UNITED STATES EXPERIMENTAL MODEL BASIN

NAVY YARD, WASHINGTON, D.C.

THE EFFECT OF OPENINGS ON THE ULTIMATE TENSILE STRENGTH OF FLAT PLATES

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Purpose of Tests:

The tests described in this report were undertaken for the purpose of investigating the effects of round and square openings upon the ultimate strength and mode of failure of flat plates loaded in tension, and the extent to which various types of reinforcement affect the results.

Description of Models:

The test specimens consisted of medium steel plates 20" x 15" x 1/8", having central round or square holes which in most cases removed one fourth of the transverse sectional area of the plate. The transverse sectional areas of all reinforcements in way of the openings were usually made equal to the material removed by the opening, so that most specimens had transverse sectional areas equal to that of the uncut plate. The models are shown in outline in Table VI, and the first 32 after test in Figs 1 to 4. In models 27, 28, 30 and 32 the strap width was one-half that used in the preceding models, so that only one-half the area removed by the hole was replaced by the straps. Models 39 to 44 were duplicates of models 33 to 38, except that different material was used.

Attachment of reinforcements to plates was by continuous fillet welds except on the inside edge in way of the hole, where V welds were used in some models. No heat treatment was given to relieve locked-up stresses.

With the exception of #45, 46 and 47, the edges of all plates and holes were finished by hand filing. All square holes had sharp corners.

Method of Test:

The specimens were tested in the 600,000 lb. Baldwin-Southwark machine. No data, other than ultimate strength, were taken. The specimens were welded to heavy end plates which were in turn pin-jointed to the heads of the testing machine, ensuring axial loading and no applied moments.

Results:

The results obtained are given in Table VI, but in order clearly to compare the effects of various features, it is necessary to arrange the models in suitable groups.

I – ROUND vs. SQUARE HOLE

TABLE I.

GROUP	AVERAGE EFFICIENCY	
	ROUND HOLE	SQUARE HOLE
A	81.2	78.6
B	81.1	78.5
C	87.5	84.8
D	87.1	83.6

GROUP	Number in Group	Specimens excluded
A	41	45, 46, 47 – burned holes.
B	37	45, 46, 47 27, 28, 30, 32 – narrow strap specimens; sectional area not equal to that of uncut plate.
C	25	45, 46, 47 27, 28, 30, 32 33 to 44, inclusive – riveted ring reinforcements and various hole sizes.
D	15	45, 46, 47 27, 28, 30, 32 33 to 44, inclusive 6, 7, 9, 10, 11, 12, 14, 16, 22, 26 – these specimens failed through the ends of the straps, and failure was probably not due primarily to the effect of the hole.

The grand average (Group A) indicates a negligible difference (about 2½%) in the effects of round and square holes on ultimate strength. The most carefully selected grouping (D), which excludes erratic failures and specimens not strictly comparable, indicates that the plates with round holes are about 3½% more efficient than those with square holes.

II – EFFECT OF REINFORCING ROUND HOLE

TABLE II

(Per cent increase in strength is with reference to specimen #2)

REINFORCEMENT ON ONE SIDE		REINFORCEMENT ON BOTH SIDES	
Specimen No.	% Improvement	Specimen No.	% Improvement
4	20.8	5	16.1
6	16.3*+	7	18.7*+
13	16.6+	14	21.2*+
17	12.9	18	20.1
21	8.5+	22	17.6*+
23	11.7		
25	19.3+		
29	24.8		
Average	16.4	Average	18.7
Average, excluding *specimens	16.4		18.1

*Specimen failed at end of reinforcement

+Stiffeners on edge instead of flat

III – EFFECT OF REINFORCING SQUARE HOLE

TABLE III

(Per cent increase in strength is with reference to specimen #3)

REINFORCEMENT ON ONE SIDE		REINFORCEMENT ON BOTH SIDES	
Specimen No.	% Improvement	Specimen No.	% Improvement
8	11.5	9	27.3*
10	16.2*+	11	18.9*+
15	8.6+	16	16.4*+
19	18.9	20	20.9
24	13.8		
26	16.2*+		
31	19.3		
Average	14.9	Average	20.9
Average, excluding *specimens	14.5		20.9

*Specimen failed at end of reinforcement

+Stiffeners on edge instead of flat

The following points may be noted in Tables II and III:

(a) The data are too erratic and inconsistent for satisfactory analysis. For example, reinforcements on one side of the plate improve the round holes more than the square holes, but for reinforcements on both sides of the plate, the results are reversed.

(b) Reinforcements on both sides are evidently better than reinforcements of the same sectional area on one side, which is to be expected from the introduction of bending stress due to eccentricity in the case of reinforcements on one side only.

(c) The comparison of reinforcements flat and on edge indicates no advantage for either arrangement. In three cases (4–6, 9–11, 31–15) flat stiffeners were better, while in four cases (5–7, 8–10, 23–25, 26–24) stiffeners on edge were more effective.

(d) No advantage is shown for joining the stiffeners together at the ends, as for example in specimens 13, 14, etc.

