SERIAL NO. **SSC-55**

Third

PROGRESS REPORT

(Project SR-119)

on

WELDED REINFORCEMENT OF OPENINGS IN STRUCTURAL STEEL MEMBERS:

Room and Low Temperature Tests of Plates with Reinforced Openings

by

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D. Vasarhelyi and R. A. Hechtman
UNIVERSITY OF WASHINGTON

Under Bureau of Ships Contract NObs-50238

(BuShips Project NS-731-034)

for

SHIP STRUCTURE COMMITTEE

Convened by

The Secretary of the Treasury

Member Agencies—Ship Structure Committee

Bureau of Ships, Dept. of Navy
Military Sea Transportation Service, Dept. of Navy
United States Coast Guard, Treasury Dept.
Maritime Administration, Dept. of Commerce
American Bureau of Shipping

Address Correspondence To:

Secretary
Ship Structure Committee
U. S. Coast Guard Headquarters
Washington 25, D. C.

SERIAL NO. **SSC-55**
BuShips Project NS-731-034

JUNE 30, 1953

SHIP STRUCTURE COMMITTEE

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ADDRESS CORRESPONDENCE TO:

SECRETARY
SHIP STRUCTURE COMMITTEE
U. S. COAST GUARD HEADQUARTERS
WASHINGTON 25, D. C.

June 30, 1953

Dear Sir:

As part of its research program related to the improvement of hull structures of ships, the Ship Structure Committee is sponsoring an investigation on the "Welded Reinforcement of Openings in Structural Steel Members" at the University of Washington. Herewith is a copy of the third progress report, SSC-55, of the investigation, entitled "Welded Reinforcement of Openings in Structural Steel Members: Room and Low Temperature Tests of Plates with Reinforced Openings" by D. Vasarhelyi and R. A. Hechtman.

Any questions, comments, criticism or other matters pertaining to the Report should be addressed to the Secretary, Ship Structure Committee.

This Report is being distributed to those individuals and agencies associated with and interested in the work of the Ship Structure Committee.

Yours sincerely,

K K Cowart

K. K. COWART
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee.

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ROOM AND LOW TEMPERATURE TESTS OF PLATES WITH REINFORCED OPENINGS

I. INTRODUCTION

This report continues the work described previously(1) in which the investigation of various room temperature properties of selected types of arc-welded reinforcement for openings in plain-carbon structural steel plates loaded under uniform tension led to the conclusion that from the standpoint of performance the square opening with rounded corners having a 1 1/8-in. radius and the circular opening appeared to give the best properties. Since this investigation covered only the behavior of specimens at room temperature, the problem of their behavior in the more critical low temperature range was unknown. Moreover, it was desirable to parallel the previous tests(1) of 36-in. by 1/4-in. plates with tests of 48-in. by 1/2-in. plates in order to use thicker plate which would have a higher transition temperature.

This progress report includes tests of four specimens 36 in. by 1/4 in. and nine specimens 48 in. by 1/2 in. in cross-section, four of the former and four of the latter being tested at low temperatures. All specimens had a 9-in. by 9-in. square opening with rounded corners reinforced by a welded face bar, single doubler plate, or insert plate. The strength characteristics, the unit strain distribution and concentration in the vicinity of the opening, and the total energy absorption were studied for all specimens. The results of the low temperature tests were compared with those obtained in the room temperature tests.

Another phase(2) of this research investigated the distribution of unit strain energy and stress in the plastic range of the material.

For brevity, the two previous reports will be referred to hereafter as the First Progress Report(1) and the Second Progress Report(2).

II. OBJECT AND SCOPE OF THE INVESTIGATION

This part of the experimental program on welded reinforcement of openings in structural steel members was planned primarily to find information concerning the behavior at low temperature of plates with a square opening with rounded corners and various types of reinforcement and to test plates of greater thickness. The influence of low temperature on such factors as general yielding, ultimate strength, energy absorption, unit strain distribution, and mode of failure was investigated.

This investigation was a continuation of the work reported in the First Progress Report(1). The results of the tests in that report are compared with the room and low temperature tests in this report.

III. TESTS AND TEST METHODS

1. Specimen Steel and Welding Electrodes.

All specimens were fabricated from the same steel used in the previous tests. Steel U is a plain-carbon semi-killed grade meeting ASTM Specification A7 - 49T and was used in the as-rolled condition. The chemical analysis for 1/4-in. Plate No. 24 gave

C	Mn	P	S	Si
0.23	0.50	0.053	0.051	0.07

and for 1/2-in. Plate No. 4,

C	Mn	P	S	Si	Ni	Cr	Cu
0.22	0.47	0.010	0.028	0.05	0.07	TR	0.066

The only significant difference in these two analyses, which were made by different laboratories, occurred in respect to the amount of phosphorus and sulphur.

The tensile properties at room temperature as determined by tests of ASTM standard flat specimens at -20° and -46°F. as determined by tests of 1-in. wide flat specimens are given in Table I. It was necessary to use a tensile specimen with a reduced width for the low temperature tests in order to utilize fixtures made for this type of test.

The Charpy keyhole notch-impact test results[3] are shown in Fig. 1 for 1/2-in. Plate No. 4. The transition temperature range fell between temperatures of about -40°F. and some temperature in excess of 160°F., the maximum at

TABLE I

MECHANICAL PROPERTIES OF PLATES OF DIFFERENT THICKNESS
SEMI-KILLED STEEL U AS ROLLED

Plate No.	Thickness in.	Temp. Deg. F.	Upper Yield Point psi	Ultimate Strength psi	Elong. in 8 in. per cent	Red. of Area per cent	Tear-Test Transition Deg. F.
			Room Temperature Tests				
5	1/2		39,900	61,900	27.1	44.8	
6*	1/2		38,800	59,500	27.4	43.5	
10	1		32,800	61,100	32.6	55.6	120
15	1/4		44,200	63,400	27.8	44.6	
16	1/4		44,100	65,300	29.5	50.9	
17	1/4		44,300	65,200	29.4	51.7	
18	1/4		45,100	65,800	29.2	50.8	-40
19	1/4		44,000	65,900	28.2	51.7	
21	1/4		44,500	66,000	28.6	50.2	
24	1/4		44,800	65,800	29.3	49.6	
25	1/2		36,500	61,500	31.2	54.0	
26	1/2		36,900	62,300	29.7	49.7	
			Low Temperature Tests				
3	1/2	-46	44,100	71,400	29.1	55.8	
4	1/2	-20	40,700	66,300	32.1	56.3	40
24	1/4	-46	55,100	73,600	27.9	50.3	

* Cut from permanently strained specimen and normalized.

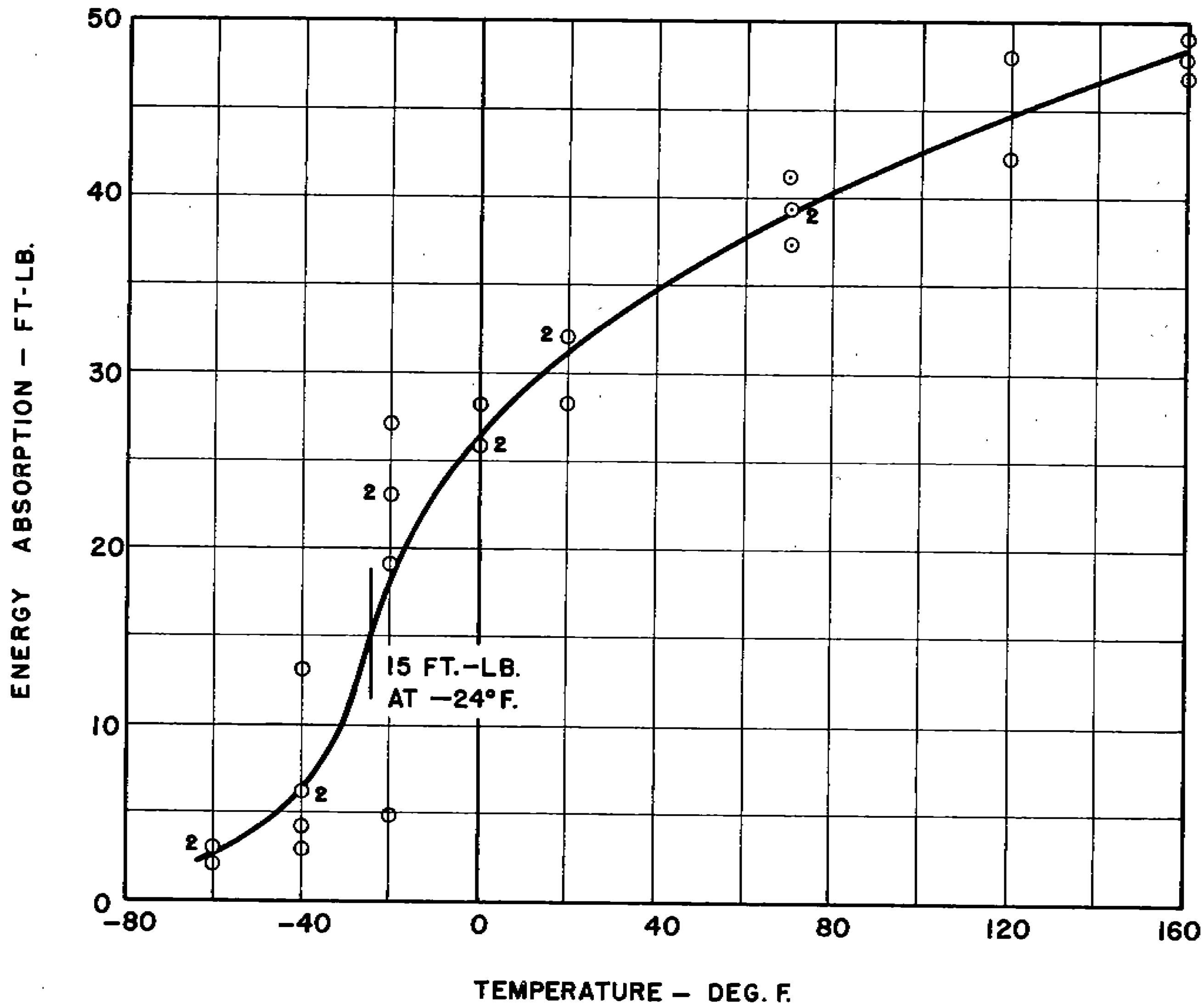


Fig. 1 . Charpy Keyhole Notch-Impact Test Results for Steel U as Rolled.

which tests were made. The transition temperature for 50 per cent of maximum energy absorption would appear to be about 20°F. The temperature for an energy absorption of 15 ft.-lb. was about -24°F.

The transition temperature as determined by the Navy tear test for specimens of full plate thickness and the average ASTM grain size were found to be as follows:

Plate No.	Plate Thickness inches	Transition Temperature, °F.	Average ASTM Grain Size
18	1/4	-40	8
4	1/2	40	6
10	1	120	5

The microstructures of these plates were shown in the First Progress Report(1).

These data were used in selecting the temperature for the low temperature tests. Except for Specimen No. 50, which was tested at -20°F., all specimens were loaded at -46°F., which temperature was considered low enough to give a predominantly cleavage failure even in the 1/4-in. plates. This latter temperature was also about the lowest which the refrigerator equipment could maintain constant while absorbing the heat given off by the specimen during plastic deformation.

The same coated welding electrodes, 1/8 and 5/32 in. in diameter, meeting AWS Specification E-6010 were used as in the first group of tests. The properties of the weld metal were not especially investigated.

2. Details of the Test Specimens.

The 1/4-in. plate specimens tested at low temperatures exactly duplicated the types tested at room temperature as reported in the First Progress Report[1]. The same method of fabrication was carefully followed. Table II gives the program and Table III the plates from which the specimens and details were cut. Sketches of the specimens including the dimensions of the welds are shown in Figs. 2 and 3.

It was necessary to make the 48-in. wide specimens from 48-in. plate. In order to increase the length of the butt weld joining the specimen to the pulling plates of the testing machine, wing plates of the same thickness and 3 in. by 8 in. in size were welded to the four corners of these specimens. These plates after the completion of the welding were flame-cut and ground to the shape shown in Fig. 2 in order to minimize the possibility of fracture.

No specimen was tested until at least seven days after the welding of the reinforcement.

3. Method of Loading.

The specimens were tested in a 2,400,000-lb. capacity universal hydraulic testing machine. They were butt welded to the pulling plates, which in turn were free to swivel on the pins of the clevises of the testing machine. The center-line of the specimens was aligned within 1/16 in. of the line joining the centers of the clevis pins.

TABLE II

DESCRIPTION OF SPECIMENS WITH 9 in. x 9 in. OPENINGS
WITH 1-1/8 in. CORNER RADIUS

Spec. No.	Size of Reinforcement in.	Percentage of Reinforcement	Cross-Section Area - sq. in. Gross	Net	Test Temp. Deg. F.
I. 36 in. x 1/4 in. Body Plate					
A. Opening Reinforced by a Face Bar.					
9*	2 x 1/4	40	9.13	7.74	72
99	2 x 1/4	40	9.00	7.74	-46
10*	1 x 1/4	16	9.15	7.22	75
31	1 x 1/4	16	9.00	7.22	-46
B. Opening Reinforced by a Single Doubler Plate.					
15*	18 x 18 x 1/4	103	9.13	9.16	76
32	18 x 18 x 1/4	103	9.00	9.16	-46
C. Opening Reinforced by an Insert Plate.					
21*	15D x 1/2	62	9.02	8.17	77
34	15D x 1/2	62	9.00	8.17	-46
II. 48 in. x 1/2 in. Body Plate					
A. Opening Reinforced by a Face Bar.					
49	2 x 1/2	33	24.32	21.24	70
50	2 x 1/2	33	24.37	21.25	20
B. Opening Reinforced by a Single Doubler Plate.					
51	18 x 18 x 1/2	96	24.17	24.01	74
52	18 x 18 x 1/2	96	24.00	24.01	-46
C. Opening Reinforced by an Insert Plate.					
55	15D x 1	66	23.63	22.09	70
55A	15D x 1	67	23.58	22.10	69
56	15D x 1	66	24.00	22.09	-46
70	12-3/4 x 12-3/4 x 1	39	24.00	21.38	76
71	12-3/4 x 12-3/4 x 1	39	24.00	21.38	-46

* Previously described in First Progress Report (1).

TABLE III

LIST OF PLATES USED FOR FABRICATION OF EACH SPECIMEN

Spec. No.	Plate No. Used For	
	Body Plate	Reinforcement
9	19	19
10	18	18
15	21	21
21	17	25
31	16	21
32	15	21
34	15	26
49	6	25
50	6	25
51	6	25
52	5	26
55	26	10
55A	25	10
56	5	10
70	3	10
71	3	10
99	15	21

Mechanical properties of these plates are given in Table I.

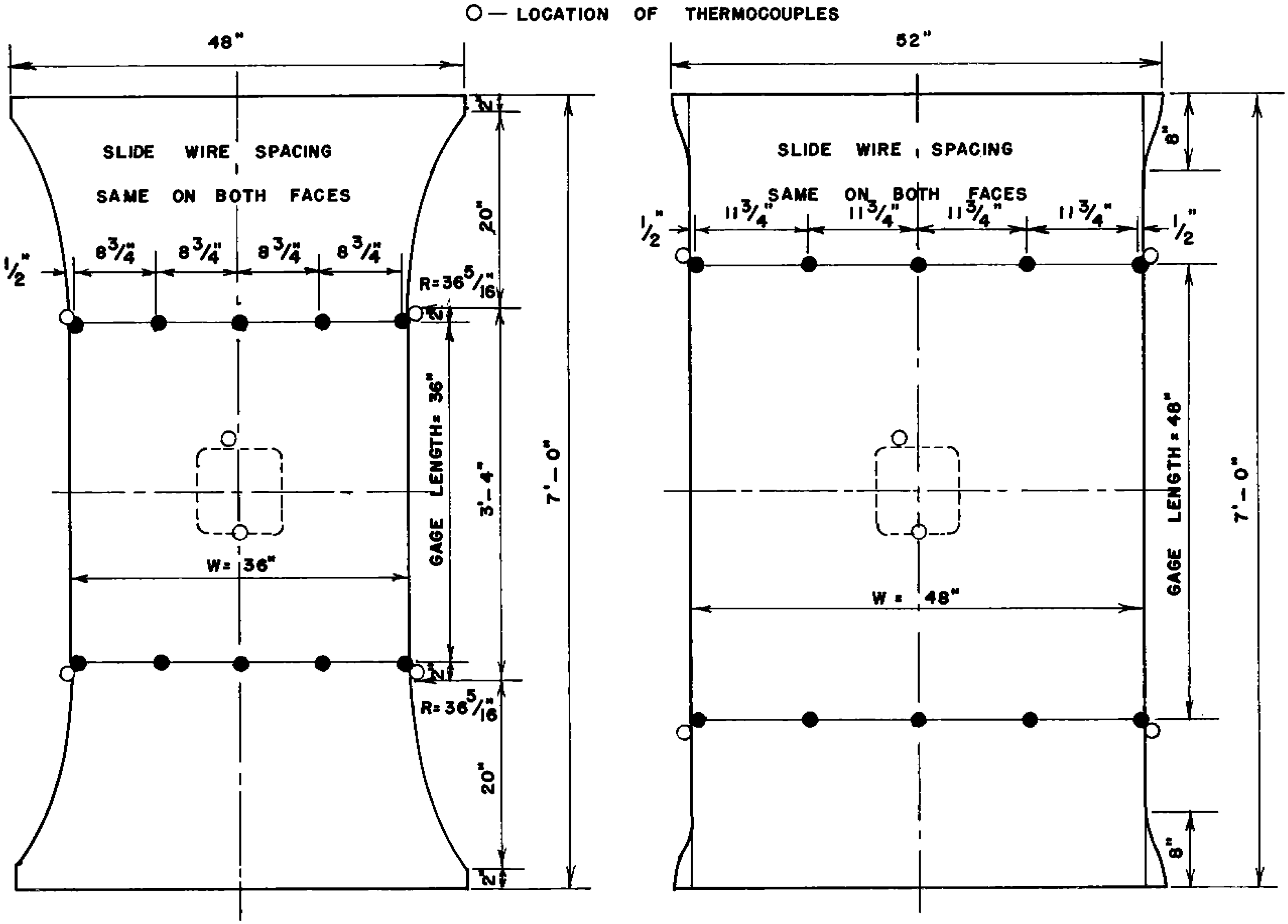


Fig. 2 . Body Plates of 36-in. x 1/4-in. and 48-in. x 1/2-in. Specimens. Location of Slide-Wire Resistance Gages and Thermocouples.

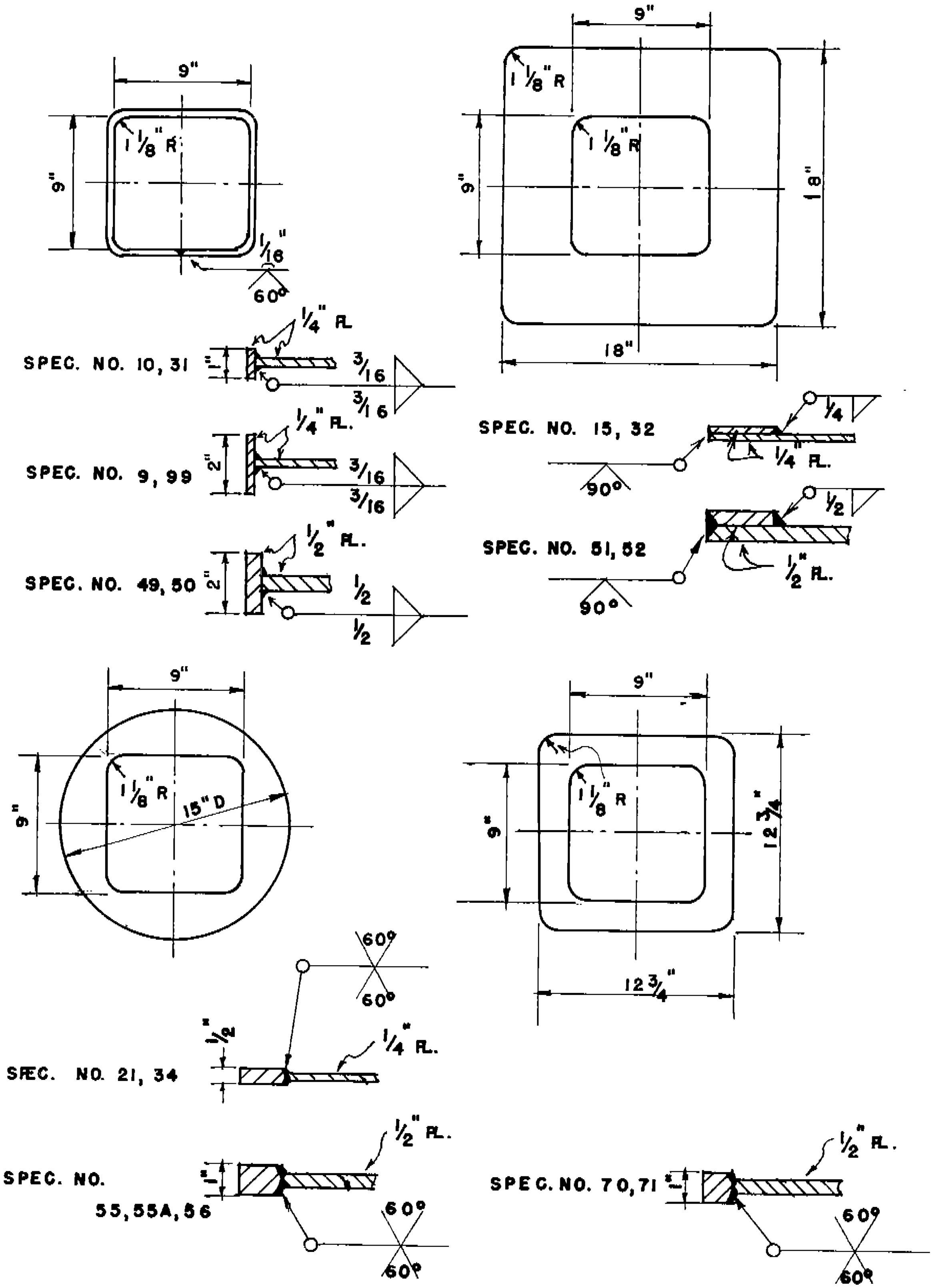


Fig. 3 . Details of the Face Bar, Doubler Plate and Insert Plate Types of Reinforcement,

The load was applied slowly and readings of the gages were taken at frequent intervals. Enough time was allowed in the low temperature tests to absorb the heat developed by the plastic stretching of the plate and to maintain a constant test temperature.

