uniform 10-second intervals and interpolating these readings to uniformly spaced loads.

The results of the calibration are shown in Figure 4. The points represent 10 separate runs with the round calibration bar, 3 of them carried to an indicated load of 1,000,000 pounds and 2 separate runs on the H column carried to an indicated load of 1,500,000 pounds.

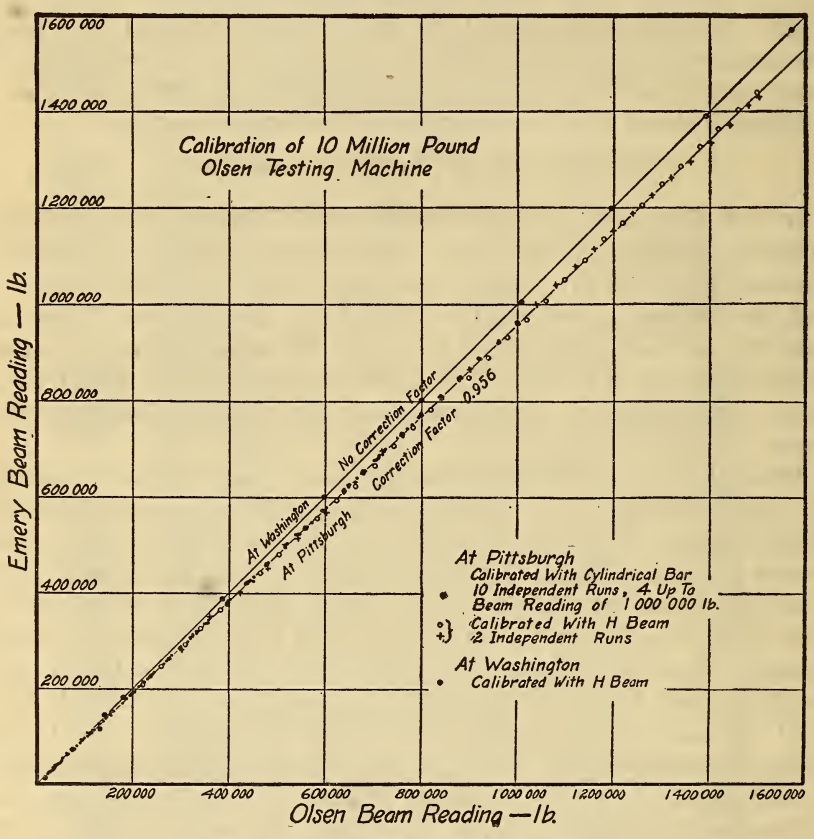

FIG. 4.—*Calibration of testing machine*

On the assumption that the calibration curve was a straight line, the correction factor 0.956 was calculated from these observations.

Finally a check was made to see whether the 2,000,000 pounds counterpoise agreed with the scale. A series of stress-strain curves were run on the H column from just below to just over 2,000,000 pounds, shifting the counterpoise in the midst of the run. All these curves, although definitely departing from straight lines, were continuous through the 2,000,000-pound point and showed no displacement due to the shift of the counterpoise.

When the machine was moved to Washington, changes were made in the piping and valves, which made the control of the oil pressure much easier. With these changes in the piping and valves it was found possible to hold the load constant within the limits of sensibility of the compressometer, making check readings possible at each load, so that from a relatively small number of readings a smooth calibration curve could be obtained.

The combination diaphragm had been destroyed in the moving and a special rubber diaphragm made by the rubber laboratory of the bureau, was installed. A calibration (fig. 4) with this new diaphragm showed no correction as great as the unavoidable errors of observation (about one-half per cent). Frequent check calibrations later have given the same results.

The correction factor (0.956) was therefore applied to all of the beam readings on columns of the second series tested at Pittsburgh. These were the 12 columns BSL12 d, e, f; 24 d, e, f; BTH12 d, e, f; 24 d, e, f.

In discussing this calibration the question has been raised whether the straight line extrapolation can be relied upon to hold from the highest calibrated load (1,500,000 pounds) to the highest load (3,840,000 pounds) observed in the tests. This question can not, of course, be answered definitely, although the principle of action of a hydraulic machine makes it seem probable. As will be seen from a discussion of the test results later, there are unexplained discrepancies in the results of the tests amounting to about 8 per cent when this correction is applied (see fig. 24, p. 71). Discrepancies of this magnitude are to be expected in column tests. However, if the correction is not applied (see fig. 25, p. 72) the discrepancies left unexplained amount to about 12 per cent

3. ADJUSTMENT OF COLUMNS FOR TEST

The columns were carefully centered in the testing machine. Finished steel plates were placed between the column and heads of the machine. The lower head was adjusted until it was parallel with the upper head. This was done in the first series by bringing the head of the machine within a few inches of the top of the column and at each of the four corners of the column, measuring with a steel scale the distance between the top of the column and the head. By tilting the lower head of the machine these distances were made equal, within 0.01 inch.

In the tests made at Washington a more sensitive method was used to obtain parallelism. After the column was centered in the machine and the four compressometers (described in the next section) attached, a stress of approximately 1,000 lbs./in.^{2} was applied. The compressometers were read. The stress was then increased to 10,000 lbs./in.^{2}

and the compressometers again read. The difference in compression read on each instrument would be the same, if the heads were bearing evenly on the column. If they were not, the load was removed, the lower head tilted, and the readings again taken until the difference in compression, recorded by the four instruments, was the same within 0.002 inch, corresponding to a maximum stress difference of 600, 500, or 400 lbs./in.^{2} for the 12, 18, and 24 foot columns, respectively.

4. COMPRESSOMETERS

Four compressometers were placed at the positions *A*, *B*, *C*, and *D*, near the edges of the H sections, as shown in Figures 1 and 3. These instruments, adjustable in length, were fastened at the top to hangers which screwed into tapped holes in the column. At the bottom, dial micrometers were similarly fastened. The end of the compressometer rods rested on the plungers of these micrometers. In order to prevent lost motion, the spindles of the micrometers were held against the ends of the rods with rubber bands.

The compressometer gauge lengths were 100, 125, and 150 inches, for the 12, 18, and 24 foot columns, respectively. The center of the gauge length was, in each case, at the mid height of the column. The micrometers read to 0.001 inch directly and, by estimation, to 0.0001 inch.

5. STRAIN GAUGES

To measure the local strains, 8-inch strain-gauge readings were taken. Gauge lines were laid off vertically straddling horizontal planes at 12 inches from the bottom, at mid height, and at 12 inches from the top of the columns. Five gauge lines were laid off at each of these three heights, four of them being near the corners of the sections while the fifth was at the center of the web. The location of these lines is shown diagrammatically in Figure 1 at the positions *1*, *2*, *3*, *4*, and *5*.

6. LATERAL DEFLECTION GAUGES

The lateral deflection at mid height of the column was measured at the center of the flanges and of the web, as shown in Figure 1 at the positions *E*, *W*, and *N*. Stretched wires, fastened to bolts 2 inches from the ends of the column, passed in front of paper scales mounted on mirrors at mid height of the column. Parallax being eliminated by the mirrors, it was easy to read the deflection to one-fiftieth inch.

Figure 5 shows a view of the operators taking the readings. The compressometers and the positions of the upper and lower strain-gauge lines as well as the mirror and scale, are shown.

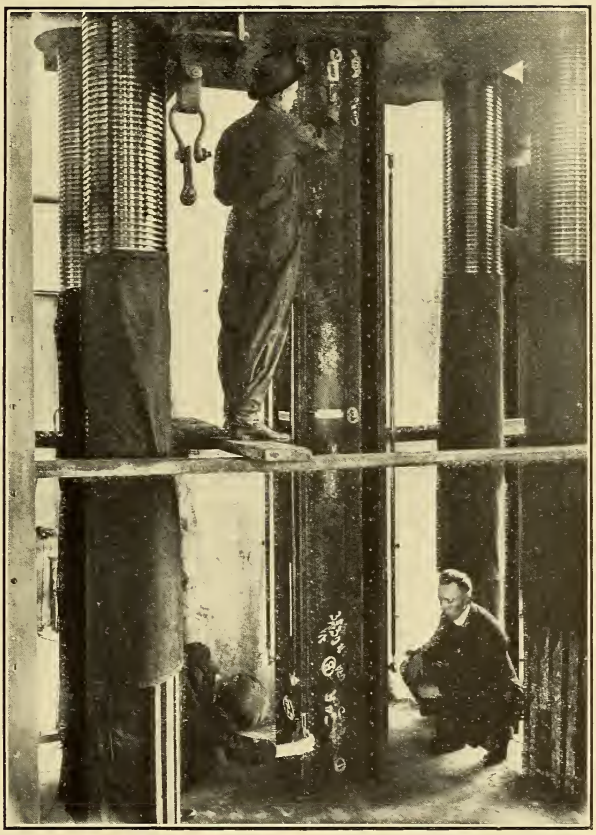

FIG. 5.—*Operators taking strain-gauge readings*

7. LOADING AND OBSERVATIONS

The pump was started and the weighing beam "balanced" to read zero with the lower head of the machine rising, before the column came in contact with the upper head of the machine. The column was then stressed to 1,000 lbs./in.^{2} and the instruments read. In the first series, the stress was raised in large steps (4,000 or 5,000 lbs./in.^{2}) to 10,000 or 15,000 lbs./in.^{2}, released to 1,000 lbs./in.^{2}, and raised a second time to 10,000 lbs./in.^{2}, then raised by increments of 1,000 lbs./in.^{2} till a maximum load was reached. As the maximum was approached, the stress increased slowly, and in order to save time the stroke of the pump was increased. In a few cases the stress was released a second time to 1,000 lbs./in.^{2} after 20,000 lbs./in.^{2} had been reached, and the test was finished on the third "run-up." At each stress the pump was stopped and the instruments were read. Although small changes in the gauge readings were noticed after each release of stress, no apparent relation between them and the column strength was found, and the retests of certain columns (BSL18a, BSH18b, FSL18c, and FSH18c) showed no noticeable effect due to previous permanent set. In addition, no noticeable differences between the behavior of the different columns was found below a stress of 20,000 lbs./in.^{2}

For the second series, therefore, the stressing was by steps of 5,000 lbs./in.^{2} up to stresses of 20,000 to 35,000 lbs./in.^{2}, then by steps of 2,000 and finally 1,000 lbs./in.^{2} as the first maximum load was approached. The pump was not stopped, as in the first series, but was run continuously with a constant stroke and a needle valve by-pass was adjusted to maintain a constant load during the observations. This gave somewhat more consistent gauge readings than were obtained in the first series, where the load fell off slightly while the pump was stopped.

In both series, as the first maximum was approached, the beam was continuously kept balanced so as to determine closely the value of the maximum load, and the pump run continuously as the maximum was passed. In the first series the maximum load was missed on one column which failed at an unexpectedly low load. To eliminate this possibility in the second series the readings of the four compressometers were plotted continuously as the test progressed. In this way the observers were able to secure three or four readings immediately preceding the first maximum at intervals of 1,000 lbs/in.^{2} stress, without spending so much time on readings at lower stresses, and in every case the machine was balanced at the maximum.

In the first series the test was stopped when the decrease in stress was sufficient to ensure that the maximum had been passed. In one case (column BSH12a) this decrease was small (300 lbs./in.^{2}) and

the test was continued under continuously increasing stress and increasing bending of the column until loads much higher than the maximum for any of the other columns had been reached. A study of the data of this test indicated that it was, in all probability, due to the phenomenon of "pick-up" previously observed in small specimens by Kármán [8] and Lilly.[9]

As it was important, if possible, to explain definitely the apparently anomalous behavior of this column, observations on the columns of the second series were continued beyond the first maximum load.

Readings of the 8-inch strain gauge were taken to the last load which was held before the maximum. After this load the columns deformed so rapidly that consistent readings could not be obtained with these hand gauges. However, observations of lateral deflection and compression (long gauge lengths) were continued at intervals of one minute, care being taken to read them in the same order and as nearly as possible at the same time. When the wires of the lateral deflection gauges or the rods of the compressometers came into contact with the column, the readings were discontinued. Load and time observations were continued until the load carried by the badly deformed column had fallen at least 2,000 lbs./in.^{2} below the first maximum. Photographs were taken of the columns after their removal from the machine.

V. FIRST SERIES TESTS

1. FABRICATION OF COLUMNS AND PREPARATION FOR TEST

The plate and angle sections (F – – –) and the channel sections (C – – –) were fabricated in the shops of the American Bridge Co. under the inspection of J. H. Griffith, of the Bureau of Standards. The material was clean, free from excessive rust and mill scale, and showed no visible defects.

The angles were straightened before punching and then checked with a chalk line. All plates were rolled to take out camber. The location of the rivet holes in the angles, plates, and channels was laid off, using a steel tape under constant tension. These holes were then accurately punched to size (not subpunched and reamed or drilled). The columns were first assembled with bolts in 30 per cent of the holes, stitch riveted, and the riveting then completed. By this means deformation due to unequal heating was largely avoided. All rivets were driven with a compression riveter using an air pressure of 75 lbs./in.^{2}

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[8] Th. von Kármán. Untersuchungen über knickfestigkeit. Forschungsarbeiten a. d. Gebiete d. Ingenieurwesens Heft 81; 1910.

[9] Lilly, Design of Columns and Struts (Chapman & Hall, London; 1908).

Whenever camber was present, either in the fabricated columns or in the solid rolled columns, they were straightened cold to be as nearly as possible straight along their neutral axes. Some flange edges were, however, not in perfect alignment since the flanges were slightly unsymmetrical with respect to the longitudinal axis. These irregularities were small, rarely amounting to one-eighth inch and never larger than three-sixteenths inch. No differences in the strength of the columns could be definitely traced to these slight irregularities. The ends were milled to length so that they were perpendicular to the longitudinal axis and very closely parallel.

2. COUPON SPECIMENS

For the fabricated columns specimens were tested for each thickness of material rolled from each heat.

For the solid rolled sections specimens were at first tested for each length of column from each heat. Later additional tests were made, so that specimens were tested from each column.

The location of the coupons in the sections is shown in Figure 2.

3. TEST RESULTS AND DISCUSSION

(a) RESULTS FROM COUPON SPECIMENS

(1) Test Results.—The results of the physical and chemical tests on the specimens are presented in Table 1 and of the supplementary tensile tests in Table 2.

TABLE 1.—*Results of physical and chemical coupon tests and report of mill tests (first series)*

MATERIAL FROM 14-INCH BETHLEHEM H 122½-POUND SECTION SPECIMEN 1½ BY ½ INCH

Specimen mark	Heat No.	Bureau of Standards report: Yield point drop of beam	Tensile strength	Average: Yield point	Tensile strength	Elongation in 8 inches	Reduction of area	Fracture	Results of chemical analysis: C	S	P	Mn	Mill test report: Yield point	Tensile strength	Elongation in 8 inches	Reduction of area	Results of chemical analysis: C	S	P	Mn
		Lbs./in.²	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*	*Per cent*	*Per cent*		*Pr. ct.*	*Pr. ct.*	*Pr. ct.*	*Pr. ct.*	*Lbs./in.²*	*Lbs./in.²*	*Per cent*	*Per cent*	*Pr. ct.*	*Pr. ct.*	*Pr. ct.*	*P.ct.*
BSL12c-T	28,329	42,700	63,800	39,500	61,200	32.0	57.5	Cup	0.18	0.032	0.016	0.70	44,090	64,930	26.2	52.7	------	0.037	0.011	----
BSL12c-R	28,329	36,000	60,300			28.8	57.6	½ cup	.16	.032	.018	.70								
BSL12c-W	28,329	39,700	59,600			27.5	57.4	Cup	.14	.032	.008	.70								
BSL18c-T	28,329	41,300	65,900	39,700	63,300	28.0	57.0	Angular	.16	.040	.009	.76								
BSL18c-R	28,329	37,200	61,600			27.5	45.9	do	.16	.041	.014	.72								
BSL18c-W	28,329	40,500	62,500			29.2	53.5	do	.18	.040	.015	.71								
BSL24b-T	28,329	43,400	66,300	42,300	67,700	29.1	53.5	do	.22	.041	.010	.75								
BSL24b-R	28,329	39,500	67,400			26.0	41.5	do	.23	.040	.016	.76								
BSL24b-W	28,329	43,900	69,400			24.0	38.1	½ cup	.22	.040	.010	.76								

MATERIAL FROM 14-INCH BETHLEHEM H 287½-POUND SECTION SPECIMEN 1½ BY ½ INCH

Specimen mark	Heat No.	Yield point drop of beam	Tensile strength	Yield point	Tensile strength	Elongation in 8 inches	Reduction of area	Fracture	C	S	P	Mn	Yield point	Tensile strength	Elongation in 8 inches	Reduction of area	C	S	P	Mn
BSH12c-T	21,229	33,300	59,900	31,400	57,800	32.0	56.7	½ cup	0.19	0.028	0.015	0.67	40,700	63,340	30.0	48.4	------	0.031	0.010	----
BSH12c-R	21,229	30,100	57,000			29.1	57.6	Cup	.17	.028	.012	.66								
BSH12c-W	21,229	30,800	56,600			29.1	53.0	Angular	.18	.031	.011	.67								
BSH18b-T	21,229	30,000	59,400	30,000	58,800	30.2	55.7	do	.20	.025	.013	.67								
BSH18b-R	21,229	28,100	59,300			31.0	51.3	½ cup	.25	.029	.008	.67								
BSH18b-W	21,229	32,000	57,800			32.5	53.7	Angular	.22	.029	.009	.64								
BSH24a-T	15,280	36,100	63,500	34,300	62,500	28.5	54.2	Cup	.21	.027	.010	.64	46,230	64,240	27.5	53.9	------	.034	.013	----
BSH24a-R	15,280	30,900	61,700			26.9	47.0	½ cup	.21	.025	.014	.64								
BSH24a-W	15,280	36,000	62,300			26.1	50.3	do	.21	.026	.010	.64								
BSH24b-T	21,229	32,100	59,500	30,700	57,300	30.8	55.9	Angular	.20	.030	.009	.65	40,700	63,340	30.0	48.4	------	.031	.010	----
BSH24b-R	21,229	28,900	56,800			30.1	54.8	do	.19	.029	.008	.63								
BSH24b-W	21,229	31,200	55,500			32.0	57.2	½ cup	.17	.033	.007	.63								
BSH24c-T	15,280	33,900	65,000	33,000	62,500	29.1	54.9	do	.20	.056	.032	.73	46,230	64,240	27.5	53.9	------	.034	.013	----
BSH24c-R	15,280	32,000	62,800			25.5	35.1	do	.22	.055	.026	.72								
BSH24c-W	15,280	33,200	59,600			26.8	46.2	Angular	.16	.047	.019	.68								

MATERIAL FROM 6 BY 4 BY ½ INCH CARNEGIE ANGLE SPECIMEN SECTION 1½ BY ⅜ INCH

A-FSL12c3-S	CX-418	44,500	68,500	41,200	66,800	23.1	47.4	Angular	0.24	0.026	0.028	0.39	38,310	62,000	26.2	57.9	0.21	0.032	0.035	0.40
A-FSL12c3-R	CX-418	40,000	65,100			25.5	49.2	do	.23	.025	.028	.38								
A-FSL12c3-L	CX-418	39,000	66,800			26.8	50.1	do	.24	.024	.030	.39								
A-FSL12a2-S	15,442	42,800	67,700	41,100	68,400	24.0	53.0	Cup	.26	.027	.032	.39	38,100	59,400	31.2	55.2	.15	.040	.017	.45
A-FSL12a2-R	15,442	40,900	70,700			24.0	45.7	do	.28	.027	.034	.39								
A-FSL12a2-L	15,442	39,600	66,800			29.0	52.0	½ cup	.25	.026	.035	.39								
A-FSL12b1-S	DX-418	42,800	68,100	40,700	67,100	26.3	51.0	Angular	.26	.027	.037	.39	Seven angles had this heat number (see column 2) painted on them when received. The mill advised the heat number should have been CX-418.							
A-FSL12b1-R	DX-418	39,700	66,200			26.5	53.3	do	.22	.028	.034	.39								
A-FSL12b1-L	DX-418	39,700	67,100			28.2	52.5	Cup	.25	.028	.038	.39								
A-FSL24a3-S	19,470	43,100	67,700	40,300	60,800	29.0	52.6	Angular	.22	.040	.011	.39	37,130	58,700	27.7	54.8	.20	.042	.018	.38
A-FSL24a3-R	19,470	38,800	59,800			29.6	51.6	do	.21	.036	.011	.39								
A-FSL24a3-L	19,470	38,900	61,000			31.0	53.4	do	.22	.036	.010	.40								
A-FSL24c2-S	18,474	40,100	58,000	38,600	57,400	27.9	57.1	Cup	.18	.034	.011	.39	37,550	56,800	32.5	51.1	.17	.034	.018	.40
A-FSL24c2-R	18,474	37,900	57,700			32.1	57.8	do	.19	.036	.008	.41								
A-FSL24c2-L	18,474	37,900	56,600			32.1	54.0	do	.18	.034	.008	.39								

MATERIAL FROM 6 BY 4 BY ⅝ INCH CARNEGIE ANGLE SECTION SPECIMEN 1½ BY ½ INCH

A-FSH12a3-S	27,044	40,000	61,600	38,400	60,700	30.2	48.6	Cup	0.24	0.050	0.009	0.41	37,200	59,620	26.5	51.8	0.22	0.045	0.014	0.44
A-FSH12a3-R	27,044	37,300	59,300			29.5	50.0	do	.22	.046	.008	.40								
A-FSH12a3-L	27,044	38,000	61,200			29.2	52.3	do	.24	.053	.008	.40								
A-FSH18a2-S	43,416	42,600	66,000	41,300	65,000	26.5	48.6	Angular	.26	.049	.015	.53	37,410	62,440	26.5	53.1	.26	.051	.017	.55
A-FSH18a2-R	43,416	41,300	64,200			26.5	52.3	do	.25	.045	.014	.53								
A-FSH18a2-L	43,416	40,000	64,800			28.0	47.4	Cup	.25	.049	.011	.54								
A-FSH24b2-S	17,040	41,300	59,300	39,900	58,900	28.1	56.8	Angular	.19	.060	.012	.38	37,280	57,380	27.5	55.1	.21	.040	.014	.46
A-FSH24b2-R	17,040	40,000	58,700			29.4	51.4	Cup	.21	.060	.012	.38								
A-FSH24b2L	17,040	38,400	58,700			30.4	57.0	Angular	.20	.063	.012	.36								

MATERIAL FROM 14 BY ⅜ INCH CARNEGIE PLATE SECTION SPECIMEN 1½ BY $\frac{5}{16}$ INCH

P-FSL12a5-E	E11,322	40,500	63,000	38,900	61,300	30.0	54.4	Cup	0.14	0.046	0.038	0.54	-------	-------	-------	-------	-------	-------	-------	----
P-FSL12a5-C	E11,322	37,300	59,700			29.5	52.1	½ cup	.14	.044	.025	.54								
P-FSL18a5-E	E11,322	41,200	64,000	41,400	64,900	27.5	54.3	Cup	.15	.044	.035	.55	-------	-------	-------	-------	-------	-------	-------	----
P-FSL18a5-C	E11,322	41,600	65,800			26.0	51.2	do	.16	.046	.020	.58								
P-FSL18c5-E	E11,322	35,800	61,900	35,000	63,700	28.8	54.5	do	.15	.041	.025	.55	-------	-------	-------	-------	-------	-------	-------	----
P-FSL18c5-C	E11,322	34,100	64,200			27.2	58.2	do	.14	.046	.034	.58								

TABLE 1.—*Results of physical and chemical coupon tests and report of mill tests (first series)*—Continued

MATERIAL FROM 14 BY $\frac{7}{16}$ INCH CARNEGIE PLATE SECTION SPECIMEN 1½ BY $\frac{5}{16}$ INCH

Specimen mark	Heat No.	Yield point drop of beam	Tensile strength	Bureau of Standards report: Average: Yield point	Tensile strength	Elongation in 8 inches	Reduction of area	Fracture	Results of chemical analysis: C	S	P	Mn	Mill test report: Yield point	Tensile strength	Elongation in 8 inches	Reduction of area	Results of chemical analysis: C	S	P	Mn
		Lbs./in.²	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*	*Per cent*	*Per cent*		*Pr. ct.*	*Pr. ct.*	*Pr. ct.*	*Pr. ct.*	*Lbs./in.²*	*Lbs./in.²*	*Per cent*	*Per cent*	*Pr. ct.*	*Pr. ct.*	*Pr. ct.*	*P.ct.*
P-FSL12b6-E	43,203	39,000	63,100	42,000	63,500	29.5	51.6	Angular	0.24	0.033	0.009	0.42	37,590	62,740	28.0	50.9	0.21	0.036	0.020	0.47
P-FSL12b6-C	43,203	45,000	64,000			26.1	51.6	do	.21	.033	.008	.42								
P-FSL18c6-E	48,393	37,000	62,600	36,700	61,700	30.0	40.3	do	.25	.033	.011	.35	36,830	64,000	26.5	52.8	.21	.027	.011	.40
P-FSL18c6-C	48,393	36,400	60,800			27.3	53.4	do	.22	.027	.010	.34								
P-FSL24a6-E	43,431	38,500	62,000	39,300	64,600	29.8	50.3	½ cup	.23	.051	.010	.41	Mill test results on 14 in by ⅝ inch plate.							
P-FSL24a6-C	43,431	40,200	67,200			26.5	50.6	do	.27	.068	.014	.43	37,110	63,680	27.7	50.7	.19	.046	.015	.44
P-FSH18b6-E	E11,322	35,300	60,700	36,100	61,300	27.9	55.2	Angular	.13	.043	.029	.52	36,100	59,540	26.5	53.4	.17	.048	.037	.52
P-FSL18b6-C	E11,322	37,000	62,000			28.3	51.0	do	.12	.048	.036	.54								
P-FSL18c7-E	34,384	38,800	61,000	36,800	59,200	29.3	53.7	½ cup	.18	.036	.010	.51	37,080	59,660	28.2	50.9	.16	.029	.017	.47
P-FSL18c7-C	34,384	34,900	57,500			28.8	52.5	do	18	.027	.008	.48								

MATERIAL FROM 14 BY ⅝ INCH CARNEGIE PLATE SECTION SPECIMEN 1½ BY ½ INCH

P-FSH12a7-E	E11,322	35,700	59,200	35,200	58,500	33.6	60.5	Angular	0.15	0.043	0.030	0.51	36,100	59,540	27.5	53.4	0.17	0.048	0.037	0.52
P-FSH12a7-C	E11,322	34,700	57,700			32.5	54.9	do	.14	.043	.030	.52								
P-FSH12a10-E	38,382	42,000	70,700	41,200	69,300	24.1	44.8	½ cup	.28	.050	.009	.44	37,200	61,900	28.0	51.0	.21	.044	.011	.49
P-FSH12a10-C	38,382	40,300	68,000			27.5	50.5	Cup	.30	.054	.008	.46								
P-FSH12c9-E	34,389	36,700	62,600	37,400	59,400	31.0	52.4	Angular	.15	.047	.014	.44	37,010	64,180	26.5	51.4	.19	.041	.015	.47
P-FSH12c9-C	34,389	38,000	56,300			27.8	44.3	do	.17	.044	.006	.44								
P-FSH18a7-E	58,379	34,000	59,400	33,700	57,900	32.5	52.7	½ cup	.13	.036	.012	.43	37,220	62,680	29.5	54.1	.21	.040	.013	.44
P-FSH18a7-C	58,379	33,400	56,300			31.5	58.2	Angular	.17	.040	.007	.40								

P-FSH18c10-E	(Am. B. stock)	38,600	65,700	37,900	64,100	29.9	49.7	Cup	.24	.044	.027	.46	-------	-------	-------	-------	-------	-------	-------	-------
P-FSH18c10-C	(Am. B. stock)	37,100	62,600			27.0	49.6	Angular	.21	.041	.029	.46								
P-FSH24a11-E	57,345	34,700	60,900	33,700	59,100	29.8	55.3	½ cup	.21	.042	.008	.42	36,760	62,620	27.5	52.8	.21	.039	.016	.46
P-FSH24a11-C	57,345	32,600	57,300			32.1	55.0	Cup	.17	.033	.023	.41								
P-FSH24c9-E	46,398	37,900	60,600	37,900	63,600	30.8	54.1	do	.24	.033	.023	.35	36,690	58,200	27.5	51.2	.21	.033	.010	.40
P-FSH24c9-C	46,398	38,000	66,700			24.9	36.1	½ cup	.27	.034	.013	.36								
MATERIAL FROM 15 INCH BY 33 POUND CARNEGIE CHANNEL SECTION SPECIMEN 1½ BY $\frac{5}{16}$ INCH																				
C-CSL24-T	60,339	43,900	59,100	42,800	57,200	24.5	48.4	Angular	0.19	0.046	0.014	0.37	37,560	61,440	28.5	54.7	0.19	0.045	0.016	0.42
C-CSL24-R	60,339	48,700	59,200			23.0	50.5	Cup	.15	.044	.020	.37								
C-CSL24-W	60,339	35,900	53,400			31.5	55.6	½ cup	.16	.045	.014	.37								

TABLE 2.—*Results of supplementary coupon tests (first series)*

Specimen	Yield point, drop of beam	Tensile strength	Reduction of area	Elongation in 8 inches	Specimen	Yield point, drop of beam	Tensile strength	Reduction of area	Elongation in 8 inches
	Lbs./in.²	*Lbs./in.²*	*Per cent*	*Per cent*		*Lbs./in.²*	*Lbs./in.²*	*Per cent*	*Per cent*
BSL12a-T	36,980	63,060	55.7	30	BSH12a-T	32,570	65,670	53.6	30
BSL12a-R	34,070	58,790	56.2	27	BSH12a-R	27,620	59,930	52.5	31
BSL12a-W	34,060	59,640	49.7	30	BSH12a-W	29,040	59,420	52.1	30
BSL12b-T	36,240	61,670	56.7	31	BSH12a1-T	30,010	64,780	53.5	27
BSL12b-R	32,910	57,400	56.3	33	BSH12a1-R	31,390	61,390	54.4	30
BSL12b-W	33,730	58,430	53.4	31	BSH12a1-W	30,450	61,850	50.8	28
					BSH12a2-T	32,790	64,940	50.9	27
BSL18a1-T	37,480	63,980	56.8	30	BSH12a2-R	27,790	59,060	54.4	30
BSL18a1-R	33,420	59,910	55.1	31	BSH12a2-W	30,130	59,150	53.4	30
BSL18a1-W	33,470	61,330	47.9	26					
BSL18a2-T	34,680	64,860	56.0	31	BSH12b-T	27,270	58,400	54.2	31
BSL18a2-R	34,630	61,530	57.4	31	BSH12b-R	25,900	56,900	55.9	31
BSL18a2-W	36,410	62,810	47.3	27	BSH12b-W	27,240	56,600	51.7	31
BSL18b-T	36,390	63,010	57.7	31	BSH18a-T	28,950	58,190	55.5	32
BSL18b-R	36,500	60,880	53.1	30	BSH18a-R	28,400	68,210	45.6	26
BSL18b-W	35,400	60,920	54.7	30	BSH18a-W	34,650	74,160	34.4	23
BSL24a-T	40,640	65,420	52.2	30	BSH18c1-T	28,880	59,410	55.7	31
BSL24a-R	36,600	63,410	57.5	28.5	BSH18c1-R	25,280	57,520	49.5	30.5
BSL24a-W	39,390	64,280	51.2	29	BSH18c1-W	27,920	56,430	52.0	32.5
					BSH18c2-T	32,280	58,600	54.4	29.5
BSL24c-T	39,810	65,330	54.6	30	BSH18c2-R	27,120	55,750	55.7	32
BSL24c-R	39,510	69,430	50.8	28	BSH18c2-W	28,540	55,620	50.0	31
BSL24c-W [1]	41,170	68,710	31.7	22					

[1] Pronounced pipe showed in broken specimen.

