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PERFORATED COVER PLATES FOR STEEL COLUMNS: COMPRESSIVE PROPERTIES OF PLATES HAVING OVALOID PERFORATIONS AND A WIDTH-TO-THICKNESS RATIO OF 68

By Ambrose H. Stang and Martin Greenspan

ABSTRACT

Tests were made to determine the mechanical properties of perforated cover plates intended to be used as a substitute for lattice bars or batten plates in built-up box-type columns. Each column was built up from one perforated plate and either two or four angles. Columns with unperforated plates were used as controls.

This paper gives the results of the tests on columns having plates of three different perforation spacings. The plates had ovaloid perforations and a width-to-thickness ratio of 68.

It was found that the perforated plates contributed to the strength and to the stiffness of the columns. The factor of stress concentration, due to the perforations, varied from 2 to 2.6 based on the gross area (1.7 to 2.1 based on the net area).

CONTENTS

I. INTRODUCTION

This paper is the third of a series dealing with the mechanical properties of perforated cover plates intended to be used as a substitute for lattice bars or batten plates in built-up box-type columns. An outline of the program and description of the test methods were presented in RP1473 [1] and the results for plates having ovaloid perforations and a width-to-thickness ratio of 40 were given in RP1474.[2]

In this paper are presented the test results for the *C4* series of plates. These plates were 25.5 in. wide by ⅜ in. thick, thus having a width-to-thickness ratio of 68. The perforated plates of this series had ovaloid perforations 11.5 in. wide. The net to gross cross-sectional area ratio was 0.55.

II. COVER-PLATE COLUMNS

1. GENERAL

The details of the *C4* plates and of the angles are shown in figure 1. The perforated *C4* plates were all of the same nominal dimensions as to length, width, and thickness, and number, size, and shape of perforations, but they differed with regard to perforation spacing (i. e., the distance between centers of adjacent perforations). The perforation spacing was 35 inches for the *C4A* plates, 47 inches for the *C4B* plates, and 59 inches for the *C4C* plates. The *C4D* plates had the same nominal dimensions as the perforated *C4* plates but had no perforations.

Each plate shown in figure 1 represents three like plates, designated (0–1), (2–3), and (4–5), and the angle shown represents many like angles which were used interchangeably with the plates to form the columns of which the cross sections are shown in the figure. The angles used with the plates to form the columns are given in table 1.

TABLE 1.—*Angles used for the C4 columns*

Column designation [1]	Angle designations
C4A (—) two angles	*C5C (4–5), C5M (0–1).*
C4A (—) four angles	*C5C (4–5), C5M (0–1), C5D (2–3), C5E (2–3)*
C4B (—) two angles	*C5C (0–1), C5E (2–3).*
C4B (—) four angles	*C5C (0–1), C5E (2–3), C5A (2–3), C5D (2–3).*
C4C (—) two angles	*C5B (0–1), C5D (2–3).*
C4C (—) four angles	*C5B (0–1), C5D (2–3), C5A (2–3), C5E (4–5).*
C4D (—) two angles	*C5L (0–1), C5M (2–3).*
C4D (—) four angles	*C5L (0–1), C5M (2–3), C5C (4–5), C5E (2–3).*

[1] The three columns represented by each of the above designations contained the same angles.

[1] Ambrose H. Stang and Martin Greenspan, *Perforated cover plates for steel columns: Program and test methods.* J. Research NBS **28,** 669 (1942) RP1473.

[2] Ambrose H. Stang and Martin Greenspan, *Perforated cover plates for steel columns: Compressive properties of plates having ovaloid perforations and a width-to-thickness ratio of 40.* J. Reserch NBS **28,** 687 (1942) RP1474.

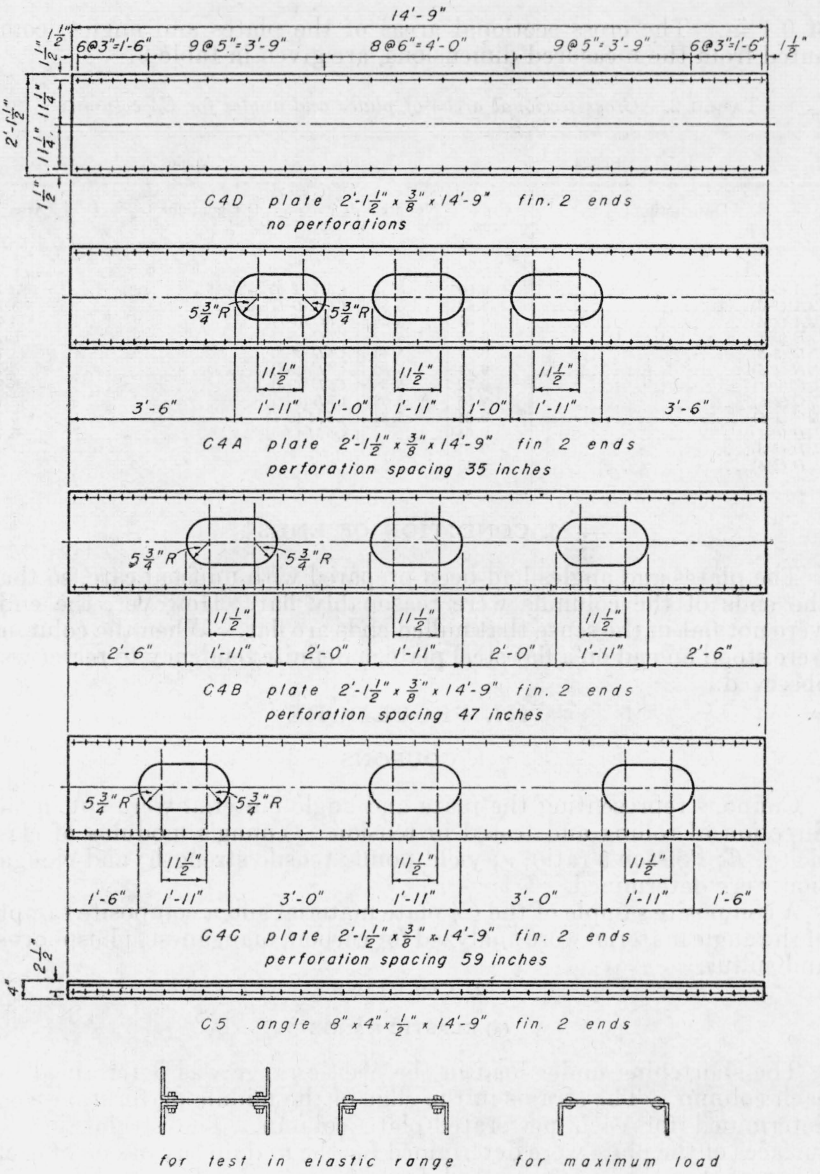

FIGURE 1.—*Plates and angles for the C4 columns.*

2. DIMENSIONS

The dimensions given in figure 1 are nominal. There were the usual commercial variations in the thicknesses and widths of the plates and angles. The variations in the dimensions of the perforations were considerably greater; for some plates the difference between the minimum and maximum perforation width was of the order of 0.1 in. The cross sectional areas of the plates and angles, computed from the measured dimensions, are given in table 2.