IV – EFFECT OF REDUCED REINFORCEMENT

Four specimens were made with the strap widths reduced one–half, which decreased the sectional area of the specimen about 12½%. Comparisons with the corresponding wide–strap specimens are shown in Table IV. For all these models the straps were flat, on one side of the plate only, and none failed at the ends of the straps.

TABLE IV

Comparable Models	Efficiencies	
	Wide Straps	Narrow Straps
4–27	90.1	76.7
8–28	80.6	82.5
29–30	93.1	88.8
31–32	86.4	76.4

These results are too erratic to permit drawing any conclusion other than that a decrease in strength caused by reducing reinforcement depends on other variables which were not controlled in these tests.

V – EFFECT OF HOLE SIZE

Specimens 33 to 44 had riveted ring reinforcements on one side of the plate only, and various hole sizes. The results obtained are shown in Table V, in which the efficiencies are referred to the tensile strength of the material in each case.

TABLE V

Specimen No.	Hole	Hole Diam. Plate Width	Efficiency
33	Round	1/4	78.7
34	"	1/2	59.3
35	"	1/3	66.9
36	Square	1/4	73.4
37	"	1/3	64.6
38	"	1/2	60.2
39	Round	1/4	72.2
40	"	1/2	57.5
41	"	1/3	69.0
42	Square	1/4	72.5
43	"	1/3	65.5
44	"	1/2	59.0

These results are plotted in Fig 5, which indicates the increase in the effect of stress concentrations as the relative hole size is made larger. Since in all these specimens the reinforcing ring remained intact while the rivets sheared, no comparisons are made with the preceding specimens.

VI – EFFECT OF ROUGH HOLE EDGES

Specimens 45, 46 and 47 were identical with No. 2, except that the hole was cut with a torch and the edges left unfinished. The average loss in strength as compared with No. 2 was 4.6%.

Discussion:

This series of specimens did not give results suitable for a satisfactory analysis. The effects of variations in reinforcements were less than the accidental variations in making the specimens, the principal one of which is probably the effects of the welding.

A number of specimens failed at the strap ends instead of through the hole, and it may be presumed that the strength would have been higher if these end connections had held properly. The strength of the end connections of doublers appears as important as the exact shape of the doubler, and it should be noted that end-connection failures occurred only in those cases where there was no transverse reinforcement along the edge of the hole.

The difference in strength due to round versus square holes under the conditions of this series of tests seems to be negligible, contrary to the usual view that square holes are much less desirable than round holes or holes with rounded corners. It can be shown that the stress concentration, within the elastic limit,

is theoretically much greater for a square than for a round hole, and that a small area will pass the yield point at a lower load for the square hole. The amount of material affected, however, will be small; and in both cases most of the material if ductile will still be elastic after the material adjacent to the hole has yielded. It is probable that this local yielding does not proceed very far before the plate as a whole reaches the yield point, and that by the time fracture occurs, it makes little difference whether the hole was round or square.

It is known, however, that the propagation of fracture in a material is accelerated by reversals of stress; and it is reasonable to expect that under such circumstances failure may occur at a smaller number of stress cycles for a square than for a round hole. It would be very desirable to repeat this investigation, using annealed specimens and cyclic loading, when and if suitable equipment is available.

TABLE VI

EFFECT OF OPENINGS ON ULTIMATE STRENGTH

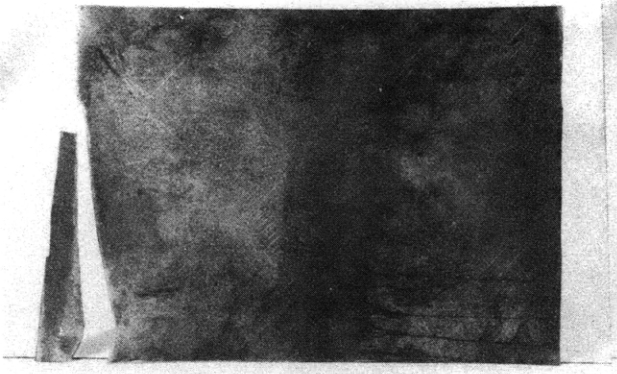
For all specimens:

Nominal Plate Size = 20" x 15" x 1/8"

Width of Opening = 1/4 Plate Width = 3 3/4" (except as noted)

Sectional Area of Reinforcement = Sectional Area of Hole (except Nos. 27, 28, 30, 32)

