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PERFORATED COVER PLATES FOR STEEL COLUMNS: COMPRESSIVE PROPERTIES OF PLATES HAVING OVALOID PERFORATIONS AND A WIDTH-TO-THICKNESS RATIO OF 53

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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 test 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.

It was found that the perforated plates contributed to the strength, and especially to the stiffness, of the columns, and that the factor of stress concentration, due to the presence of 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 fourth 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 results for plates having widths of 15 in. and of 25.5 in. have been given in previous Research Papers [1, 2, 3].[1]

In this paper are presented the test results for the *C3* series of plates. These plates were 20 in. wide by ⅜ in. thick, thus having a width-to-thickness ratio of 53. The perforated plates of this series had ovaloid perforations 9 in. wide. The net-to-gross cross-sectional area ratio was 0.55.

II. COVER-PLATE COLUMNS

1. GENERAL

The details of the *C3* plates and of the angles are shown in figure 1. The perforated *C3* plates were all of the same nominal dimensions as to length, width, thickness and number, size, and shape of perforation but differed with regard to perforation spacing (i. e., the distance between centers of adjacent perforations). The perforation spacing was 30 in. for the *C3A* plates, 42 in. for the *C3B* plates, and 54 in. for the *C3C* plates. The *C3D* plates had the same nominal dimensions as the perforated *C3* 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 C3 columns*

Column designation [1]	Angle designations
C3A (---) 2 angles	*C5A(2–3)*, *C5E(0–1)*.
C3A (---) 4 angles	*C5A(2–3)*, *C5E(0–1)*, *C5D(0–1)*, *C5L(2–3)*.
C3B (---) 2 angles	*C5D(0–1)*, *C5L(2–3)*.
C3B (---) 4 angles	*C5D(0–1)*, *C5L(2–3)*, *C5C(2–3)*, *C5L(4–5)*.
C3C (---) 2 angles	*C5C(2–3)*, *C5L (4–5)*.
C3C (---) 4 angles	*C5C(2–3)*, *C5L(4–5)*, *C5C(0–1)*, *C5D(4–5)*.
C3D (---) 2 angles	*C5A(0–1)*, *C5E(4–5)*.
C3D (---) 4 angles	*C5A(0–1)*, *C5E(4–5)*, *C5A(2–3)*, *C5E(0–1)*.

[1] The 3 columns represented by each of the above designations contained the same angles.

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.

[1] Figures in brackets indicate the literature references at the end of this paper.