TABLE 2.—*Cross-sectional areas of plates and angles for C4 columns*

Plates			Angles	
Designation	Gross area	Net area	Designation	Area
	in.^{2}	*in.*^{2}		*in.*^{2}
C4A (0-1)	9.60	5.31	*C5A (2-3)*	5.78
C4A (2-3)	9.63	5.33	*C5B (0-1)*	5.78
C4A (4-5)	9.67	5.35	*C5C (0-1)*	5.74
C4B (0-1)	9.63	5.32	*C5C (4-5)*	5.75
C4B (2-3)	9.77	5.40	*C5D (2-3)*	5.73
C4B (4-5)	9.74	5.36	*C5E (2-3)*	5.77
C4C (0-1)	9.72	5.38	*C5E (4-5)*	5.81
C4C (2-3)	9.65	5.32	*C5L (0-1)*	5.79
C4C (4-5)	9.64	5.33	*C5M (0-1)*	5.73
C4D (0-1)	9.64		*C5M (2-3)*	5.71
C4D (2-3)	9.51			
C4D (4-5)	9.43			

3. CONDITION OF ENDS

The plates and angles had been prepared with unusual care, so that the ends of the columns were reasonably flat. However, the ends were not flat in the sense that milled ends are flat. When the columns were stood on end on a flat steel plate, a definite tendency to teeter was observed.

III. PROCEDURE

1. COUPONS

Coupons representing the plate and angle material were cut in the direction of rolling and tested in tension. Young's modulus of elasticity, E; Poisson's ratio, ν; yield point; tensile strength; and elongation were determined.

A composite sample of the *C4* plate material and a composite sample of the angle material were analyzed for carbon, manganese, phosphorus, and sulfur.

2. COLUMNS

(a) ELASTIC RANGE

The shortening under load in the elastic range was determined for each column. The strains in the edge of the middle perforation were determined for each perforated-plate column. The strains in the surfaces of the plate were determined for the middle bay of one of each group of three like perforated-plate columns having four angles. The distribution of stress in the middle bay of each of these columns was calculated from the strain data, and the values of the elastic constants obtained from the coupon tests.

(b) MAXIMUM LOAD

One two-angle column of each group of three like two-angle columns was subjected to maximum-load test after the bolts had been replaced by rivets. Data to complete the stress-strain curves and data for stress-deflection curves were taken.

IV. RESULTS

1. COUPONS

The results of the tensile tests of the coupons are given in table 3.

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

Coupon designation	Thickness	Young's modulus of elasticity, E	Poisson's ratio, ν	Yield point	Tensile strength	Elongation in 8 in.
PLATE COUPONS						
	In.	*Kips/in.*[2]		*Kips/in.*[2]	*Kips/in.*[2]	*Percent*
C4A(1-2)	0.376	29,700	0.281	38.0	59.7	33.6
C4A(3-4)	.377	29,700	.282	38.1		
C4B(1-2)	.385	30,000	.284	38.7	61.6	28.9
C4B(3-4)	.382	29,700	.280	37.8	59.4	32.5
C4C(1-2)	.381	29,900	.288	37.2	59.1	33.5
C4C(3-4)	.377	29,800	.284	38.4	61.2	34.5
C4D(1-2)	.377	29,700	.283	38.0	59.7	30.8
C4D(3-4)	.373	29,700	.286	38.0	59.7	34.5
ANGLE COUPONS						
C5A(1-2)	0.510	29,600	0.286	36.3	59.0	33.5
C5A(3-4)	.506	30,000	.290	35.6	58.7	33.5
C5B(1-2)	.506	29,700	.286	36.0	59.5	31.3
C5B(3-4)	.510	29,700	.278	35.9	58.7	35.8
C5C(1-2)	.508	29,400	.281	36.5	58.8	31.3
C5C(3-4)	.501	29,700	.286	34.8	58.3	33.0
C5D(1-2)	.500	29,800	.287	37.0	63.7	33.1
C5D(3-4)	.507	29,700	.288	36.9	64.5	33.0
C5E(1-2)	.508	29,700	.285	37.5	59.6	31.3
C5E(3-4)	.508	29,600	.281	36.0	59.1	33.1
C5L(1-2)	.503	29,500	.290	36.1	58.7	35.8
C5L(3-4)	.511	29,600	.286	36.6	59.1	34.6
C5M(1-2)	.501	29,600	.282	35.3	58.1	31.2
C5M(3-4)	.504	29,100	.270	35.0	58.2	33.6

The chemical composition of the coupon material is given in table 4.

TABLE 4.—*Chemical composition of coupon material*

Composite sample	Carbon	Manganese	Phosphorus	Sulfur
	Percent	*Percent*	*Percent*	*Percent*
Plates *C4*	0.18	0.58	0.009	0.03
Angles *C5*	.21	.56	.014	.03

2. COLUMNS

(a) MODULUS OF COLUMN AND EFFECTIVE AREA OF PLATE

The moduli, E', of the columns, and the effective-area factors, K, with respect to shortening under compressive load, for the plates, are given in table 5.[3]

[3] See pages 679 and 680 of Research Paper RP1473.

TABLE 5.—*Moduli of columns, effective-area factors of plates, and maximum stresses*

Plate designation	Number of angles	Based on gross cross-sectional area			Based on net cross-sectional area		
		Modulus E'	Effective-area factor, K	Ratio, maximum stress / P/A	Modulus E'	Effective-area factor, K	Ratio, maximum stress / P/A
		Kips/in.[2]			*Kips/in.*[2]		
C4A(0-1)	2	24,300	0.62		30,600	1.12	
C4A(2-3)	2	24,300	.62		30,500	1.12	
C4A(4-5)	2	24,300	.62		30,500	1.11	
Avg		24,300	0.62	−2.24	30,500	1.12	−1.78
C4A(0-1)	4	26,200	0.61		30,200	1.11	
C4A(2-3)	4	26,300	.63		30,300	1.13	
C4A(4-5)	4	26,200	.61		30,100	1.11	
Avg		26,200	0.62	−1.98	30,200	1.12	−1.72
C4B(0-1)	2	24,700	0.65		31,100	1.18	
C4B(2-3)	2	24,600	.64		31,000	1.17	
C4B(4-5)	2	24,600	.64		31,000	1.16	
Avg		24,600	0.64	−2.63	31,000	1.17	−2.09
C4B(0-1)	4	26,400	0.64		30,500	1.17	
C4B(2-3)	4	26,200	.62		30,200	1.12	
C4B(4-5)	4	26,300	.63		30,300	1.14	
Avg		26,300	0.63	−2.27	30,300	1.14	−1.97
C4C(0-1)	2	25,400	0.70		31,800	1.26	
C4C(2-3)	2	25,300	.69		31,800	1.25	
C4C(4-5)	2	25,200	.69		31,700	1.25	
Avg		25,300	0.69	−2.48	31,800	1.25	−1.97
C4C(0-1)	4	26,700	0.67		30,700	1.21	
C4C(2-3)	4	26,600	.66		30,700	1.21	
C4C(4-5)	4	26,600	.66		30,600	1.19	
Avg		26,600	0.66	−2.43	30,700	1.20	−2.11
C4D(0-1)	2	29,500			29,500		
C4D(4-5)	2	29,300			29,300		
Avg		29,400	1.00		29,400	1.00	
C4D(0-1)	4	29,500			29,500		
C4D(4-5)	4	29,600			29,600		
Avg		29,500	1.00		29,500	1.00	

(b) STRESSES

(1) *On the edge of the perforation.*—The distribution of stress on the edge of the middle perforation is indicated in figures 2, 3, and 4. Each curve represents the average result for three like columns having the same perforation spacing.