No.	DESCRIPTION			PLATE			FAILURE		EFFICIENCY %	% IMPROVEMENT DUE TO REINFORCEMENT	
	Arrangement	Straps Single or Double	Straps Flat or on Edge	Actual Thickness inches	Gross Area sq.in.	Ultimate Strength lbs./in.²	Load lbs.	Stress lbs./in.²		Round Hole	Square Hole
1	None	None	None	0.121	1.815	70,900	124,400	68,500	96.6	–	–
2	○	None	None	0.121	1.815	70,900	96,000	52,900	74.6	–	–
3	□	None	None	0.121	1.815	70,900	93,200	51,300	72.4	–	–
4		S	F	0.133	1.993	70,900	127,600	63,900	90.1	20.8	–
5		D	F	0.133	1.993	70,900	122,300	61,400	86.6	16.1	–
6		S	E	0.134	2.010	70,900	123,500	61,500	86.8	16.3	–
7		D	E	0.131	1.965	70,900	123,500	62,800	88.6	18.7	–
8		S	F	0.133	1.993	70,900	114,000	57,200	80.6	–	11.5
9		D	F	0.123	1.844	70,900	120,400	65,300	92.2	–	27.3
10		S	E	0.123	1.844	70,900	110,000	59,600	84.1	–	16.2
11		D	E	0.125	1.875	70,900	114,400	61,000	86.1	–	18.9
12		S	F	0.133	1.993	70,900	121,300	60,800	85.8	–	18.5
13		S	E	0.133	1.993	70,900	123,000	61,700	87.1	16.6	–
14		D	E	0.133	1.993	70,900	127,800	64,100	90.4	21.2	–
15		S	E	0.1315	1.972	70,900	110,000	55,700	78.6	–	8.6
16		D	E	0.1315	1.972	70,900	117,600	59,700	84.2	–	16.4
17		S	F	0.123	1.845	70,900	110,200	59,700	84.2	12.9	–
18		D	F	0.133	1.995	70,900	126,800	63,500	89.6	20.1	–
19		S	F	0.124	1.860	70,900	112,500	61,000	86.1	–	18.9
20		D	F	0.123	1.845	70,900	114,400	62,000	87.4	–	20.9
21		S	E	0.124	1.860	70,900	106,900	57,400	81.0	8.5	–
22		D	E	0.123	1.845	70,900	114,800	62,200	87.8	17.6	–
23		S	F	0.133	1.995	70,900	118,000	59,100	83.4	11.7	–
24		S	F	0.132	1.978	70,900	115,600	58,400	82.4	–	13.8
25		S	E	0.132	1.978	70,900	124,800	63,100	89.0	19.3	–
26		S	E	0.131	1.965	70,900	117,000	59,600	84.1	–	16.2
27		S	F	0.135	2.025	70,900	110,000	54,400	76.7	2.8	–
28		S	F	0.123	1.844	70,900	108,000	58,500	82.5	–	14.0
29		S	F	0.123	1.844	70,900	121,800	66,000	93.1	24.8	–
30		S	F	0.123	1.844	70,900	116,000	62,900	88.8	18.9	–
31		S	F	0.133	1.995	70,900	122,000	61,200	86.4	–	19.3
32		S	F	0.133	1.995	70,900	108,200	54,200	76.4	–	5.7
33	80 RIVETS	S	F	0.126	1.890	39000	58000	30700	78.7	Hole width=1/4 plate width	
34	36 RIVETS	S	F	0.125	1.875	39000	43600	23250	59.6	" " =1/2 " "	
35	25 RIVETS	S	F	0.124	1.860	39000	48600	26100	66.9	" " =1/3 " "	
36	24 RIVETS	S	F	0.129	1.933	41200	58700	30250	73.4	" " =1/4 " "	
37	32 RIVETS	S	F	0.129	1.933	41200	51600	26650	64.6	" " =1/3 " "	
38	48 RIVETS	S	F	0.128	1.920	41200	47600	24800	60.2	" " =1/2 " "	
39	28 RIVETS	S	F	0.120	1.800	69500	90400	50200	72.2	" " =1/4 " "	
40	36 RIVETS	S	F	0.128	1.920	69500	76800	40000	57.5	" " =1/2 " "	
41	25 RIVETS	S	F	0.115	1.720	69500	82400	48000	69.0	" " =1/3 " "	
42	24 RIVETS	S	F	0.116	1.740	69500	87600	50400	72.5	" " =1/4 " "	
43	32 RIVETS	S	F	0.129	1.940	69500	88400	45600	65.5	" " =1/3 " "	
44	48 RIVETS	S	F	0.116	1.740	69500	71400	41000	59.0	" " =1/2 " "	
45	○	–	–	0.130	1.950	69500	95800	49100	70.6	Hole burned with torch	
46	○	–	–	0.129	1.933	69500	93000	48100	69.1	" " " "	
47	○	–	–	0.118	1.770	69500	86400	48800	70.2	" " " "	



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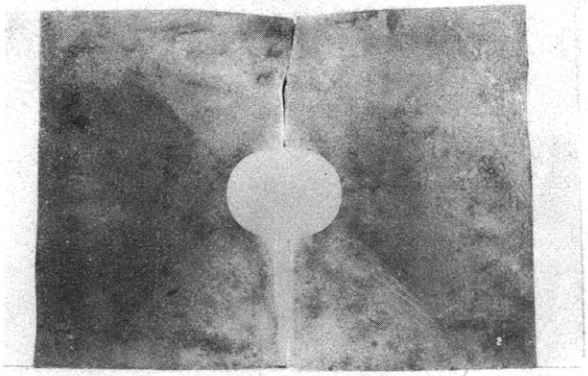

