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TESTS OF EIGHT LARGE H-SHAPED COLUMNS FABRICATED FROM CARBON-MANGANESE STEEL

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ABSTRACT

As part of its program to investigate the behavior of compression members of carbon-manganese steel, such as were used for the compression chords of the Bayonne arch bridge, the bridge department of the Port of New York Authority requested the cooperation of the National Bureau of Standards in an investigation of the strength and behavior under load of large H-shaped columns fabricated from plates and angles and material representative of those which went into the actual structure. Eight columns were tested.

The shortening and lateral deflection under load were measured. The strain was also measured on seven 2-inch vertical gage lines near the top and bottom of the column and at midheight. The properties of the material were determined by tensile tests of coupons.

It was found that:

1. The loading was more eccentric than in the tests of tower and chord columns described in Research Papers RP831 and RP897.

2. All the columns deflected in a direction perpendicular to the web. Apparently there was no relation between the direction in which the columns deflected and the distribution of yield strength of the material across the column.

3. For seven of the eight columns the strength exceeded the capacity of the testing machine (10,000 kips).

4. The column efficiency was obtained by dividing the column yield strength by the weighted yield strength of the column material. For the columns having cover plates 1.5 in. thick the average column efficiency was 95.0 percent and for the columns having cover plates 1.25 in. thick, 96.5 percent.

CONTENTS

I. INTRODUCTION

Because few tests have been made on large fabricated columns of high-strength steel, the bridge department of the Port of New York Authority requested the cooperation of the National Bureau of Standards in an investigation of the strength and behavior under load of large H-shaped columns fabricated from plates and angles.

II. THE SPECIMENS AND THE METHOD OF TESTING

1. THE COLUMNS

(a) DESCRIPTION

The nominal dimensions and properties of the columns are given in table 1. There were eight columns fabricated by riveting from

TABLE 1.—*Nominal dimensions and properties of the 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.	in.⁴	in.⁴	in.	in.		
4	HM1 to HM4	Carbon-manganese.	145	9	8	12,186	2,899	9.17	4.47	12.6	25.9
4	HM5 to HM8	do	135	9	8	10,835	2,566	8.96	4.36	13.0	26.6

plates and angles of carbon-manganese steel. The steel was from different heats and the results of the tests of the coupons showed that the tensile properties varied over a rather wide range.

The dimensions of the columns are shown in figure 1. The columns were designated HM followed by the numerals 1, 2, etc., for the individual columns. The web plates and the angles were the same size for all the columns. For the four columns HM1, HM2, HM3, and HM4, the cover plates were 1.5 in. thick and for the remaining four, HM5, HM6, HM7, and HM8, the cover plates were 1.25 in. thick.

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 coupons cut from the same plate or angle, and its location in the column was recorded.

(b) TESTING PROCEDURE

All the columns were tested as flat-end columns by the use of the equipment and methods described in National Bureau of Standards

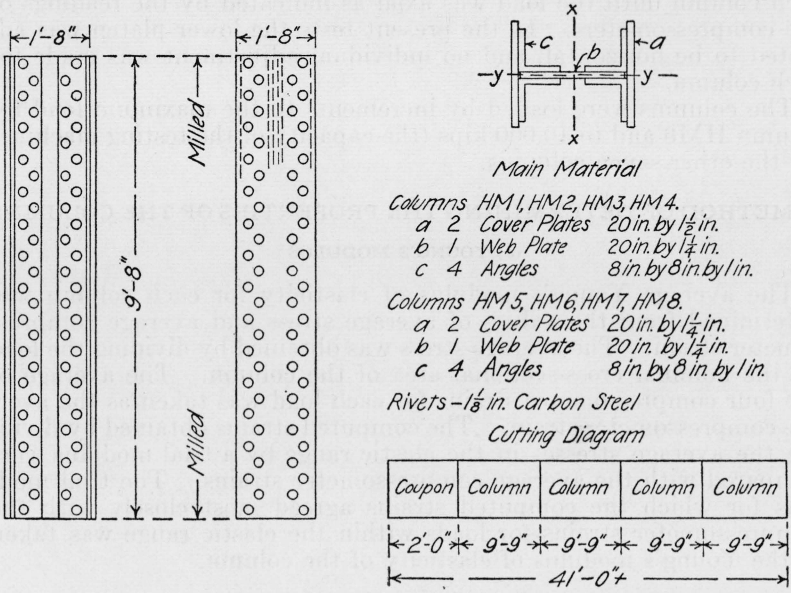

FIGURE 1.—*Dimensions of the columns.*

h Pape RP831, Tests of Steel Tower Columns for the George Washington Bridge.[1]

(1) *Compressometers.*—Compressometers similar to those used for the tower columns, except that the gage length was 5 ft, were used to measure the shortening of the columns under load. The locations of the four compressometers are shown in figure 2.

(2) *Lateral deflection.*—The lateral deflection of the columns was measured by the use of the taut-wire, mirror-scale deflectometer. The distance between the supports for the wire was 8 ft 8 in., and the middle of the wire was at midheight of the column. One division on the scale was 0.1 in., and readings were estimated to 0.1 of a division. The locations of the three deflectometers are shown in figure 2.

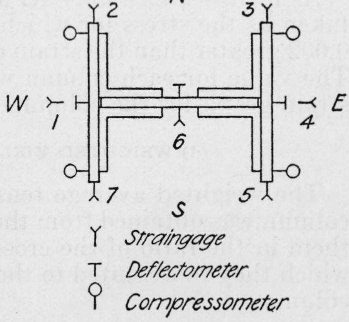

FIGURE 2.—*Locations of the straingage lines, the deflectometers, and the compressometers on the columns.*

(3) *Strains.*—At elevations of 37.5 in. from the bottom, at midheight, and at 37.5 in. from the top of each column, seven 2-in. vertical gage lines were laid off at the locations shown in figure 2.

[1] J. Research NBS 15, 317 (1935) RP831.

The strains were measured manually by the use of a Whittemore strain gage.

(4) *Loading*.—In tests on the tower columns (RP831) the lower platen of the testing machine was adjusted in its spherical seat for each column until the load was axial as indicated by the readings of the compressometers. In the present tests the lower platen was adjusted to be horizontal, and no individual adjustment was made for each column.

The columns were loaded by increments to the maximum load for column HM6 and to 10,000 kips (the capacity of the testing machine) for the other seven columns.

2. 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 average of the four 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

As in Research Paper RP831 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 longitudinal piece 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.

3. COUPONS

(a) GENERAL

The coupons were machined from the piece 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 plate three coupons were taken, one at the middle, one at the edge of the plate, and one midway between these two coupons. From each angle 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.[3] These coupons had a gage length of 8 in., a width at the reduced section of 1.5 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 Materials of the Technical Committee on Mechanical Testing of the American Society for Testing Materials.[4] 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.

(d) EXTENSOMETER

The strains in some coupons 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 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.

(e) TESTING MACHINE

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

(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

[3] Figure 1, Stand. Am. Soc. Testing Materials [1] 68 (1933).
[4] Proc. Am. Soc. Testing Materials [1] 31, 602 (1931).

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.

III. RESULTS FOR THE COUPONS

1. TENSILE TESTS

The results of the tensile tests of the coupons are given in table 2. The properties of the material are average values for the longitudinal members of the same size and shape.

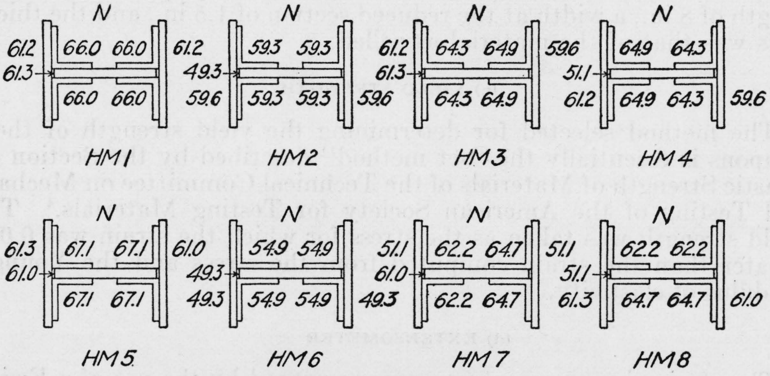

FIGURE 3.—*Average yield strength, in kips per square inch, of the coupons representing each longitudinal piece of the columns.*

A typical Ewing stress-strain graph for the carbon-manganese steel is shown in figure 9 of Research Paper RP 831.

The speed of the movable head of the testing machine was much lower than is customarily used when determining the yield strength. 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 of samples from coupons having the highest and the lowest tensile strength for each thickness and each shape. The results are given in table 3.

IV. RESULTS FOR THE COLUMNS

1. YIELD STRENGTH OF THE LONGITUDINAL PIECES

The average yield strength of the material for each longitudinal piece of the column is shown in figure 3.