4. Cooling of the Specimens.

In order to cool the specimens for the low temperature tests, the specimen and the clevises of the testing machine were enclosed in an almost air-tight canvas bag, over which four layers of woolen blankets were wrapped. Air chilled to the required temperature was circulated continuously through the bag from a combined mechanical and dry-ice refrigerating system. The regulation of the air flow provided a control of the testing temperature, which was maintained within 2°F.

The temperature of the specimen was measured at frequent intervals by copper-constantan thermocouples at the six points shown on Fig. 2. The thermocouples were soldered to the clean steel surface and covered with 1/4-in. thick felt pads. The thermocouples at the different locations did not show a temperature difference greater than 3°F.

5. Gaging and Measurements.

The gaging and measurements were so designed as to allow identical observations both at room temperature and low temperature and were remotely controlled, since no direct observations on the plates could be made in the low temperature tests.

The principal measurements of the elongation were made straddling the region around the opening by slide-wire gages located on both faces of the plate on four equal spacings across the width as shown in Fig. 2. Since the gage length was equal to the width of the specimen, a gage length of 36 in. was used for Specimens No. 9, 10, 15, 21, 31, 32, 34, and 99 and of 48 in. for Specimens No. 49 to 52 and 55, 55A, 56, 71, and 72.

The unit strain distribution was determined by SR-4 gages applied to both faces of the plate to remove the effect of bending. The locations of the SR-4 gages for the different types of specimens are shown in Figs. 4 and 5. The SR-4 gaging of Specimens No. 70 and 71 followed the pattern of Specimens No. 51 and 52.

IV. RESULTS OF TESTS

1. Introduction and Definition of New Terms.

Three factors were varied in the tests reported herein: the body plate width and thickness, the type of reinforcement, and the testing temperature. The shape of the 9-in. by 9-in. opening was the same for all specimens, square with rounded corners. The results of the tests are shown in

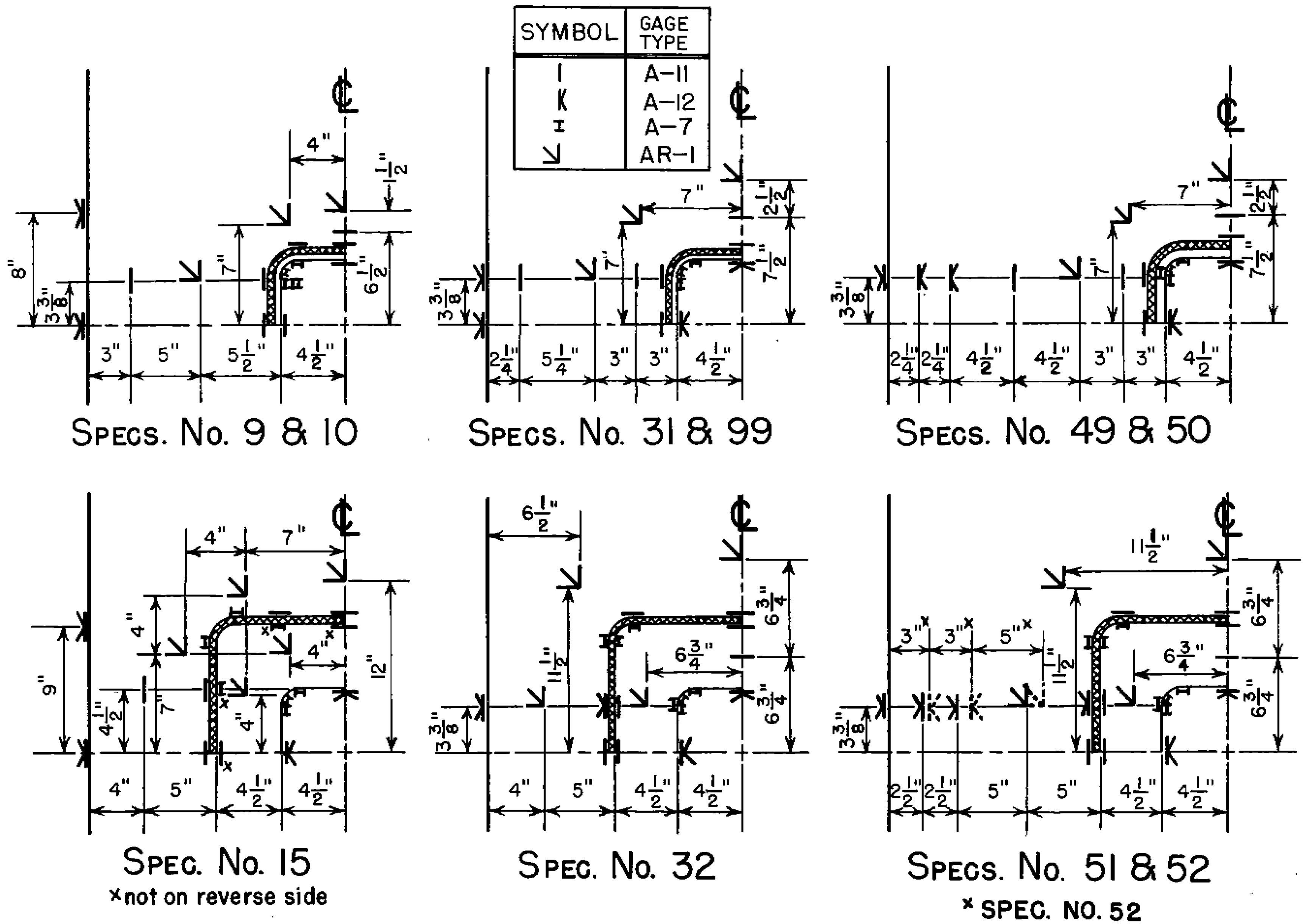


Fig. 4 . Location of SR-4 Gages Around the Opening of the Specimen.

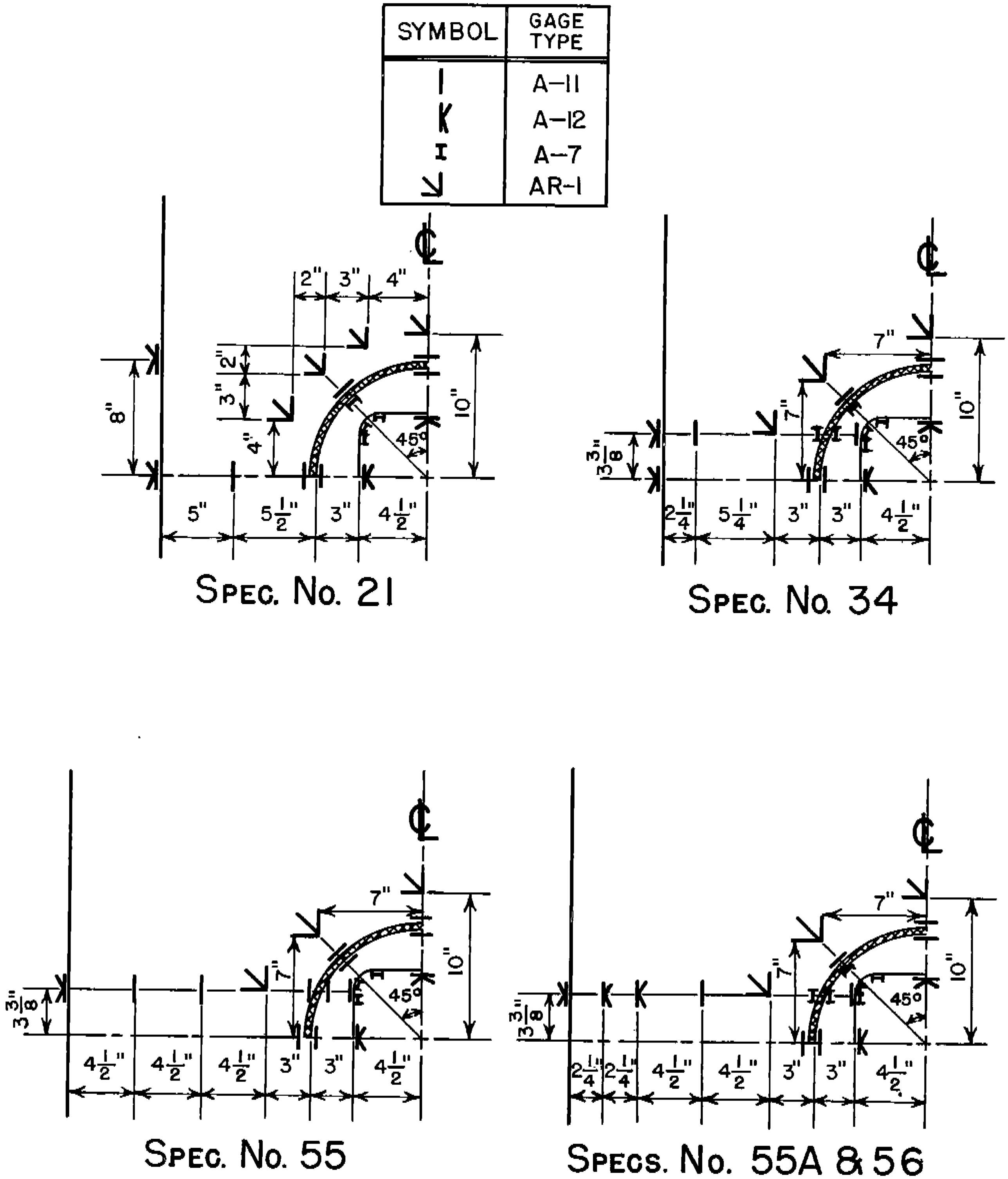


Fig. 5 . Location of SR-4 Gages Around the Opening in the Specimen.

Figs. 6 to 43 and Tables IV to VI.

Most of the terms used in this report were previously defined(1). Several new terms require explanation or clarification. The percentage of cleavage in the fracture was taken as the ratio in per cent of the cleavage portion of the net cross-section of the specimen along the fracture line including any unbroken part of the plate width. The percentage of shear was determined in the same manner.

In computing the percentage of reinforcement, the ratio in per cent between the net cross-section area added by the reinforcement at the critical section and the cross-section area of the material removed from the body plate by the opening was used. Thus the percentage of reinforcement as it is defined here gives identical values for similar types of 1/4- and 1/2-in. thick specimens.

The average unit strain energy is defined as the total energy absorption within the gaged area divided by the volume between the gage lines. The unit elongation was equal to the average elongation within the gage length divided by the gage length.

2. Distribution across Plate of the Elongation on a Gage Length Equal to the Width of the Specimen.

The distribution across plate of the elongation on a gage length equal to the width of the plate for both room and low temperature tests is shown in Figs. 6 to 13. The

TABLE IV

STRENGTH AND ENERGY ABSORPTION OF 36" x 1/4" and 48" x 1/2" PLATES WITH OPENINGS
AT ROOM AND AT LOW TEMPERATURES

Spec. No.	Per Cent of Reinf.	Test Temp.	Fracture* Per Cent			General Yielding			Ultimate Strength			Energy Absorp.**		Nature of Final Fracture
			C	S	Un-broken	Load	Ave. Stress Gross	Ave. Stress Net	Load	Ave. Stress Gross	Ave. Stress Net	To Ultimate Load	To Failure	
		Deg.F.				kips	ksi	ksi	kips	ksi	ksi	1000's in-lb		
						36" x 1/4" Body Plate. Face Bar Reinforcement.								
9	40	72	0	44	56	329	35.5	41.8	451.0	50.1	59.2	747	1063	Weld to Reinf.
99	40	-46	97	3	0	340	37.8	44.0	507.0	56.4	65.5	1062	1019	Through opening.
10	16	75	0	69	31	313	34.8	43.9	467.0	51.9	65.5	1214	1504	Through opening.
31	16	-46	75	25	0	364	40.4	50.4	527.0	58.6	73.0	1857	1880	Through opening.
						36" x 1/4" Body Plate. Single Doubler Plate Reinforcement.								
15	103	76	0	65	35	362	40.2	40.2	522.5	58.1	58.1	729	1099	Through opening.
32	103	-46	63	22	15	441	49.0	48.1	548.0	60.9	59.8	894	1104	Through opening.

* Proportion in per cent of total net cross-section area at fracture surface including fracture and unbroken section, if any. C = Cleavage. S = Shear.

** 36-in. gage length for 36" x 1/4" plates. 48-in. gage length for 48" x 1/2" plates.

TABLE IV (Cont.)

STRENGTH AND ENERGY ABSORPTION OF 36" x 1/4" and 48" x 1/2" PLATES WITH OPENINGS AT ROOM AND AT LOW TEMPERATURES

Spec. No.	Per Cent of Reinf.	Test Temp.	Fracture* Per Cent C	S	Un-broken	General Yielding Load	Ave. Stress Gross	Net	Ultimate Strength Load	Ave. Stress Gross	Net	Energy Absorp.** to Ultimate Load	To Failure	Nature of Final Fracture
		Deg.F.				kips	ksi	ksi	kips	ksi	ksi	1000's in-lb		
36" x 1/4" Body Plate. Insert Plate Reinforcement.														
21	62	77	0	66	34	300	33.3	36.4	478.0	53.1	57.9	1155	1484	Through opening.
34	62	-46	96	4	0	376	41.8	46.0	551.5	61.3	67.5	1652	1542	Through opening.
48" x 1/2" Body Plate. Face Bar Reinforcement.														
49	33	70	0	77	23	740	30.4	34.8	1255	51.6	59.0	3510	4710	Weld to reinf.
50	33	-20	99	1	0	880	36.6	41.5	1410	58.8	66.8	5892	5610	Through opening.
48" x 1/2" Body Plate. Single Doubler Plate Reinforcement.														
51	96	74	0	81	19	770	31.9	32.1	1385	57.4	57.7	4730	5360	Weld to reinf.#
52	96	-46	100	0	0	950	39.6	39.6	1460	60.8	60.8	4303	4187	Through body plate.#
48" x 1/2" Body Plate. Insert Plate Reinforcement.														
55	66	70	57	28	15	800	33.8	36.2	1275	54.0	57.7	4240	4660	Through opening#
55A	67	69	0	79	21	800	33.9	36.2	1288	54.8	58.3	4082	4328	Through opening.
56	66	-46	100	0	0	900	38.2	40.8	1360	57.6	61.5	3424	3220	Through body plate.
70	39	76	1	50	49	800	33.3	37.6	1276	53.1	59.7	3362	3699	Through opening
71	39	-46	100	0	0	800	33.3	37.6	1176	48.8	55.0	2084	2084	Through opening

Initial failure in pulling plate. Spec. No. 51 reloaded after 3 days, Spec. No.52 after 9 days, and Spec. No. 55 after 10 days.

TABLE V

AVERAGE UNIT STRAIN ENERGY AND AVERAGE ELONGATION TO ULTIMATE AND TO FAILURE FOR ALL SPECIMENS

Spec. No.	Test Temp. Deg. F.	Average Elongation To Ultimate in.	Average Elongation To Failure in.	Average Unit Strain Energy Ult. lb.in / cu.in.	Average Unit Strain Energy Failure lb.in / cu.in.
		36" x 1/4" Body Plate. Face Bar Reinforcement.			
9	72	1.97	2.73	2340	3329
99	-46	2.55	2.38	3326	3193
10	75	3.04	4.00	3909	4843
31	-46	1.93	4.16	5980	7400
		36" x 1/4" Body Plate. Single Doubler Plate Reinforcement.			
15	76	1.70	2.70	1999	3013
32	-46	1.93	2.39	2451	3090
		36" x 1/4" Body Plate. Insert Plate Reinforcement.			
21	77	2.86	3.72	3519	4521
34	-46	3.55	3.15	5630	5255
		48" x 1/2" Body Plate. Face Bar Reinforcement.			
49	70	3.36	5.08	3082	4136
50	-20	4.90	4.58	5174	4938
		48" x 1/2" Body Plate. Single Doubler Plate Reinforcement.			
51	74	4.04	5.15	3834	4345
52	-46	3.58	3.58	3496	3496
		48" x 1/2" Body Plate. Insert Plate Reinforcement.			
55	70	3.97	4.28	3654	4016
55A	69	3.94	4.20	3518	3750
56	-46	3.05	2.75	2951	2774
70	76	3.25	4.00	2960	4016
71	-46	2.00	2.00	1831	1831

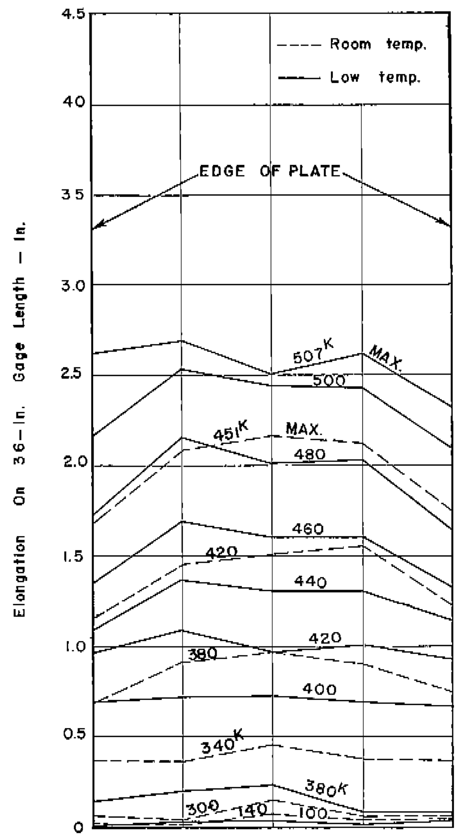


Fig. 6. Distribution across Plate of Elongation on a Gage Length Equal to the Width of the Plate, Specs. 9 and 99.

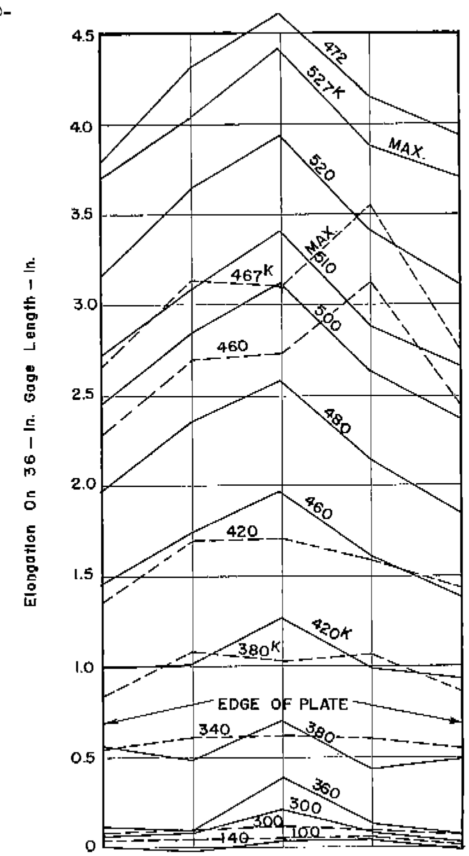


Fig. 7. Distribution across Plate of Elongation on a Gage Length Equal to the Width of the Plate, Specs. 10 and 31.

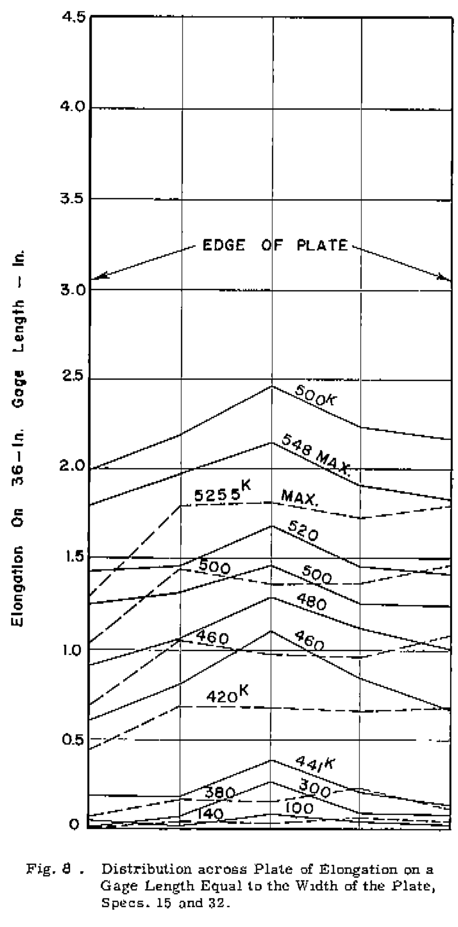


Fig. 8. Distribution across Plate of Elongation on a Gage Length Equal to the Width of the Plate, Specs. 15 and 32.

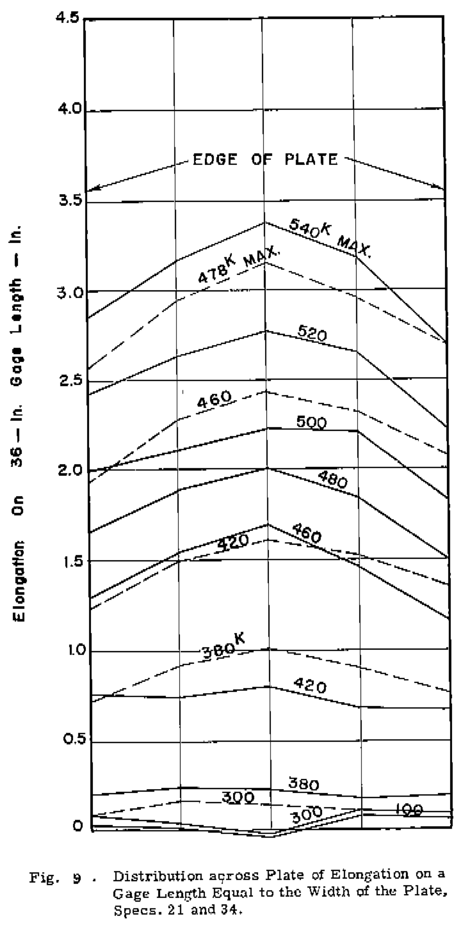


Fig. 9. Distribution across Plate of Elongation on a Gage Length Equal to the Width of the Plate, Specs. 21 and 34.