(2) CHEMICAL ANALYSES.—It is seen from the chemical analyses that the steel was the ordinary structural material of about 0.20 per cent carbon. The sulphur and phosphorus were within the limits permitted by the A. S. T. M. specifications. The only marked difference in the chemical composition of the specimens lies in the manganese content, which ranges from 0.63 to 0.76 per cent in the solid rolled sections and from 0.34 to 0.58 per cent in the fabricated sections.

(3) YIELD POINT AND TENSILE STRENGTH OF INDIVIDUAL SPECIMENS.—The number of test specimens that failed to meet the specifications in regard to the value of the tensile strength and its relation to the yield point by drop of beam, as shown in the Bureau of Standards tests, is given in Table 3. Only one specimen (from column CSL24c) had a tensile strength less than the specified 55,000 lbs./in.²

TABLE 3.—*Number of coupon specimens that failed to pass the A. S. T. M. specifications*

[Serial A 7-16. First series]

Material from—		Tensile strength: Less than 55,000 lbs./in.²	Tensile strength: More than 65,000 lbs./in.²	Ratio, yield point to tensile strength less than 0.5	
Original tests	Solid rolled light sections	0	4	0	
	Solid rolled heavy sections	0	0	1	
	Fabricated light sections	0	11	0	
	Fabricated heavy sections	1	4	0	
				Uncorrected	Corrected
Supplementary tests	Solid rolled light sections	0	4	0	0
	Solid rolled heavy sections	0	3	16	2

About 20 per cent of the specimens had a tensile strength greater than 65,000 lbs./in.² These were approximately equally distributed between the two types of columns. All but one of the specimens in the original tests gave values for the yield point greater than one-half the tensile strength. In the supplementary coupon tests the testing machine was run at a slower speed (0.013 inch per minute) instead of 0.37 inch per minute. Since A. S. T. M. specifications allow speeds up to 2 inches per minute in determining the yield point by "drop of beam" on specimens of this size, the systematic difference of over 10 per cent (see Table 10, p. 41) was much greater than had been expected. As a consequence of this lowering of the measured yield point with the slower speed, 16 of the supplementary coupon tests showed a yield point less than one-half the ultimate. After applying the correction factor discussed below, this number was reduced to two.

From a commercial standpoint, the material evidently met the specifications under which it was purchased. The departures (which were small) from the specified limits shown by individual specimens in the Bureau of Standards tests were to be expected in view of the relatively large number of specimens tested.

TABLE 4.—*Average values from the results of tests on coupon specimens (first series)*

	Material from—	Average tensile strength	Average yield point	Ratio of yield point to tensile strength
		Lbs./in.²	*Lbs./in.²*	*Per cent*
Group A	Light fabricated sections, columns FSL	63,300	39,300	62.1
	Heavy fabricated sections, columns FSH	61,600	37,900	61.5
	Light solid sections, columns BSL	64,090	40,470	63.1
	Heavy solid sections, columns BSH	59,780	31,910	53.4
Group B	14 by ⅜ inch plate	63,300	38,430	60.7
	14 by 1/16 inch plate	62,060	38,180	61.6
	14 by ⅝ inch plate	61,700	36,710	59.5
	6 by 4 by ½ inch angle	64,100	40,380	63.1
	6 by 4 by ⅝ inch angle	61,530	39,870	64.8
Group C	14-inch H, 122½ pounds:			
	Position T	65,300	42,500	65.1
	Position R	63,100	37,600	59.6
	Position W	63,800	41,400	64.9
	14-inch H, 287½ pounds:			
	Position T	61,500	33,100	53.8
	Position R	59,500	30,000	50.5
	Position W	58,400	32,600	55.8
	6 by 4 by ½ inch angle:			
	Position A-S	64,800	42,700	65.9
	Position A-R	63,900	39,500	61.8
	Position A-L	63,700	39,000	61.2
	6 by 4 by ⅝ inch angle:			
	Position A-S	62,300	41,300	66.3
	Position A-R	60,700	39,500	65.1
	Position A-L	61,600	36,400	59.1
	Plates:			
	Position P-E	62,500	37,700	60.3
	Position P-C	61,700	37,300	60.4

(4) AVERAGE RESULTS OF YIELD POINT AND TENSILE STRENGTH.—Average results of the original coupon tests for the different columns and different types of material used in the fabricated columns are given in Table 4. Table 4, group A, gives the values of the averages of the yield point, tensile strength, and ratio of yield point to tensile strength for the light and heavy fabricated sections and the light and heavy solid rolled sections.

In both the fabricated and the solid rolled sections the light (thin section) material had the higher tensile strength, yield point, and ratio of yield point to tensile strength. This difference is shown also by the average values of the physical properties for the material used in the fabricated sections (Table 4, group B). For both the plate and angle material the average tensile strength and yield point decrease with increasing thickness of the material.

The average values for the specimens cut from different locations in the sections are shown in Table 4, group C. With one exception (6 by 4 by ½ inch angles) the tensile strengths and, with two exceptions (6 by 4 by ½ inch and 6 by 4 by ⅝ inch angles), the yield points are highest at the outstanding edges of the sections. The differences in tensile strength across the section were small. The differences in yield point were relatively much greater, being greatest (approximately 12 per cent) in the 6 by 4 by ⅝ inch angles and the H14, 122½-pound sections, and negligible (approximately 1 per cent) in the plates.

(b) RESULTS FROM COLUMN TESTS

(1) Sample Log Sheets.—Typical log sheets of the complete tests on two comparable columns, BSH24b and FSH24b are given

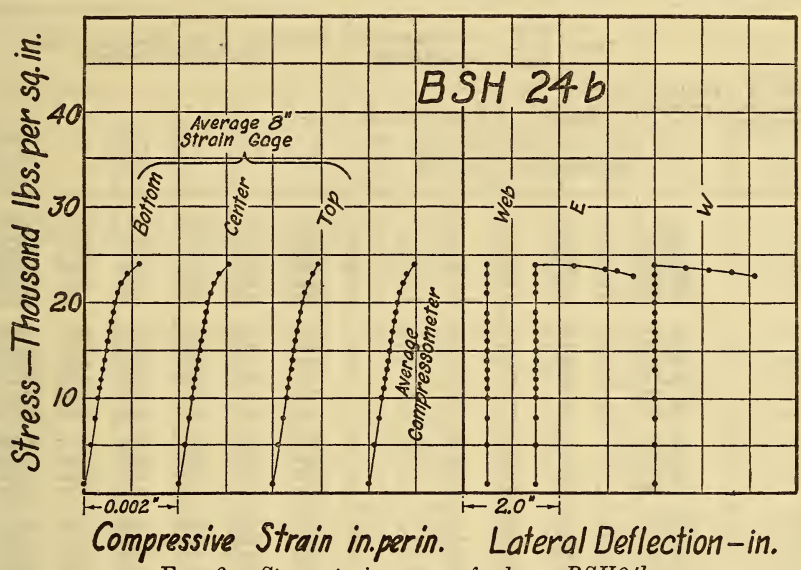

Fig. 6.—*Stress-strain curves of column BSH24b*
For location of gauges see Figure 1

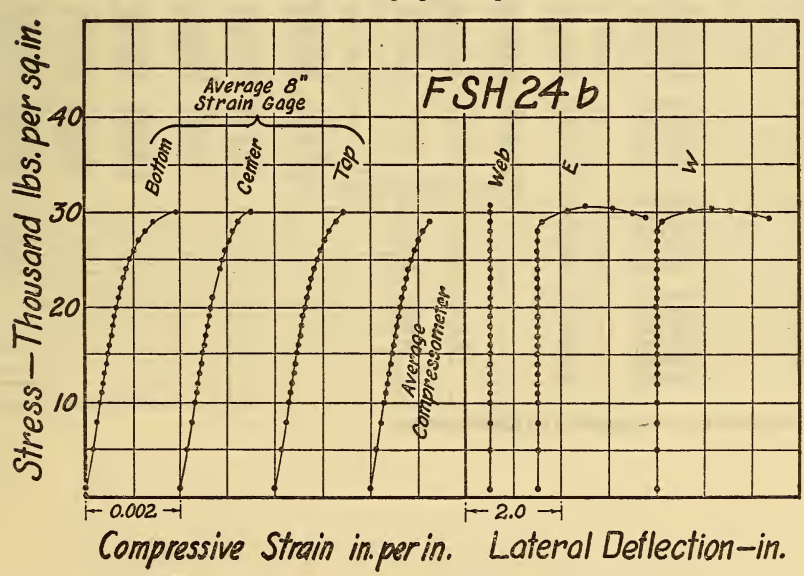

Fig. 7.—*Stress-strain curves of column FSH24b*
For location of gauges see Figure 1

in Table 5 and Table 6. From these the stress-strain curves of Figure 6 and Figure 7 and the elastic properties of the column were obtained.

TABLE 5.—*Log sheet BSH24b*

[Column mark, B6B; tested with flat ends; section, 14-inch Bethlehem H, 287½ pounds, length, 24 feet; radius of gyration, 3.81 inches; slenderness ratio, 75.6; weight in pounds, 6,850; sectional area, 83.95 square inches; initial condition, good metal, no flaws.]

Applied stress in pounds per square inch	Total load pounds	Time		Temperature	Lateral deflection at mid height			8-inch strain gauge differences, 12 inches from bottom of column					
		Before—			Unit=1/50 inch								
		Hr.	Min.	°C.	E	W	N	1	2	3	4	5	Average
								Inch	*Inch*	*Inch*	*Inch*	*Inch*	*In./in.*
1,000	83,946	10	20	11	0	0	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.000000
1,000	83,946	10	22	12	0	0	0	.0001	.0001	.0000	−.0001	.0000	.000000
5,000	419,730	10	30	12	−2	0	0	.0010	.0013	.0010	.0013	.0010	.000140
10,000	839,460	10	39	13	−2	−1	1	.0025	.0026	.0025	.0026	.0022	.000207
15,000	1,259,190	10	56	13	−2	−2	0	.0045	.0040	.0039	.0037	.0035	.000490
1,000	83,946	11	00	13	−1	−1	0	.0003	.0002	.0002	−.0001	.0002	.000020
5,000	419,730	11	09	13	−2	−2	0	.0015	.0013	.0014	.0011	.0012	.000162
10,000	839,460	11	18	13	−2	−2	0	.0028	.0027	.0028	.0021	.0023	.000317
15,000	1,259,190	11	31	13	−2	−2	1	.0042	.0039	.0041	.0037	.0035	.000485
18,000	1,511,028	11	41	14	−2	−2	1	.0054	.0049	.0054	.0045	.0046	.000620
20,000	1,678,920	11	54	14	−2	−2	1	.0063	.0057	.0067	.0052	.0055	.000735
1,000	83,946	1	37	16	−2	−2	0	.0009	.0007	.0013	.0002	.0007	.000095
1,000	83,946	1	37	16	−2	−2	0	.0000	.0000	.0000	.0000	.0000	.000000
5,000	419,730	1	47	16	−2	−2	0	.0012	.0010	.0013	.0010	.0008	.000130
8,000	671,586	1	53	16	−2	−3	0	.0020	.0018	.0021	.0017	.0016	.000230
10,000	839,460	1	59	16	−2	−3	0	.0027	.0022	.0026	.0022	.0020	.000292
11,000	923,406	2	03	16	−2	−3	0	.0029	.0026	.0028	.0027	.0024	.000335
12,000	1,007,352	2	06	16	−2	−3	0	.0031	.0028	.0030	.0030	.0025	.000360
13,000	1,097,298	2	10	16	−2	−3	0	.0035	.0031	.0034	.0032	.0029	.000402
14,000	1,175,244	2	14	16	−2	−3	0	.0037	.0034	.0036	.0035	.0031	.000432
15,000	1,259,190	2	19	16	−2	−3	0	.0040	.0036	.0039	.0039	.0033	.000467
16,000	1,343,136	2	24	16	−2	−3	0	.0042	.0038	.0042	.0041	.0037	.000500
17,000	1,427,082	2	36	16	−2	−3	0	.0045	.0041	.0044	.0044	.0038	.000530
18,000	1,511,028	2	42	16	−2	−3	0	.0048	.0044	.0048	.0047	.0042	.000572
19,000	1,594,974	2	47	16	−2	−3	0	.0051	.0047	.0051	.0052	.0045	.000615
20,000	1,678,920	2	50	16	−1	−2	0	.0054	.0050	.0055	.0053	.0048	.000650
21,000	1,762,866	2	53	16	0	−1	0	.0059	.0056	.0060	.0057	.0051	.000707
22,000	1,846,812	2	57	16	+4	+3	−1	.0065	.0064	.0068	.0065	.0059	.000798
23,000	1,930,759	3	01	16	31	30	−1	.0071	.0078	.0082	.0070	.0065	.000915
24,000	2,014,704	3	06	16	37	37	−1	.0079	.0086	.0140	.0090	.0075	.001175
[Compressometers removed]													
23,990	2,012,000	3	15	------	43	43	(1)	------	------	------	------	------	------
23,870	2,001,000	3	16	------	49	48	------	------	------	------	------	------	------
23,720	1,990,000	3	17	------	55	55	------	------	------	------	------	------	------
23,590	1,978,000	3	18	------	62	61	------	------	------	------	------	------	------
23,470	1,969,000	3	19	------	72	72	------	------	------	------	------	------	------
23,390	1,961,000	3	20	------	77	76	------	------	------	------	------	------	------
23,220	1,949,000	3	21	------	84	82	------	------	------	------	------	------	------
23,140	1,943,000	3	22	------	94	94	------	------	------	------	------	------	------
23,100	1,938,000	3	23	------	102	100	------	------	------	------	------	------	------
23,010	1,930,000	3	24	------	------	------	------	------	------	------	------	------	------
22,900	1,923,000	3	25	------	------	------	------	------	------	------	------	------	------

[1] Wire bearing on web; unable to get further readings.

TABLE 5.—*Log sheet BSH24b*—Continued

Applied stress in pounds per square inch	8-inch strain gauge differences, straddling the center						8-inch strain gauge differences, 12 inches from top of column					
	1	2	3	4	5	Average	1	2	3	4	5	Average
	Inch	*Inch*	*Inch*	*Inch*	*Inch*	*In./in.*	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*	*In./in.*
1,000	0.0000	0.0000	0.0000	0.0000	0.0000	0.000000	0.0000	0.0000	0.0000	0.0000	0.0000	0.000000
1,000	.0000	.0001	.0000	−.0001	.0000	.00000	.0000	.0000	.0000	.0000	.0000	.000000
5,000	.0008	.0011	.0013	.0010	.0008	.000125	.0011	.0011	.0019	.0010	.0009	.000150
10,000	.0020	.0024	.0027	.0023	.0020	.000285	.0025	.0023	.0032	.0024	.0021	.000312
15,000	.0035	.0038	.0041	.0035	.0036	.000462	.0040	.0037	.0046	.0036	.0034	.000483
1,000	.0001	−.0001	.0000	−.0002	−.0002	−.000010	.0004	.0002	−.0002	−.0003	.0000	.000000
5,000	.0010	.0011	.0013	.0009	.0008	.000138	.0014	.0013	.0017	.0008	.0009	.000152
10,000	.0022	.0024	.0026	.0022	.0020	.000285	.0027	.0025	.0033	.0022	.0022	.000322
15,000	.0035	.0038	.0041	.0035	.0035	.000460	.0040	.0037	.0048	.0036	.0034	.000488
18,000	.0046	.0047	.0047	.0044	.0045	.000572	.0050	.0047	.0060	.0043	.0044	.000610
20,000	.0059	.0054	.0054	.0049	.0054	.000675	.0057	.0053	.0074	.0050	.0052	.000715
1,000	.0010	.0001	−.0001	.0000	.0002	.000030	.0009	.0003	.0013	−.0002	.0002	.000062
1,000	.0000	.0000	.0000	.0000	.0000	.000000	.0000	.0000	.0000	.0000	.0000	.000000
5,000	.0008	.0010	.0012	.0009	.0010	.000122	.0009	.0011	.0015	.0010	.0009	.000135
8,000	.0015	.0019	.0021	.0017	.0017	.000222	.0017	.0019	.0026	.0018	.0017	.000242
10,000	.0019	.0024	.0026	.0022	.0023	.000285	.0021	.0024	.0031	.0024	.0022	.000305
11,000	.0022	.0026	.0029	.0026	.0026	.000322	.0025	.0026	.0033	.0027	.0026	.000342
12,000	.0025	.0030	.0032	.0029	.0028	.000360	.0027	.0029	.0036	.0030	.0028	.000375
13,000	.0029	.0033	.0034	.0033	.0031	.000400	.0030	.0031	.0039	.0033	.0030	.000407
14,000	.0031	.0035	.0037	.0033	.0034	.000425	.0032	.0034	.0042	.0035	.0032	.000437
15,000	.0033	.0038	.0041	.0035	.0036	.000458	.0034	.0036	.0045	.0038	.0035	.000470
16,000	.0037	.0040	.0043	.0038	.0039	.000492	.0037	.0037	.0047	.0040	.0038	.000497
17,000	.0040	.0043	.0046	.0040	.0041	.000525	.0038	.0039	.0049	.0043	.0041	.000525
18,000	.0042	.0045	.0048	.0043	.0045	.000557	.0042	.0042	.0053	.0045	.0044	.000565
19,000	.0045	.0047	.0050	.0047	.0046	.000588	.0044	.0045	.0057	.0048	.0046	.000600
20,000	.0049	.0051	.0054	.0048	.0049	.000628	.0048	.0048	.0060	.0050	.0050	.000640
21,000	.0059	.0054	.0057	.0049	.0054	.000682	.0050	.0051	.0065	.0056	.0054	.000690
22,000	.0074	.0059	.0060	.0051	.0059	.000758	.0056	.0054	.0075	.0060	.0058	.000757
23,000	.0098	.0065	.0062	.0052	.0066	.000858	.0059	.0058	.0088	.0068	.0065	.000845
24,000	.0145	.0085	.0070	.0046	.0078	.001060	.0062	.0057	.0116	.0084	.0076	.000988
[Compressometers removed]												
23,990	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
23,870	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
23,720	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
23,590	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
23,470	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
23,390	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
23,220	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
23,140	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
23,100	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
23,010	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
22,900	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

TABLE 5.—*Log sheet BSH24b*—Continued

Applied stress in pounds per square inch	Compression in 150-inch gauge length					Time		Temperature	Remarks
	A	B	C	D	Average	After—			
						Hr.	Min.	°C.	
	Inch	*Inch*	*Inch*	*Inch*	*In./in.*				
1,000	0.0000	0.0000	0.0000	0.0000	0.000000	10	22	12	Stroke of pump 1 inch for check.
1,000	−.0008	−.0003	−.0002	−.0002	−.000002	10	24	12	
5,000	.0172	.0241	.0226	.0170	.000135	10	32	12	
10,000	.0402	.0480	.0500	.0428	.000302	10	41	13	
15,000	.0675	.0758	.0772	.0683	.000481	10	58	13	
1,000	−.0079	−.0090	−.0048	.0022	−.000033	11	03	13	
5,000	.0230	.0300	.0260	.0190	.000163	11	12	13	
10,000	.0442	.0530	.0530	.0445	.000324	11	20	13	
15,000	.0672	.0752	.0773	.0685	.000480	11	33	13	
18,000	.0840	.0929	.0941	.0849	.000593	11	44	13	
20,000	0960	.1058	.1054	.0970	.000674				
	.					11	56	14	
1,000	.0117	.0157	.0062	.0022	.000059	1	42	16	
1,000	.0000	.0000	.0000	.0000	.000000	1	49	16	
5,000	.0162	.0198	.0220	.0177	.000126	1	55	16	
8,000	.0300	.0345	.0382	.0323	.000225	2	01	16	
10,000	.0389	.0438	.0478	.0413	.000286	2	05	16	
11,000	.0439	.0488	.0528	.0465	.000320	2	08	16	
12,000	.0485	.0536	.0572	.0514	.000351	2	12	16	
13,000	.0532	.0585	.0619	.0561	.000383	2	16	16	
14,000	.0583	.0633	.0667	.0607	.000415	2	21	16	
15,000	.0627	.0679	.0711	.0651	.000445	2	32	16	
16,000	.0674	.0729	.0758	.0702	.000477	2	38	16	
17,000	.0727	.0790	.0816	.0754	.000514	2	45	16	
18,000	.0780	.0839	.0864	.0806	.000548	2	49	16	
19,000	.0829	.0883	.0902	.0857	.000578	2	52	16	
20,000	.0886	.0942	.0952	.0907	.000614	2	55	16	Cracking.
21,000	.0979	.1014	.1035	.0978	.000668	2	59	16	
22,000	.1109	.1133	.1116	.1073	.000738	3	03	16	
23,000	.1298	.1286	.1227	.1192	.000834	3	09	16	
24,000	.1619	.1556	.1343	.1316	.000972				Ultimate strength. The peak was not obtained; it was missed somewhere between load 2,014,707 and 2,098,650 pounds.
	[Compressometers removed]								
23,990									
23,870									
23,720									
23,590									
23,470									
23,390									
23,220									
23,140									
23,100									
23,010									
22,900									

TABLE 6.—*Log sheet for FSH 24b*

[Column mark , C6B; tested with flat ends; section built up; length, 24 feet; radius of gyration, 3.56 inches; slenderness ratio, 80.8; weight in pounds, 6,866; sectional area, 84.14 square inches; initial condition, good; riveting, O. K.; alignment, good; metal; no flaws]

Applied stress in pounds per square inch	Total load	Time		Temperature	Lateral deflection at mid height, Unit=$\frac{1}{50}$ inch			8-inch strain gauge differences 12 inches from bottom of column					
	Pound	Before—			E	W	N	1	2	3	4	5	Average
		Hr.	*Min.*	*° C.*				*Inch*	*Inch*	*Inch*	*Inch*	*Inch*	*In./in.*
1,000	84,142	10	50	10	0	0	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.000000
1,000	84,142	10	55	10	0	0	1	.0001	.0000	.0000	.0000	.0001	.000000
5,000	420,710	11	02	10	1	1	1	.0010	.0016	.0014	.0011	.0008	.000148
10,000	841,420	11	12	10	1	1	1	.0026	.0030	.0029	.0025	.0017	.000317
15,000	1,262,130	11	30	10	1	1	1	.0030	.0046	.0042	.0039	.0034	.000477
1,000	84,142	12	47	10	0	0	0	.0000	.0004	.0002	.0000	.0001	.000018
5,000	420,710	12	56	10	1	1	0	.0011	.0017	.0015	.0011	.0007	.000152
10,000	841,420	1	05	10	1	1	0	.0025	.0032	.0029	.0026	.0021	.000332
15,000	1,262,130	1	21	11	2	2	1	.0038	.0046	.0042	.0040	.0035	.000502
18,000	1,514,556	1	59	11	2	2	1	.0049	.0055	.0051	.0050	.0043	.000620
20,000	1,682,840	2	03	11	2	2	1	.0056	.0064	.0058	.0056	.0050	.000710
1,000	84,142	2	07	11	0	0	0	.0003	.0010	.0006	.0004	.0004	.000068
1,000	84,142	2	07	11	0	0	0	.0000	.0000	.0000	.0000	.0000	.000000
1,000	420,710	2	14	12	1	1	1	.0011	.0012	.0012	.0011	.0008	.000135
5,000	673,136	2	20	12	2	2	1	.0020	.0021	.0020	.0020	.0013	.000235
10,000	841,420	2	24	12	2	2	1	.0026	.0026	.0025	.0025	.0018	.000300
11,000	925,562	2	28	12	2	2	2	.0029	.0030	.0028	.0028	.0021	.000340
12,000	1,009,704	2	32	12	2	2	2	.0033	.0032	.0031	.0032	.0024	.000380
13,000	1,093,846	2	36	13	2	2	1	.0033	.0034	.0033	.0032	.0028	.000400
14,000	1,177,988	2	41	13	2	2	1	.0037	.0037	.0036	.0035	.0030	.000437
15,000	1,262,130	2	47	13	2	2	2	.0039	.0039	.0038	.0038	.0033	.000467
16,000	1,346,272	2	55	13	2	2	1	.0041	.0042	.0041	.0040	.0035	.000498
17,000	1,430,414	3	09	13	2	2	1	.0044	.0045	.0044	.0043	.0039	.000538
18,000	1,514,556	3	15	13	2	2	1	.0047	.0048	.0045	.0046	.0043	.000572
19,000	1,598,698	3	21	13	2	2	1	.0049	.0051	.0048	.0050	.0044	.000605
20,000	1,682,840	3	24	13	2	2	1	.0052	.0054	.0051	.0052	.0048	.000642
21,000	1,766,982	3	28	13	2	2	1	.0057	.0058	.0055	.0056	.0051	.000692
22,000	1,851,124	3	32	13	2	2	1	.0061	.0063	.0058	.0060	.0055	.000742
23,000	1,935,266	3	36	13	2	3	1	.0066	.0068	.0062	.0064	.0061	.000802
24,000	2,019,408	3	40	13	2	3	1	.0072	.0074	.0066	.0068	.0066	.000865
25,000	2,103,550	3	45	13	3	4	1	.0079	.0080	.0070	.0075	.0073	.000942
26,000	2,187,692	3	50	13	3	4	1	.0087	.0089	.0074	.0082	.0079	.001027
27,000	2,271,834	3	54	13	3	5	1	.0096	.0098	.0077	.0089	.0087	.001117
28,000	2,355,976	4	00	13	5	7	1	.0113	.0114	.0080	.0096	.0097	.001250
29,000	2,440,118	4	07	13	9	11	2	.0143	.0140	.0078	.0104	.0111	.001440
[Compressometers removed]													
30,000	2,524,260				24	28	3	.0235	.0227	.0058	.092	.0157	.001922
30,350	2,553,000	4	25		32	37	3						
30,310	2,550,000	4	26		35	40	3						
30,270	2,547,000	4	27		39	44	3						
30,500	2,566,500	4	28		46	51	3						
30,320	2,551,000	4	29		56	61	3						
30,160	2,536,000	4	30		65	71	3						
29,750	2,502,000	4	32		85	91	3						
29,400	2,474,000	4	34		105	111	3						