TABLE 2.—*Results of the tensile tests of columns*

COLUMN HM1—CARBON-MANGANESE

Column material		Yield strength (average)	Tensile strength (average)	Elongation in 8 inches (average)	Reduction of area (average)
Shape	Nominal size				
	In.	*kips/in.²*	*kips/in.²*	*Percent*	*Percent*
1 plate	20 by 1.5	61.2	106.3	18.5	42.4
1 plate	20 by 1.5	61.2	106.3	18.5	42.4
1 plate	20 by 1.25	61.3	107.5	17.6	37.5
2 angles	8 by 8 by 1	66.0	97.5	20.0	49.8
2 angles	8 by 8 by 1	66.0	97.5	20.0	49.8
Weighted average		63.2	102.9	19.0	44.6

COLUMN HM2—CARBON-MANGANESE

1 plate	20 by 1.5	59.6	104.0	19.0	41.8
1 plate	20 by 1.5	59.6	104.0	19.0	41.8
1 plate	20 by 1.25	49.3	88.3	26.0	56.1
2 angles	8 by 8 by 1	59.3	97.4	19.0	39.7
2 angles	8 by 8 by 1	59.3	97.4	19.0	39.7
Weighted average		57.7	98.5	20.2	43.4

COLUMN HM3—CARBON-MANGANESE

1 plate	20 by 1.5	61.2	106.3	18.5	42.4
1 plate	20 by 1.5	59.6	104.0	19.0	41.8
1 plate	20 by 1.25	61.3	107.5	17.6	37.5
2 angles	8 by 8 by 1	64.3	100.2	18.2	43.8
2 angles	8 by 8 by 1	64.9	97.0	19.7	48.9
Weighted average		62.3	102.8	18.6	43.1

COLUMN HM4—CARBON-MANGANESE

1 plate	20 by 1.5	61.2	106.3	18.5	42.4
1 plate	20 by 1.5	59.6	104.0	19.0	41.8
1 plate	20 by 1.25	51.1	93.3	22.2	56.1
2 angles	8 by 8 by 1	64.9	97.0	19.7	48.9
2 angles	8 by 8 by 1	64.3	100.2	18.2	43.8
Weighted average		60.5	100.4	19.4	46.3

COLUMN HM5—CARBON-MANGANESE

1 plate	20 by 1.25	61.3	107.5	17.6	37.5
1 plate	20 by 1.25	61.0	104.9	19.0	42.6
1 plate	20 by 1.25	61.0	104.9	19.0	42.6
2 angles	8 by 8 by 1	67.1	97.2	18.5	46.4
2 angles	8 by 8 by 1	67.1	97.2	18.5	46.4
Weighted average		63.8	101.9	18.5	43.3

COLUMN HM6—CARBON-MANGANESE

1 plate	20 by 1.25	49.3	88.3	26.0	56.1
1 plate	20 by 1.25	49.3	88.3	26.0	56.1
1 plate	20 by 1.25	49.3	88.3	26.0	56.1
2 angles	8 by 8 by 1	54.9	93.3	21.7	50.6
2 angles	8 by 8 by 1	54.9	93.3	21.7	50.6
Weighted average		51.8	90.5	24.1	53.6

TABLE 2.—*Results of the tensile tests of columns*—Continued

COLUMN HM7—CARBON-MANGANESE

Column material: Shape	Column material: Nominal size	Yield strength (average)	Tensile strength (average)	Elongation in 8 inches (average)	Reduction of area (average)
	In.	*kips/in.*[2]	*kips/in.*[2]	*Percent*	*Percent*
1 plate	20 by 1.25	51.1	93.3	22.2	56.1
1 plate	20 by 1.25	51.1	93.3	22.2	56.1
1 plate	20 by 1.25	61.0	104.9	19.0	42.6
2 angles	8 by 8 by 1	62.2	96.9	21.0	49.7
2 angles	8 by 8 by 1	64.7	96.9	19.5	51.8
Weighted average		58.4	97.0	20.7	51.2

COLUMN HM8—CARBON-MANGANESE

Column material: Shape	Column material: Nominal size	Yield strength (average)	Tensile strength (average)	Elongation in 8 inches (average)	Reduction of area (average)
1 plate	20 by 1.25	61.3	107.5	17.6	37.5
1 plate	20 by 1.25	61.0	104.9	19.0	42.6
1 plate	20 by 1.25	51.1	93.3	22.2	56.1
2 angles	8 by 8 by 1	64.7	96.9	19.5	51.8
2 angles	8 by 8 by 1	62.2	96.9	21.0	49.7
Weighted average		60.3	99.7	19.9	47.8

TABLE 3.—*Chemical composition of the carbon-manganese steel*

Description of samples			Chemical composition				
Thickness	Shape	Tensile strength	Carbon	Manganese	Phosphorus	Sulphur	Silicon
In.		kips/in.[2]	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
1	Angle	93.3	0.31	1.55	0.029	0.015	0.20
1	do	100.2	.33	1.70	.020	.021	.17
1.25	Plate	86.0	.30	1.49	.034	.029	.17
1.25	do	109.3	.39	1.88	.024	.024	.17
1.5	do	101.2	.32	1.91	.024	.022	.18
1.5	do	108.5	.37	1.95	.027	.024	.19

2. SHORTENING

Typical graphs of average column stress plotted against the strain for each compressometer on column HM6 are shown in figure 4. The curves were all drawn parallel. These graphs are typical of those for the other columns. A comparison of these graphs with those for a tower column shown in figure 10 of Research Paper RP831 indicates that the loads on these H-shaped columns were somewhat more eccentric than those on the tower columns.

For each load, also, the average strain for each column was computed from the values for the four compressometers. These average strains were used for the average stress-strain graphs for each column shown in figure 5.

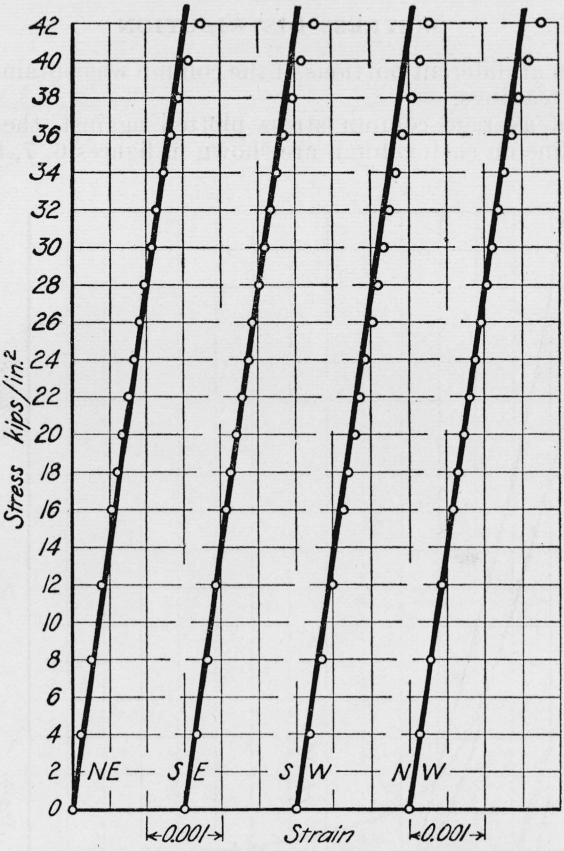

Figure 4.—*Typical graphs of average column stress plotted against the stress for each compressometer on column* HM6.

The properties of the columns are given in table 4.

Table 4.—*Properties of the columns*

Column	Young's modulus of elasticity	Proportional limit [1]	Weighted yield strength of material	Column yield strength	Column efficiency (based on column yield strength)	Column was loaded to		Remarks
						Load	Stress	
	kips/in.²	kips/in.²	kips/in.²	kips/in.²	*Percent*	kips	kips/in.²	
HM1	29,000	28	63.2	60.5	95.7	10,005	69.0	
HM2	27,150	28	57.7	54.5	94.5	10,005	69.0	
HM3	28,300	32	62.3	59.5	95.5	10,005	69.0	
HM4	29,000	24	60.5	57.0	94.2	10,005	69.0	
Average					95.0			
HM5	28,200	32	63.8	60.5	94.8	9,990	74.0	
HM6	27,600	28	51.8	50.5	97.5	9,940	73.6	Final maximum.
HM7	28,800	34	58.4	56.5	96.7	9,990	74.0	
HM8	28,100	28	60.3	58.5	97.0	9,990	74.0	
Average					96.5			

[1] 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.

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3. STRESS DISTRIBUTION

The strain at different portions of the column was obtained from the strain-gage readings.

Graphs of average column stress plotted against the strain for each gage line on each column are shown in figures 6, 7, 8, 9, 10, 11, 12, and 13.

