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TESTS OF STEEL TOWER COLUMNS FOR THE GEORGE WASHINGTON BRIDGE

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ABSTRACT

The Bridge Department of the Port of New York Authority has designed and built the George Washington (suspension) Bridge across the Hudson River at New York City. The Port Authority requested the cooperation of the National Bureau of Standards in an investigation of the strength and other properties of the large fabricated steel columns. The columns were made of carbon steel, silicon steel, and carbon-manganese steel and were tested in the hydraulic compression machine at the Bureau.

The shortening of the columns was measured, using compressometers and electric telemeters, and the lateral deflection was measured at midheight. The tensile properties of the material were determined from coupons.

It was found that:

1. The loading was nearly axial.

2. For stresses within the elastic range of the column, the strains indicated by the compressometers and the telemeters were very nearly the same.

3. For stresses within the elastic range of the columns, there was no appreciable difference between the strains in the plates and in the angles, and therefore the stresses were practically the same.

4. For stresses which were nearly the maximum stresses in the column, the lateral deflection was very small.

5. There was no significant change in the relative positions of the main members under load.

6. The carbon-steel columns exhibited the phenomenon of pick-up, i. e., a definite first maximum load, a constant or slightly decreasing load for a considerable further shortening of the column, followed by a pick-up to a second higher maximum load after the columns were markedly deformed. The silicon-steel columns showed no definite first maximum load, but the load increased very slowly for a considerable shortening of the column and then more rapidly with further shortening. The carbon-manganese-steel columns showed no indication of more than one maximum load.

7. The column yield strength for the silicon-steel columns was 1.55 times that for the carbon-steel columns. For the carbon-manganese-steel columns it was 1.71 times that for the carbon-steel columns. These ratios are practically the same as the ratios of the average yield strengths of the materials.

8. The practical constancy of these ratios is shown by the column efficiency. For these columns having a slenderness ratio of 28.9, the column efficiency, defined as the quotient of the column yield strength divided by the weighted yield strength of the column material, was approximately 100 percent. For the carbon-manganese-steel columns the efficiency was 100 percent; for the carbon-steel and silicon-steel columns, 98 percent. These values are about the same as those observed in previous tests on columns having a slenderness ratio of about 40, when allowance is made for the effect of the speed of the testing machine on the yield strength of the column material.

9. At failure the outstanding angles buckled between diaphragms on the concave sides of the columns. No rivets failed. The local buckling occurred only after considerable shortening of the column and was not the primary cause of failure.

10. The tests confirm for these columns the conclusion from previous column tests that the tensile yield strength of the material determined at a speed of the testing machine comparable with that used in the column tests will furnish a close measure of the strength of short sturdy columns.

CONTENTS

I. INTRODUCTION

1. PURPOSE

The Bridge Department of the Port of New York Authority has designed and built the George Washington (suspension) Bridge [1] between Fort Washington, New York City, and Fort Lee, New Jersey. It crosses the Hudson River by a single span of 3,500 ft and two side spans of 610 and 650 ft.

Large box-section columns of silicon steel are an important structural element of the towers of this bridge. Because few tests have been made on large fabricated columns of silicon steel, information was desired on the strength and the behavior of these columns under load. The Port of New York Authority requested the National Bureau of Standards to cooperate in an investigation of the strength and other properties of these large fabricated steel columns.

[1] Eng. News-Rec. **21**, 100, 819 (1928). Trans. Am. Soc. C. E., **97** (1933,) Pop 1818–1826)

The Bureau's hydraulic compressive testing machine having a capacity of 10,000 kips [2] is the largest testing machine in this country. The test columns therefore were designed to have a strength less than the capacity of this machine and a length not exceeding 24 ft, the longest specimen which can be placed in the machine using available equipment. Except for length, the test columns were models of the bridge members to a scale of about one-half the linear dimensions.

II. THE SPECIMENS AND THE METHOD OF TESTING

1. GENERAL

The specimens are listed in table 1 with their nominal dimensions and properties.

TABLE 1.—*Nominal dimensions and properties of the test columns*

Number of specimens tested	Symbol	Kind of steel	Cross-sectional area of steel	Length	Moment of inertia		Radius of gyration		Slenderness ratio	
					I_{x-x}	I_{y-y}	r_{x-x}	r_{y-y}	x-x	y-y
			in.²	ft	in.⁴	in.⁴	in.	in.		
2	TC1, TC2	Carbon	159	24	15, 794	15, 794	9. 97	9. 97	28. 9	28. 9
2	TS1, TS2	Silicon	159	24	15, 794	15, 794	9. 97	9. 97	28. 9	28. 9
2	TM1, TM2	Carbon-manganese	151	24	14, 995	14, 995	9. 97	9. 97	28. 9	28. 9

2. SYMBOLS

The following symbols were used for convenience in identifying the specimens:

Design T=Steel tower columns,[3] George Washington Bridge.

Material { C=Carbon steel. S=Silicon steel. M=Carbon-manganese steel.

The numbers 1 and 2 were used to designate the individual columns in each group. Thus, the column TS2 was one of the two duplicate steel columns fabricated from silicon steel.

The longitudinal pieces of each column, that is, the longitudinal plates and angles, were cut as shown in the cutting diagram in figure 1. Each longitudinal piece of the column was match-marked to correspond with the coupon cut from the same plate or angle, and the location of each piece relative to the position of the column in the testing machine was recorded.

3. TESTING MACHINE

All the specimens were tested as flat-ended columns in a vertical hydraulic compressive testing machine [4] having a capacity of 10,000 kips.

No precision apparatus was available for calibrating this machine to capacity. At various times, by the use of load and deformation reading on columns, comparisons had been made with the Emery machine (having a capacity of 2,300 kips) up to loads of 1,600 kips.

[2] One kip=1,000 lb.
[3] Approximatly scale models of the bridge members.
[4] Described in B.S. J. Research **3**, 507 (1929) RP108.

Extrapolation to higher loads has been made by load-deformation curves on larger columns. It is believed that the error in the loads

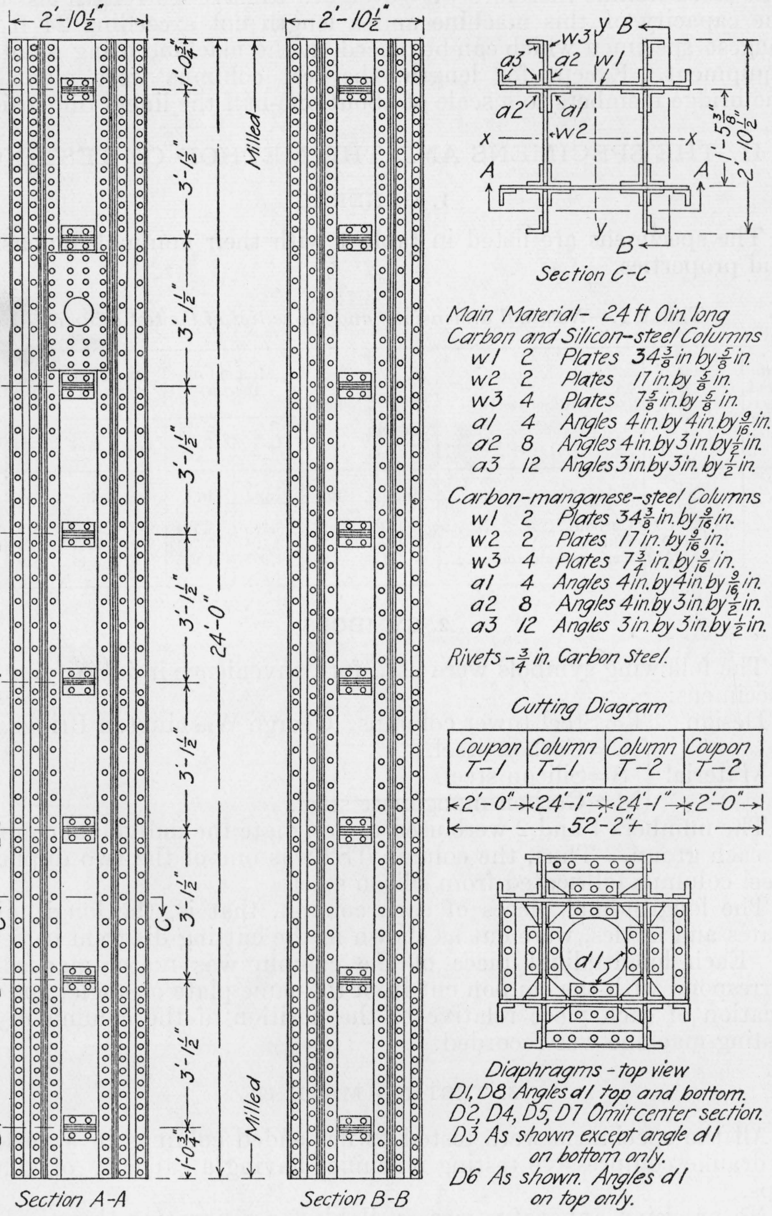

FIGURE 1.—*Dimensions of the test columns.*

on the columns for this investigation did not exceed 3 percent, and that the calibration of this machine did not alter by as much as 1 percent during these tests.

