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PROGRESS REPORT
(FIRST)

ON

WELDED REINFORCEMENT OF OPENINGS IN STRUCTURAL STEEL MEMBERS

BY

D. VASARHELYI AND R. A. HECHTMAN
University of Washington

Under Bureau of Ships Contract NObs-50238
(Index No. NS-731-034)

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Dear Sir:

Herewith is a copy of the first Progress Report on the investigation of "Welded Reinforcement of Openings in Structural Steel Members" by D. Vasarhelyi and R. A. Hechtman. This investigation is being conducted at the University of Washington for the Ship Structure Committee and covers the work completed to August 1950.

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

PREFACE

The Navy Department through the Bureau of Ships is distributing this report for the SHIP STRUCTURE COMMITTEE to those agencies and individuals who were actively associated with the research work. This report represents results of part of the research program conducted under the Ship Structure Committee's directive "to improve the hull structures of ships by an extension of knowledge pertaining to design, materials and methods of fabrication."

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WELDED REINFORCEMENT OF OPENINGS
IN STRUCTURAL STEEL MEMBERS

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PROGRESS REPORT

(FIRST)

WELDED REINFORCEMENT OF OPENINGS IN STRUCTURAL STEEL MEMBERS

by

D. Vasarhelyi and R. A. Hechtman
University of Washington

for

SHIP STRUCTURE COMMITTEE

Under Navy Contract NObs-50238
Index No. NS731-034

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WELDED REINFORCEMENT OF OPENINGS
IN STRUCTURAL STEEL MEMBERS

I. INTRODUCTION

The introduction of an opening within a structural member is often necessary to permit the passage of conduit or personnel. These openings weaken the structural member by decreasing its cross-section area as well as by producing a region of stress concentration. Various methods of reinforcing such openings have been developed in order to increase the net cross-section area of the member, but only a little theoretical or experimental information is available concerning the effectiveness of the different types of reinforcement and the magnitudes of the stresses present in and around the reinforcement.

The experimental investigation reported herein had as its purpose the determination of the effectiveness of four types of arc-welded reinforcement for openings in plain-carbon structural steel plates loaded under uniform tension. The opening was centrally located in each plate and had a width equal to one-fourth of the width of the plate. The effect of the opening and of the various types of reinforcement upon the load at yielding, the ultimate strength, the ductility, and the unit strain distribution in the vicinity of the opening was investigated and compared with similar observations for plates without openings.

The test program covered in this report is the initial part of a larger program of tests. Included in the present report are tests at room temperature of two plain plates without openings, three plates with unreinforced openings, and eighteen plates with arc-welded reinforcement around the opening. Three types of welded reinforcement were investigated: face bars, single doubler plates, and insert plates. The plates without reinforcement and those with each type of reinforcement were fabricated with three different shapes of openings: circular, square with rounded corners, and square with sharp corners.

Following the List of Figures at the beginning of this report will be found a table giving the references in the text to each figure.

II. PREVIOUS THEORETICAL WORK

The present investigation was prefaced by a somewhat thorough search of the technical literature for solutions by the theory of elasticity of the various cases of plates with openings loaded under uniform tension in one direction. Solutions were found for plates of constant thickness and infinite width with circular, elliptical, or ovaloid holes, and for a circular hole in a plate of constant thickness and finite width. Solutions were also found for plates of constant thickness and infinite width with a circular opening reinforced by a section of increased thickness around the opening. A summary and bibliography of these references are given in Appendix A.

The available theoretical solutions were only qualitatively applicable to the types of reinforcement used in this program of tests. Three important conclusions, however, were indicated by the various mathematical analyses of the elastic stresses in plates of infinite width and constant thickness with circular openings reinforced by an increase of the plate thickness immediately around the opening:

1. An increase of the amount of reinforcement decreases the maximum circumferential stress on the rim of the opening, but as additional amounts of reinforcement are added they become increasingly

less effective in reducing this circumferential stress.

2. While the reinforcement decreases the maximum circumferential stresses around the opening, it simultaneously increases the maximum shear stresses adjacent to the reinforcement. This increase in the maximum shear stresses renders it impossible that any reinforcement may restore the full strength possessed by a plate without an opening.
3. The amount of area added by the reinforcement is more effective in reducing the circumferential stresses than the bending stiffness of the reinforcement.

No experimental data were found in the literature which were directly applicable to this problem.

III. OBJECT AND SCOPE OF THE EXPERIMENTAL INVESTIGATION

The experimental program of tests was planned primarily to find information useful for the development of design codes for structural members with reinforced openings where arc-welding was the method of fastening. The object of the investigation, therefore, was to obtain data such as the load at which initial yielding would occur, the maximum strength, the energy absorption and ductility, and the unit strain distribution in the region of the opening for plates with typical types and amounts of welded reinforcement.

The scope of the initial part of the investigation included five series of specimens tested at room temperature: plain plates without openings, plates with unreinforced openings, plates with openings reinforced by face bars, plates with openings reinforced by single doubler plates, and plates with openings reinforced by insert plates.

Each of the series of specimens with openings included three shapes of opening: circular, square with rounded corners, and square with sharp corners. The body or main plate of each specimen was cut from 1/4-inch plate. The program of tests which will follow this initial program includes specimens of greater thickness as well as specimens of the different thicknesses tested at low atmospheric temperatures.

IV. TESTS AND TEST METHODS

1. Specimens Steel and Welding Electrode.

All the specimens for this series of tests were completely fabricated from the same heat of steel. This steel, hereafter designated as Steel U, was a plain-carbon semi-killed grade meeting ASTM Spec. No. A 7-49T and was used in the as-rolled condition. The chemical analysis of this steel was as follows:

C	Mn	P	S	Si
0.23	0.50	0.053	0.051	0.07

The tensile properties of this steel as determined by tests of two ASTM standard flat tensile specimens cut from each plate are given in Table 1. The microstructures of samples cut from one plate of each thickness are shown in Fig. 1.

The coated welding electrode was 1/8 in. and 5/32 in. in diameter and met AWS Spec. E-6010.

2. Details of Test Specimens.

The specimens were designed and welded in accordance with Navy Specification Navships 451. The welds were designed to have an efficiency of 100 per cent according to these specifications. Sketches showing the five types of specimens and the details of the welding appear in Figs. 2, 3, 4, and 5. Table 2 lists the test program.

All plates had a test section with the same dimensions, 36 in. wide by 1/4 in. thick, as shown in Fig. 2. Figs. 2 to 5, inclusive, show the shape of the opening which was located in the center of the test section and the details of the welded reinforcement. The outer edges of the specimens and the circumference of the opening were flame-cut to shape and ground to remove the roughness left by the flame-cutting. The doubler plates and the insert plates were also flame-cut to shape. However, the face bars were sawed to width from 48-in. plates rather than flame-cut, in order that the internal stresses in the face bars might be similar to those in hot-rolled bars, which would ordinarily be used for this kind of structural detail. The face bars were cold-bent to shape and spliced with single V-butt welds on the vertical centerline of the specimen. Those for the circular opening were made in one piece and those for the two types of square openings in two halves. Table 3 lists the plates from which the details for each specimen were cut.

All fillet and edge welds were laid in one pass of the welding electrode. The double V-butt welds required one pass on each side of the plate. Plate bevels for edge or butt welds were prepared by hand grinding. The surface of the edge bead on the circumference of the opening in the specimens with doubler plates was ground to remove the surface roughness.

Because heat-straightening might introduce undesirable stresses and adversely affect the ductility of the steel, very careful precautions were taken to minimize the shrinkage resulting from the hand-welding process to the degree that straightening would be unnecessary. A jig was built in which the specimen to be welded could be clamped between two heavy plates and rotated through an angle of 180 degrees to permit the laying of all welds in the flat downhand position. The welding procedure was arranged so that the welds were placed in short steps which were systematically laid from side to side of the reinforcement and from face to face of the specimen. Moreover, no pass started or ended in the vicinity of the region which the fracture would later traverse. Time was allowed between these short passes and before removal of the plate from the jig after the completion of all welding to permit the specimen to cool. The maximum warpage which resulted from this welding procedure was not greater than 1/2 in. in the seven-foot length of the specimen.

The method of fabrication followed very closely the usual procedure in a fabricating shop except that more care was taken in cutting the structural details to exact dimensions and in holding the welds to the specified size than is required by commercial specifications. The specimens were not tested until at least seven days after welding.

3. Method of Testing Plate Specimens.

The plate specimens were tested in a 2,400,000-lb. capacity universal hydraulic testing machine. The specimens were mounted in the testing machine by butt-weld connections to the pulling heads. The two pulling heads were free to swivel on the pins of two clevises attached to the heads of the testing machine by spherical joints. The vertical centerline of the specimen was aligned to within 1/16-in. of the line joining the centers of the two clevis pins. A typical plate specimen mounted in the testing machine and ready for testing may be seen in Fig. 6.

The load was applied slowly to the specimen, and readings of the gages taken at frequent intervals. The same schedule of loads was applied to all specimens in order that comparisons of the elongations and unit strains might be made at the same loads.

4. Gaging and Measurements.

The principal measurements made were the elongation on a 36-in. gage length straddling the region around the opening and the unit strain distribution in one quadrant of the specimen lying between the vertical and the horizontal certerlines. The 36-in. gage length bridged most of the portion of the specimen in which the unit stresses were non-uniform. The 36-in. gages were located on both faces of the plate on four equal spacings across the width of the specimen as shown in Fig. 2.

SR-4 electric strain gages were used to determine the unit strain distribution in the one quadrant of the specimen in the elastic range and the early plastic range. These electric strain gages were mounted on both faces of the plates to remove the effect of bending from the readings. The number of SR-4 gage readings on the single specimens varied from 33 to 56 according to the shape and the kind of the reinforcement. The location of the electric strain gages on the different types of specimens is shown in Figs. 7 to 10, inclusive.

A number of auxiliary observations were made. The first specimens tested were coated with Stresscoat for the purpose of indicating the principal stress trajectories and the points of initial yielding. However, since the Stresscoat was sprayed and tested under conditions of varying temperature and humidity, the behavior of the brittle lacquer was somewhat erratic. Accordingly, ordinary whitewash was used on the later tests. The location and the direction of the principal shear stresses at initial yielding and during the subsequent plastic flow were clearly shown by the whitewash.

The distortion of the opening at the higher loads and the progression of the fracture were measured with a scale graduated in one-hundredth inches as well as the lateral buckling of the regions under compression stress adjacent to the opening. These various auxiliary observations were useful in evaluating qualitatively the state of stress in the specimen within the plastic stress range.

Since the tests were made at room temperature, the temperature of the specimen was measured with sufficient accuracy by a mercury thermometer which was in intimate thermal contact with the plate surface and insulated from the surrounding atmosphere.

V. RESULTS OF TESTS

1. Introduction and Definition of Terms.

The results of the twenty-three tests of plain plates, plates with unreinforced openings, and plates with reinforced openings will be presented in the following section. No two of the twenty-one plate specimens with openings were alike, and, accordingly, comparisons of the results of these tests must be made on a rather broad or general basis. Duplicate tests of any of these specimens would undoubtedly have given somewhat different results. It was found quite often that the plates with the same shape of opening behaved more nearly alike than the plates with the same type of reinforcement. Trends are shown wherever the data indicated definite relations between the variables. All the tests described in this report resulted in completely ductile fractures.

Some of the terms to be used in the following section should be clearly defined. The elongations measured over a 36-in. gage length at five points across the width of the plate as shown in Fig. 2 were averaged and the resulting value called the average elongation on the 36-in. gage length. The term, load at general yielding, of the specimens was applied to the point where a definite elbow appeared in the plot of the total load on the plate against the average elongation on the 36-in. gage length.

The ultimate load, the maximum load sustained by the specimen, was divided by the original net cross-section area of the specimen to give the value of the maximum average net stress or ultimate strength of the plates. The total load on the specimen was plotted against the average elongation on the 36-in. gage length for each specimen. The area under this curve, or any portion of it, represented the energy absorption of the specimen up to the point under consideration. Two values of the energy absorption have been reported, the energy to ultimate load and the energy to failure.

The three shapes of opening will be referred to as circular, square with rounded corners, and square. The dimensions and the corner radii of these openings are shown in Figs. 2 to 5, inclusive. The plates without openings will be called plain plates.

In computing the percentage of reinforcement, the unreinforced plates with openings one-fourth of the full width of the specimen were considered as having zero percentage of reinforcement. The percentage of reinforcement was computed as the ratio in percent between the additional net cross-section area added to the unreinforced specimen and the cross-section area of the material removed from the body plate by the opening. A reinforced plate with a net cross-section area equal to the area of the plain plate would have a percentage of reinforcement of 100 percent.

2. Distribution across Plate of Elongation on 36-in. Gage Length.

The elongation was measured in the direction of the applied tension at five points across the width of the specimens as described in Fig. 2. The distribution across the plate width of the elongation on the 36-in. gage length is shown in Figs. 11 to 33, inclusive, for each of the twenty-three plate specimens. Measurements were taken after passing the ultimate load, but were not plotted in these figures because they were more dependent on the progressing fracture than on the elongation of the material.

The elongation of the specimens remained fairly symmetrical about the vertical centerline of the plate until fracture began at, or just before the ultimate load. With few exceptions the elongation was greater in the center of the specimen than at its edges, both for plain plates and plates with openings. The distribution of the elongation across the plates was more or less the same in shape for all the plates and was not changed by the different shapes of openings or the different types of reinforcement.

The elongations at the five points across the width of the plate were averaged to obtain the average elongation on the 36-in. gage length. A comparison of the average elongation to ultimate load and to failure is shown in Fig. 34. The values of the average elongation at ultimate load ranged from 36 to 85 percent of the values of the average elongation at failure. Among the plates with square openings, this ratio ranged from 36 percent for Spec. No. 19 to 59 percent for Specs. No. 3 and 20; among the plates with square openings with rounded corners, from 58 percent for Spec. No. 22 to 78 percent for Specs. No. 4 and 21; and among the plates with circular openings, from 73 percent for Spec. No. 6 to 85 percent for Specs. No. 2 and 18. For the three shapes of openings, the ratio between the average elongation to ultimate load and the average elongation to failure increased in the following order: square opening, square opening with rounded corners, and circular opening.