TABLE 6.—*Log sheet for FSH 24b*—Continued

Applied stress in pounds per square inch	8-inch strain gauge differences straddling the center						8-inch strain gauge differences 12 inches from top of column					
	1	2	3	4	5	Average	1	2	3	4	5	Average
	Inch	*Inch*	*Inch*	*Inch*	*Inch*	*In./in.*	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*	*In./in.*
1,000	0.0000	0.0000	0.0000	0.0000	0.0000	0.000000	0.0000	0.0000	0.0000	0.0000	0.0000	0.000000
1,000	.0001	.0001	.0000	.0000	.0001	.000002	.0001	.0001	.0001	.0000	.0000	.000007
5,000	.0009	.0010	.0013	.0010	.0010	.000130	.0006	.0013	.0015	.0012	.0010	.000140
10,000	.0021	.0024	.0026	.0025	.0023	.000298	.00018	.0028	.0028	.0027	.0021	.000305
15,000	.0034	.0037	.0041	.0039	.0037	.000470	.00034	.0047	.0043	.0044	.0040	.000520
1,000	.0001	.0002	.0001	.0001	.0002	.000018	.0002	.0001	.0001	.0003	.0003	.000005
5,000	.0007	.0008	.0012	.0010	.0007	.000110	.0005	.0015	.0015	.0013	.0008	.000140
10,000	.0021	.0022	.0026	.0025	.0023	.000292	.00018	.0031	.0028	.0027	.0024	.000320
15,000	.0033	.0035	.0041	.0039	.0037	.000462	.00031	.0044	.0042	.0042	.0037	.000487
18,000	.0041	.0043	.0050	.0048	.0045	.000567	.00038	.0055	.0047	.0052	.0043	.000587
20,000	.0048	.0050	.0056	.0054	.0052	.000650	.00047	.0062	.0054	.0061	.0055	.000698
1,000	.0000	.0001	.0001	.0001	.0000	.000002	.00001	.0007	.0001	.0009	.0002	.000050
1,000	.0000	.0000	.0000	.0000	.0000	.000000	.00000	.0000	.0000	.0000	.0000	.000000
5,000	.0009	.0010	.0013	.0010	.0011	.000132	.0005	.0014	.0014	.0009	.0009	.000128
8,000	.0017	.0018	.0022	.0020	.0019	.000240	.0014	.0021	.0022	.0018	.0018	.000232
10,000	.0022	.0024	.0027	.0025	.0025	.000307	.0017	.0027	.0028	.0023	.0022	.000292
11,000	.0025	.0026	.0029	.0028	.0027	.000337	.0022	.0030	.0029	.0028	.0028	.000342
12,000	.0027	.0029	.0032	.0031	.0030	.000372	.0023	.0032	.0033	.0030	.0030	.000370
13,000	.0031	.0032	.0036	.0034	.0032	.000415	.0028	.0036	.0036	.0032	.0032	.000410
14,000	.0033	.0034	.0038	.0036	.0036	.000442	.0030	.0040	.0038	.0036	.0034	.000445
15,000	.0035	.0037	.0041	.0039	.0039	.000477	.0034	.0041	.0040	.0038	.0035	.000470
16,000	.0037	.0038	.0043	.0041	.0041	.000500	.0035	.0044	.0043	.0041	.0036	.000498
17,000	.0039	.0041	.0046	.0044	.0043	.000532	.0037	.0047	.0045	.0043	.0041	.000532
18,000	.0041	.0043	.0049	.0047	.0046	.000565	.0040	.0048	.0046	.0045	.0042	.000552
19,000	.0045	.0047	.0052	.0050	.0049	.000607	.0043	.0052	.0048	.0049	.0045	.000592
20,000	.0048	.0049	.0054	.0053	.0052	.000640	.0046	.0056	.0051	.0054	.0049	.000635
21,000	.0051	.0052	.0058	.0055	.0055	.000677	.0050	.0060	.0054	.0056	.0052	.000680
22,000	.0054	.0055	.0061	.0059	.0059	.000720	.0055	.0063	.0054	.0062	.0056	.000725
23,000	.0058	.0059	.0066	.0064	.0064	.000777	.0058	.0069	.0057	.0068	.0060	.000780
24,000	.0061	.0062	.0071	.0068	.0068	.000825	.0063	.0074	.0062	.0071	.0062	.000830
25,000	.0065	.0064	.0077	.0073	.0073	.000880	.0070	.0083	.0065	.0078	.0072	.000920
26,000	.0069	.0069	.0082	.0079	.0079	.000945	.0074	.0091	.0068	.0084	.0076	.000982
27,000	.0072	.0073	.0090	.0086	.0084	.001012	.0081	.0100	.0070	.0093	.0083	.001067
28,000	.0075	.0076	.0101	.0095	.0092	.001098	.0094	.0115	.0072	.0093	.0088	.001155
29,000	.0075	.0076	.0120	.0111	.0101	.001207	.0113	.0141	.0069	.0100	.0096	.001297
	[Compressometers removed]											
30,000	.0058	.0059	.0185	.0171	.0127	.001500	.0179	.0230	.0049	.0080	.0107	.001612
30,350												
30,310												
30,270												
30,500												
30,320												
30,160												
29,750												
29,400												

TABLE 6.—*Log sheet for FSH 24b*—Continued

Applied stress in pounds per square inch	Compression in 150 inches gauge length					Time		Temperature	Remarks
	A	B	C	D	Average	After—			
	Inch	*Inch*	*Inch*	*Inch*	*In./in.*	*Hr.*	*Min*	*° C.*	
1,000	0.0000	0.0000	0.0000	0.0000	0.000000	10	53	10	1-inch stroke for check.
1,000	.0001	.0001	.0000	.0002	.000001	10	57	10	
5,000	.0152	.0204	.0246	.0202	.000134	11	05	10	
10,000	.0380	.0451	.0519	.0465	.000303	11	15	10	
15,000	.0621	.0684	.0769	.0700	.000462	11	33	10	
1,000	.0030	.0012	.0005	.0004	.000045	12	50	10	
5,000	.0144	.0192	.0247	.0200	.000130	12	58	10	
10,000	.0373	.0441	.0516	.0461	.000299	1	07	10	
15,000	.0643	.0700	.0792	.0728	.000477	1	23	11	
18,000	.0833	.0885	.0992	.0930	.000607	2	01	11	
20,000	.0949	.1000	.1115	.1049	.000689	2	05	11	3-inch stroke.
1,000	.0090	.0077	.0112	.0111	.000065	2	09	11	1-inch stroke.
1,000	.0000	.0000	.0000	.0000	.000000	2	17	12	
5,000	.0132	.0194	.0230	.0182	.000123	2	22	12	
8,000	.0260	.0335	.0389	.0332	.000219	2	26	12	
10,000	.0361	.0433	.0497	.0429	.000286	2	30	12	
11,000	.0409	.0491	.0549	.0482	.000322	2	34	12	
12,000	.0463	.0533	.0603	.0537	.000356	2	38	13	
13,000	.0521	.0585	.0656	.0589	.000392	2	44	13	
14,000	.0562	.0633	.0708	.0648	.000425	2	49	13	
15,000	.0614	.0683	.0762	.0692	.000458	3	00	13	
16,000	.0662	.0728	.0809	.0739	.000489	3	11	13	
17,000	.0712	.0778	.0861	.0794	.000524	3	19	13	
18,000	.0757	.0825	.0911	.0840	.000555	3	23	13	3-inch stroke.
19,000	.0810	.0876	.0965	.0891	.000590	3	26	13	
20,000	.0856	.0924	.1013	.0939	.000622	3	30	13	
21,000	.0910	.0982	.1082	.1008	.000664	3	34	13	
22,000	.0969	.1061	.1144	.1171	.000724	3	38	13	
23,000	.1040	.1113	.1234	.1159	.000757	3	42	13	Slight cracking.
24,000	.1110	.1190	.1323	.1241	.000811	3	48	13	
25,000	.1196	.1273	.1437	.1349	.000876	3	52	13	Scaling.
26,000	.1272	.1358	.1559	.1453	.000940	3	56	13	
27,000	.1352	.1438	.1688	.1576	.001009	4	02	13	
28,000	.1435	.1533	.1872	.1745	.001097	4	11	13	
29,000	.1495	.1595	.2168	.2020	.001213	4	22	13	
[Compressometers removed]									
30,000									
30,350									
30,310									Peak for 3-inch stroke, normal speed.
30,270									
30,500									
30,320									Peak for 3-inch stroke, fast speed.
30,160									
29,750									
29,400									

(2) Stress-Strain Curves.—The stress-strain curves for the compressometers and for average readings of the strain gauges at the three positions were plotted for each column, and from them the proportional limit and the "useful limit point" (as defined by the A. S. C. E. committee) were determined and the modulus of elasticity computed. These stress-strain curves were very smooth.

(3) Lateral Deflection.—The lateral deflections, taken at the position *N* (fig. 1) on the web were in all cases very small, even at failure of the column. This was to be expected, because of the larger radius of gyration in this direction. The lateral deflections at the positions *E* and *W* (fig. 1) on the flange were small until the load

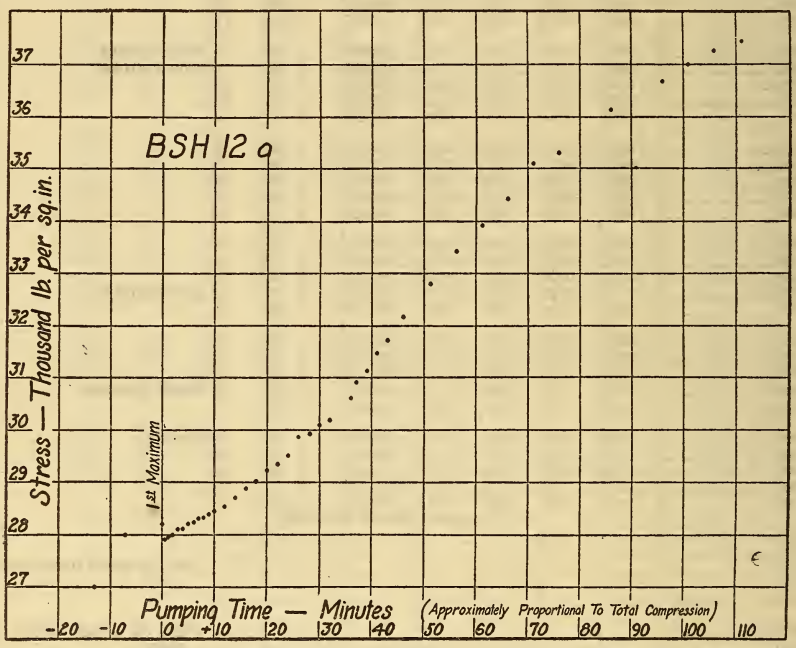

Fig. 8.—*Stress-strain curve of column BSH12a*

approached the maximum. They then increased rapidly up to failure of the column. The curves *E* and *W* of Figure 6 and Figure 7 show how suddenly these curves broke.

The uniformity of the stress-strain curves and the sudden break in the lateral deflection curves showed that the loads on the columns were nearly axial.

(4) Failure of Column BSH12a.—As was explained under "loading and observations," the pump speed was generally increased as the maximum load was approached in order to hasten the completion of the test. On column BSH12a the speed was increased after the stress of 21,000 lbs./in.^{2} had been reached. It was still further increased when the stress of 25,000 lbs./in.^{2} was passed.

The stress gradually increased to a maximum of 28,200 lbs./in.^{2}, fell to 27,900 lbs./in.^{2}, only to increase again almost immediately (see fig. 8). In the belief that the maximum observed was due to some experimental error, the pumping was continued with a constant speed and stroke. Instead of falling off again the stress rose steadily until it reached 37,600 lbs./in.^{2} The weighing beam still showed no signs of dropping, but the column had a lateral deflection of about 3½ inches and the lower head of the machine commenced to slip on its spherical bearing. The test was then discontinued because of the fear lest a sudden slip of the column under the heavy load (over 3,000,000 pounds) might result in injury to the machine.

A study of the test data made it seem clear that the maximum observed at 28,200 lbs./in.^{2} was a real maximum corresponding to those observed in the other columns, and that the subsequent rise of stress was due to the phenomenon of "pick-up" of load or recovery of stability of short columns, which had previously been noted by Lilly [10] and Kármán [11] in small struts. This interpretation was later confirmed by the behavior of columns in the second series, where this phenomenon was more particularly studied. The high stresses obtained after the "pick-up" are not comparable with the stresses involved in the failure of the other columns of the series. For this reason the stress of 28,200 lbs./in.^{2} is used as the column strength in discussing the results.

(5) Failure of Column BSH24b.—The maximum load of column BSH24b was not actually observed, but lay between 24,000 and 25,000 lbs./in.^{2}

(6) Retests.—The retest of the four columns, BSL18a, BSH18b, FSL18c, and FSH18c, in order to produce more pronounced failure gave in all cases practically the same value for the column strength as had been found in the initial test. The results shown in Table 7 are so close to those obtained before that no further comment is necessary. The average of the two tests was used in computing the results.

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[10] See footnote 9, p. 14.

[11] See footnote 8, p. 14.

TABLE 7.—*Summary of column tests (first series)*

Radius of gyration in inches	Slenderness ratio	Specimen	Length	Area	Weight	Column strength	Average column strength	Useful limit point	Average useful limit point
	$\frac{L}{r}$		*Feet*	*Square inches*	*Pounds*	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*
	45.9	FSL12a	12	37.06	1,512	36,550	36,230	29,000	28,800
		FSL12b	12	37.06	1,512	35,810		28,500	
		FSL12c	12	37.55	1,532	36,330		29,000	
3.14	68.8	FSL18a	18	37.32	2,284	32,720	[2] 32,690	28,000	27,800
		FSL18b	18	37.32	2,284	33,230		28,000	
		FSL18c	18	37.32	2,284	32,110		27,500	
		FSL18c [1]	18	37.32	2,284	32,690		----------	
	91.7	FSL24a	24	37.21	3,036	31,580	31,230	28,000	28,000
		FSL24b	24	37.08	3,026	30,930		28,000	
		FSL24c	24	37.45	3,056	31,180		28,000	
	40.4	FSH12a	12	85.34	3,482	37,640	37,000	26,000	25,200
		FSH12b	12	84.85	3,462	36,270		25,000	
		FSH12c	12	85.10	3,472	37,070		24,500	
3.56	60.6	FSH18a	18	86.18	5,274	31,200	[2] 31,110	25,000	25,000
		FSH18b	18	84.87	5,194	30,720		25,000	
		FSH18c	18	85.52	5,234	30,530		25,000	
		FSH18c [1]	18	85.52	5,234	31,980		----------	
	80.8	FSH24a	24	85.25	6,956	32,860	31,300	28,000	26,200
		FSH24b	24	84.14	6,866	30,500		25,500	
		FSH24c	24	84.76	6,916	30,240		25,000	
4.07	70.8	CSL24a	24	39.68	3,238	34,020	34,560	32,000	31,300
		CSL24b	24	39.93	3,258	33,910		30,800	
		CSL24c	24	39.93	3,258	35,760		31,000	
	40.5	BSL12a	12	35.78	1,460	35,000	35,490	32,000	31,300
		BSL12b	12	36.03	1,470	35,640		31,000	
		BSL12c	12	35.42	1,445	35,830		31,000	
3.55	60.8	BSL18a	18	34.64	2,120	36,520	[2] 35,480	31,500	31,300
		BSL18a [1]	18	34.64	2,120	35,050		----------	
		BSL18b	18	35.46	2,170	35,000		32,000	
		BSL18c	18	35.78	2,190	35,350		30,500	
	81.0	BSL24a	24	36.03	2,940	37,860	36,640	33,000	33,300
		BSL24b	24	35.42	2,890	35,260		32,500	
		BSL24c	24	35.91	2,930	36,810		34,500	
	37.8	BSH12a	12	82.84.	3,380	28,200	26,610	23,000	22,200
		BSH12b	12	83.09	3,390	25,760		21,000	
		BSH12c	12	82.84	3,380	25,860		22,500	
3.81	56.7	BSH18a	18	83.01	5,080	26,670	[2] 25,960	20,000	20,700
		BSH18b	18	82.03	5,020	25,210		21,000	
		BSH18b [1]	18	82.03	5,020	25,340		----------	
		BSH18c	18	82.11	5,025	26,710		21,000	
	76.5	BSH24a	24	83.82	6,840	28,440	27,210	25,000	23,300
		BSH24b	24	83.95	6,850	[3] 24,500		21,000	
		BSH24c	24	83.33	6,800	28,680		24,000	

[1] Retests. [2] Average of test and retest used in computing average. [3] See remarks on p. 31.

(7) GENERAL SUMMARY TABLES AND CURVES.—The final results of the compression tests on these columns are given in Table 7. In the previous investigation on steel columns, referred to in the Introduction,[12] the special committee of the American Society of Civil Engineers defined the "useful limit point" as "the point which is determined graphically by drawing a line tangent to the envelope of

[12] See footnote 1, p. 3.

the stress-strain curve, having a slope of one-half that of the last run-up line for its straight or nearly straight portion." They found a marked relationship between the "useful limit point" found from the column test and that found from the tensile test. In this investigation, the "useful limit point" was not found for the coupon specimens, but it has been determined from each of the column tests and the average results are also given in Table 7 for reference and com-

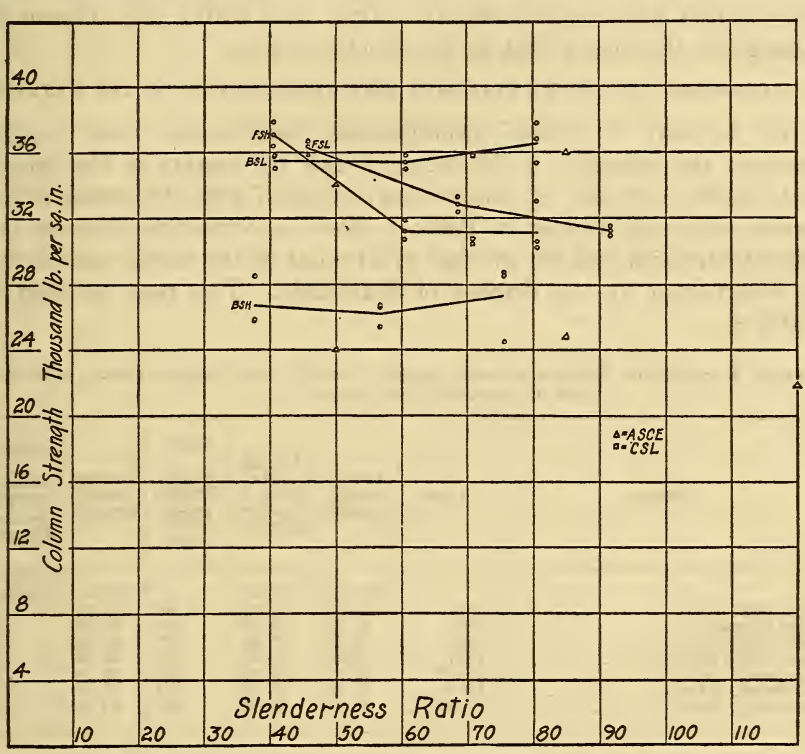

FIG. 9.—*Column strengths and slenderness ratio first series and selected A. S. C. E. tests*

FSH=Fabricated heavy
FSL=Fabricated light
BSH=Solid rolled heavy
BSL=Solid rolled light

parison with the average column strengths. The values of the computed column strength; that is, the maximum load divided by the cross section area, are shown in Figure 9, plotted against the slenderness ratios of the columns. On the same chart, for comparison, are plotted the results of the A. S. C. E.[13] tests for selected solid rolled columns of similar type (Types 5, 5A, and 5B) but smaller cross sectional area.

[13] See footnote 1, p. 3.

4. INTERPRETATION OF THE RESULTS

(a) COMPARISON OF COLUMN STRENGTH WITH SLENDERNESS RATIO

The plotted points show no regularity, indicating that other factors are more important than the slenderness ratio in determining the strength of these columns. Supposedly duplicate columns give widely different values. The fabricated sections (FSL and FSH) show the expected decrease of strength with increasing length, but the 14-inch solid rolled columns (BSL and BSH) are apparently stronger in the longer than in the shorter lengths.

(b) COMPARISON OF COLUMN STRENGTH WITH TENSILE TESTS ON THE MATERIAL

To account for these discrepancies, correlations were sought between the strength of the columns and the results of the tensile tests on the coupons. A comparison of Table 7 with the results of the tensile tests summarized in Table 4 shows a correlation between the column strength and the average yield point of the tensile specimens, as determined by the Bureau of Standards. This may be seen in Table 8.

TABLE 8.—*Relation between average column strengths and average results of tensile tests on coupons (first series)*

Column	Type	Average column strength	Average yield point of tensile specimen	Ratio $\frac{\text{column strength}}{\text{tensile yield point}}$	Average tensile strength	Ratio $\frac{\text{column strength}}{\text{tensile strength}}$
		Lbs./in.²	*Lbs./in.²*		*Lbs./in.²*	*Lbs./in.²*
Light, solid rolled	BSL	35,840	40,470	0.386	64,090	0.559
Light fabricated	FSL	33,400	39,300	.850	63,300	.528
Heavy fabricated	BSH	33,070	37,900	.873	61,600	.537
Heavy, solid rolled	FSH	26,630	31,910	.835	59,780	.445
Fabricated, 12-foot	FS-12	36,615	39,700	.923	64,200	.520
Fabricated, 18-foot	FS-18	31,905	37,600	.849	62,100	.514
Fabricated, 24-foot	FS-24	31,185	38,700	.806	60,400	.516

The average yield point of the material and the comparative constancy of the ratio of column strength to yield point (maximum difference, 5.8 per cent) for the wide variation of column strength (maximum difference, 25.7 per cent) clearly indicates the close correlation of the yield point of the material with the strength of the columns.

Moreover, the strengths of the fabricated columns (FSH) show an unexpected drop for the 18-foot columns $\left(\frac{L}{r}=60.6, \text{ fig. } 9\right)$ which is accompanied by a lower average yield point as shown by Table 8. The channel columns form an apparent exception, having a lower average column strength and a higher average yield point than the light, solid rolled columns. The exception disappears, however, when the comparison is confined to the most nearly comparable 24-foot columns.

Table 8 shows that the average tensile strengths in the different groups of columns are also in the same order as the column strength. This suggests a correlation between column strength and tensile strength of the material. A closer examination of the data, however,

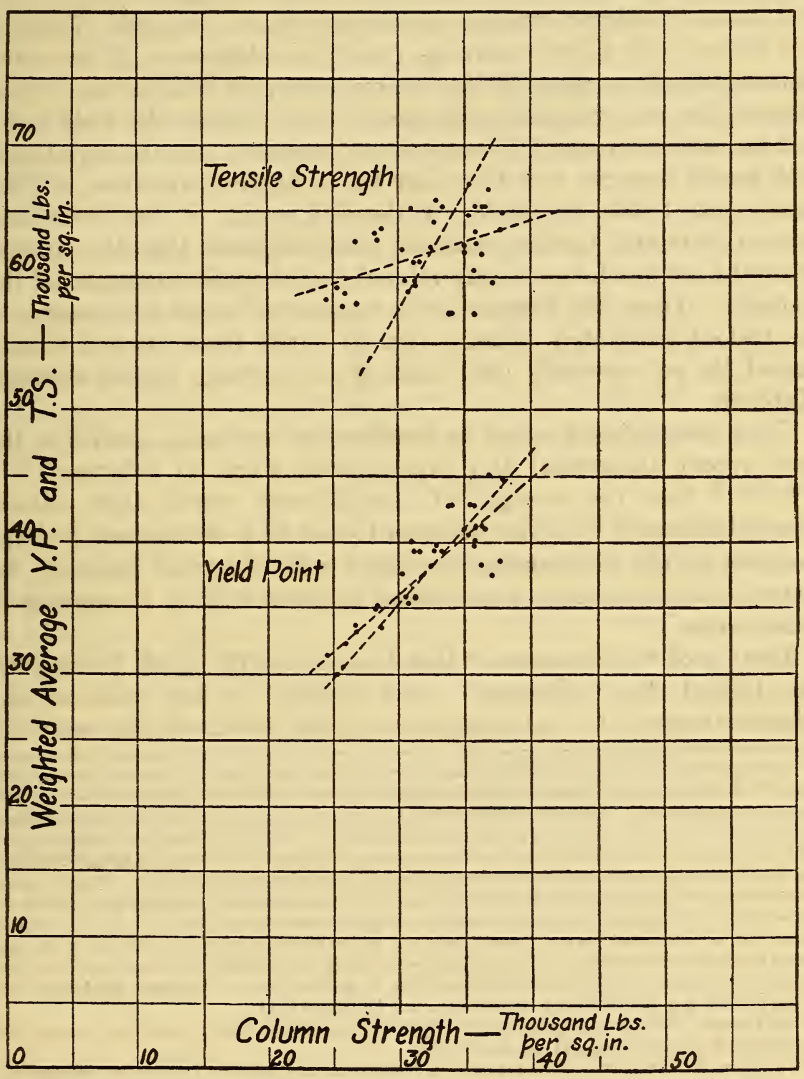

Fig. 10.—*Correlation between column strengths and results of tensile tests on coupons (first series)*

Dotted lines are regression lines

shows that the correlation with tensile strengths is much less close than with the tensile yield point. This may be seen from Figure 10, in which the weighted average yield points and tensile strengths of the individual columns are plotted against the corresponding column

strength. The narrow band of points plotted for yield point, indicating a close correlation, is in marked contrast to the broader scatter of the points plotted for tensile strength. The correlation coefficient [14] of column strength with yield point calculated from these values is 0.87, while that with tensile strength is only 0.43. The ratios of column strength to average tensile strength (Table 8) also show much wider variations (maximum difference, 22 per cent) almost as large as those of the column strengths themselves. Since there is also a correlation coefficient of 0.45 between the yield point and the tensile strength, it seemed very probable that the correlation with tensile strength was due solely to the higher correlation of yield point with tensile strength. A detailed study of the individual column tests still further confirms the conclusion that the column strengths are much less closely related to the tensile strengths of the material. Thus, for instance, the unexpected drop in strength of the 18-foot fabricated columns (fig. 9) noted above, is not accompanied by an especially low value of the average tensile strength (Table 8).

These comparisons served to confirm the conclusion, drawn in the more recent theoretical and experimental work on columns [15, 16, 17, 18, 19, 20, 21, 22] that the strength of a sufficiently sturdy steel column whose slenderness ratio lies between 40 and 90 is determined in large measure by the phenomena associated with the yield point of the material in compression, and in small measure only by its manner of construction.

Because of the closeness of this dependence W. C. M. Pettingill [23] has defined the "efficiency" of a column as the ratio of the column strength to the compressive yield point of the material.

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[14] Where two series of observed quantities show a partial dependence of one upon the other, so that high values of the one are on the average accompanied by high (or low) values of the other and vice versa, they are said to be correlated. The correlation coefficient is a numerical measure of this correlation computed by standard methods from the pairs of corresponding quantities. In the limiting case where one quantity is completely determined by the other the correlation coefficient is 1 (or −1). In the other limiting case where the two quantities are wholly independent the correlation coefficient is zero. The nearer the value of the correlation coefficient approaches to 1 (or −1) the more closely is the one quantity determined by the other. For method of computing correlation coefficients see, for example, G. U. Yule, "An introduction to the theory of statistics," London; 1912. A briefer presentation with application to an engineering problem may be found in "Correlation between tensile and bending tests of cast iron," by Winslow Herschel, Technology Monthly and Harvard Eng. Jl., **2**, Nos. 7 and 8. February and March; 1916.

[15] See footnote 2, p. 3; footnote 6, p. 7; footnote 7, p. 9; footnote, 8 p. 14.

[16] Fr. Engesser, Die Knickfestigkeit gerader Stäbe, Zts. des hannov. Ing. u. Arch. Ver., p. 445, 1889; Centralblatt d. Bauverwaltung, **11**, pp. 483–486; 1891.

[17] Considere, Résistance des pièces comprimées, Congrès International des procédés de construction, Paris, p. 371; 1891.

[18] Jasinsky, Zu den knickfragen Schweiz bauzeitung, **25**, p. 172; 1895.

[19] James E. Howard, Notes on tests of steel columns in progress at Watertown Arsenal, Proc. A. S. C. E., **9**, pp. 413–417; 1909.

[20] R. V. Southwell, The strength of struts, Eng., **94**, pp. 249–250; 1912.

[21] R. V. Southwell, The strength of struts, Progress in theory and experiment during the war, Aircraft Eng., **1**, pp. 44–45; 1920.

[22] Fr. Voss, Prüfung von Druckstäben für Brücken des Kaiser-Wilhelm-Kanals, Der Bauingenieur, **3**, pp. 8–11; 1922.

[23] R. V. Southwell, The strength of struts, Aircraft Eng., **1**, pp. 136–138; 1920.

The "yield point" of a material even when its stress-strain curve shows a practically horizontal portion is a somewhat arbitrarily defined stress,[24] the numerical value assigned to it being within rather wide limits dependent upon the shape and size of the test specimen, the type of testing machine, and especially the speed of testing. In addition, with comparable test conditions different values are obtained in tension and compression.

However, with closely comparable test conditions differences in the numerical value assigned by a test to the yield point, either in tension or compression, do furnish a measure of differences in the inelastic yielding of the material.

The analysis of the data was, therefore, planned to compare the column strengths with the tensile yield point of the material as shown by the coupon tests (the compressive yield point not having been determined), using as a basis their ratio, the "efficiency" of the column. Because it has been suggested that there is a relation between column strength and tensile strength of the material, the same computations have been carried through for tensile strength as for yield point and are presented in the tables and figures for comparison.

(c) AREA WEIGHTING

In comparing in detail the column strength with yield point it was felt that the unweighted average yield points of Table 4 did not give as close a representation of the average properties of the material as could be obtained from a weighted average. The area of the section which was represented by each tensile coupon seemed to be a rational basis for assigning weights. Accordingly, the yield points of the materials entering into the fabricated columns were weighted by their corresponding nominal areas, the tensile test specimens from each heat number being assumed to be representative of corresponding material of the same heat number. The results are tabulated in Table 9, columns 4 and 7.

[24] A. S. T. M. Tentative definitions of terms relating to methods of testing, E. 6–23 T.