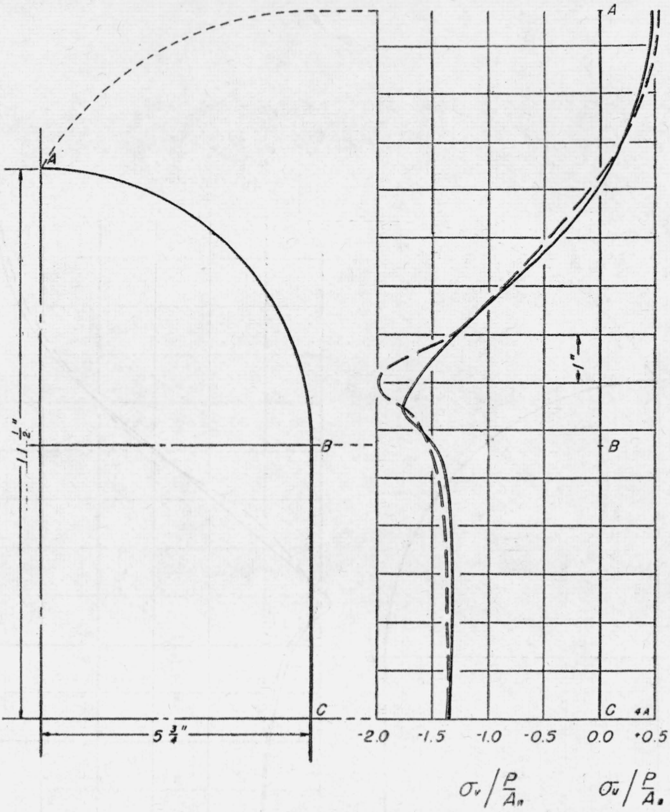

Figure 2.—*Columns C4A, perforation spacing 35 inches. Distribution of stress on the edge of the middle perforation.*

The solid line is for the two-angle column and the dashed line for the four-angle column. Based on net area

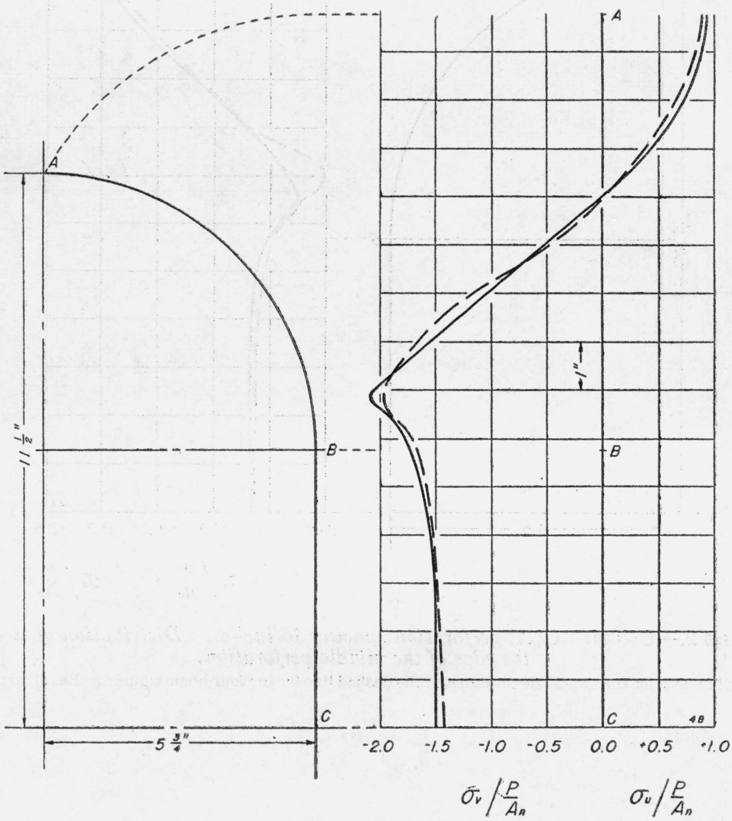

FIGURE 3.—*Columns C4B, perforation spacing 47 inches. Distribution of stress on the edge of the middle perforation.*

The solid line is for the two-angle column and the dashed line for the four-angle column. Based on net area.

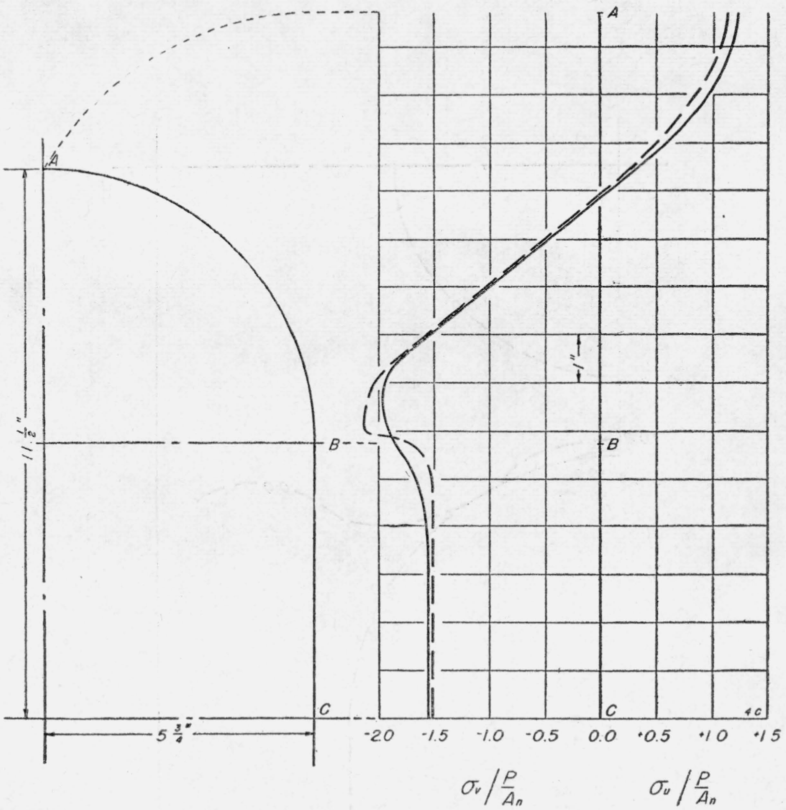

FIGURE 4.—*Columns C4C, perforation spacing 59 inches. Distribution of stress on the edge of the middle perforation.*

The solid line is for the two-angle column and the dashed line for the four-angle column. Based on net area.

The vertical axis of the graph in each figure is a development of one quadrant of the edge of the perforation. The point B is the point of tangency of the circular and straight parts of the edge.

In the stress ratios $\sigma_{u,v}/(P/A_n)$, A_n is the net area of the column, and σ_u and σ_v are the maximum and the minimum principal stresses, respectively. The stress ratios based on gross area, $\sigma_{u,v}/(P/A)$ may be obtained by multiplying $\sigma_{u,v}/(P/A_n)$ by 1.26 for the two-angle, and 1.15 for the four-angle, columns.

The maximum stresses are given in table 5.

(2) *On the surfaces of the plate.*—The distributions of stress on the surfaces of the middle bay for the perforated-plate columns having four angles are indicated in figures 5 to 16, inclusive. The stress ratios shown in these figures are based on net area. The stress ratios based on gross area may be obtained by multiplying the given values by 1.15 for these four-angle columns.

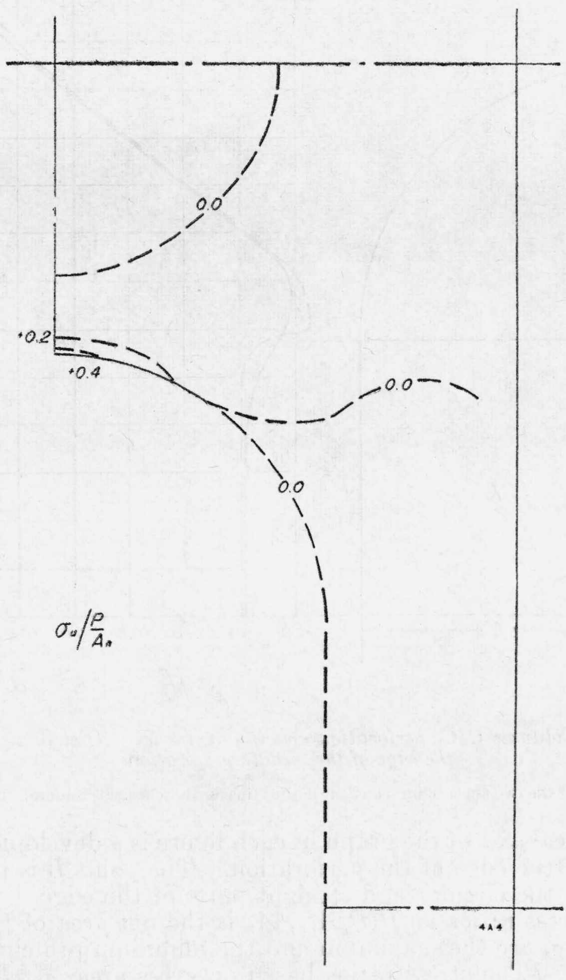

FIGURE 5.—*Column C4A (2–3) (four angles), perforation spacing 35 inches. Isogram of maximum principal stress.*

Based on net area.