The shape of the opening also affected the total amount of elongation occurring before failure. The magnitudes of the average elongation to failure varied within approximately the same range for the plates with circular and those with square openings with rounded corners, but were greater for all the specimens with these two shapes of opening than for any of the plates with square openings. The average elongation to failure on the 36-in. gage length ranged from 4.01 in. for Spec. No. 10 to 1.82 in. for Spec. No. 3 as compared to values of 9.83 and 12.35 in. for the two plain plates. The largest elongation to failure of all of the plates with openings was only 40 percent of the lesser of the two values of the elongation to failure for the plain plates.

The following tabulation lists the specimens in decreasing order of magnitude of the average elongation to failure:

Order of Magnitude	Spec. No.	Shape of Opening	Type of Reinforcement
1	10	Square, Rounded Corners	Face Bar
2	21	Square, Rounded Corners	Insert Plate
3	17	Circular	Insert Plate
4	5	Circular	Face Bar
5	11	Circular	Doubler Plate
6	16	Square, Rounded Corners	Doubler Plate
7	18	Circular	Insert Plate
8	2	Circular	None

As this tabulation indicates, the average elongation to failure was not consistently large for any particular type of reinforcement. However, the largest elongation sustained by a plate without reinforcement around the opening was only eighth in order of magnitude or 78 percent of the value for Spec. No. 10.

The average elongation in 8 in. of the nine 1/4-in. plates listed in Table 1 was 29.1 percent. If the average unit elongation from the tensile coupon tests is used to predict the total elongation in the 36-in. gage length of the plain plates, the value would be 10.5 in. This value compares with the actual average elongation of 9.83 and 12.35 for Specs. No. 1 and 23.

3. Comparison of Load on Specimen and Average Elongation on 36-in. Gage Length.

The total tension load on the specimen was plotted aginst the average elongation on the 36-in. gage length to obtain the results shown in Figs. 35 to 39, inclusive. The specimens are grouped in each plot according to the type of reinforcement.

The results shown in Fig. 35 for the two plain plates were alike except that Spec. No. 23 sustained a greater average elongation to failure than Spec. No. 1. Necking of the cross section of the plain plates began at the ultimate load and continued until fracture started at a load not far below the ultimate load.

The plates with unreinforced openings as shown in Fig. 36 followed almost a common curve as the load increased until a point near the ultimate load of each specimen was reached. Spec. No. 3 with the square opening sustained a smaller average elongation than Spec. No. 4 with the square opening with rounded corners. Spec. No. 2 with the circular opening underwent the largest average elongation of the three plates.

The behavior of the plates with reinforced openings, shown in Figs. 37, 38 and 39, was similar to that of the unreinforced plates except that higher loads were reached because of the increased cross-section area added by the reinforcement. The smallest average elongation consistently occurred in the plates with square openings, while the average elongation of the plates with square openings with rounded corners and of those with circular openings varied considerably, but were of the same order of magnitude.

Since all the load-average elongation curves possessed a common shape up to a point near their ultimate load, it seemed likely that some relation existed between the magnitudes of the ultimate load and the average elongation to ultimate load on the 36-in. gage length. Fig. 40 shows this comparison. The ultimate load increased in direct proportion to the logarithm of the average elongation to ultimate load on the 36-in. gage length.

4. General Yielding in the Plain Plates and the Plates with Openings.

Yielding began in very small regions of the specimens at low loads as will be shown in a subsequent section of this report. However, only very slight changes in the slope of the load-average elongation curves in Figs. 36 to 39 took place until yielding had spread to a larger portion of the area around the opening. This point of the load-average elongation curve at which a sharp change of slope occurred was termed the load at general yielding.

The values of the load and the average net stress at general yielding are plotted in Fig. 41 and given in Table 4. While the values of the total load on the specimen varied considerably, the values of the average net stress at yielding were more nearly uniform and varied from 36,360 psi for Spec. No. 21 to 45,500 psi for Spec. No. 6. The net cross-section area of the former specimen was 8.17 sq. in. and of the latter 7.25 sq. in. The average net stress at general yielding in the plain plates was 42,220 and 43,330 psi for Specs. No. 1 and 23. An examination of the values in Fig. 41 and Table 4 indicated that there was no simple relation between the average net stress at general yielding and the shape of the opening or the type and amount of reinforcement.

In Table 1, the average upper yield points of the plates of various thickness were 44,500 psi for the 1/4-in. plate, 36,500 psi for the 1/2-in. plate and 32,800 psi for the 1-in. plate. The average net stress at general yielding ranged from 36,360 to 45,500 psi for the plates with openings and was 42,220 and 43,330 psi for the two 1/4-in. thick plain plates.

5. Ultimate Strength of Plain Plates and Plates with Openings.

The ultimate strength of the plain plates and the plates with openings is shown in Fig. 42 and tabulated in Table 4. The values of the ultimate load for the plates with openings varied from 357,500 lb. for Spec. No. 3 to 555,000 lb. for Spec. No. 11, and the values of the ultimate strength from 47,690 psi for Spec. No. 19 to 67,800 psi for Spec. No. 5. The ultimate strength of the two plain plates was 65,390 and 64,780 for Specs. No. 1 and 23. The ultimate strength of the plates with openings was either approximately equal to or less than the ultimate strength of the plain plates. The average ultimate strengths of the plates of different thickness as determined by the tensile coupon tests are reported as follows in Table 1: 65,700 psi for the 1/4-in. plates and 61,100 psi for both the 1/2-in. and the 1-in. plates. The ultimate strength of the 36-in. wide plain plates was approximately the same as for the small tensile coupons. The ultimate strengths of the plates with openings ranged from approximately 75 to 100 percent of the ultimate strengths of the plain plates and the tensile coupons.

The relation between the ultimate load sustained by the plates with openings and the percentage of reinforcement is shown in Fig. 43, and the relation between the ultimate strength and the percentage of reinforcement in Fig. 44. In these two figures, the plotted points fell into bands according to the shape of opening used in the specimen. The ultimate load and the ultimate strength increased in the order of the shape of the opening as follows: square, square with rounded corners, and circular. A much smaller variation within the bands for each shape of opening was noted as the effect of the type and the amount of reinforcement.

The ultimate load increased as shown in Fig. 43 with an increase of the percentage of reinforcement. However, the ultimate strength of the plates in Fig. 44 decreased as the percentage of reinforcement increased. While a definite curve cannot be accurately drawn through the plotted points, the ultimate load increased and the ultimate strength decreased at about the same rate for all three shapes of openings as the percentage of reinforcement was increased.

The plots in Figs. 43 and 44 would be identical if the ultimate load and the ultimate strength had been plotted against the net cross-section area of the plates. Therefore, it may be said that the ultimate load increased and the ultimate strength decreased as the net cross-section area of the plates with openings was increased.

Since the ultimate load and the ultimate strength decreased in Figs. 43 and 44 as the corner radius of the opening decreased, it was apparent that the notch-effect of the opening was very significant. The relation between the ultimate strength of the plates with openings and the notch acuity of the opening is shown in Fig. 45. The notch acuity of the opening has been expressed in the form of the ratio, R_O/R_N, the ratio of the half-width of the opening to the notch radius which is in this case the corner radius of the opening. The actual measured corner radius of each specimen has been used to compute this ratio. An increase in the ratio R_O/R_N indicates an increase in the sharpness of the notch as represented by the opening. In Fig. 45 the ultimate strength of the plates with openings decreased in a linear manner with the logarithm of the ratio R_O/R_N.

6.- <u>Energy Absorption of the Plain Plates and the Plates with Openings.</u>

The energy absorption to ultimate load and to failure of the plain plates and the plates with openings is plotted in Fig. 46 and tabulated in Table 4. The energy absorption to ultimate load was 4,018,000 and 4,062,000 in-lb. for the two plain plates, Specs. No. 1 and 23, and among the twenty-one plates with openings varied from 229,000 in-lb. for Spec. No. 19 to 1,358,000 in-lb. for Spec. No. 11. The energy absorption to ultimate load for the plates with openings ranged from 6 to 34 percent of the values for the plain plates.

The energy absorption to failure was 5,276,000 and 6,779,000 in-lb. for the two plain plates, Specs. No. 1 and 23, and among the plates with openings varied from 538,000 in-lb. for Spec. No. 3 to 1,569,000 in-lb. for Spec. No. 11. The energy absorption to failure for the plates with openings ranged from 9 to 26 percent of the values for the plain plates.

The maximum values of the energy to ultimate load and the energy to failure for the plates with square openings were less than the minimum value for the plates with the other two shapes of opening.

Fig. 47 shows the comparison of the energy absorption to failure and the percentage of reinforcement as well as the net cross-section area of the plate. The plotted points in this figure fall into two bands, a group of lower values of energy absorption for the plates with square openings and a widely scattered group of higher values for the plates with the other two shapes of opening, the square opening with rounded corners and the circular opening. An increase in the percentage of reinforcement for the plates with square openings brought about no significant change in the energy absorption to failure. The trend for the plates with the other shapes of openings is less discernible, but no sizeable increase or decrease in the energy absorption to failure resulted in the plates with square openings with rounded corners or the plates with circular openings when the percentage of reinforcement was increased.

The effect of the notch acuity of the different shapes of openings upon the ultimate strength of the plates with openings was found to be rather clearly defined. A similar relation was found for the energy absorption of the same plates, and Fig. 48 shows this relation. In general, the logarithm of the energy absorption to failure of the plates with openings decreased linearly with the logarithm of the ratio, R_O/R_N. The trend, however, was somewhat less clearly defined for the energy to failure than for the ultimate strength.

7. Effectiveness of the Reinforcement.

One purpose of the reinforcement is that of restoring as much as possible the properties of the plain plate. The ratio of the value of some particular property of the plate with an opening to the similar value of the plain plate may be called the efficiency with respect to the property under consideration. Table 5 tabulates the efficiencies of the various plates with openings with respect to general yielding, ultimate strength, and energy absorption. The shape of the opening as well as the type and amount of reinforcement is indicated for each specimen. The average of the values for the two plain plates was used as the basis for each comparison.

The values of the efficiencies in Table 5 indicate how adequate the reinforcement was in restoring the properties of the plain plate. Inasmuch as the average net stress at general yielding did not vary appreciably for the plates with openings, the efficiency with respect to the load and average net stress at general yielding did not vary through a very wide range. However, the ultimate strength and the energy absorption of the plates with openings were greatly affected by the shape of the opening and the type and amount of reinforcement.

Fig. 49 is a type of plot in which the efficiency with respect to two different variables can be compared. In this comparison of the efficiencies with respect to the ultimate load and the energy absorption to failure, the points plotted in the upper right-hand corner represent the specimens which gave the highest efficiencies. The specimens which gave the best performance were those with circular openings or with square openings with rounded corners, while the specimens with the worst performance included all those with square openings. Fig. 49 also indicates that the specimens which sustained the greatest ultimate load consistently absorbed the largest amount of energy to failure.

A plot similar to Fig. 49 is shown in Fig. 50, in which the efficiencies with respect to the ultimate strength and the energy absorption to failure are plotted. The specimens which sustained the highest ultimate strength absorbed the largest amount of energy to failure.

With the aid of Figs. 49 and 50, the specimens which gave the best performance can be selected. A line has been drawn which delineates those specimens whose efficiencies were greater than 80 percent with respect to ultimate load, 88 percent with respect to ultimate strength, and 15 percent with respect to energy absorption to failure. The performance of these superior plates with reinforced openings is described in Table 6. The following observation can be made concerning these specimens:

1. The nine plates which gave the best performance had either circular openings or square openings with rounded corners, and all had welded reinforcement around the opening.
2. Spec. No. 11 which gave the best performance and Specs. No. 5 and 18 the next best all had circular openings.
3. The nine best specimens included two with face bar reinforcement, three with insert plate reinforcement, and four with doubler plate reinforcement.

One interesting observation about the plates with square openings, either reinforced or unreinforced, is that their performance was worse in every case than that of the unreinforced plates with the circular opening and the square opening with rounded corners, Specs. No. 2 and 4, respectively.

8. <u>Unit Strain Concentration in the Plates in the Region around the Opening</u>

Many SR-4 electric strain gages were located in one quadrant of the plates with openings, the quadrant lying between the vertical and the horizontal centerlines of the specimen. Elastic strain concentration curves based on the data of these observations are shown in Figs. 52 to 72, inclusive. The vertical direction in these diagrams coincides with the direction of the tension load. The sketch in Fig. 51 explains the manner in which the unit strain concentration is presented for the following locations:

1. For the plates with circular openings, the horizontal certerline, the unit strain being taken in the vertical direction.
2. For the plates with square openings with rounded corners, a horizontal line passing through the point of tangency between the vertical edge of the opening and the corner arc, the unit strains being taken in the vertical direction.
3. For the plates with square openings, a horizontal line through the corner of the opening, the unit strains being taken in the vertical direction.
4. The circumference of the opening for all specimens, the unit strains being taken in a direction tangential to the edge of the opening.

The strain measurements shown near the corner of the square opening in plates with square openings were actually located 1/4-in. from the corner as shown in Figs. 7 to 10. Therefore, the readings of these gages would not determine the maximum unit strain which would occur very near to the corner.

The unit strain concentration factors were computed from the SR-4 strain gage readings in the following manner. The total load on the specimen was plotted against the SR-4 strain reading at each of the gage points. The curve through these plotted points in the elastic range was approximately a straight line. The slopes of the various curves were compared with the slope of the same plot in the region of the plate remote from the opening. Thus, the ratios determined by this comparison were in reality the unit strain concentration as compared to the unit strain in the region of the plate undergoing a uniform stress distribution across the plate width.