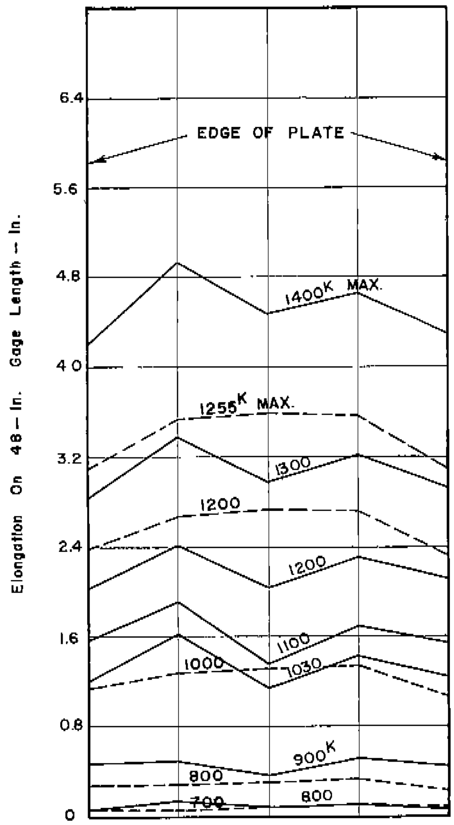


Fig. 10 . Distribution across Plate of Elongation on a Gage Length Equal to the Width of the Plate, Specs. 49 and 50.

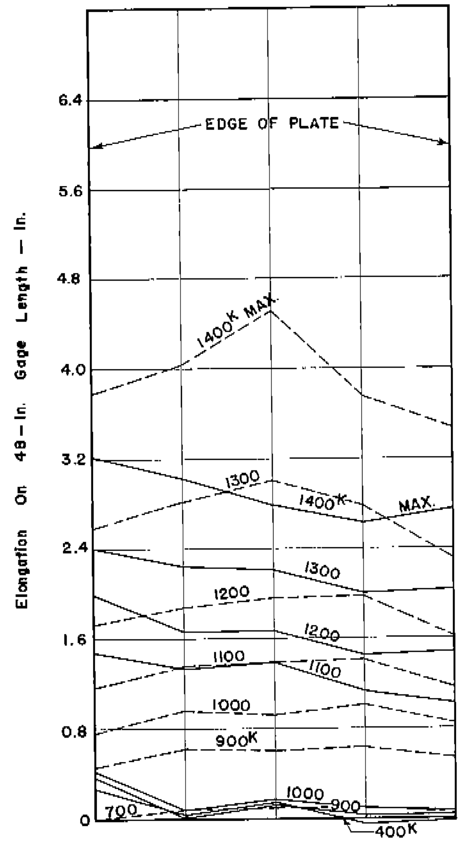


Fig. 11 . Distribution across Plate of Elongation on a Gage Length Equal to the Width of the Plate, Specs. 51 and 52.

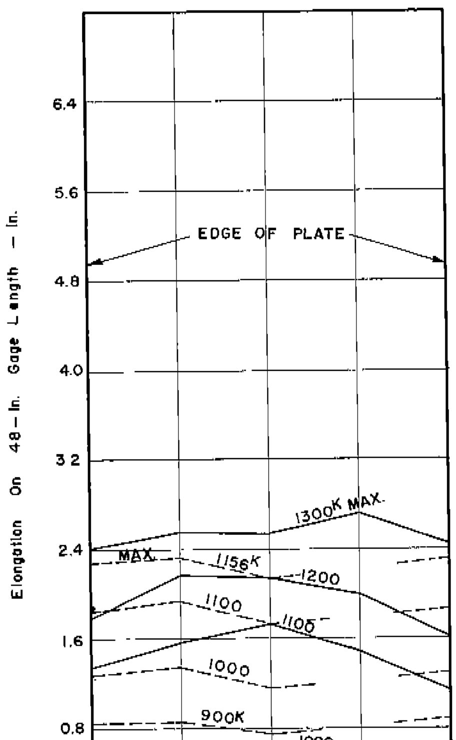


Fig. 12 . Distribution across Plate of Elongation on a Gage Length Equal to the Width of the Plate, Specs. 55 and 56.

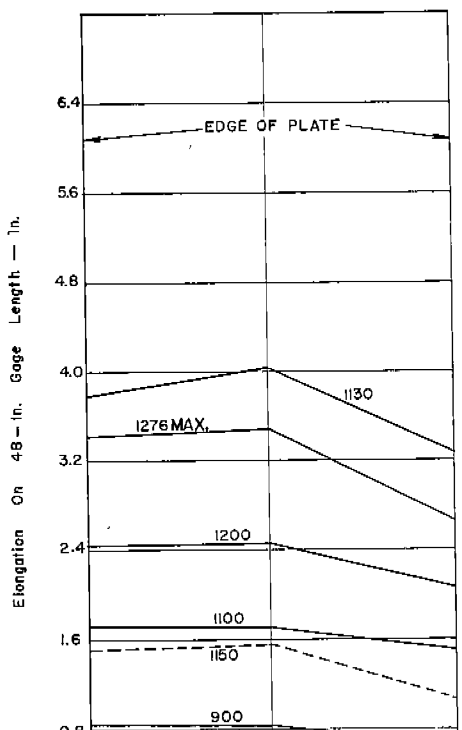


Fig. 13 . Distribution Across Plate of Elongation on a Gage Length Equal to the Width of the Plate, Specs. No. 70 and 71.

values for low temperature are shown with solid lines; those for room temperature, with dotted lines.

The elongation in both temperature ranges followed the same general pattern. It remained fairly symmetrical about the vertical centerline of the plate until fracture began at, or just before the ultimate load. The elongation was maximum in the center of the plates. The distribution patterns did not show any characteristics which could be attributed to the particular type of reinforcement.

At equal loads the elongation of the room temperature specimens was greater than for those tested at low temperature, even for Specimens No. 52 and 56, although the fracture in both of these plates passed completely outside the reinforcement.

3. Comparison of Load on Specimen and Elongation on Gage Length Equal to Width of Specimen.

The five elongations at the given gage locations across the plate were averaged. The relation between the applied load and this average elongation is shown in Figs. 14 to 21 for the various specimens. The principal data from these figures are summarized in Table IV.

The shapes of the load-elongation curves for identical specimens tested at room and low temperature were similar up to the ultimate load, except that the strength level for the plates tested at the lower temperatures was higher. Beyond

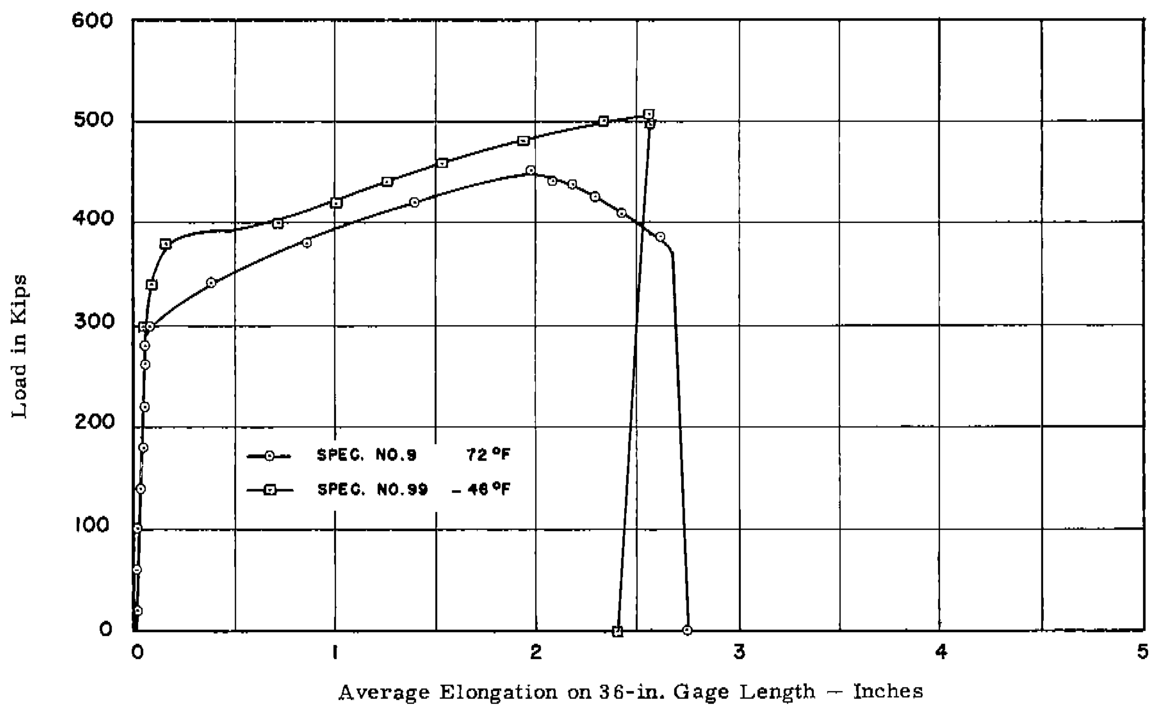


Fig. 14 . Comparison of Load and Average Elongation on a Gage Length Equal to the Width of the Plate, Specs. No. 9 and 99.

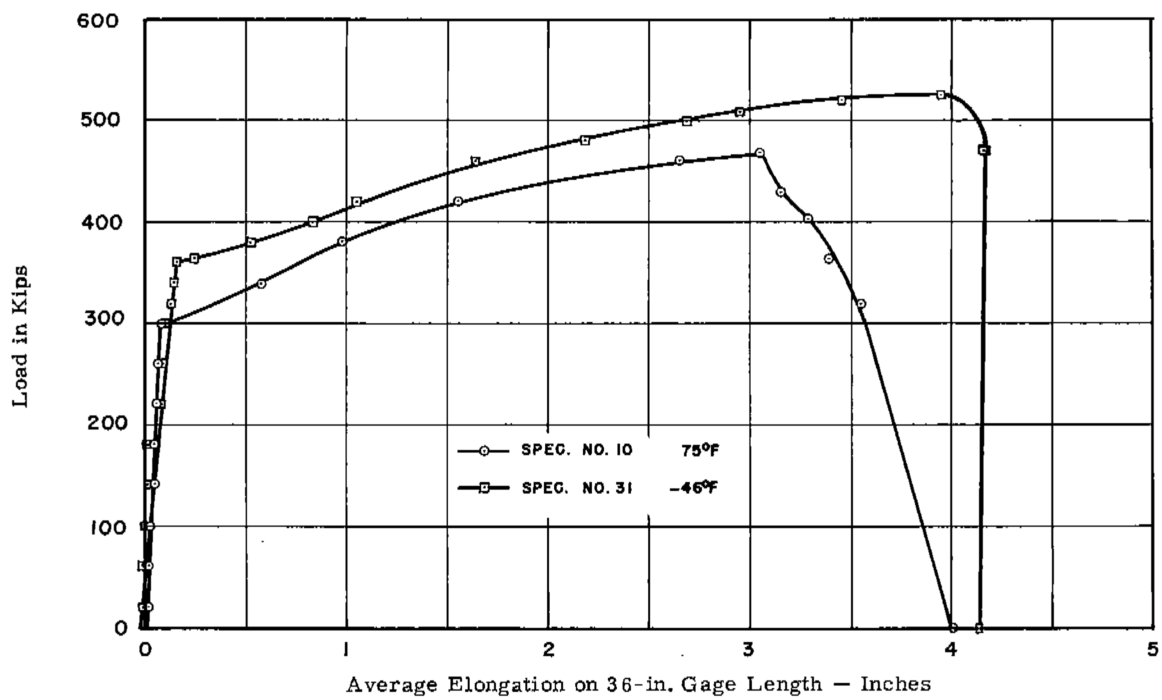


Fig. 15 . Comparison of Load and Average Elongation on a Gage Length Equal to the Width of the Plate, Specs. No. 10 and 31.

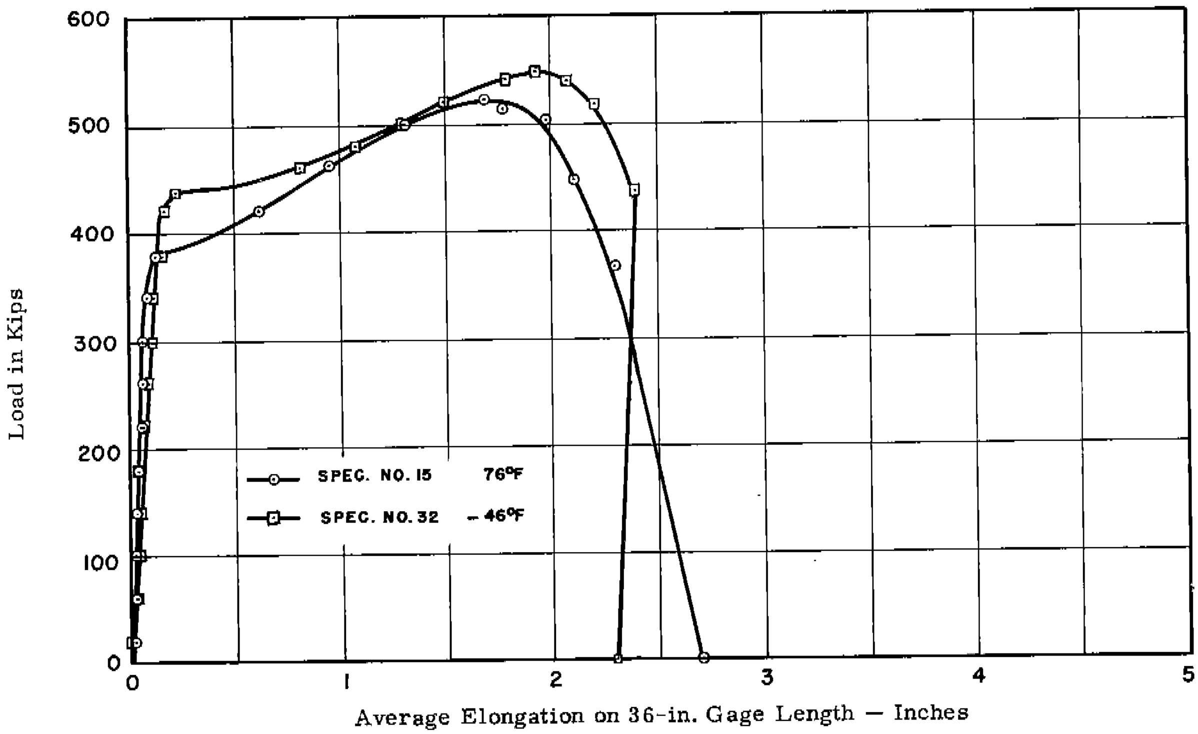


Fig. 16 . Comparison of Load and Average Elongation on a Gage Length Equal to the Width of the Plate, Specs. No. 15 and 32.

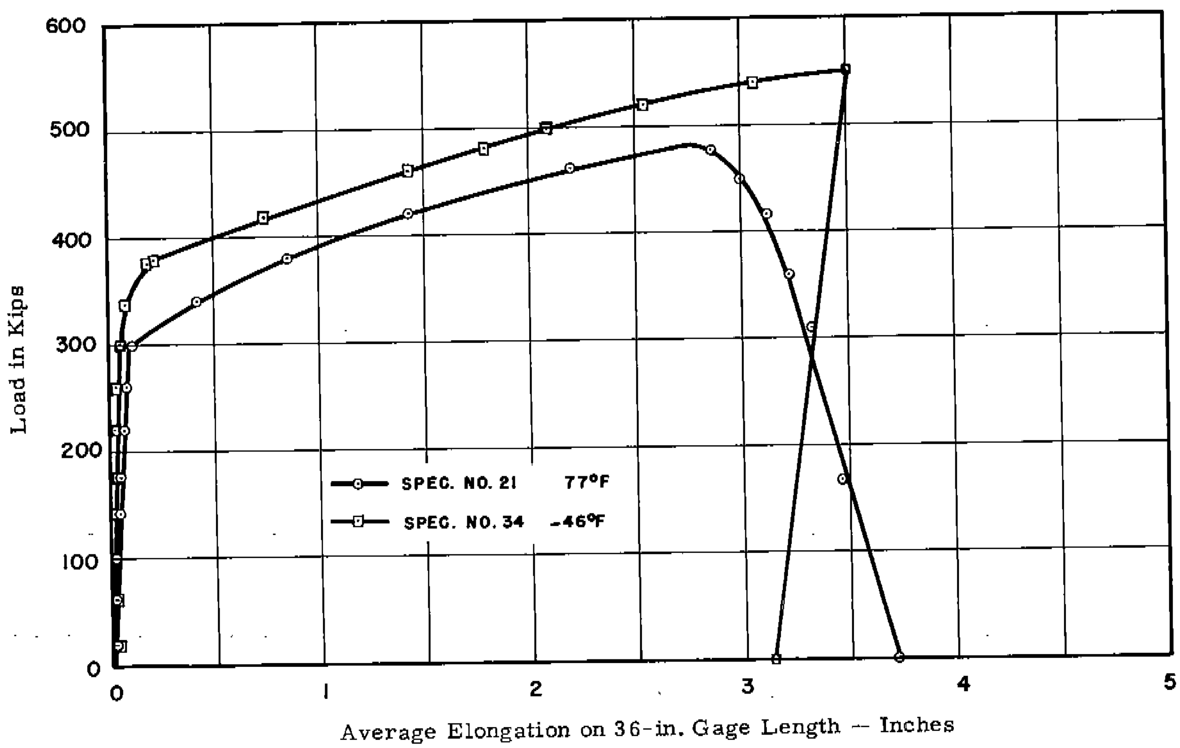


Fig. 17 . Comparison of Load and Average Elongation on a Gage Length Equal to the Width of the Plate, Specs. No. 21 and 34.

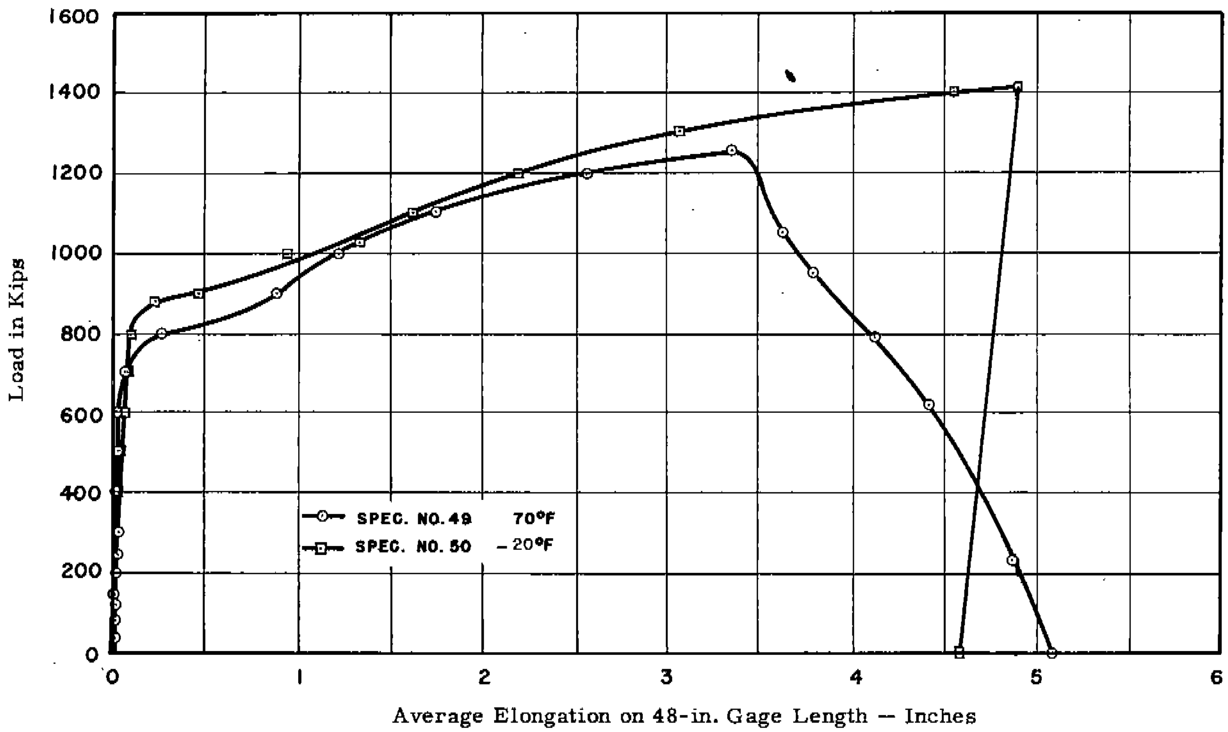


Fig. 18 . Comparison of Load and Average Elongation on a Gage Length Equal to the Width of the Plate, Specs. No. 49 and 50.