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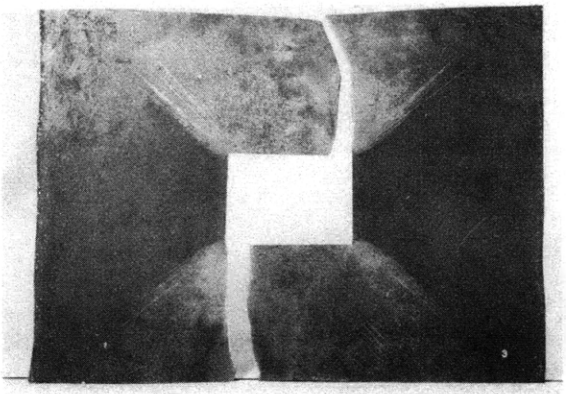

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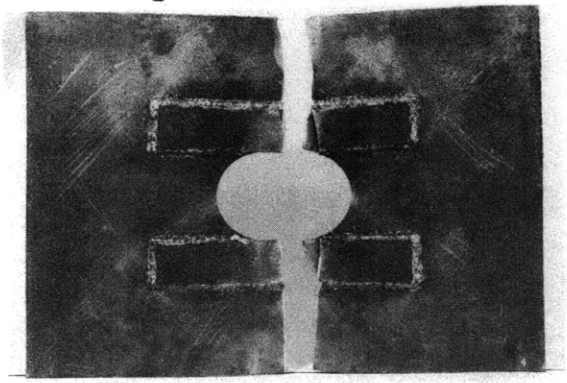

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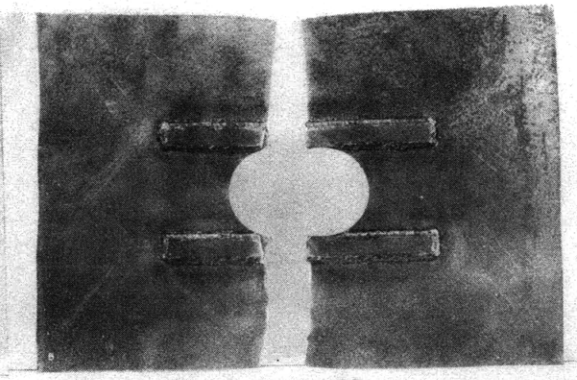

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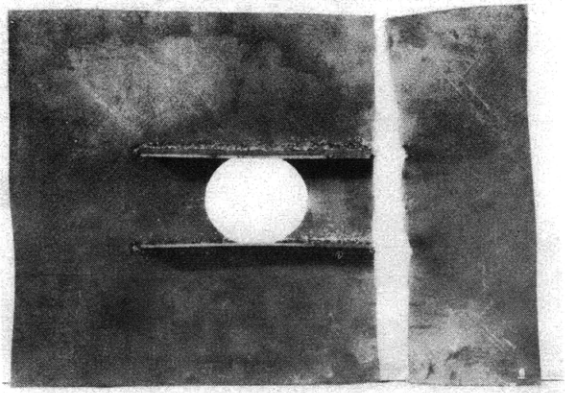

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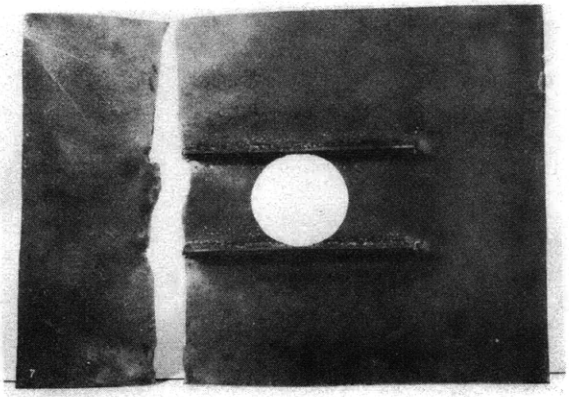

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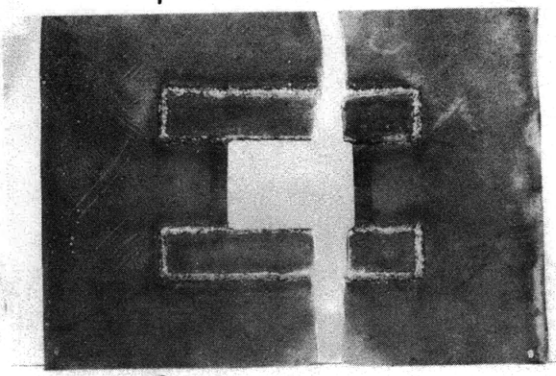

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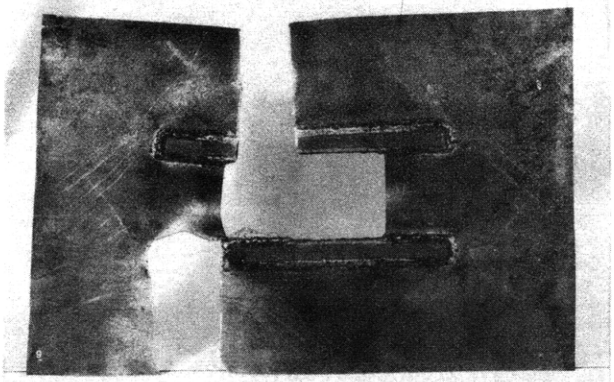