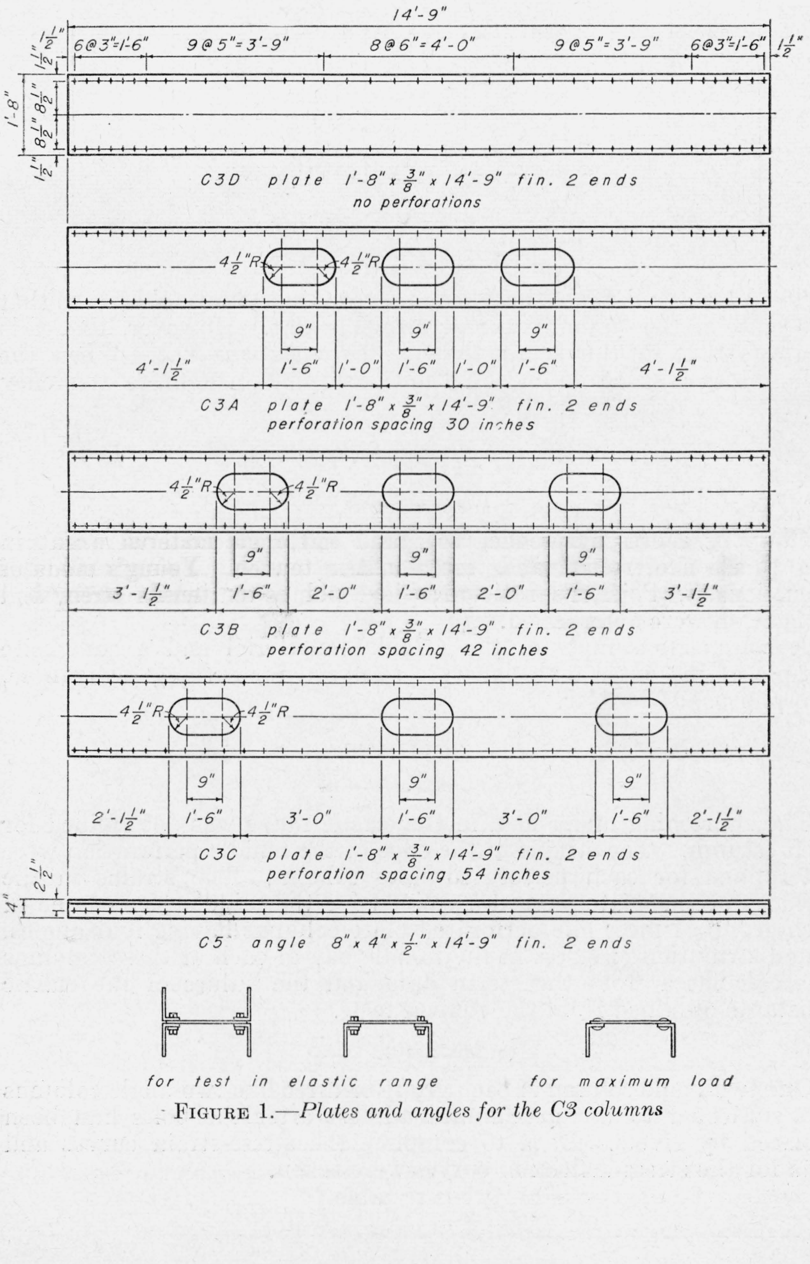


FIGURE 1.—*Plates and angles for the C3 columns*

TABLE 2.—*Cross-sectional areas of plates and angles for the C3 columns*

Plates			Angles	
Designation	Gross area	Net area	Designation	Area
	in.^{2}	*in.*^{2}		*in.*^{2}
C3A(0-1)	7.64	4.25	*C5A(0-1)*	5.79
C3A(2-3)	7.60	4.22	*C5A(2-3)*	5.78
C3A(4-5)	7.56	4.18	*C5C(0-1)*	5.74
C3B(0-1)	7.75	4.31	*C5C(2-3)*	5.76
C3B(2-3)	7.65	4.25	*C5D(0-1)*	5.73
C3B(4-5)	7.65	4.25	*C5D(4-5)*	5.78
C3C(0-1)	7.72	4.28	*C5E(0-1)*	5.78
C3C(2-3)	7.60	4.21	*C5E(4-5)*	5.81
C3C(4-5)	7.50	4.13	*C5L(2-3)*	5.77
C3D(0-1)	7.67		*C5L(4-5)*	5.80
C3D(2-3)	7.62			
C3D(4-5)	7.57			

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, μ; yield point, tensile strength, and elongation were determined.

A composite sample of the *C3* 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 the maximum-load test after the bolts had been replaced by rivets. Data to complete the stress-strain curves and data for the stress-deflection curves were taken.

IV. RESULTS

1. COUPONS

The results of the tensile tests of the coupons are given in table 3, and the chemical composition of the coupon material is given in table 4.

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

Coupon designation	Thickness	Young's modulus of elasticity, E	Poisson's ratio, μ	Yield point	Tensile strength	Elongation in 8 in.
PLATE COUPONS						
	in.	*Kips/in.*[2]		*Kips/in.*[2]	*Kips/in.*[2]	%
C3A(1-2)	0.381	29,400	0.278	37.2	58.6	36.0
C3A(3-4)	.379	29,600	.282	38.0	59.0	30.5
C3B(1-2)	.385	29,500	.282	38.4	58.7	31.9
C3B(3-4)	.384	29,700	.282	37.1	58.7	34.9
C3C(1-2)	.383	29,500	.283	37.3	59.8	33.8
C3C(3-4)	.377	29,400	.278	37.3	59.7	35.5
C3D(1-2)	.382	29,400	.281	38.0	60.4	32.4
C3D(3-4)	.379	29,600	.276	38.6	60.5	32.7
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	58.1	33.5
C5C(1-2)	.508	29,400	.281	36.4	58.8	31.3
C5C(3-4)	.501	29,700	.285	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

TABLE 4.—*Chemical composition of coupon material*

Composite sample	Carbon	Manganese	Phosphorus	Sulfur
	%	%	%	%
Plates *C3*	0.17	0.54	0.008	0.033
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.[2]

[2] See pages 679 and 680 of reference [1].

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

Plate designation	Number of angles	Based on gross area			Based on net area		
		Modulus, E'	Effective-area factor, K	Ratio $\frac{\text{Maximum stress}}{P/A}$	Modulus, E'	Effective-area factor, K	Ratio $\frac{\text{Maximum stress}}{P/A}$
		Kips/in.^{2}			*Kips/in.*^{2}		
C3A(0-1)	2	24,800	0.61		30,100	1.10	
C3A(2-3)	2	24,600	.60		29,900	1.07	
C3A(4-5)	2	24,700	.60		30,000	1.09	
Avg		24,700	0.60	−2.16	30,000	1.09	−1.78
C3A(0-1)	4	26,600	0.64		29,900	1.15	
C3A(2-3)	4	26,500	.62		29,800	1.11	
C3A(4-5)	4	26,600	.64		30,000	1.15	
Avg		26,600	0.63	−1.97	29,900	1.14	−1.75
C3B(0-1)	2	25,400	0.67		30,900	1.20	
C3B(2-3)	2	25,400	.67		30,900	1.20	
C3B(4-5)	2	25,600	.68		31,100	1.23	
Avg		25,500	0.67	−2.37	31,000	1.21	−1.95
C3B(0-1)	4	26,900	0.68		30,300	1.22	
C3B(2-3)	4	26,900	.67		30,200	1.21	
C3B(4-5)	4	26,900	.68		30,200	1.21	
Avg		26,900	0.68	−2.28	30,200	1.21	−2.03
C3C(0-1)	2	25,800	0.70		31,400	1.27	
C3C(2-3)	2	25,700	.69		31,200	1.24	
C3C(4-5)	2	25,800	.69		31,300	1.26	
Avg		25,800	0.69	−2.55	31,300	1.26	−2.10
C3C(0-1)	4	26,900	0.67		30,200	1.21	
C3C(2-3)	4	27,100	.70		30,400	1.26	
C3C(4-5)	4	27,100	.69		30,400	1.26	
Avg		27,000	0.69	−2.39	30,300	1.24	−2.13
C3D(0-1)	2	29,400			29,400		
C3D(2-3)	2	29,300			29,300		
C3D(4-5)	2	29,200			29,200		
Avg		29,300	1.00		29,300	1.00	
C3D(0-1)	4	29,300			29,300		
C3D(2-3)	4	29,300			29,300		
C3D(4-5)	4	29,200			29,200		
Avg		29,300	1.00		29,300	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.

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, $\sigma_{uv}/(P/A)$, may be obtained by multiplying $\sigma_{u,v}/(P/A_n)$ by 1.22 for the two-angle and 1.12 for the four-angle columns. The maximum stress ratios are given in table 5.