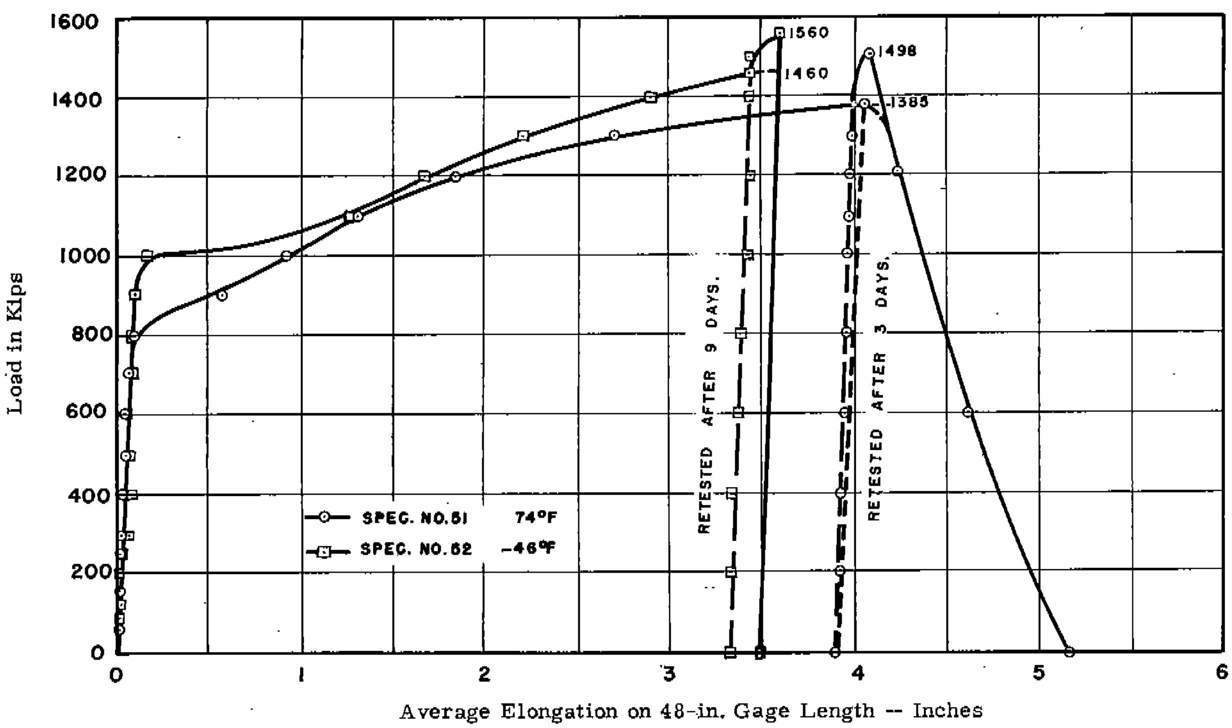


Fig. 19 . Comparison of Load and Average Elongation on a Gage Length Equal to the Width of the Plate, Specs. No. 51 and 52.

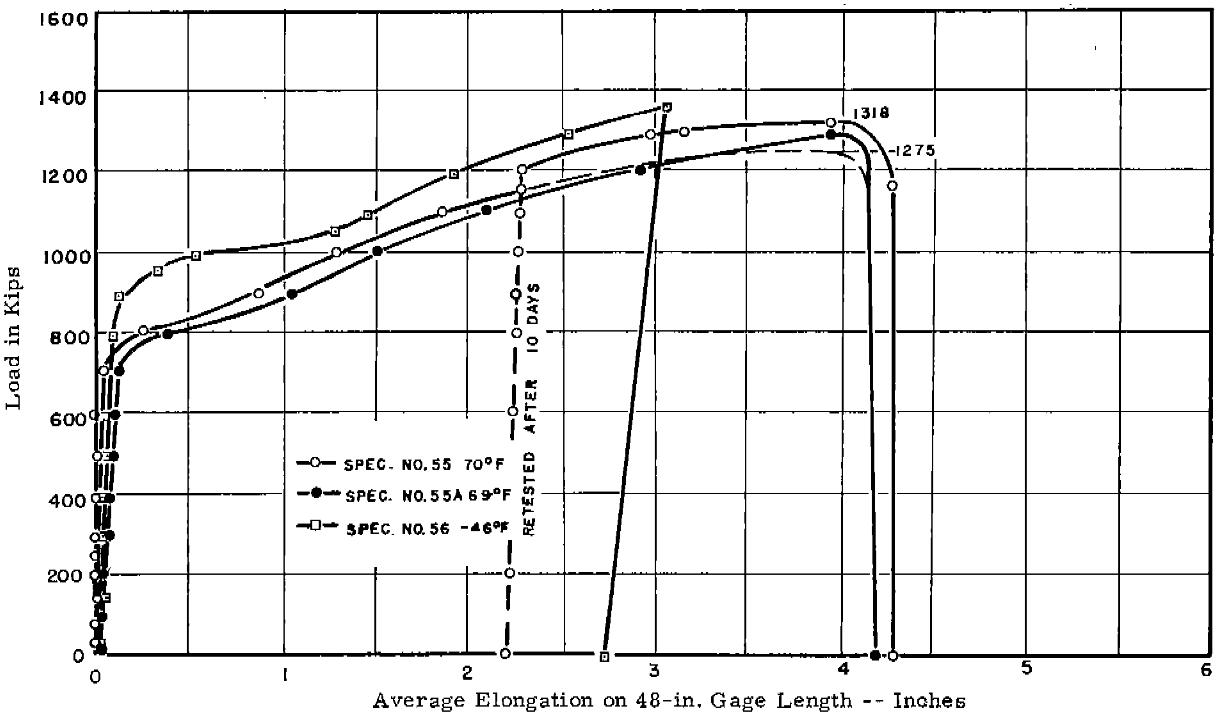


Fig. 20 . Comparison of Load and Average Elongation on a Gage Length Equal to the Width of the Plate, Specs. No. 55, 55A, and 56.

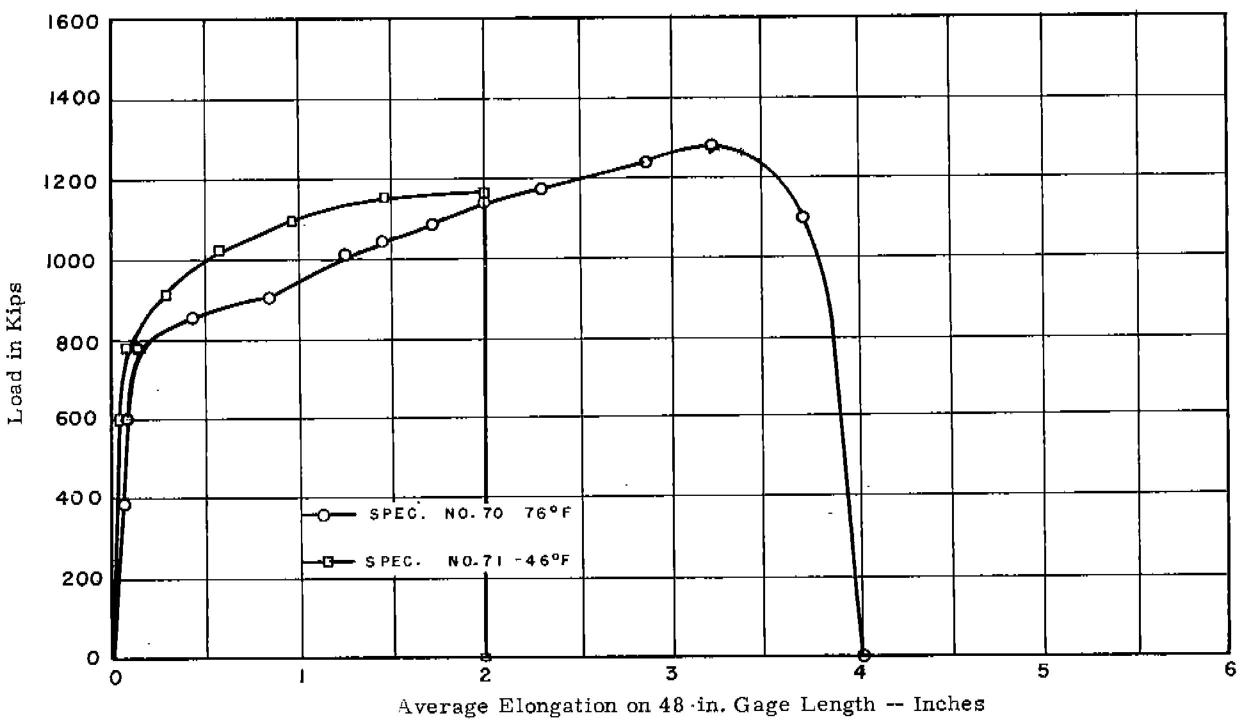


Fig. 21 . Comparison of Load and Average Elongation on a Gage Length Equal to the Width of the Plate, Specs. No. 70 and 71.

the ultimate load the shape of these curves depended primarily upon the percentage of cleavage in the fracture. Specimens No. 99, 34, 50, 52, 56, and 71, all having between 96 and 100 per cent cleavage, suffered sudden fractures at the ultimate load with no additional elongation beyond that point. As a shear fracture developed beyond the ultimate load in Specimens No. 31, 32, and 55, all having between 57 and 75 per cent cleavage, the load fell off gradually to the point where a sudden cleavage fracture occurred and the load dropped off sharply. The more ductile behavior of Specimens No. 9, 10, 15, 21, 49, 51, and 55A with zero per cent cleavage and Specimen No. 70 with 1 per cent cleavage was apparent in the gradual reduction of the load as the shear fracture progressed across the plate. The amount of elongation occurring after ultimate load in this last group of specimens depended largely on the portion of the width of the specimen which remained unbroken and therefore bore no close relation to the amount of elongation up to the ultimate load.

Specimens tested both at room and at low temperature exhibited a noticeable necking in the direction of the width of the plates and a simultaneous reduction of the thickness over the affected area. The ones which failed by a shear type fracture showed in addition a reduction of thickness along the fracture. This localized reduction of thickness of course was not present wherever the crack was of the cleavage type.

Figures 39 to 43 show the nature of the fracture for the various specimens.

Several of the 1/2-in. specimens, Specimens No. 51, 52, and 55, were subject to strain-aging during the course of the test. Cleavage failures occurred in the pulling plate, and time elapsed before these plates were again loaded. The history of these specimens is given in Figs. 19 and 20. Since the remaining specimens were not affected by strain-aging, a fair comparison could be made only by removing this effect from the results of these three tests. Figures 19 and 20 show the actual and the assumed load-elongation curves for Specimens No. 51, 52, and 55. The values of ultimate load, ultimate strength and energy to ultimate load and to failure given in Table IV were computed on the basis of these assumed values. A discussion of the strain-aging effects in these three specimens follows in Section 10.

A comparison of the average elongation to ultimate load for identical specimens at room and low temperature is shown in Fig. 22. The average elongation to ultimate load was greater in each case for the low temperature specimen except for Specimens No. 51, 52, 55, 55A, and 56, and 70

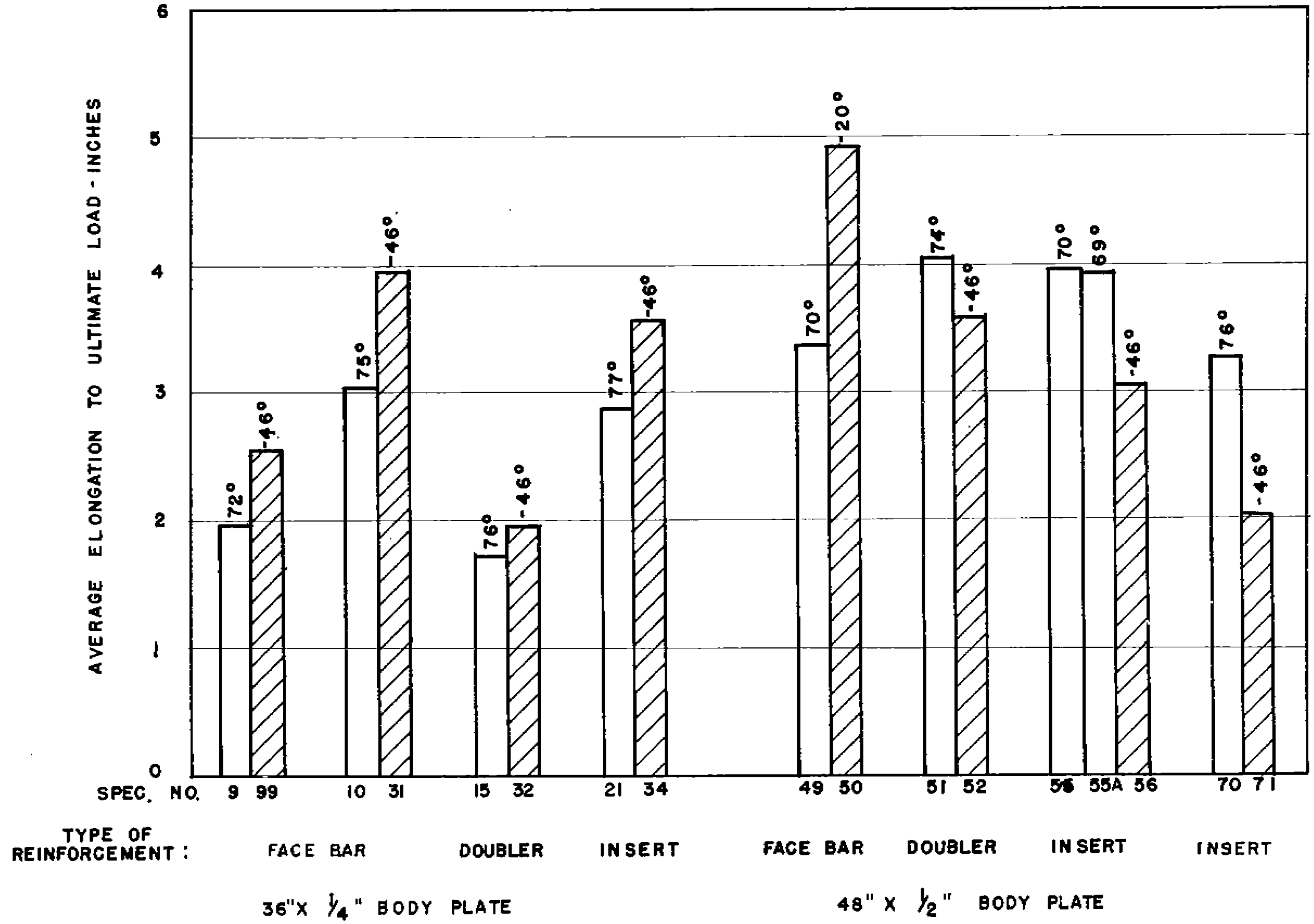


Fig. 22. Average Elongation to Ultimate Load at Room and at Low Temperature.

and 71. It is significant that Specimens No. 52 and 56 broke through the body plate, while all other plates failed either through the opening or in the weld at the outer edge of the reinforcement. The average elongation to ultimate load of Specimen No. 71 was the smallest sustained by any of the plates in this report.

4. General Yielding of Specimens.

The load and the average stress on the net cross-section at general yielding are shown in Fig. 23 and Table IV. When the average stress at general yielding for each low temperature specimen was compared with that of the identical specimen at room temperature, the values of the ratios ranged from 127 to 105 per cent for the 1/4-in. plates and from 123 to 100 per cent for the 1/2-in. plates. If the results of Specimens No. 70 and 71 are disregarded, a general, though not very distinct trend was indicated. As the dimension of the reinforcement at the edge of the opening in the direction of the body plate thickness increased, the value of this ratio tended to decrease.

5. Ultimate Load and Ultimate Strength.

The ultimate load and ultimate strength developed by the various specimens are shown in Fig. 24 and Table IV. Among the 1/4-in. plates, the ultimate strength ranged from 57.9 to 65.5 ksi for the room temperature tests and from

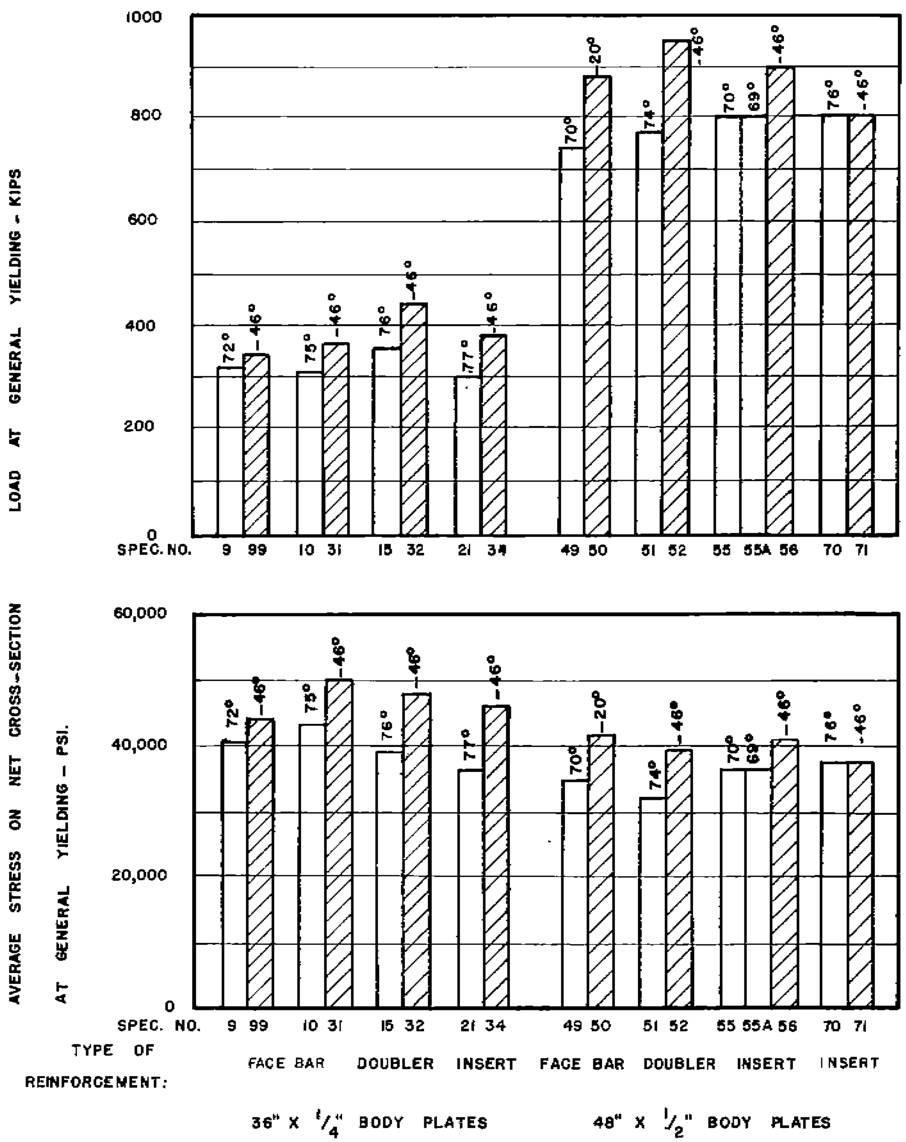


Fig. 23. Load and Average Stress on Net Cross-Section at General Yielding at Room and at Low Temperature.

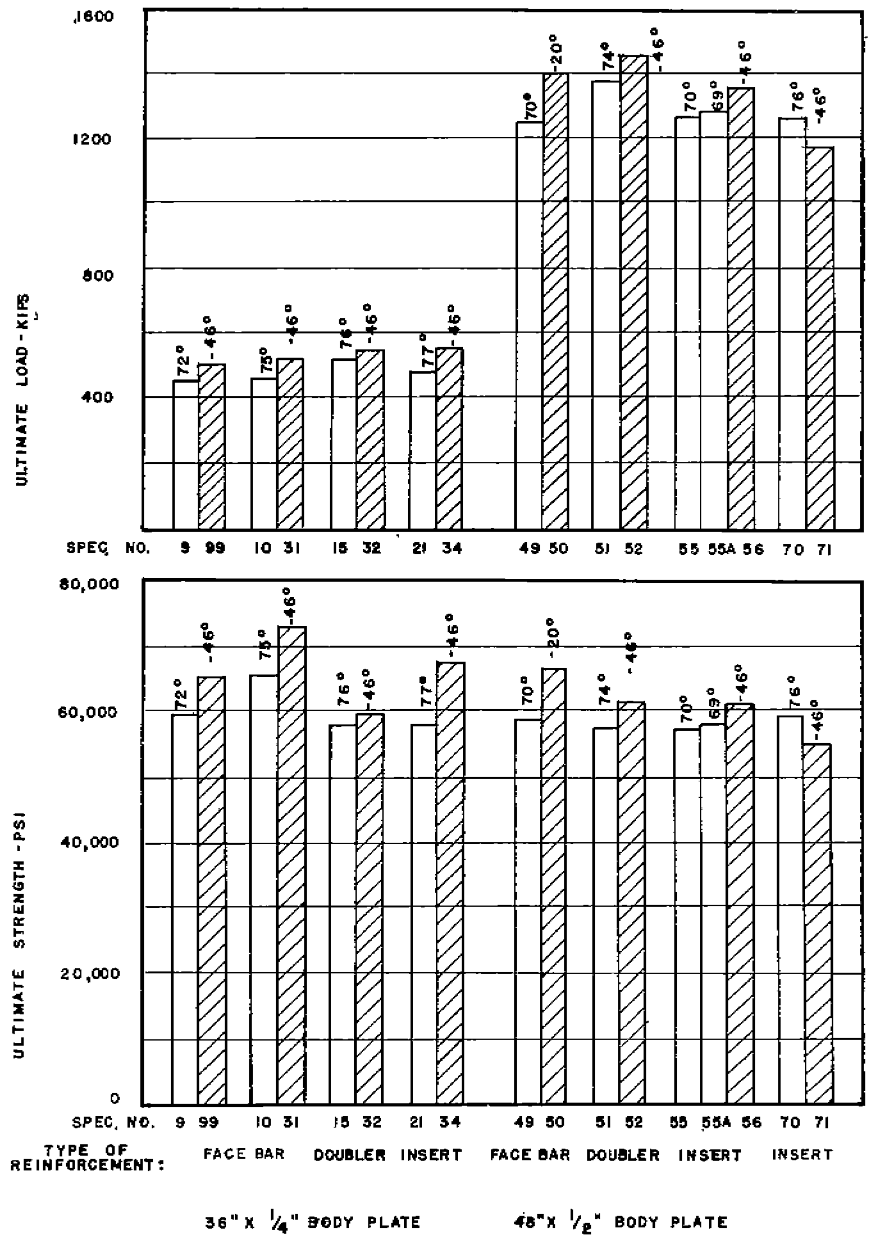


Fig. 24. Ultimate Load and Ultimate Strength at Room and at Low Temperature.