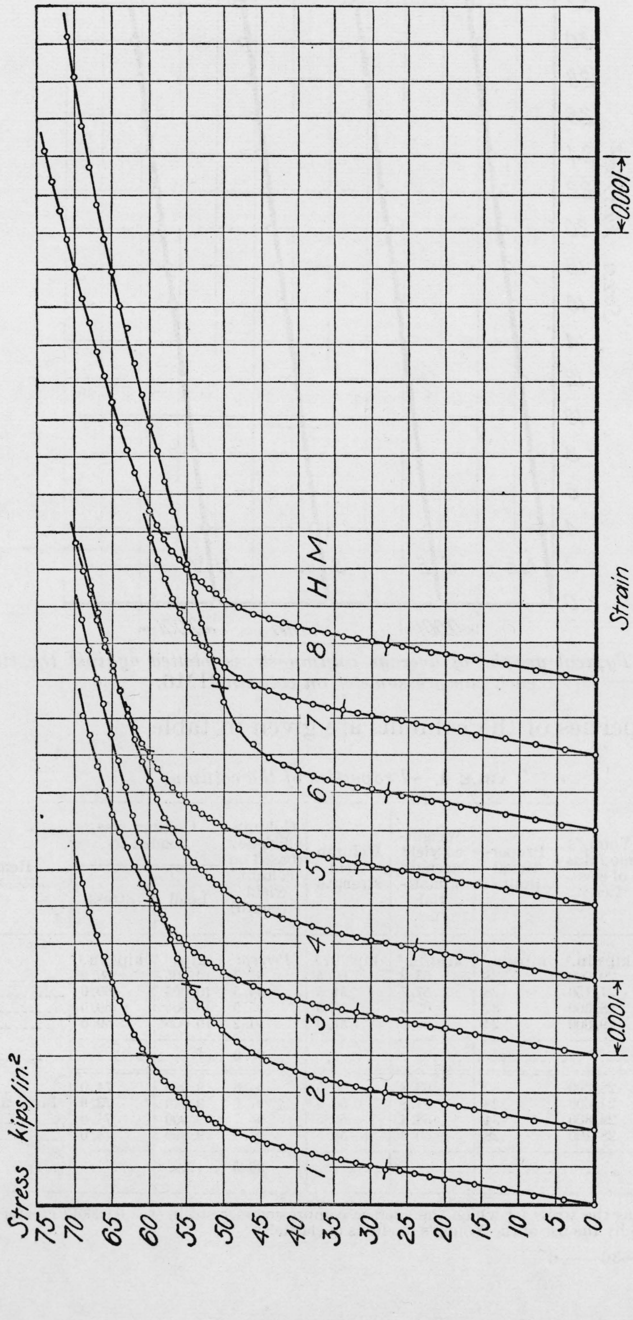

FIGURE 5.—*Stress-strain graphs for each column.*

(The strains are the average of the values for the four compressometers.)

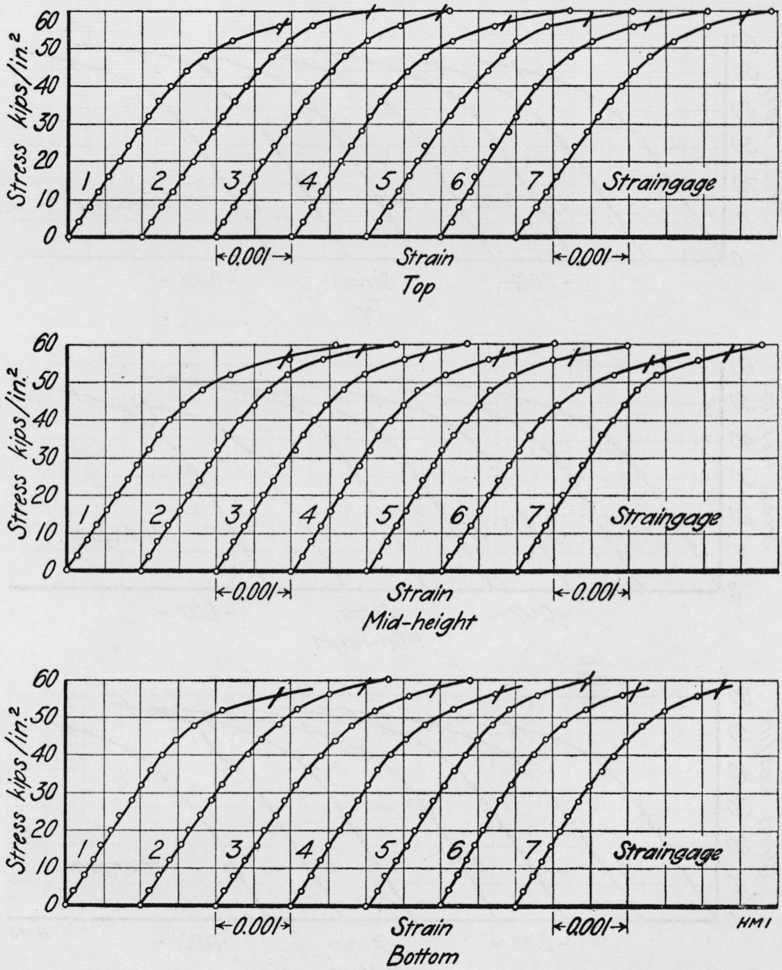

FIGURE 6.—*Stress-strain graphs for the strain-gage lines on column* HM1.

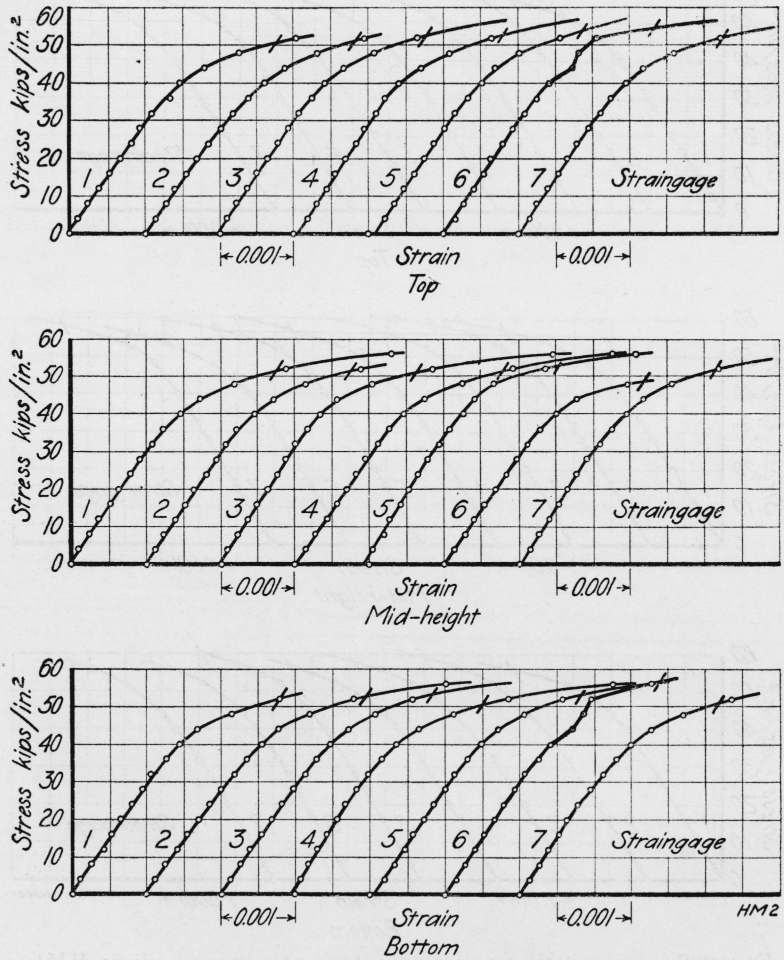

FIGURE 7.—*Stress-strain graphs for the strain-gage lines on column* HM2.

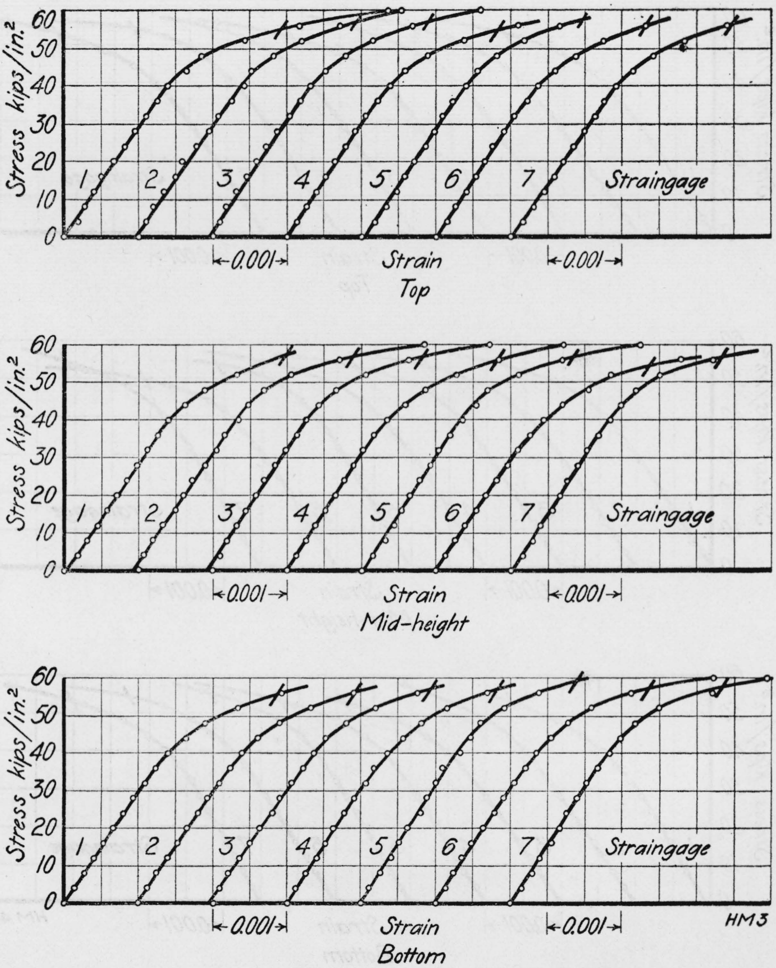

FIGURE 8.—*Stress-strain graphs for the strain-gage lines on column* HM3.