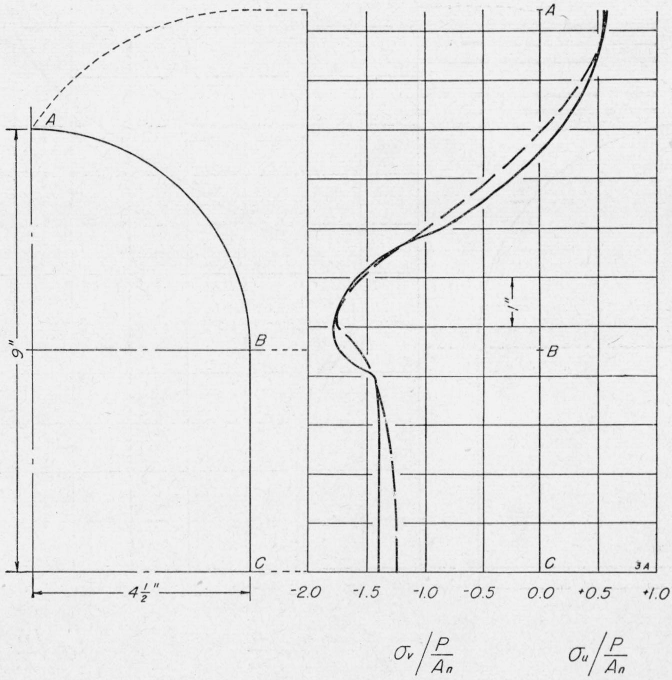


FIGURE 2.—*Columns C3A, perforation spacing 30 inches. Distribution of stress on the edge of the middle perforation.*

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

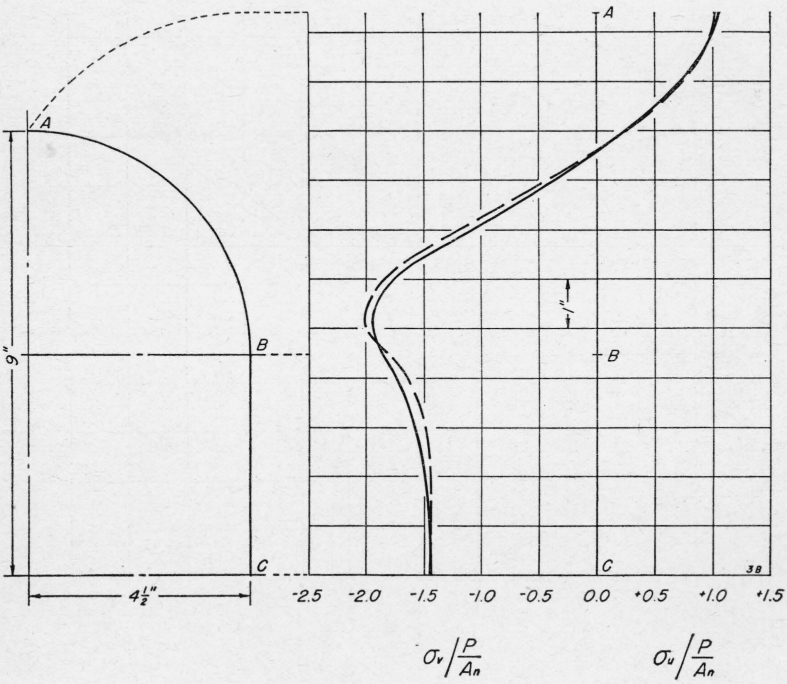


FIGURE 3.—*Columns C3B, perforation spacing 42 inches. Distribution of stress on the edge of the middle perforation.*

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

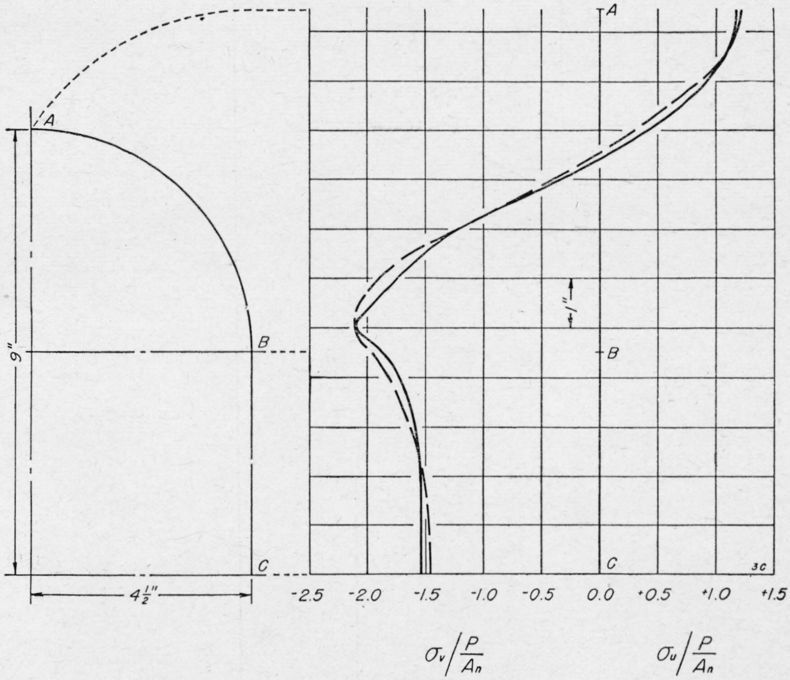


FIGURE 4.—*Columns C3C, perforation spacing 54 inches. Distribution of stress on the edge of the middle perforation.*

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

(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 1.12 for these four-angle columns.

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 zero; of $\sigma_v/(P/A)$, -1; and of θ, 90 degrees.