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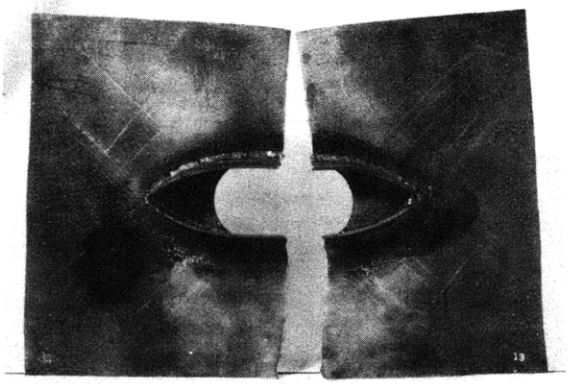

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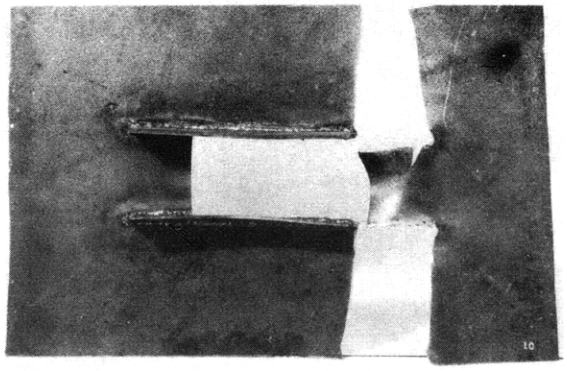

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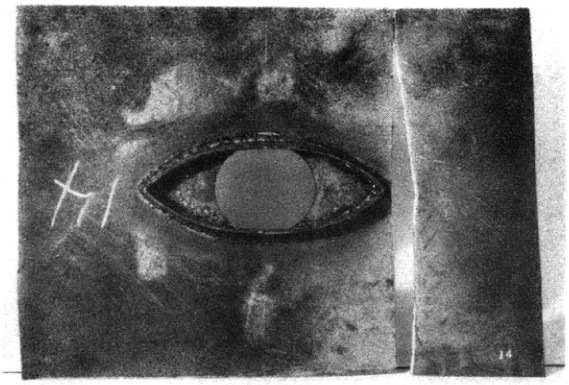

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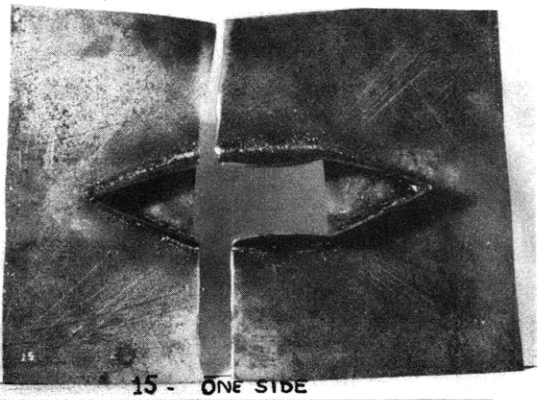

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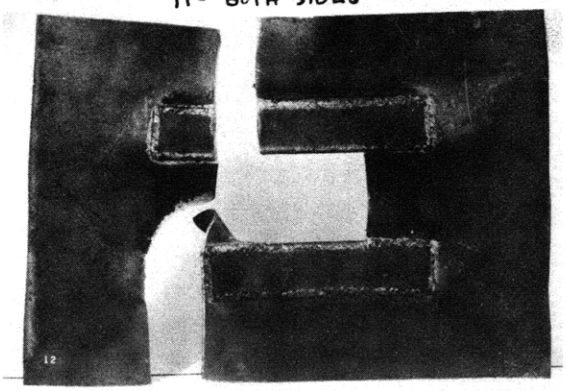

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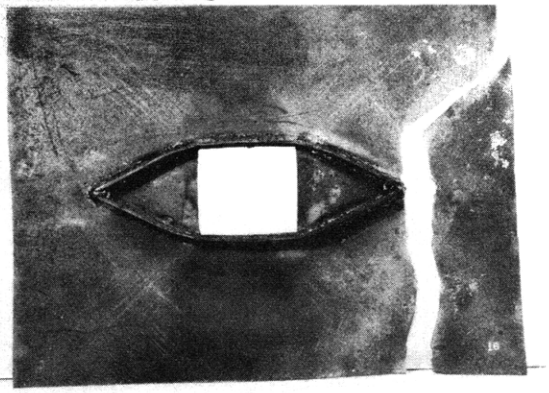

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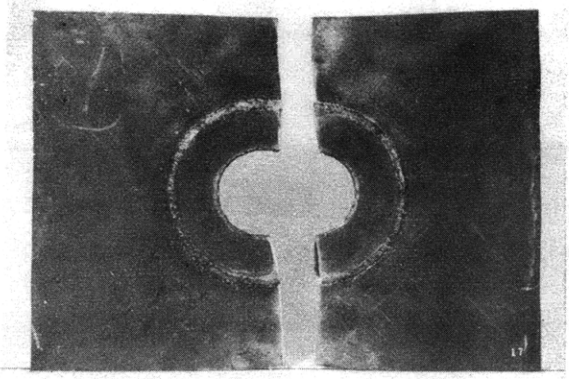