This approach was necessary because of the nature of the SR-4 readings. First, these readings when plotted along with the load on the specimen gave a curve from which many of the plotted points at lower loads deviated considerably. This effect could probably be attributed to the residual stresses present in the specimen because of flame-cutting and welding. The direct tension increasing, these effects became proportionally less than at lower loads. Second, some of the SR-4 gages indicated an early departure from linearity as the result of yielding at loads varying from approximately 30,000 to 60,000 lb. for all the specimens.

Each shape of opening possessed the same characteristic form of strain concentration curve for unit strains in the vertical direction whose shape was only somewhat affected by the type of reinforcement. The shape of the strain concentration curve for circumferential unit strains was somewhat similar for the plates with square openings with rounded corners and for those with square openings, but was different for the plates with circular openings.

In Figs. 52, 59, and 66, the unit strain concentrations are shown for plates with unreinforced openings. The unit strain along the circumference of the opening in Spec. No. 2 with a circular opening (see Fig. 52) changed gradually from tension at the horizontal certerline to compression at the vertical centerline. For Spec. No. 4 with a square opening with rounded corners and Spec. No. 3 with a square opening (see Figs. 59 and 66), the unit strain increased sharply from tension at the horizontal certerline to a much larger tension value at the corner and then dropped abruptly to compression as the corner was passed. The shapes of the unit strain concentration along the circumference of the opening in the plates with and without reinforcement were similar for each shape of opening.

The shape of the unit strain concentration curves on the horizontal sections of the specimens will now be examined. The shapes of the unit strain concentration curves along the horizontal section through the opening were similar, in general, except for small differences characteristic of the type of reinforcement. In the case of the plates with a single doubler plate and some of the specimens with insert plates, a second point of high unit strain concentration appeared at the outer edge of the reinforcement.

The greatest difference then in the shape of the unit strain distribution curves on the various sections of the specimens occurred along the circumference of the opening where the strain gradient was much steeper in the plates with square openings with rounded corners and the plates with square openings than in the plates with circular openings. In a very short distance along the circumference of the opening in the vicinity of the corner of the opening, the unit strains for the two types of square opening decreased very rapidly on both sides of the point of the maximum tension value. The slope of the strain gradient on each side of the point of the maximum tension value was very gradual in the case of the circular opening.

The addition of arc-welded reinforcement changed the characteristics of the unit strain concentration curves in two important respects, as compared to the curves for the unreinforced plates:

1. The magnitudes of the unit tension strains in the vertical direction along the horizontal section through the opening were increased near the edge of the opening and reduced near the edge of the plate.
2. A second maximum, in some cases greater than the concentration value at the circumference, appeared in the region of the weld between the doubler plate or the insert plate reinforcement and the body plate.
3. The unit strain concentration at the edge of the plate was reduced.
4. The magnitudes of the unit compression strains along the vertical centerline in the region of the opening were reduced.

The effect of the reinforcement was similar for all three shapes of opening.

The unit strain concentration in the region of the opening has been discussed so far in a purely qualitative manner. The closer examination of the behavior and the magnitudes of the unit strain concentrations in the various plates suggest, that the method of fabrication of the specimens is responsible for some of the discrepancies. The introduction of shrinkage stresses along the edges of the specimens by the flame-cutting process was followed by the addition of other residual stresses by the welding process. After welding, the specimens were observed to have slightly dished shape in the vicinity of the opening. This dished shape was reduced to a flat plane during the course of the test only after extensive yielding had progressed across the width of the plate at a load far in excess of the loads at which the SR-4 gages were read. It can be deduced that these residual stress effects from the fabrication process would materially affect the unit strain concentration resulting only from the application of load.

The SR-4 gage giving the highest unit strain readings was located on a flame-cut edge in the case of the unreinforced plates and the plates with insert plate reinforcements, on a weld bead in the case of the plates with doubler plate reinforcement, and on a 1/4-in. face bar immediately opposite two fillet-weld beads in the case of the plates with face bar reinforcement. The residual strains resulting from the combination of flame-cutting and welding would introduce uncertainty into the readings of these gages.

9. Deformation and Fracture of Plates with Openings.

The twenty-three specimens, both the plain plates and the plates with openings, failed with a completely ductile fracture in the room temperature tests reported herein. Some description of the manner of failure will be given in the following paragraphs.

The plots of the load against the average elongation on the 36-in. gage length shown in Figs. 35 to 39, inclusive, were all very much the same in shape. The over-all behavior of the rather large region between the 36-in. gage lines was similar in all the specimens. However, in much smaller regions, especially around the opening, the manner of deformation differed considerably among the various specimens.

Table 7 compares the load at which general yielding of the plates began with the load at which yielding first appeared as evidenced by Luders lines. When the location of the first Luders lines is shown inside the opening in Table 7, the Luders lines appeared on the circumference of the opening. These Luders lines appeared in Specs. No. 8, 10, and 22 at loads equal to about 20 percent of the load at general yielding, in six other specimens at, or just beyond the load at general yielding, and in the remaining plates with openings at a load between 50 and 100 percent of the load at general yielding. The results of the SR-4 gage readings recorded small amounts of plastic strain, at loads between 30,000 and 60,000 lb. These various observations found small amounts of plastic deformation occurring in the plates in the region of the opening at loads below that necessary to cause general yielding of the specimen.

The sketches in Table 7 show the points where the maximum unit strain concentration occurred and the first Luders lines appeared. In general, it may be seen that the first Luders lines were located at, or very close to the points of maximum unit strain concentration.

Figs. 52 to 72 showed that the shape of the unit strain concentration curves around the circumference of the opening was somewhat alike for the plates with square openings or square openings with rounded corners, but completely different for the plates with circular openings. These differences in strain concentration were also indicated by the Stresscoat analysis of the region around the opening. Fig. 73 shows the results of this analysis for the three shapes of openings in plates without reinforcement. The cracking of the Stresscoat delineated the areas of high strains for each load. It may be seen in Fig. 73 that the extent of the crack pattern has been shown for each load and that the region of high strain covered the least area in the plates with the square opening and the most area in the plates with the circular opening. The area of the highly strained regions around opening increased as the corner radius of the opening increased.

After eleven of the plates with openings had passed the load at which general yielding began, the circumference of the opening in the two regions of compression strain began to buckle laterally. Photographs of this buckled edge of the opening are shown in Fig. 74 for plates with the different types of reinforcement. The direction of this lateral deflection was always opposite to the direction in which the specimen as a whole was slightly dished by the distortion resulting from the welding. The distance between the nodal points of the buckled edge of the opening was greatest for the plates with square openings and least for those with circular openings and varied from a length equal to about half of the total width of the specimen in the case of the square opening to a length somewhat longer than the width of the opening in the case of the circular opening.

The following plates buckled laterally: without reinforcement, Specs. No. 2, 3, and 4; with doubler plate reinforcement, Specs. No. 11 to 16, inclusive; and with insert plate reinforcement, Specs. No. 20 and 22. All of the specimens with doubler plate reinforcement and two of the six specimens with insert plate reinforcement buckled laterally during loading. None of the plates with face bar reinforcement buckled laterally.

A comparison of the load on the specimen and the maximum deflection of this buckled edge is shown in Fig. 75. The lateral deflection increased as the load was increased. When the curves in Fig. 75 were extrapolated back to zero deflection, they were found to intersect the vertical axis of the diagram at a load approximately equal to the load at general yielding.

Five of the eleven specimens which buckled laterally had ultimate strengths exceeding 60,000 psi. Four of the nine specimens listed in Table 6 as giving the best performance buckled laterally. No indication was found that this lateral buckling of the edges of the opening under compression strain had any significant effect upon the ultimate strength or the energy absorption to failure of the plates with openings.

The first crack or the beginning of fracture appeared at the maximum load in the plates with openings, and the load thereafter fell off as the fracture traversed the width of the plate. An exception to this behavior occurred in Specs. No. 8 and 13, in which small cracks appeared at the corners of the square opening at 97 percent of the ultimate load. The sketches in Table 7 show that the fracture began at the points of maximum unit strain concentration in every specimen except Specs. No. 7, 9, and 22, in which the initial fracture occurred by shear in the weld between the body plate and the reinforcement at a point adjacent to the location of the maximum unit strain concentration. The fracture started in all the plates with openings at, or very near the point of maximum strain concentration. Moreover, the first Luders lines appeared in the same regions.

Photographs of the specimens after fracture are shown in Figs. 76 to 79, inclusive. The fracture began at the edge of the opening, passed through the reinforcement at its narrowest width, and then continued horizontally across the plate. An exception to this behavior occurred in Specs. No. 7, 9, and 22 which failed by shear in the weld between the body plate and the outer edge of the reinforcement. In these three plates, the reinforcement was left intact and the fracture passed around it. In none of the tests did the specimen break completely in two halves, and a small part of the cross-section was always left intact.

After the fracture had begun to traverse the width of the plate, observations of the load on the specimen and the total length of the fracture were taken at intervals until the fracture reached the outer edge of the specimen. The readings of the load and the progress of the fracture were plotted as shown in Fig. 80 for eighteen of the plates with openings. It was found that the load on the specimen decreased approximately in a linear manner with the total length of the fracture. In a rather crude way this data indicated that the load which the partly fractured specimen could carry was proportional to the total remaining unbroken cross-section area of the specimen.

10. Brief Summary of the Experimental Results of the Tests of Plain Plates and Plates with Openings.

Before the results of the tests of plain plates and of plates with openings are discussed, the more important experimental observations of the investigation will be summarized. They are as follows:

1. All the plain plates and the plates with openings sustained completely ductile fractures in tests at room temperature.

2. The average elongation to failure on the 36-in. gage length for the plates with openings varied from 16 to 36 percent of the average of the values for the two plain plates. The plain plates underwent approximately the same amount of elongation to failure as the much smaller tensile coupons.
3. All the plates with circular openings or with square openings with rounded corners underwent a greater average elongation to failure on the 36-in. gage length than any of the plates with square openings.
4. The average net stress at general yielding of the plates with openings ranged from 36,360 to 45,500 psi and may be compared with the average for the plain plates of 42,880 psi and with the average for the tensile coupon tests of the 1/4-in. plates of 44,500 psi.
5. The ultimate load sustained by the plates with openings increased in direct proportion to the logarithm of the average elongation to ultimate load on the 36-in. gage length.
6. The ultimate load sustained by the plates with openings varied from 61 to 95 percent of the ultimate load sustained by the two plain plates.
7. The ultimate strength of the plates with openings varied from 47,690 to 67,800 psi or from approximately 75 to 100 percent of the ultimate strength of the plain plates and the tensile coupons.

8. The ultimate load and the ultimate strength of the plates with openings increased in the order of the shape of the opening as follows: square, square with rounded corners, and circular. The strength was affected only to a small degree by the type and the amount of reinforcement.

9. The ultimate load increased, but the ultimate strength decreased for the plates with openings as the percentage of reinforcement increased. The rate of increase or decrease was about the same for the three shapes of openings.

10. The ultimate strength of the plates with openings decreased in a linear manner with the logarithm of the ratio, R_O/R_N, where R_O was the half-width of the opening and R_N the corner radius of the opening.

11. The energy absorption to ultimate load of the plates with openings ranged from 6 to 34 percent of the same values for the plain plates, while the energy absorption to failure for the plates with openings varied from 9 to 26 percent of the same values for the plain plates.

12. No clear relationship between the energy absorption to failure and the percentage of reinforcement was found for the plates with openings. No sizeable change in the energy absorption to failure was brought about by increasing the percentage of reinforcement.

13. The logarithm of the energy absorption to failure of the plates with openings decreased linearly with the logarithm of the ratio, R_O/R_N.

14. The specimens which gave the best performance with respect to their strength and energy-absorbing capacity were those plates with circular openings or with square openings with rounded corners, while the plates with square openings consistently gave the worst performance.

15. The nine plates with openings giving the best performance included two specimens with face bar reinforcement, three with insert plate reinforcement, and four with doubler plate reinforcement.

16. The performance of all the plates with square openings, either reinforced or unreinforced, was inferior to that of the unreinforced plates with circular openings or square openings with rounded corners.

17. The plates with openings which sustained the highest ultimate load and the highest ultimate strength also absorbed the greatest amount of energy to failure.

18. In a very short distance along the circumference of the opening in the vicinity of the corner of the opening, the unit strains for the two types of square opening decreased very rapidly on both sides of the point of the maximum tension value. The slope of the strain gradient on each side of the point of the maximum tension value was very gradual in the case of the circular opening.

19. The major effect upon the unit strain distribution of adding reinforcement to the plates with unreinforced openings

was to increase the magnitudes of the unit strains in the region of the opening and reduce the magnitudes near the outer edge of the plate.

20. The residual strains resulting from the fabrication process made any quantitative analysis of the observed unit strains difficult.

21. Luders lines indicating local yielding appeared in some of the plates with openings at loads equal to approximately 20 percent of the load required to bring about general yielding of the specimen.

22. The area of the highly strained regions around the opening increased as the corner radius of the opening increased.

23. The location of the first Luders lines and the point where fracture started were at, or very near, the points on the circumference of the opening where the maximum unit strains were measured.

24. No indication was found that the lateral buckling of the edges of the opening under compression strain had any significant effect upon the ultimate strength or the energy absorption to failure of the plates with openings.

VI. DISCUSSION OF TEST RESULTS

1. General Yielding, Ultimate Strength, and Energy Absorption of Plain Plates and Plates with Openings.

Plastic deformation occurred at low loads in small regions of the plates with openings in the vicinity of the corners of the opening, where the highest unit strain concentration was found. Since these regions were very small in area compared to the whole specimen as shown in Fig. 73, the effect of this localized yielding upon the slope of the load-average elongation curve in its early stages was not very great.