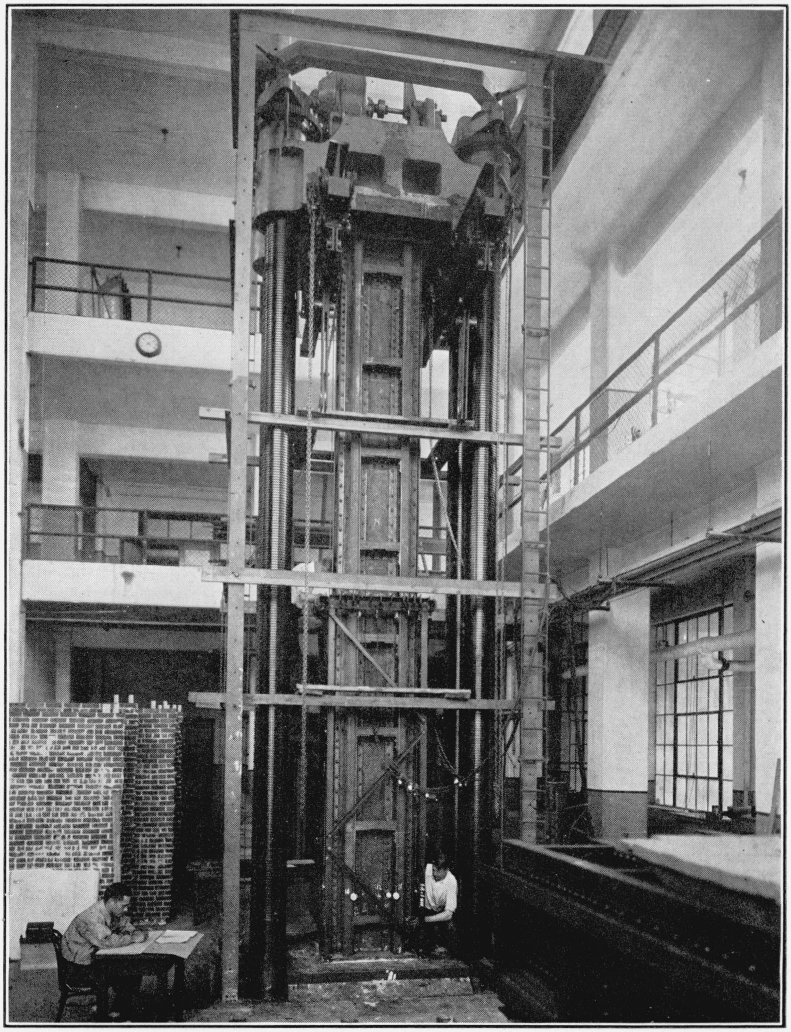

FIGURE 2.—*A column in the testing machine.*

Figure 3.—*Lower end of compressometers on a column.*

The rods actuated the dial micrometers.

The loads were applied through steel bearing plates at each end of the specimen. A soft mixture of plaster of paris was used between the bearing plates and the platens of the machine to decrease local deformation of the plates.

The specimen was loaded to a stress not exceeding 10 kips/in.^{2} and the lower platen of the machine adjusted in its spherical seat until the load was axial as indicated by the readings of the compressometers.

4. THE TEST COLUMNS

(a) DESCRIPTION

The dimensions of the test columns are given in figure 1. It is apparent from section C-C that the cross section is symmetrical with respect to the centroidal axes x-x and y-y. The plates, w–1, were continuous across the column, but the corresponding plates parallel to y-y were in 3 pieces w–3, w–2, and w–3. There were holes in the plates w–1 to receive pins used for placing the column in the testing machine. The column was reinforced around the holes. Two of the columns were of carbon steel, two of silicon steel, and two of carbon-manganese steel.

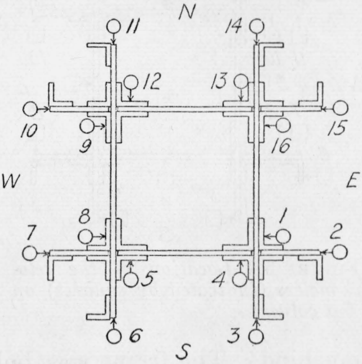

FIGURE 4.—*Location of the compressometers (indicated by circles) on a column.*

The nominal properties of these columns and of the columns in the George Washington Bridge towers are given in table 2. A steel test column in the testing machine is shown in figure 2.

TABLE 2.—*Nominal properties of the test columns and of the columns in George Washington Bridge*

Properties	Test column	Bridge column
Area, in.^{2}	159	716
Moment of inertia, in.^{4}	15,794	264,526
Length, ft	24	50
Radius of gyration, in	9.97	19.2
Slenderness ratio (l/r)	28.9	31.2
Ratio $\left\{\frac{\text{Web thickness}}{\text{Web width}}\right.$	$\frac{1}{15.0}$	$\frac{1}{7.9}$

(b) TESTING PROCEDURE

(1) *Compressometers.*—Compressometers having a gage length of 20 ft were used to measure the shortening of the columns under load. The middle of the gage length was at midheight of the column. The lower ends of the rods actuated dial micrometers attached to the column at the lower gage mark as shown in figure 3. One division on the dials was 0.001 in., and readings were estimated to 1/10 of a division. The location of the compressometers is shown in figure 4.

(2) *Telemeters.*—Eighteen telemeters [5] having a gage length of 8 in. were located on vertical gage lines near midheight of the columns,

[5] Proc. Am. Soc. Testing Materials [II] **23**, 592 (1923); Tech. Pap. BS **17**, 737 (1924) T247.

as shown in figures 5 and 6. One division on the scale of the milliammeter connected to the telemeter corresponded to a strain in the column of about 0.001 in. in the gage length of 8 in. The range of these instruments was 10 divisions, equivalent to a strain of 0.00125 (in./in.).

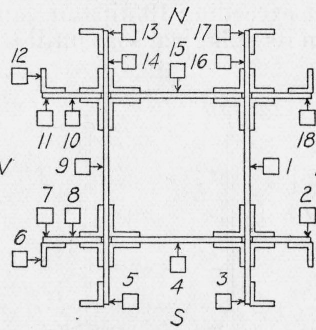

FIGURE 5.—*Location of the telemeters (indicated by squares) on a column.*

The telemeters were calibrated before the columns were tested and the strain in the columns computed from the calibration factor and the reading of the milliammeter.

(3) *Lateral Deflection.*—The diaphragms projecting from the test column precluded the use of the taut wire and mirror-scale deflectometer for measuring the lateral deflection. Therefore a frame of structural steel shown in figure 7 was erected around the lower half of each of the columns after it had been centered in the testing machine. The frame was bolted to the lower bearing plate. The upper end of the frame, at midheight of the column, was used as a base for measuring the deflection of the column under load. Dial micrometers attached to rods of suitable length were used manually to measure the distance between the frame and the column by inserting the conical ends of the spindle and of the rod into deflection points (center punch marks) in the frame and in the column. One division on the dial was 0.001 in. Two observers took the readings on opposite sides of the column simultaneously. For each load increment, readings were taken at the 44 stations shown in figure 8, 11 on each side of the column.

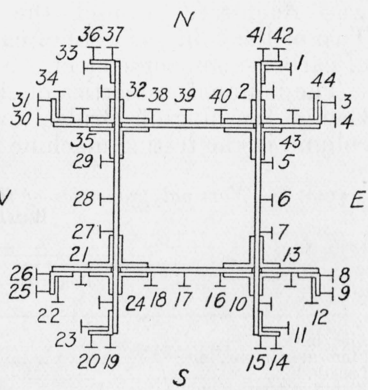

FIGURE 8.—*Stations (indicated by lines) at which lateral deflection was measured at midheight of a column.*

(4) *Loading.*—For 1 column of each of the three kinds of steel the load was increased by increments until the deflection of the column brought it into contact with the compressometers. The compressometers were then removed and the pump of the testing machine operated at a constant speed. Load readings were taken at intervals of 1 minute until the load had reached the maximum and then decreased. The load increments were equivalent to an average stress of 4 kips/in.^{2} in the column until the maximum load was approached; thereafter the increments were smaller. The compressometers, the telemeters, and the lateral deflections were read for each increment of load until the compressometers were removed.