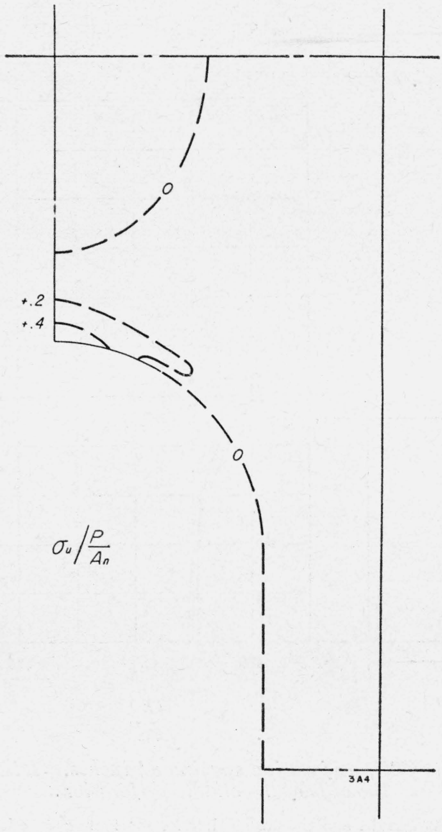


FIGURE 5.—*Column C3A(2–3) (four angles), perforation spacing 30 inches. Isogram of maximum principal stress.*

Based on net area.

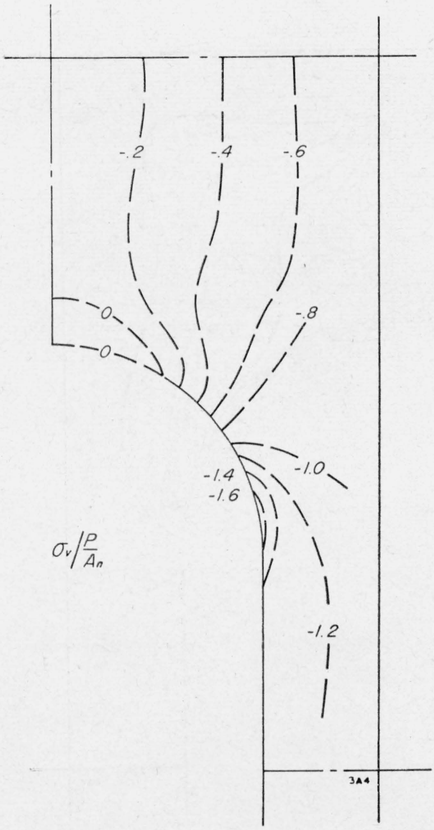


FIGURE 6.—*Column C3A(2–3) (four angles), perforation spacing 30 inches. Isogram of minimum principal stress.*

Based on net area.

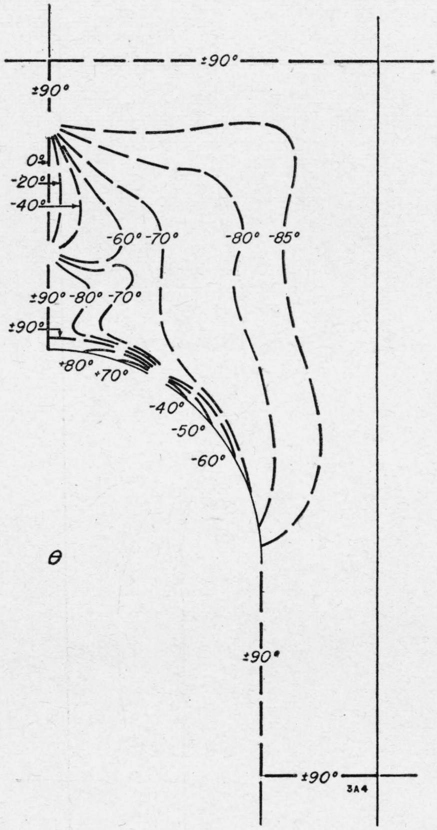


FIGURE 7.—*Column C3A(2–3) (four angles), perforation spacing 30 inches. Isoclinics.*

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

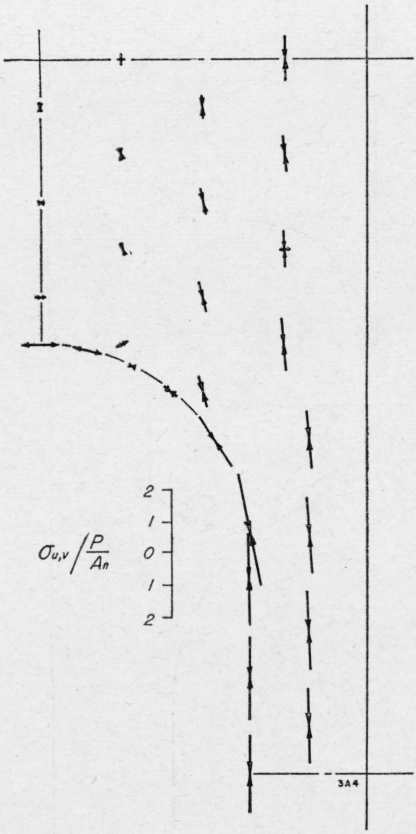


FIGURE 8.—*Column C3A(2–3) (four angles), perforation spacing 30 inches Magnitude and direction of the principal stresses.*

Based on net area.