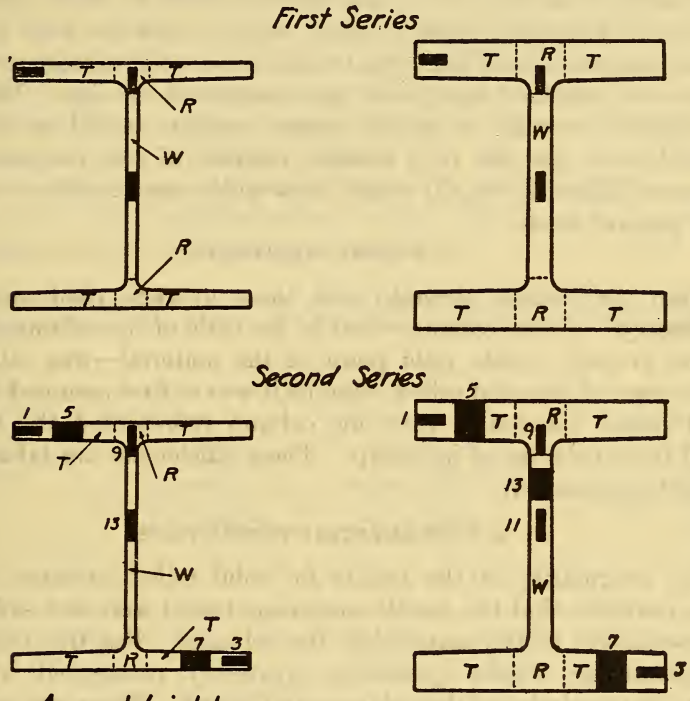
TABLE 9.—*Column efficiency, ratio of column strength to weighted average tensile yield point (and also tensile strength)*

FIRST SERIES

Column	$\frac{L}{r}$	Column strength	Weighted average tensile strength	Ratio $\frac{C.S.}{T.S.}$	Average	Corrected: Weighted average yield point	Corrected: Efficiency	Corrected: Average	Uncorrected: Weighted average yield point [1]	Uncorrected: Efficiency	Uncorrected: Average
1	2	3	4	5	6	7	8	9	10	11	12
		Lbs./in.²	*Lbs./in.²*			*Lbs./in.²*			*Lbs./in.²*		
BSL12 a	40.5	35,000	61,800	0.566	0.576	40,620	0.862	0.876	(41,120)	0.851	0.863
BSL12 b	40.5	35,640	60,440	.590		39,780	.896		(41,120)	.867	
BSL12 c	40.5	35,830	62,530	.573		41,120	.871		41,120	.871	
BSL18 a	60.8	35,790	63,430	.564	.558	40,100	.893	.874	(40,510)	.883	.873
BSL18 b	60.8	35,000	62,310	.562		40,890	.856		(40,510)	.864	
BSL18 c	60.8	35,350	64,630	.547		40,510	.873		40,510	.873	
BSL24 a	81.0	37,860	64,910	.583	.554	44,840	.844	.828	(42,860)	.883	.855
BSL24 b	81.0	35,260	67,000	.526		42,860	.823		42,860	.823	
BSL24 c	81.0	36,810	66,560	.553		45,090	.816		(42,860)	.859	
BSH12 a	37.8	28,200	63,350	.445	.444	34,900	.808	.818	(32,300)	.873	.824
BSH12 b	37.8	25,760	57,820	.446		30,490	.845		(32,300)	.798	
BSH12 c	37.8	25,860	58,820	.440		32,300	.801		32,300	.801	
BSH18 a	56.7	26,670	62,710	.425	.438	33,620	.793	.814	(30,000)	.889	.874
BSH18 b	56.7	25,280	59,110	.428		30,000	.843		30,000	.843	
BSH18 c	56.7	26,710	58,070	.460		33,120	.806		(30,000)	.890	
BSH24 a	76.5	28,440	62,970	.452	.441	35,150	.809	.816	35,150	.810	.816
BSH24 b	76.5	24,500	58,330	.420		31,370	.781		31,370	.781	
BSH24 c	76.5	28,680	63,690	.450		33,440	.858		33,440	.858	
						No correction needed					
FSL12 a	45.9	36,550	65,390	.559	.555	40,980	0.892	.882	----------	------	------
FSL12 b	45.9	35,810	65,340	.548		41,060	.872				
FSL12 c	45.9	36,330	65,270	.557		41,190	.882				
FSL18 a	68.8	32,720	64,100	.510	.513	39,290	.833	.843	----------	------	------
FSL18 b	68.8	33,230	65,280	.509		39,290	.846				
FSL18 c	68.8	32,400	62,190	.521		38,110	.850				
FSL24 a	91.7	31,580	61,110	.517	.501	39,270	.804	.790	----------	------	------
FSL24 b	91.7	30,930	65,160	.475		40,030	.773				
FSL24 c	91.7	31,180	61,110	.510		39,270	.794				
FSH12 a	40.4	37,640	63,570	.592	.600	38,570	.976	.972	----------	------	------
FSH12 b	40.4	36,270	61,710	.588		38,230	.949				
FSH12 c	40.4	37,070	59,660	.621		37,450	.990				
FSH18 a	60.6	31,200	59,710	.523	.524	35,700	.874	.872	----------	------	------
FSH18 b	60.6	30,720	58,870	.522		35,300	.870				
FSH18 c	60.6	31,260	59,350	.527		35,840	.872				
FSH24 a	80.8	32,860	65,750	.500	.499	39,760	.826	.827	----------	------	------
FSH24 b	80.8	30,500	59,730	.511		35,890	.850				
FSH24 c	80.8	30,240	62,090	.487		37,610	.804				
CSL24 a	70.8	34,020	57,200	.595	.604	42,800	.795	.808	----------	------	------
CSL24 b	70.8	33,910	57,200	.593		42,800	.792				
CSL24 c	70.8	35,760	57,200	.625		42,800	.836				
A. S. C. E. columns						Corrected					
106 (H8, 62)	50.0	34,000	----------	------	------	40,250	0.845	------	----------	------	------
225 (H8, 90.5)	50.0	24,000	----------	------	------	27,810	.863	------	----------	------	------
114 (H8, 32)	85.0	36,000	----------	------	------	43,670	.824	------	----------	------	------
183 (H8, 90.5)	85.0	24,800	----------	------	------	29,320	.846	------	----------	------	------
181 (H8, 90.5)	120.0	21,800	----------	------	------	31,160	.700	------	----------	------	------

[1] Values in parentheses were obtained from coupons cut from another column of the same group.

For obtaining the weighted average yield point of the solid rolled columns the weights were assigned on the basis of the areas shown in Figure 11. The tensile specimen T was assumed to be representative of the areas marked T, the specimen R of the areas marked R, and the specimen W of the area marked W. The corresponding



Area Weights

	Percent Area T	R	W
ASCE Tests			
H 8,32	64	19	17
H 8,62	65	20	15
H 8,90.5	64	21	15
1st & 2nd Series - Weighting A			
H 14,122.5	67	16	17
H 14,287.5	65	18	17
2nd Series - Weighting B			
H 14,122.5	74	9	17
H 14,287.5	77	7	16

Coupon Weights

Second Series

	Coupon No.	Weighting B 122.5	Weighting B 287.5	Weighting A 122.5	Weighting A 287.5
T	1,3	1/6	1/10	1/2	1/2
	5,7	1/3	2/5	0	0
R	9	1	1	1	1
W	11	—	1/4	—	0
	13	1	3/4	1	1

Fig. 11.—*Area weighting for solid rolled sections*

percentage areas, which were used as weights, are given in the table on Figure 11. This method of weighting is called "weighting A," to distinguish it from the fuller "weighting B" of the second series. The exact value of the weighted average yield point will, of course, vary with these arbitrarily assigned weights. The weights may, however, be varied considerably without producing a significant

difference in the weighted average. For example, varying the area assumed to be represented by R by 50 per cent would not change the weighted average yield point in any case by more than 2 per cent, and in all cases the change would be in the same direction. Several other weightings which were tried gave practically identical results. The justification for the actual figures chosen is—first, that some method of averaging must be used; second, that the basis assumed seems reasonable; and third, that using these weights more consistent results are obtained than with the unweighted average. Using the unweighted average or poorly chosen weights would in effect be equivalent to the use of a smaller number of test coupons. The curves of Figure 13 (p. 43) would show wider scatter without altering their general trend.

(d) COLUMN EFFICIENCIES

From the column strength and these average yield points the "efficiency" of each column—that is, the ratio of the column strength to the average tensile yield point of the material—was calculated. In the case of the solid rolled columns it was at first assumed that the yield points calculated from one column represented the material in all three columns of its group. These efficiencies are tabulated in Table 9, column 11.

(e) SUPPLEMENTARY TENSILE TESTS

The irregularity of the results for solid rolled columns made it seem probable that the tensile specimens tested were not sufficiently representative of the material in the columns. For this reason the supplementary tensile specimens previously mentioned were cut from the remainder of the columns and tested. These coupons were cut from the crop ends of all columns from which coupons had not previously been taken, except the columns BSL18a and BSH18c. No crop ends were available for these columns, and the coupons were cut from the body of the columns at the points of contraflexure. Similar specimens were also cut from the column BSH12a to allow a correction to be made, if necessary, for the effect of the previous strain upon the physical properties of the coupons. No such effect was, however, observed. (See Table 2.)

To study the behavior of the material more carefully, the deformation of these specimens was measured with a Ewing extensometer. This necessitated running the testing machine at a lower speed (0.012 inch per minute) than the speed (0.37 inch per minute) at which the original tests were run. The systematic difference between the yield point by "drop of beam" from these supplementary tests and from the original tensile tests has been noted above.

(f) CORRECTION FOR SYSTEMATIC DIFFERENCE

To correct for this difference the following method was employed: The columns were in sets of three of identical construction. For the columns BSL12, 18, and 24 and BSH12 and 18 tensile specimens from one of each set were tested in the original tests, and from the other two in the supplementary tests. The efficiency of each column was first calculated. The two efficiencies computed from the supplementary tensile tests were then averaged (Table 10, column 10) and divided by the corresponding efficiency computed from the original coupon tests, thus giving the ratio of the supplementary to the original values (Table 10, column 11). The average of these, 1.127, was applied as a correction factor to the weighted average yield points of the supplementary tests. The corrected average yield points are given in Table 9, column 7.

TABLE 10.—*Correction for systematic difference in yield points between original and supplementary coupon tests. No systematic difference in tensile strengths*

FIRST SERIES

Column	Tensile strength			Yield point			Column strength	Efficiency		
	Original	Supplementary	Ratio original to supplementary	Original	Supplementary	Ratio original to supplementary		Original	Supplementary	Ratio original to supplementary
1	2	3	4	5	6	7	8	9	10	11
	Lbs./in.²	*Lbs./in.²*		*Lbs./in.²*	*Lbs./in.²*		*Lbs./in.²*			
BSL12a		61,800			36,020		35,000		97.2	
BSL12b		60,440			35,280		35,640		101.0	
BSL12c	62,530			41,120			35,830	87.2		
Average	62,530	61,120	1.023	41,120	35,650	1.153		87.2	99.1	1.138
BSL18a		63,430			35,560		35,790		100.6	
BSL18b		62,310			36,240		35,000		96.6	
BSL18c	64,630			40,510			35,350	87.3		
Average	64,630	62,870	1.028	40,510	35,900	1.128		87.3	98.6	1.129
BSL24a		64,910			39,780		37,860		95.2	
BSL24b	67,000			42,860			35,260	82.3		
BSL24c		66,560			39,990		36,810		92.1	
Average	67,000	65,740	1.019	42,860	39,890	1.074		82.3	93.6	1.137
BSH12a		63,350			30,950		28,200		91.1	
BSH12b		57,820			27,020		25,760		95.3	
BSH12c	58,820			32,300			25,860	80.1		
Average	58,820	60,590	.971	32,300	28,990	1.114		80.1	93.2	1.163
BSH18a		62,710			29,820		26,670		89.4	
BSH18b	59,110			30,000			25,280	84.3		
BSH18c		58,070			29,390		26,710		91.0	
Average	59,110	60,390	.979	30,000	29,610	1.012		84.3	90.2	1.070
BSH24a	62,970			35,150			28,440	81.0		
BSH24b	58,330			31,370			24,500	78.1		
BSH24c	63,690			33,440			28,680	85.8		
Average	61,660			33,320				81.6		
Average			1.004			1.096				1.127

As a check on the validity of this process, the same correction factor was calculated from the yield points directly (Table 10, column 7). As was to be expected, the individual results of this comparison fluctuated more widely, but the average agreed sufficiently closely (difference 3 per cent) with the results from the efficiencies to show that the method of correction was reasonable.

No such correction was needed for the tensile strengths. The maximum deviation (Table 10, column 4) of the average "supple-

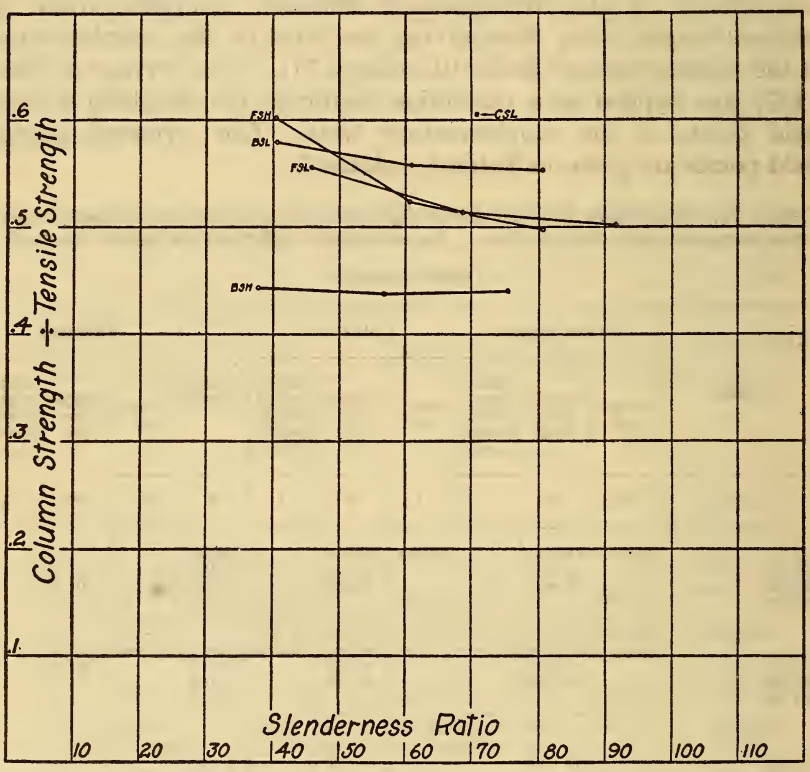


Fig. 12.—*Ratio of column strength to weighted average tensile strength of coupons (first series)*

mentary" from the "original" was less than 3 per cent and the average ratio was 1.004, indicating that there was no appreciable systematic difference in the measured tensile strengths due to the speed of testing.

The use of this correction factor is, of course, not as satisfactory as strictly comparable tests would have been, but in view of the large variations in individual columns of the same structure and length the method of comparison seems justified.

(g) CORRECTED EFFICIENCIES

From these corrected average yield points corrected column efficiencies were calculated for the solid rolled columns. These are tabulated in Table 9, column 8. It is to be noted that although the corrected average yield points give more consistent results and therefore furnish a better means of comparing the tests, all the conclusions could be drawn, although with less accuracy, from the uncorrected efficiencies. The conclusions therefore do not depend

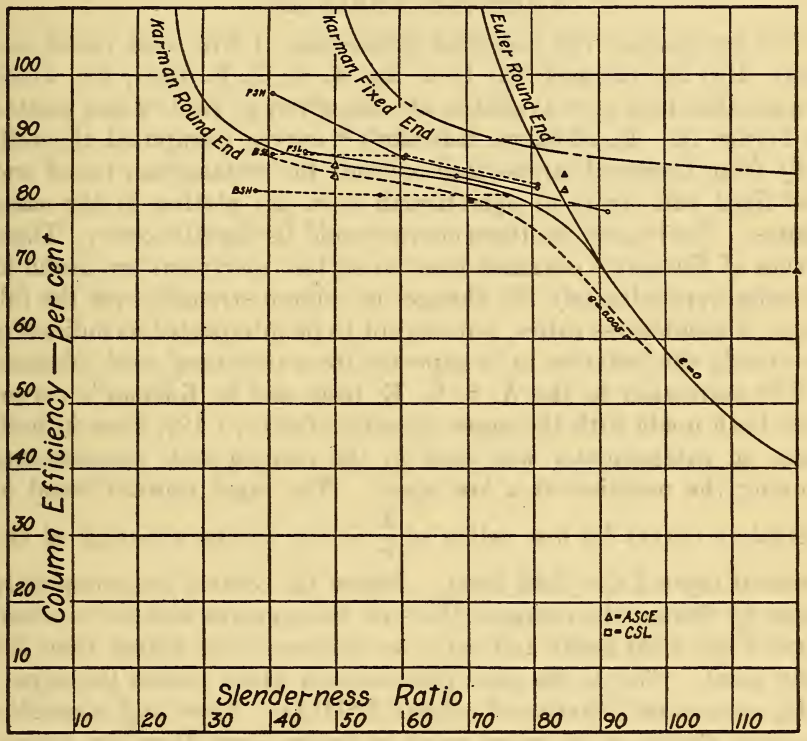


FIG. 13.—*Column efficiency; ratio of column strength to weighted average tensile yeild point of coupons (first series and selected A. S. C. E. tests)*

e=effective eccentricity of load
r=least radius of gyration

for their validity upon the validity of the correction factor used for converting the yield points determined in the supplementary tests to conform with those obtained from the original tests. The average ratio of the column strengths to the weighted average tensile strengths for each group of three similar columns (Table 9, column 6) are plotted in Figure 12 with the slenderness ratios as abscissas. The corrected efficiencies are similarly plotted in Figure 13.

(h) COMPARISON OF CURVES

The ratios of column strength to tensile strength (fig. 12) do not fluctuate so widely as the column strengths (fig. 9), but they are much more discordant than the efficiencies (fig. 13), which, for all the tests, lie within a relatively narrow band. These figures show in another way the close correlation (seen in fig. 10) of column strength with tensile yield point, in contrast to the much lower correlation with tensile strength.

(i) RESULTS OF FORMER TESTS

For comparison the corrected efficiencies of five solid rolled sections (H8; 32, 62, and 92) from the A. S. C. E. tests, for which comparable data were available, are also given in Table 9 and plotted in Figure 13. In addition, Kármán's [25] curves (computed theoretically from observed stress-strain curves) for rectangular, round end and fixed end struts of open-hearth steel are plotted in the same figures. For H sections these curves would lie slightly lower. These curves of Kármán's obtained from small test specimens are useful in showing approximately the changes in column strength over the full range of slenderness ratios, but are not to be interpreted as indicating accurately the behavior to be expected from structural steel columns.

The correction to the A. S. C. E. tests and to Kármán's curves were both made with the same correction factor, 1.127, since in both cases an extensometer was used in the coupon test, necessitating running the machine at a low speed. The rapid upward trend of Kármán's curves for low values of $\frac{L}{r}$ is due to the stressing of the material beyond the yield point. Before the column has completely failed by flexure the extreme fibers on the concave side are strained beyond the yield point and carry an average stress higher than the yield point. This is the same phenomenon which caused the apparently anomalous behavior of column BSH12a. These high strengths can not, therefore, be relied upon in design since they are accompanied by marked deformations and the stability of the column is precarious.

(j) PROBABLE CAUSES OF DISCREPANCIES

All of the average efficiency curves, except those for the thick solid rolled sections BSH and the channel section CSL, lie between the two curves of Kármán.[25] They show excellent agreement with the exception of the 12-foot heavy fabricated sections FSH12 $\left(\frac{L}{r}=45.9\right)$ the heavy solid rolled sections BSH, and the channel

[25] See footnote 8, p. 14.

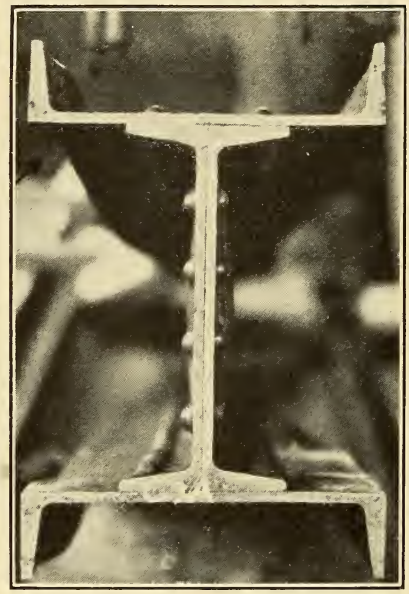


Fig. 14.—*Column CSL24a after test, showing distorted flanges marked by arrow*

sections CSL. The high value obtained for the 12-foot heavy fabricated columns FSH12 may be caused by an underestimation of the yield point due to an insufficient number of coupons, but might also be explained by the fact that in the neighborhood of $\frac{L}{r}=40$ small changes in the effective fixation of the ends may restrain the flexure of the column sufficiently to allow all the material to be stressed beyond the yield point and thus produce large changes in the results due to the rise of the stress-strain curve above the yield point. (See Kármán's curve, fig. 13.)[27] The somewhat lower efficiencies obtained for the heavy solid rolled (BSH) (and, perhaps, also the channel CSL) sections might easily be due to inaccurate estimation of the yield point of the material. Coupons from different portions of the section differed as much as 18 per cent (see, for instance, BSL12c Table 1 and BSH12a and BSH18a Table 2) while coupons from corresponding portions of the section cut at different places along the same column (see, for instance, BSH12a, BSH12a1, and BSH12a2, Table 2) differed as much as 13 per cent in their yield points. Under such circumstances, an average from only three tensile specimens could hardly be expected to give a very accurate determination of the yield point. The low efficiencies of the heavy solid rolled sections may, therefore, be only apparent, due to an overestimation of the yield point upon which the column strength largely depends. This suggestion is rendered more probable by results of the second series of tests (see pp. 77–79) and is further supported by the fact that the thick rolled sections show the largest discrepancies between individual columns. The discrepancy of over 26 per cent between the yield points of the coupons CSL24–T and CSL24–W (Table 1) suggests that a similar explanation may apply to the channel sections. There is, however, not sufficient evidence to assign a definite cause to any of these discrepancies.

(k) SECONDARY FAILURE

None of the columns, except possibly the channel sections (CSL) showed any evidence of secondary or detailed failure of the component parts of the column or of the riveting, and the satisfactory agreement of their efficiencies precludes the possibility that such effects materially affected the results. The slight warping of the unsupported flanges of the channel sections, as seen in Figure 14 suggests that the low efficiency of these columns may be due in part to secondary failure caused by the insufficient thickness of these flanges, although, as mentioned above, an inaccurate determination of the yield point

[27] See footnote 8, p. 14.

of the material may have been a contributing cause. Since only one length of these columns was tested, no definite conclusions can be drawn.

All of the other columns were of sufficiently sturdy design. The webs were amply strong to carry the shear and the webs and flanges were thick enough to prevent their buckling.

VI. SECOND SERIES TESTS

1. FABRICATION OF COLUMNS

The columns of the second series were fabricated in the Steelton shops of the Bethlehem Steel Co., under the inspection of Robert W. Hunt & Co., and then shipped to Bethlehem where the accurate machining in preparation for testing was carried out.

Aside from insuring that the properly numbered pieces were used to fabricate the columns of corresponding number, their inspection was confined to examining the material for defects obvious on visual examination, and to seeing that in fabrication only that care should be used which is common in commercial fabrication to insure that the product would not be rejected.

The inspectors reported that they identified each piece of material entering into the columns and saw that it was put into the proper place in the column during the fabrication.

On the character of the fabrication they reported:

Holes were punched full size.

No drifting was done on most holes, except to drift the angles into their proper position to get good holes during assembling.

Size of rivets was three-fourths inch.

Size of holes was $\frac{13}{16}$ inches.

Rivets were driven hot.

Riveting was done by pressure.

The shop work was good commercial fabrication and no other work was done on the columns at the Steelton plant.

At Bethlehem, the columns were straightened, then the ends were machined to the lengths specified and the holes near the ends, for test purposes, were drilled and tapped. No other work was done on the columns at this plant.

2. COUPONS

A much more elaborate set of coupon tests were made for this series in order to determine more closely the average properties of the material.

After the plates and angles were rolled mill tests were run to see that the material was approximately of the character desired. The material was then laid out. The column material and the test coupons were marked on the plates and before cutting were stamped with identification numbers. A record was kept of the heat number, ingot number, and slab or bloom number as well as the location of the column material and the coupons.

For the solid rolled sections a record was kept of their location in ingot and bloom and the test coupons were marked and stamped on the excess portion of each column before they were cut to length. It was, therefore, possible to relate each portion of the columns directly to the test coupons cut from closely adjacent material. The location of the test coupons and the layout of the columns was chosen to have the test coupons, as nearly as possible, uniformly distributed through the ingot and at the same time uniformly distributed among the columns.

The coupons were located in the sections as shown in Figure 2. The odd-numbered specimens were tested at the Bureau of Standards and the even-numbered by the Bethlehem Steel Co., at Bethlehem, Pa.

3. TEST RESULTS AND DISCUSSION

(a) COUPONS

(1) Chemical Analyses.—Because of the large number of coupons chemical analysis of each coupon would have been needlessly expensive. Accordingly, a selection of material from each heat was given a complete analysis. These tests showed no special alloying elements.

A larger number of specimens was then chosen, distributed over the cross section of the material and from top and bottom of ingot and analyzed for carbon, manganese, silicon, and phosphorus. The results of these tests are given in Table 11. No marked segregation was found. The analysis shows the material to be the ordinary structural material of about 0.20 per cent carbon content. The sulphur and phosphorus are within the limits permitted by the A. S. T. M. specifications. The only marked differences in chemical composition lie in the carbon content which ranges from a minimum of 0.12 per cent for the solid rolled sections *S* to a maximum of 0.30 per cent for the solid rolled sections *H* and in the manganese content which ranges from 0.44 per cent in the plate and angle sections up to 1.00 per cent in the solid rolled sections *H*.

Table 11.—*Chemical analysis of steel (second series)*

Heat No.	Material from—	Identification symbol	Carbon	Manganese	Silicon	Phosphorus	Sulphur
			Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*
29008	6 by 4 by ½ inches angle	2A-FSL24a-1	0.17	0.45	0.02	--------	0.052
		2A-FSL24a-3	.16	.46	--------	--------	.053
		2A-FSL24a-5	.16	.45	--------	--------	.047
		2A-FSL24c-1	.14	.44	--------	--------	.049
		2A-FSL24c-3	.15	.44	--------	--------	.044
		2A-FSL24c-5	.15	.44	--------	--------	.046
	6 by 4 by ⅝ inches angle	1A-FSH12a-1	.16	.46	--------	--------	.050
		1A-FSH12a-3	.16	.46	--------	--------	.047
		1A-FSH12a-5	.14	.45	--------	--------	.047
		4A-FSH18a-1	.16	.46	.02	0.025	.049
		4A-FSH18a-3	.15	.45	--------	--------	.048
		4A-FSH18a-5	.17	.45	.01	.026	.050

TABLE 11.—*Chemical analysis of steel (second series)*—Continued

Heat No.	Material from—	Identification symbol	Carbon	Manganese	Silicon	Phosphorus	Sulphur
			Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*
	5/8-inch plate	1CP-FSH24a-1	0.17	0.48			0.040
		1CP-FSH24a-3	.17	.46			
		2CP-FSH12a-1	.14	.48			.034
		2CP-FSH12a-3	.13	.49			
6050	7/16-inch plate	1CP-FSL24a-1	.15	.44			.041
		1CP-FSL24a-3	.16	.48			
		2CP-FSL12a-1	.17	.49			.037
		2CP-FSL12a-3	.14	.49			
	3/8-inch plate	WP-FSL18a-1	.15	.44			.040
		WP-FSL18a-3	.15	.44			
		WP-FSL24c-1	.14	.48	0.08	0.004	.035
		WP-FSL24c-3	.14	.48			
33088	Bethlehem H-14-122½	BSL18b-1	.17	.67			
		BSL18b-3	.16	.67			
		BSL18b-5	.16	.67			
		BSL18b-7	.16	.68			
		BSL18b-9	.17	.70			
		BSL18b-13	.17	.68			
		BSL24a-1	.17	.68	.04	.007	.033
		BSL24a-3	.17	.68			
		BSL24a-5	.17	.68			
		BSL24a-7	.17	.68			
		BSL24a-9	.12	.65			
		BSL24a-13	.14	.66			.039
26137	Bethlehem H-14-287½	BSH12c-1	.17	.64			
		BSH12c-3	.17	.64			
		BSH12c-5	.16	.63			
		BSH12c-7	.16	.64			
		BSH12c-9	.16	.63	.02	.008	.032
		BSH12c-11	.15	.63			
		BSH12c-13	.16	.63			
		BSH18c-1	.17	.64			
		BSH18c-3	.17	.64			
		BSH18c-5	.18	.64			
		BSH18c-7	.18	.65			
		BSH18c-9	.18	.64			
		BSH18c-11	.19	.65			
		BSH18c-13	.17	.65			
26132		BTH12a-1	.24	.96	.05	.011	.035
		BTH12a-3	.24	1.00			
		BTH12a-5	.24	.96			
		BTH12a-7	.24	.95			
		BTH12a-9	.22	.95			
		BTH12a-11	.23	.95			
		BTH12a-14	.24	.96			
		BTH18a-1	.27	.96			
		BTH18a-3	.30	1.00			
		BTH18a-5	.27	.98			
		BTH18a-7	.29	.99	.05	.009	.036
		BTH18a-9	.22	.95			
		BTH18a-11	.29	.95			

(2) AREA WEIGHTING OF RESULTS OF TENSILE TESTS.—After considering various methods of weighting the values of yield point and tensile strength to obtain an average value for each column, the following method, a modification of that used in the first series, was adopted.

For the fabricated sections the unweighted average from coupons Nos. 1 and 3 for the plate, and Nos. 1, 3, and 5 from the angles (fig. 2) were taken as representing the values for the plate or angle adjacent to the coupons. Since no systematic change of these results was

found along the ingot the average of all the values from the ingot was taken as representing the plates and angles not immediately adjacent to the test coupons. The values for the columns were then obtained by weighting the values for each piece of the column by the nominal area of its section. These averages corresponded almost exactly to the weighted averages used in the first series, the only difference being the larger number of test coupons and the slightly displaced position of the specimen *P3* (or *P4*) (fig. 2).

The solid rolled sections were, as before, divided into the three parts *T*, *R* and *W* (fig. 11 weighting *B*). To each of these was assigned the average of the test specimens falling within each, 1, 3, 5, and 7 in *T*, 9 in *R*, and 11 and 13 (or 13 alone) in *W*. In forming these averages the results from each coupon were given weights approximately proportional to their area. In specimens 1, 3, 9, 10, 11, and 12 the area of the reduced section was about 3/4 square inch; in 5 and 7 about 1½ square inches for the light and about 3 square inches for the heavy columns, and in 13 about 2¼ square inches, which have the same ratios as the weights assigned under "coupon weighting" in Figure 11. It is evident that the weighted averages obtained in this way (weighting *B*) do not correspond exactly to those obtained in the first series from the three specimens, *T*, *R*, and *W* (weighting *A*), corresponding to Nos. 1, 9, and 13 (or No. 11), respectively, but being obtained from a larger number of test specimens weighting *B* should give results nearer to the true average values for the section, than weighting *A*.