The other columns were loaded in the same way, except that when the load approached the end of the elastic range of the column, the

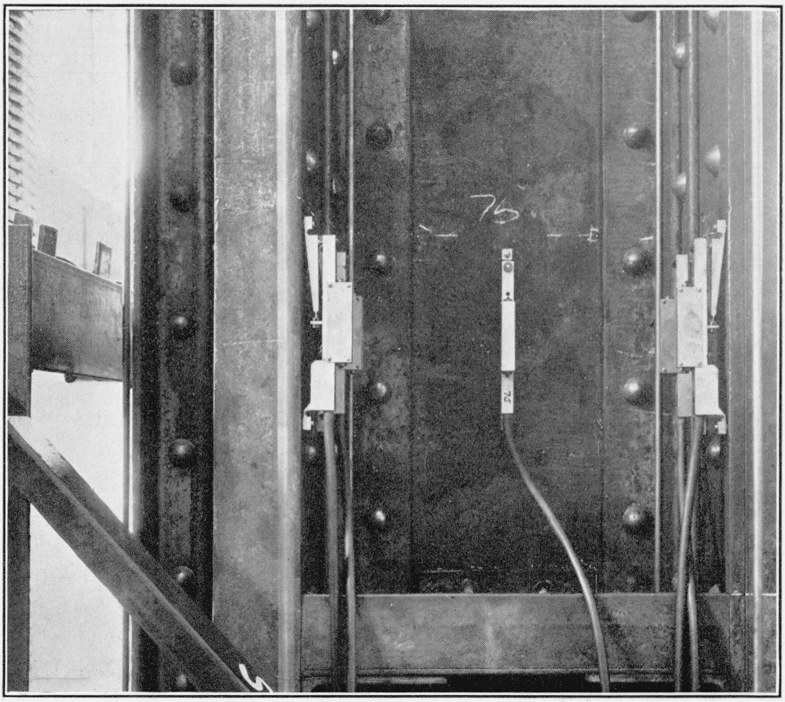

FIGURE 6.—*Telemeters (8-in. gage) near midheight on the north side of a column.*

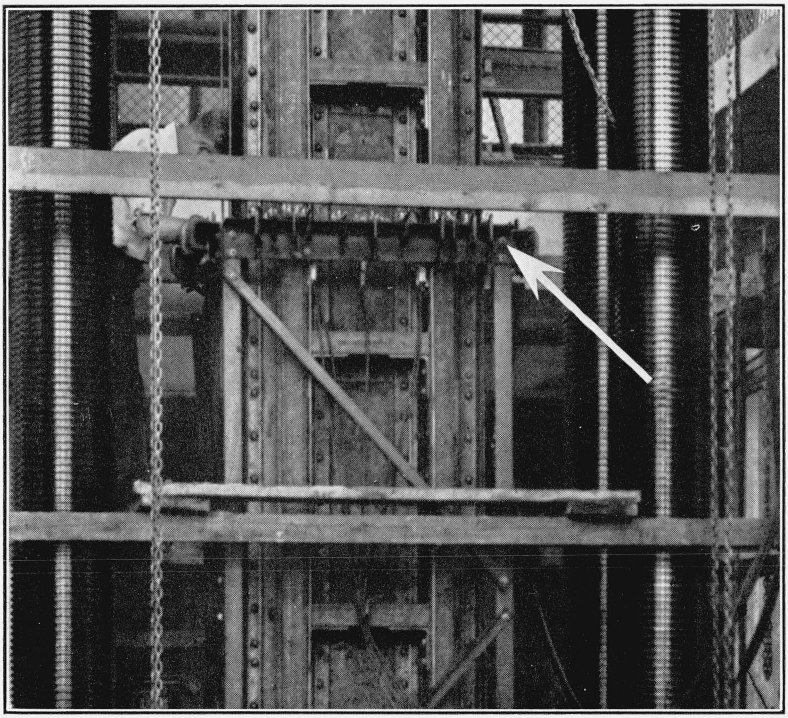

FIGURE 7.—*Frame used as a base for measuring the lateral deflections at midheight of a column.*

load was decreased to a low value once and then increased until the column had yielded plastically, when the load was again decreased to a low value once and then increased to the maximum.

5. METHOD OF DETERMINING THE PROPERTIES OF THE COLUMNS

(a) YOUNG'S MODULUS

The average Young's modulus of elasticity for each column was determined from the values of average stress and average compressometer strain. The average stress was obtained by dividing the load by the nominal cross-sectional area of the column. The arithmetical average of the 16 compressometer strains for each load was taken as the average compressometer strain. The computed strains obtained by dividing the average stresses in the elastic range by a trial modulus were compared with the average compressometer strains. The trial modulus for which the computed strains agreed most closely with the compressometer strains for loads within the elastic range was taken as the Young's modulus of elasticity of the column.

(b) PROPORTIONAL LIMIT

A proportional limit for each column was determined as the stress for which the average compressometer strain was 0.000012 greater than the strain computed by the use of the Young's modulus.

(c) COLUMN YIELD STRENGTH

For reasons discussed later, the yield strength of the column was taken as the stress for which the average compressometer strain was 0.002 greater than the strain computed by using the Young's modulus. The value for each column was obtained graphically from the stress-strain graph for the column.

(d) WEIGHTED YIELD STRENGTH OF THE MATERIAL

The weighted average tensile yield strength of the material in the column was obtained from the yield strengths of coupons by weighting them in the ratio of the cross-sectional area of the main member which they represented to the total nominal cross-sectional area of the column.

(e) COLUMN EFFICIENCY

The column efficiency was obtained by dividing the column yield strength by the weighted yield strength of the material in the column.

6. COUPONS

(a) GENERAL

The coupons were machined from the pieces marked "Coupon" in the cutting diagram in figure 1. This diagram shows the relation of the coupons to the longitudinal pieces used in fabricating each column. From each of the plates 34⅜ in. wide for the columns TC1, TS1, and TM1, two coupons were taken, one at the middle and one at the edge of the plate. For all the other plates one coupon was taken at the middle of the plate. For all of the angles one coupon was taken at the middle of one of the legs of the angle.

(b) SHAPE AND SIZE

The axis of each coupon was parallel to the rolling direction (axis) of the plate or angle. The coupons were standard ASTM tensile specimens for plates, shapes, and flats.[6] These coupons had a gage length of 8 in., a width at the reduced section of 1½ in., and the thickness was that of the material as rolled.

(c) YIELD STRENGTH

The method selected for determining the yield strength of these coupons is essentially the "set method" described by the Section on Elastic Strength of Material of the Technical Committee on Mechanical Testing of the American Society for Testing Materials.[7] The yield strength was taken as the stress for which the strain was 0.002 greater than the strain computed from the stress and the Young's modulus of elasticity. The values obtained in this way agreed closely with those obtained by the drop of beam for those coupons which showed a definite drop of beam. For some of the carbon steel coupons no strain measurements were made and the yield strength was determined by the drop of beam method.

(d) TESTING MACHINE

The coupons were tested in a screw-power, beam-and-poise machine having a capacity of 100 kips.

(e) EXTENSOMETER

The strains in some coupons of each kind of steel were measured by the use of a Ewing extensometer having a gage length of 8 in. One division on the scale of this instrument corresponded to a strain of 0.000025 in the coupon. The readings were estimated to 0.1 division. For the coupons of silicon and of carbon-manganese steel upon which a Ewing extensometer was not used, the strains were measured by the use of a Berry strain gage having a gage length of 8 in. The yield strength was determined graphically by a method which gave values approximating closely those obtained by the use of the Ewing extensometer.

(f) SPEED OF THE MOVABLE PLATEN

For the coupons on which a Ewing extensometer was used, the speed of the movable platen of the testing machine under no load was 0.04 in./min and this speed was maintained until the stress was about three-quarters of the yield strength. For higher stresses the speed was 0.01 in./min. After the extensometer was removed the speed was 0.4 in./min until the coupon ruptured.

For the coupons on which a Ewing extensometer was not used, the speed was 0.04 in./min until the yield strength was observed. For higher stresses the speed was 0.4 in./min.

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[6] Figure 1, Stand. Am. Soc. Testing Materials [I] **68** (1933).

[7] Proc. Am. Soc. Testing Materials [I] **31**, 602 (1931).

III. RESULTS FOR THE COUPONS

1. TENSILE TESTS

The results of the tensile tests of the coupons are given in table 3. The properties of the material are average values for the longitudinal members of the same size and shape. The values of the yield strength are drop-of-beam values for the carbon-steel coupons and stress-strain graph values for the silicon and the carbon-manganese-steel coupons.