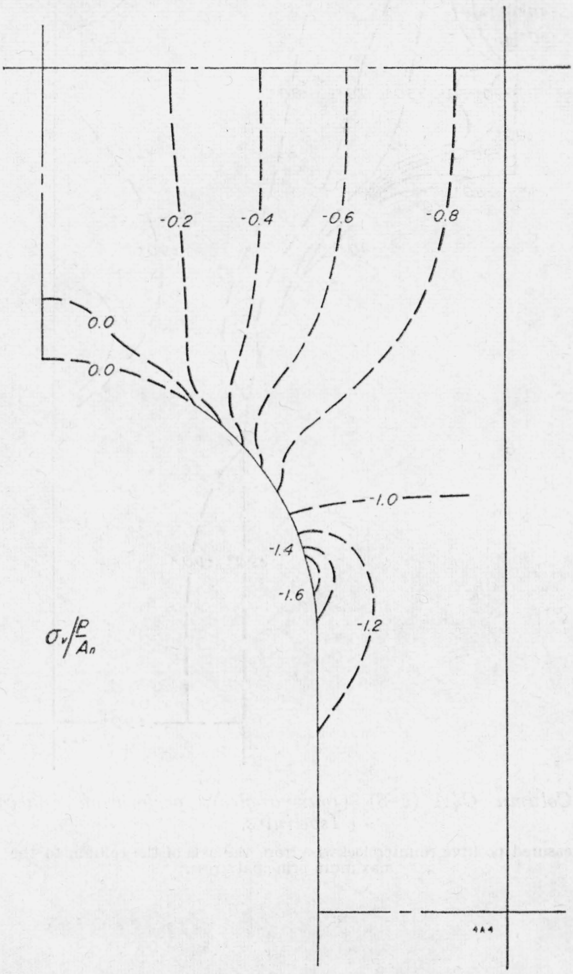

FIGURE 6.—*Column C4A (2–3) (four angles), perforation spacing 35 inches. Isogram of minimum principal stress.*

Based on net area.

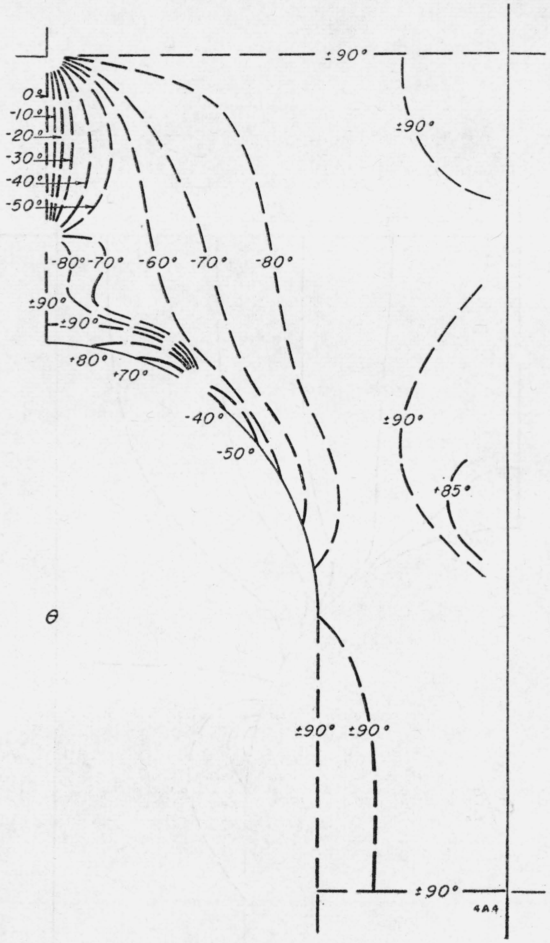

FIGURE 7.—*Column C4A (2–3) (four angles), perforation spacing 35 inches. Isoclinics.*

The angle θ is measured positive counterclockwise from the axis of the column to the direction of the maximum principal stress.

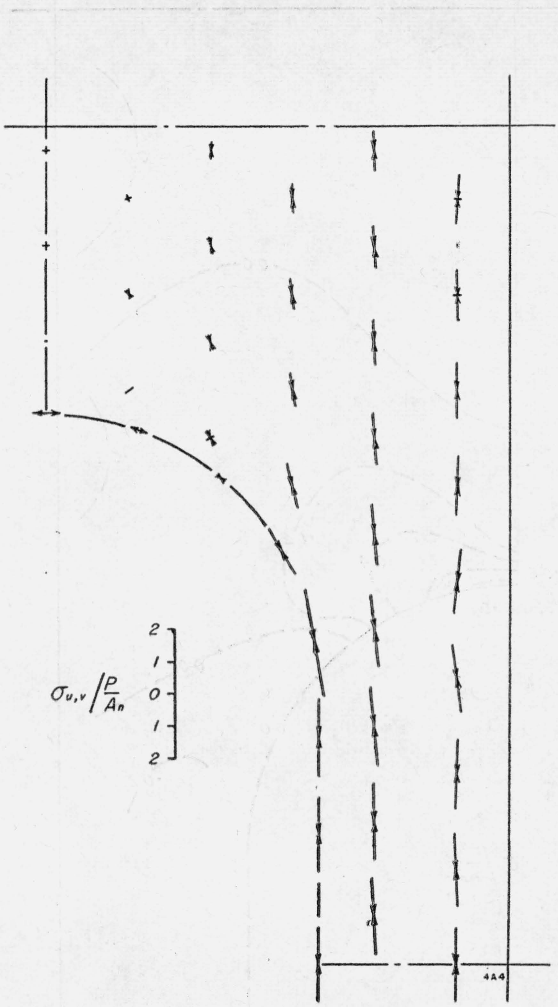

FIGURE 8.—***Column*** *C4A (2-3) (four angles), perforation spacing 35 inches. Magnitude and direction of the principal stresses.*

Based on net area.