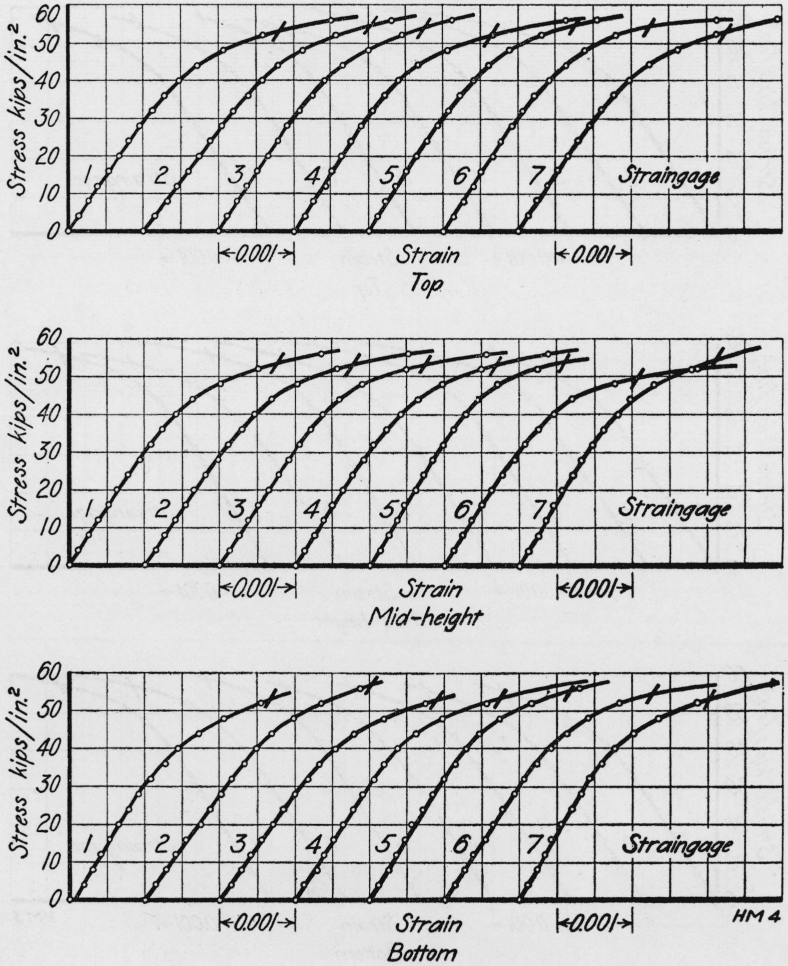

FIGURE 9.—*Stress-strain graphs for the strain-gage lines on column* HM4.

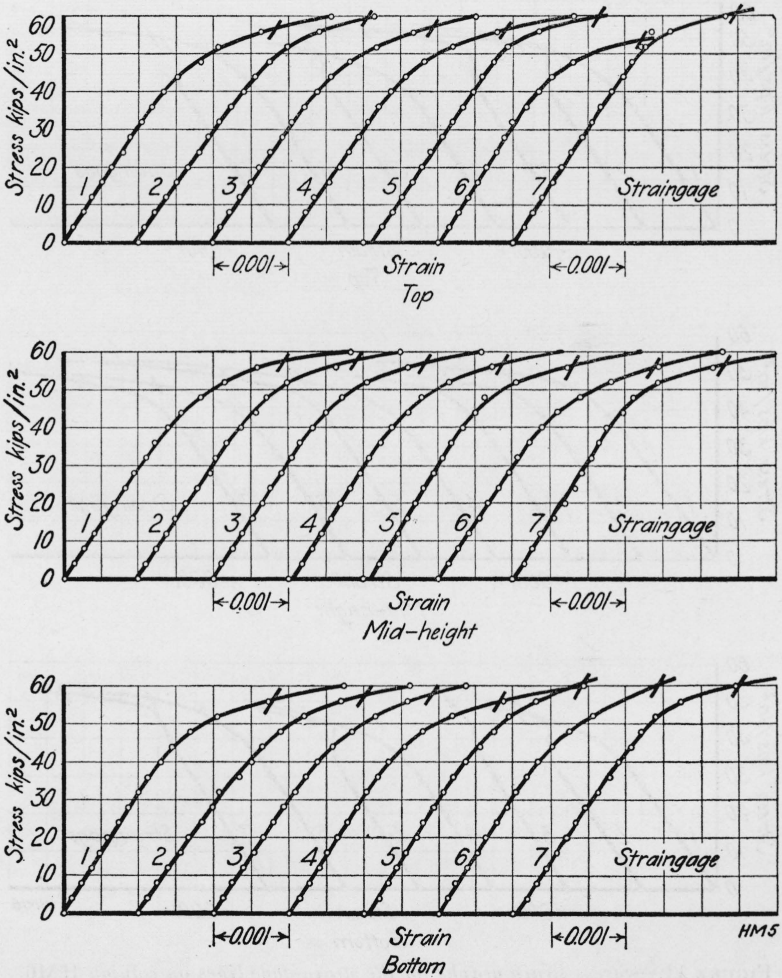

FIGURE 10.—*Stress-strain graphs for the strain-gage lines on column* HM5.

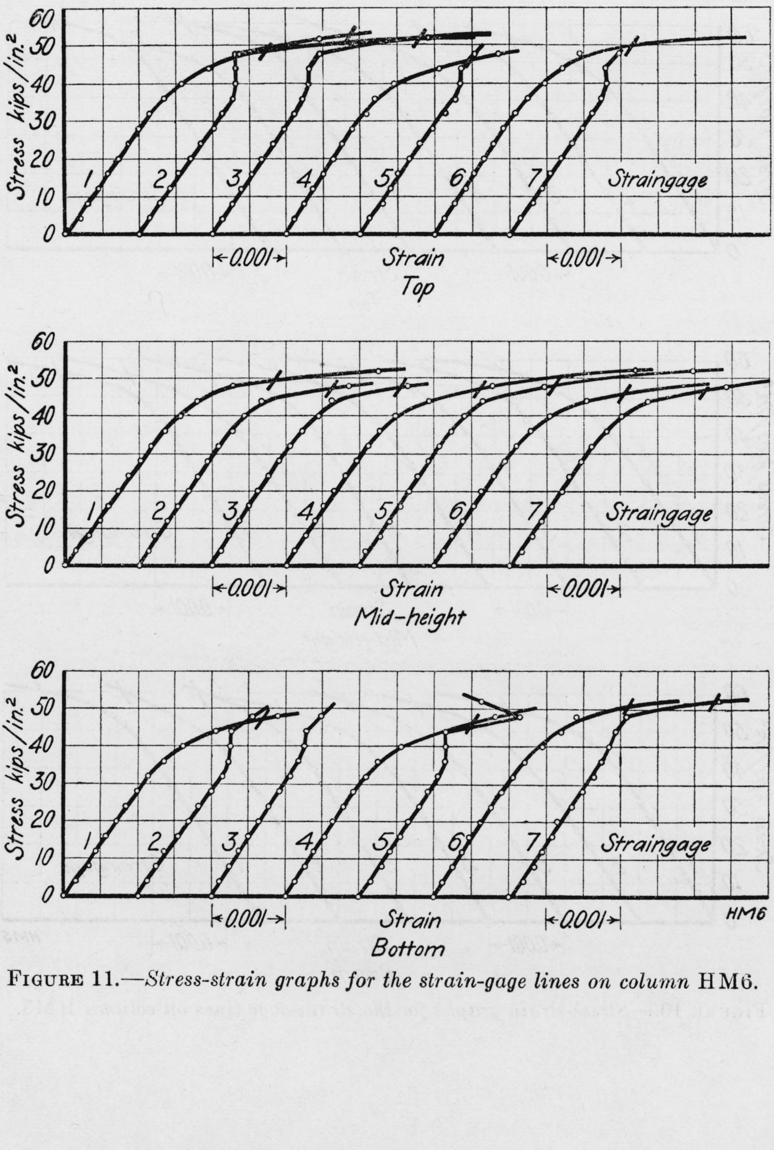

FIGURE 11.—*Stress-strain graphs for the strain-gage lines on column* HM6.