TABLE 3.—*Results of the tensile tests of coupons*

Column material		Number of coupons tested	Yield strength (average)	Tensile strength (average)	Elongation in 8 in. (average)	Reduction of area (average)
Shape	Nominal size, in.					
COLUMN TC1—CARBON STEEL						
			kips/in.^{2}	kips/in.^{2}	*Percent*	*Percent*
2 plates	34⅜ by ⅝	4	32.7	57.4	31.4	56.7
2 plates	17 by ⅝	2	33.5	57.4	31.8	58.8
4 plates	7⅝ by ⅝	4	31.4	56.3	31.2	61.0
4 angles	4 by 4 by 9/16	4	33.0	57.5	31.6	55.8
8 angles	4 by 3 by ½	8	32.8	58.8	27.4	54.9
12 angles	3 by 3 by ½	12	39.2	63.3	28.4	53.1
Weighted average			34.0	58.7	30.2	56.4
COLUMN TC2—CARBON STEEL						
2 plates	34⅜ by ⅝	2	31.7	57.6	30.0	58.0
2 plates	17 by ⅝	2	33.1	56.6	32.6	60.8
4 plates	7⅝ by ⅝	4	31.5	56.2	32.9	58.8
4 angles	4 by 4 by 9/16	4	32.4	57.0	31.5	56.4
8 angles	4 by 3 by ½	8	33.9	59.4	28.3	55.8
12 angles	3 by 3 by ½	12	39.4	63.3	28.0	51.5
Weighted average			33.9	58.7	30.2	56.6
COLUMN TS1—SILICON STEEL						
2 plates	34⅜ by ⅝	4	55.1	96.8	17.6	41.5
2 plates	17 by ⅝	2	42.8	78.0	22.8	48.8
4 plates	7⅝ by ⅝	4	48.2	91.7	19.8	44.6
4 angles	4 by 4 by 9/16	3	51.1	88.5	21.1	44.8
8 angles	4 by 3 by ½	8	55.2	93.9	18.2	45.1
12 angles	3 by 3 by ½	12	58.3	94.3	19.8	45.8
Weighted average			52.9	91.8	19.5	44.7
COLUMN TS2—SILICON STEEL						
2 plates	34⅜ by ⅝	2	51.4	91.9	20.6	44.0
2 plates	17 by ⅝	2	43.8	78.6	20.5	47.8
4 plates	7⅝ by ⅝	4	48.5	91.3	19.4	42.3
4 angles	4 by 4 by 9/16	4	53.2	91.9	20.3	45.4
8 angles	4 by 3 by ½	8	55.6	94.1	18.7	43.8
12 angles	3 by 3 by ½	12	59.2	96.4	20.4	45.5
Weighted average			52.5	91.3	20.1	44.7
COLUMN TM1—CARBON-MANGANESE STEEL						
2 plates	34⅜ by 9/16	4	58.9	99.5	18.9	48.3
2 plates	17 by 9/16	2	54.9	94.8	20.9	48.0
4 plates	7¾ by 9/16	4	56.6	98.8	18.0	44.9
4 angles	4 by 4 by 9/16	4	55.7	93.4	22.0	51.8
8 angles	4 by 3 by ½	8	56.5	94.7	18.7	43.6
12 angles	3 by 3 by ½	12	56.0	93.4	20.1	51.0
Weighted average			56.7	96.0	19.6	48.0

TABLE 3.—*Results of the tensile tests of coupons*—Continued

COLUMN TM2—CARBON-MANGANESE STEEL

Column material		Number of coupons tested	Yield strength (average)	Tensile strength (average)	Elongation in 8 in. (average)	Reduction of area (average)
Shape	Nominal size, in.					
			kips/in.²	kips/in.²	*Percent*	*Percent*
2 plates	34⅜ by 9/16	2	59.8	102.1	19.2	48.8
2 plates	17 by 9/16	2	55.0	96.0	20.8	51.0
4 plates	7¾ by 9/16	4	56.2	97.6	18.5	49.1
4 angles	4 by 4 by 9/16	4	55.6	92.5	20.8	54.7
8 angles	4 by 3 by ½	8	56.7	94.7	19.0	40.7
12 angles	3 by 3 by ½	12	56.2	93.9	20.1	49.7
Weighted average			57.0	96.7	19.7	48.6

Ewing stress-strain graphs for typical coupons of the 3 kinds of steel are shown in figure 9.

The speed of the movable head was much lower than is customarily used when determining the yield strength. If the yield strength is

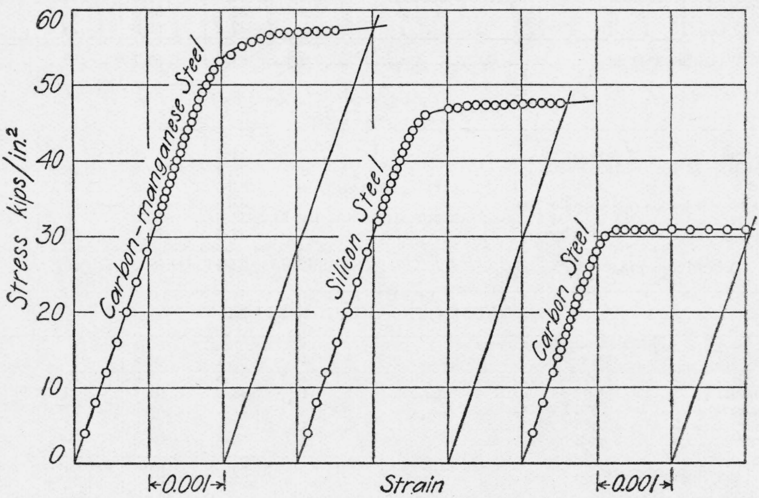

FIGURE 9.—*Typical Ewing stress-strain graphs for the 3 kinds of steel.*

determined by the drop of the beam the value is dependent on the speed—the higher the speed, the higher the yield strength.[8] For these coupons the rate at which the stress was increased is more nearly the rate for the columns than the rate customarily used for coupons.

2. CHEMICAL COMPOSITION

Chemical analyses were made by the Chemistry Division of samples from the coupons having the highest and the lowest tensile strength for each kind of steel, each thickness, and each shape. The results are given in table 4.

[8] Proc. Am. Soc. Testing Materials [I] 28, 105 (1928).

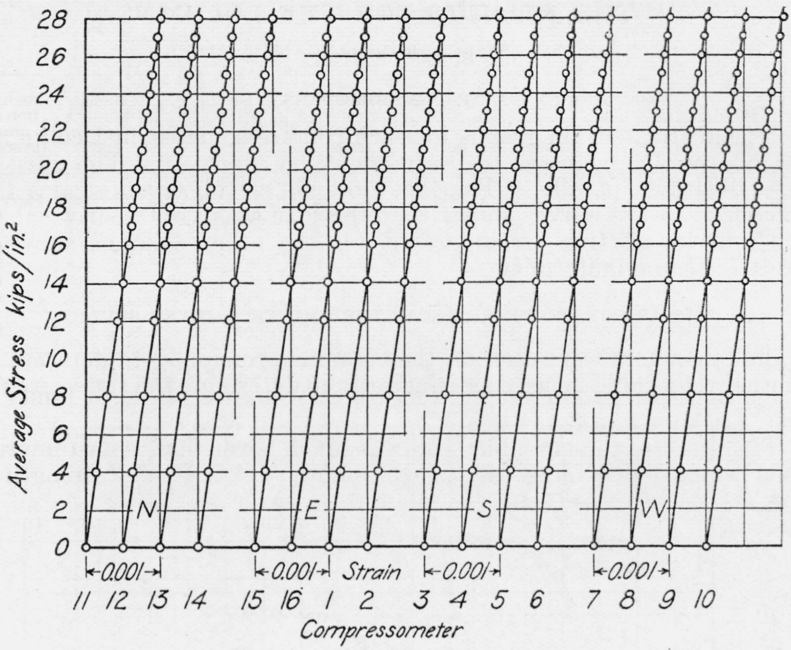

FIGURE 10.—*Typical stress-strain graphs for each compressometer on one column, TM1 carbon-manganese steel.*

The maximum stress was 61.6 kips/in.².

TABLE 4.—*Chemical composition of the steels*

CARBON STEEL

Description of samples			Chemical composition				
Thickness	Shape	Tensile strength	Carbon	Manganese	Phosphorus	Sulphur	Silicon
in.		kips/in.²	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
½	Angle	55. 1	0. 18	0. 56	0. 015	0. 033	0. 03
½	do	66. 9	. 24	. 55	. 018	. 037	. 03
9⁄16	do	53. 3	. 14	. 46	. 012	. 031	. 02
9⁄16	do	61. 0	. 18	. 53	. 026	. 048	. 04
⅝	Plate	53. 0	. 14	. 33	. 009	. 023	. 11
⅝	do	61. 6	. 19	. 46	. 019	. 022	. 11

SILICON STEEL

½	Angle	84. 9	0. 34	0. 80	0. 030	0. 038	0. 25
½	do	109. 0	. 43	1. 09	. 029	. 039	. 35
9⁄16	do	84. 1	. 44	. 81	. 018	. 029	. 29
9⁄16	do	102. 8	. 41	1. 07	. 036	. 032	. 34
⅝	Plate	75. 5	. 31	. 63	. 009	. 023	. 29
⅝	do	98. 8	. 44	. 80	. 029	. 027	. 34

CARBON-MANGANESE STEEL

½	Angle	89. 8	0. 30	1. 47	0. 027	0. 019	0. 18
½	do	99. 7	. 37	1. 54	. 030	. 022	. 17
9⁄16	do	90. 7	. 30	1. 54	. 028	. 018	. 17
9⁄16	do	95. 6	. 33	1. 50	. 027	. 020	. 18
9⁄16	Plate	93. 6	. 30	1. 67	. 028	. 022	. 18
9⁄16	do	105. 2	. 36	1. 72	. 023	. 026	. 17

IV. THE RESULTS FOR THE COLUMNS

1. SHORTENING

(a) COMPRESSOMETERS

Typical stress-strain graphs for each compressometer on 1 column, TM1 carbon-manganese steel, are shown in figure 10. The curves were all drawn parallel. The fact that all the observed strains lie very close to the curves shows that the load was very nearly axial. The individual stress-strain graphs for the other columns showed about the same uniformity.