While the highly strained regions in the plates with circular openings were located at the two opposite sides of the opening, there were four regions of high strain at the four corners of the two types of square opening. Although the initiation of yielding occurred in quite a different manner in the plates with square openings and square openings with rounded corners as compared to the plates with circular openings, the effect of this localized yielding in producing a point of general yielding in the specimen as a whole was apparently much the same for all three shapes of opening, because all these plates sustained an average net stress at general yielding of the whole plate which was equal to, or somewhat less than the average stress at which the plain plates yielded.

The ultimate strength of the plates with openings decreased in a linear manner as shown in Fig. 45 with the logarithm of the ratio, R_O/R_N, where R_O was the half-width of the opening and R_N the corner radius of the opening. A similar relation between the ultimate strength in the wide-plate tests (1) and the acuity of their notches was found and is shown in Figs. 81, 82, and 83. In these tests the thickness of the plate was 3/4 in. and the ratio of the width of the opening to the width of the specimen one-fourth, while the width of the specimens was varied from 12 to 72 in. The notch radius remained constant. A plot for a similar series of tests (2) is shown in Fig. 84. The thickness and the width

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1, 2. These references appear in the Bibliography of Appendix A.

of the plate remained constant for these last tests as well as the value of one-fourth for the ratio of the width of the opening to the width of the specimen. The notch radius was varied. The same relation between the ultimate strength and the acuity of the opening was found in these wide-plate tests as was observed in the tests reported herein. Unfortunately, other tests of structural steel plates in which the type of specimen more nearly resembled the plates with square and circular openings were not found.

It is interesting that in Figs. 81 to 84, inclusive, the plotted points fell into a band, and the specimens with the greater percentages of cleavage in the fracture were located at the bottom of the band and the specimens with smaller percentages of cleavage at the top of the band.

The ultimate strength of the plates with openings was related to the acuity of the notch. A somewhat similar relation was found in Fig. 48 for the energy absorbed to failure. The logarithm of the energy absorption to failure decreased in a linear manner with the logarithm of the ratio, R_O/R_N. Since the values of the energy absorption for the wide-plate tests (1) depended upon the size of the specimens and could not easily be reduced to a common basis of comparison and, moreover, because the energy absorption to failure was not reported for the other quoted tests (2), no corroboration of these findings of this investigation could be made.

The relations in Figs. 45 and 48 between the ultimate strength and the energy absorption to failure on one hand and the acuity of the opening on the other hand indicated that the notch-effect of the opening was more effective in reducing the energy absorption than the ultimate strength. The ultimate strength of the plates with openings varied between approximately 75 and 100 percent of the strength of the plain plates, but the energy absorption to failure of the former was only 9 to 26 percent of the same values for the latter. While the ultimate strength of the plates with openings approached that of the plain plate, the energy absorption to failure of the former never was but a small fraction of the energy absorption of the latter.

The relations expressed in Figs. 45 and 48 provide a means of predicting the potential ultimate strength and the energy absorption of specimens with the same relative width of opening and the same types of reinforcement as those already tested, but with different shapes of opening. In particular, these figures could be used for plates with square openings with rounded corners where the corner radius had a value other than D/8, the radius used in these tests.

Some correlation was found between the distribution of the unit strains measured in the elastic range of the steel and the final fracture of the specimen. The points on the circumference of the opening where the maximum unit strain in the elastic range of the specimen was measured were also the same points where the first Luders lines appeared and at, or near which the fracture subsequently was initiated.

The ultimate strength of the best plates with openings was equal to that of the plain plates and decreased for the poorer plates with openings in a logical manner as the acuity of the opening increased. It seemed reasonable to conclude that the initial residual strains and distortions from fabrication by welding had no significant effect upon the ultimate strength of the plates with arc-welded reinforcement.

2. Effectiveness of the Reinforcement.

When the investigation was begun, two criteria were arbitrarily selected as the means of determining the performance of the plates with openings, the ultimate strength or ultimate load and the energy absorption to failure. The results of this investigation indicated that the plates with openings which sustained the highest ultimate loads and the highest ultimate strength also absorbed the greatest amount of energy to failure. This last statement must be carefully limited to apply only to plates undergoing a completely ductile type of fracture.

The design of the nine specimens which gave the best performance will be examined. The three types of reinforcement were represented in the three best specimens, Specs. No. 5, 11, and 18, and these three plates all had circular openings. However, plates with square openings with rounded corners came closely behind these in performance rating. It is interesting that none of the three specimens which failed by shear in the weld at the outer edge of the reinforcement were included in this list of the best specimens. The limited number of tests made suggested that possibly the best plates with openings were those in which the combined effect of the shape of the opening and the type and amount of reinforcement was just sufficient to prevent a shear failure at the outer boundary of the reinforcement. This conclusion may be contradicted by subsequent tests.

The performance of all the plates with square openings was poor in comparison with the plates with the other two shapes of openings. In fact, the results of these tests showed that an unreinforced opening with a circular shape or a square shape with rounded corners having a corner radius of D/8 was to be preferred to any of the square openings, whether reinforced or unreinforced.

Some comment should be made about Spec. No. 19 which had the lowest ultimate strength of all the plates. A sketch of this specimen is shown in Fig. 5. It seems possible that the net width of the reinforcement at the corners was reduced in this specimen beyond the minimum desirable width. Perhaps, an insert plate of larger diameter would have substantially increased the strength of this specimen.

The ultimate load increased, but the ultimate strength decreased as the percentage of reinforcement was increased. The greater the percentage of reinforcement, the less efficient the reinforcement became. This result of these tests was in accord with the predictions of theory (16).

No clear relationship between the energy absorption to failure and the percentage of reinforcement was found for the plates with openings. No sizeable change in the energy absorption to failure was brought about by increasing the percentage of reinforcement. None of the types of reinforcement used in these tests was effective in increasing appreciably the energy absorption of an unreinforced plate with an opening.

From the result of these tests, some estimate could be made of the best possible performance of a plate with a reinforced opening. While the average net stress at initial yielding of the plate as a whole and at ultimate strength would approach, or equal the same values for the plain plate, the energy absorption to failure would probably not exceed 15 or 20 percent of that of the plain plate.

VII. CONCLUSIONS

Room temperature tests have been made of two plain plates without openings, three plates with unreinforced openings, and eighteen plates with arc-welded reinforcement around the opening. Three types of welded reinforcement were investigated: face bars, single doubler plates, and insert plates. The plates without reinforcement and those with each type of reinforcement were fabricated with three different shapes of opening: circular, square with rounded corners, and square with sharp corners. No two of the twenty-one plates with openings were alike. Duplicate tests of any of these specimens would undoubtedly have given somewhat different results.

All these tests resulted in completely ductile fractures, and all conclusions must be limited to this kind of fracture. The results of the present series of tests appear to justify the following tentative conclusions with respect to the plates with openings:

1. The opening was many times as effective in decreasing the energy absorption of the plates as their ultimate strength. While the ultimate strength of the plates with openings varied from 75 to 100 percent of the values for the plain plates and the tensile coupons, the energy absorption to failure varied from only 9 to 26 percent of the value for the plain plates.

2. Arc-welded reinforcement increased the ultimate strength of the plates, but brought about no noticeable change in their energy absorption.
3. The openings and the reinforcement did not appreciably influence the general yielding. Local yielding occurred at very low loads, but the average net stress at general yielding of the plates as a whole was approximately equal to, or slightly less, than the tensile coupon yield point.
4. The specimens which gave the best performance with respect to their strength and energy-absorbing capacity were those plates with circular openings or with square openings with rounded corners. The nine plates giving the best performance included two specimens with face bar reinforcement, three with insert plate reinforcement, and four with doubler plate reinforcement.

VIII. ACKNOWLEDGEMENT

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TABLE I

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

Plate No.	Thick-ness in.	Upper Yield Point psi	Ultimate Strength psi	Elongation in 8-in. per cent	Reduction of Area Per cent
10	1	32,800	61,100	32.6	55.6
25	1/2	36,500	61,100	31.2	54.0
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
19	1/4	44,000	65,900	28.2	51.7
20	1/4	44,700	66,000	28.4	49.5
21	1/4	44,500	66,000	28.6	50.2
22	1/4	43,800	65,600	28.9	49.6
23	1/4	45,400	66,100	30.4	49.8
24	1/4	44,800	65,800	29.3	49.6

Tensile properties are average of results of two tests of ASTM standard flat tensile coupons.

TABLE 2

DESCRIPTION OF SPECIMENS WITH 1/4-IN. BODY PLATE*

Spec. No.	Opening: Shape	Opening: Corner Radius in.	Size of Reinforcement	Percentage of Reinforcement	Cross-Section Area - Sq.in.: Gross	Cross-Section Area - Sq.in.: Net
			Plain Plates			
1	None	- -	- -	100	9.07	9.07
23	None	- -	- -	100	9.14	9.14
			Plates with Unreinforced Openings			
2	Circular	- -	- -	0	9.21	6.92
3	Square	1/32	- -	0	9.18	6.82
4	Square	1-1/8	- -	0	9.15	6.87
			Plates with Openings Reinforced by a Face Bar			
5	Circular	- -	2"x1/4"	40	9.11	7.76
6	Circular	- -	1"x1/4"	17	9.15	7.25
7	Square	1/4	2"x1/4"	40	9.11	7.72
8	Square	3/16	1"x1/4"	16	9.02	7.13
9	Square	1-1/8	2"x1/4"	40	9.13	7.74
10	Square	1-1/8	1"x1/4"	16	9.15	7.22
			Plates with Openings Reinforced by a Single Doubler Plate			
11	Circular	- -	18"D.x1/4"	102	9.11	9.13
12	Circular	- -	13-1/2"D.x1/4"	50	9.14	7.99
13	Square	1/32	18"x18"x1/4"	104	9.17	9.21
14	Square	1/32	13-1/2"x13-1/2"x1/4"	51	9.14	8.02
15	Square	1-1/8	18"x18"x1/4"	103	9.13	9.16
16	Square	1-1/8	13-1/2"x13-1/2"x1/4"	52	9.13	8.01
			Plates with Openings Reinforced by an Insert Plate			
17	Circular	- -	12-3/4"D.x1/2"	39	9.11	7.71
18	Circular	- -	10-1/2"D.x1"	50	9.13	8.08
19	Square	1/32	15"D.x1/2"	33	9.04	7.55
20	Square	1/32	12-3/4"x12-3/4"x1/2"	39	9.13	7.72
21	Square	1-1/8	15"D.x1/2"	62	9.02	8.17
22	Square	1-1/8	12-3/4"x12-3/4"x1/2"	39	9.04	7.66

* All tests made at room temperature.

TABLE 3

LIST OF PLATES USED FOR
FABRICATION OF EACH SPECIMEN

Spec. No.	No. of Plate Used for Body Plate*	No. of Plate Used for Reinforcement*
1	18	
2	24	
3	24	
4	23	
5	20	20
6	23	23
7	18	18
8	17	17
9	19	19
10	18	18
11	22	21
12	22	21
13	21	21
14	20	21
15	21	21
16	20	21
17	16	25
18	22	10
19	17	25
20	19	25
21	17	25
22	19	25
23	16	

* Mechanical properties of plates given in Table 1.
Sketches of specimens in Figs. 2-5, inclusive.

TABLE 4

STRENGTH AND ENERGY ABSORPTION OF 1/4-IN. PLAIN PLATES AND PLATES WITH OPENINGS

Spec. No.	Opening: Shape	Opening: Corner Radius in.	Percentage of Reinforcement	Test. Temp. Deg. F.	General Yielding: Load lbs.	General Yielding: Average Stress psi, Gross	General Yielding: Average Stress psi, Net	Ultimate Strength: Load lbs.	Ultimate Strength: Average Stress psi, Gross	Ultimate Strength: Average Stress psi, Net	Energy Absorption in 1000's, in-lb.: To Ultimate Load	Energy Absorption in 1000's, in-lb.: To Failure
1	None	- -	100	81	380,000	42,200	42,220	588,500	65,390	65,390	4,018	5,276
23	None	- -	100	76	390,000	43,330	43,330	583,000	64,780	64,780	4,062	6,779
2	Circular	- -	0	76	291,500	32,400	43,200	440,000	48,900	65,150	1,136	1,164
3	Square	1/32	0	72	292,000	32,500	43,250	357,500	39,800	52,900	338	538
4	Square	1-1/8	0	78	292,000	32,500	43,250	421,000	46,700	62,350	717	899
5	Circular	- -	40	74	324,000	36,000	42,500	517,000	57,400	67,800	1,277	1,420
6	Circular	- -	17	73	324,000	36,000	45,500	457,000	50,800	64,200	725	910
7	Square	1/4	40	75	322,000	35,800	42,230	397,000	44,100	52,070	422	750
8	Square	3/16	16	74	288,000	32,000	40,420	391,500	43,500	54,950	447	780
9	Square	1-1/8	40	72	319,000	35,500	41,840	451,000	50,100	59,150	747	1,063
10	Square	1-1/8	16	75	313,000	34,800	43,930	467,000	51,900	65,540	1,214	1,504
11	Circular	- -	102	75	360,000	40,050	40,050	555,000	61,670	61,670	1,358	1,569
12	Circular	- -	50	73	331,500	36,900	42,100	488,000	54,200	62,000	771	983
13	Square	1/32	104	76	337,500	37,500	37,500	451,500	50,170	50,170	387	728

TABLE 4 (Cont.)