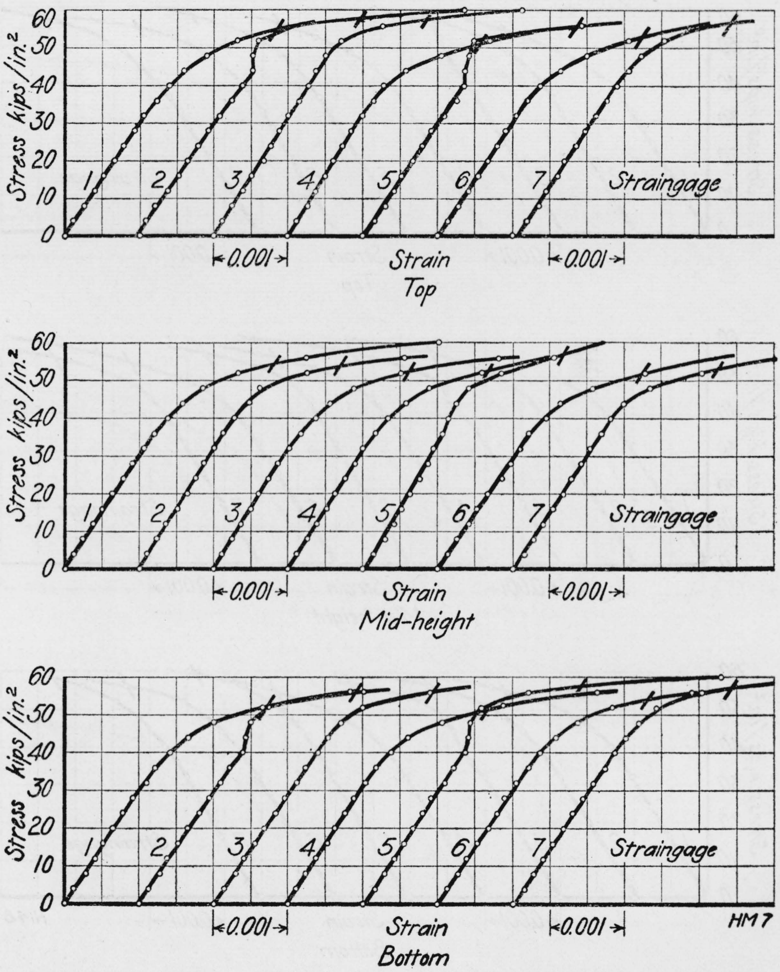

FIGURE 12.—*Stress-strain graphs for the strain-gage lines on column* HM7.

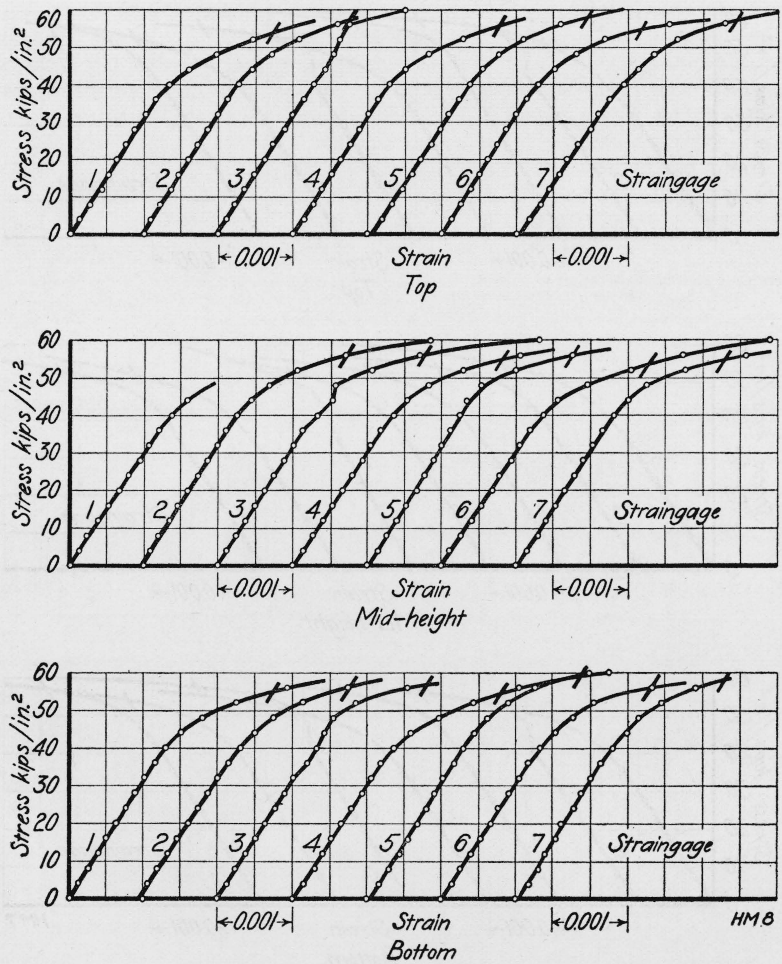

FIGURE 13.—*Stress-strain graphs for the strain-gage lines on column* HM8.

The differences in the slope of the curves below 30 kips/in.^{2} are, in all probability, not caused by differences in the Young's modulus of elasticity for the material at the gage line but by the shortness of the gage length (2 in.), the unavoidable errors in the strain-gage readings, and especially the fact that the stress may not have been uniformly distributed over the cross section of the column as assumed when plotting the graphs. The strain-gage readings were discontinued before the strain at the gage lines was sufficient to allow the yield strength to be determined in the same way as for the column yield strength. The yield strength for the strain-gage lines was, therefore, taken as the stress for which the strain was 0.001 greater than the strain computed by using the Young's modulus. The yield strengths were obtained graphically from the stress-strain graphs. Some of the values were obtained from the extrapolated portion of the curve. The values are given in table 5.

TABLE 5.—*Yield strengths for the strain-gage lines on the columns*

[These yield strengths are the stresses for which the strain was 0.001 greater than the strain computed using Young's Modulus. They were obtained graphically from the stress-strain graphs]

Column	Yield strength, kips/in.^{2}											
	Strain gage 1			Strain gage 2			Strain gage 3			Strain gage 4		
	Top	Middle	Bottom	Top	Middle	Bottom	Top	Middle	Bottom	Top	Middle	Bottom
HM1	56.0	57.0	(56.0)	(60.0)	58.5	59.0	59.5	58.0	58.0	57.0	57.0	57.0
HM2	50.5	51.5	52.0	51.0	51.5	52.5	(52.5)	51.0	(53.0)	(52.5)	51.0	50.5
HM3	55.0	(57.5)	55.5	57.0	57.0	56.0	57.0	57.0	(57.0)	55.0	55.5	(57.5)
HM4	53.0	53.5	(53.0)	54.5	53.0	(57.0)	54.0	52.5	(53.0)	52.0	53.0	(53.5)
HM5	56.5	58.0	56.5	59.5	58.0	58.0	57.0	57.0	58.0	56.5	(57.0)	56.0
HM6	[1](48.5)	49.5	47.0	(53.0)	47.5	------	52.0	47.5	------	46.0	47.5	46.5
HM7	(55.0)	54.5	52.0	58.0	54.0	56.0	57.5	52.5	(56.0)	51.0	(52.5)	51.5
HM8	(54.0)	------	55.5	(57.0)	56.5	(56.5)	------	56.0	(57.0)	(56.0)	55.0	54.5

Column	Yield strength, kips/in.^{2}									
	Strain gage 5			Strain gage 6			Strain gage 7			Average
	Top	Middle	Bottom	Top	Middle	Bottom	Top	Middle	Bottom	
HM1	58.0	57.0	60.0	57.0	(55.0)	(57.0)	58.5	58.0	(58.0)	57.7
HM2	(54.0)	53.0	(53.0)	(54.5)	(48.5)	(56.5)	(52.0)	51.5	51.0	52.1
HM3	(57.5)	56.5	(59.5)	56.0	54.0	57.5	(56.5)	(56.5)	58.0	56.6
HM4	55.0	(54.0)	55.5	54.5	49.5	(54.0)	53.0	(54.0)	(53.0)	53.5
HM5	(59.5)	(56.5)	(61.0)	53.5	56.0	(60.5)	(61.0)	(56.5)	(60.0)	57.7
HM6	------	48.0	------	(50.0)	46.0	51.0	------	47.0	52.5	48.7
HM7	55.5	(57.0)	57.5	(53.0)	52.0	54.0	(57.0)	(53.0)	(57.0)	54.6
HM8	(58.0)	56.0	59.0	54.5	54.0	56.0	(57.0)	55.0	(58.5)	55.7

[1] Values in parentheses throughout this table are extrapolated values.