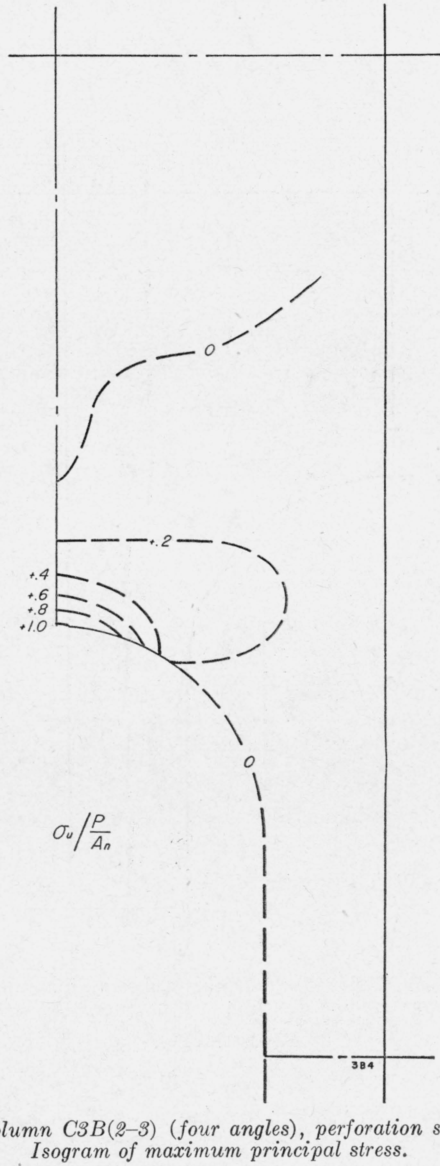


Figure 9.—*Column C3B(2–3) (four angles), perforation spacing 42 inches. Isogram of maximum principal stress.*

Based on net area.

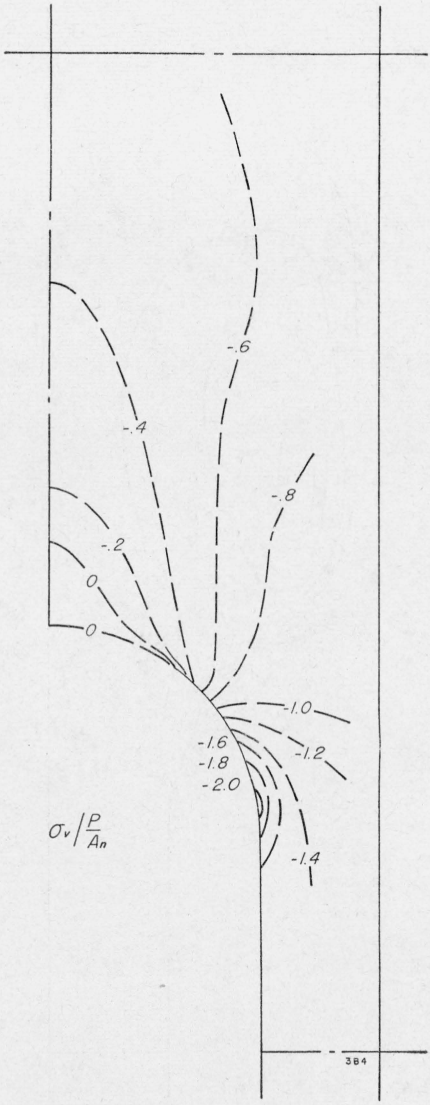


FIGURE 10.—*Column C3B(2–3) (four angles), perforation spacing 42 inches. Isogram of minimum principal stress.*

Based on net area.

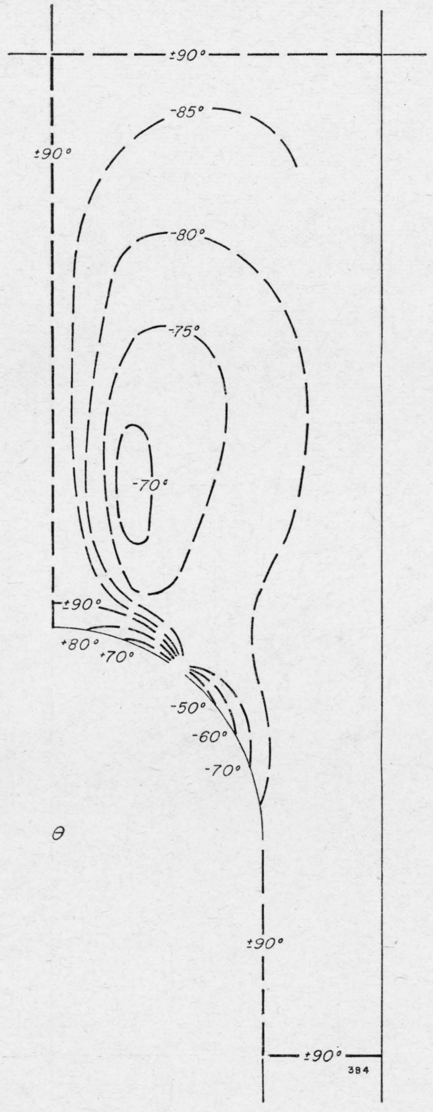


FIGURE 11.—*Column C3B(2–3) (four angles), perforation spacing 42 inches. Isoclinics.*

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

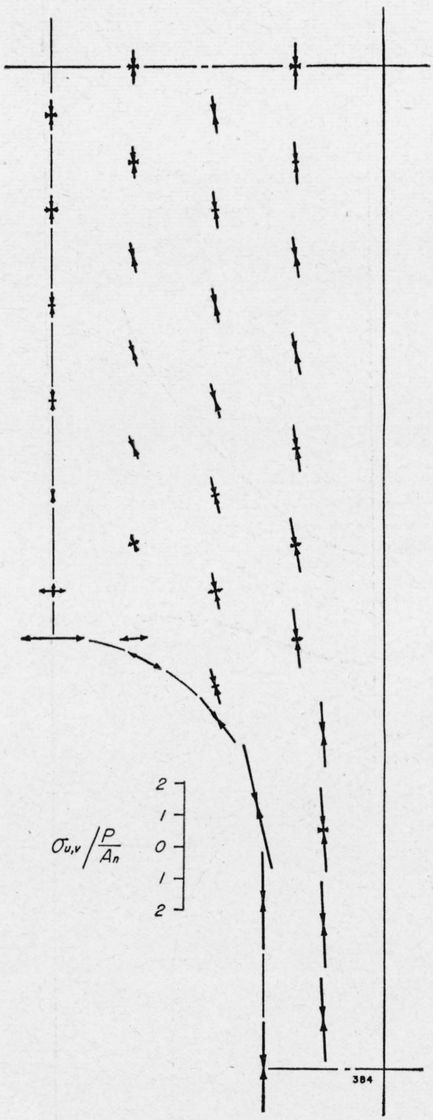


FIGURE 12.—*Column C3B(2–3) (four angles), perforation spacing 42 inches. Magnitude and direction of the principal stresses.*

Based on net area.