(b) COMPARISON OF COMPRESSOMETER AND TELEMETER STRAINS

The telemeters were used on the columns principally to determine whether they could be used satisfactorily to determine the stress in the

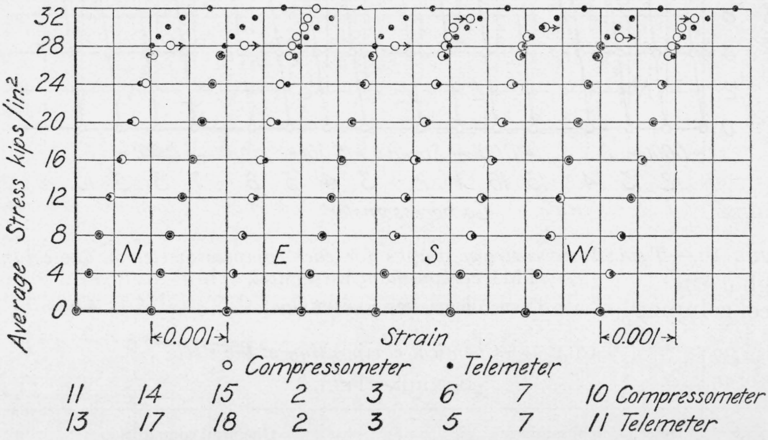

FIGURE 11.—*Stress-strain graphs for the compressometers and for the telemeters which were on the same main members of column* TC1 *carbon steel.*

The maximum stress was 36.9 kips/in.².

steel. On the columns eight of the telemeters were on main members of the column having compressometers. The typical stress-strain graphs shown in figure 11, on one column (TC1 carbon steel) for the last loading, indicate that the compressometers and telemeters gave nearly the same values within the elastic range and that the stress at midheight of the column was nearly the same as the average stress computed from the compressometer readings.

(c) AVERAGE STRESS-STRAIN GRAPHS

The average value of the strains indicated by the 16 compressometers for each load is plotted against the stress for columns TC2, TS1, and TM1 in figure 12. On these columns the load was increased continuously until failure occurred. The corresponding graphs for columns TC1, TS2, and TM2, for which the load was released before failure occurred, are shown in figure 13 together with the graphs of figure 12. These graphs may be compared with the tensile stress-strain graphs for typical coupons shown in figure 9.

(d) ELASTIC PROPERTIES

The elastic properties of the columns are given in table 5. Young's modulus of elasticity for the carbon-steel columns was somewhat

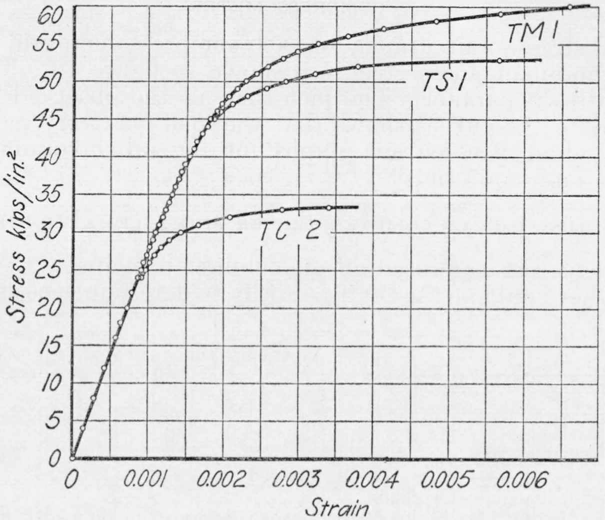

FIGURE 12.—*Stress-strain graphs for the columns on which the load was not released.*

The average compressometer strains were plotted.

higher than for the other columns. For the carbon-steel and silicon-steel columns on which the load was released, the modulus was slightly

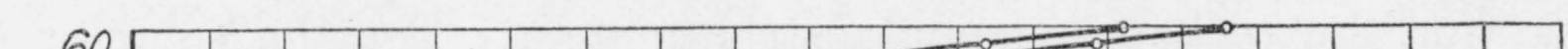

FIGURE 13.—*Stress-strain graphs for the columns.*

The average compressometer strains were plotted. The average of the maximum stresses for the carbon-manganese-steel columns was 62.0 kips/in.²; for the silicon-steel columns, 55.2 kips/in.²; and for the carbon-steel columns 36.8 kips/in.².

greater for the second and third loading than for the first loading. For the carbon-manganese-steel columns the modulus was the same for each of the three loadings.

TABLE 5.—*Elastic properties of the columns*

Column number	Kind of steel	Maximum stress for—			Young's modulus of elasticity		
		First loading	Second loading	Third loading	First loading	Second loading	Third loading
		kips/in.^{2}	kips/in.^{2}	kips/in.^{2}	kips/in.^{2}	kips/in.^{2}	kips/in.^{2}
TC1	Carbon	19.0	27.0	[a] 36.9	28,500	28,700	28,700
TC2	do	[a] 36.8			29,100		
TS1	Silicon	[a] 55.7			28,200		
TS2	do	24.0	40.0	[a] 54.8	28,200	28,500	28,500
TM1	Carbon-manganese	[a] 61.6			28,150		
TM2	do	24.0	40.0	[a] 62.3	28,350	28,350	28,350

Column number	Kind of steel	Proportional limit [b]			Set after	
		First loading	Second loading	Third loading	First loading	Second loading
		kips/in.^{2}	kips/in.^{2}	kips/in.^{2}	*Strain*	*Strain*
TC1	Carbon	[c]	21.0	27.0	0.000027	0.000169
TC2	do	19.0				
TS1	Silicon	25.0				
TS2	do	[c]	28.0	39.0	.000021	.000145
TM1	Carbon-manganese	26.0				
TM2	do	[c]	28.0	40.0	.000013	.000143

[a] Final maximum stress, preceding failure.
[b] Determined as the stress for which the average compressometer strain was 0.000012 greater than the strain computed by the use of the Young's modulus of elasticity.
[c] Not reached.

For the columns on which the load was not released the values given for the first loading may be taken as the original proportional limit. The value for the silicon-steel column is almost the same as that for the carbon-manganese-steel column. For the columns on which the load was released, the proportional limit for the second loading was from 2 to 3 kips/in.^{2} greater than the value for the first loading for the duplicate column on which the load was not released, indicating that the first loading to within 2 kips/in.^{2} of the original proportional limit increased the proportional limit for the second loading. The maximum stress for the second loading exceeded the original proportional limit of the columns, and the proportional limit for the third loading was the same as the maximum stress to which the columns had previously been loaded. For column TS2 the difference between the proportional limit for the third loading and the previous maximum stress (1 kip/in.^{2}) is so small that, in all probability, it is not significant.

The permanent set depended, of course, upon the stress to which the column had previously been loaded. After loading nearly to the original proportional limit there was a small but measurable permanent set. Although loaded to smaller maximum stresses, the permanent set of the carbon-steel column was greater than for the other columns. The silicon-steel and the carbon-manganese-steel columns were loaded to the same maximum stresses, but the permanent sets were less for the carbon-manganese-steel column.

(e) COMPARISON OF STRAINS IN PLATES AND ANGLES

The stress-strain graphs, figure 10, for the compressometers on the plates and on the angles show that for stresses within the elastic ranges of the columns there was no appreciable difference between the strains in the plates and in the angles and therefore that the stresses were practically the same.

The average strain was computed for compressometers 2, 3, 6, 7, 10, 11, 14, and 15 on the plates and for compressometers 1, 4, 5, 8, 9, 12, 13, and 16 on the angles for stresses which were within 4 kips/in.² of the maximum stresses in the columns. The results are given in table 6.

TABLE 6.—*Comparison of the compressometer strains in plates and in angles of the columns*

[The plus sign indicates that the strain in the angles was greater than the strain in the plates]

Column no	TC1	TC2	TS1	TS2	TM1	TM2
Steel	Carbon	Carbon	Silicon	Silicon	Carbon-manganese.	Carbon-manganese.
Average stress, kips/in.²	33	33	52	52	60	60
Average strain in plates	.002495	.002756	.003789	.004015	.006582	.006278
Average strain in angles	.002527	.002800	.003793	.004011	.006617	.006297
Difference, percent	+1.3	+1.6	+0.1	−0.1	+0.5	+0.3
Average difference, percent	+1.4		0.0		+0.4	

The average strain in the angles was approximately the same as the average strain in the plates; for the silicon-steel columns, the strains were equal within 0.1 percent; for the carbon-steel columns, the strain in the angles was greater by 1.4 percent, and for the carbon-manganese-steel columns, the strain in the angles was greater by 0.4 percent.

The difference in the average stress in the angles and in the plates was much less than the difference in the strains because near the maximum stress the stress-strain curve is almost parallel to the axis of strain. The longitudinal members of the steel tower columns, therefore, behaved as a unit under compressive loads.

2. LATERAL DEFLECTION

The deflections at each deflection point are shown in figure 14 for a stress on each column which was within 4 kips/in.² of the maximum stress for the carbon- and silicon-steel columns and within 7 kips/in.² for the carbon-manganese-steel columns. For convenience, the deflections of the opposite sides of the column are both plotted on the side toward which the column deflected, dotted and solid lines being used to distinguish between the deflections of the two sides.

The difference between the solid and dotted lines represents the local deformation of the section. At these loads the local deformation did not exceed 0.05 in., except at the outstanding angles, and the lateral deflection in no case exceeded 0.25 in. These values are small in comparison with the lateral dimensions of the sections (34½ in.) and the length of the columns (288 in.). At approximately 90 percent of the final maximum load, the maximum observed deflection in all cases was less than 0.001 of the length of the column.