The averages for the comparison tests made at Bethlehem were obtained in the same way by the use of the corresponding even numbered coupons.

(3) Reliability of Area Weighting.—A close approximation to the true average values for any section could, of course, only be obtained from test coupons sufficiently numerous to allow reliable interpolation to be made for all portions of the sectional area not included in the area of the coupons. A method of weighting any smaller number of tests which would most closely approximate this value, could only be obtained by a large number of tests on a large number of different sections.

In view of the other unavoidable errors in the tests, it was felt that the small gain in accuracy to be expected from more reliable average values would not be great enough to justify the greatly increased work involved in testing a much larger number of coupons.

(4) Weighted Averages.—Table 12 gives the weighted average results of the coupon tests. The tensile strengths computed from the Bureau of Standards tests agree as closely as could be expected with those computed from the tests made at Bethlehem. The average of the Bureau of Standards tests was 59,160 lbs./in.^{2} and of

the Bethlehem tests slightly higher 60,030 lbs./in.^{2}, a difference of less than 1.5 per cent. For the yield points the agreement was not so close, the average for the Bureau of Standards being 38,450 lbs./in.^{2} and for Bethlehem 37,520 lbs./in.^{2} or 2.6 per cent lower. The systematic difference in yield point determination in the two machines is probably due to the smaller inertia lag in the lighter beam of the hydraulic machine at Bethlehem.

TABLE 12.—*Weighted average results of tensile tests on coupons*

Column		$\frac{L}{r}$	Yield point		Tensile strength	
			Bureau of Standards	Bethlehem	Bureau of Standards	Bethlehem
			Lbs./in.^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}
FSL12	d	45.8	38,110	37,530	57,340	58,010
	e	45.8	38,010	37,980	57,230	57,980
	f	45.8	38,250	36,740	56,890	57,960
FSL24	d	89.8	37,220	37,000	56,720	58,140
	e	89.8	36,300	36,050	56,050	57,800
	f	89.8	36,040	35,670	55,900	57,490
FSH12	d	40.4	33,860	35,030	56,790	57,920
	e	40.4	35,060	35,100	57,310	58,160
	f	40.4	33,570	33,950	56,710	57,760
FSH24	d	79.2	34,060	35,850	57,040	58,440
	e	79.2	34,030	35,780	56,900	58,100
	f	79.2	34,020	34,250	56,830	57,780
BSL12	d	40.5	36,160	34,550	56,660	55,900
	e	40.5	36,970	35,250	57,060	57,050
	f	40.5	38,380	----------	58,020	59,400
BSL24	d	81.0	38,400	37,950	57,480	57,800
	e	81.0	38,040	37,350	58,360	60,850
	f	81.0	37,220	----------	57,130	58,300
BSH12	d	37.8	38,070	36,970	55,810	56,400
	e	37.8	39,450	38,480	59,120	59,020
	f	37.8	40,150	----------	58,340	59,290
BSH24	d	74.0	38,830	37,730	55,720	55,890
	e	74.0	39,060	38,130	57,930	57,700
	f	74.0	39,970	----------	56,000	57,130
BTH12	d	37.8	43,320	41,800	66,800	68,300
	e	37.8	44,810	41,100	66,470	67,000
	f	37.8	43,910	----------	68,090	69,200
BTH24	d	75.6	44,260	42,700	68,160	68,900
	e	75.6	44,080	41,200	67,900	68,500
	f	75.6	43,800	----------	68,000	68,700

For the further computations the results of the tests at the Bureau of Standards were used in order to have all the yield-point determinations as nearly comparable as possible. No significant differences in the results would be found by using the results of the Bethlehem tests.

(b) COLUMNS

(1) SAMPLE LOG SHEETS.—Typical log sheets of the complete tests on two comparable columns FSH12f and BTH12f are given in Table 13 and Table 14.

TABLE 13.—*Log sheet of column FSH12f*

[Area by measurement, 83.1 square inches; corrected area, 83.1 square inches; total weight, 3,440 pounds; weight per foot, 282.7 pounds; weight rivets=48 pounds; total weight less rivets=3,392 pounds; length, 12 feet; r=3.56 inches; $\frac{L}{r}$, 40.4]

Applied stress in pounds per square inch	Total load	Time		Temperature	Overall compressometer readings on testing machine				Plumb bob on testing machine		Compressometer readings—100-inch gauge length					Deflections			Column plumb bobs		Base dials				Remarks
		Begin	End		SE	SW	NW	NE	NW	SE	A	B	C	D	Sum	East	West	Web	W	F	SE	SW	NW	NE	
	Pounds	*p. m.*	*p. m.*	*° F.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	
000	000	12.14	12.23	71½	0.0400	0.0005	0.3390	0.1210	00	00	0.0575	0.0717	0.0688	0.0420	0.2400	2.30	2.25	3.16	00	00	9888	9900	6830	7420	
1,000	83,100	12.26	12.31	71	.0290	.0094	.3610	.1390	00	00	.0588	.0729	.0731	.0449	.2497	2.30	2.25	3.16	00	00	9210	9250	6440	7700	
5,000	415,500	12.35	12.39	71	.0500	.0100	.3870	.1720	1/32 w.	1/32 e.	.0721	.0868	.0878	.0591	.3058	2.30	2.25	3.16	00	00	8650	8620	5920	6200	
10,000	831,000	12.42	12.45	71	.0890	.0490	.4100	.1910	1/32 w.	1/32 e.	.0909	.1049	.1039	.0751	.3748	2.30	2.25	3.16	1/32 e.	1/32 s.	8150	8190	5460	5680	
15,000	1,246,500	12.49	12.52	69	.1200	.0750	.4350	.2200	1/32 w.	1/32 e.	.1073	.1205	.1194	.0931	.4403	2.30	2.25	3.16	1/32 e.	1/32 s.	7700	7760	5005	5200	
20,000	1,662,000	12.55	12.59	71	.1530	.1005	.4650	.2530	1/16 w.	1/16 e.	.1281	.1409	.1398	.1131	.5219	2.30	2.25	3.16	1/32 e.	1/32 s.	7280	7380	4650	4750	
22,000	1,828,200	1.00	1.03	71	.1690	.1200	.4790	.2680	1/16 w.	1/16 e.	.1388	.1507	.1488	.1229	.5612	2.30	2.25	3.16	1/32 e.	1/32 s.	7009	7200	4460	4560	
24,000	1,994,400	1.05	1.09	70½	.1850	.1350	.4950	.2850	1/16 w.	1/16 e.	.1494	.1605	.1592	.1340	.6031	2.30	2.25	3.16	1/32 e.	1/32 s.	6880	7000	4280	4380	
26,000	2,160,600	1.12	1.16	71½	.2005	.1530	.5115	.3003	1/16 w.	1/16 e.	.1622	.1718	.1725	.1470	.6535	2.30	2.25	3.16	1/32 e.	1/32 s.	6630	6790	4113	4150	
28,000	2,326,800	1.18	1.22	71	.2370	.1750	.5350	.3290	1/16 w.	1/16 e.	.1772	.1860	.1878	.1631	.7141	2.30	2.25	3.16	1/32 e.	1/32 s.	6390	6530	3850	3850	
30,000	2,493,000	1.25	1.30	70	.2820	.2300	.5910	.3920	1/16 w.	1/16 e.	.2051	.2069	.2171	.1995	.8286	2.30	2.23	3.15	1/32 e.	1/32 s.	5800	5950	3190	3190	Drifting; strain lines on flanges, bottom, and web.
31,000	2,576,100	1.33	1.37	71	.3920	.3500	.6150	.2300	------	------	.2570	.2500	.3150	.3000	------	2.30	2.23	3.14	------	------	4800	4700	2900	2800	O. G.=out of gauge.
31,010	2,577,000	1.40	------	------	------	------	------	------	------	------	.3194	.2890	.5520	.5208	------	1.90	1.67	3.13	------	------	------	------	------	------	
30,866	2,565,000	1.41	------	------	------	------	------	------	------	------	.3363	.3000	.6270	.5982	------	1.72	1.52	3.11	------	------	------	------	------	------	
30,854	2,564,000	1.42	------	------	------	------	------	------	------	------	.3572	.3150	.7000	.6745	------	1.60	1.40	3.11	------	------	------	------	------	------	
30,854	2,564,000	1.43	------	------	------	------	------	------	------	------	.3822	.3330	.7750	.7542	------	1.50	1.24	3.12	------	------	------	------	------	------	Binding on web.
30,854	2,564,000	1.44	------	------	------	------	------	------	------	------	.4070	.3590	.8450	.8280	------	1.40	1.15	------	------	------	------	------	------	------	
30,854	2,564,000	1.45	------	------	------	------	------	------	------	------	.4380	.3850	------	.8920	------	1.30	1.04	------	------	------	------	------	------	------	
30,866	2,565,000	1.46	------	------	------	------	------	------	------	------	.4710	.4110	------	.9620	------	1.20	.95	------	------	------	------	------	------	------	Deflected to south, 3 inches.
30,878	2,566,000	1.47	------	------	------	------	------	------	------	------	------	------	------	------	------	1.12	.87	------	------	------	------	------	------	------	3-inch bulge on flanges in middle of column.
36,927	2,570,000	1.48	------	------	------	------	------	------	------	------	------	------	------	------	------	1.03	.78	------	------	------	------	------	------	------	
30,963	2,573,000	1.49	------	------	------	------	------	------	------	------	------	------	------	------	------	.95	.70	------	------	------	------	------	------	------	
31,023	2,578,000	1.50	------	------	------	------	------	------	------	------	------	------	------	------	------	.87	.60	------	------	------	------	------	------	------	
31,083	2,583,000	1.51	------	------	------	------	------	------	------	------	------	------	------	------	------	.78	.50	------	------	------	------	------	------	------	
31,227	2,595,000	1.52	------	------	------	------	------	------	------	------	------	------	------	------	------	.67	.46	------	------	------	------	------	------	------	
31,384	2,608,000	1.53	------	------	------	------	------	------	------	------	------	------	------	------	------	.59	.33	------	------	------	------	------	------	------	
31,492	2,617,000	1.54	------	------	------	------	------	------	------	------	------	------	------	------	------	.48	.28	------	------	------	------	------	------	------	
31,546	2,621,500	1.55	------	------	------	------	------	------	------	------	------	------	------	------	------	.36	.14	------	------	------	------	------	------	------	
31,288	2,600,000	1.56	------	------	------	------	------	------	------	------	------	------	------	------	------	.18	.05	------	------	------	------	------	------	------	
30,409	2,527,000	1.57	------	------	------	------	------	------	------	------	------	------	------	------	------	.04	.20	------	------	------	------	------	------	------	
28,941	2,405,000	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	

TABLE 13.—*Log sheet of column FSH12f*—Continued

Applied stress in pounds per square inch	Time		Temperature	Bottom 8-inch strain gauge No. 17488					Middle 8-inch strain gauge No. 10774					Top 8-inch strain gauge No. 12123					Standard bar			Remarks
	Begin	End		No. 1	No. 2	No. 3	No. 4	No. 5	No. 1	No. 2	No. 3	No. 4	No. 5	No. 1	No. 2	No. 3	No. 4	No. 5	No. 17488	No. 10774	No. 12123	
	p. m.	*p. m.*	°*F.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	
000	12.14	12.23	71½	0.1355	0.1270	0.1336	0.1186	0.1266	0.0500	0.0665	0.0850	0.0875	0.0940	0.0652	0.0780	0.1129	0.1552	0.1385	0.1200	0.0830	0.1010	
1,000	12.26	12.31	71	.1365	.1289	.1340	.1200	.1301	.0510	.0680	.0915	.0895	.0940	.0672	.0780	.1238	.1552	.1390	.1200	.0830	.1010	
5,000	12.35	12.39	71	.1390	.1328	.1397	.1270	.1310	.0560	.0702	.0930	.0870	.0984	.0733	.0836	.1255	.1610	.1438	.1200	.0830	.1010	
10,000	12.42	12.45	71	.1490	.1411	.1448	.1350	.1381	.0631	.0805	.1000	.1025	.1185	.0810	.0925	.1332	.1702	.1492	.1200	.0830	.1008	
15,000	12.49	12.52	69	.1585	.1481	.1547	.1430	.1460	.0702	.0830	.1055	.1105	.1172	.0862	.1022	.1442	.1770	.1562	.1200	.0830	.1010	
20,000	12.55	12.59	71	.1675	.1584	.1625	.1520	.1522	.0784	.0948	.1170	.1183	.1250	.0970	.1112	.1512	.1853	.1606	.1200	.0830	.1010	
22,000	1.00	1.03	71	.1712	.1622	.1667	.1562	.1568	.0824	.0970	.1175	.1244	.1290	.1018	.1130	.1545	.1918	.1659	.1200	.0830	.1008	
24,000	1.05	1.09	70½	.1754	.1678	.1709	.1611	.1602	.0863	.1002	.1220	.1262	.1325	.1062	.1174	.1600	.1975	.1642	.1200	.0830	.1008	
26,000	1.12	1.16	71½	.1811	.1744	.1770	.1675	.1679	.0910	.1046	.1288	.1310	.1389	.1138	.1248	.1674	.2042	.1730	.1200	.0830	.1008	
28,000	1.18	1.22	71	.1920	.1841	.1841	.1771	.1750	.0966	.1075	.1319	.1364	.1448	.1220	.1366	.1775	.2020	.1782	.1200	.0830	.1010	
30,000	1.25	1.30	70	.2250	.2200	.2131	.2105	.2220	.1080	.1120	.1433	.1505	.1536	.1605	.1990	.2280	.2545	.2570	.1200	.0830	.1010	
31,000	1.33	1.37	71	O. G.	O. G.	.2450	.2340	O. G.	.1182	.1120	.2330	.2350	O. G.	.2722	O. G.	.2720	O. G.	O. G.	.1200	.0830	.1010	

TABLE 14.—*Log sheet of column BSH12d*

[Area, 84.5 square inches; corrected area, 83.8 square inches; total weight, 3,420 pounds; weight per foot, 285 pounds; length, 12 feet 0 inches; r=3.81 inches; $\frac{L}{r}$, 37.8]

Applied stress in pounds per square inch	Total load	Time		Temperature	Overall compressometer readings on testing machine				Machine plumb bob		Compressometer readings 100-inch gauge length					Deflections			Column plumb bobs		Base dials				Remarks
		Begin	End		SE.	SW.	NW.	NE.	NW.	SE.	A	B	C	D	Total	East	West	Web	W	F	SE.	SW.	NW	NE.	
	Pounds	*p. m.*	*p. m.*	°*F.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	
000	000	12.37	12.45	71	0.0003	0.1120	0.2420	0.1120	00	00	0.0670	0.0404	0.1410	0.0984	0.3468	2.84	2.28	2.50	00	00	0.5890	0.7114	0.6820	0.8170	
1,000	83,800	12.48	12.53	70	.0002	.1007	.2440	.1290	$\frac{1}{32}$ w.	$\frac{1}{32}$ e.	.0686	.0402	.1420	.1009	.3517	2.84	2.28	2.50	00	00	.5850	.7450	.6410	.8460	
5,000	419,000	12.55	1.01	70½	.0220	.1220	.2690	.1570	$\frac{1}{16}$n.w.	$\frac{1}{16}$s.e.	.0820	.0526	.1554	.1152	.4052	2.84	2.28	2.50	00	00	.4800	.6900	.5900	.7980	
10,000	838,000	1.03	1.08	71	.0540	.1610	.2930	.1720	$\frac{1}{16}$n,w.	$\frac{1}{16}$s.e.	.1000	.0708	.1720	.1305	.4733	2.84	2.28	2.50	00	00	.4350	.4450	.4460	.6500	
15,000	1,257,000	1.11	1.16	71½	.0890	.1910	.3200	.1960	$\frac{1}{16}$n.w.	$\frac{1}{16}$s.e.	.1171	.0885	.1890	.1471	.5417	2.84	2.28	2.50	00	00	.3925	.4002	.4005	.6003	
20,000	1,676,000	1.18	1.23	71¼	.1120	.2200	.3470	.2240	$\frac{1}{16}$n.w.	$\frac{1}{16}$s.e.	.1350	.1058	.2062	.1645	.6115	2.84	2.28	2.50	00	00	.3540	.3640	.3650	.5650	
22,000	1,843,600	1.24	1.28	71½	.1240	.2310	.3590	.2360	$\frac{1}{16}$n.w.	$\frac{1}{16}$s.e.	.1421	.1132	.2141	.1715	.6409	2.84	2.28	2.50	00	00	.3400	.3500	.3510	.4500	
24,000	2,011,200	1.31	1.35	71½	.1360	.2430	.3740	.2490	⅛n.w.	⅛s.e.	.1493	.1209	.2222	.1796	.6720	2.84	2.28	2.50	00	00	.3240	.3350	.3550	.4340	
26,000	2,178,800	1.37	1.42	71½	.1490	.2560	.3810	.2630	⅛n.w.	⅛s.e.	.1570	.1290	.2312	.1875	.7047	2.83	2.29	2.50	00	00	.3007	.3119	.3170	.4150	
28,000	2,346,400	1.46	1.50	72	.1630	.2690	.4001	.2700	⅛n.w.	⅛s.e.	.1665	.1384	.2424	.1969	.7442	2.83	2.29	2.50	00	00	.2880	.3000	.2997	.3860	
30,000	2,514,000	1.52	1.57	71¾	.1810	.2850	.4119	.2890	⅛n.w.	⅛s.e.	.1769	.1500	.2539	.2081	.7889	2.82	2.29	2.50	00	00	.2670	.2810	.2770	.3650	Strain lines web and flanges.
31,000	2,597,800	1.59	2.03	71½	.1910	.2940	.4300	.3000	⅛n.w.	⅛s.e.	.1829	.1580	.2615	.2168	.8192	2.82	2.30	2.50	00	00	.2550	.2690	.2620	.3520	Drifting under load.
32,000	2,681,600	2.05	2.08	72	.2004	.3005	.4420	.3170	⅛n.w.	⅛s.e.	.1919	.1669	.2692	.2251	.8531	2.81	2.30	2.50	$\frac{1}{32}$ e.	00	.2420	.2580	.2490	.3350	Strain lines on flanges and web diagonal.
33,000	2,765,400	2.11	2.15	72	.2240	.3230	.4620	.3410	⅛n.w.	⅛s.e.	.2065	.1811	.2813	.2418	.9107	2.80	2.30	2.50	$\frac{1}{32}$ e.	00	.2200	.2470	.2270	.3006	
34,000	2,849,200	2.17	2.20	72	.2700	.3660	-----	-----	-----	-----	.2444	.2080	-----	-----	-----	2.80	2.31	2.44	-----	-----	.1670	.1900	-----	-----	
33,508	2,808,000	2.25	-----	-----	-----	-----	-----	-----	-----	-----	.2449	.2330	.2965	.2642	-----	2.80	2.33	2.15	-----	-----	-----	-----	-----	-----	
33,473	2,805,000	2.26	-----	-----	-----	-----	-----	-----	-----	-----	.3182	.2350	.2958	.3410	-----	2.80	2.35	2.04	-----	-----	-----	-----	-----	-----	
33,437	2,802,000	2.27	-----	-----	-----	-----	-----	-----	-----	-----	.4100	.2400	.2955	.4290	-----	2.80	2.35	1.92	-----	-----	-----	-----	-----	-----	
33,413	2,800,000	2.28	-----	-----	-----	-----	-----	-----	-----	-----	.5040	.5330	.2955	.5210	-----	2.80	2.36	1.80	-----	-----	-----	-----	-----	-----	
33,425	2,801,000	2.29	-----	-----	-----	-----	-----	-----	-----	-----	.6000	.5710	.2955	.6210	-----	2.80	2.37	1.65	-----	-----	-----	-----	-----	-----	
33,449	2,803,000	2.30	-----	-----	-----	-----	-----	-----	-----	-----	-----	.3050	.3020	.7220	-----	2.78	2.37	1.50	-----	-----	-----	-----	-----	-----	
33,461	2,804,000	2.31	-----	-----	-----	-----	-----	-----	-----	-----	-----	.3350	.3150	-----	-----	2.76	-----	1.40	-----	-----	-----	-----	-----	-----	West wire binding.
33,556	2,812,000	2.32	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	2.74	-----	1.25	-----	-----	-----	-----	-----	-----	
33,592	2,815,000	2.33	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	2.73	-----	1.15	-----	-----	-----	-----	-----	-----	
33,675	2,822,000	2.34	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	2.71	-----	1.05	-----	-----	-----	-----	-----	-----	

TABLE 14.—*Log sheet of column BSH12d*—Continued

Applied stress in pounds per square inch	Total load	Time		Temperature	Overall compressometer readings on testing machine				Machine plumb bob		Compressometer readings 100-inch-gauge length					Deflections			Column plumb bobs		Base dials				Remarks
		Begin	End		SE.	SW.	NW.	NE.	NW.	SE.	A	B	C	D	Total	East	West	Web	W	F	SE.	SW.	NW.	NE.	
	Pounds	*p. m.*	*p. m.*	*°F.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	
33,747	2,828,000	2.35														2.70		0.95							
33,831	2,835,000	2.36														2.68		.81							
33,938	2,844,000	2.37														2.63		.71							
34,129	2,860,000	2.38														2.61		.59							
34,391	2,882,000	2.39														2.57		.42							
34,666	2,905,000	2.40														2.51		.24							
34,952	2,929,000	2.41														2.45		.09							
35,322	2,960,000	2.42														2.38		.07							
35,483	2,973,500	2.43														2.29		−.03							Washer found touching bottom platen.
35,859	3,005,000	2.44														2.20		−.05							
36,026	3,019,000	2.45														2.10		+.25							
36,253	3,038,000	2.46														1.94		.26							
36,408	3,051,000	2.47														1.82		.20							
36,516	3,060,000	2.48														1.63		.20							
36,539	3,062,000	2.49														1.48		.16							
36,551	3,063,000	2.50														1.28		.15							
36,551	3,063,000	2.51														1.10									Web binding.
36,587	3,066,000	2.52														0.92									
36,635	3,070,000	2.53														0.70									
36,706	3,076,000	2.54														0.52									
36,838	3,087,000	2.55														0.35									
36,897	3,092,000	2.56														0.18									
36,969	3,098,000	2.57														0.00									
37,076	3,107,000	2.58														−0.12									
37,112	3,110,000	2.59														−0.30									
37,160	3,114,000	3.00														−0.50									
37,196	3,117,000	3.01														−0.70									
37,196	3,117,000	3.02														−1.00									
37,172	3,115,000	3.03														−1.30									
37,112	3,110,000	3.04														−1.60									
37,029	3,103,000	3.05														−2.00									
36,909	3,093,000	3.06														−2.30									
36,730	3,078,000	3.07														−2.65									
36,516	3,060,000	3.08														−3.00									

TABLE 14.—*Log sheet of column BSH12d*—Continued

Applied stress in pounds per square inch	Time		Temperature	Bottom 8-inch strain gauge No. 11488					Middle 8-inch strain gauge No. 10774					Top 8-inch strain gauge No. 12123					Standard bar			Remarks
	Begin	End		No. 1	No. 2	No. 3	No. 4	No. 5	No. 1	No. 2	No. 3	No. 4	No. 5	No. 1	No. 2	No. 3	No. 4	No. 5	No. 17488	No. 10774	No. 12123	
	p. m.	*p. m.*	°*F.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	*In.*	
000	12.37	12.45	71	0.1812	0.1870	0.1654	0.1585	0.1080	0.1305	0.0825	0.0588	0.0535	0.0910	0.0921	0.0974	0.1678	0.1202	0.1702	0.1800	0.0830	0.1328	
1,000	12.48	12.53	70	.1828	.1882	.1610	.1550	.1085	.1315	.0840	.0595	.0550	.0865	.0928	.0976	.1690	.1226	.1702	.1801	.0830	.1325	
5,000	12.55	1.01	70½	.1885	.1938	.1690	.1640	.1161	.1325	.0892	.0665	.0595	.0920	.1002	.1038	.1769	.1276	.1741	.1800	.0830	.1322	
10,000	1.03	1.08	71	.1962	.2011	.1821	.1636	.1219	.1405	.0980	.0755	.0665	.1081	.1086	.1114	.1818	.1357	.1745	.1800	.0830	.1325	
15,000	1.11	1.16	71½	.2032	.2088	.1876	.1735	.1310	.1455	.1045	.0830	.0726	.1250	.1157	.1200	.1915	.1439	.1892	.1800	.0830	.1322	
20,000	1.18	1.23	71¼	.2106	.2118	.1959	.1790	.1380	.1495	.1120	.0905	.0816	.1365	.1230	.1262	.1991	.1512	.1973	.1800	.0830	.1321	
22,000	1.24	1.28	71½	.2138	.2222	.1976	.1842	.1420	.1562	.1162	.0900	.0846	.1378	.1254	.1307	.2031	.1542	.1992	.1800	.0830	.1321	
24,000	1.31	1.35	71½	.2170	.2246	.2020	.1865	.1431	.1602	.1198	.0935	.0865	.1418	.1291	.1347	.2049	.1576	.2001	.1800	.0830	.1324	
26,000	1.37	1.42	71½	.2216	.2275	.2049	.1924	.1455	.1598	.1245	.1000	.0907	.1450	.1349	.1372	.2104	.1616	.2034	.1800	.0830	.1322	
28,000	1.46	1.50	72	.2280	.2304	.2119	.1952	.1496	.1635	.1298	.1098	.0970	.1535	.1428	.1412	.2168	.1676	.2071	.1800	.0830	.1321	
30,000	1.52	1.57	71¾	.2238	.2329	.2198	.2000	.1532	.1672	.1355	.1085	.1038	.1440	.1517	.1470	.2278	.1731	.2169	.1799	.0830	.1323	
31,000	1.59	2.03	71½	.2380	.2347	.2215	.2057	.1565	.1690	.1405	.1075	.1096	.1520	.1554	.1500	.2278	.1755	.2218	.1800	.0830	.1323	
32,000	2.05	2.08	72	.2448	.2368	.2300	.2101	.1622	.1732	.1448	.1130	.1165	.1590	.1580	.1538	.2288	.1798	.2241	.1800	.0830	.1321	
33,000	2.11	2.15	72	.2550	.2411	.2393	.2180	.1660	.1795	.1508	.1206	.1180	.1620	.1655	.1577	.2408	.1874	.2252	.1800	.0830	.1321	
34,000	2.17	2.20	72	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	

(2) Stress-Strain Curves.—From these log sheets the stress-strain curves for the compressometers and for average readings of

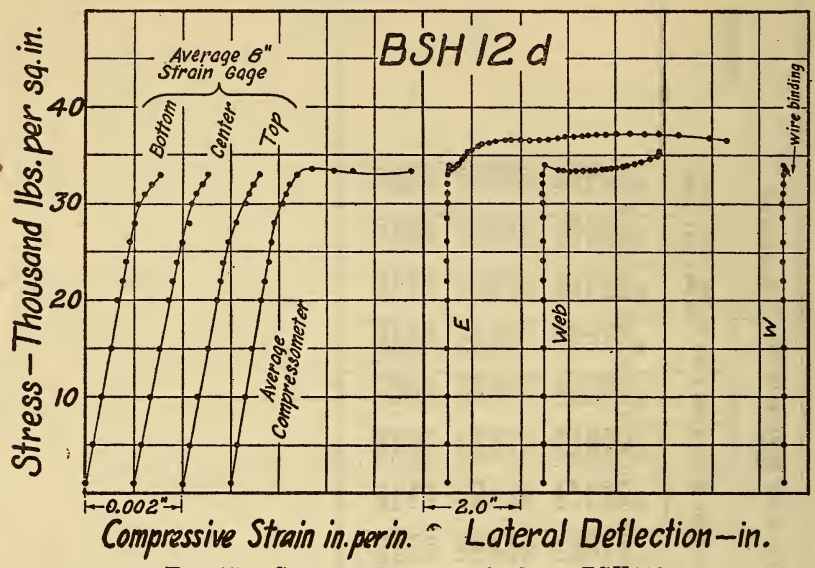


Fig. 15.—*Stress-strain curves of column FSH12f*

For location of gauges see Figure 1

the strain gauges at the three positions were plotted, and from them the elastic properties of the column were obtained. The curves

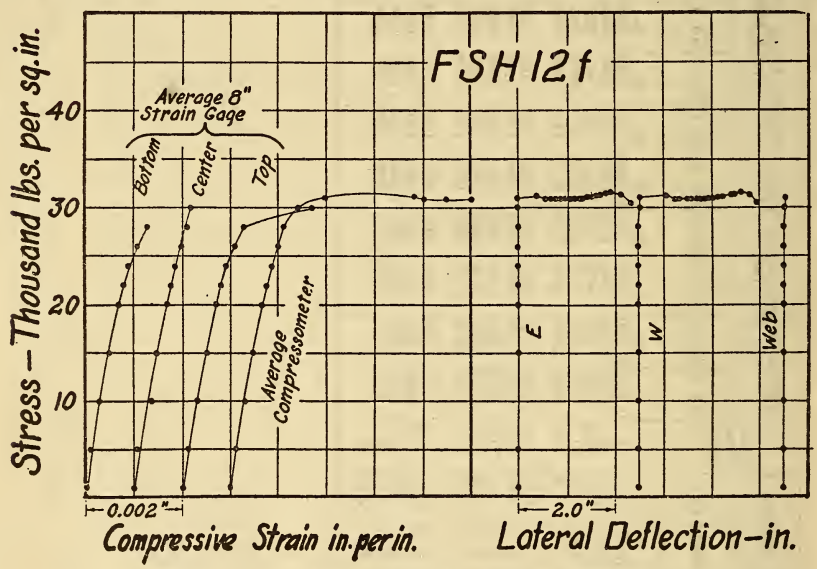


Fig. 16.—*Stress-strain curves of column BSH12d*

For location of gauges see Figure 1

from Table 13 and Table 14 are shown in Figures 15 and 16. As in the first series, these curves below the first maximum were smooth.