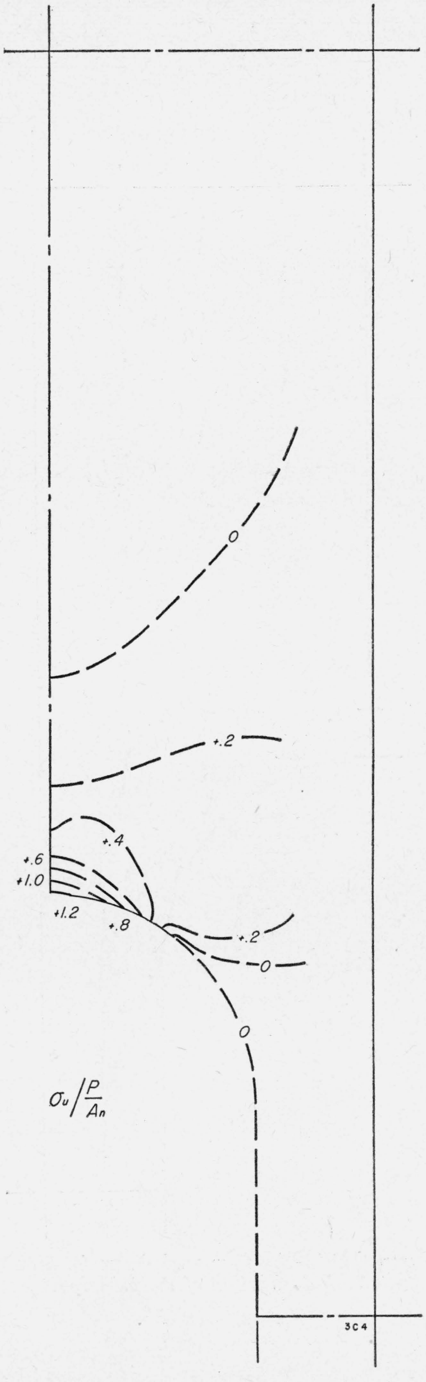


FIGURE 13.—*Column C3C(2–3) (four angles), perforation spacing 54 inches. Isogram of maximum principal stress.*

Based on net area.

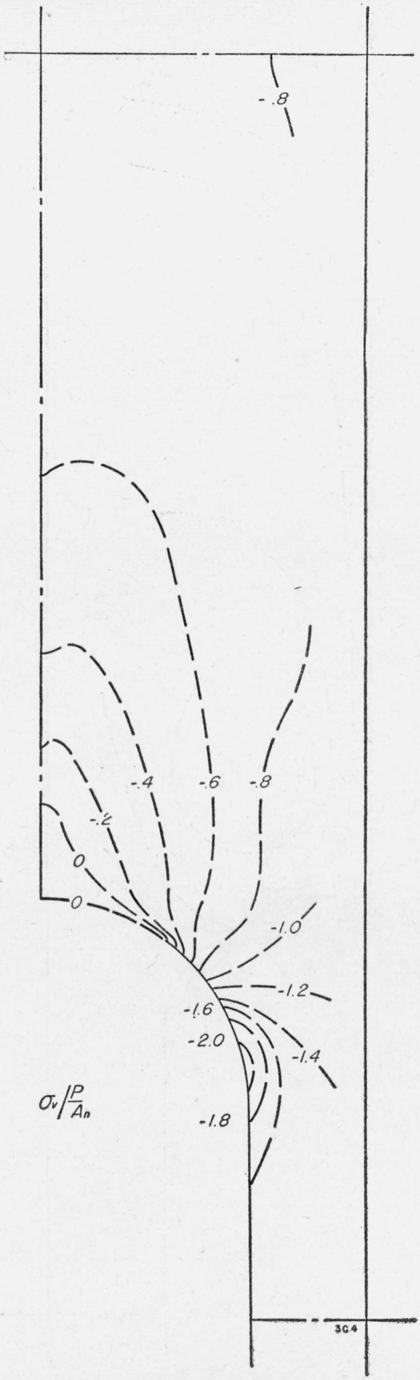


FIGURE 14.—*Column C3C(2–3) (four angles), perforation spacing 54 inches. Isogram of minimum principal stress.*

Based on net area.