STRENGTH AND ENERGY ABSORPTION OF 1/4-IN. PLAIN PLATES AND PLATES WITH OPENINGS

Spec. No.	Opening		Percentage of Reinforcement	Test. Temp. Deg. F.	General Yielding			Ultimate Strength			Energy Absorption in 1000's in-lb.	
	Shape	Corner Radius in.			Load lbs.	Average Stress psi		Load lbs.	Average Stress psi		To Ultimate Load	To Failure
						Gross	Net		Gross	Net		
14	Square	1/32	51	71	300,000	33,300	38,100	406,000	45,100	51,600	328	621
15	Square	1-1/8	103	76	362,000	40,220	40,220	522,500	58,060	58,060	729	1,099
16	Square	1-1/8	52	73	300,000	33,300	38,100	487,000	54,100	61,900	779	1,154
17	Circular	- -	39	74	322,000	35,800	41,880	495,000	55,000	64,390	1,196	1,361
18	Circular	- -	50	75	340,000	37,800	43,200	521,500	58,000	66,300	1,268	1,400
19	Square	1/32	33	76	301,000	33,400	39,660	362,000	40,200	47,690	229	548
20	Square	1/32	39	72	320,000	35,600	41,620	427,000	47,500	55,540	545	836
21	Square	1-1/8	62	77	300,000	33,300	36,360	478,000	53,100	57,940	1,155	1,484
22	Square	1-1/8	39	73	319,000	35,500	41,490	437,000	48,600	56,840	600	974

TABLE 5

EFFICIENCY OF PLATES WITH OPENINGS AS COMPARED WITH PLAIN PLATES

Spec. No.	Opening		Reinforcement	Efficiency Compared to Plain Plate - Percent					
				General Yielding		Ultimate Strength		Energy Absorption	
	Shape	Corner Radius in.		Load	Average Stress	Load	Average Stress	To Ult. Load	To Failure
			Plates with Unreinforced Openings						
2	Circular	- -	- -	76	101	75	100	28	19
3	Square	1/32	- -	76	101	61	82	8	9
4	Square	1-1/8	- -	76	101	72	96	18	15
			Plates with Openings Reinforced by a Face Bar						
5	Circular	- -	2"x1/4" Face Bar	84	100	88	104	32	24
6	Circular	- -	1"x1/4" Face Bar	84	106	78	99	18	15
7	Square	1/4	2"x1/4" Face Bar	84	99	68	80	10	12
8	Square	3/16	1"x1/4" Face Bar	77	95	67	84	11	13
9	Square	1-1/8	2"x1/4" Face Bar	83	98	77	91	18	18
10	Square	1-1/8	1"x1/4" Face Bar	81	103	80	101	30	25
			Plates with Openings Reinforced by a Single Doubler Plate						
11	Circular	- -	18"Dx1/4" Doubler	94	94	95	95	34	26
12	Circular	- -	13-1/2"Dx1/4" Doubler	86	98	83	95	19	16

TABLE 5 (Cont.)

EFFICIENCY OF PLATES WITH OPENINGS AS COMPARED WITH PLAIN PLATES

Spec. No.	Opening: Shape	Opening: Corner Radius in.	Reinforcement	Efficiency Compared to Plain Plate - Percent: General Yielding: Load	General Yielding: Average Stress	Ultimate Strength: Load	Ultimate Strength: Average Stress	Energy Absorption: to Ult. Load	Energy Absorption: to Failure
			Plates with Openings Reinforced by a Single Doubler Plate						
13	Square	1/32	18"Sq.x1/4" Doubler	88	88	77	84	10	12
14	Square	1/32	13-1/2"Sq.x /4" Doubler	78	89	69	86	8	10
15	Square	1-1/8	18"Sq.x1/4" Doubler	94	94	89	89	18	18
16	Square	1-1/8	13-1/2"Sq.x1/4" Doubler	78	89	83	95	19	19
			Plates with Openings Reinforced by an Insert Plate						
17	Circular	--	12-3/4"Dx1/2" Insert	84	98	84	99	30	22
18	Circular	--	10-1/2"Dx1" Insert	88	101	89	102	31	23
19	Square	1/32	15"Dx1/2" Insert	78	93	62	73	6	9
20	Square	1/32	12-3/4"Sq.x1/2" Insert	83	97	73	85	14	14
21	Square	1-1/8	15"Dx1/2" Insert	78	85	82	89	29	25
22	Square	1-1/8	12-3/4"Sq.x1/2" Insert	83	97	75	87	15	16

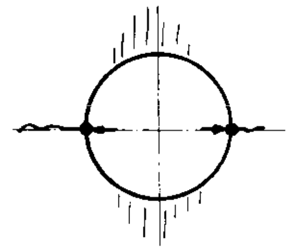
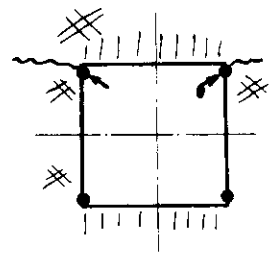
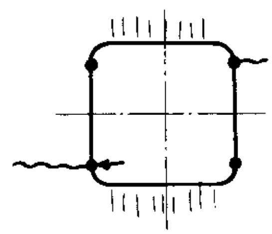
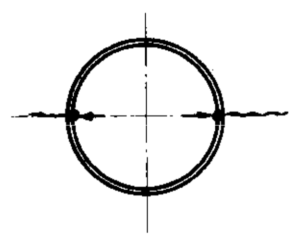
TABLE 6

TYPES OF REINFORCEMENT GIVING THE GREATEST EFFICIENCIES FOR PLATES WITH OPENINGS SUSTAINING COMPLETELY DUCTILE FRACTURES

Spec. No.	Shape of Opening	Reinforcement	Percentage of Reinforcement	Efficiency Compared to Plain Plate–Per			
				Load at general Yielding	Ultimate Load	Ultimate Strength	Energy Failur
5	Circular	2"x1/4" Face Bar	40	84	88	104	24
10	Square, Rounded Corners	1"x1/4" Face Bar	16	81	80	101	25
11	Circular	18"Dx1/4" Doubler Plate	102	94	95	95	26
12	Circular	12-1/2"Dx1/4" Doubler Plate	50	86	83	95	16
15	Square, Rounded Corners	18"Sq.x1/4" Doubler Plate	103	94	89	89	18
16	Square, Rounded Corners	13-1/2"Sq.x1/4" Doubler Plate	52	78	83	95	19
17	Circular	12-3/4"Dx1/2" Insert Plate	39	84	84	99	22
18	Circular	10-1/2"Dx1" Insert Plate	50	88	89	102	23
21	Square, Rounded Corners	15"Dx1/2" Insert Plate	62	78	82	89	25
	Maximums for all Specimens		103	94	95	104	26

TABLE 7

GENERAL YIELDING AND FRACTURES OF PLATES WITH OPENINGS

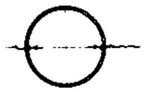
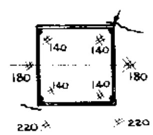
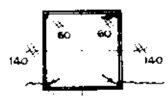
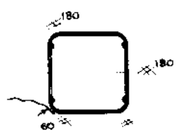
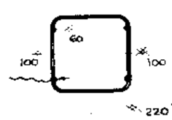
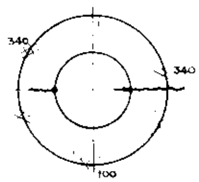
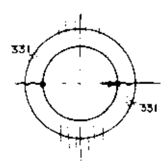
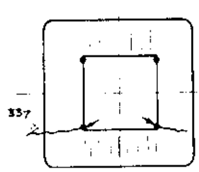
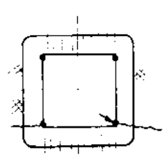
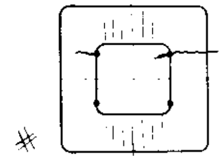
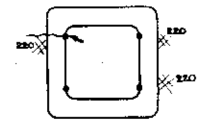
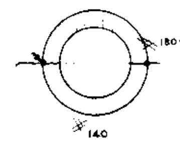
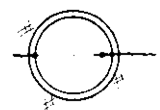
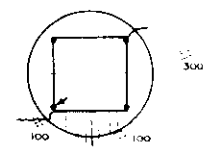
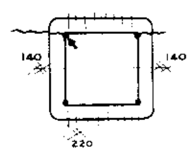
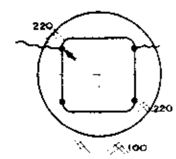
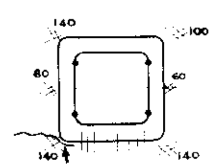
Spec. No.	Load in Kips at: First Luders Line	Load in Kips at: General Yielding	Load in Kips at: First Crack	Load in Kips at: Ultimate Load	Location of First Luders Lines, First Crack, Maximum Unit Strain Concentration, and Lateral Buckling*
2	291.5	291.5	440.0	440.0	
3	220.0	292.0	357.5	357.5	
4	280.0	292.0	421.0	421.0	
5	324.0	324.0	517.0	517.0	

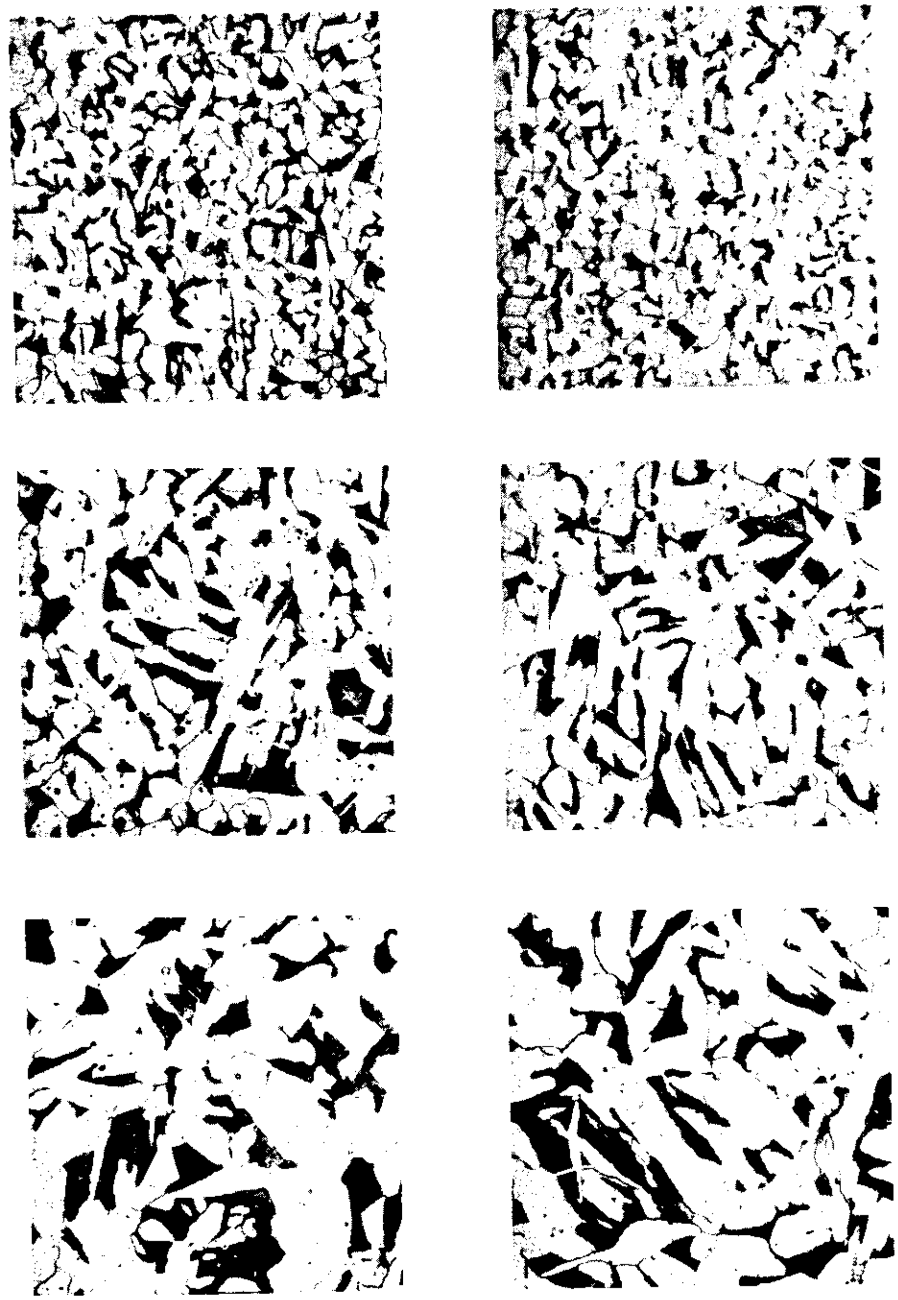
* Legend:

- ● 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 7 (cont.)

GENERAL YIELDING AND FRACTURES OF PLATES WITH OPENINGS

Spec. No.	Load in Kips at First Luders Line	Load in Kips at General Yielding	Load in Kips at First Crack	Load in Kips at Ultimate Load	Location of First Luders Lines, First Crack, Maximum Unit Strain Concentration, and Lateral Buckling*
6	324.0	324.0	457.0	457.0	
7	140.0	322.0	397.0	397.0	
8	60.0	288.0	380.0	391.5	
9	180.0	319.0	451.0	451.0	
10	60.0	313.0	467.0	467.0	
11	100.0	360.5	555.0	555.0	
12	331.5	331.5	488.0	488.0	
13	337.5	337.5	440.0	451.5	
14	220.0	300.0	406.0	406.0	
15	362.0	362.0	522.5	522.5	
16	220.0	300.0	487.0	487.0	
17	140.0	322.0	495.0	495.0	
18	260.0	340.0	521.5	521.5	
19	100.0	301.0	362.0	362.0	
20	140.0	320.0	427.0	427.0	
21	100.0	300.0	478.0	478.0	
22	60.0	319.0	437.0	437.0	



1/4-In. Plate

1/2-In. Plate

1-In. Plate

Core   Rim

Fig. 1. Microstructures of Typical Plates of Each Thickness Used for Specimens. Sections Taken Parallel to Direction of Rolling. Magnification 200X. Nital Etch.