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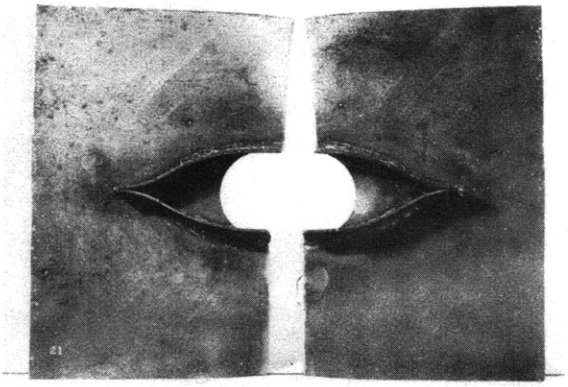

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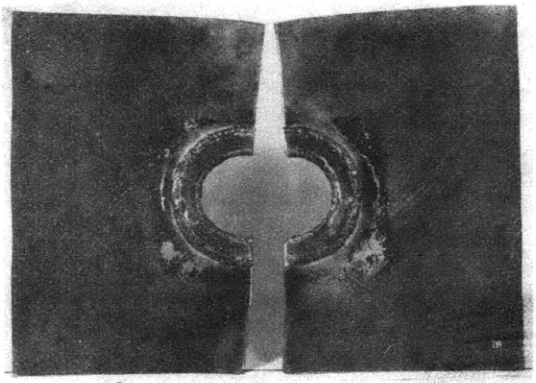

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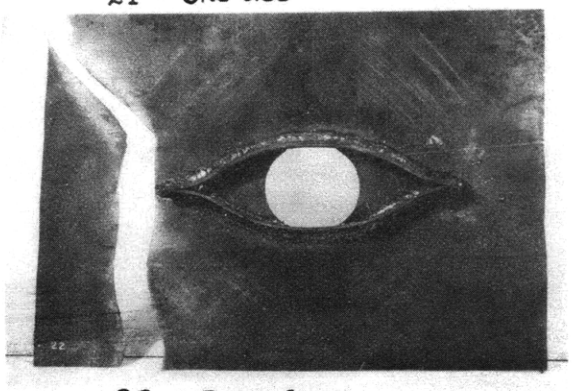

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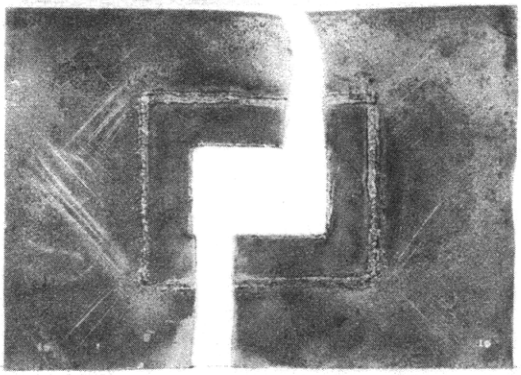

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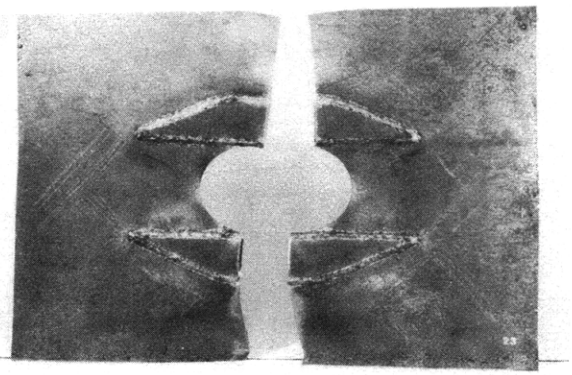

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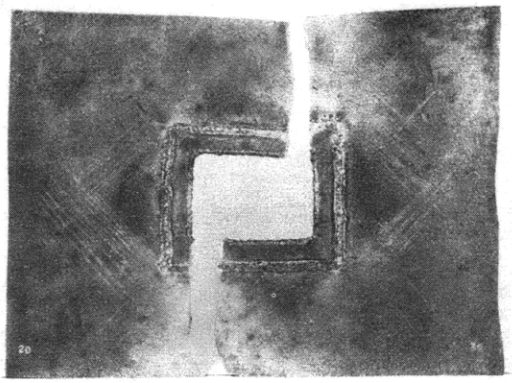

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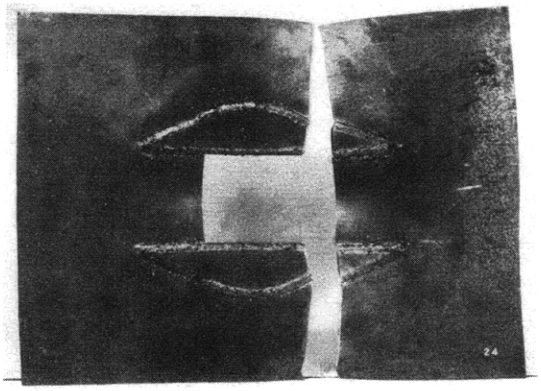