59.8 to 73.0 ksi for the low temperature tests. The same variation for the 1/2-in. plates was from 57.7 to 59.7 ksi and 55.0 to 66.8 ksi. Thus with respect to ultimate strength also, the differences in the geometry of the specimens were more accentuated at the lower temperature.

The ultimate strength of each specimen tested at low temperature was greater than that of the identical specimen at room temperature except for Specimens No. 70 and 71.

The ultimate strength of the plate material for the body plates and reinforcement of Specimens No. 9, 99, 10, and 31, as given in Table I, was essentially the same. However, a distinctly higher strength was developed by Specimens No. 10 and 31, which had a 1-in. by 1/4-in. face bar. A 2-in. by 1/4-in. face bar was used in Specimens No. 9 and 99.

6. Energy Absorption

The energy absorption to ultimate load and to failure is given in Table IV. Figure 25 compares the values of the energy absorption to ultimate load for the room and the low temperature tests. Among the 1/4-in. plates a greater energy absorption to ultimate load was developed by each low temperature specimen than by the identical specimen at room temperature.

However, among the 1/2-in. plates no consistent trend

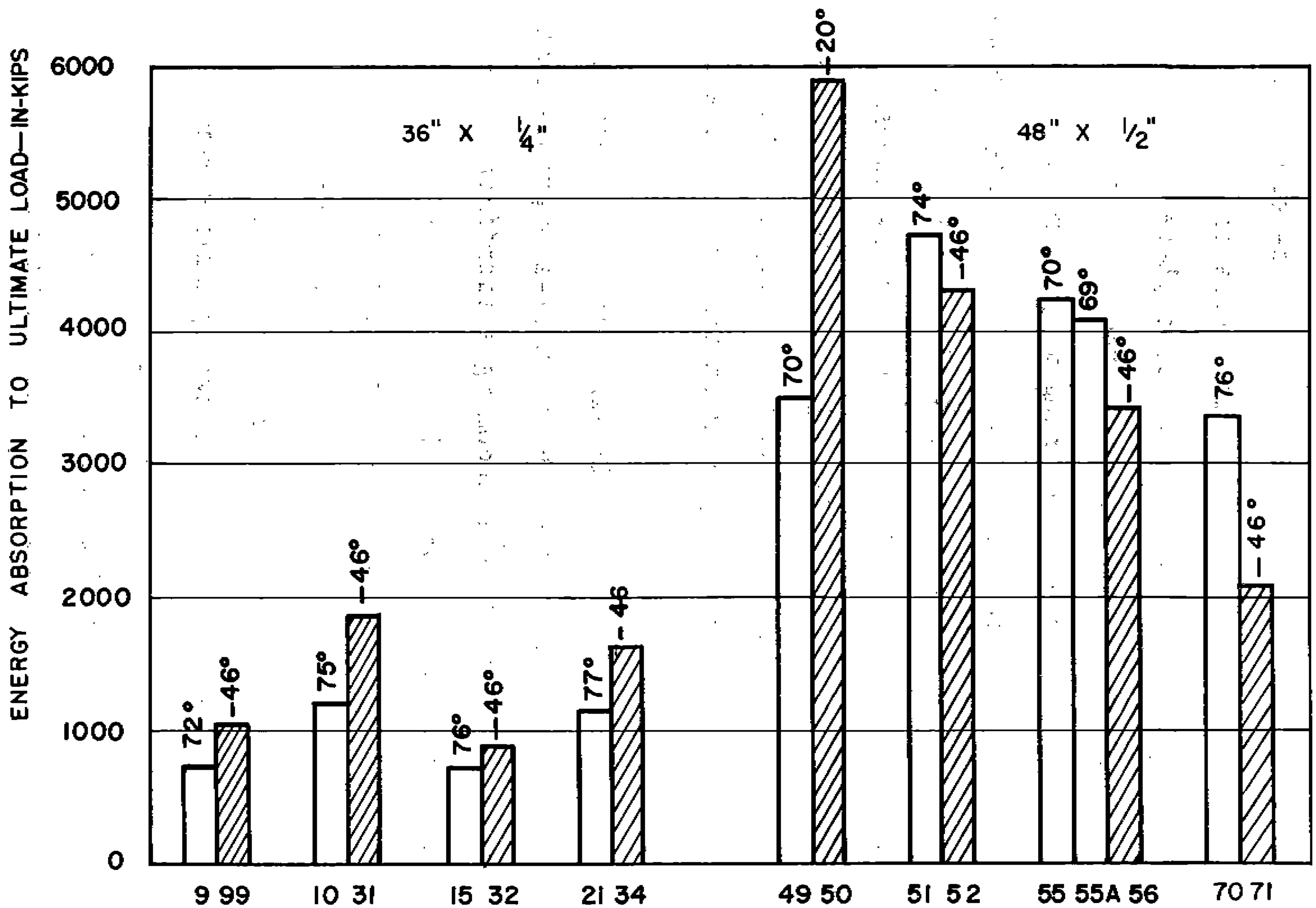


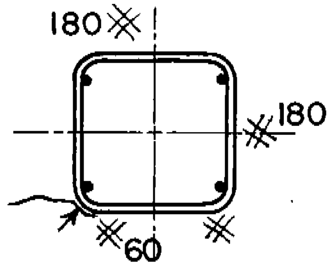
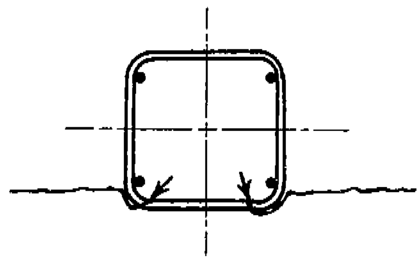
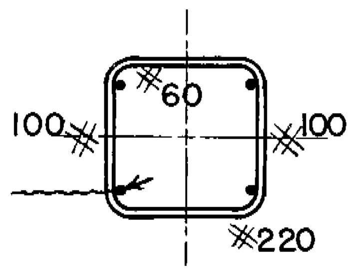
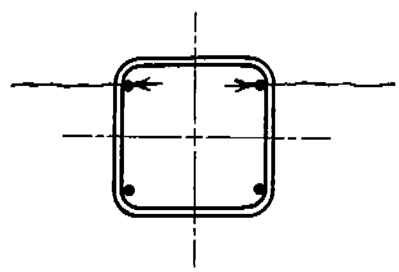
Fig. 25. Energy Absorption to Ultimate Load at Room and at Low Temperature.

was apparent. Specimens No. 52 and 56, which failed through the body plate outside of the reinforcement, developed less energy to ultimate load than did their corresponding plates at room temperature. The failure of these plates was perhaps somewhat premature but still occurred at a stress level at which a failure through the opening was imminent. Of the pairs of specimens, which failed through the opening, Specimens No. 49 and 50 followed the trend of the 1/4-in. plates, and Specimens No. 70 and 71 followed exactly the opposite trend. While the relative energy absorption of the 1/4-in. plates at the two temperatures followed a simple pattern, it appeared to obey a more complex relation for the 1/2-in. plates.

The random behavior of the 1/2-in. plates as compared to the consistent trend of the 1/4-in. plates suggests that the thickness of the plate was becoming a significant factor in governing their behavior. It should be noted that 1/2-in. Specimen No. 70 and 71 were the same in type as 1/4-in. Specimen No. 22, which developed the lowest energy absorption of all the 1/4-in. plates with the square opening with rounded corners[1]. These two specimens were also lowest in energy absorbing capacity among the 1/2-in. plates. The energy absorption to ultimate load of Specimen No. 71 at -46°F. was little more than half that developed by

TABLE VI

GENERAL YIELDING AND FRACTURES OF THE SPECIMENS

Spec. No.	Load in Kips at: First Luders Lines	Load in Kips at: General Yielding	Load in Kips at: First Crack	Load in Kips at: Ultimate Load	Percentage of Cleavage in Fracture	Location of First Luders Lines, First Crack, Max. Unit Strain Concentration, and Lateral Buckling *
			36 x 1/4 in. Body Plate			
9	60	319	451	451	0	
99		340	507	507	97	
10	60	313	467	467	0	
31		364	527	527	75	

* Legend:

● Max. unit strain concentration according to SR-4 gage readings

※ Luders lines appearing before general yielding of specimen.

|||| Lateral buckling of plate in regions of compression stress.

← Point of first crack.

~~~ Fracture
~~~

TABLE VI (Cont.)

GENERAL YIELDING AND FRACTURE OF THE SPECIMENS

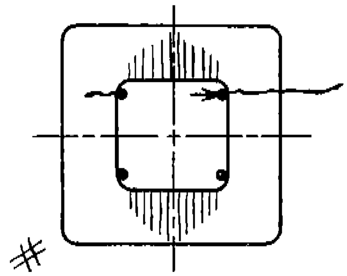
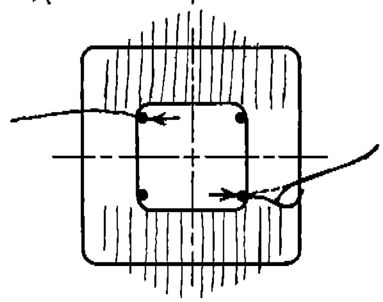
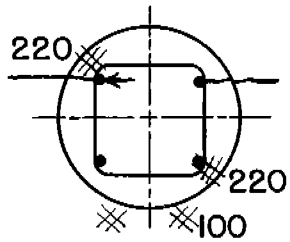
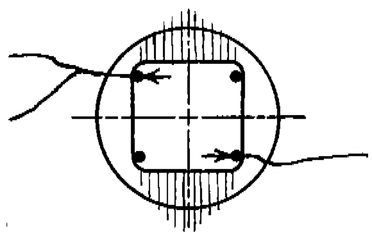
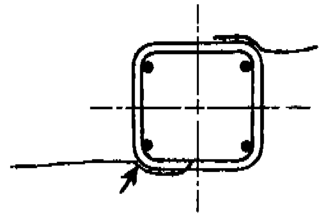
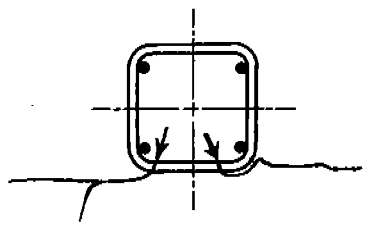
Spec. No.	Load in Kips at: First Luders Lines	General Yielding	First Crack	Ultimate Load	Percentage of Cleavage in Fracture	Location of First Luders Lines, First Crack, Max. Unit Strain Concentration, and Lateral Buckling*
15	362	362	522.5	522.5	0	
32		441	548	548	63	
21	100	300	478	478	0	
34		376	551.5	551.5	96	
			48 x 1/2 in. Body Plate			
49	700	740	1255	1255	0	
50		880	1410	1410	99	

TABLE VI (Cont.)

GENERAL YIELDING AND FRACTURE OF THE SPECIMENS

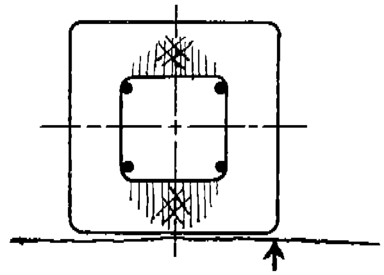
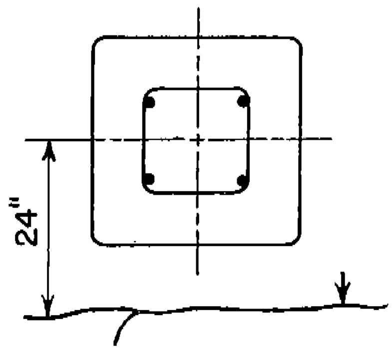
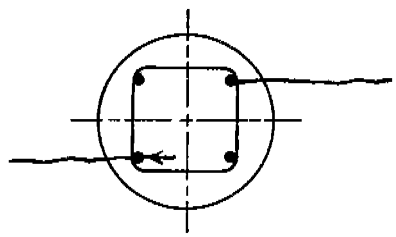
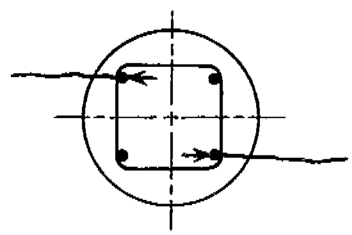
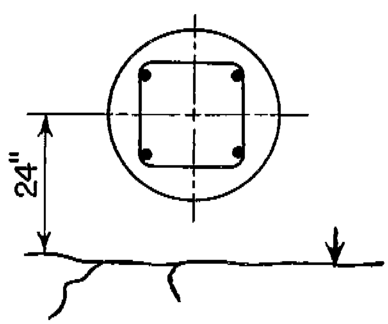
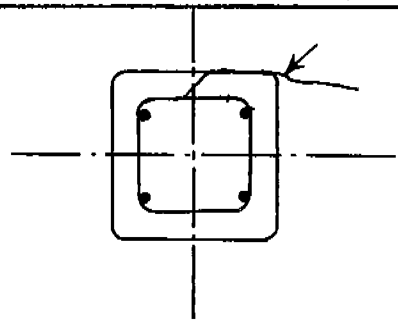
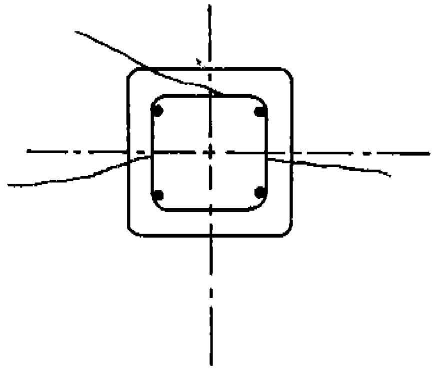
Spec. No.	Load in Kips at First Luders Lines	General Yielding	First Crack	Ultimate Load	Percentage of Cleavage in Fracture	Location of First Luders Lines, First Crack, Max. Unit Strain Concentration, and Lateral Buckling*
51	500	770	1300	1385	0	
52		950	1560	1560	100	
55	700	800	1275	1275	57	
55A	700	800	1288	1288	0	
56		900	1360	1360	100	

TABLE VI (Cont.)

GENERAL YIELDING AND FRACTURE OF THE SPECIMENS

Spec. No.	Load in Kips at First Luders Lines	General Yielding	First Crack	Ultimate Load	Percentage of Cleavage in Fracture	Location of First Luders Lines, First Crack, Max. Unit Strain Concentration, and Lateral Buckling*
70	700	800	1276	1276	17	
71		800	1176	1176	100	

Specimen No. 56, which had the next lowest energy absorption. It would appear that any 1/2-in. plate with a higher stress concentration factor or any plate 3/4 in. or greater in thickness could be expected to develop a relatively lower energy absorption at room temperature and to suffer a large reduction in energy absorption at low temperatures.

Any comparison of the energy absorption of the various specimens must take into account the dimensions of the different types of specimens. Three cross-section sizes were used: 36 in. by 1/4 in., 36 in. by 1/2 in., and 48 in. by 1/2 in. The gaged area was 36 in. long for the 36 in. wide and 48 in. for those 48 in. wide. It was found for these similar types of specimens that the total energy absorption was more or less proportional to the volume of the gaged region.

In the First Progress Report(1), the energy absorption to failure was used as the basis of discussion, while in this report the energy absorption to ultimate load is used. This change in viewpoint came about from two factors:

1. The energy absorption at ultimate load corresponds to the maximum load-carrying capacity of a member and the point beyond which its structural usefulness is questionable.
2. In these tests, the energy absorption beyond ultimate load was as much a function of the portion of

the plate width which was fractured as of the geometry of the specimen.

7. Comparison of Energy Absorption to Ultimate Load with Ultimate Strength and Elongation to Ultimate Load.

The First Progress Report[1] found,

1. That the ultimate load increased in proportion to the logarithm of the elongation to ultimate load.
2. That the specimens which reached the highest ultimate load and ultimate strength also absorbed the most energy.

A clearer picture of these relations has been established in this report.

Figure 26 shows the linear relation between the logarithm of the energy absorption to ultimate load and the ultimate strength. The results of all tests from the First and Second Progress Reports[1,2] and this report are included in this figure. Four conclusions may be drawn from these data.

1. The rate of increase of the energy absorption to ultimate load became greater as the ultimate strength increased.
2. The values for the 1/4-in. specimens with the higher stress concentration factors fell to the left on the plot, those with the lower factors to the right.
3. Lowering the testing temperature moved the values to the right on the plot in the case of the 1/4-in.

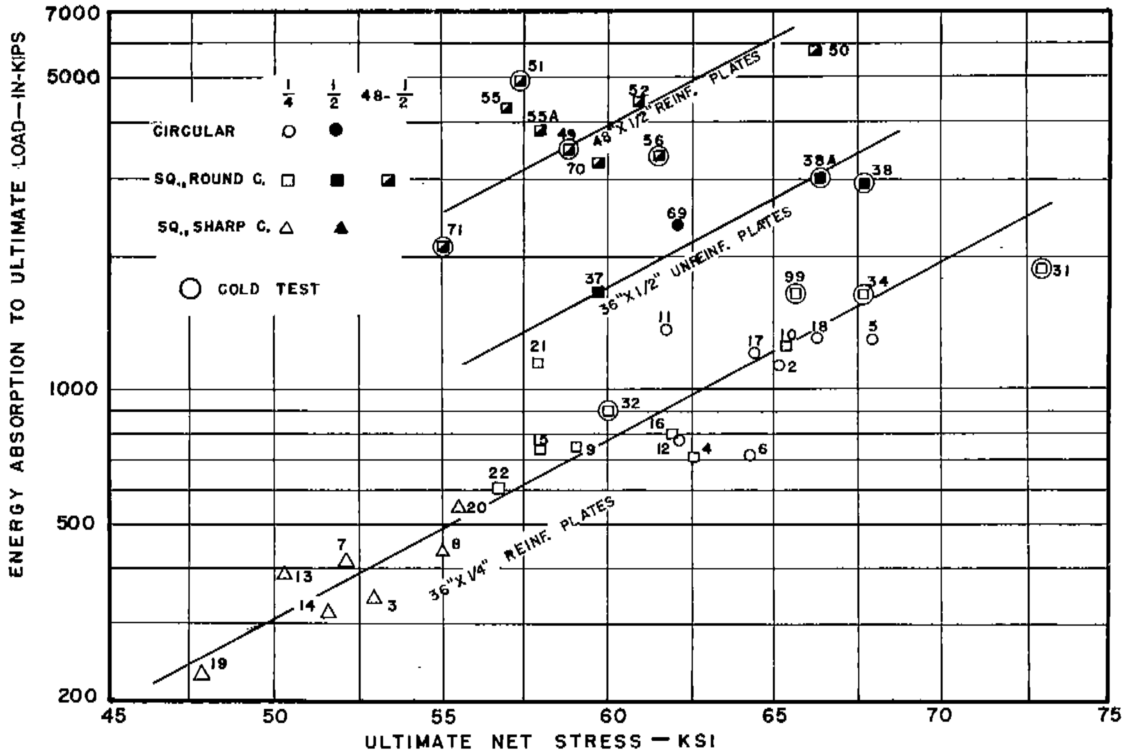


Fig. 26 . Comparison of Energy Absorption to Ultimate Load with Ultimate Strength.

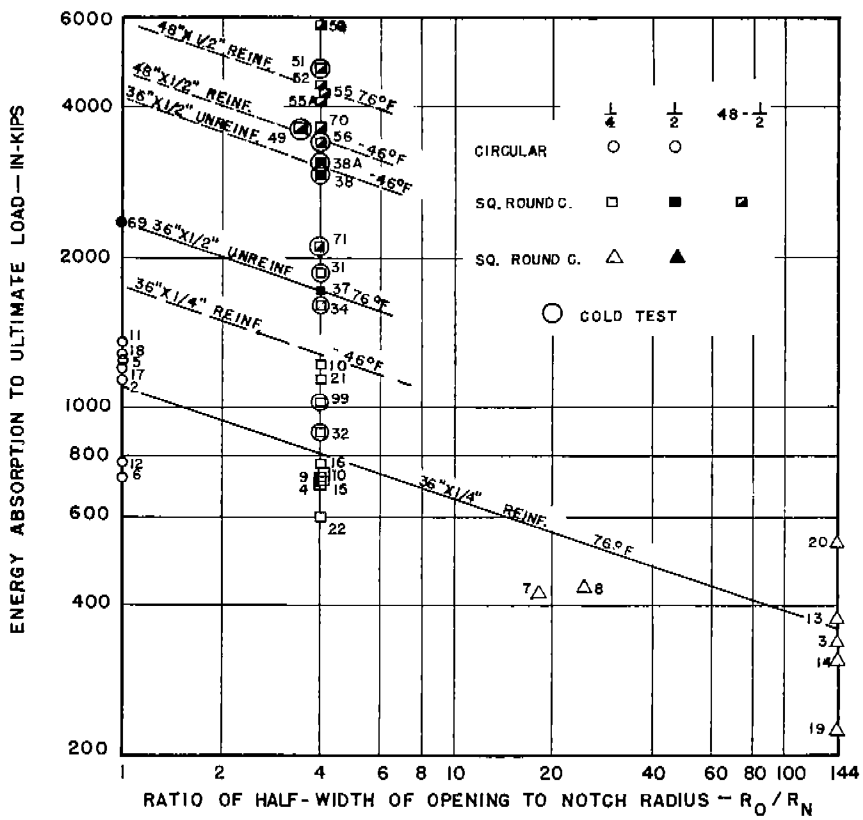


Fig.26a. Relation between the Energy Absorption to Ultimate Load of Plates with Openings and the Notch Acuity of the Opening.

and unreinforced 1/2-in. plates, but had a random effect upon the values for the reinforced 1/2-in. plates.

4. The increase of energy absorption as the size of the specimen was increased was not linearly proportional to the increase of volume in the gaged area. The 1/2-in. reinforced specimens absorbed about 4.7 times as much energy to ultimate load as the 1/4-in. plates. The volume of the gaged section for the former was approximately 2.0 times and of the latter approximately 3.9 times the same volume for the 1/4-in. plates. This increase of energy appeared to be independent of the stress concentration prevailing in the particular specimen.