(3) "Pick-up" and "Hang-on" of Load.—As was mentioned in the introduction, the behavior of one of the columns (BSH12a, fig. 8 and p. 30) in the first series led to particular attention being directed to the behavior of the columns after the first maximum stress. Shortly after the maximum was passed, the lateral deflections of the column became so great that the compressometers and strain gauges ceased to function. However, since the pump was run at a constant speed, the pumping time was roughly proportional to the total axial shortening of the column, so that it could be used as a measure of the deformation. From comparison with the few compressometer readings obtained, a rough check on the constants could be made. For the lighter columns the speed of the overall compression after the column began to yield was about 0.1 inch per minute, but for the heavier only about 0.07 inch per minute. In Figure 17 are plotted curves showing the change of stress with pumping time for all the columns, from shortly before the first maximum until the end of the test. For some of the columns (for example, BTH12d and FSH12f) there was a marked "pick-up" of load. After the first maximum was passed the load fell at first rapidly and then more slowly, finally rising again to a second maximum, which in some cases was higher and in some cases lower than the first maximum.

In some cases (see, for instance, FSH12d and BSL12d) while there was no "pick-up" of stress there was a definite "hang-on" of load. After the first rapid decrease, the load remained for some time nearly constant or fell only slowly, finally falling rapidly when the "hang-on" ceased. A comparison of the three curves FSH12f, e, and d or the three curves BSL12f, e, and d, show that this "hang-on" is of the same nature as the "pick-up," but less pronounced. In each set of three columns, the curves are arranged in the order of the length of "pick-up" or "hang-on."

The following explanation based on the theoretical discussions and tests of Considère, Kármán, Lilly, and Southwell[28] seems to account for the behavior of all the columns in this respect.

When a column has passed its first maximum stress and commenced to show marked flexure, two opposing effects may determine its later behavior. First: Some of the material may be stressed beyond the yield point up to points on the second rising portion of the stress-strain curve. These higher stresses would be reached, first, on the concave sides of the flexed column, so that not only would the resistance of the column be increased, but the center of resistance would be shifted toward the concave side lessening the effective eccentricity of the applied load. This effect would tend to increase the load which the column will carry. Second, as the flexure increases, the moment arm of the applied load increases so that the stresses on

[28] See footnote 17, p. 36; footnote 8, p. 14; footnote 9, p. 14; footnote 20, p. 36.

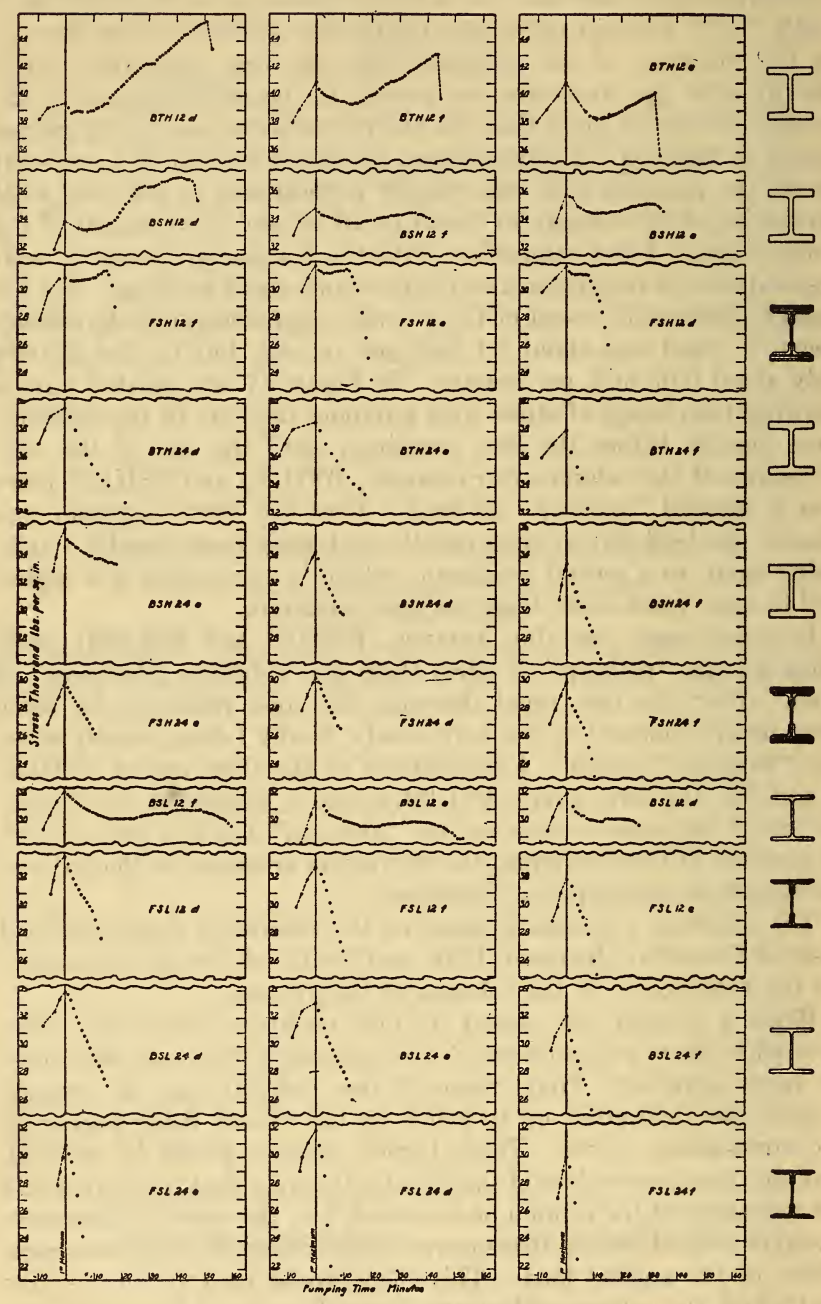


FIG. 17.—*"Pick-up" and "hang-on" of stress*

Pumping time approximately proportional to overall compression of column (second series)

the concave side increase more rapidly than the load. This effect would tend to decrease the load which the column will carry.

The behavior of the column would depend upon the relative magnitude of these two effects. The second effect should be the greater—the longer, the lighter, and the more eccentric the column, whether the effective eccentricity be due to inhomogeneity of the material, curvature of the column axis or other asymmetries of the column or eccentricity of application of the load. Consistent with this interpretation, we find the most rapid decrease of load after the maximum in the longest and lightest columns. (As in the columns FSL24, d, e, and f, see fig. 17.) With shorter or heavier columns the decrease of load is less rapid, changing to a pronounced hang-on (as in the columns BSL12d or FSH12d) or actual pick-up (as in the column BSL12f) until in the shortest and heaviest columns (as in the columns BTH12, d, e, and f) the pick-up is pronounced. For still shorter or heavier or more nearly axially loaded columns, there might even be no actual decrease of load, but merely a slower rate of increase of load as the yield point of the material was passed. Effects of all these three kinds were observed by Kármán [29] in his tests of small columns. The column (BSH12a) in the first series, whose behavior (see fig. 8) directed attention to these phenomena, showed only a slight minimum before the pick-up and was evidently near the limit at which no minimum of load would appear. There will be, then, a range of slenderness and column construction within which one test might show a definite first maximum stress with small deformation followed by a small drop and a large pick-up, while a duplicate column might show a steadily increasing stress up to collapse at a high "first maximum stress" under large deformations. For columns in this range the "first maximum stress" would lose value as a criterion of column behavior. The "first maximum" might occur either near the yield point where the column still is relatively stable, or far above any safe stress where the stability is highly precarious and the column is likely to collapse under small changes of end conditions. It seems probable that some part at least of the discrepancies found in early column tests may have been due to this fact.

Some other criterion depending on the slope of the stress deformation curve would have to be found in order to make a reasonable comparison. The best criterion could only be determined by a series of tests on columns in this range, in which the stress deformation curves were carefully determined.

Also consistent with this interpretation is the double curvature shown by practically all of these curves of Figure 17, beyond the first maximum, first concave upward and then concave downward,

[29] See footnote 8, p. 14.

following roughly the changes in curvature of the stress-strain curve of ductile materials of this type. The exceptions to this are either columns which were so light or so slender as to show practically no hang-on (FSL12f and FSL12e) or columns for which the tests were stopped before downward curvature had begun (BTH12f and BTH12e).

The amount of hang-on or pick-up observed in the different columns was limited by different effects. The sudden drop in the last load observed in the three columns BTH12, was due to a sudden shift in the lower head of the testing machine. In each of these the lateral deflection of the center was more than 2 inches and the friction of the spherical bearing of the lower head of the testing machine was not sufficient to hold it in place against the bending moment of the column. In these columns the maximum stresses observed do not represent the maximum stresses the column would have carried if the lower head had been fixed. A similar shift of the platen of the testing machine caused the sudden drop of the last load observed in the column BSH12d. In this column, however, the second maximum load had already been passed with the column still stable in the testing machine.

In the fabricated columns secondary crumpling of the flanges of the cover plates (see fig. 26, p. 72), although not noticeable at the first maximum load, was distinctly observed shortly after the first maximum was passed. From then on the crumpling increased rapidly. The sharp downward turn near the end of the curves for the three columns FSH12 was apparently due to this secondary effect. To the same effect is apparently due the relatively steeper drop of curves in the fabricated compared with the corresponding solid rolled columns.

As the flexure of the columns became pronounced, one end of the flanges lifted from the testing machine, the lift increasing with increasing lateral deflection. This lift was greatest in the shortest and heaviest columns (fig. 18) in some cases being so great that more than half the area of the flanges and the whole of the web was lifted from the platen, the load being carried on less than half the area of the ends. The resulting shift in the center of application of the load diminished the bending moment at the center of the column but increased it toward the end, which may, in part, account for the points of contraflexure appearing so near the ends of the columns (see, for example, fig. 3) instead of near the quarter points, which would be their position in a fixed end Euler column. This lift of the ends emphasizes the fact frequently pointed out, that tests with flat ends must not be interpretated as tests of "fixed end" columns. It must not be inferred, however, that these columns would have carried appreciably greater loads if their ends had been "fixed."

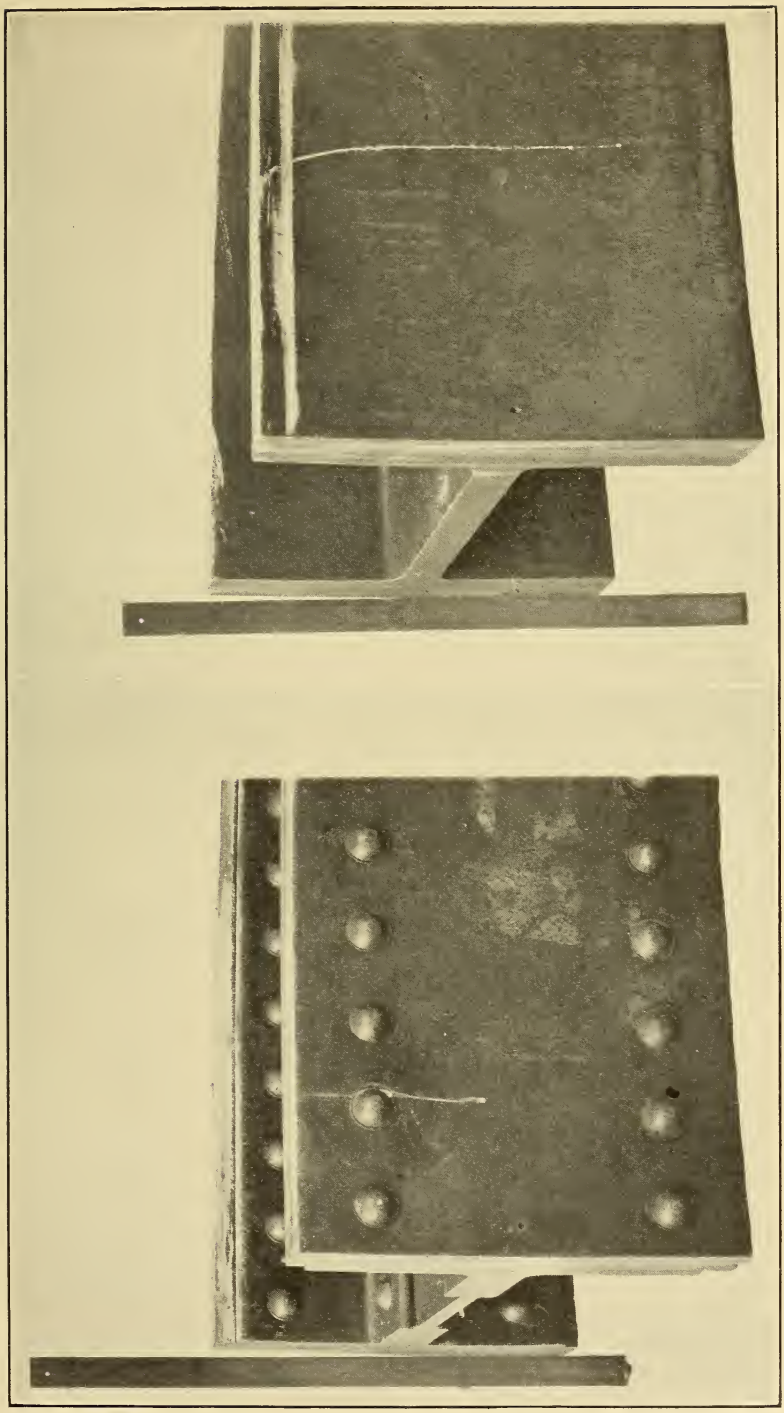


Fig. 18.—*Lift of ends of columns FSH12f and BSH12e from base of testing machine. Straight edge in contact where the column end bore on the platen of the testing machine*

As no great difference in any of the effects just mentioned was observed between the three columns of any one set, the difference in behavior between any three of a set was probably caused by differences in effective eccentricity of the loading of the columns.

The three columns of any one set were as nearly identical in material, dimensions, construction, and conditions of test as was practicable. These differences in effective eccentricities of loading must then have been due to minor uncontrollable differences in the columns, such as small inhomogeneities in the material, minor asymmetries of shape, and slight differences in the application of load.

The differences in the columns which produced these large changes in the phenomena of pick-up or hang-on which occur after the first maximum load was passed had only slight effect upon the value of the first maximum itself. Thus, for example, in the columns BTH12 although the second maxima differ by 12 per cent the first maxima differ by less than 4 per cent. The contrast is even more marked if we correct, by calculating the efficiency, for the yield point of the material as determined by the tensile coupon tests. The difference in the first maxima is reduced to 2.7 per cent while that of the second maxima is increased to 15.4 per cent.

It is, of course, impossible to say just how great the discrepancy between the second maxima would have been if the slipping of the lower head of the testing machine had not prevented carrying the test further. However, the course of the corresponding curves for the columns BSH12 makes it seem probable that greater differences rather than less would have been found.

In addition, the columns of this group showing the greatest pick-up (column BTH12d) and greatest second maximum showed the lowest first maximum and lowest efficiency of the group. Theoretically, the conditions (homogeneity of material, symmetry of shape and accurate centering of load) which should cause the larger pick-up in a group of identical columns should also result in a higher value of the first maximum load. Evidently, for this particular group of three, this expected increase of the first maximum load was so small as to be masked by other differences. If the effect is appreciable, however, it should appear in the average from a sufficiently large number of columns.

Averaging the first maximum load for all the columns appearing in the first, second, and third columns of Figure 17, we find that 33,890, 33,850, and 33,480 lbs./in.^{2}, respectively, the difference between first and third being 1.2 per cent. Averaging similarly the efficiencies, we find 0.884, 0.876, and 0.874, respectively, the difference between first and third being 1.1 per cent. Differences in the first maxima due to effective eccentricities seem then to be appreciable in these

tests, but small, of the order of 1 per cent as contrasted with differences of the order of 10 to 15 per cent in the second maxima, where they occur.

These second maximum values represent a state of very precarious stability of the columns. They are reached only when the columns are already badly deformed and very small changes in the columns or the test conditions may suddenly make them unstable. This was particularly noticeable in the columns BTH (fig. 18) which showed the highest second maxima. These second maxima can not, therefore, furnish any reliable measure of safety of a column in practice.

On the other hand, the practically definite first maximum stress, occurring before any appreciable lateral deflection of the column, and fairly reproducible when the column material and test conditions are reproduced should furnish a good measure of the strength of the column in practical use. This justifies the practice followed in this report of recording the first maximum stress observed in a column test as the "column strength" under the given test conditions. However, as was previously pointed out, this would not be justified in case no maximum were observed before the column was badly deformed.

(4) Lateral Deflection.—In discussing lateral deflection it is convenient to distinguish between "normal" and "anomalous" directions of deflections. A lateral deflection parallel to the flanges measured at E or W (fig. 1) on the flanges of the column represents a flexure of the column about the axis of the least moment of inertia. Euler's theory, based on purely elastic action under axial load, indicates that flexure in this direction will grow to large values before any flexure about the perpendicular axis becomes appreciable. This direction parallel to the flanges we shall call the "normal" direction of lateral deflection and the direction of deflections perpendicular to this, measured parallel to the web at N (fig. 1) on the web, which according to Euler's theory should not become noticeable, we shall call the "anomalous" direction of lateral deflection.

In all the columns at low loads the deflections were in the normal direction (fig. 19), but as the first maximum load was approached "anomalous" deflections appeared in about one-third of the columns. Four types of the further progress of the lateral deflection were observed. These are illustrated in the path diagrams [30] of Figures 18 and 19, Figure 18 showing the earlier stages to a larger scale. In the first type of deflection, that shown by the majority of the columns (see BSH12e figs. 19 and 20) the deflection continued in the normal direction until the column collapsed. In the other three types the direction of deflection changed abruptly as the first maximum load was approached. In the second type (BTH12e, figs. 19 and 20) the change of direction was roughly 45°, and from the first maximum to final collapse of the column the lateral deflection continued to

[30] The utility of these diagrams in studying lateral deflections of columns was pointed out by Basquin in B. S. Tech. Paper No. 263, p. 423.

increase both in the normal and the anomalous directions by roughly equal amounts. In the third type (BSH24e, figs. 19 and 20) the change of direction was approximately 90°. After the change of direction the deflection in the normal direction increased but slowly while the deflection in the anomalous direction increased rapidly to the final collapse of the column. In the fourth type (BTH12d and

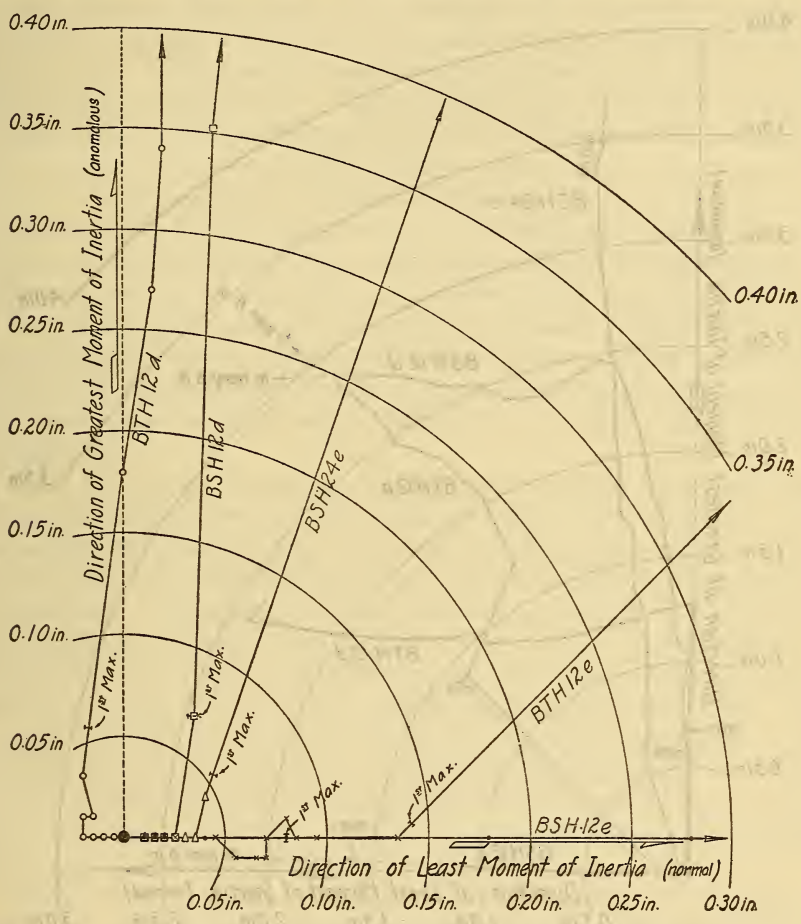


FIG. 19.—*Beginning of anomalous lateral deflection*
The same as central portion of Figure 20 on larger scale (second series)

BSH12d, figs. 19 and 20) the deflection changed direction as in the third type, but after the load had passed the minimum and had commenced to pick-up, there was another abrupt change of 90°. The deflection in the anomalous direction ceased to increase while that in the normal direction again increased rapidly till the final collapse of the column.

The small decrease of deflection shown in the anomalous direction was probably only apparent, as the method of measuring lateral deflection was free from systematic error only for small deflections.

The lateral deflections in the anomalous direction were evidently associated with the phenomenon of pick-up. In all cases in which the lateral deflection in the anomalous direction amounted to as

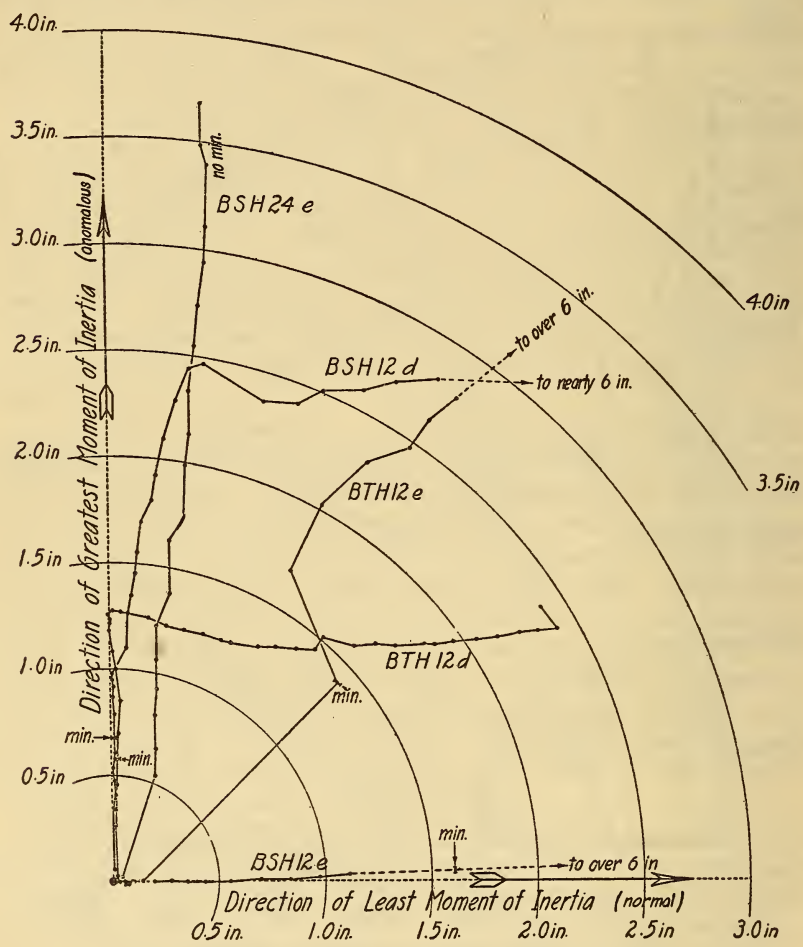


Fig. 20.—*Anomalous lateral deflection (second series)*

much as one-third of that in the normal direction, the column of each set of three which showed the greatest pick-up (see fig. 17) showed the greatest ratios of deflection in the anomalous direction to that in the normal. Further, the three columns (BTH12d and f and BSH12d) which showed the fourth type of lateral deflection with two changes

of direction each practically at 90°, were the three columns which showed the highest pick-up of all the columns tested.

All of these observations are in accord with the double modulus theory of column action proposed by Considère, developed and tested experimentally by Kármán, and later independently proposed by Southwell.[31]

According to this theory the resistance of a column to lateral bending is not only a function of the radius of gyration of the section but also of a "shape factor" depending on the actual distribution of the material in the section.[32] Applying the theory to these H sections, it follows that under some conditions the critical stress for flexure in the anomalous direction will be slightly (probably not more than 2 or 3 per cent) less than the critical stress for flexure in the normal direction. The difference, however, is only small and a slight eccentricity in the normal direction might be sufficient to overcome the difference and cause the column to deflect in the normal direction. If this theory adequately represents the phenomena, deflection in the anomalous direction is more likely to occur in the columns with lower eccentricity which, in turn, would be expected to show greater pick-up. The association between lateral deflection and pick-up should then be expected.

When the pick-up has progressed far enough so that the stress rises above the first maximum load, which was the critical stress for the anomalous deflection, it may reach the slightly higher critical stress for deflection in the normal direction, thus producing the second shift of direction. Accordingly, it was found that in the columns BTH12d and BSH12d the stress (41,850 and 37,200 lbs./in.^{2}, respectively) at which the second 90° change takes place was higher than the first maximum stress (39,410 and 34,000 lbs./in.^{2}, respectively). For the column BTH12f the stress (40,010 lbs./in.^{2}) at the second turn was slightly lower than the first maximum (41,010 lbs./in.^{2}), but this column had by that time also deflected over 0.3 inch in the normal direction which would have lowered considerably the critical stress for flexure in this direction.

Basquin[32] was unable to account for the anomalous deflections which he studied in the A. S. C. E. and A. R. E. A. tests by the use of Kármán's theory and concluded that they were due to accidental eccentricities in the columns.

The anomalous deflections observed in the present series of tests, however, are clearly of a different kind from those discussed by Basquin. In those tests more sensitive means were used for detecting lateral deflection than in the present tests and the deflections

[31] See footnote 17, p. 36; footnote 8, p. 14; footnote 20, p. 36.
[32] See footnote 3, p. 3.

were not observed beyond the first maximum load where they were still less than 0.10 inch in magnitude. Further, in the A. S. C. E. and A. R. E. A. tests no large deflections in the anomalous direction were noted by Basquin for columns whose principal radii of gyration had a ratio greater than 1.65. In this series the ratio ranged from 1.74 for the columns, B – L – to 2.01 for the columns, F – H –. It is probable that if more sensitive instruments had been used small deflections of the order of 0.005 inch in the anomalous direction comparable to some of those observed in the A. S. C. E. tests might also have been observed in this series. If the explanation of the anomalous lateral deflection of the kind observed in the present tests

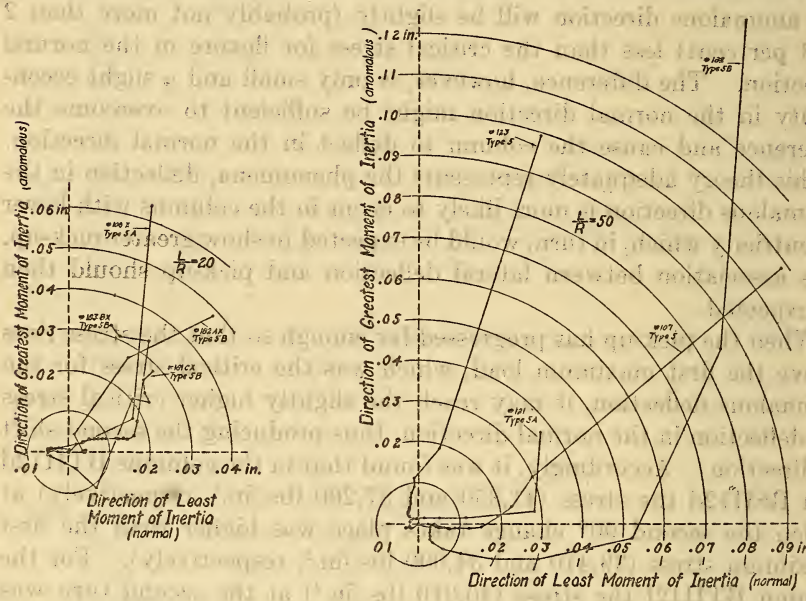


FIG. 21.—*Anomalous lateral deflection of A. S. C. E. columns, types 5(H8,32), 5A(H8,62), and 5B(H8,90.5)* $\frac{L}{r}$ *20 and 50*

is correct, they should not be expected to occur in the columns of slenderness ratio 85 and 120 studied by Basquin, but rather in the columns of $\frac{L}{r}=50$ or the special supplementary columns of $\frac{L}{r}=20$. For this reason the test records of the most nearly comparable columns in the A. S. C. E. series (5, 5A, and 5B) of $\frac{L}{r}=50$ and 20, were examined. Figure 21 shows the lateral deflection curves of eight of these columns which showed appreciable deflections in the anomalous direction. A comparison of these curves with those of Figure 19 will show their general similarity. In each there is, in general, the small slowly progressing deflection in the normal direction followed by an abrupt change and rapid deflection in the anomalous direction.

As the loading in the A. S. C. E. tests was stopped almost immediately after the maximum load was reached, no definite statement can be made, but it seems certain that if the loading of the A. S. C. E. columns of $\frac{L}{r}=50$ and 20 had been carried further, anomalous deflections would have been found fully comparable with those observed in the present series.