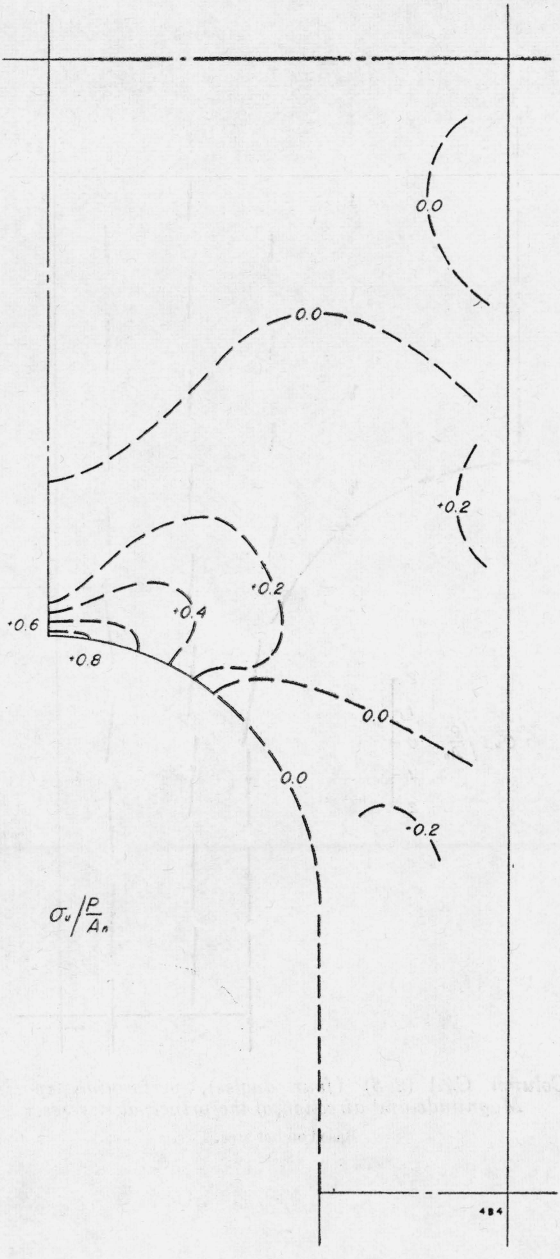

FIGURE 9.—*Column C4B (2–3) (four angles), perforation spacing 47 inches. Isogram of maximum principal stress.*

Based on net area.

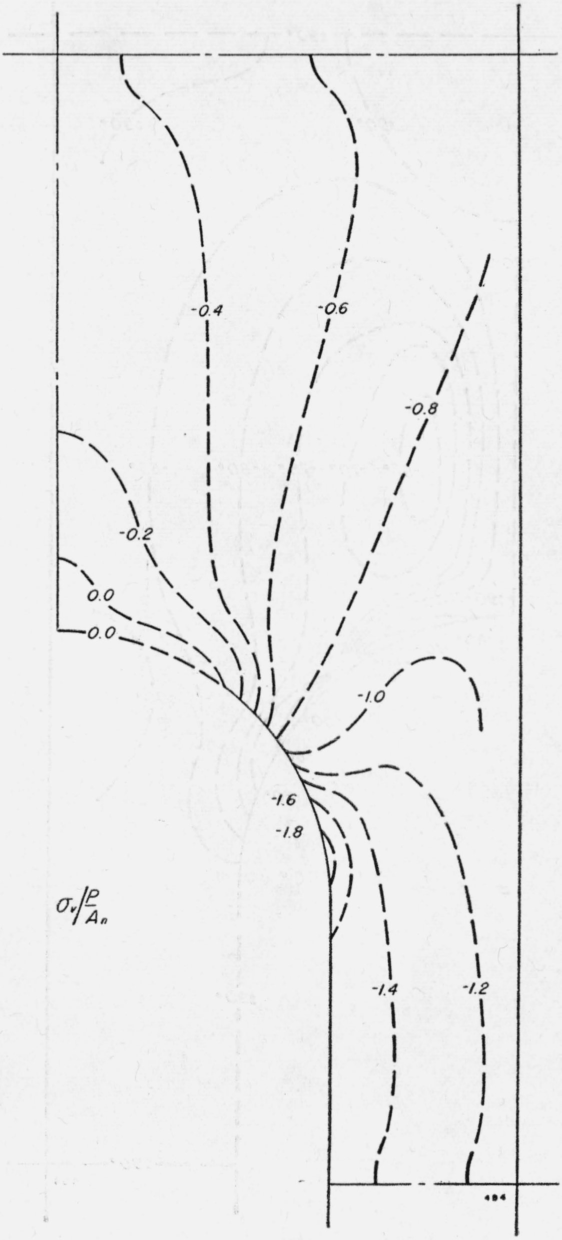

FIGURE 10.—*Column C4B (2–3) (four angles), perforation spacing 47 inches. Isogram of minimum principal stress.*

Based on net area.

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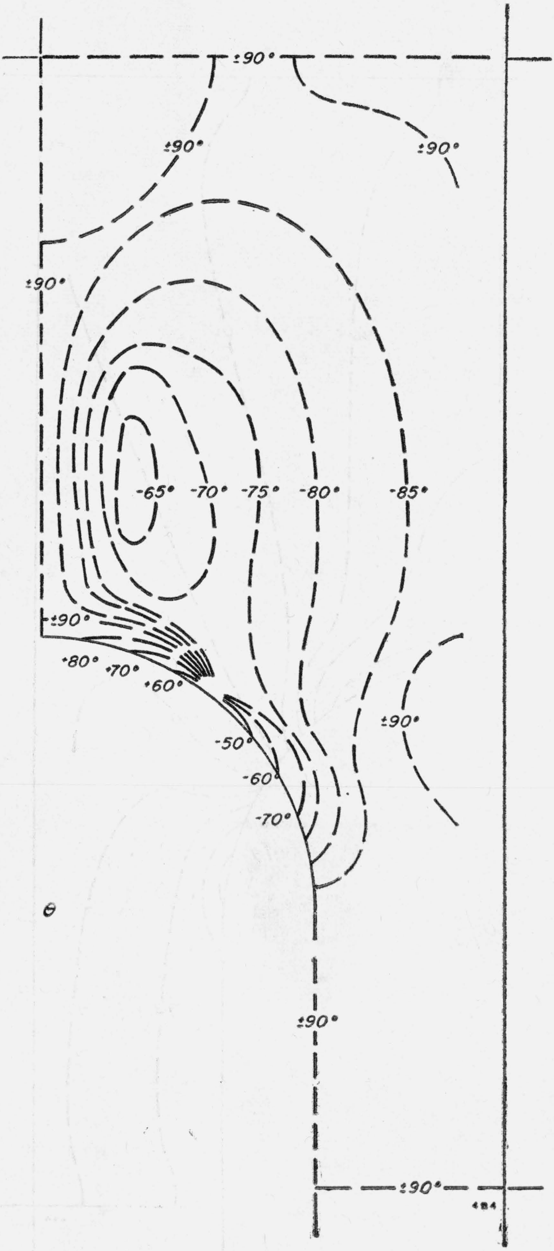

FIGURE 11.—*Column C4B (2-3) (four angles), perforation spacing 47 inches. Isoclinics.*

The angle θ is measured positive counter-clockwise from the axis of the column to the direction of the maximum principal stress.

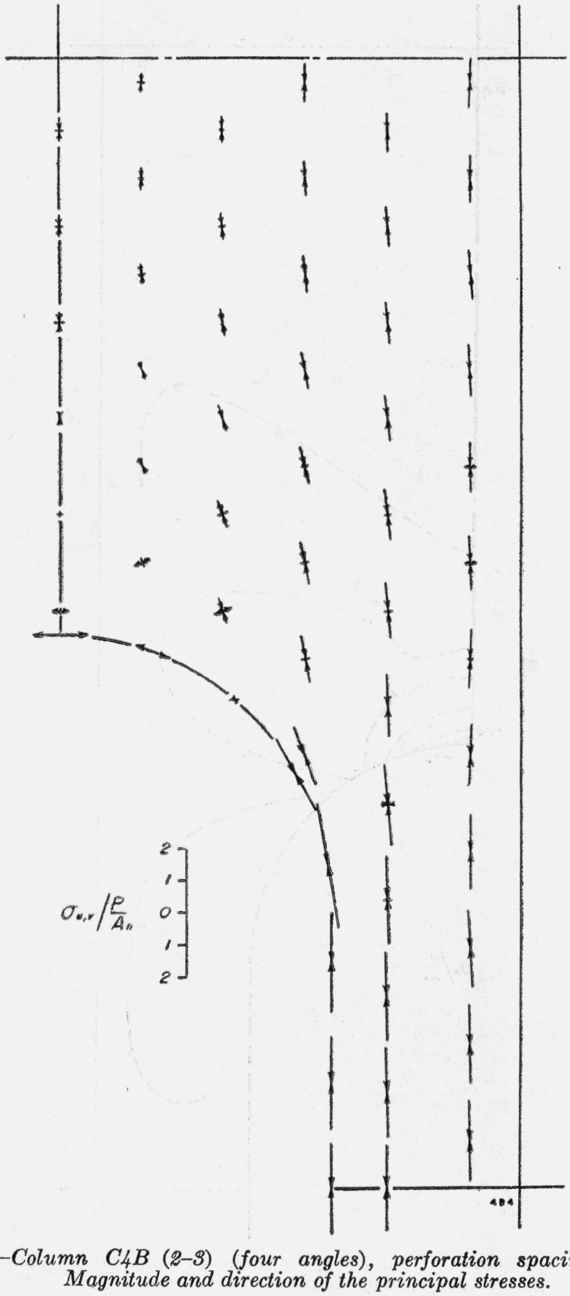

FIGURE 12.—*Column C4B (2–3) (four angles), perforation spacing 47 inches. Magnitude and direction of the principal stresses.*
Based on net area.