These four conclusions have a significant meaning when applied to design. Any improvement in the design of the reinforcement, such as a reduction of the stress concentration factor or a better distribution of the reinforcing material which brings about a greater ultimate strength, increases the energy absorbing capacity of the detail in more than direct proportion. Moreover, it would appear that the application of the results of these tests to the design of reinforcement for plates over 1/2 in. in thickness may lead to an overly optimistic estimate of their energy absorbing capacity below their transition temperatures.

In the First Progress Report[1], the energy absorption to failure was plotted against the notch acuity, $\frac{R_O}{R_N}$, the ratio of the half-width of the opening to the corner radius of the opening. Figure 26(a) compares the energy absorption to ultimate load and the ratio $\frac{R_O}{R_N}$. The width of the scatter bands in the latter figure was smaller than in the plot using the energy absorption to failure. The relation between the energy absorption to ultimate load and the ratio, $\frac{R_O}{R_N}$, for the 1/4-in. plates at -46°F. and the unreinforced 1/2-in. plates at room temperature was similar to that for the 1/4-in. plates at room temperature. Since the ratio, $\frac{R_O}{R_N}$, was not varied for the remaining specimens, no definite trend for them was established.

When the unit strain energy to ultimate load was compared in Fig. 27 with the unit elongation to ultimate load, for the reinforced plates, the points for both the room and the low temperature tests fell along the same line; and a method was provided for comparing the energy absorption of the similar specimens of different sizes. All the plates considered in this figure had a square opening with a rounded corner. The data for this figure are given in Table V.

8. <u>Percentage of Reinforcement</u>.

The importance of the percentage of reinforcement is indicated in Figs. 28 to 30, where it is related to the

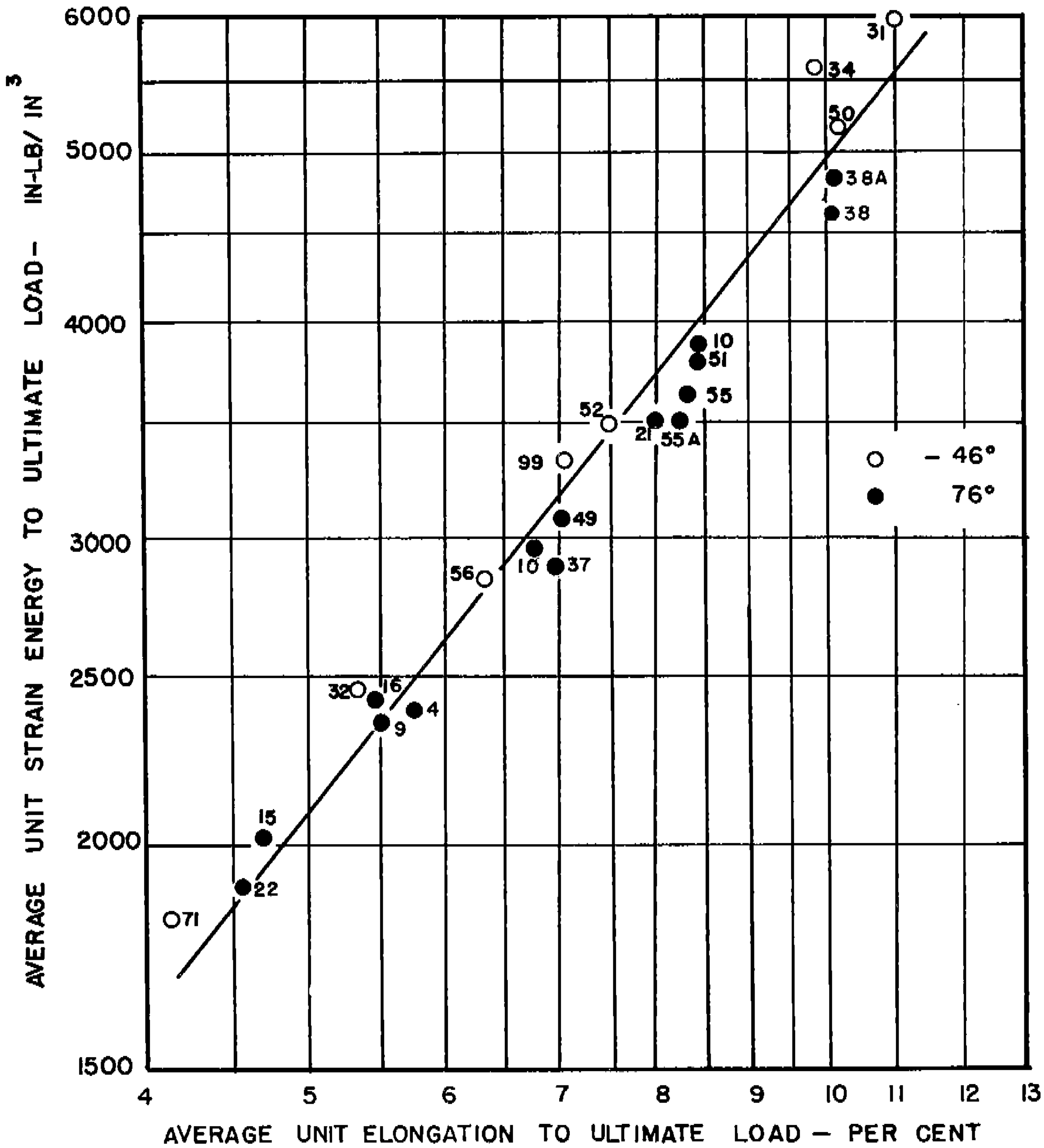


Fig. 27 . Comparison of Average Unit Strain Energy and Average Unit Elongation to Ultimate Load at Room and at Low Temperature.

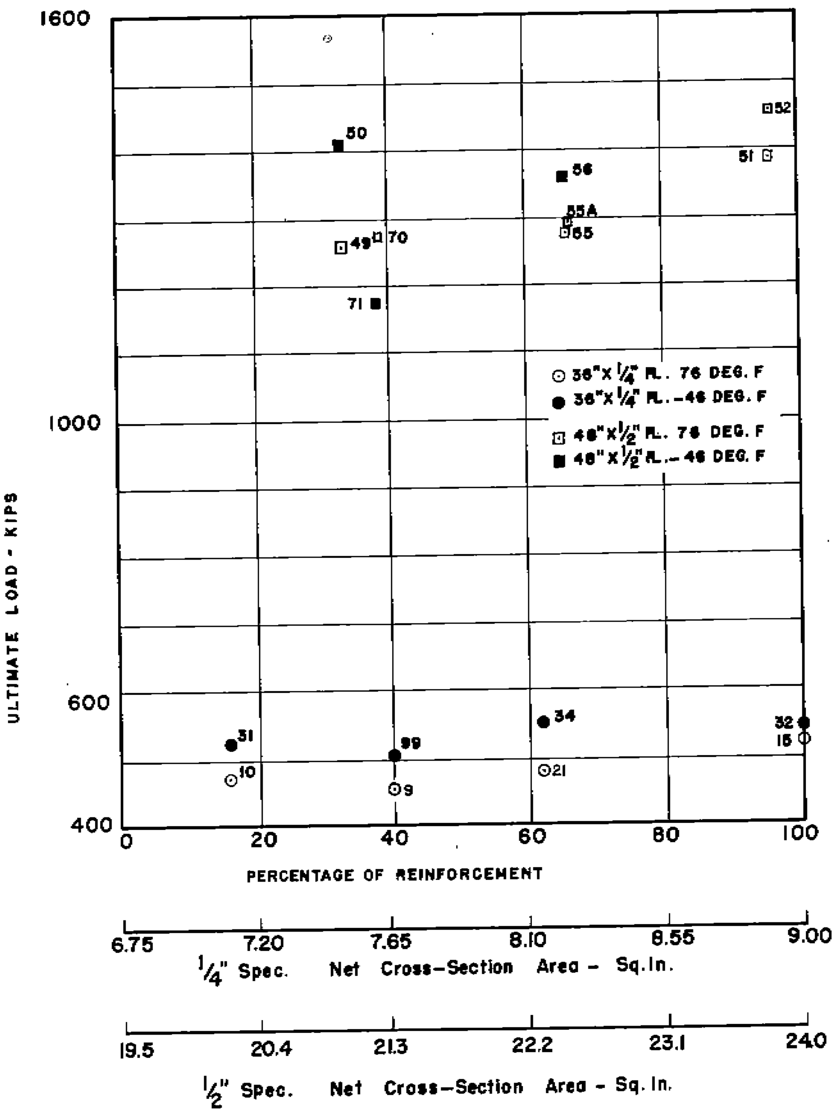


Fig. 28 . Comparison of Ultimate Load and Percentage of Reinforcement.

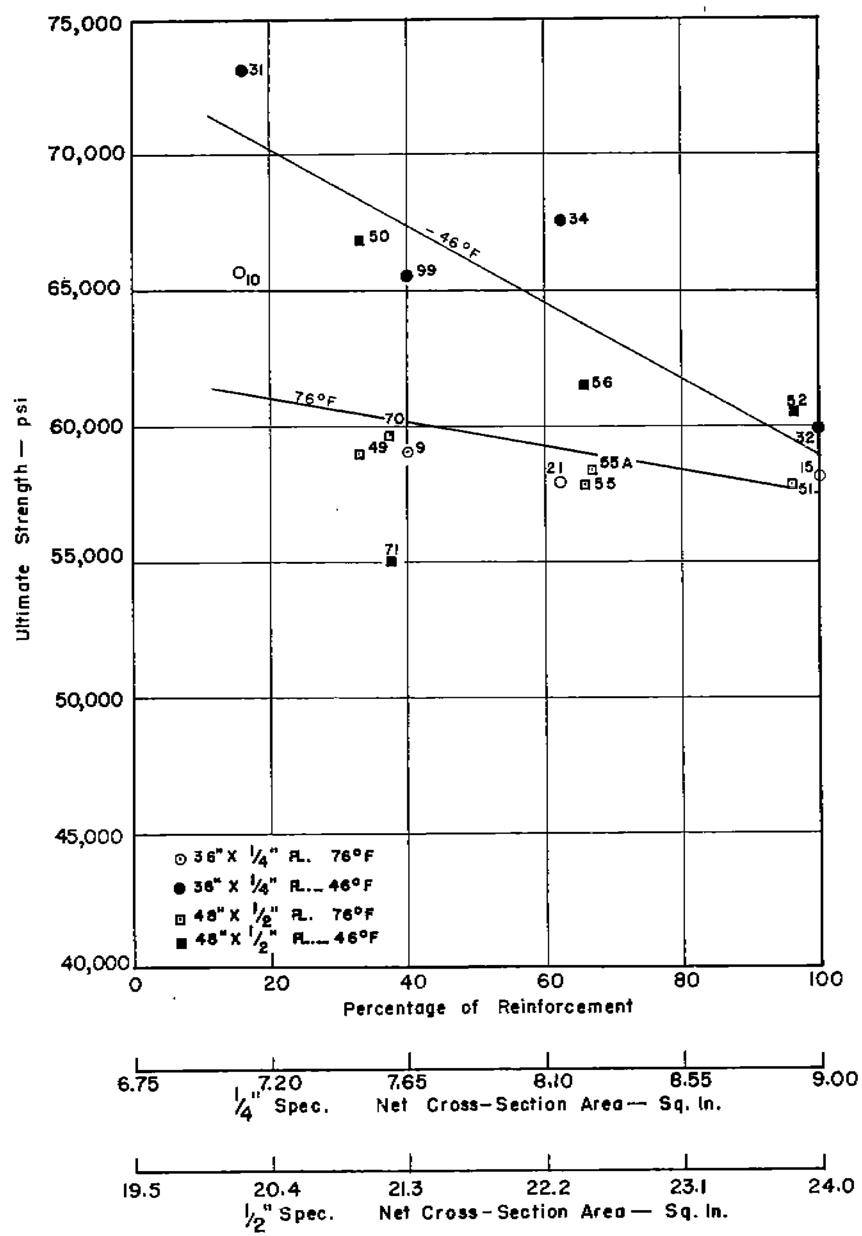


Fig. 29. Comparison of Ultimate Strength and Percentage of Reinforcement.

ultimate load, ultimate strength, and energy absorption to ultimate load. In Fig. 30 the points plotted as A and B were computed for a 48-in. by 1/2-in. body plate size without reinforcement on the assumption that the unit strain energy absorption at ultimate load was occurring at the same rate as for the 36-in. by 1/2-in. plates, Specimens No. 37 and 38. Some justification for this procedure may be found in Fig. 27. These two points were added to help clarify the behavior of the 1/2-in. plates.

Due to the fact that the test series included a wide variety of types of specimens and no duplicates were tested, any comparison of the test results is somewhat crude. However, some observations have been drawn from these figures. Increasing the percentage of reinforcement,

1. Decreased the ultimate strength, the rate of decrease being greater for the tests at -46°F. than for those at room temperature.
2. Increased slightly the energy absorbing capacity of the 1/2-in. plates.
3. Reduced the energy absorbing capacity of the 1/4-in. plates at -46°F.
4. Made little change in the energy absorbing capacity of the 1/4-in. plates at room temperature.

In consideration of the generally opposite effects for the two plate thicknesses of increasing the percentage of

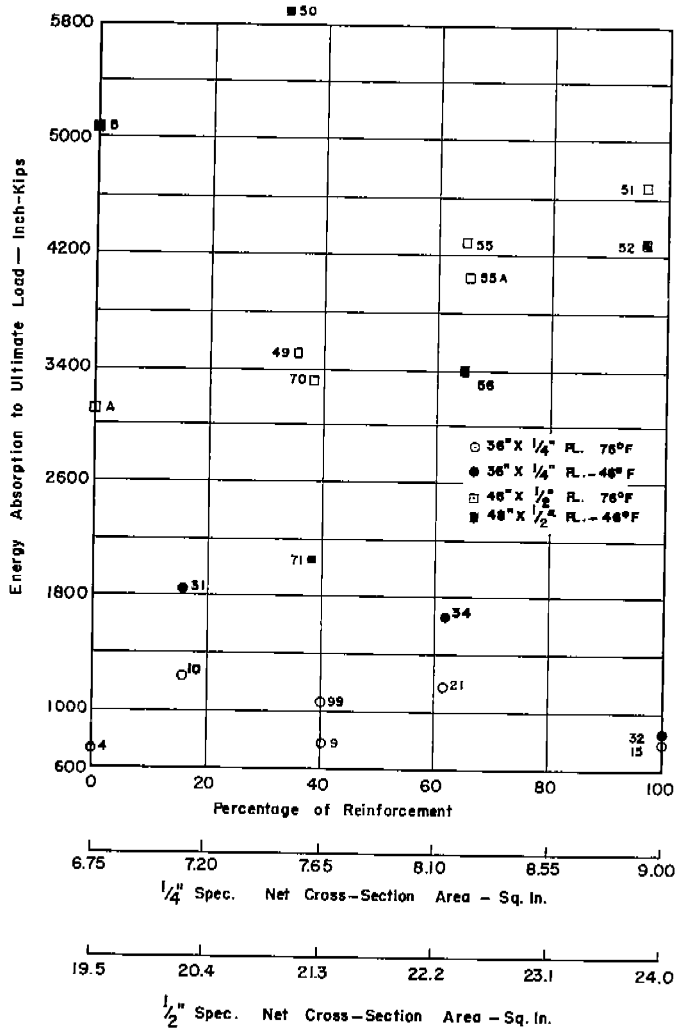


Fig. 30. Comparison of Energy Absorption to Failure and Percentage of Reinforcement.

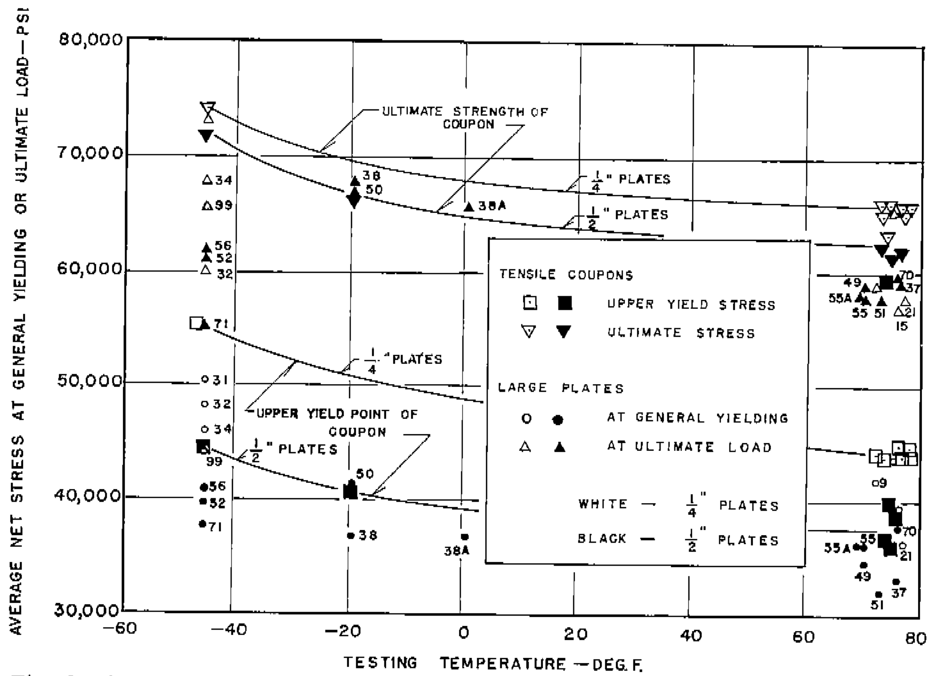


Fig. 50a. Comparison of Average Net Stress at General Yielding and Ultimate Load with Same Properties of Tensile Coupons.

reinforcement, it must be remembered that the transition temperatures determined by the Navy tear test were -40°F. for the 1/4-in. plate and 40°F. for the 1/2-in. plate. The testing temperature for the plates with openings of -46°F. was in the vicinity of the transition temperature of the 1/4-in. plates and well below that of the 1/2-in. plates.

Since the 1/4-in. and the 1/2-in. plates did not respond to changes in the percentage of reinforcement in the same manner, the former cannot always be used to forecast the behavior of thicker plates. In any scale model test to investigate cleavage fracture, the transition temperature should be scaled downwards as well as the dimensions of the specimen.

The forthcoming Fourth Progress Report(4) will show that the principal effect of properly proportioned reinforcement in the plastic stress range, as compared with no reinforcement is:

1. To reduce the maximum stress concentration factor around the opening.
2. To reduce the high rate of strain energy absorption concentrated around the opening.

The plots of the unit elastic strain concentration factors in the First Progress Report(1) and this report in Figs. 31 to 38 showed that the strain-raising effect of the opening, whether reinforced or not, was closely concentrated

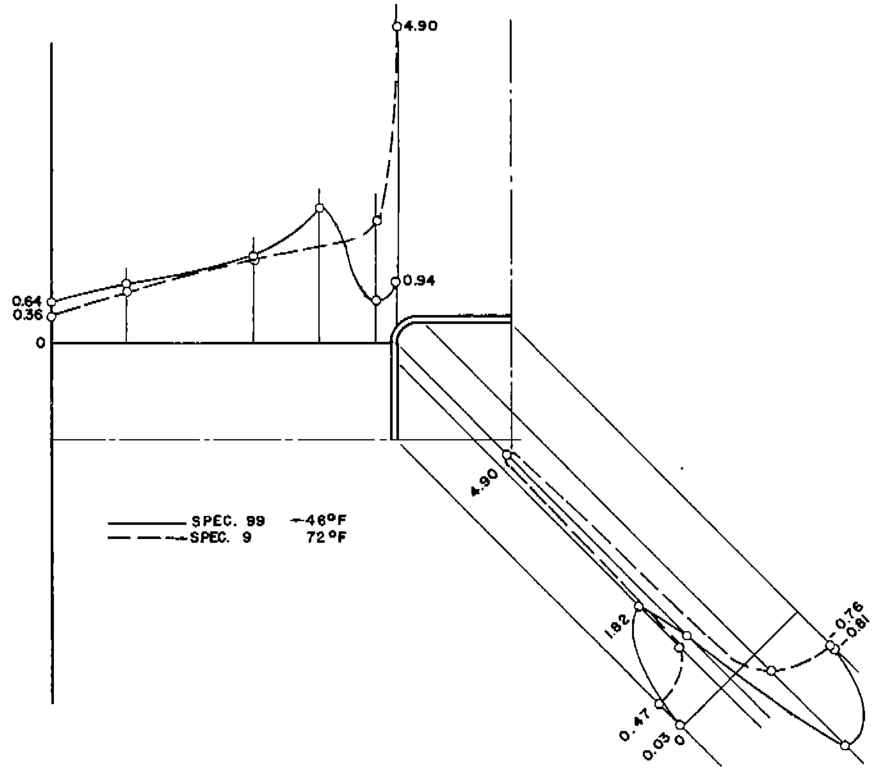


Fig. 31. Elastic Unit Strain Concentration in the Region of the Opening in 36 x 1/4 in. Plate. Face Bar Reinforcement. Specs. No. 9 and 99.

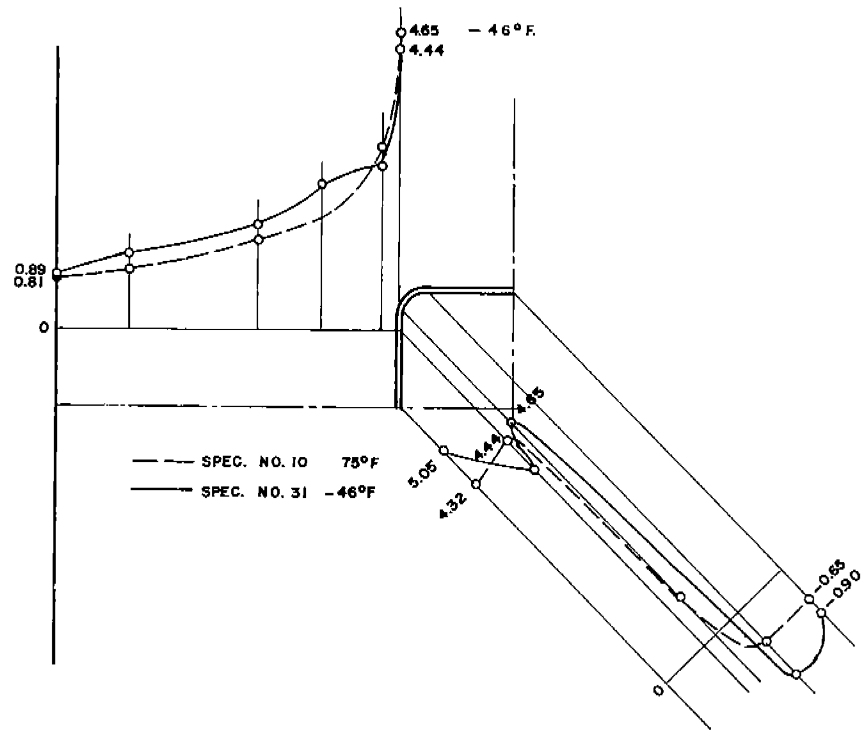


Fig. 32. Elastic Unit Strain Concentration in the Region of the Opening in 36 x 1/4 in. Plate. Face Bar Reinforcement. Specs. No. 10 and 31.