For most of the columns the deflection of the outstanding angles (a3, fig. 1) was about the same as that of the plates, showing that at these high loads there was no change of any importance in the relative positions of the main members under load. The columns behaved as sturdy columns, no significant weakening by local deformation occurring until marked plastic deformation had been produced in the column as a whole.

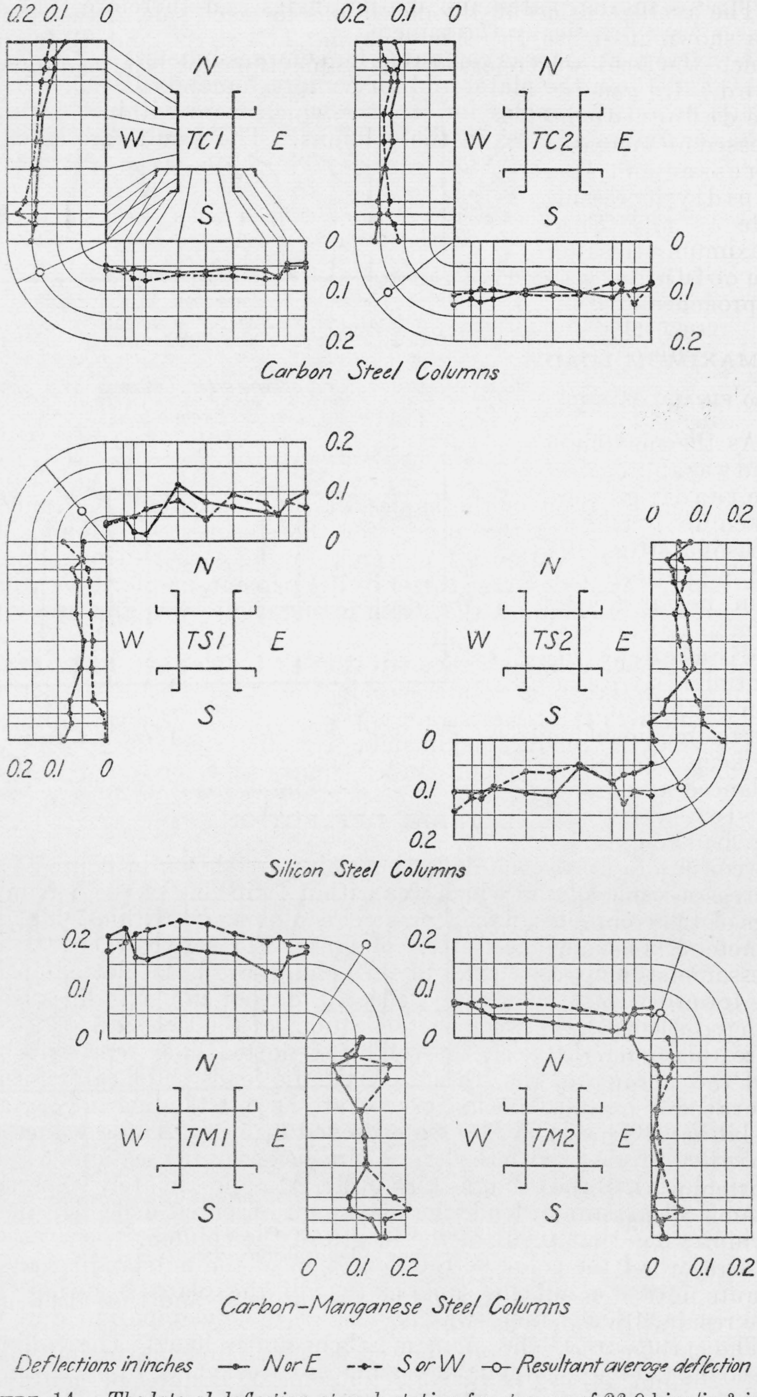

FIGURE 14.—*The lateral deflection at each station for stresses of 33.0* kips/in.^{2} *in the carbon-steel columns, 52.0* kips/in.^{2} *in the silicon-steel columns, and of 57.0* kips/in.^{2} *in the carbon-manganese-steel column* TM1 *and of 55.0* kips/in.^{2} *in column* TM2.

The average values of the deflections for each side of the columns are shown in figure 15. For columns TC1, TS2, and TM2, upon which the load was released, the values for the last loading were used. In general, the deflection increased for increased stresses and at a rapidly increasing rate as the final maximum stress for the columns was approached.

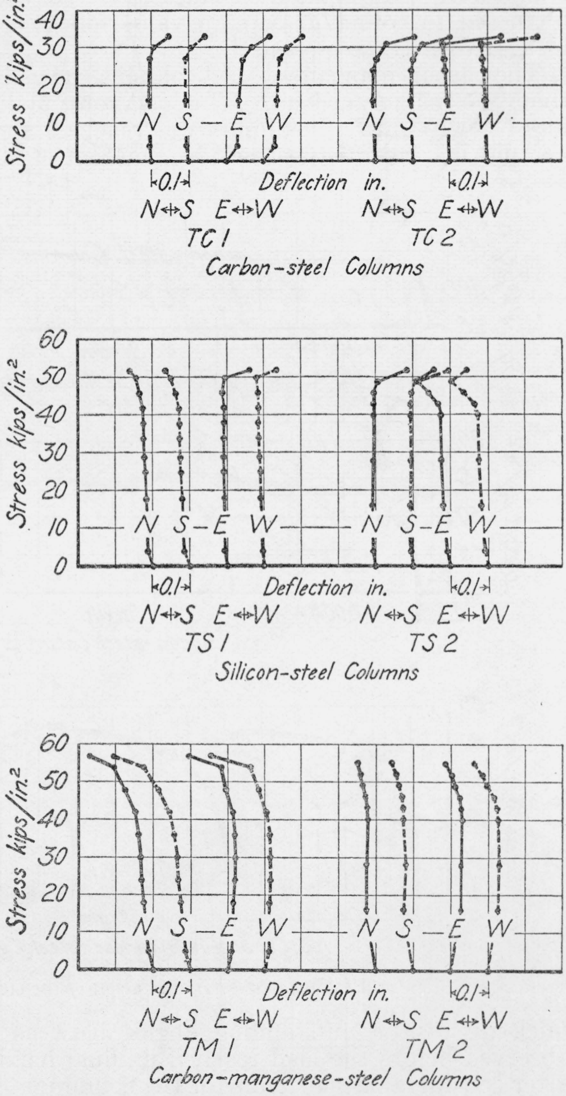

FIGURE 15.—*Average values of the deflections for each side of the columns at different loads.*

3. MAXIMUM LOAD

(a) FINAL LOADING

As the maximum load was approached the readings were taken for each increase in stress of 1 kip/in.² until the column began to deform plastically, as indicated by the continuous operation of the pump of the testing machine to keep the beam balanced at a given, or slowly increasing, load and also by the continuous, slow increases in the readings of the compressometers. The compressometers and the frame for measuring deflections were then removed, and the pump was operated continuously at a speed which caused a shortening of the column of about 0.1 in./min. The load was recorded each minute until it reached its final maximum value and then decreased. The results are shown in figure 16.

The carbon-steel columns showed definite "first maximum" loads, the loads holding nearly constant for some 20 minutes of continuous pumping, and in the case of column TC2 showing a slight but definite decrease. On further pumping, the loads on these columns picked up to second maximum values and then decreased with rapidly increasing local deformation.

The silicon-steel columns showed no definite first maximum load, but with continuous pumping the load increased very slowly for over 5 minutes. The load then started to rise again more rapidly and increased to a final maximum value followed by a decrease as the local deformation increased.

The carbon-manganese-steel columns showed no indication of more than one maximum load. The load continually increased more and more slowly until a maximum was reached, and then decreased with a rapid increase of the local deformation of the column. Incipient

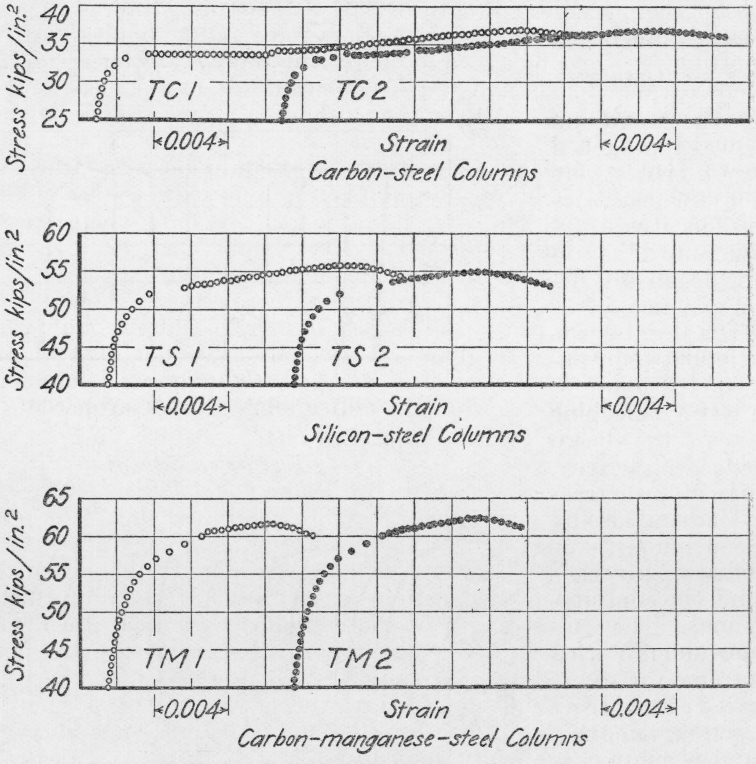

FIGURE 16.—*Final loading of the columns.*

buckling of the outstanding angles between the diaphragms was observed before the load reached its final maximum value, but only after considerable shortening of the column.