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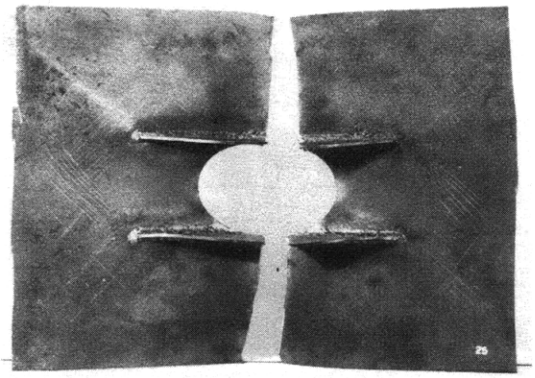

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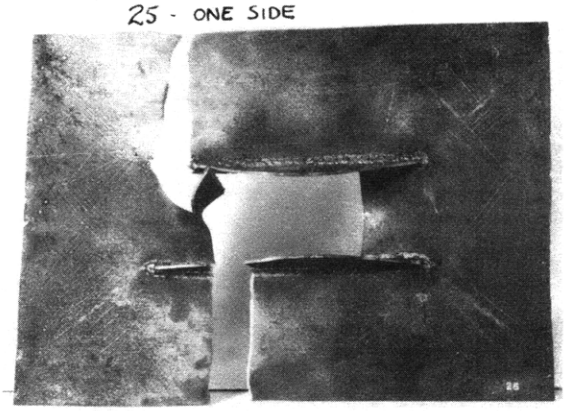
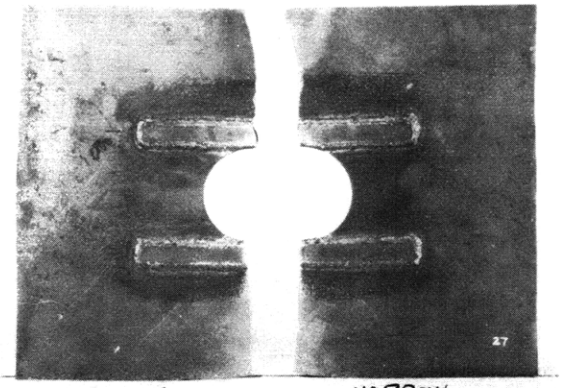
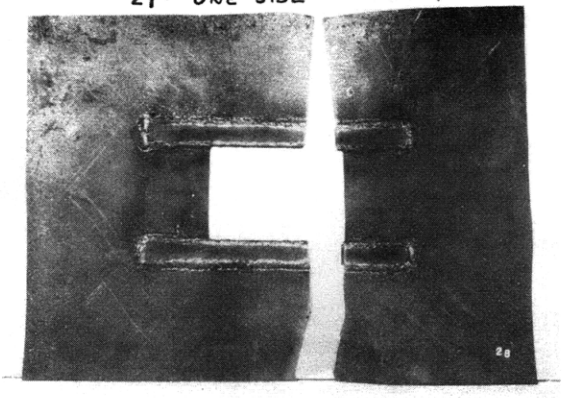