The average tensile yield strength of all the angles was 5.7 kips/in.^{2} greater than that for all the plates. There were no strain-gage lines on the angles; therefore no stress-strain graphs were drawn for the angles. For stresses greater than about 40 kips/in.^{2}, however, it is probable that the angles carried more than the proportion of the load computed from the ratio of their cross-sectional area to the total cross-sectional area.

The average ratio of the yield strength of the plates (cover plates and web) at the strain-gage lines to the tensile yield strength of the coupons was about 90 percent and, in general, was less for the webs than for the cover plates.

There were irregularities in some of the stress-strain graphs, particularly strain gage 6, top and bottom, column HM2 (fig. 7); strain gages 2, 3, 5, and 7, top and bottom, columns HM6 (fig. 11); strain gages 2 and 5, top and bottom, column HM7 (fig. 12); and strain gage 3, top, middle, and bottom, column HM8 (fig. 13).

Because these irregularities appear only for the strain-gage lines at the top and bottom (except for column HM8) it seemed probable that they were caused, at least in part, by a nonuniform distribution of the stress over the cross section of the column.

A study of the stress-strain graphs showing irregularities and the values of the yield strength shown in figure 3 indicates that the irregularities occurred in members having a lower yield strength than that of the other members of the column, and it seems probable that the irregularities were caused by a greater proportion of the load being carried by the adjacent members. The strain in a member having an appreciably lower yield strength than adjacent members would be expected to be about the same as the average strain for the adjacent members.

For column HM2 the yield strength of the coupons from the web was about 10 kips/in.^{2} less than that for the cover plates and the angles. For column HM6 the irregularities occurred in the edges of the cover plates at each of the four corners. The web and the cover plates had the same coupon yield strength, but the yield strength of the angles was about 6 kips/in.^{2} greater. Apparently the edges of the cover plates behaved somewhat differently from either the middle of the cover plates or the web, because these edges received less support from the angles. For column HM7 the yield strengths of the coupons from the angles and the web were about 10 kips/in.^{2} greater than those from the cover plates. As for column HM6 the irregularities occurred in two of the edges of the cover plates but at diagonally opposite corners, the northwest and the southeast. Because the yield strength of the coupons from the two angles adjacent to the west cover plate was less than that for the two angles adjacent to the east cover plate irregularities might be expected for strain gages 2 and 7 instead of 2 and 5.

For column HM8 irregularities occurred only for strain gage 3 on the north edge of the east cover plate. This was the only column showing irregularities for the top, middle, and bottom strain gage lines. The yield strength of the coupons from the web was almost 10 kips/in.^{2} lower than that of the east cover plate, but irregularities did not occur in the web as they did for column HM2, perhaps because in column HM8 the yield strength of the angles was several kips/in.^{2} greater than that of the cover plates.

The yield strength of the coupons from the east cover plate was slightly less than that of the west cover plate, and the yield strength of the north angles 2.5 kips/in.^{2} less than that of the south angles, which may account for the irregularities occurring only in the edge of the cover plate, at the northeast corner of the column.

These graphs may be compared with the stress-strain graphs for four steel columns fabricated by riveting from a web plate and four angles shown on pages 85 to 106, Tests of Metals, Watertown Arsenal, Mass., 1912. The strain-gage readings for two additional columns are given on page 51 of the Tests of Metals, 1913. For those columns the gage lines extended the entire length of the edges of the four flanges.

The stress-strain graphs may be misleading because the average stress for the column was used as ordinate. The actual stress at a particular strain-gage line may be considerably greater or less than the average value. In order to show the strains in the column more clearly, at the suggestion of W. R. Osgood the graphs were plotted on a perspective outline of the cross section of the column. The strains are shown in figures 14, 15, 16, 17, 18, 19, 20, and 21.

In general, the strain in the outer edges of the flanges for a given stress greater than about 48 kips/in.^{2} was less than the strain at the middle of the cover plates. Also the strain in the middle of the web was less than the strain at the middle of the cover plates for the top and bottom of the column but greater than the strain at the middle of the cover plates at the midheight of the column.

Apparently there are greater differences in the strains for columns HM5, HM6, HM7, and HM8 having cover plates 1.25 in. thick than for columns HM1, HM2, HM3, and HM4 having cover plates 1.5 in. thick.

In general, the strains appear to be more nearly the same for the columns with webs and cover plates having about the same yield strength.

The stress-strain graphs showing irregularities correspond to perspective graphs which show little or no increase in strain for an increase in stress. Because each column was fabricated from a number of longitudinal pieces, it did not behave as a unit under load.

Whether the maximum load on the columns which behaved erratically was affected by this behavior is an interesting question. If the maximum load could have been determined on all of the columns the results might have thrown some light on this subject. It seems advisable in the future when obtaining strain-gage measurements for the purpose of determining the distribution of strain in fabricated steel columns, to obtain such measurements on all of the longitudinal pieces, including the angles of H-shaped columns. This would be especially desirable for columns fabricated by welding to determine the effect of stress-relieving heat treatment.

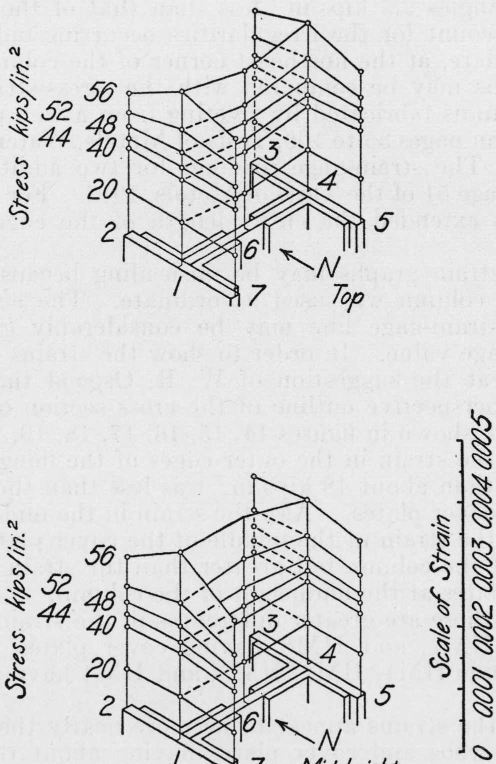

FIGURE 14.—*Strains in column HM1.*

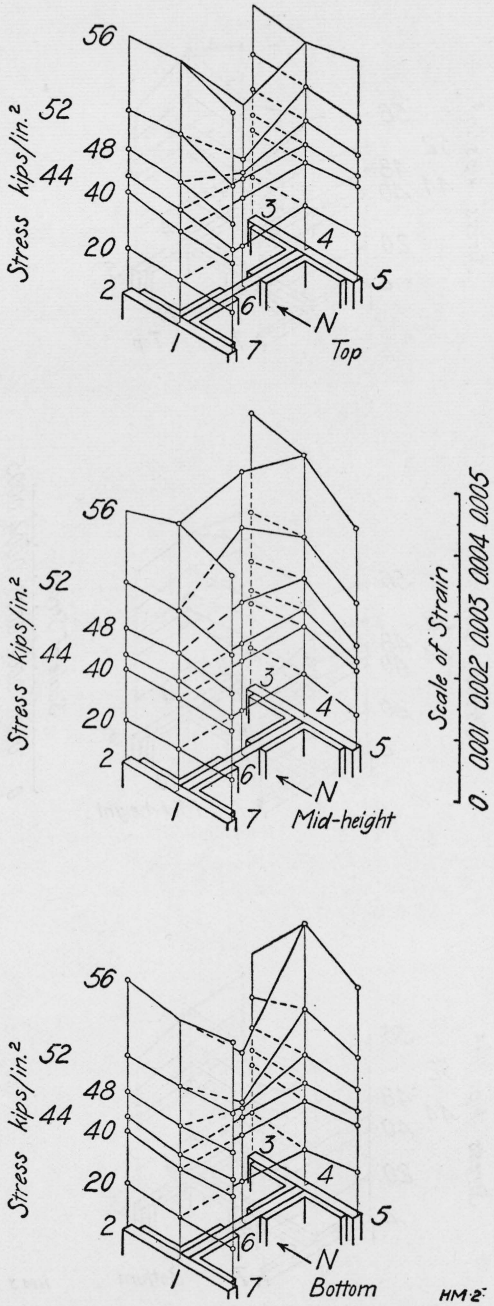

FIGURE 15.—*Strains in column* HM2.