(b) "PICK-UP" OF LOAD

The behavior of these columns is similar in this respect to that of some of the small specimens tested by von Kármán.[9]

The behavior of the carbon-steel columns in particular is also similar to that of the heavy 12-foot H columns (l/r=37.8 to 40.5) tested some years ago at the Bureau.[10] In those tests, after the first maxi-

[9] Th. von Kármán. Untersuchungen über Knickfestigkeit, Mitt. über Forsch. arb. (VDI) **81,** 31 (1910).
[10] BS Tech. Pap. **21,** (1926) T328. See particularly p. 57–60.

mum load was passed the stress fell off by amounts ranging from about 0.2 kip/in.^{2} to over 2.0 kips/in^2. before the increase to the second maximum load began. In discussing these tests it was pointed out that [11] "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."

In the present tests the columns were relatively considerably heavier ($l/r=28.9$) so that the absence of a definite decrease between the first maximum and second maximum loads was to be expected.

The difference in the behavior of the columns of the different materials is accounted for by the different character of the stress-strain graph for the material. Practically all of the stress-strain graphs for the carbon-steel coupons showed a sharp knee and a definite horizontal portion, or yield point. Graphs of this kind were fewer for the coupons of silicon steel and the stress-strain graphs for nearly all of the carbon-manganese-steel coupons showed a blunt knee with a continual rise as the strain increased.

As was pointed out in the discussion of the previous tests, the final maximum load of a column showing pick-up represents a state of very precarious stability of the column. It is reached only when the columns are already badly deformed and very small changes in the columns or the test conditions may make the columns unstable. In the previous series of tests differences as great as 15 percent were observed in the final maximum loads of duplicate columns under carefully controlled test conditions. The final maximum load of any column showing pick-up should not be used for designing columns for a structure, the failure of which would endanger life or property.

(c) STRENGTH

The column strengths given in BS Technologic Paper T328 were the values of the first maximum stress. It was stated that "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."

With regard to the procedure that should be followed when no maximum is observed before the column is badly deformed, it was stated that "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."

In tensile tests of steels which do not show a definite yield point, it has become customary to define a yield strength in terms of the stress necessary to produce a definite strain (usually 0.002) in the coupon in excess of the computed elastic strain. It seemed probable that a similar definition of a column yield strength would be satisfactory for columns for which no definite first maximum load is observed, and for this reason the column yield strengths were computed on this basis.

[11] BS Tech. Pap. **21,** 59 (1926) T328.

The column yield strength, the first maximum and final maximum stress, and the column efficiency are given in table 7. For the carbon-steel and silicon-steel columns for which a definite first maximum load was observed, the column yield strength is substantially identical with the first maximum stress. An examination of the data in BS Technologic Paper T328 shows that a similar relation holds for the shorter columns which showed hang-on or pick-up of load.

TABLE 7.—*Strength and efficiency of the columns*

Column number	Kind of steel	Final maximum load	Weighted yield strength of material	Column yield strength[1]	First maximum stress	Final maximum stress	Column efficiency (based on column yield strength)
		kips	kips/in.^{2}	kips/in.^{2}	kips/in.^{2}	kips/in.^{2}	*Percent*
TC1	Carbon	5,860	34.0	33.4	33.6	36.9	98
TC2	do	5,846	33.9	33.3	33.5	36.8	98
	Average	5,853	34.0	33.3	33.5	36.8	98
TS1	Silicon	8,862	52.9	51.9	53.0	55.7	98
TS2	do	8,720	52.5	51.6	53.5	54.8	98
	Average	8,791	52.7	51.7	53.2	55.2	98
TM1	Carbon-manganese	9,293	56.7	56.8	----------	61.6	100
TM2	do	9,402	57.0	57.2	----------	62.3	100
	Average	9,348	56.8	57.0	----------	62.0	100

[1] Stress for which the strain is 0.002 greater than the elastic strain.

The column yield strength for the silicon-steel columns was 1.55 times that for the carbon-steel columns. For the carbon-manganese-steel columns it was 1.71 times that for the carbon-steel columns.

The column efficiency was 98 percent for the carbon-steel and for the silicon-steel columns and 100 percent for the carbon-manganese-steel columns.

Since the speed of the movable platen of the testing machine used for determining the yield strength of the coupons (0.01 to 0.04 in./min) was lower than that customarily used (up to 2 in./min on an 8-in. gage length), the yield strengths of the coupons were somewhat lower than those ordinarily obtained for structural steel. Had the customary speed been used, the values for the column efficiency would have been less.

The results in BS Technologic Paper T328 were corrected to a speed of 0.37 in./min on the basis of measurements at speeds of 0.012 and 0.37 in./min. The yield point observed at the higher speed was on the average 1.127 times that observed at the lower speed. Had the results been corrected to the lower speed instead of the higher, the efficiencies obtained for the columns having a slenderness ratio of about 40 would have ranged from 91 to 110 percent instead of 81 to 97 percent. Hence the efficiencies obtained in the present series of tests are consistent with those obtained in the previous tests when based on weighted yield strengths of the material obtained at the same speed.

The consistency of all these results indicates that in the case of sturdy columns which show no maximum load before the columns

FIGURE 17.—*A carbon-steel column,* TC2 *after test.*

The maximum stress was 36.0 kips/in². The deflection of the column from the cord at the left is apparent.

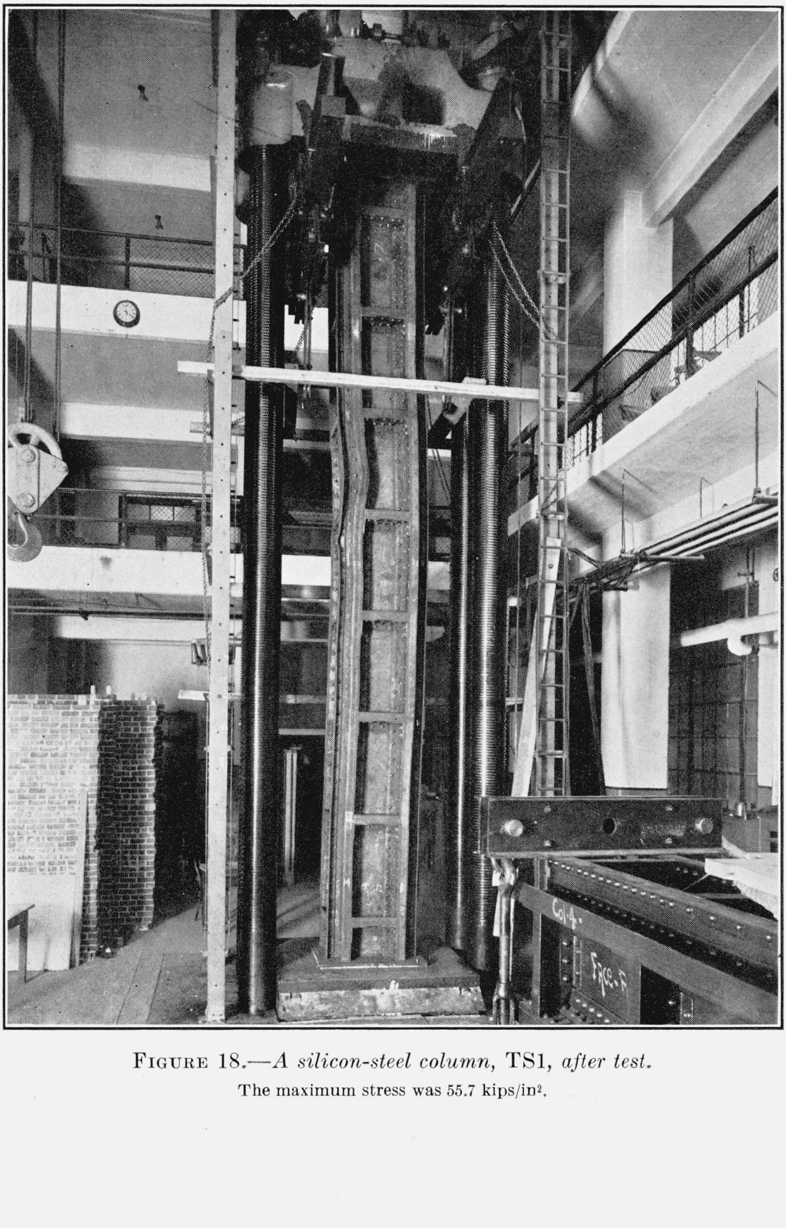

FIGURE 18.—*A silicon-steel column,* TS1, *after test.*

The maximum stress was 55.7 kips/in^2.

are markedly deformed, the column yield strength as here defined is a satisfactory practical measure of the strength of the column.

Further tests may indicate the possibility of defining a somewhat better measure, but the difference will be of little if any practical significance in large columns with their necessarily inhomogeneous material.