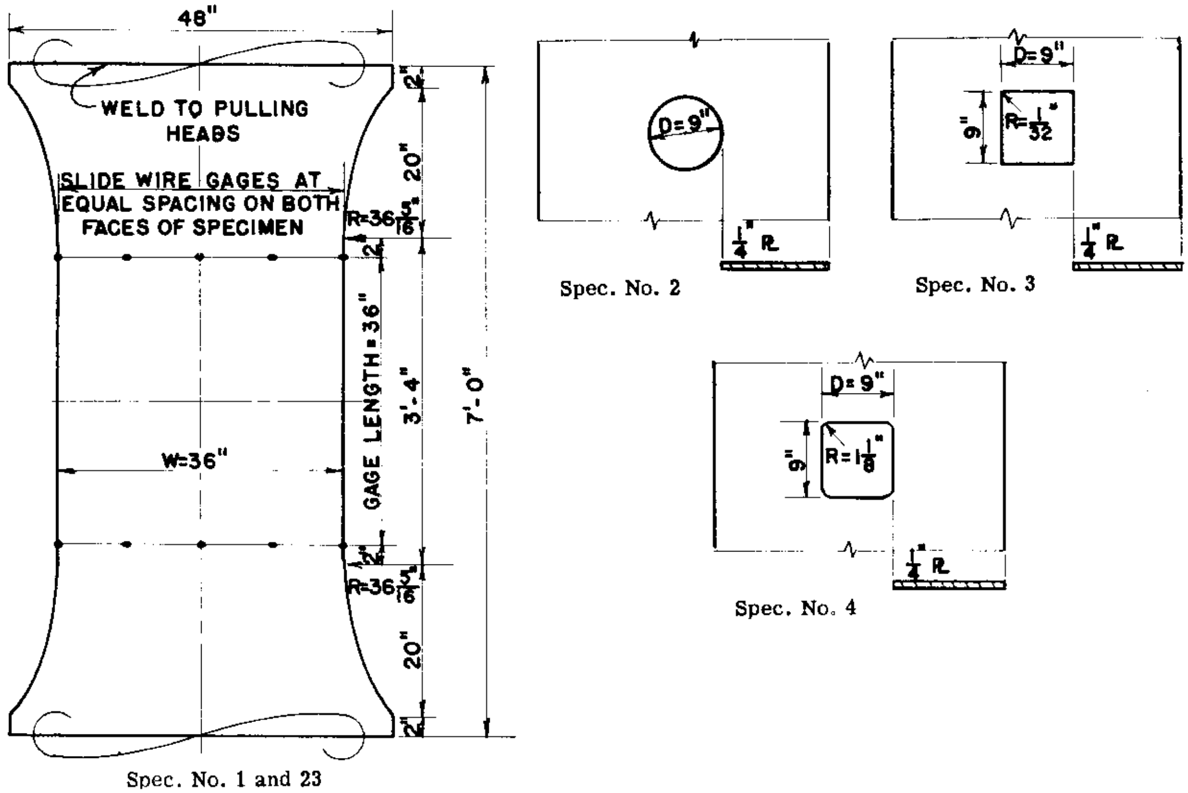


Fig. 2. Details of Plain Plates and Plates with Unreinforced Openings.

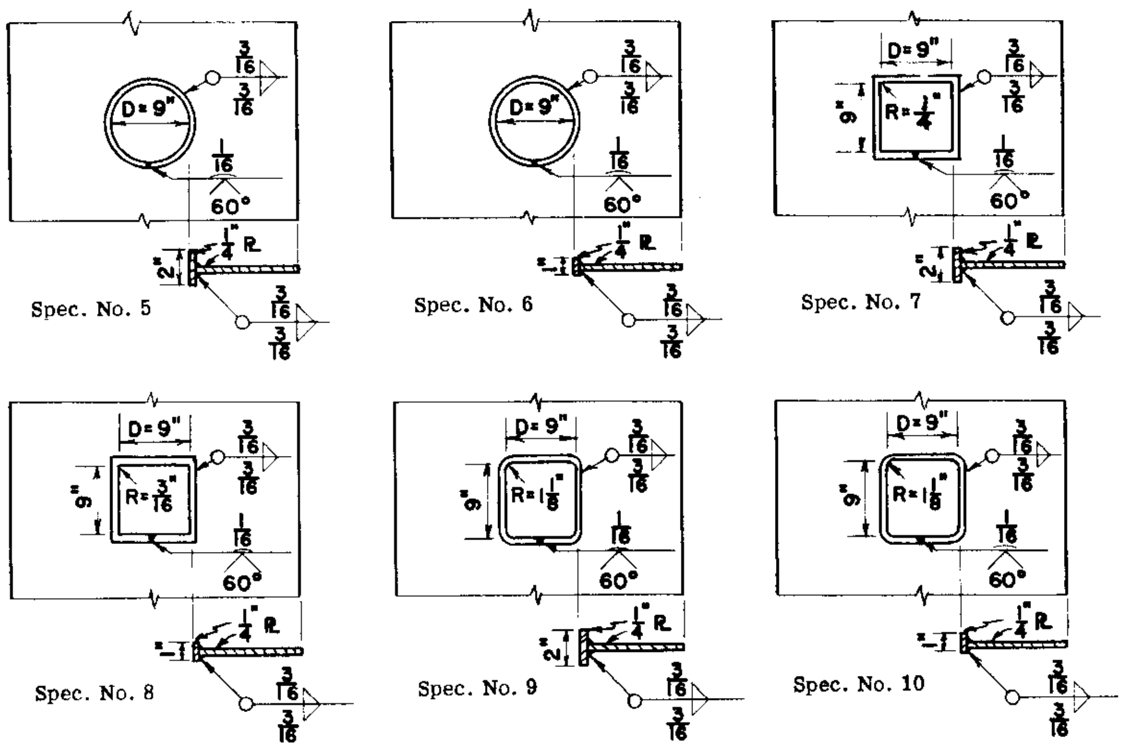


Fig. 3. Details of Plates with Openings Reinforced by a Face Bar.

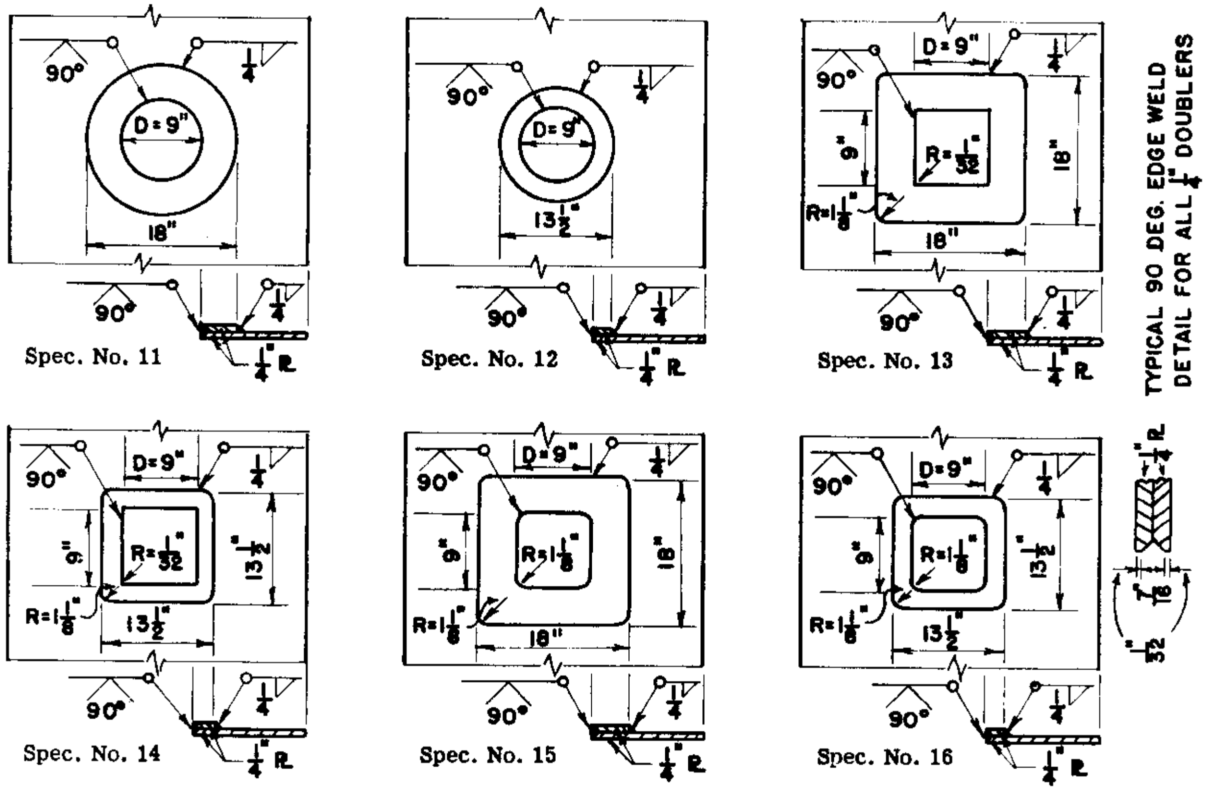


Fig. 4. Details of Plates with Openings Reinforced by a Single Doubler Plate.

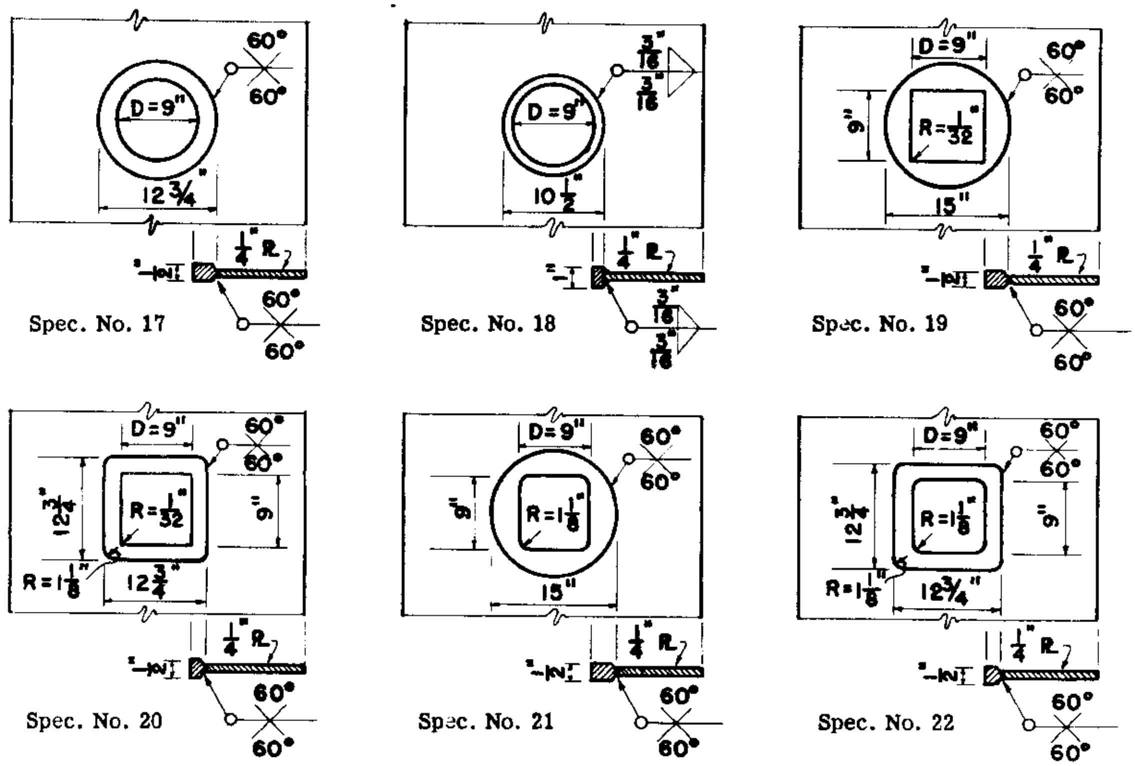


Fig. 5. Details of Plates with Openings Reinforced by an Insert Plate.

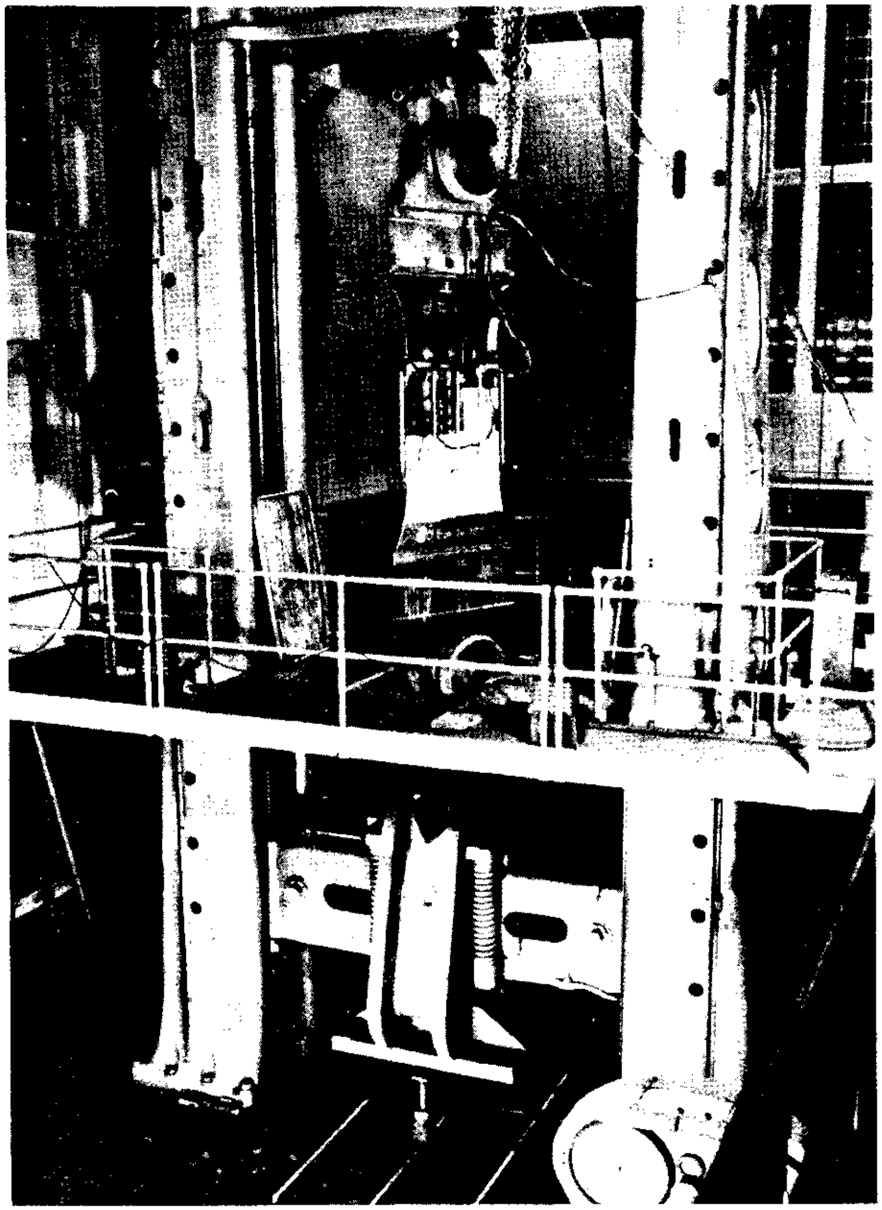


Fig. 6. Typical Specimen Mounted in 2,400,000-lb. Testing Machine and Ready for Testing.