The conclusion that the anomalous deflections of these columns was due to the difference in the neighborhood of the yield point between the tangent modulus [34] of steel undergoing further deformation and that undergoing a decrease of deformation, which is characteristic of the Considère-Kármán theory, would have been further strengthened had marked decrease of strain been observed in the 8-inch gauge lines on the convex side of the columns. Consistent curves showing this effect have been reported by Whittemore,[35] but in the present series of tests the rapid increase of deformation made consistent reading on the gauges impossible shortly before the first maximum stress was reached. The stress-strain curves on the convex side showed the same upward curvature found by Whittemore, but only two gauge lines, Nos. 3 and 4 on the bottom of column BSH12e, actually showed a decrease of strain. It is probable, however, that decrease of strain occurred on the convex side of all the columns as the first maximum load was passed.

(5) Secondary Failure.—In no case was there any indication of secondary failure until after the first maximum load had been passed. The lateral deflections at the first maximum were in all cases small and no crumpling, warping, or other evidence of failure of the flange, or web was visible until the load had fallen considerably below the maximum, so that if the tests had been stopped (as in the first series) shortly after the first maximum load was passed no evidence of secondary failure would have been found. However, as was noted under the discussion of "pick-up," after the first maximum load was passed, secondary crumpling of the flanges of some of the columns began and increased rapidly until final failure of the column affecting materially the "pick-up" or "hang-on" of load. This never occurred, however, before the load had fallen considerably, with marked lateral deflection.

The columns, then, were all of sufficiently sturdy design. The webs were amply strong to carry the shear and the flanges were thick enough to prevent weakening of the column by secondary buckling.

[34] The tangent modulus is the slope of the tangent to the stress-strain curves. Below the proportional limit it beomes identical with the ordinary modulus of elasticity. See Basquin loc. cit.

[35] H. L. Whittemore, "Compressive Tests of Steel-Built I-Columns" Tests of Metals, Watertown Arsenal, 1912, pp. 85–106.

(6) General Summary Tables and Curves.—The results of the column tests are given in Table 15. In this table the correction factor 0.956 was applied to the columns noted. Because of the possible uncertainty in the extrapolation of the calibration curve (see p.10) the uncorrected values are given in Table 16 for comparison. The weighted average yield point and tensile strength used were those determined from the Bureau of Standards tests (Table 12, columns 3 and 5).

Table 15.—*General summary of column tests (second series)*

Column		$\frac{L}{r}$	Column strength first maximum stress	Minimum stress	Second maximum stress	Final stress	Ratio column strength / tensile strength	Average ratio	Efficiency	Average efficiency
			Lbs./in.²	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*				
FSL12	d	45.8	33,680	----------	----------	27,780	0.587	0.575	0.884	0.862
	e	45.8	32,000	----------	----------	25,200	.559		.842	
	f	45.8	32,890	----------	----------	26,260	.578		.860	
FSL24	d	89.8	31,910	----------	----------	22,120	.563	.551	.857	.847
	e	89.8	30,950	----------	----------	21,540	.552		.853	
	f	89.8	30,000	----------	----------	22,630	.537		.832	
FSH12	d	40.4	31,830	----------	----------	24,450	.561	.555	.940	.924
	e	40.4	31,820	31,380	31,650	23,780	.557		.908	
	f	40.4	31,010	30,850	31,550	28,940	.547		.924	
FSH24	d	79.2	30,320	----------	----------	26,700	.532	.529	.890	.885
	e	79.2	30,000	----------	----------	26,340	.527		.882	
	f	79.2	30,000	----------	----------	23,210	.528		.882	
BSL12 [1]	d	40.5	32,120	30,100	30,430	29,830	.567	.558	.888	.860
	e	40.5	31,500	29,730	30,050	28,370	.552		.853	
	f	40.5	32,180	30,320	30,940	29,790	.554		.839	
BSL24 [1]	d	81.0	31,960	----------	----------	25,050	.556	.538	.832	.819
	e	81.0	31,060	----------	----------	24,030	.532		.817	
	f	81.0	30,120	----------	----------	23,300	.527		.809	
BSH12	d	37.8	34,000	33,410	37,200	36,520	.609	.606	.893	.892
	e	37.8	35,980	34,690	35,370	34,810	.609		.912	
	f	37.8	35,000	33,960	34,630	34,080	.600		.872	
BSH24	d	74.0	34,370	----------	----------	29,890	.617	.613	.885	.883
	e	74.0	36,000	----------	----------	33,510	.621		.922	
	f	74.0	33,600	----------	----------	26,700	.600		.841	
BTH12 [1]	d	37.8	39,410	38,691	45,439	43,484	.590	.603	.910	.920
	e	37.8	41,010	37,623	40,288	35,641	.617		.915	
	f	37.8	41,010	39,470	43,070	39,860	.602		.934	
BTH24 [1]	d	75.6	39,740	----------	----------	32,970	.583	.571	.898	.881
	e	75.6	38,620	----------	----------	33,570	.569		.876	
	f	75.6	38,120	----------	----------	33,460	.561		.870	

[1] Correction factor 0.956 applied to column loads (see p.)16. Uncorrected values given in Table 16.

TABLE 16.—*Supplement to general summary of column tests (second series)*

[Results on columns BSL12, BSL24, BTH12, and BTH24 not corrected for calibration of testing machine]

Column		$\frac{L}{r}$	Column strength, first maximum stress	Minimum stress	Second maximum stress	Final stress	Ratio $\frac{\text{column strength}}{\text{tensile strength}}$	Average ratio	Efficiency	Average efficiency
			Lbs./in.²	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*				
BSL12	d	40.5	33,590	31,480	31,820	31,190	0.593	0.558	0.928	0.899
	e	40.5	32,940	31,090	31,430	29,660	.578		.892	
	f	40.5	33,650	31,710	32,350	31,150	.580		.877	
BSL24	d	81.0	33,430	----------	----------	26,190	.582	.539	.871	.857
	e	81.0	32,480	----------	----------	25,130	.557		.854	
	f	81.0	31,490	----------	----------	24,370	.551		.846	
BTH12	d	37.8	41,210	40,460	47,520	45,470	.617	.603	.951	.961
	e	37.8	42,890	39,340	42,130	37,270	.645		.957	
	f	37.8	42,890	41,280	45,010	41,690	.630		.976	
BTH24	d	75.6	41,560	----------	----------	34,480	.610	.571	.939	.922
	e	75.6	40,380	----------	----------	35,110	.595		.916	
	f	75.6	39,870	----------	----------	34,990	.586		.912	

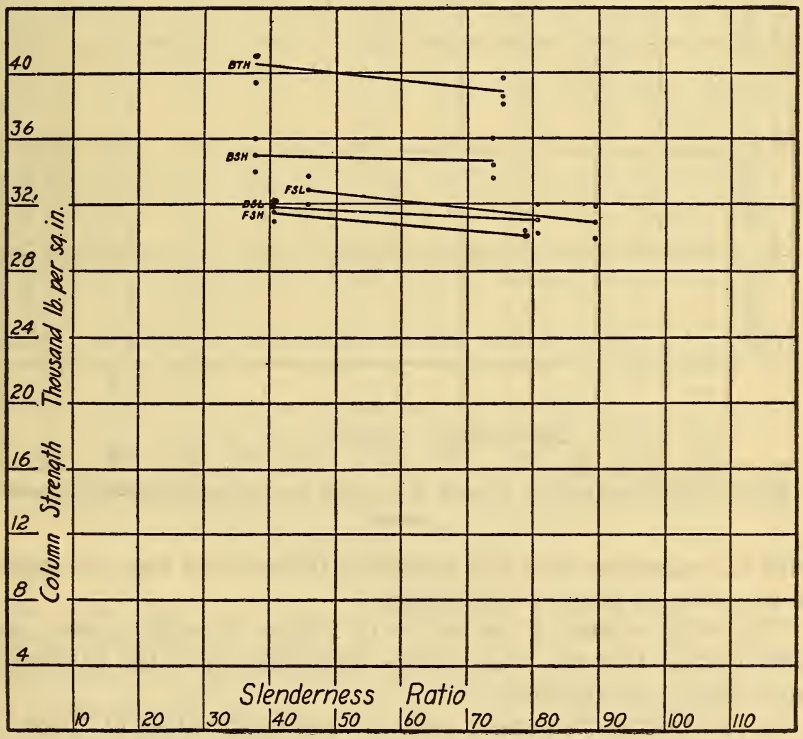


FIG. 22.—*Column strength (second series)*

In Figures 22, 23, and 24 are plotted the column strength, column strength divided by weighted average tensile strength, and the efficiency, only the average of each group of these columns being plotted in Figures 23 and 24. On Figure 24 (as on fig. 13 in the first series) are plotted Kármán's curves for small round end and fixed end columns of open-hearth steel, to indicate the relation of the tests to the full scale of slenderness ratios. Figure 25 is the same as Figure 24

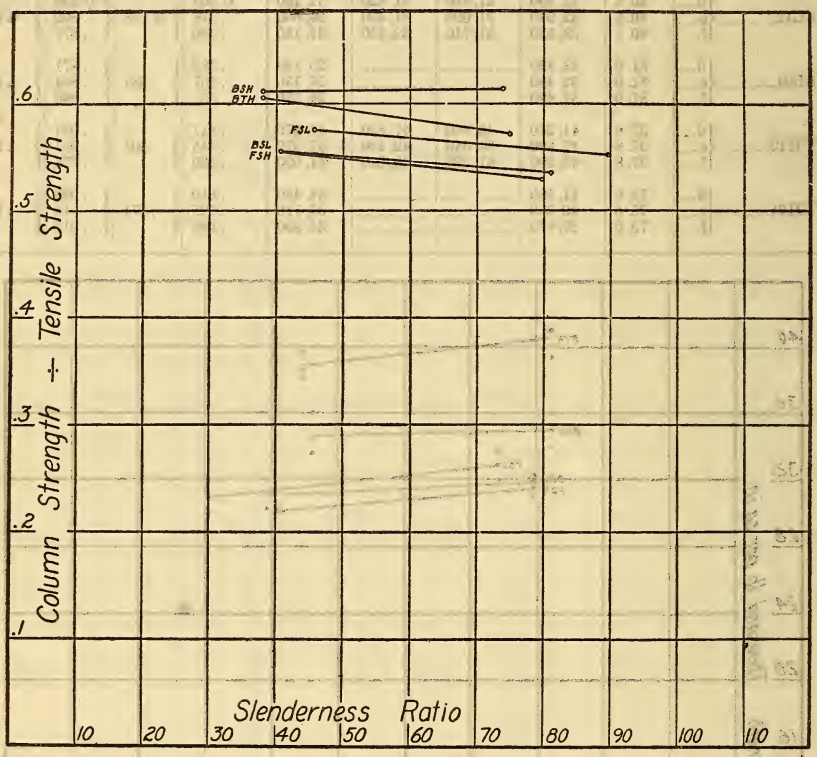


Fig. 23.—*Ratio of column strength to weighted average tensile strength (second series)*

with the exception that the correction factor 0.956 was not applied to the columns tested at Pittsburgh.

The wider scatter of the curves of Figure 25 make it seem even more certain that the straight line extrapolation of the calibration curve (fig. 4) was justified.

In the further discussion only the corrected values of Table 15 and Figure 24 will be used. However, the use of the uncorrected values would not alter the general conclusions. It would merely increase the unexplained outstanding discrepancies from 8 to about 12 per cent.

4. INTERPRETATION OF RESULTS

Here, as in the first series, the column strengths (fig. 21) differ widely, there being over 30 per cent difference between comparable columns. As before, the ratio of column strength to weighted average tensile strength (fig. 22) fluctuates less widely, but in one group (BSH) it shows the anomaly of increasing instead of decreasing with increasing slenderness ratio.

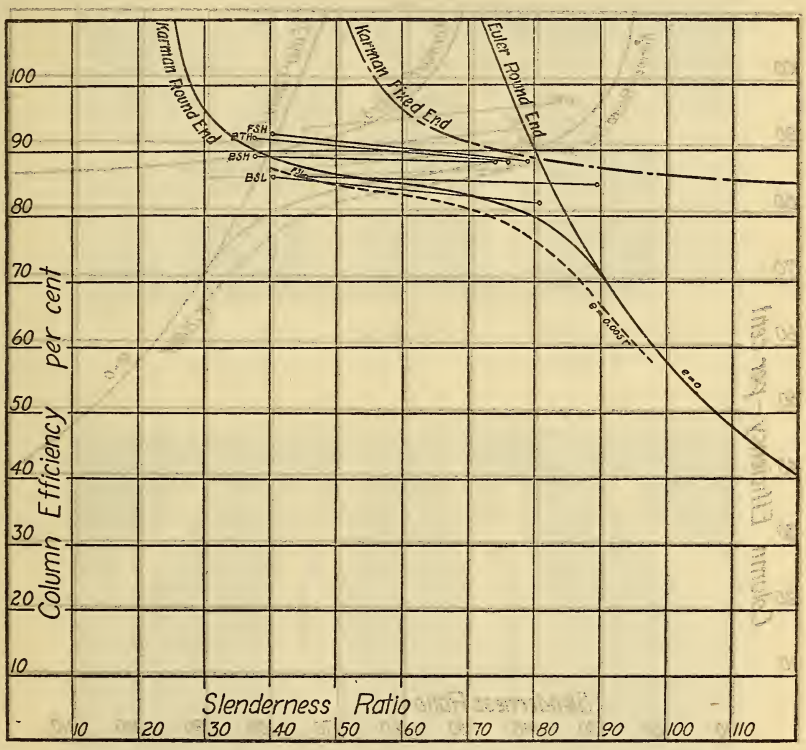


FIG. 24.—*Column efficiency; ratio of column strength to weighted average tensile yield point of coupons (second series)*

e=effective eccentricity of load
r=least radius of gyration

Most concordant of all are the efficiencies (fig. 24) the average points for each group of three columns lying within a band less than 8 per cent wide, sloping slightly downward with increasing slenderness ratio. The discrepancies are much less than in the first series of tests. This was to be expected since the much more complete series of coupons insured a more reliable determination of the average yield point than was possible from the smaller number in the first series

The results of the second series confirm more fully the conclusions that the strength of a sufficiently sturdy steel column, whose slenderness ratio lies between 40 and 90 is determined most largely by the

phenomena associated with the yield point of the material and depends only in small measure on its slenderness ratio or manner of construction.

They indicate also that the tensile yield point determined by a uniform test procedure from a sufficient number of coupons will furnish a basis for predicting the strength of sturdy columns within fairly close limits.

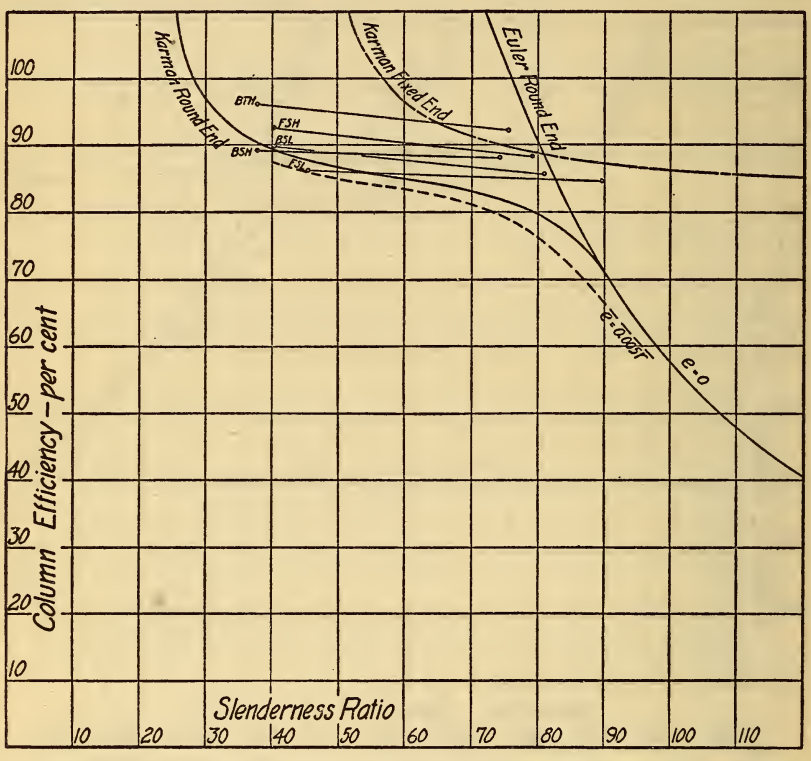


Fig. 25.—*Column efficiency; ratio of column strength to weighted average tensile yield point of coupons (second series)*

Loads on columns BTH – and BSL – uncorrected for calibration of testing machine
e=effective eccentricity of load
r=least radius of gyration

These conclusions are probably most strikingly illustrated by the six columns BSH12d, e and f and FSH12d, e and f. The columns after failure (fig. 26) differ greatly in appearance. One of the solid rolled columns (BSH12d) shows pronounced anomalous double curvature, the other two only a normal curvature about the axis of least moment of inertia. All of the three fabricated columns show marked crumpling of the outstanding flanges which is absent in the solid rolled columns. Even among these there is a noticeable difference, one (FSH12e) shows considerable normal lateral deflection. The

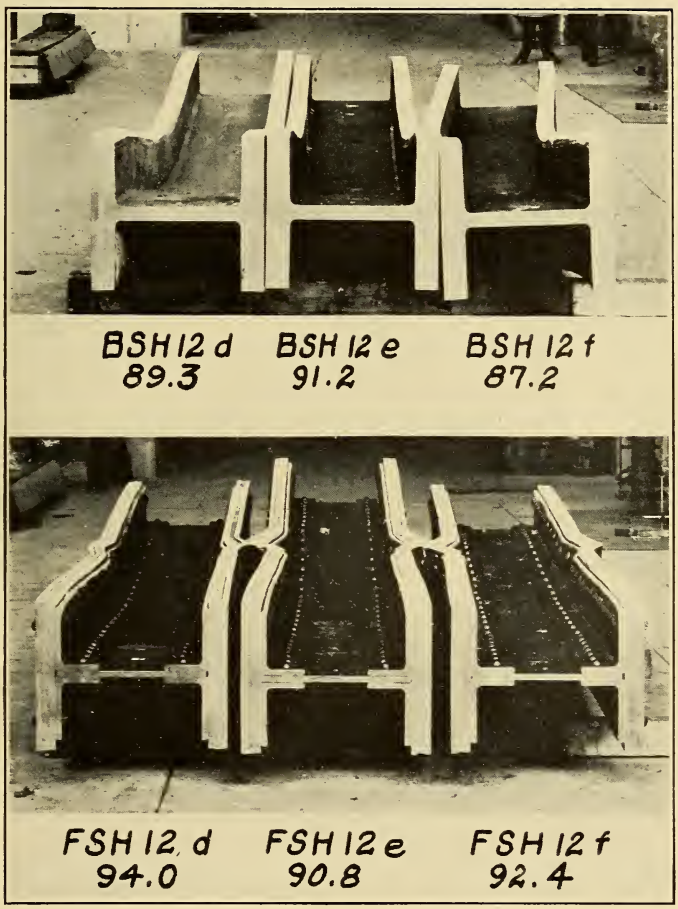


Fig. 26.—*Columns BSH12 and FSH12 after failure*

Figures given are per cent efficiencies. No column of the six differs in efficiency by as much as 4 per cent from the average of the group

others show less normal deflection and one (FSH12d) shows over half an inch anomalous lateral deflection. One might be tempted from a glance at these failed columns to conclude that the fabricated columns had a serious flange weakness resulting in a definite lowering of their strength, and that the doubly curved solid rolled column had been tested with large eccentricity either due to inaccurate mounting in the machine or to inhomogeneous structure.

The test results, show, however, that no one of these six columns differed in efficiency as much as 4 per cent from the mean of the group. These three fabricated columns with their seemingly weak flanges actually average 3 per cent higher in efficiency than these three solid rolled columns—a difference, however, which is of no significance in view of the unavoidable errors of the test. This particular comparison is not affected by any question as to the extrapolation of the calibration curve of the testing machine since all six of these columns were tested after the machine was set up in Washington, and was repeatedly giving consistent calibration curves. All of these six columns showed definite pick-up or hang-on (fig. 17), and the log sheets record that no crumpling of the flanges was observed until the maximum load was passed and lateral deflection had become pronounced. Thus, in spite of the difference in detailed behavior of these six columns under test, the results show that the major controlling factor in determining their stength was the quality of the material and that this was fairly well measured by the tensile yield point.

VII. COMPARISON OF THE TWO SERIES OF TESTS

1. SCOPE

Each of these series indicated the preponderating influence upon the strength of the columns of the properties of the material as measured by the tensile yield point. It seems desirable to see whether the comparison of the two series strengthens the conclusions.

2. COLUMN TESTS

The procedure in testing the columns was practically the same in the two series. Only two differences seem at all significant. In the second series a more sensitive method was used to ensure accurate alignment of the columns in the testing machine. The lateral deflection curves, however, show that no large, only small, eccentricities existed in any of the tests and the study of pick-up and hang-on made in the second series indicates that only small differences of the order of 1 per cent should be expected in the column strengths due to eccentricities.

In the first series loads of 10,000 and sometimes 20,000 lbs./in.^{2} were applied and removed in an effort to find significant effects of set under low load.

The retests of the four columns BSL18a, BSH18b, FSL18c, and FSH18c (Table 7) show that the previous loading history of a column up to the first maximum could have only a negligible effect on its strength.

So far as the column tests are concerned the results of the two series should then be comparable.

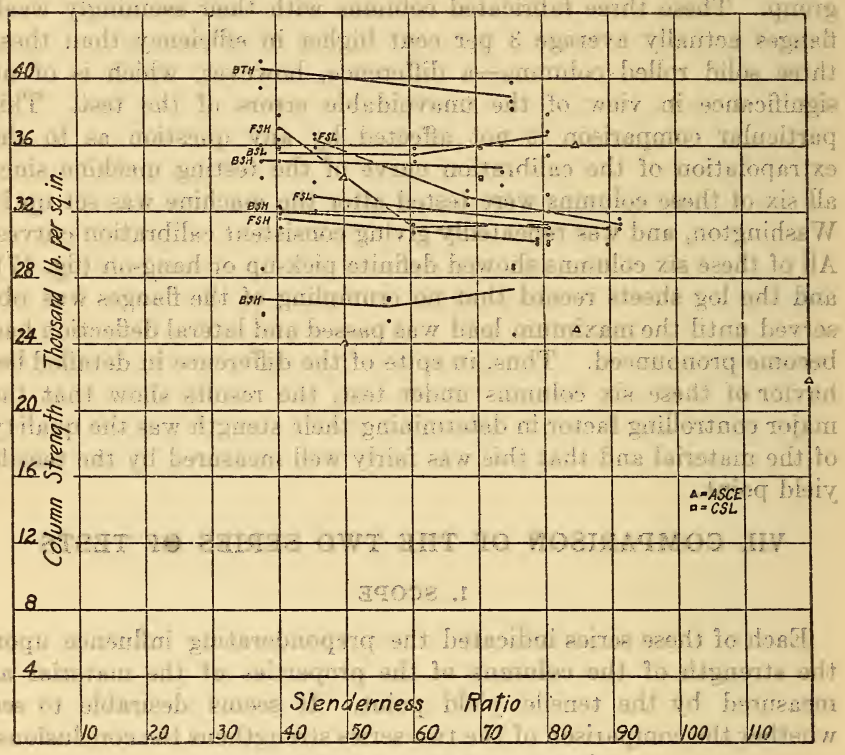


Fig. 27.—*Column strengths (all tests)*

3. COUPON TESTS

In planning the coupon tests of the second series care was taken to include coupons as nearly comparable as possible to those in the first series (fig. 2) so that by using only comparable coupons in the two series, the weighted average yield points determined would be comparable for both.

To ensure comparable results the weighted average yield point of the solid rolled sections of the second series were recomputed using only the results of the specimens 1, 3, 9, and 13 for the light and 1, 3, 9, and 11 for the heavy sections, and the same weights as in the first

series. To distinguish between the two sets of values this method of computing the weighted average yield points was designated "weighting A" while that using the full number of coupons was called "weighting B."

For the fabricated columns the coupons in both series were directly comparable in their distribution over the section so that no such distinction was necessary.

4. SUMMARY TABLE AND CURVES

On this basis Table 17 was computed, summarizing the results of all the tests. The results are plotted in Figures 27, 28, and 29.

TABLE 17.—*General summary of all tests "weighting A" and "corrected" efficiencies used on solid rolled sections*

Series	Column		$\frac{L}{r}$	Column strength	Column strength / Tensile strength	Average	Efficiency [1]	Average
				Lb./in.[2]				
1	FSL12	a	45.9	36,550	0.559	0.555	0.892	0.882
1		b	45.9	35,810	.548		.873	
1		c	45.9	36,330	.557		.882	
2		d	45.8	33,680	.587	.575	.884	.862
2		e	45.8	32,000	.559		.842	
2		f	45.8	32,890	.578		.860	
1	FSL18	a	68.8	32,720	.510	.513	.834	.843
1		b	68.8	33,230	.508		.846	
1		c	68.8	[2] 32,400	.521		.850	
1	FSL24	a	91.7	31,580	.517	.501	.804	.790
1		b	91.7	30,930	.475		.773	
1		c	91.7	31,180	.510		.794	
2		d	89.8	31,910	.563	.551	.857	.847
2		e	89.8	30,950	.552		.853	
2		f	89.8	30,000	.537		.832	
1	FSH12	a	40.4	37,640	.592	.600	.976	.972
1		b	40.4	36,270	.588		.949	
1		c	40.4	37,070	.621		.990	
2		d	40.4	31,830	.561	.555	.940	.924
2		e	40.4	31,820	.557		.908	
2		f	40.4	31,010	.547		.924	
1	FSH18	a	60.6	31,200	.523	.524	.874	.872
1		b	60.6	30,720	.522		.870	
1		c	60.6	[2] 31,260	.527		.872	
1	FSH24	a	80.8	32,860	.500	.499	.826	.827
1		b	80.8	30,500	.511		.850	
1		c	80.8	30,240	.487		.804	
2		d	79.2	30,320	.532	.529	.890	.885
2		e	79.2	30,000	.527		.882	
2		f	79.2	30.000	.528		.882	
1	CSL24	a	70.8	34,020	.595	.604	.795	.808
1		b	70.8	33,910	.593		.792	
1		c	70.8	35,760	.625		.836	
1	BSL12	a	40.5	35,000	.566	.576	.862	.876
1		b	40.5	35,640	.590		.896	
1		c	40.5	35,830	.573		.871	
2		d	40.5	32,120	.564	.556	.834	.808
2		e	40.5	31,500	.552		.801	
2		f	40.5	32,180	.552		.788	
1	BSL18	a	60.8	[2] 35,790	.564	.558	.893	.874
1		b	60.8	35,000	.562		.856	
1		c	60.8	35,350	.547		.873	
1	BSL24	a	81.0	37,860	.583	.554	.844	.828
1		b	81.0	35,260	.526		.823	
1		c	81.0	36,810	.553		.816	
2		d	81.0	31,960	.554	.536	.798	.777
2		e	81.0	31,060	.529		.764	
2		f	81.0	30,120	.526		.768	

[1] These values differ from those given in Table 15, because of the different area weighting. In Table 15 weighting B was used.
[2] Average of test and retest.

TABLE 17.—*General summary of all tests "weighting A" and "corrected" efficiencies used on solid rolled sections*—Continued

Series	Column		$\frac{L}{r}$	Column strength	Column strength / Tensile strength	Average	Efficiency [1]	Average
				Lb./in.[2]				
1	BSH12	a	37.8	28,200	0.445	0.444	0.808	0.818
1		b	37.8	25,760	.446		.845	
1		c	37.8	25,860	.440		.801	
2		d	37.8	34,000	.602	.603	.847	.840
2		e	37.8	35,980	.606		.847	
2		f	37.8	35,000	.601		.827	
1	BSH18	a	56.7	26,670	.425	.438	.793	.814
1		b	56.7	[2] 25,280	.428		.843	
1		c	56.7	26,710	.460		.806	
1	BSH24	a	76.5	28,440	.452	.441	.809	.816
1		b	76.5	24,500	.420		.781	
1		c	76.5	28,680	.450		.858	
2		d	74.0	34,370	.604	.607	.842	.855
2		e	74.0	36,000	.623		.887	
2		f	74.0	33,600	.594		.836	
2	BTH12	d	37.8	39,410	.584	.597	.860	.864
2		e	37.8	41,010	.610		.862	
2		f	37.8	41,010	.597		.869	
2	BTH24	d	75.6	39,740	.581	.568	.827	.830
2		e	75.6	38,620	.568		.840	
2		f	75.6	38,120	.556		.822	

[1] These values differ from those given in Table 15, because of the different area weighting. In Table 15 weighting B was used.
[2] Average of test and retest.

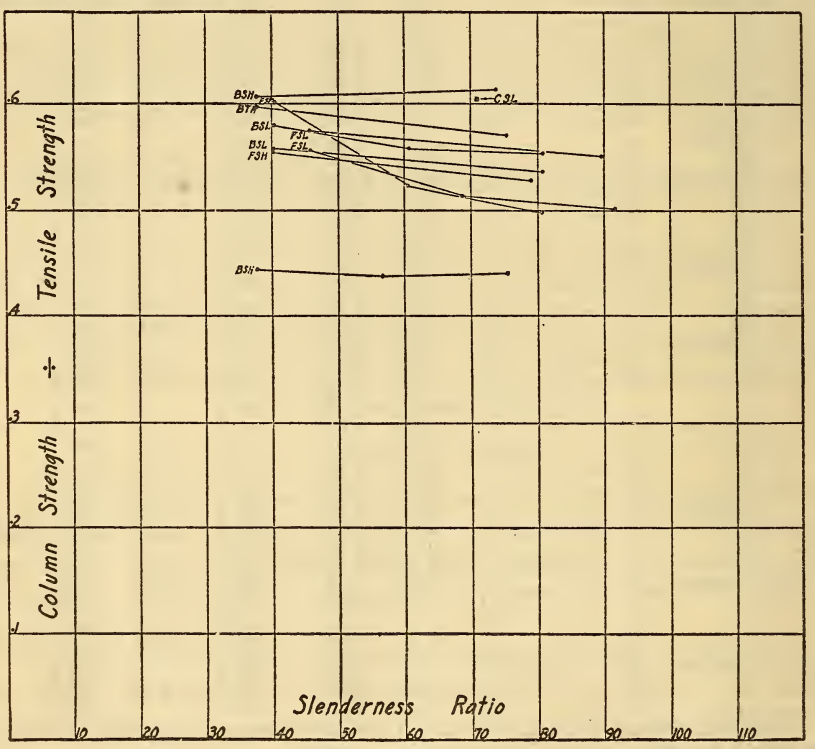


FIG. 28.—*Ratio of column strength to weighted average tensile strength (all tests, weighting A)*

These figures emphasize the comparisons made in Figures 9, 12, and 13 of the first series and Figures 22, 23, and 24 of the second series.