(d) DESCRIPTION OF THE FAILURE

For the carbon-steel (TC) and the silicon-steel (TS) columns the yield strength of the outstanding angles was greater than the weighted yield strength of the column material. For the carbon-manganese-steel (TM) columns the yield strength of the outstanding angles was somewhat less than the weighted yield strength of the column material. As the load was increased, Lüder's lines appeared on the plates of the carbon-steel and the silicon-steel columns before they appeared on the outstanding angles. As the load continued to increase, the deflection of the column as a whole caused buckling of the outstanding angles as shown in figures 17 and 18.

As the load was increased, Lüder's lines appeared on the outstanding angles of the carbon-manganese-steel columns before they appeared on the plates, as shown in figure 19. The way in which the carbon-manganese-steel columns failed is shown in figure 20.

For all the columns the outstanding angles buckled between the diaphragms on the concave sides of the column. Some shallow buckles also occurred in the plates and in the angles at the intersection of the plates. No rivets failed. The local buckling occurred only after considerable shortening of the column and was not the primary cause of failure. The primary failure was by plastic yielding as is also shown by the close agreement of the tensile yield strength of the material with the column yield strength when both are determined at comparable speeds of the testing machine.

V. CONCLUSIONS

1. The loading was nearly axial.

2. The strains under loads up to the end of the elastic range of the columns indicated by the compressometers and by the telemeters were very nearly the same.

3. The stress-strain graphs for the columns were very similar to those for the coupons.

4. Young's modulus of elasticity for the columns made from carbon steel was somewhat higher than that for the columns made from carbon-manganese steel and from silicon steel.

For the carbon-steel and the silicon-steel columns on which the load was released and then reapplied, the modulus was slightly greater for the second and third loading than for the first loading. For the carbon-manganese-steel columns, the modulus was the same for each of the three loadings.

5. The proportional limit was taken as the stress at which the observed strain exceeded the value computed from Young's modulus of elasticity by 0.000012. For the columns on which the load was not released the proportional limit was almost the same for the silicon-steel columns and for the carbon-manganese-steel columns. For the columns on which the load was released the proportional

limit for the second loading was from 2 to 3 kips/in.^{2} greater than for the first loading.

6. After loading to nearly the proportional limit for the first loading, there was a small but measurable set. The set was the least for the carbon-manganese steel and the greatest for the carbon-steel columns.

7. For stresses within the elastic ranges of the columns there was no appreciable difference between the strains in the plates and in the angles, and therefore the stresses were practically the same. For stresses beyond the elastic range of the columns, the average strain in the angles of the carbon-steel columns was 1.4 percent greater than the average strain in the plates; for the silicon-steel columns the strains were the same, and for the carbon-manganese-steel columns the strain in the angles was 0.4 percent greater. The differences in stress were much less than these values; therefore the plates and angles behaved as a unit under compressive loads.

8. For stresses which were nearly the maximum stresses in the columns the lateral deflections were very small. The deflections of the outstanding angles were about the same as those of the plates, showing that there was no significant change in the relative positions of the longitudinal members under load. Under load these columns behaved as sturdy columns.

9. The carbon-steel columns exhibited the phenomenon of pick-up, i. e., a definite first maximum load, a constant or slightly decreasing load for a considerable further shortening of the column, followed by a pick-up to a second higher maximum load after the columns were markedly deformed. The silicon-steel columns showed no definite first maximum load, but the load increased very slowly for a considerable shortening of the column and then more rapidly with further shortening. The carbon-manganese-steel columns showed no indication of more than one maximum load.

10. The column yield strength, taken as the stress for which the average strain is 0.002 greater than the elastic strain, appears to be a satisfactory measure of the strength of columns which do not show a maximum load before the column is deformed by that amount. The column yield strength for the silicon-steel columns was 1.55 times that for the carbon-steel columns. For the carbon-manganese-steel columns it was 1.71 times that for the carbon-steel columns. These ratios are practically the same as the ratios of the average yield strengths of the materials.

11. The practical constancy of these ratios is shown by the column efficiencies. For these columns having a slenderness ratio of 28.9, the column efficiency, defined as the quotient of the column yield strength divided by the weighted yield strength of the column material, was approximately 100 percent. For the carbon-manganese-steel columns the efficiency was 100 percent; for the carbon-steel and silicon-steel columns, 98 percent. These values are about the same as those observed in previous tests on columns having a slenderness ratio of about 40, when allowance is made for the effect of the speed of the testing machine on the yield strength of the column material.

12. For all the columns the outstanding angles buckled between the diaphragms on the concave sides of the columns. Shallow buckles also occurred in the plates and in the angles at intersection of the plates. No rivets failed. The local buckling occurred only after

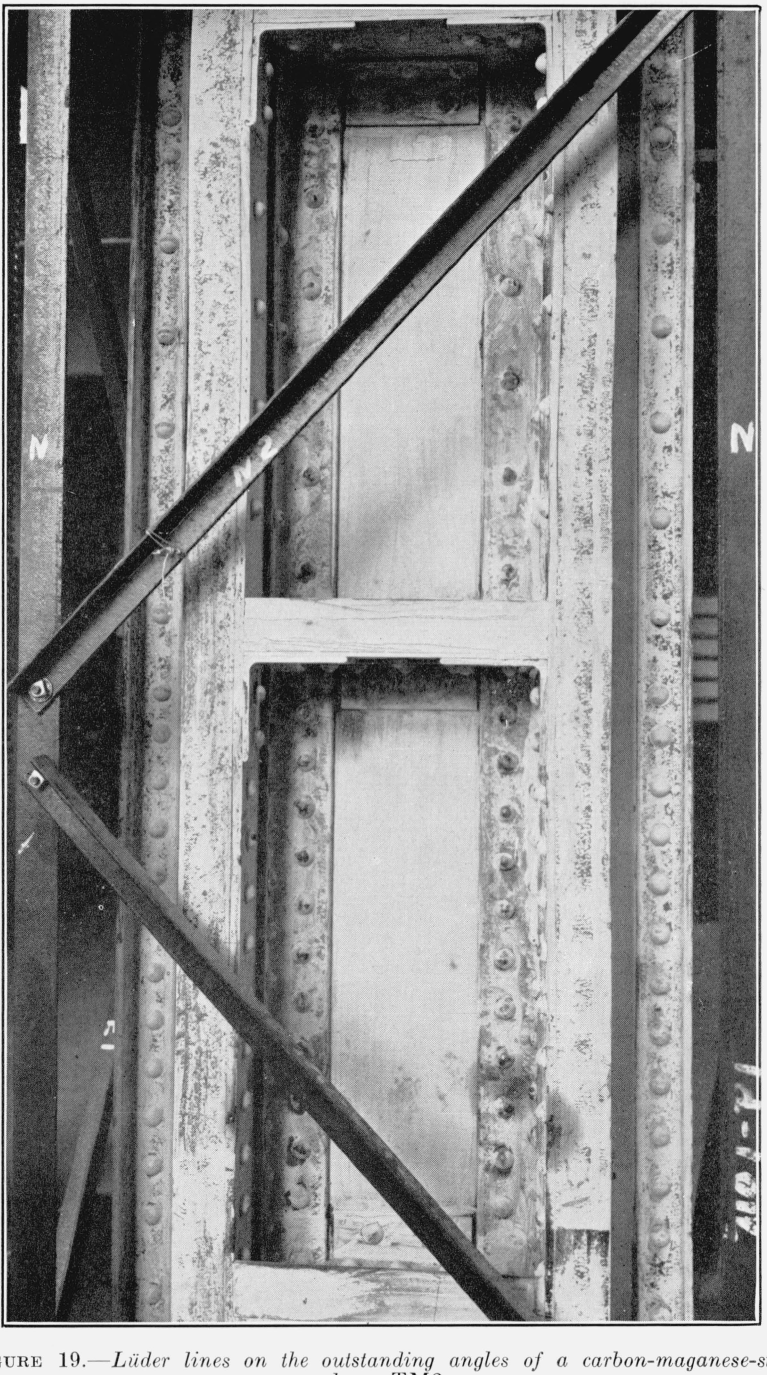

FIGURE 19.—*Lüder lines on the outstanding angles of a carbon-maganese-steel column* TM2.

No Lüder lines were observed on the plates.

FIGURE 20.—*A carbon-manganese-steel column,* TM2, *after test.*
The maximum stress was 62.3 $kips/in^2$.

considerable shortening of the column and was not the primary cause of failure.

13. The tests confirm for these columns the conclusion from previous column tests that the tensile yield strength of the material determined at a speed of the testing machine comparable with that used in the column tests will furnish a close measure of the strength of short sturdy columns.

The program and testing procedure were prepared by O. H. Ammann, L. S. Moiseiff, and R. S. Johnston, representing the Port of New York Authority, and by L. J. Briggs, L. B. Tuckerman, and H. L. Whittemore, representing the National Bureau of Standards. The following members of the staff of the Port of New York Authority assisted in making the tests and obtaining the data: A. H. Baker, F. J. Hinners, S. K. Hoppen, B. H. Lefeve, L. D. Mork, R. B. Morris, and G. A. Woods.

WASHINGTON, July 29, 1935.

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