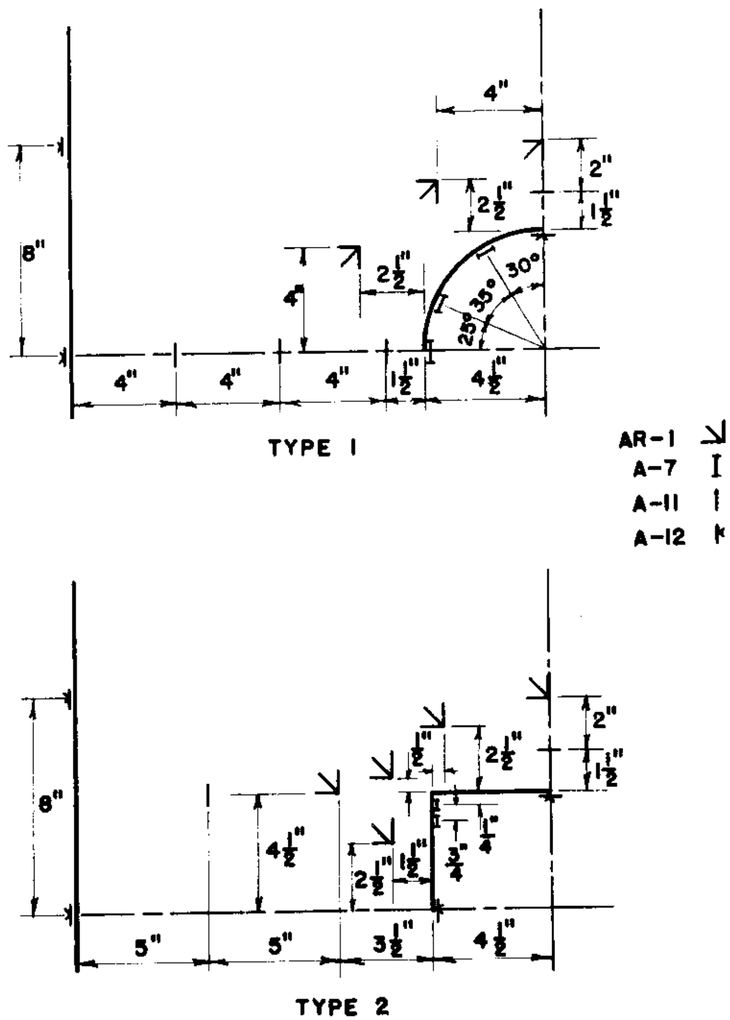


Fig. 7. Location of SR-4 Electric Strain Gages on Specimens with Unreinforced Openings.

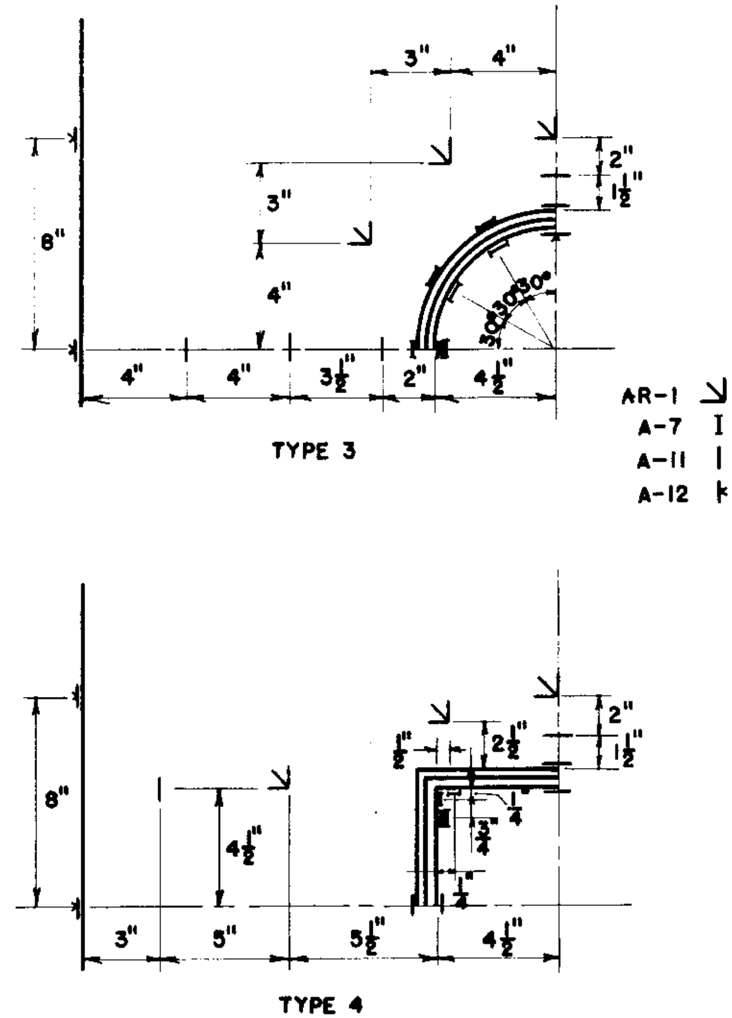


Fig. 8. Location of SR-4 Electric Strain Gages on Specimens with Opening Reinforced by a Face Bar.

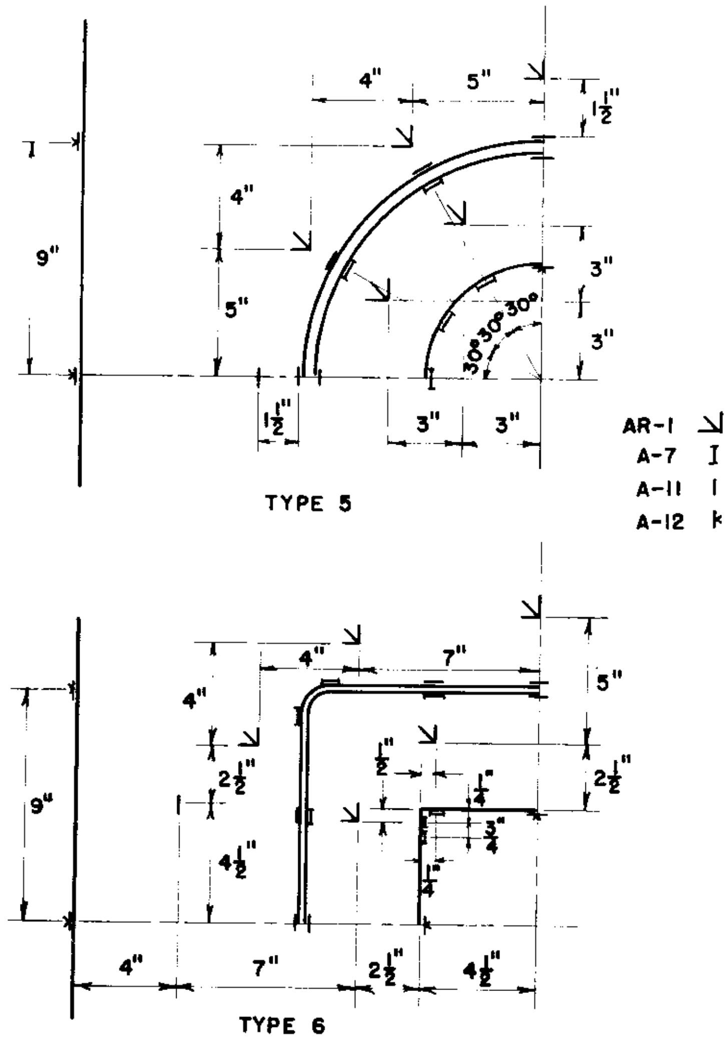


Fig. 9. Location of SR-4 Electric Strain Gages on Specimens with Opening Reinforced by a Single Doubler Plate.

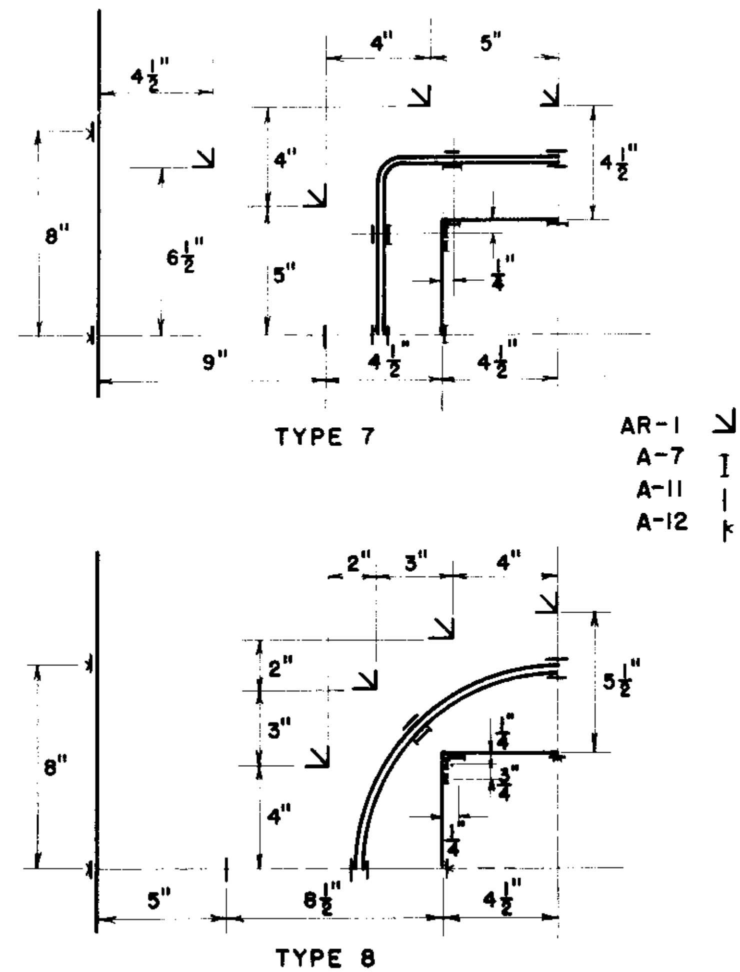


Fig. 10. Location of SR-4 Electric Strain Gages on Specimens with Opening Reinforced by an Insert Plate.

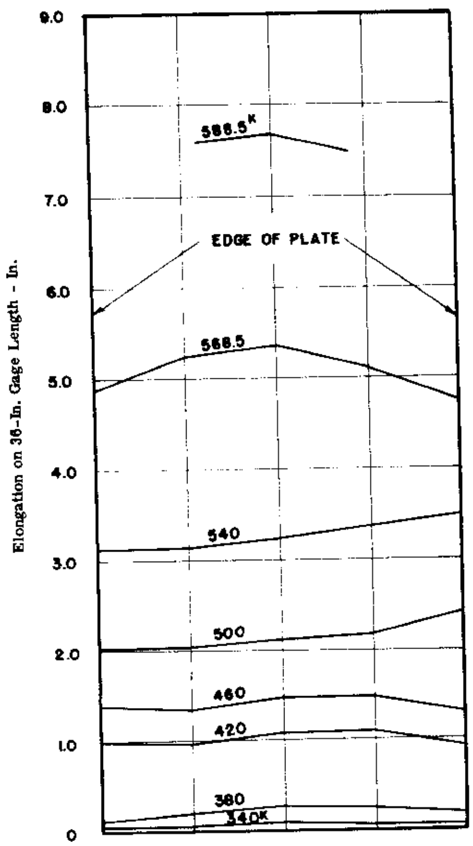


Fig. 11. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 1. Plain Plate.

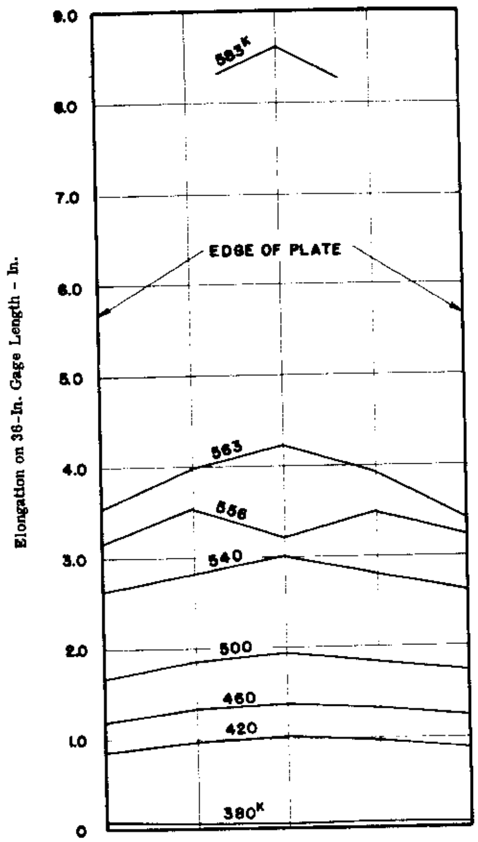


Fig. 12. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 23. Plain Plate.