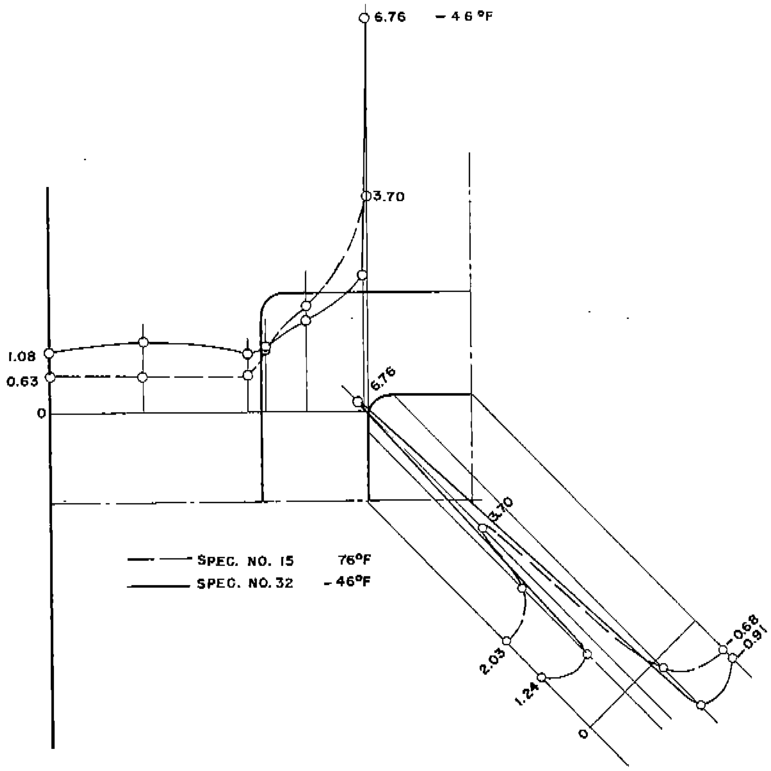


Fig. 33. Elastic Unit Strain Concentration in the Region of the Opening in 36 x 1/4 in. Plate. Doubler Plate Reinforcement. Specs. No. 15 and 32.

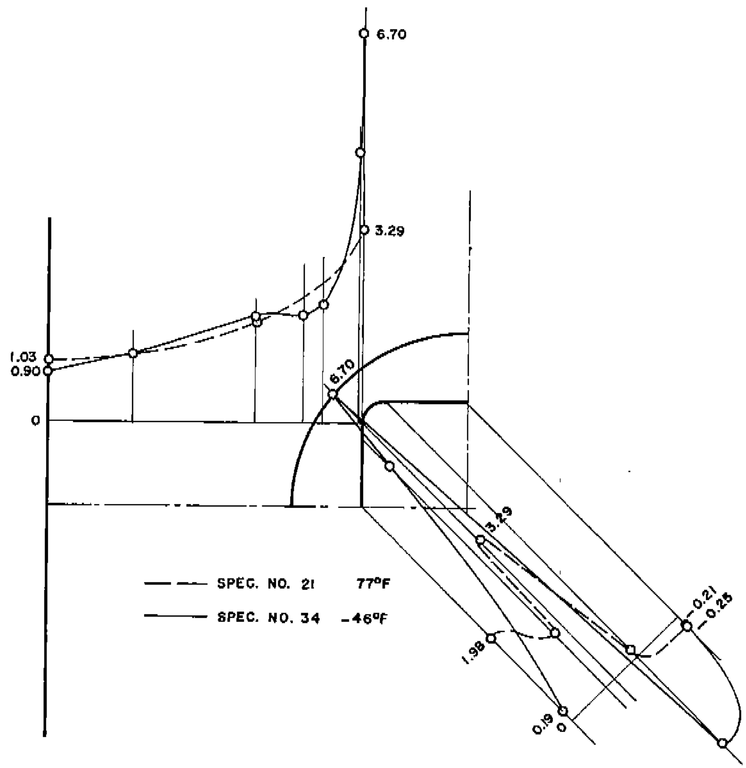


Fig. 34. Elastic Unit Strain Concentration in the Region of the Opening in 36 x 1/4 in. Plate. Insert Plate Reinforcement. Specs. No. 21 and 34.

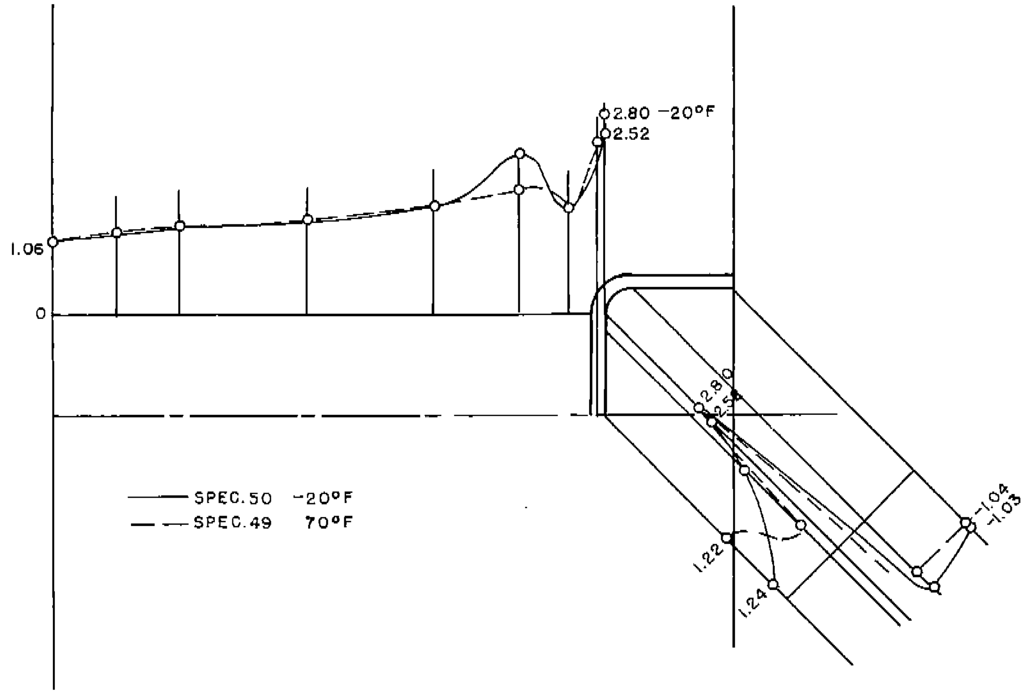


Fig.35. Elastic Unit Strain Concentration in the Region of the Opening in 48 x 1/2 in. Plate, at Low and at Room Temperature. Face Bar Reinforcement. Specs. No. 49 and 50.

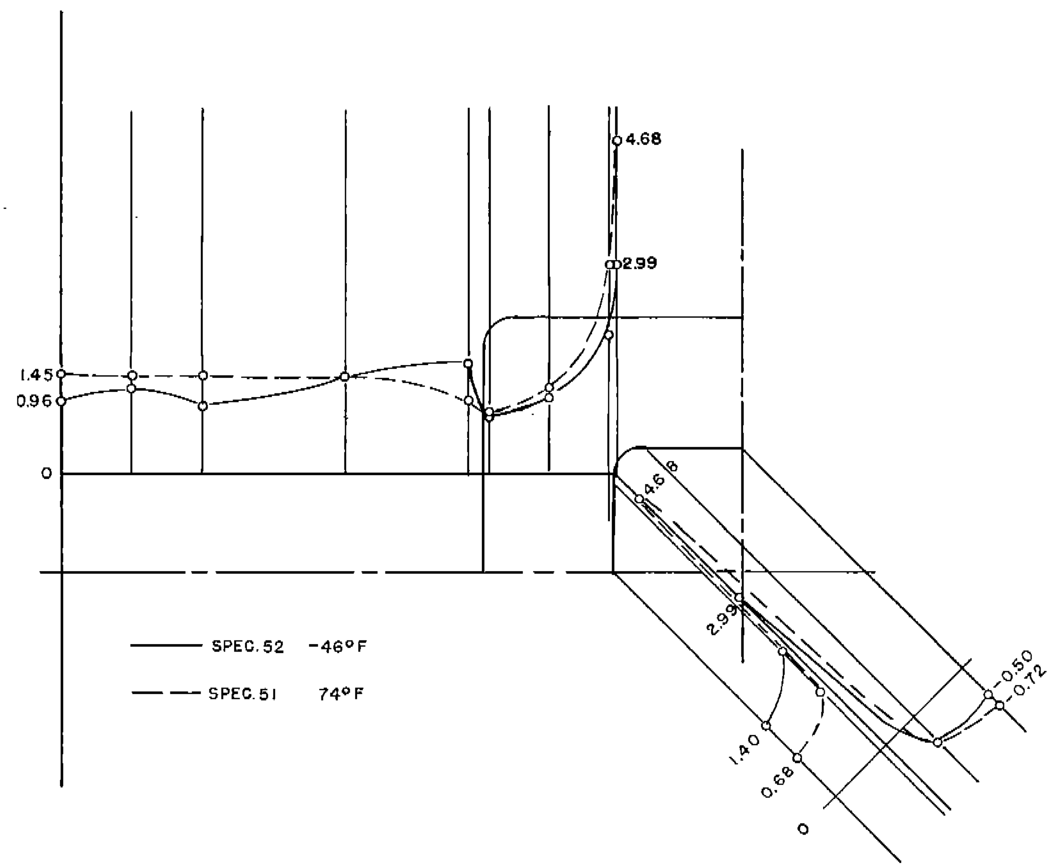


Fig.36. Elastic Unit Strain Concentration in the Region of the Opening in 48 x 1/2 in. Plate, at Low and at Room Temperature. Doubler Plate Reinforcement. Specs. No. 51 and 52.

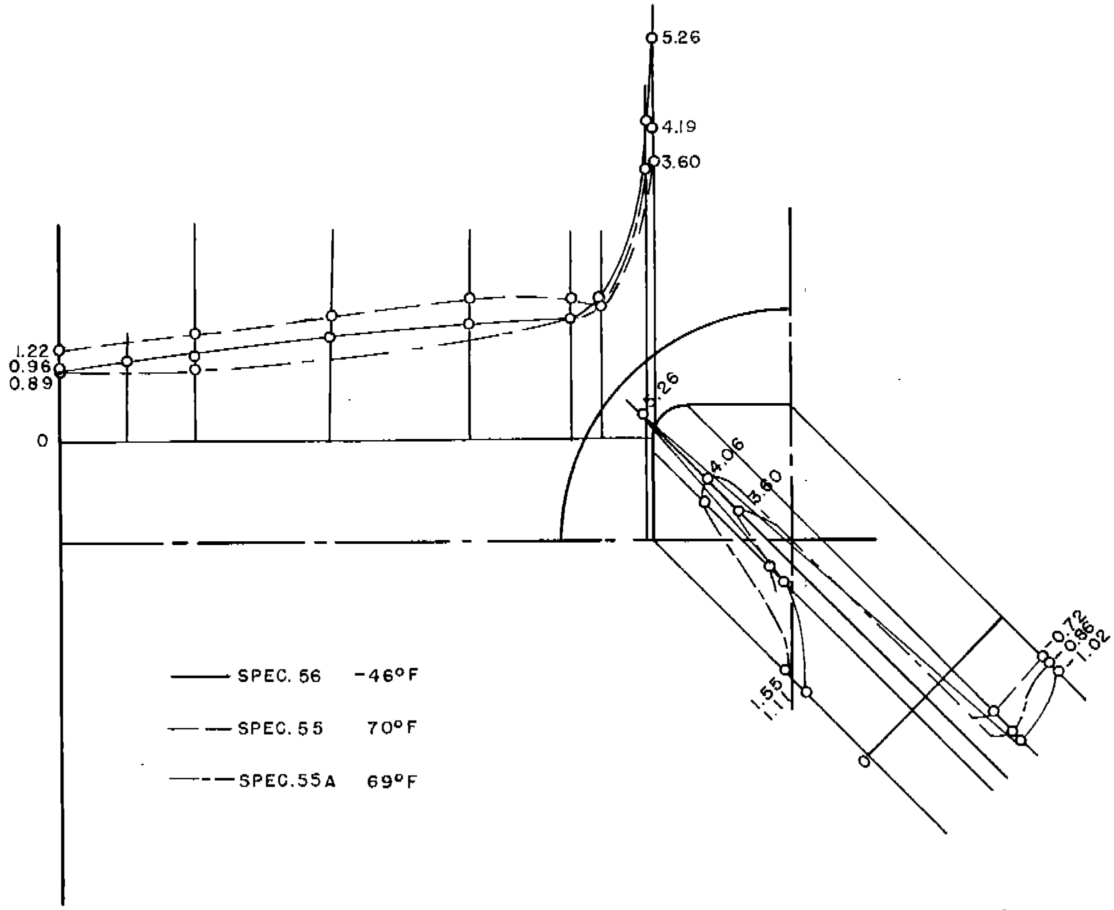


Fig.37. Elastic Unit Strain Concentration in the Region of the Opening in 43 x 1/2 in. Plate at Low and at Room Temperature. Insert Plate Reinforcement. Specs. No. 55, 55A and 56.

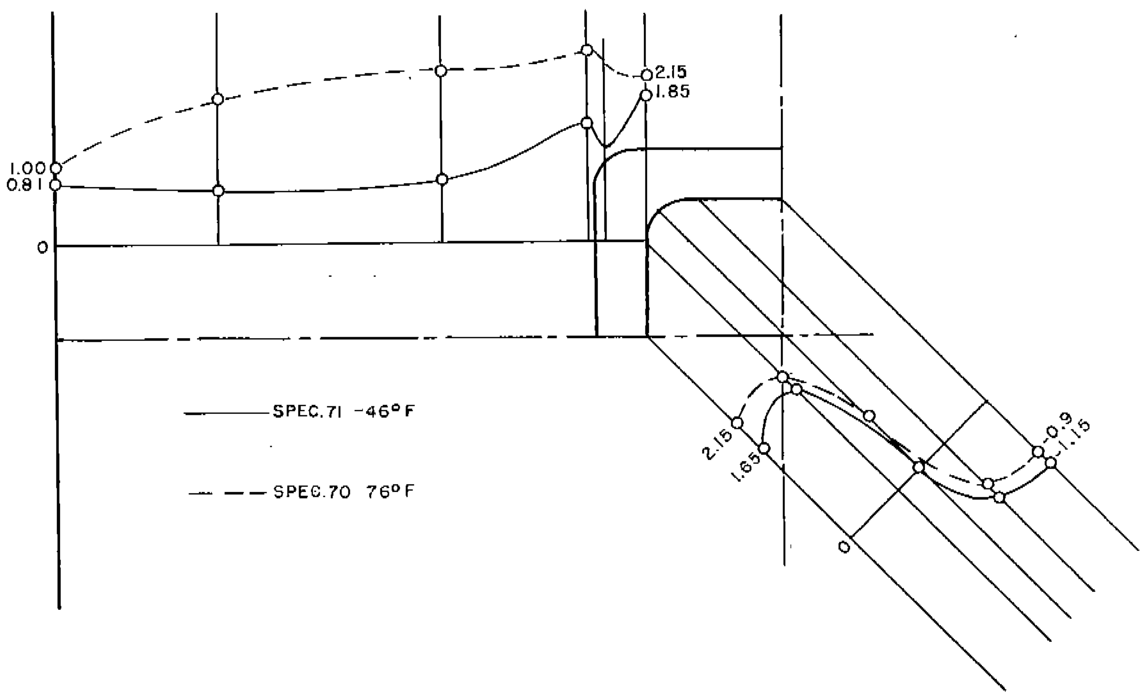


Fig.38. Elastic Unit Strain Concentration in the Region of the Opening in 48 x 1/2 in. Plate, at Low and at Room Temperature. Insert Plate Reinforcement. Specs. No. 70 and 71.

around the opening. A consideration of these facts aids in analyzing the greater improvement in the ultimate strength resulting from the lower percentages of reinforcement. The specimens in this program with less than about 40 per cent reinforcement were of types which tended to concentrate the reinforcement around the edge of the opening in the region where the greatest stress and energy concentration occurred. Thus, the reinforcement was concentrated where it appeared to be most beneficial.

It would seem at this stage of the investigation that the best reinforcement for any opening operating at temperatures well below the transition temperature for the steel should be of a type which concentrates the reinforcing material fairly close to the edge of the opening without its breadth in the direction of the plate thickness becoming too great.

9. Efficiency of the Plates with Openings.

No direct basis of comparison between plain plates without openings and the plates with openings was available for the low temperature tests of the 1/4- and 1/2-in. specimens and the room temperature tests of 1/2-in. plates. However, the results of the tensile coupon tests in Table I were compared with the results of the plates with openings having the same thickness of body plate as shown in Fig. 30(a). It may be seen in this figure that the strength of the plates with openings, whether at general yielding or ultimate load, was always less than the strength of the tensile coupons at the same temperature. It is interesting that the points for the 1/2-in. plates at -46°F. fell further below the tensile upper yield point and ultimate strength than those for the 1/2-in. plates at the higher temperatures, further evidence that the temperature was being approached at which low-energy cleavage fractures would occur.

An estimate of the effectiveness of this present series with respect to energy absorption cannot be made directly. However, the maximum efficiency of about 25 per cent found in the specimens in the First Progress Report[1] would not be exceeded by any considerable margin, if at all, by any of the specimens in this report, since the energy absorption in the more recent tests was of the same order of magnitude as that of the previous tests.

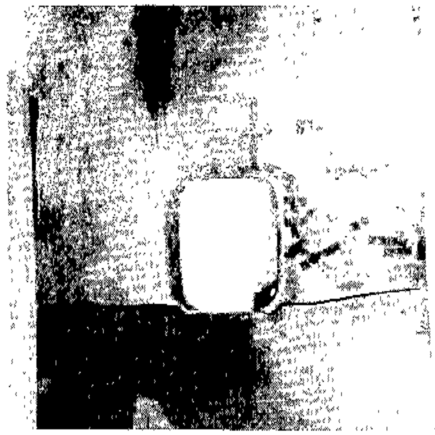
10. Unit Strain Concentration in the Region Around the Opening at Room and Low Temperature.

Elastic strain concentration curves based on the data of SR-4 strain gage readings are shown on Figs. 31 to 38. The results of the room and low temperature tests for the two identical specimens are shown on each figure (dotted lines for room temperature, plain lines for low temperature). The unit strain concentration on these figures is presented as follows:

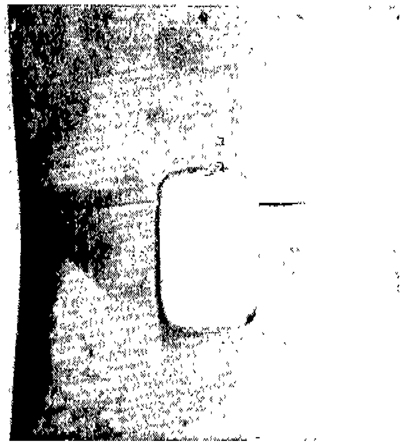
1. The unit strains in the vertical direction on a horizontal line passing through the point of tangency between the vertical edge of the opening and the corner arc.
2. The unit strains tangential to the edge of the opening on the circumference of the opening.

The unit strain concentrations were computed from the SR-4 gage readings in the same manner as described in the First Progress Report(1). They are the ratios of the slope of the strain plots at a particular point on the specimen to the slope of an identical plot in the region of the plate remote from the opening, where uniform stress conditions would prevail.