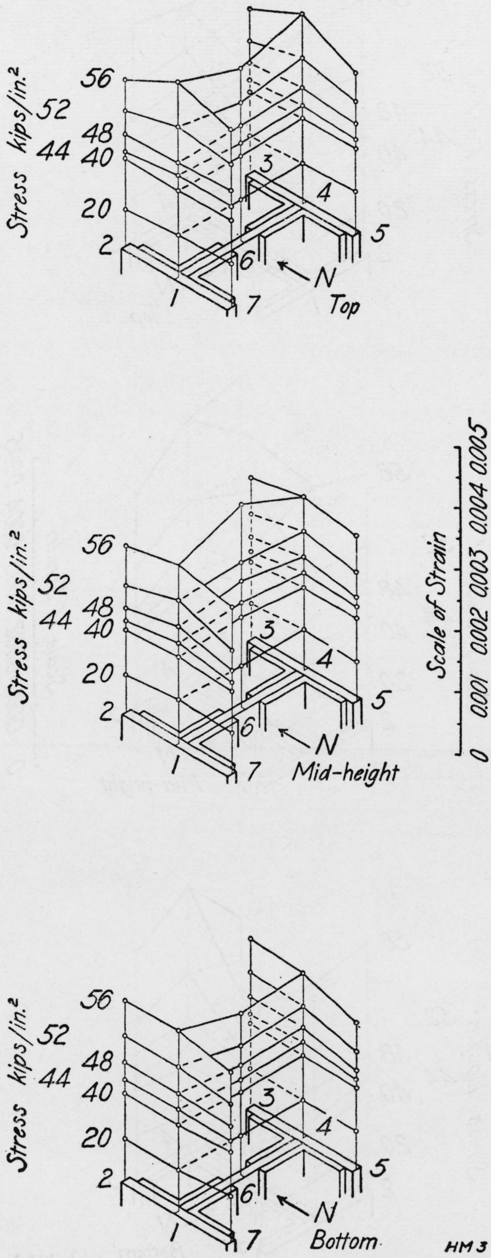

FIGURE 16.—*Strains in column* HM3.

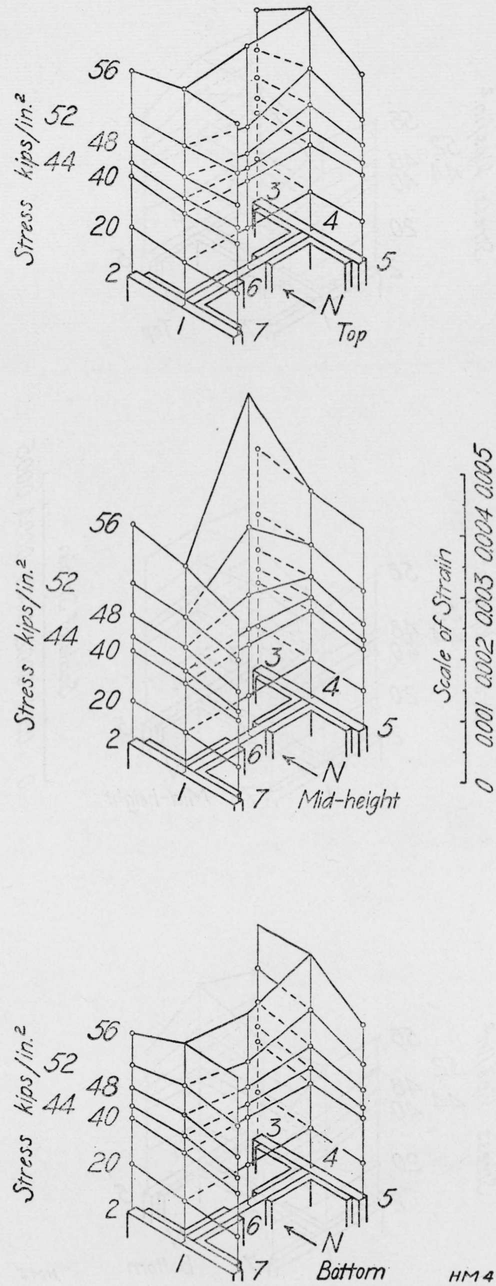

FIGURE 17.—*Strains in column* HM4.

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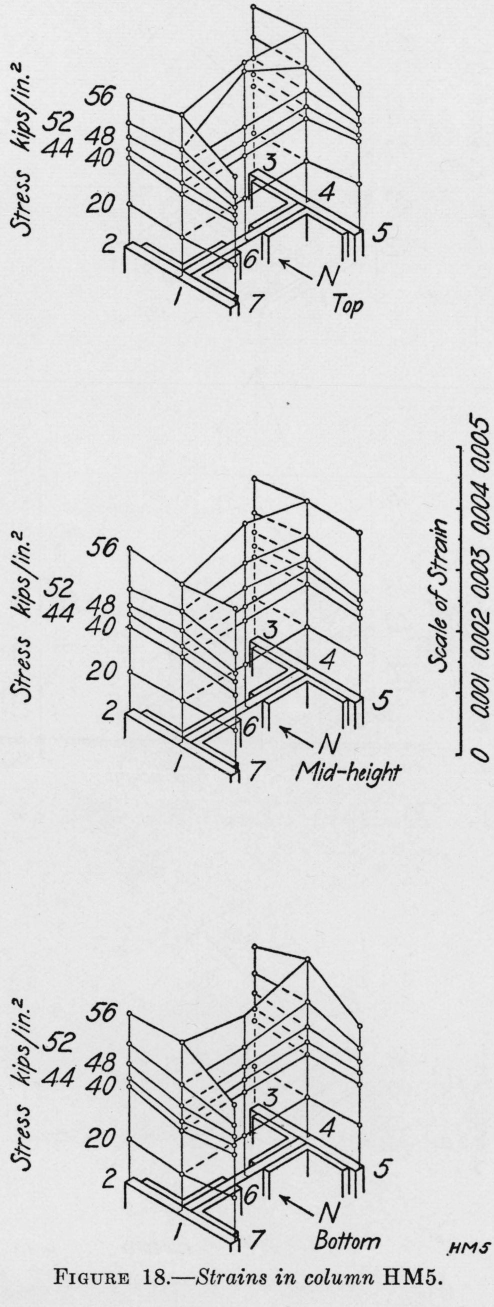

FIGURE 18.—*Strains in column* HM5.

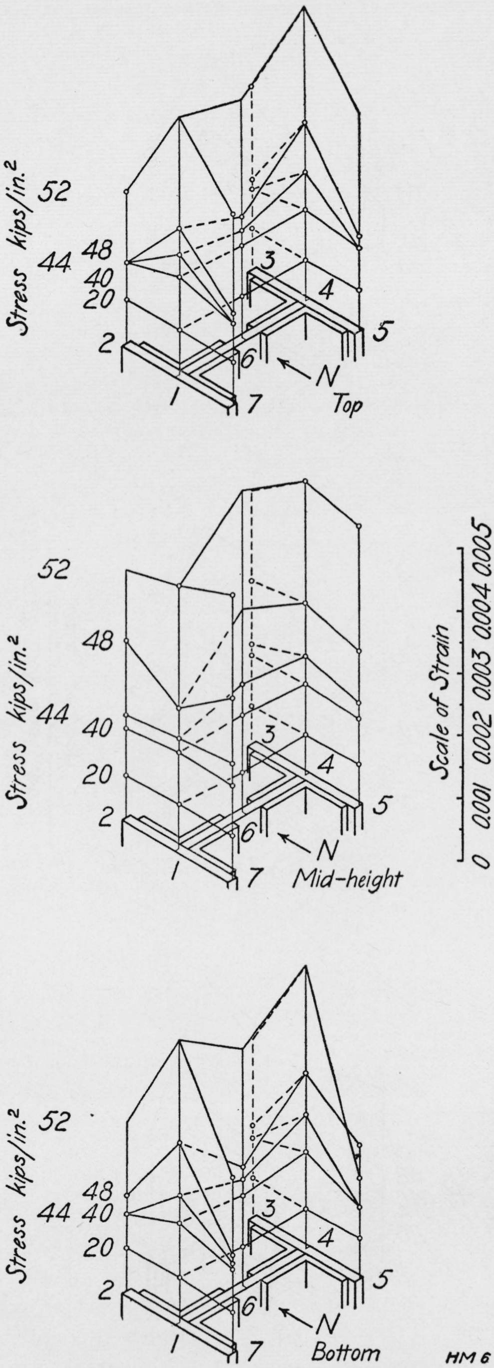

FIGURE 19.—*Strains in column* HM6.