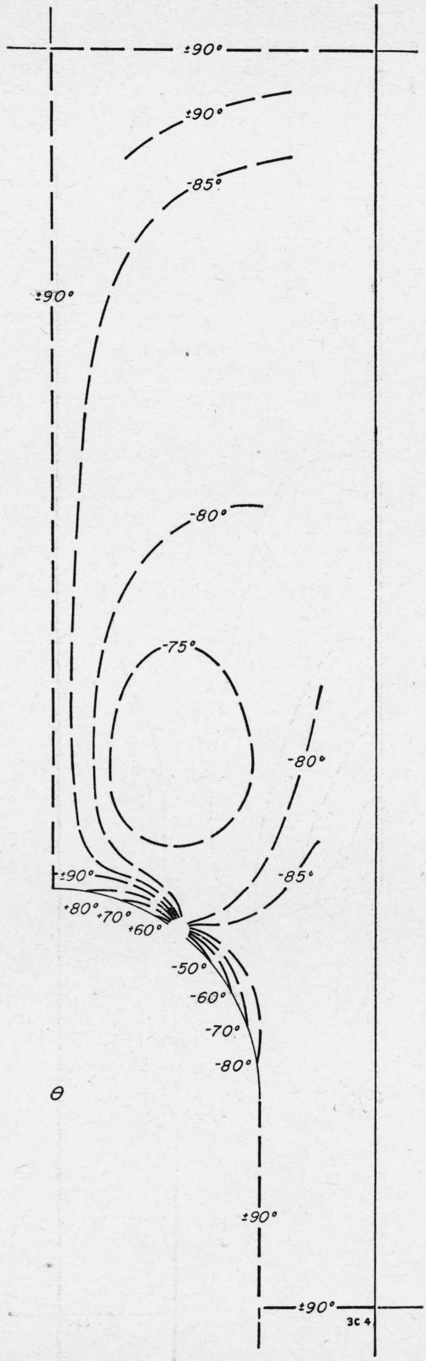


FIGURE 15.—*Column C3C(2–3) (four angles), perforation spacing 54 inches. Isoclinics.*

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

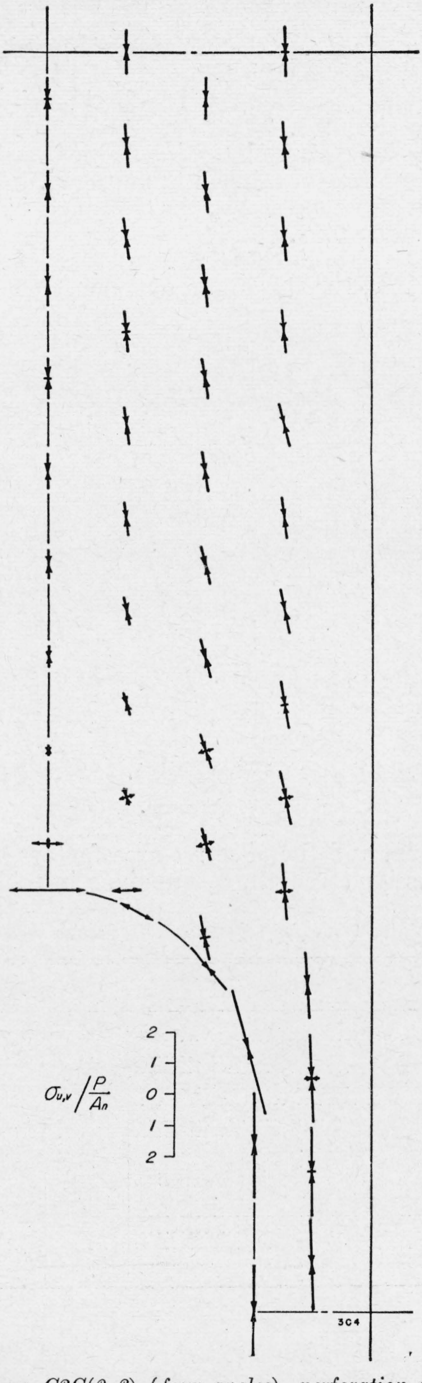


FIGURE 16.—*Column C3C(2–3) (four angles), perforation spacing 54 inches. Magnitude and direction of the principal stresses.*

Based on net area.

(c) MAXIMUM-LOAD TEST

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

The stresses on gross area may be obtained by multiplying the stresses on net area by 0.82.

(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 0.82.

(3) *Maximum Load and Effective Area of Plate.*—The maximum loads for the columns, the maximum average stress on the gross area

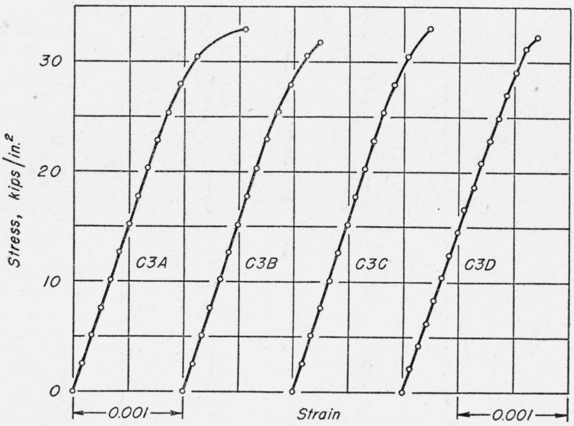


FIGURE 17.—*Columns C3–(two angles). Stress-strain graphs.*

Based on net 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.[3]

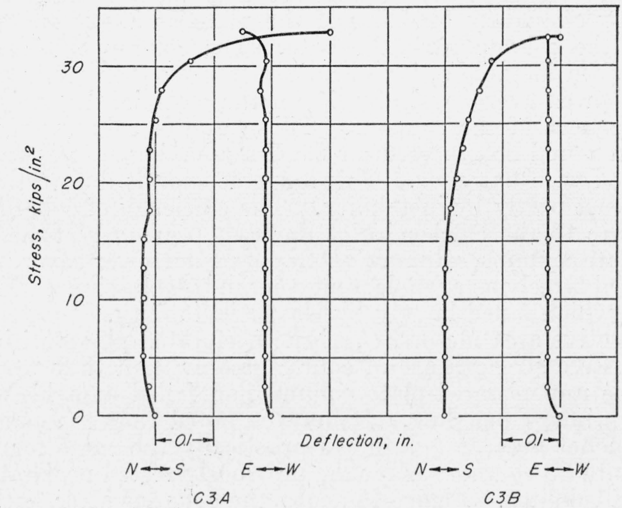
TABLE 6.—*Maximum loads for columns and effective-area factors for plates*

Column designation	*C3A*	*C3B*	*C3C*	*C3D*
Perforation spacing, in	30	42	54	([a])
Area of angles, in.²	11.57	11.50	11.57	11.60
Gross area of plate, in.²	7.60	7.65	7.60	7.62
Net area of plate, in.²	4.22	4.25	4.21	7.62
Total area, gross, in.²	19.17	19.15	19.17	19.22
Total area, net, in.²	15.79	15.75	15.78	19.22
Maximum compressive load, kips	521	516	535	624
Compressive stress on gross area at failure, kips/in.²	27.2	26.9	27.9	32.5
Compressive strees on net area at failure, kips/in.²	33.0	32.8	33.9	32.5
Effective-area factor of plate with respect to compressive strength, *C*:				
Based on gross area	0.59	0.57	0.64	1.00
Based on net area	1.06	1.03	1.16	----------
Slenderness ratio	----------	----------	----------	71
Column efficiency, percent	----------	----------	----------	87

[a] No perforation.