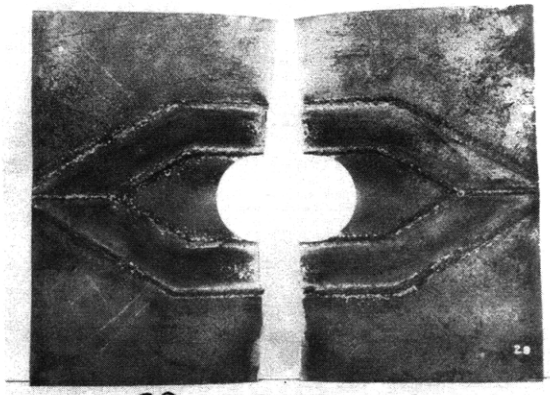
26 - ONE SIDE



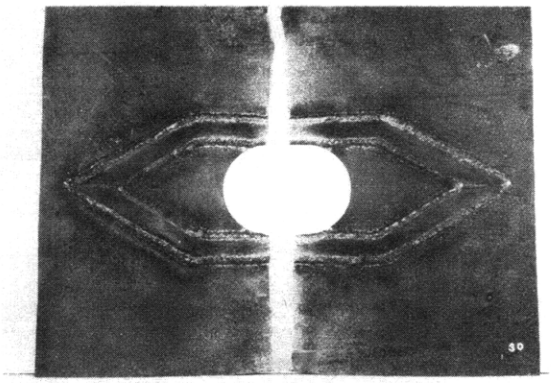
27 - ONE SIDE - NARROW



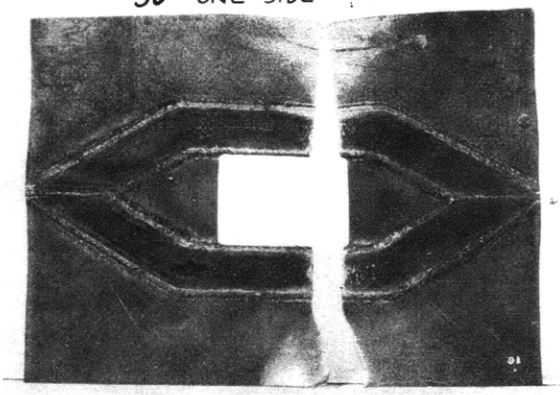
28 - ONE SIDE - NARROW



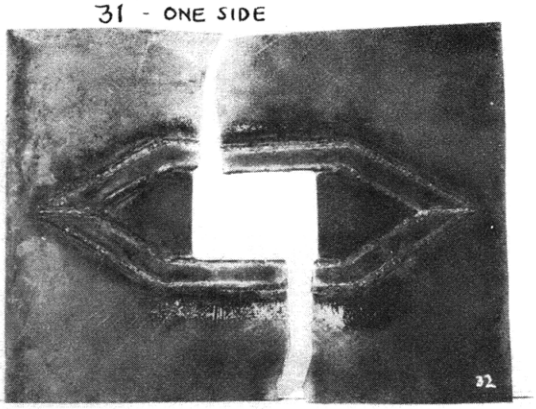
29 - ONE SIDE



30 - ONE SIDE - NARROW



31 - ONE SIDE



32 - ONE SIDE - NARROW

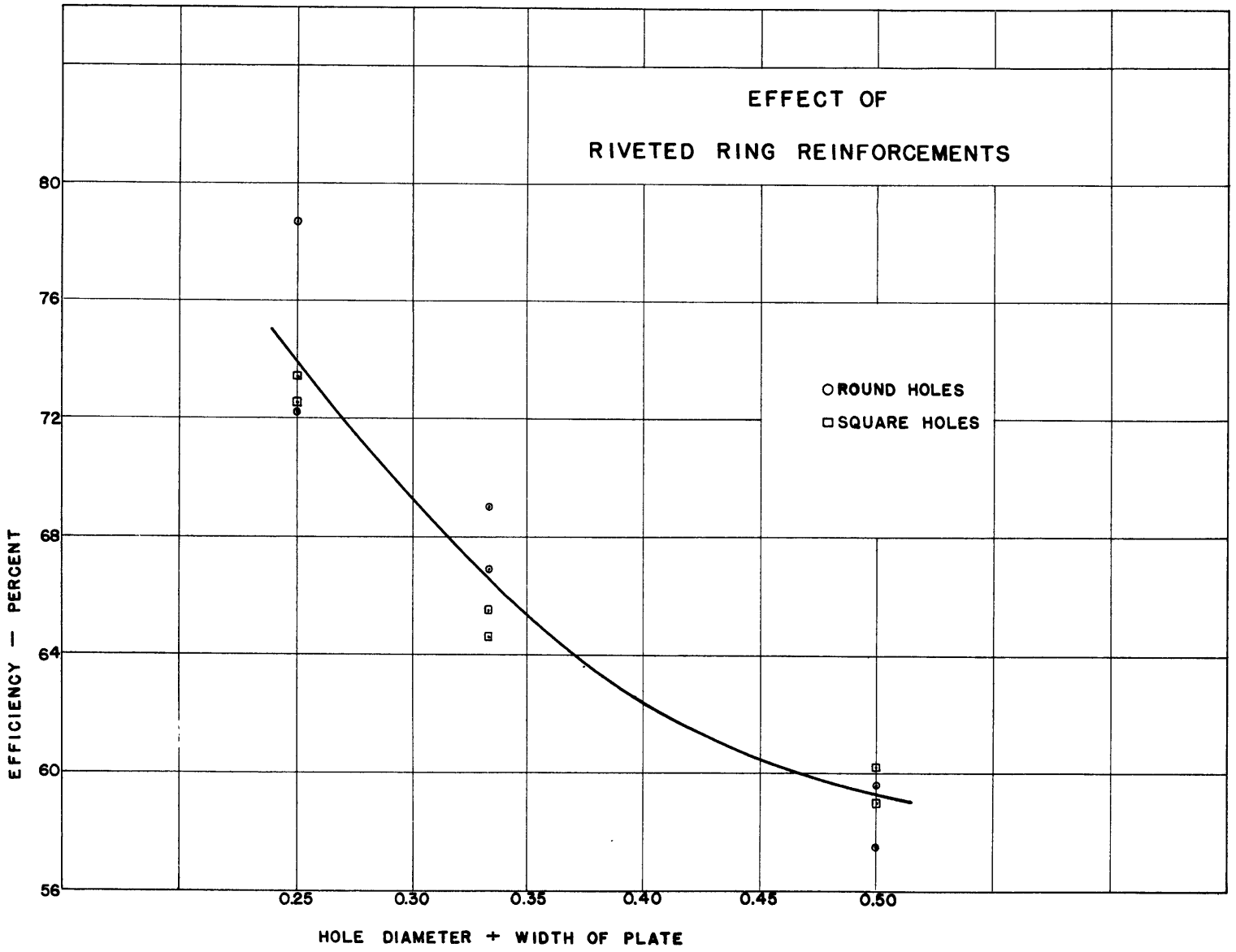

EFFECT OF
RIVETED RING REINFORCEMENTS
ROUND HOLES
SQUARE HOLES
EFFICIENCY — PERCENT
80
76
72
68
64
60
56
0.25
0.30
0.35
0.40
0.45
0.50
HOLE DIAMETER ÷ WIDTH OF PLATE

FIG. 5