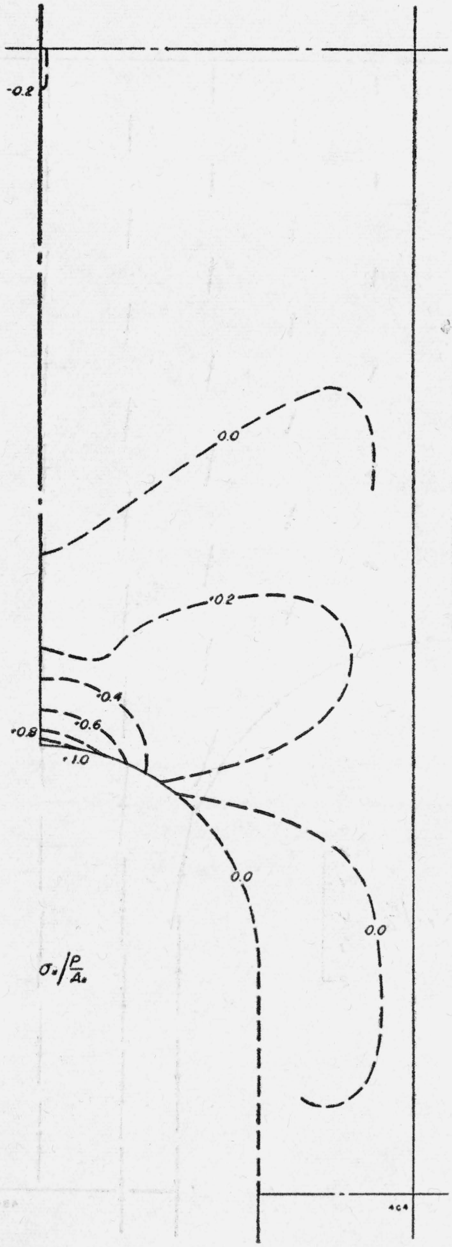

FIGURE 13.—*Column C4C (2–3) (four angles), perforation spacing 59 inches. Isogram of maximum principal stress.*

Based on net area.

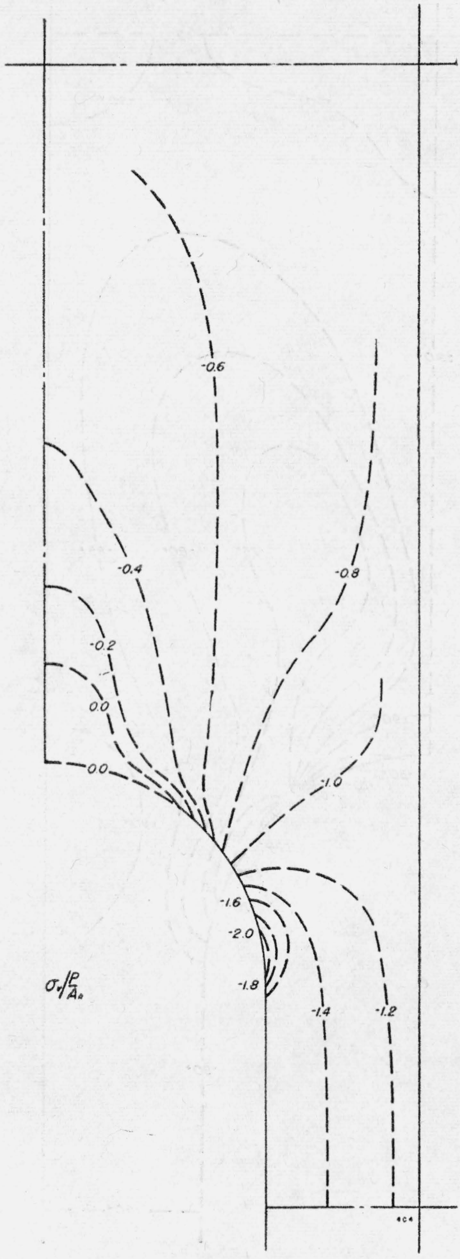

FIGURE 14.—*Column C4C (2–3) (four angles)*, perforation spacing 59 inches.
Isogram of minimum principal stress.
Based on net area.

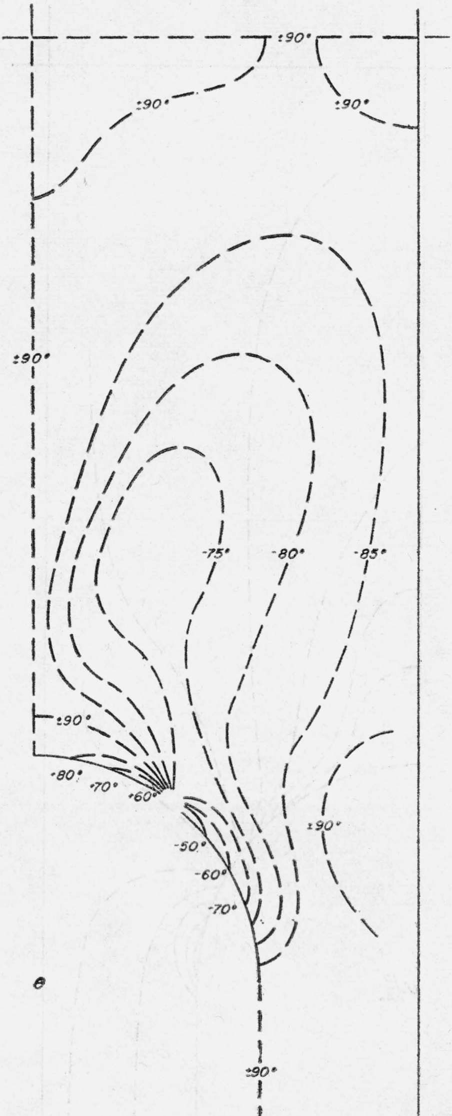

FIGURE 15.—*Column C4C (2–3) (four angles), perforation spacing 59 inches. Isoclinics.*

The angle θ is measured positive counterclockwise from the axis of the column to the direction of the maximum principal stress.