The perforated-plate columns *C3A*, *C3B*, and *C3C* 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 perfora-

[3] See page 685 of reference [1].



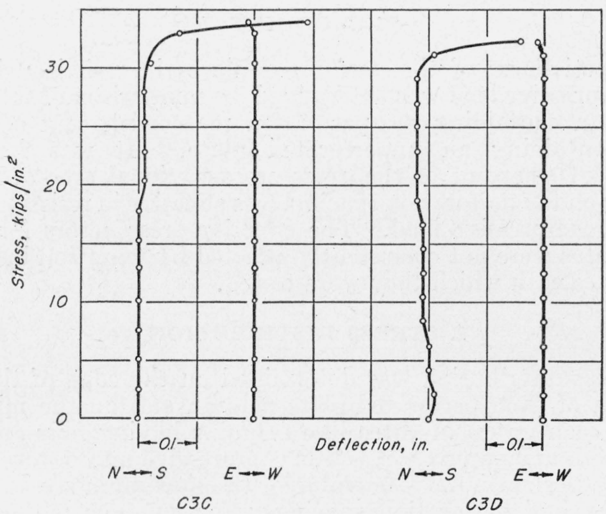


FIGURE 18.—*Columns C3–(two angles). Stress-deflection graphs.*

Based on net area. When the deflection is North, *N*, the bending stress is tensile on the plate side.

tion, 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 *C3D* started to deflect toward the plate side, as would be expected from the double-modulus theory, but it failed by secondary buckling of the plate at about one-third the height of the column from the base. The column efficiency of 87 percent, given in table 6, is 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 71 tested with flat ends. This low-efficiency is due to the failure being at least partly by instability. The efficiency of column *C3D* is intermediate to the efficiencies of the two previously tested unperforated-plate columns, column *C2D* having a narrower cover plate and which failed largely as a whole, and column *C4D* having a wider cover plate and which failed largely by elastic instability.

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 owing to primary buckling. It may be noted that the compressive stresses on net area at failure are practically the same for the perforated-plate *C3* columns as for the previously tested perforated-plate *C2* and *C4* columns. Figure 19 shows 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 60 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 increased with increase 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.

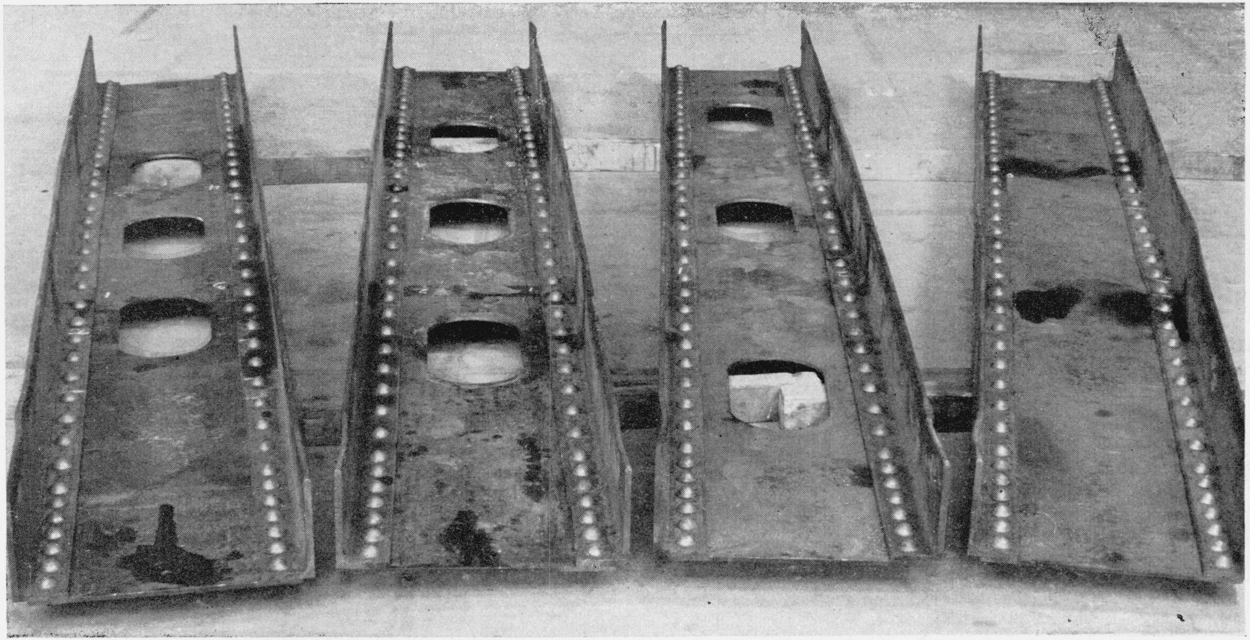


FIGURE 19.—*Columns C3–(two angles) after maximum load tests.*

From left to right the columns are *C3A*, *C3B*, *C3C*, *and C3D*.

3. STRENGTH

The effectiveness of the perforated plates with respect to strength was somewhat lower than with respect to resistance to shortening and was little affected by change of perforation spacing.

VI. REFERENCES

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[3] 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 68*, J. Research NBS **29**, 279 (1942) RP1501.

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