Corresponding to the wider range of materials there is an even wider scattering of the column strengths (fig. 27.). The ratios of column strength to weighted average tensile strength show better agreement (fig. 28), but are still widely scattered. The efficiencies (fig. 29), however, all lie within a narrow band.

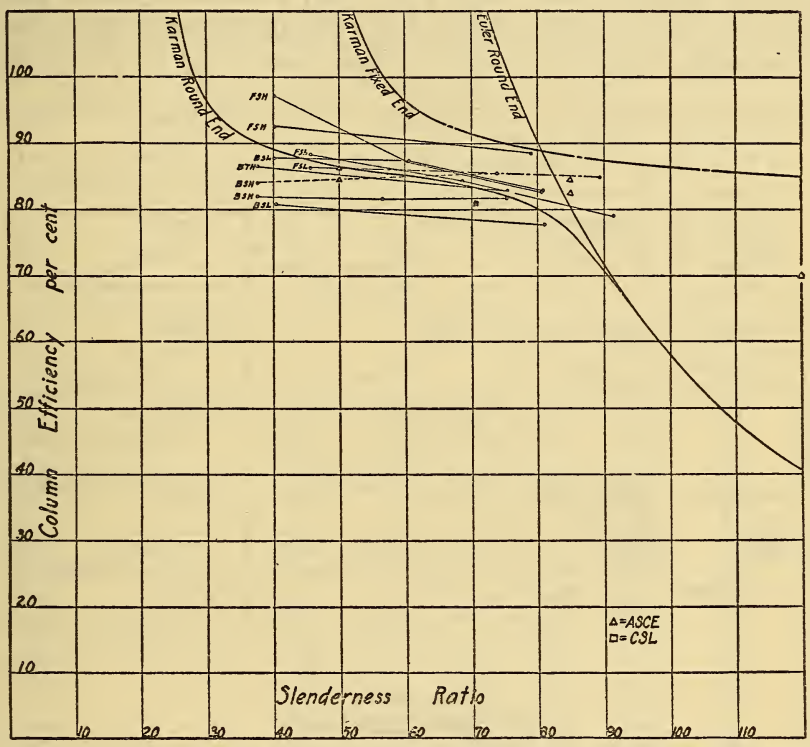


Fig. 29.—*Column efficiency; ratio of column strength to weighted average tensile yield point of coupons (all tests weighting A, see pp. 39 and 48)*

It is noticeable, however, that there is here a somewhat greater discrepancy than in either of the two single series. Examination shows that this discrepancy is largely due to the apparently lower efficiencies of the solid rolled columns.

5. PROBABLE CAUSES OF DISCREPANCIES

In discussing the probable cause of discrepancies in the first series, it was concluded that the low efficiencies of heavy rolled sections were probably only apparent, due to an overestimation of the yield point, upon which column strength largely depends. In that series there were no data available by which this supposition could be tested. The larger number of coupon tests in the second series,

however, make possible an estimate of the error probably involved in the inadequate sampling of the material of the solid rolled sections, represented by weighting *A*.

In Figure 30 are plotted the yield points of the Bureau of Standards coupons from all the solid rolled columns tested in the second series. The abscissas were made proportional to the sectional area lying between the centers of the corresponding test coupons. Thus the horizontal distance from 1 and 3 to 5 and 7 on the curves is proportional to four times the sectional area included between the centers of specimens 1 and 5 (or 3 and 7); from 5 and 7 to 9 on the curves

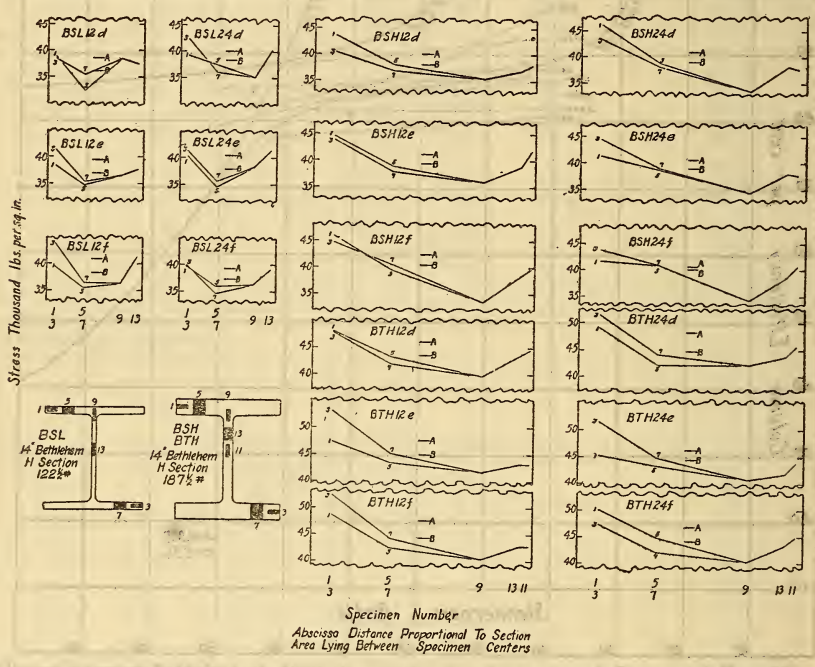


FIG. 30.—*Distribution of yield points over the cross section of the solid rolled columns (second series)*

A represents average yield point, weighting A
B represents average yield point, weighting B

proportional four times the sectional area included between the centers of specimens 5 and 9; from 9 to 13 (and 13 to 11) on the curves proportional to twice the sectional area included between the centers of specimens 9 and 13 (and 13 and 11). The factor 4 is used in the first two cases because there are four flanges and the factor 2 in the second case to take account of the other end of the web not represented by specimens.

By using these abscissas, the average height of the curves should represent a close approximation to the actual average yield point. On each curve is marked the weighted average yield point determined

by weighting A and weighting B. Weighting B in all cases represents more nearly the actual average yield point of the section than does weighting A, and in all cases weighting A gives too high a value. (See also Table 18.)

There is no direct evidence that the variation of yield point over the section in the solid rolled columns of the first series was similar to that shown in Figure 30 for the columns of the second series. It seems, however, nearly certain that more adequate coupon tests for the first series comparable to those in the second series would have indicated a lower average yield point, consequently a higher calculated efficiency. The evidence, however, is conclusive that the three

TABLE 18.—*Comparison of yield points by different area weightings*

Column	Yield points in pounds per square inch					Ratios	
	Tensile specimens		Averages				
	5	7	$\frac{5+7}{2}$	Weighting B	Weighting A	$\frac{\frac{5+7}{2}}{B}$	$\frac{A}{B}$
BSL12d	32,590	35,600	34,100	36,160	38,510	0.943	1.066
BSL12e	34,270	35,710	34,990	36,970	39,360	.948	1.067
BSL12f	35,420	36,450	35,940	38,380	40,840	.937	1.064
BSL24d	37,520	36,110	36,820	38,400	40,070	.960	1.045
BSL24e	34,850	35,690	35,270	38,040	40,670	.927	1.069
BSL24f	36,030	34,570	35,300	37,220	39,220	.949	1.054
BSH12d	38,220	36,910	37,570	38,070	40,150	.986	1.056
BSH12e	39,200	37,850	38,530	39,450	42,500	.978	1.078
BSH12f	39,680	40,370	40,030	40,150	42,300	.998	1,056
BSH24d	38,840	38,040	38,440	38,830	40,810	.990	1.051
BSH24e	38,740	39,010	38,880	39,060	40,590	.996	1.040
BSH24f	40,630	40,660	40,650	39,970	40,200	1.018	1.007
BTH12d	43,310	41,840	42,580	43,320	45,810	.984	1.060
BTH12e	43,350	45,090	44,220	44,810	47,560	.986	1.061
BTH12f	42,250	43,970	43,110	43,910	47,140	.981	1.072
BTH24d	42,040	44,040	43,040	44,260	48,040	.974	1.087
BTH24e	43,140	44,740	43,940	44,080	45,950	.998	1.042
BTH24f	44,470	41,820	43,150	43,800	46,390	.982	1.056
Averages						.974	1.057

coupons T, R, and W (figs. 2 and 11) of the first series can not be relied upon to give a close estimate of the average yield point of the material in these solid rolled sections.

Figure 30, however, suggests that a better average from a small number of coupons could be obtained by specimens (such as 5 and 7) located approximately half way down the flanges. Table 18 was prepared to check this idea. On the assumption that weighting B gives a close estimate of the average yield point, the average yield point for specimens 5 and 7 is on the average only 2.6 per cent too low with a maximum discrepancy of 7.3 per cent (BSL24e) and in only one case (BSH24f) does it give too high a value (1.8 per cent).

Since an underestimate of the yield point would result in conservative estimate of the column strength, it seems that from two specimens such as 5 and 7 (figs. 2 and 30) a closer and safer estimate of the properties of the section could be obtained than from the three specimens *T*, *R*, and *W* (figs. 2 and 11), which all give a high estimate of the yield point, averaging 5.7 per cent too high with a maximum of 8.7 per cent. As pointed out before, the best location of

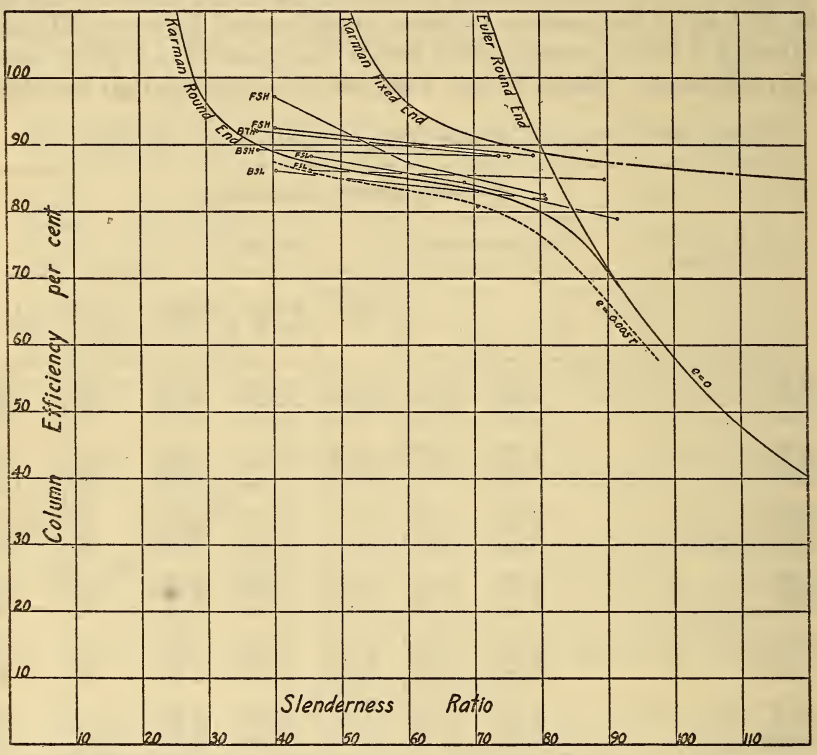


FIG. 31.—*Column efficiency; ratio of column strength to weighted average tensile yield point of coupons (selected tests). Both series. Weighting B (see pp. 39 and 48)*

e=effective eccentricity of load

r=least radius of gyration

coupons, and best method of averaging could only be decided definitely by a much larger number of coupons in a series of tests planned for this purpose.

6. SELECTED RESULTS

Because of the evident insufficiency of the coupon tests in the first series, Figure 29 gives an inadequate idea of the closeness with which the strengths of these columns correlate with the average tensile yield point of the material. The closeness of the correlation is brought out more clearly by excluding the solid rolled and channel sections of the first series, for which insufficient coupon tests were

made, and using the more reliable weighting B for the solid rolled sections of the second series. For the same reason the few points obtained from the A. S. C. E. tests are excluded. The results are shown in Figure 31. With the exception of the point representing the columns FSH12a, b, and c of the first series whose apparent discrepancy was previously discussed all of these selected points lie within a band less than 8 per cent wide sloping slightly downward with increasing slenderness ratio.

7. CORRELATIONS AND REGRESSION EQUATION

The previous discussion has been based largely upon the graphic study of the test results. These give a clear picture of the general relationships. However, in data with such large outstanding discrepancies the graphic presentation lacks the definiteness of a numerical statement. For this reason it seemed worth while to make a fairly complete statistical study of the data.[36]

Table 17 was chosen as a basis in spite of the recognized inadequacy of the average yield points obtained by weighting A, because it contained in comparable form the results of the full series of tests. The inadequate determination of the yield points could only result in an under- and not over-estimation of the correlations found.

The factors in the table which might influence the column strength are the slenderness ratio, yield point, and tensile strength. There is, of course, no theoretical reason for assuming the relation between them to be linear. In fact, it is certain that the variation of column strength with slenderness ratio is not linear. However, the test results are so widely scattered and cover so short a range of slenderness ratios that a linear relation is the only one available without bringing in theoretical considerations extraneous to the tests. Assuming, then, linear regressions the following correlation coefficients were found:

Between column strength and slenderness ratio	−0.20
Between column strength and yield point	+.89
Between column strength and tensile strength	+.54

The correlation coefficient of 0.89 is so high as to fully confirm the conclusion that the yield point is a major factor in determining the column strength. The correlation coefficient of 0.54 with tensile strength is also high enough to be significant. It can not, however, be wholly independent of the correlation with yield point since

$$\sqrt{0.89^2+0.54^2}=1.039>1$$

The correlation coefficient between yield point and tensile strength was found to be 0.56 giving a partial correlation coefficient of column strength with tensile strength of only +0.10. There is some indication that even this small residual correlation coefficient is partly

[36] See footnote 14, p. 36

spurious. A comparison of the ratio of weighting A to weighting B, of Table 18, with the corresponding tensile strengths from Table 12 shows a definite relationship, with a correlation coefficient between them of 0.35.

The errors made in the yield-point determinations of weighting A have, then, a correlation coefficient with tensile strength some three times as great as the residual correlation (+0.10) of column strength with tensile strength.

The apparent correlation of column strength with tensile strength, therefore, does not represent a real relationship, but is caused almost wholly by the fact that in the materials used the yield point and tensile strength depend somewhat upon common causes.

This was, of course, to be expected since in all of the columns, the first maximum load was reached before the material was deformed much beyond the yield point so that the properties of the material under greater deformations could not directly affect the column strength.

The negative correlation coefficient (−0.20) with slenderness ratio was to be expected, since both theory and experiment indicate a falling off of column strength with slenderness ratio. Its low value, compared with the high correlation coefficient (0.89) with yield point, emphasizes the fact that within the range of slenderness covered by these tests the properties of the material influence the column strength far more than differences in radius of gyration, or length of the column.

It has been assumed in the previous discussions that the efficiency; that is, $\frac{\text{column strength}}{\text{yield point}}$, gave a measure of column behavior (within the range of the tests) in which the effects of variations of the material were largely eliminated. The elimination of differences due to the material should, on the other hand, bring out more clearly the differences due to differing slenderness ratio. Calculation shows the efficiency to have a correlation coefficient with yield point of only −0.11, but with a slenderness ratio of −0.44. The efficiency is then a measure of the behavior of these columns nearly independent of the differences in the material.

Although the change of column strength with slenderness ratio, as shown by these tests is small, it is definite, and it seemed worth while to make a numerical estimate of its magnitude. Accordingly, it was assumed that the relationship between efficiency and slenderness ratio was linear of the form $A\left(1-B\frac{L}{r}\right)$ and the most probable value of A and B computed. This gives for the most probable value of the column strength, the regression formula

$$\text{Column strength} = 0.915 \times \text{yield point}\left(1-0.00119\frac{L}{r}\right)$$

This is not to be interpreted as a "column formula." The tests did not cover sufficient range and were not sufficiently free from error to justify establishing an empirical column formula to represent them. It is a regression formula which expresses the most probable value of column strength derivable from these tests in terms of the tensile yield point of the material and the dimensions of the column. Further, the factor of 0.915 would vary certainly over 10 per cent, depending on the test procedure used in determining the tensile yield point.

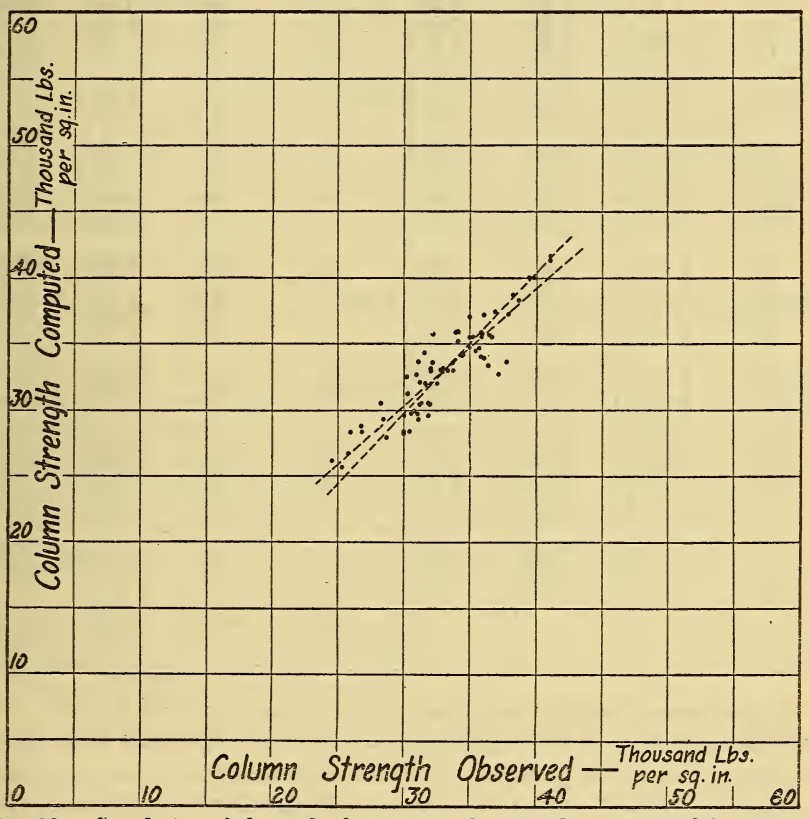


FIG. 32.—*Correlation of observed column strength with values computed from regression equation: Column strength=0.915×yield point* $\left(1-0.00119\ \frac{L}{r}\right)$, *all tests weighting A* (*see pp. 39 and 48*)

It is only of value in judging how completely the strength of these columns is determined by the tensile yield point of the material and their dimensions, and estimating the order of magnitude of the decrease within increasing slenderness ratio.

The observed values of the column strength and the value computed by the regression formula are given in Table 19. In Figure 32 these values are plotted together with the regression lines.

TABLE 19.—*Comparison of observed column strength with column strength computed from regression formula*

[Column strength = 0.915 yield point $\left(1-.00119\frac{L}{r}\right)$. All tests weighting A]

Column		$\frac{L}{r}$	Column strength		Column		$\frac{L}{r}$	Column strength	
			Observed	Computed				Observed	Computed
			Lbs./in.²	*Lbs./in.²*				*Lbs./in.²*	*Lbs./in.²*
FSL12	a	45.9	36,550	35,470	BSL12	a	40.5	35,000	35,400
	b	45.9	35,810	35,540		b	40.5	35,640	34,670
	c	45.9	36,330	35,650		c	40.5	35,830	35,830
	d	45.8	33,680	32,990		d	40.5	32,120	33,560
	e	45.8	32,000	32,900		e	40.5	31,500	34,300
	f	45.8	32,890	33,110		f	40.5	32,180	35,590
FSL18	a	68.8	32,720	33,030	BSL18	a	60.8	35,790	34,060
	b	68.8	33,230	33,030		b	60.8	35,000	34,730
	c	68.8	32,400	32,040		c	60.8	35,350	34,410
FSL24	a	91.7	31,580	32,040	BSL24	a	81.0	37,860	37,100
	b	91.7	30,930	32,660		b	81.0	35,260	35,470
	c	91.7	31,180	32,040		c	81.0	36,810	37,310
	d	89.8	31,910	30,440		d	81.0	31,960	33,160
	e	89.8	30,950	29,690		e	81.0	31,060	33,650
	f	89.8	30,000	29,480		f	81.0	30,120	32,450
FSH12	a	40.4	37,640	33,620	BSH12	a	37.8	28,200	30,520
	b	40.4	36,270	33,320		b	37.8	25,760	26,660
	c	40.4	37,070	32,640		c	37.8	25,860	28,240
	d	40.4	31,830	29,510		d	37.8	34,000	35,110
	e	40.4	31,820	30,560		e	37.8	35,980	37,160
	f	40.4	31,010	29,260		f	37.8	35,000	36,990
FSH18	a	60.6	31,200	30,330	BSH18	a	56.7	26,670	28,710
	b	60.6	30,720	29,990		b	56.7	25,280	25,620
	c	60.6	31,260	30,450		c	56.7	26,710	28,280
FSH24	a	80.8	32,860	32,910	BSH24	a	76.5	28,440	29,260
	b	80.8	30,500	29,710		b	76.5	24,500	26,110
	c	80.8	30,240	31,130		c	76.5	28,680	27,830
	d	79.2	30,320	28,250		d	74.0	34,370	34,080
	e	79.2	30,000	28,230		e	74.0	36,000	33,900
	f	79.2	30,000	28,220		f	74.0	33,600	33,570
CSL24	a	70.8	34,020	35,890	BTH12	d	37.8	39,410	40,050
	b	70.8	33,910	35,890		e	37.8	41,010	41,580
	c	70.8	35,760	35,890		f	37.8	41,010	41,220
					BTH24	d	75.6	39,740	40,030
						e	75.6	38,620	38,290
						f	75.6	38,120	38,660

The closeness with which these points group around the 45° line and the smallness of the angle between the two regression lines gives an idea of the completeness of the determination of the column strength by these two factors, tensile yield point and slenderness ratio alone. The "computed" and observed column strength have the high correlation coefficient 0.91.

8. OUTSTANDING DISCREPANCIES

The outstanding discrepancies may be due to a large number of causes. Eccentricities, either of structure or of loading, will account for 1 or 2 per cent; the use of linear regression formulas will account for some more.

Theoretically, the "shape" factor[37] deduced from the Considère-Kármán theory should also produce some discrepancies. If, however, these were at all large, there should be a definite association between column strength and type of construction. No definite association was found. A lack of perfect correlation between the tensile yield point determined in the tests and the compressive yielding upon which the column strength theoretically depends is, of course, another possible cause. However, the greatest cause of the outstanding discrepancies seems to the authors to be the inaccuracy in the determination of the tensile yield point from the coupons.

It seems certain that a larger number of coupons properly selected would have given more consistent results for the first series of tests.

The systematic differences of over 12 per cent in yield point found between the Bureau of Standards tests run at different speeds, and those of 2.6 per cent found between tests at the Bureau of Standards and Bethlehem indicate that if the tensile testing procedure had been more uniform throughout the work the discrepancies would probably have been still further reduced.

VIII. YIELD POINT AS A MEASURE OF COLUMN STRENGTH

The results of all the tests confirm, therefore, for these heavy columns, the conclusions from the column investigations previously cited, that the strength of a structural steel column in this range of slenderness (between 40 and 90) and sufficiently sturdy to exclude secondary or detailed failure, depends primarily upon the yield point of the material of which they are constructed and in small measure only upon their manner of construction or slenderness ratio.

The high correlation coefficient (0.89) found between the column strength and the tensile yield point by drop of beam indicates that the tensile yield point of the column material is a valuable measure of the strength of a sturdy column.

IX. EFFECT OF END CONSTRAINT AND SLENDERNESS RATIO

The present series of tests was not comprehensive enough to warrant any definite conclusions as to the law of variation with slenderness ratio, nor were sufficiently long columns tested to show the effect of end constraint in the range where the modulus of elasticity becomes the controlling factor. They do, however, show a definite decrease of the strength of "flat end" columns with increasing slenderness ratios of approximately 6 per cent between the slenderness ratios 40 and 90.

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[37] See p. 65.

X. TESTING OF YIELD POINTS

A need for further investigation of the methods to be used in determining the yield point is suggested by the following observations:

1. The strength of the columns bore no relation to the yield point determined in the commercial mill tests made under A. S. T. M. specifications. This was also noted in previous tests of the A. S. C. E. column committee.

2. The strength of the columns here tested bore a definite relation to the yield point by drop of beam determined at the Bureau of Standards under uniform conditions which lay within the speed limits prescribed by the A. S. T. M. Standard method E 1–18, which are retained in the new tentative standard E 8–24 T.

3. The yield points by drop of beam, as determined at two different speeds (0.013 and 0.37 inch per minute), both within the limits of the A. S. T. M. standard method E 1–18 and the new tentative standard E 8–24 T showed a systematic difference of about 12 per cent.

4. The yield point by drop of beam determined by the Bureau of Standards and by the Bethlehem Steel Co., both at a speed of 0.37 inch per minute, but upon different types of machines, showed a systematic difference of 2.6 per cent.

5. Differences as great as 27 per cent were found between the yield points by drop of beam as determined by the mill tests and by the Bureau of Standards, although the ultimate strengths determined in the two series of tests were in substantial agreement.

The report of committee O of the A. S. T. M.[38] recommended that the yield point (elastic limit) "should be taken with the dividers at a slow speed to secure approximate reliability and uniformity of the results." This recommendation was not incorporated in the A. S. T. M. specifications, but the drop of beam determination was retained with a limitation of pulling speed to 6 inches per minute.[39] This was modified by the report of the committee E–1, adopted in 1918,[40] which limited the pulling speed to 2 inches per minute on an 8-inch gauge length for steels of less than 80,000 lbs./in.^{2} ultimate strength. These values are retained in the new tentative specification E 8–24 T.[41] In some few specifications (for example, A 39, 40, 41, and 42–18) the pulling speed is expressly limited to three-fourths inch per minute. In English and German practice it is customary to use dividers or extensometers in determining the yield point.

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[38] Proc. A. S. T. M., 6 pp. 109–119; 1906; Report of Committee O.

[39] Report of Committee K, Proc. A. S. T. M., 9, pp. 264–272; 1909.

[40] A. S. T. M. Standards, p. 760; 1918.

[41] Proc. A. S. T. M. 24, pt. 1, p. 1087; 1924.

The A. S. C. E. column committee proposed to specify the characteristics of the material by means of their "useful limit point" instead of by means of the yield point. This would require the use of an accurate extensometer and materially increase the cost of testing.

It seems evident that some method of determination which is both reliable and practicable is needed as a basis for the definition of the yield-point characteristics of materials intended for compression members.

The results of these tests suggest that it may be possible to so standardize the drop of beam test as to give uniform and consistent results free from systematic differences due to personal equation and testing machine differences.

XI. SUGGESTIONS FOR FUTURE TESTS

In these tests two columns commercially identical in construction and length, both meeting the requirements of A. S. T. M. specification A 7–16 differed by 47 per cent in column strength. When correction was made (inadequately in some cases, as later tests showed) for the variations in tensile yield point of the material the maximum discrepancy between any two columns due to all other causes including inaccurate determination of yield point, differences in test conditions, widely different construction, and slenderness ratios varying from less than 40 to over 90, was less than 20 per cent.

This contrast makes it clear that consistent results can be obtained in column testing only by including a carefully planned series of coupon tests, adequate to determine all the significant variations in the material used.

Only when this is done can it be expected that a series of tests such as the A. S. C. E. tests will definitely determine the relative value of different types of construction.

XII. CONCLUSIONS

1. The columns tested were sturdy columns, having webs and flanges sufficiently thick to prevent secondary or detail failure.

2. The precautions in testing ensured very nearly axial loading, only small differences in the column strength of the order of 1 or 2 per cent being definitely attributable to eccentricities.

3. No differences in the column strength definitely attributable to the differences in type of construction could be found although theoretically some small differences due to this cause should be present. The pick-up of load, however, showed marked differences due to differences in construction.

4. The pick-up of load and anomalous lateral deflections observed were consistent with the Considère-Kármán double modulus theory of column action.

5. Within the range of these tests (slenderness ratios of 40 to 90) only a small decrease of the column strength with increasing slenderness was observed, approximately 6 per cent over the whole range.

6. The efficiency of the columns, defined as the ratio of the column strength to the average tensile yield point of the material, determined under uniform test conditions from coupons cut from the columns was fairly constant in view of the wide differences found in the column strengths. No such constant relationship was found between the other properties measured.

7. Consistent with this a high (0.89) correlation coefficient was found between the column strength and the tensile yield point.

8. The differences in the observed strength of these sturdy columns $\left(\frac{L}{r}=40 \text{ to } 90\right)$ were, therefore, in very large measure due to the differences in the yield point of the material and in small measure only to the type of construction or slenderness ratio.

9. The tensile yield point of the material determined under uniform test conditions from coupons cut from the columns furnished a close measure of the strength of the columns.

10. Yield points determined in the commercial mill tests apparently bore no relation to the strength of the columns.

11. In view of the controlling influence of the yield point of the material upon the strength of columns, a more precise standard definition and method of measurement of yield point are needed.

12. In future column tests more care should be taken to provide for an adequate series of coupon tests.

WASHINGTON, June 11, 1926.