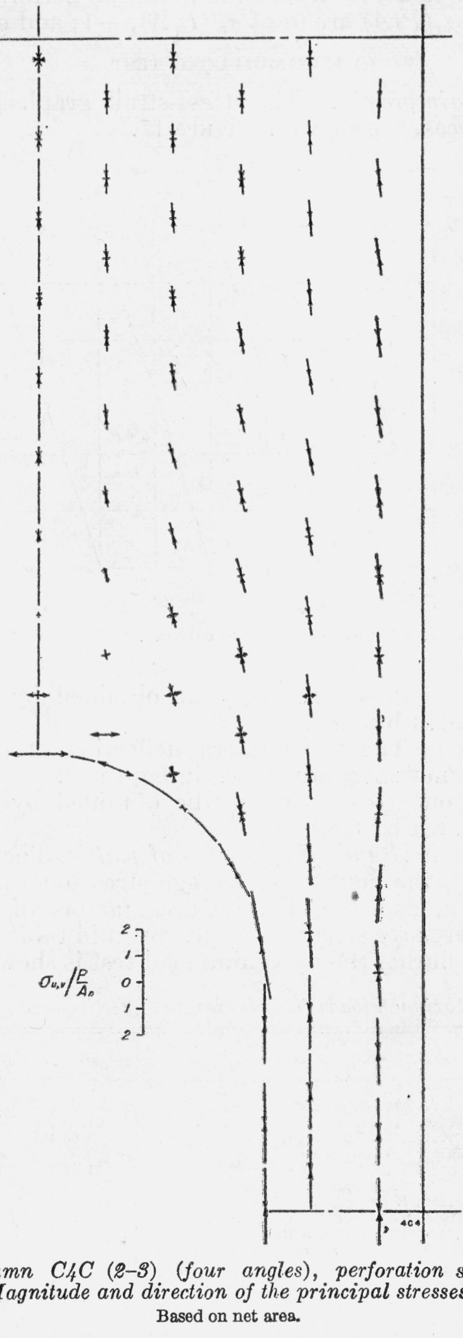

FIGURE 16.—*Column C4C (2-3) (four angles), perforation spacing 59 inches. Magnitude and direction of the principal stresses.*
Based on net area.

The effect of the perforation on the stress distribution may be judged from the fact that for a solid plate (no perforation) the values everywhere of $\sigma_u/(P/A)$ are 0; of $\sigma_v/(P/A)$, -1; and of θ, 90 degrees.

(c) MAXIMUM-LOAD TEST

(1) *Stress-strain graphs.*—The stress-strain graphs for the columns, based on net areas, are shown in figure 17.

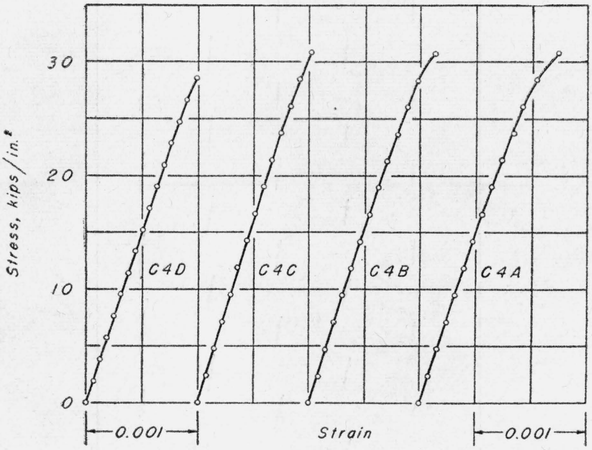

FIGURE 17.—*Columns C4–(two angles). Stress-strain graphs.*
Based on net area.

The stresses on gross area may be obtained by multiplying the stresses on net area by 0.80.

(2) *Deflections.*—The stress-lateral-deflection graphs for the columns, based on net area, are shown in figure 18.

The stresses on gross area may be obtained by multiplying the stresses on net area by 0.80.

(3) *Maximum load and effective area of plate.*—The maximum loads for the columns, the maximum average stress on the gross area and on the net area, and the effective-area factors of the plates with respect to compressive strength, C, are given in table 6.[4]

Column *C4C* during the maximum load test is shown in figure 19.

TABLE 6.—*Maximum loads for columns and effective-area factors for plates*

Column designation	*C4A*	*C4B*	*C4C*	*C4D*
Perforation spacing, *in*	35.0	47.0	59.0	(a)
Area of angles, *in.*²	11.48	11.52	11.51	11.50
Gross area of plate, *in.*²	9.63	9.74	9.64	9.51
Net area of plate, *in.*²	5.33	5.36	5.33	9.51
Total area, gross, *in.*²	21.11	21.26	21.15	21.01
Total area, net, *in.*²	16.81	16.88	16.84	21.01
Maximum compressive load, *Kips*	531	543	557	638
Compressive stress on gross area at failure, *Kips/in.*²	25.2	25.5	26.3	30.4
Compressive stress on net area at failure, *Kips/in.*²	31.6	32.2	33.1	30.4
Effective-area factor of plate with respect to compressive strength, *C*:				
Based on gross area	0.62	0.65	0.71	1.00
Based on net area	1.12	1.18	1.28	----
Slenderness ratio	----	----	----	72.5
Column efficiency, *Percent*	----	----	----	83

[a] No perforations.

[4] See page 685 of Research Paper RP1473.

The perforated-plate columns, *C4A*, *C4B*, and *C4C*, failed by primary buckling away from the plate side of the column, as would be expected from the consideration that, in the neighborhood of a perforation, the gravity axis of the column is displaced away from the plate side. Local buckling of the outstanding legs of the angles of the columns occurred near the ends of the column. The plates buckled near the middle perforation.

The unperforated-plate column, *C4D*, started to fail toward the plate side, as would be expected from the double-modulus theory, but finally failed suddenly by secondary buckling of the plate and angles near one end with little additional deflection of the columns as a whole. The column efficiency of 83 percent, given in table 6, is

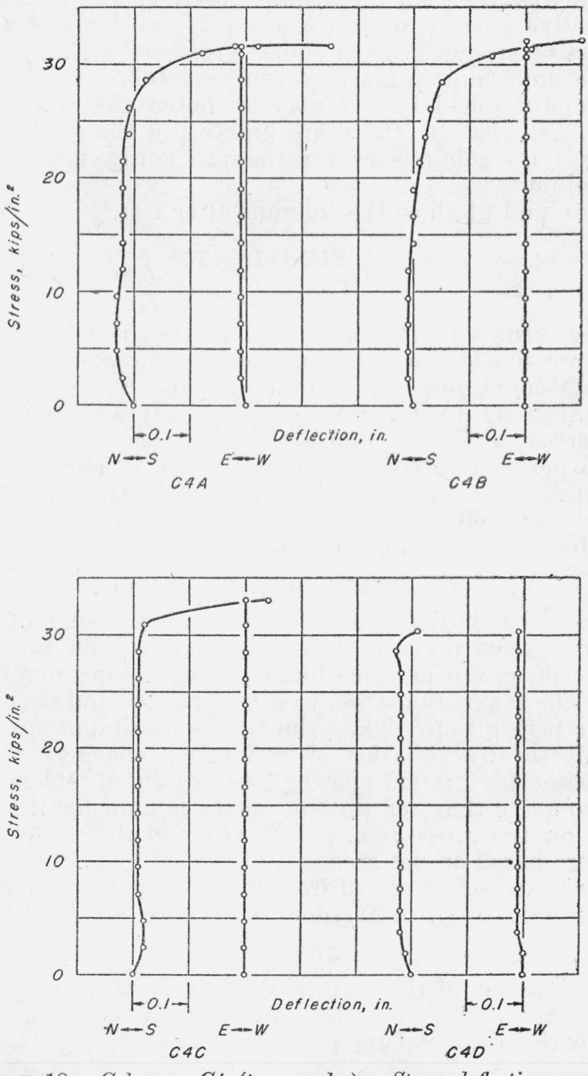

FIGURE 18.—*Columns C4–(two angles). Stress-deflection graphs.*
Based on net area. When the deflection is north, *N*, the bending stress is tensile on the plate side.

the ratio of the average stress at failure to the weighted average yield point of the material determined from the tensile tests of the coupons. This value of column efficiency is lower than would be expected for a column having a slenderness ratio of 72.5, tested with flat ends. Calculations based on the distance between the rows of rivets, the measured plate thickness, the elastic constants as determined from the coupon test results, and on the assumption that the plate edges were simply supported, give the critical buckling stress in the plate as 29.1 kips/in^2. The compressive stress at failure was 30.4 kips/in^2.