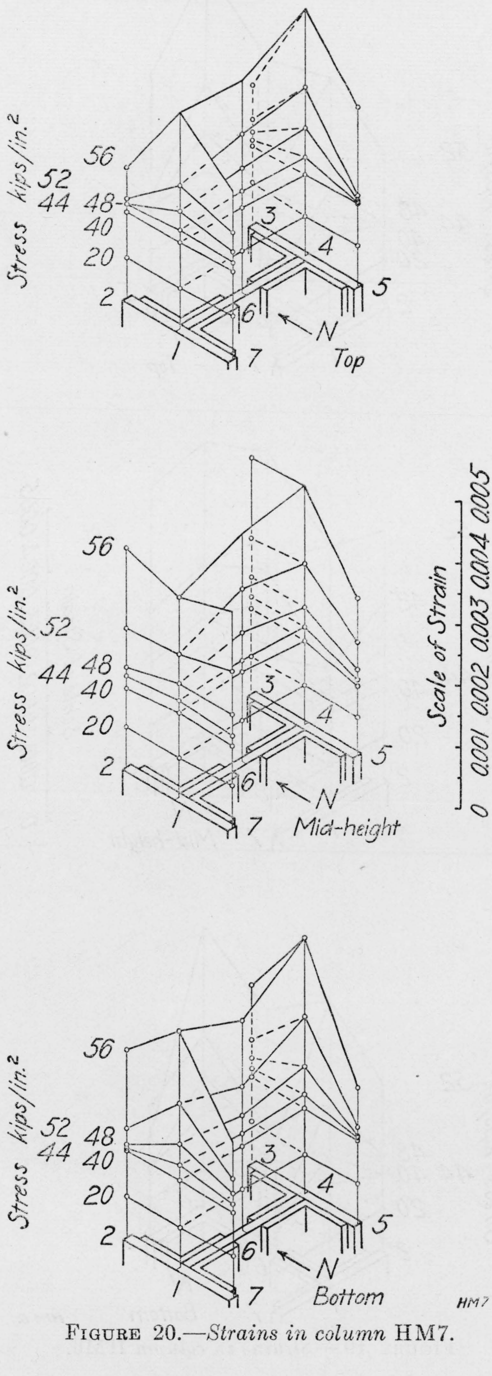

FIGURE 20.—*Strains in column* HM7.

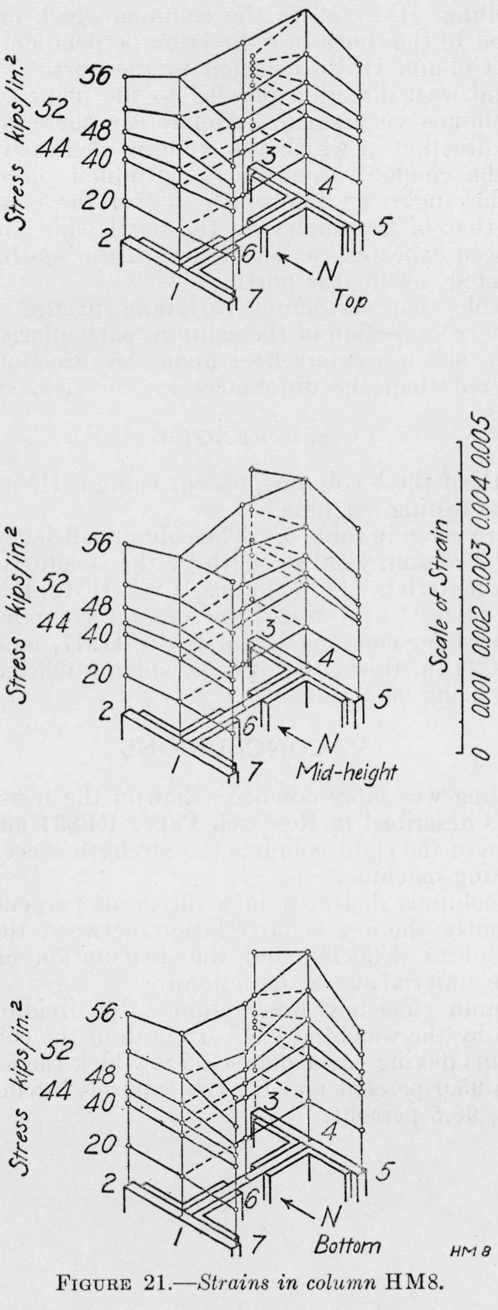

FIGURE 21.—*Strains in column* HM8.

4. LATERAL DEFLECTION

The lateral deflections of the columns are shown in figure 22. Except for column HM8, all of the columns which deflected appreciably deflected to the south in a direction perpendicular to the plane of the web. Column HM8 deflected to the north. The deflection in the east and west direction parallel to the plane of the web was for all the columns very small. Apparently there was no relation between the direction in which the columns deflected and the yield strength of the coupons from the longitudinal pieces. The yield strength of the angles on the south side of the column HM8 was greater than that of the angles on the north side and the column might have been expected to deflect toward the south. However, it actually deflected toward the north.

It is probable that accidental variations in the distribution of stress over the cross section of the column, particularly near the ends of the column, had a greater effect upon the direction in which the column deflected than the differences in the yield strength of the main members.

5. STRENGTH

The strength of these columns, except column HM6, exceeded the capacity of the testing machine.

The loads are given in table 4. The column efficiency was obtained by dividing the column yield strength by the weighted yield strength of the column material. For columns HM1, HM2, HM3, and HM4, having cover plates 1.5 in. thick, the average column efficiency was 95.0 percent and for columns HM5, HM6, HM7, and HM8 having cover plates 1.25 in. thick, the average column efficiency was somewhat greater, being 96.5 percent.

V. CONCLUSIONS

1. The loading was more eccentric than in the tests of tower and chord columns described in Research Paper RP831 and RP897.
2. For seven of the eight columns the strength exceeded the capacity of the testing machine.
3. All the columns deflected in a direction perpendicular to the web. Apparently there was no relation between the direction in which the columns deflected and the distribution of tensile yield strength of the material across the column.
4. The column efficiency was obtained by dividing the column yield strength by the weighted yield strength of the column material. For the columns having cover plates 1.5 in. thick the average column efficiency was 95.0 percent and for the columns having cover plates 1.25 in. thick, 96.5 percent.

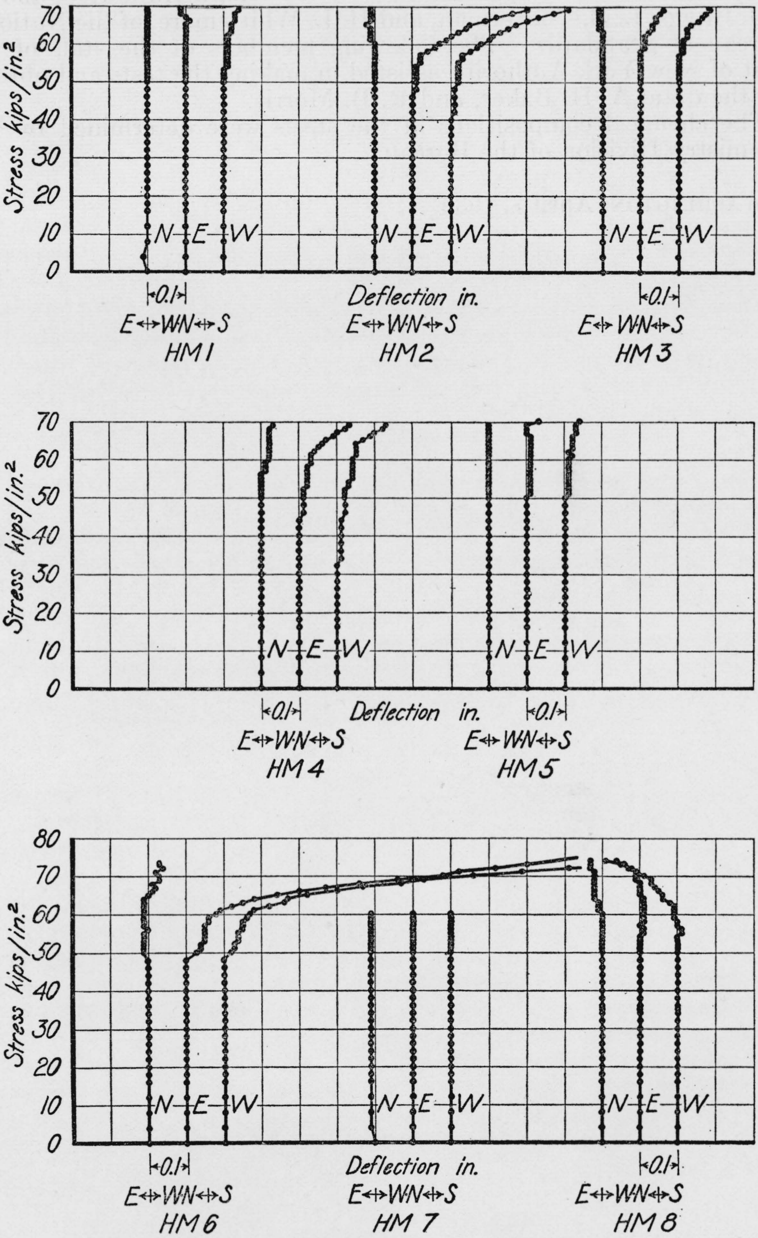

FIGURE 22.—*The lateral deflections of the columns.*

The program and testing procedure were prepared by O. H. Ammann chief engineer; L. S. Moisseiff, consulting engineer; and R. S. Johnston, research engineer, of the Port of New York Authority; and by L. J. Briggs, L. B. Tuckerman, and H. L. Whittemore, of 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, and R. B. Morris.

The chemical compositions of the steels were determined by the Chemistry Division of the Bureau.

WASHINGTON, April 7, 1936.