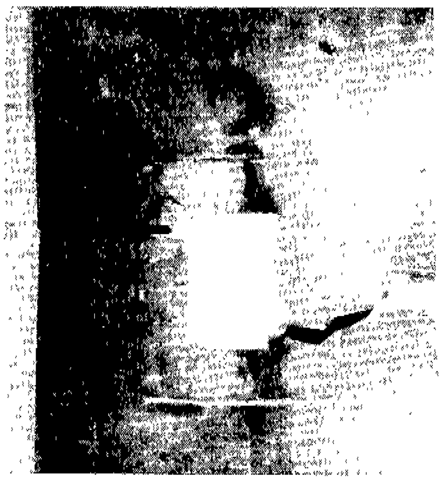
The general shape of the unit strain concentration curves for the plates was the same, both at room and low temperature, when the plates with the same type of reinforcement are compared. However, for every pair of identical specimens except Specimens No. 9 and 99, the maximum unit strain concentration at the corner of the opening was greater at the lower temperature. Since no measurable change in the modulus of elasticity of steel takes place between room temperature and -46°F., it seems reasonable to conclude that the maximum elastic strain concentration, and therefore the stresses as well, would be somewhat greater



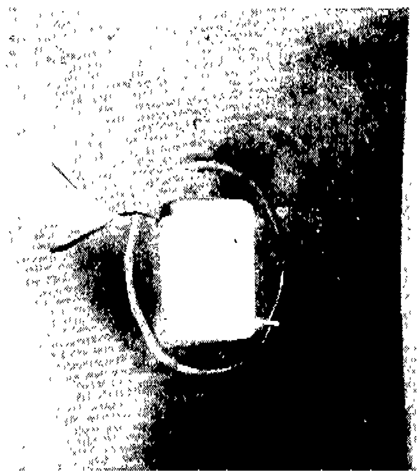
Specimen No. 99



Specimen No. 31



Specimen No. 32



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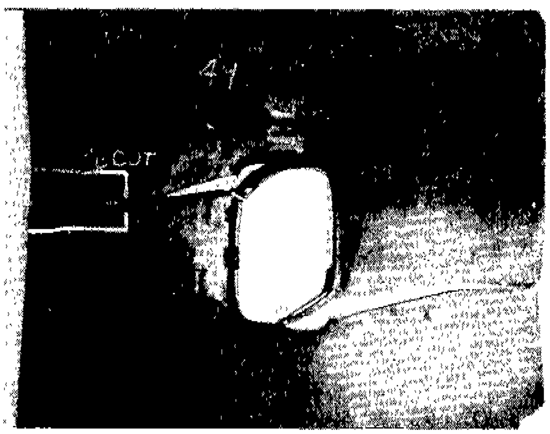
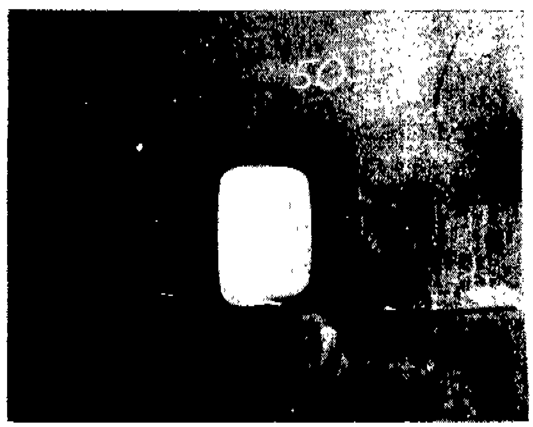
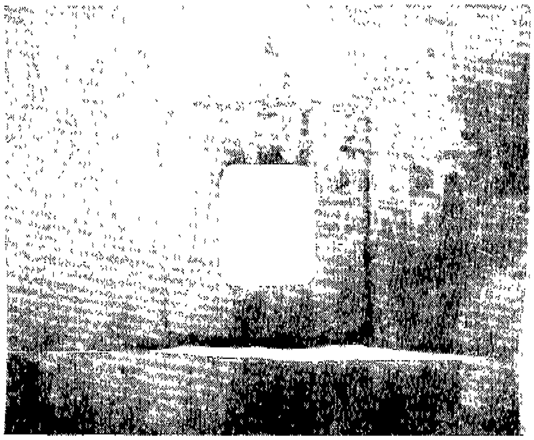


Specimen No. 49

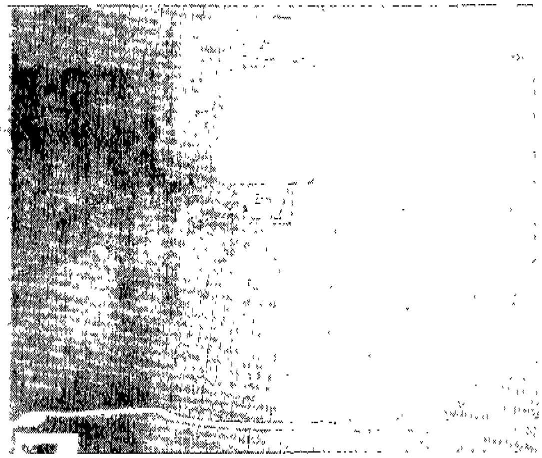


Specimen No. 50

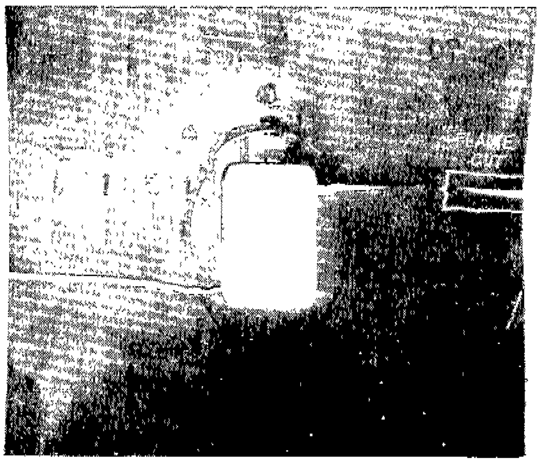
Fig. 39 Photographs of Specimens After Fracture



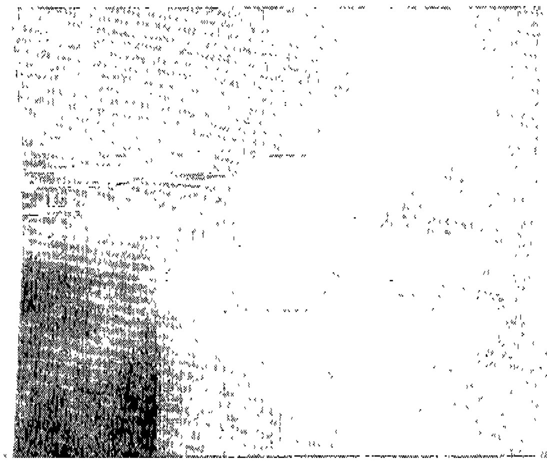
Specimen No. 51



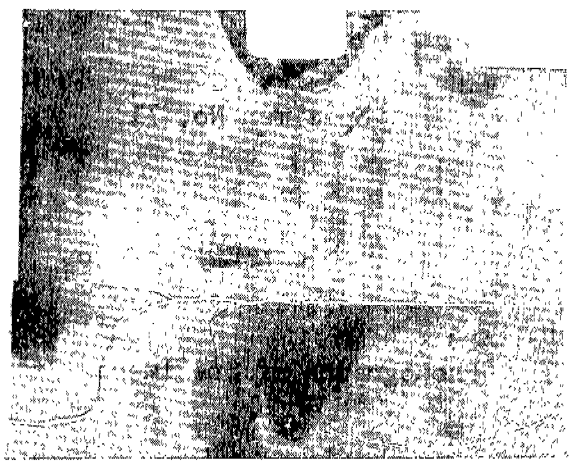
Specimen No. 52



Specimen No. 55

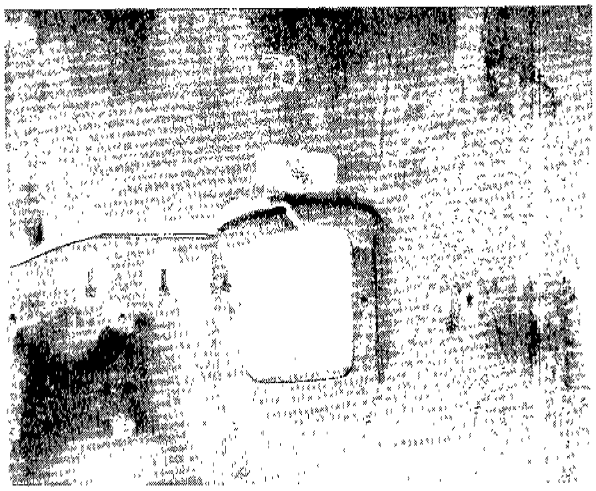


Specimen No. 55A

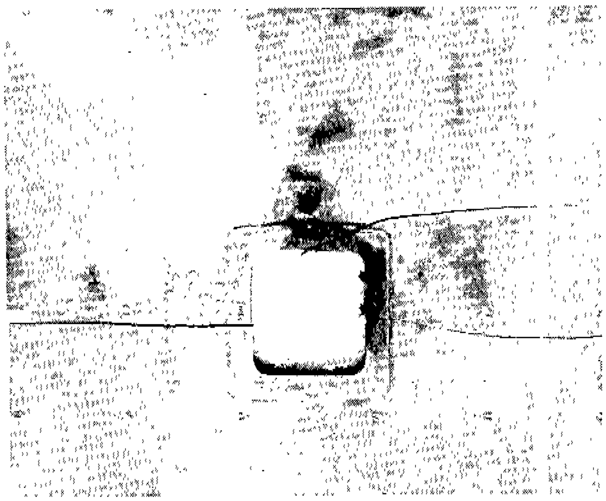


Specimen No. 56

Fig. 40 Photographs of Specimens After Fracture



Specimen No. 70



Specimen No. 71

Fig. 41. Photographs of Specimens After Fracture

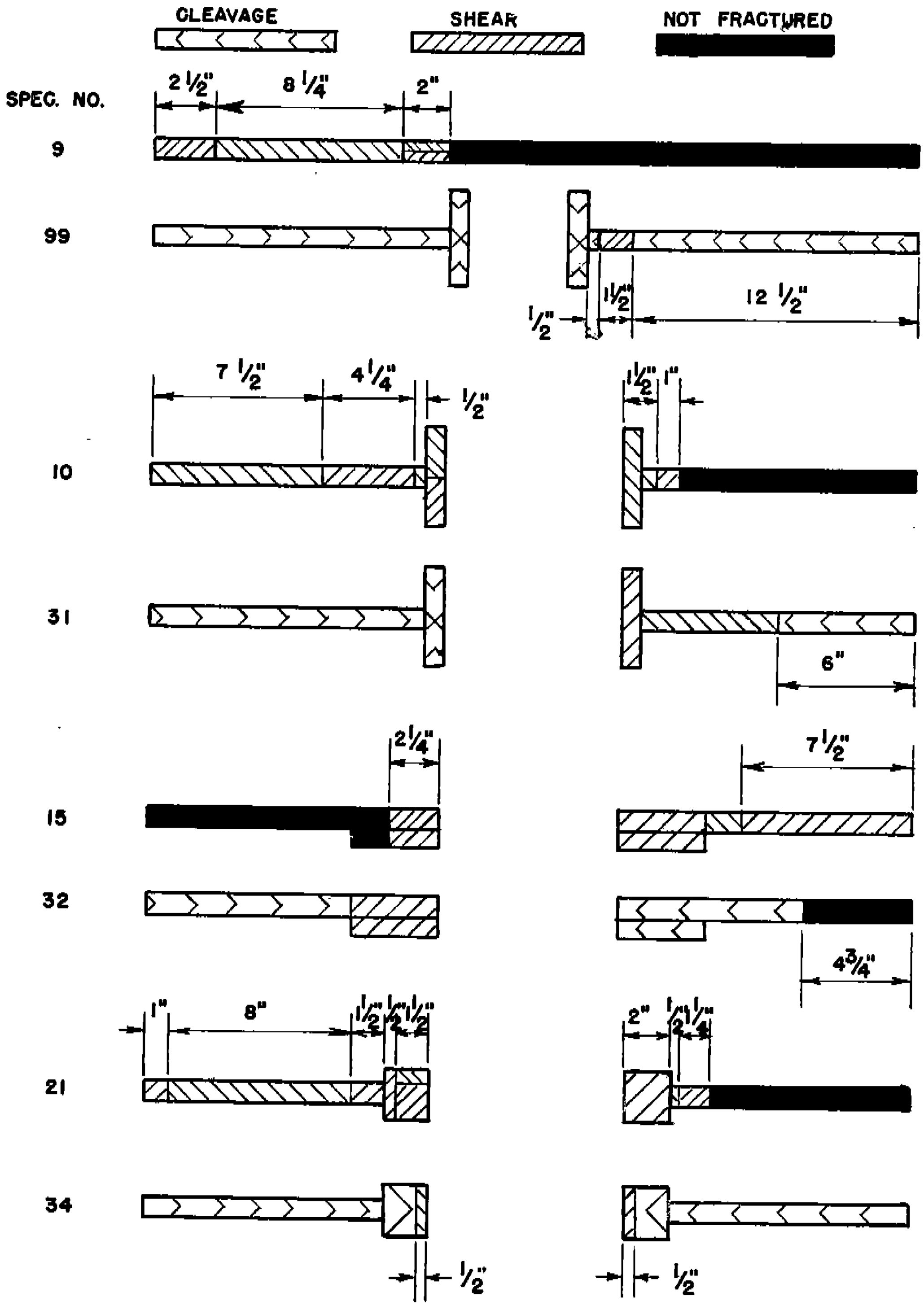


Fig. 42 . Nature of the Fractured Edges of the Specimens.

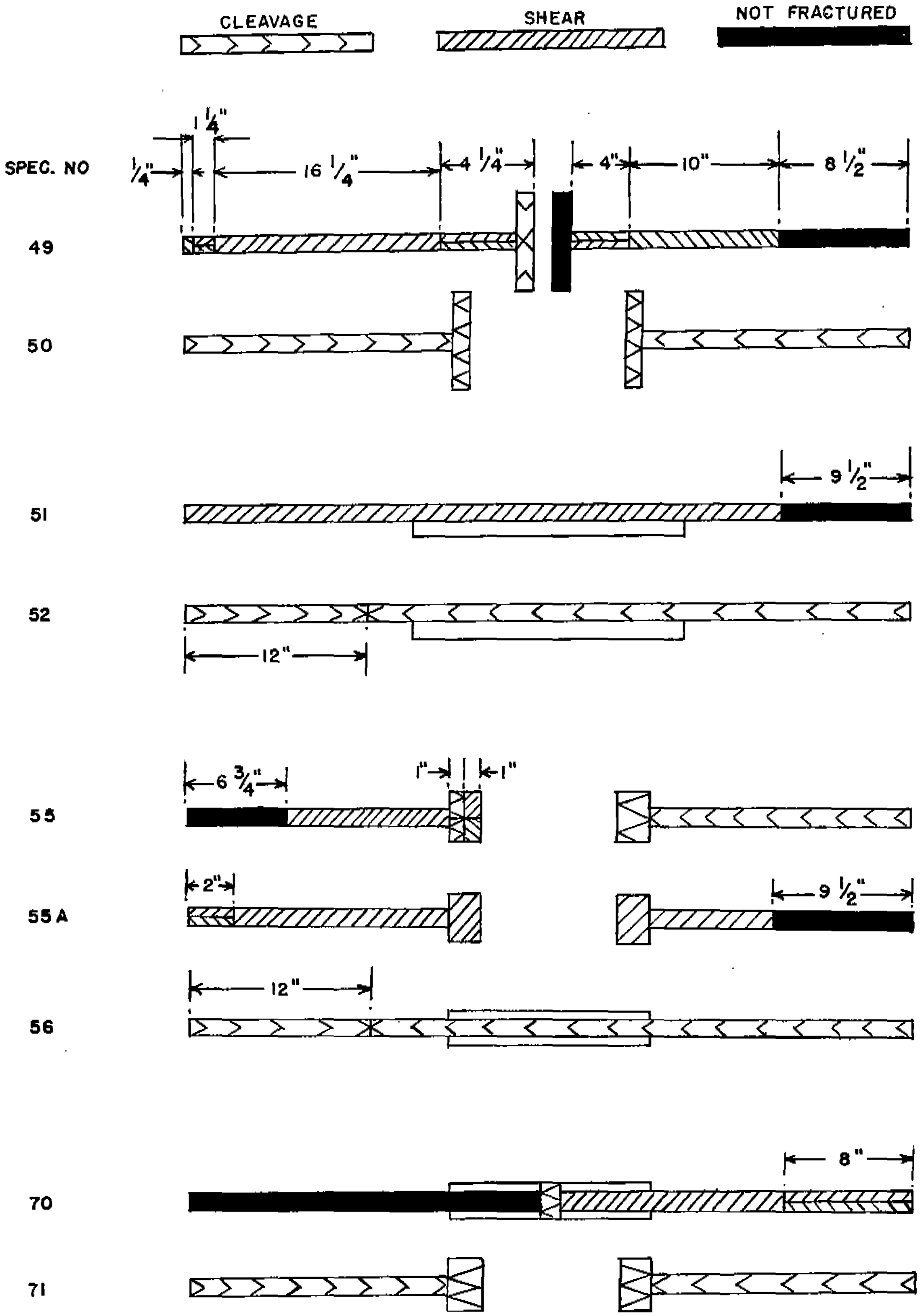


Fig. 43 . Nature of the Fractured Edges of the Specimens.

at lower temperatures in plates with openings than at room temperature. The Second Progress Report[2] has already shown that higher relative energy absorption in the plastic stress range occurred around the opening in the test at the lower temperature, and this evidence is substantiated by the results of the forthcoming Fourth Progress Report[4]. It seems therefore that lowering the testing temperature for plates with reinforced openings tended to intensify the concentration of stress and energy around the opening. This finding constitutes evidence that the behavior of identical plates with openings is not the same at room and at low temperatures, either in the elastic or the plastic stress state. Further test data are needed to fully verify these comments.

The unit strain distribution near the outer edge of the body plate in the 48-in. by 1/2-in. plates more nearly approaches uniformity than in the 36-in. by 1/4-in. plates. At this greater ratio of plate width to hole diameter, (5.3:1), the strain distribution near the edge of the plate in the elastic range was approximately that predicted by the assumption of infinite plate width.

11. Strain-Aging Effects and Incidental Causes of Failure.

Three 1/2-in. specimens suffered premature failures in the pulling plate, were rewelded, and retested. The history of these plates is as follows:

Specimen No.	Testing Temp.	First Failure		Period of Strain Aging	Increase in Load upon Reloading	Final Fracture Per Cent	
		Load	Per Cent of Actual Ultimate Load				
	°F	kips		Days	Per Cent	C	S
51	74	1382	92.4	3	8.4	0	81
52	-46	1460	93.6	9	6.9	100	0
55	70	1156	77.6	10	3.8	57	28

In this table, the percentage of the ultimate load is given in terms of the actual ultimate load, and not the assumed value in Table IV. The increase in load upon reloading is a measure of the amount by which the reloading curve rose above the unloading curve in Figs. 19 and 20.

The location of the first failure in all three specimens occurred in the weld connecting the body plate to the 1/2-in. pulling plate. The fracture started at the outer edge of the specimen. The cause of these incidental failures was clear only in the case of Specimen No. 52, in which the fracture started at an occlusion in the weld. The stress-raising effects of the surface roughness of the weld and the radius at the end connection of the specimens to the pulling plate contributed to these fractures.

The reinforcement for Specimens No. 51 and 52 consisted of a 1/2-in. doubler plate, and for Specimen No. 55 of a

1-in. insert plate. The transition temperature given in Table I for a typical 1/2-in. plate was 40°F. and for the 1-in. plate 120°F. The 1-in. reinforcement for Specimen No. 70, which was not strain-aged showed evidence of cleavage at room temperature. It is not surprising that Specimen No. 55 with a 1-in. thick reinforcement broke with 57 per cent cleavage while Specimen No. 51 with a 1/2-in. thick reinforcement failed with no cleavage, although both plates were tested at room temperature.

Several other facts are of interest. Three days of room temperature strain-aging were sufficient to raise the strength level of these specimens. As far as Steel U is concerned, this aging effect developed brittleness in the 1-in. plate at room temperature, but not in the 1/2-in. plate. The identical plates, No. 55 and 55A, behaved so much alike in all respects that strain-aging in the former appeared to have no measurable effect upon ductility, although it did raise the strength level. Similarly, there did not appear to be any reduction in the ductility of Specimens No. 51 and 52, although duplicate tests were not available here for comparison.

The short-time strain-aging occurring after loading to about 90 per cent of the ultimate load tended to increase the percentage of cleavage in the fracture but brought about no apparent decrease in either the ultimate strength or the energy absorption. This observation might not be applicable to longer periods of aging following the attainment of similar stress levels, to the effects of strain-aging resulting from small amounts of plastic deformation, or to steels with different strain-aging characteristics. Incidental stress-raisers contributed to the final failure of Specimen No. 52 and 56 at -46°F. The fracture was initiated at a small tack weld fastening a gage to the body plate and continued across the plate. However, since the ultimate strength developed by these specimens was in excess of 60,000 lb. per sq. in., the strength of neither plate was appreciably diminished, if at all, by these incidental failures.

V. CONCLUSIONS

One very important general conclusion has resulted from these tests and may be stated as follows:

1. Cleavage fractures with high energy absorption and high ultimate strength are possible in welded structures, provided that all stress-raising effects are sufficiently reduced and that the operating temperature of the structure is not far below the fracture transition temperature for the steel as determined by the Navy tear test.

The following specific conclusions appear to be justified by the recent results of this investigation:

2. The 36-in. by 1/4-in. plates did not predict adequately the behavior of thicker plates when cleavage fracture became a factor.
3. The influence of the geometry of the specimens was more apparent at the lower temperatures than at room temperature.
4. It would seem at this stage of the investigation that the best reinforcement for an opening at any operating temperature should be of a type which concentrates the reinforcing material fairly close to the edge of the opening without its breadth in the direction of the plate thickness becoming too great.

These conclusions are in addition to those of the previous progress reports[1,2].

VI. ACKNOWLEDGMENTS

This investigation, at the University of Washington, sponsored by the Ship Structure Committee, is in progress in the Structural Research Laboratory of the Department of Civil Engineering, of which Professor R. B. Van Horn is head. The research program is directed by Dr. R. A. Hechtman, Associate Professor of Structural Research. Dr. D. Vasarhelyi, Assistant Professor of Civil Engineering, was the project engineer, and was assisted by Mr. Robert McHugh and Mr. Y. T. Yoshimi.

The authors express their appreciation to Mr. John Vasta of the Bureau of Ships, Navy Department, Dr. Finn Jonassen of the National Research Council, and Dean H. E. Wessman and Professor F. B. Farquharson of the University of Washington for their suggestions and encouragement.

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2. D. Vasarhelyi and R. A. Hechtman,"Welded Reinforcement of Openings in Structural Steel Members: A Determination of Strain Energy Distribution and True Stress in the Plastic Range in Plates with Openings", Second Progress Report; Ship Structure Committee, Serial No. SSC-50, March 10, 1952.

3. Data supplied by American Bureau of Shipping.

4. D. Vasarhelyi, R. A. Hechtman, and Y. T. Yoshimi, "Welded Reinforcement of Openings in Structural Steel Members, Cleavage Fracture and Plastic Flow in Structural Steel Plates with Openings", Fourth Progress Report; Ship Structure Committee, Serial No. SSC-56, To be Published.