The test results being somewhat greater than the calculated buckling stress probably was due to the fact either that the angles were more rigidly connected to the plate than was assumed or that the effective plate width was less than the distance between the rows of rivets.

The effective area factors, C, of the perforated plates with respect to compressive strength are of course greater than they would have been if the unperforated-plate column had failed at a higher stress due to primary buckling. It may be noted that the compressive stresses on net area at failure are practically the same for the perforated-plate *C4* columns as for the previously tested perforated-plate *C2* columns.

Figures 20 and 21 show the columns after test.

V. SUMMARY

1. MODULUS

The effectiveness of the perforated plates in resisting shortening under compressive load was determined by comparison of the modulus of a column containing the perforated plate with that of a similar column containing an unperforated plate. It was found that from 61 to 70 percent of the gross cross-sectional area of the plate, depending on the perforation spacing, was effective in resisting shortening under compressive load. The effective-area factors for the perforated plates were not consistently affected by variation in the number of angles with which they were tested.

2. STRESS DISTRIBUTION

The stress distribution was determined on the edge of the middle perforation of each perforated plate column and on the middle bay of one of each group of three like columns having four angles. In every case the maximum stress was compressive and occurred on the edge of the perforation. The value of the maximum stress was only slightly affected by variation of perforation spacing. For columns with the same perforation spacing, the maximum stress was higher for the two-angle than for the four-angle column for the same average stress on the gross area. This was not always true when the stresses were based on net area.

The maximum stress varied from 2 to 2.6 times the average stress on the gross area, or 1.7 to 2.1 times the average stress on the net area.

3. STRENGTH

The effectiveness of the perforated plates with respect to strength was somewhat higher than with respect to resistance to shortening and increased with increase of the perforation spacing.

WASHINGTON, July 2, 1942.

○

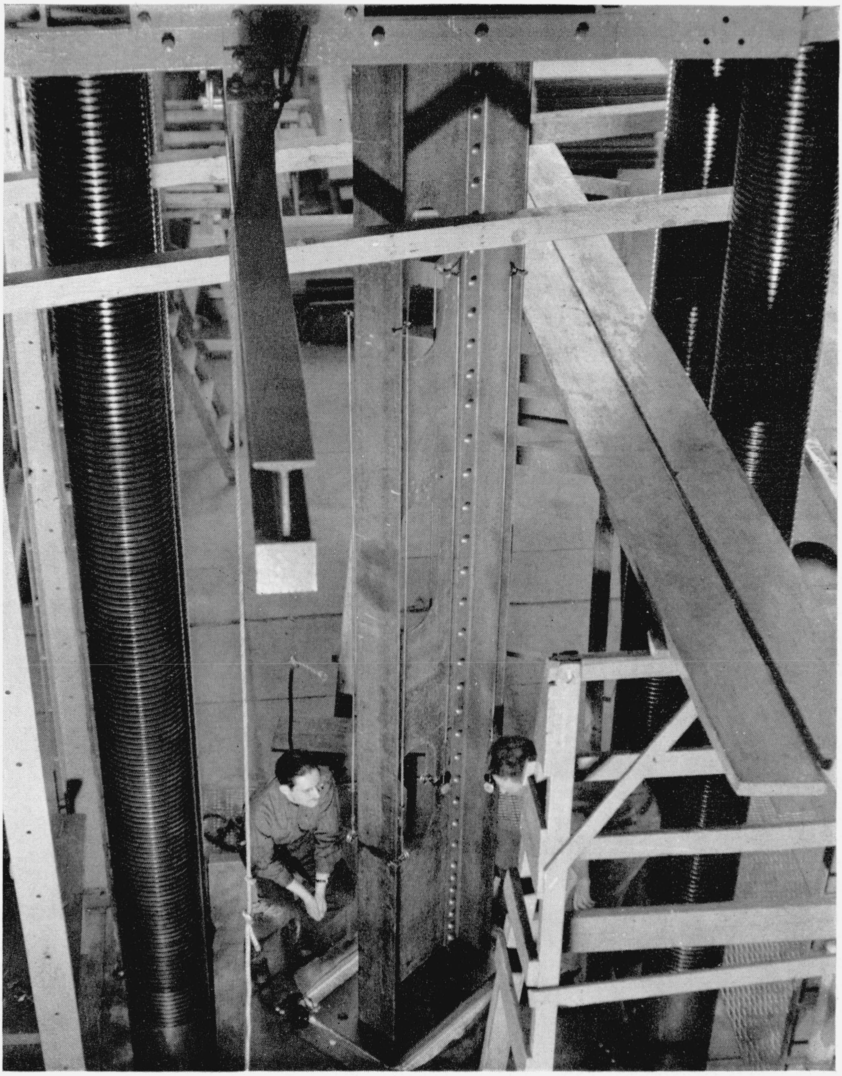

FIGURE 19.—*Column C4C during the maximum load test.*

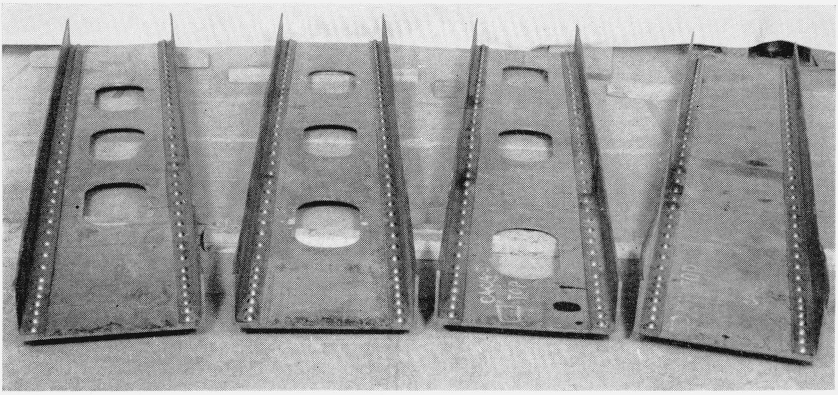

FIGURE 20.—*Columns C4–(two angles) after maximum load tests.*

From left to right the columns are *C4A*, *C4B*, *C4C*, and *C4D*.

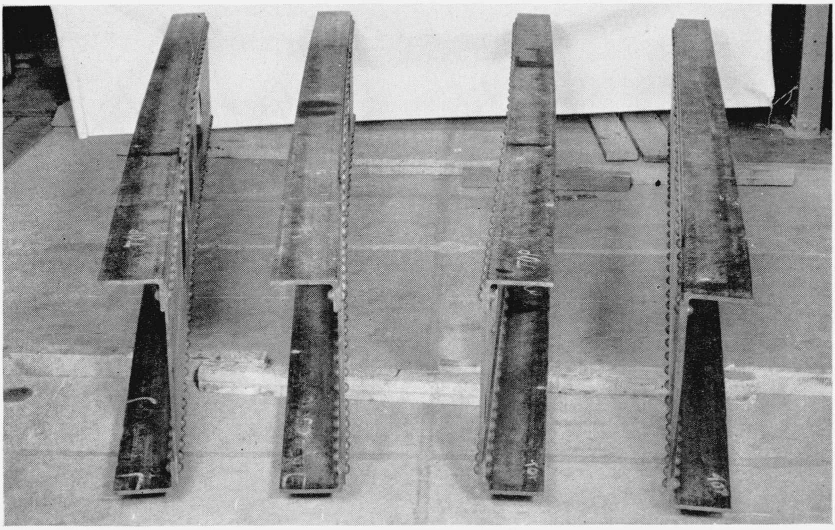

FIGURE 21.—*Columns C4–(two angles) after maximum load tests.*

From left to right the columns are *C4A*, *C4B*, *C4C*, and *C4D*.

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[Continued on p. 4 of cover]

[Continued from p. 3 of cover]

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