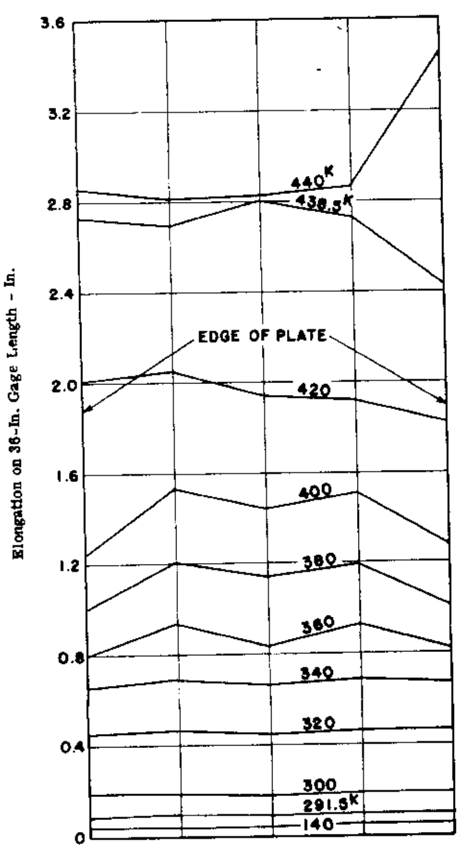


Fig. 13. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 2. Circular Opening.

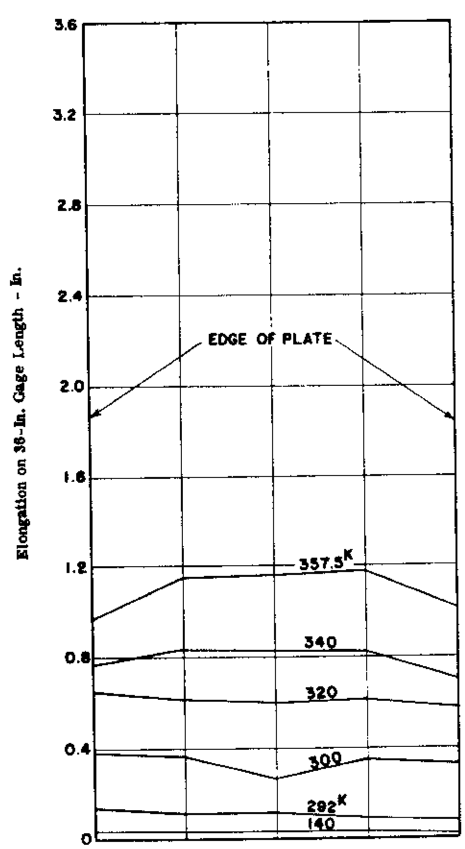


Fig. 14. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 3. Square Opening.

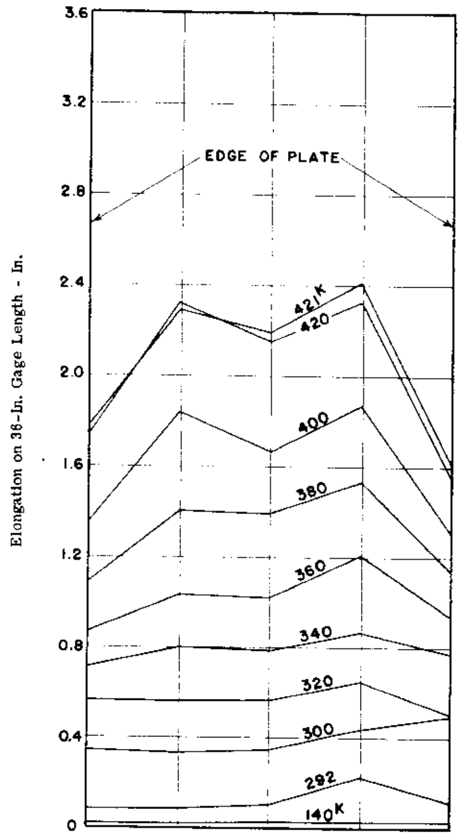


Fig. 15. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 4. Square Opening with Rounded Corners.

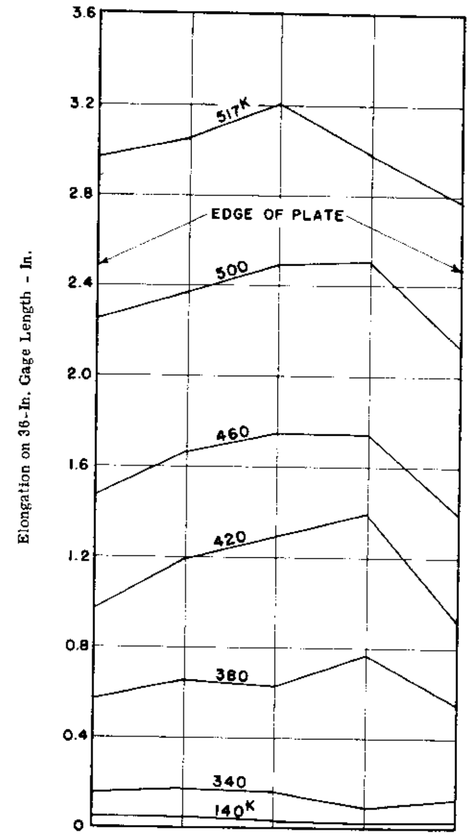


Fig. 16. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 5. Circular Opening. Face Bar Reinforcement.

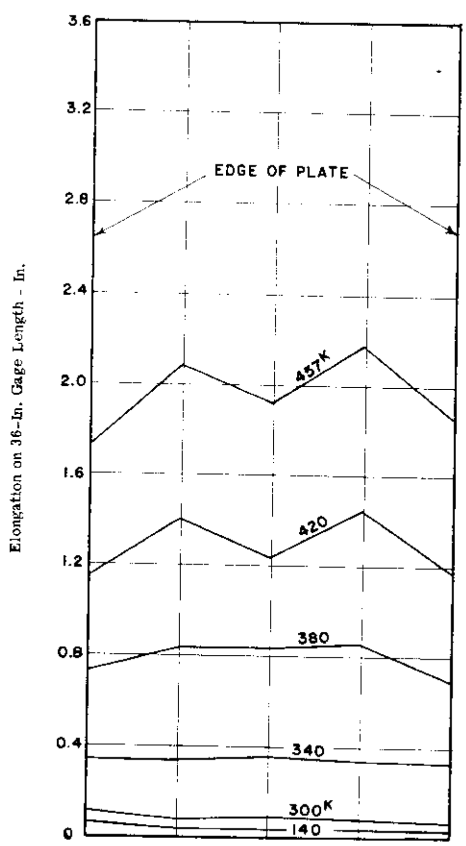


Fig. 17. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 6. Circular Opening. Face Bar Reinforcement.

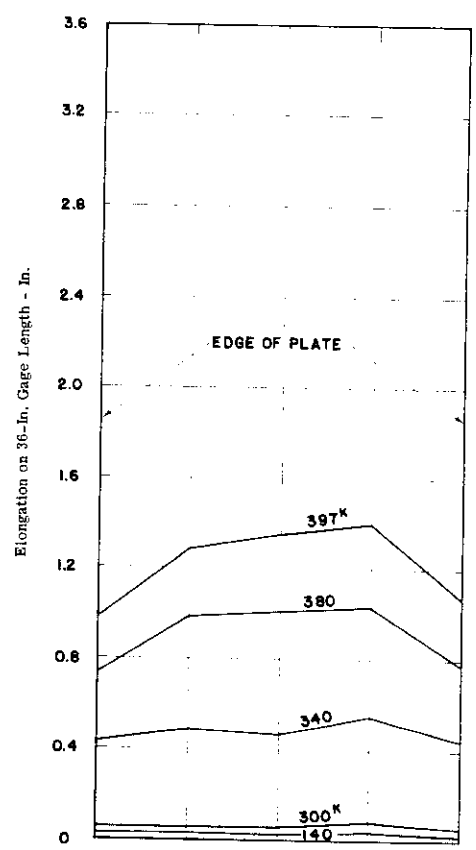


Fig. 18. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 7. Square Opening. Face Bar Reinforcement

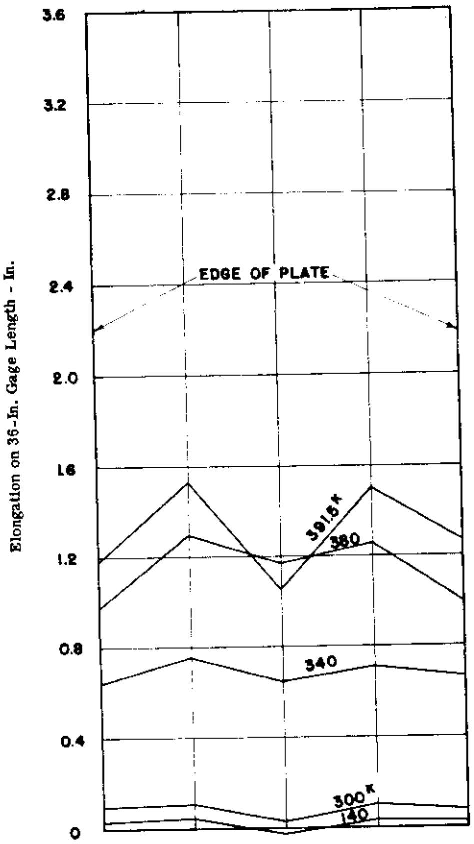


Fig. 19. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 8. Square Opening. Face Bar Reinforcement.

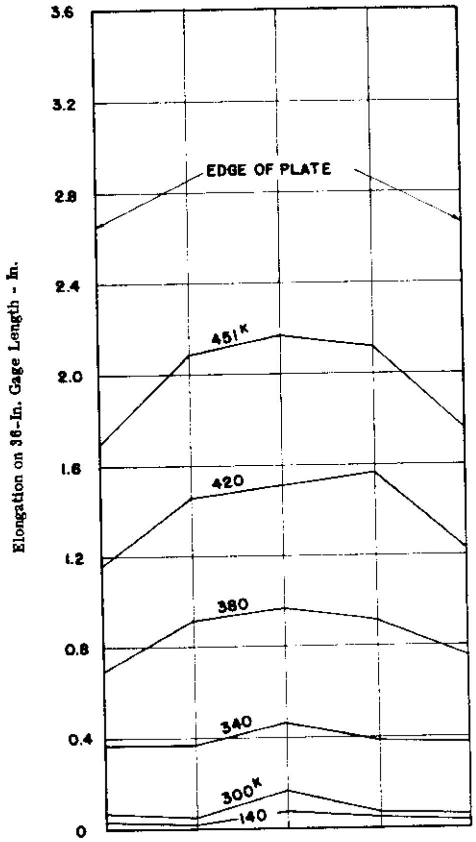


Fig. 20. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 9. Square Opening with Rounded Corners. Face Bar Reinforcement.

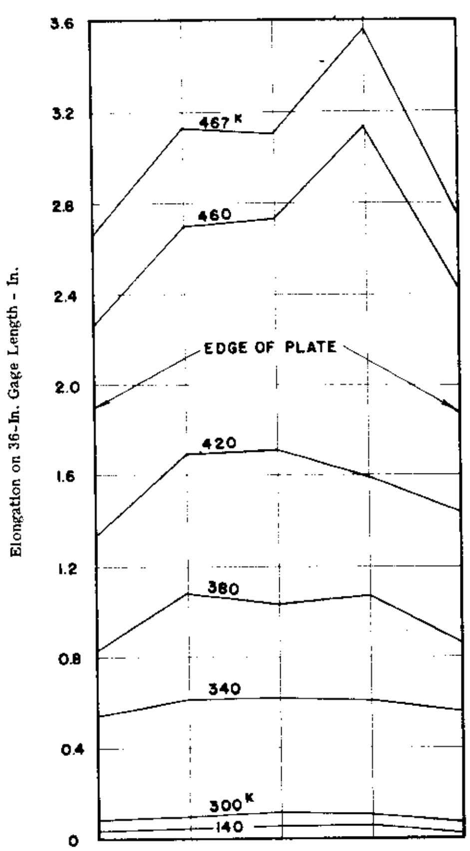


Fig. 21. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 10. Square Opening with Rounded Corners. Face Bar Reinforcement.

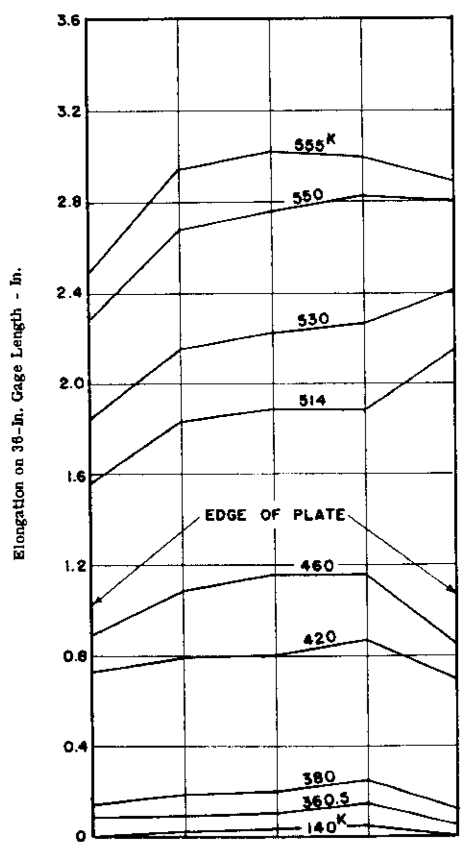


Fig. 22. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 11. Circular Opening. Single Doubler Plate Reinforcement.

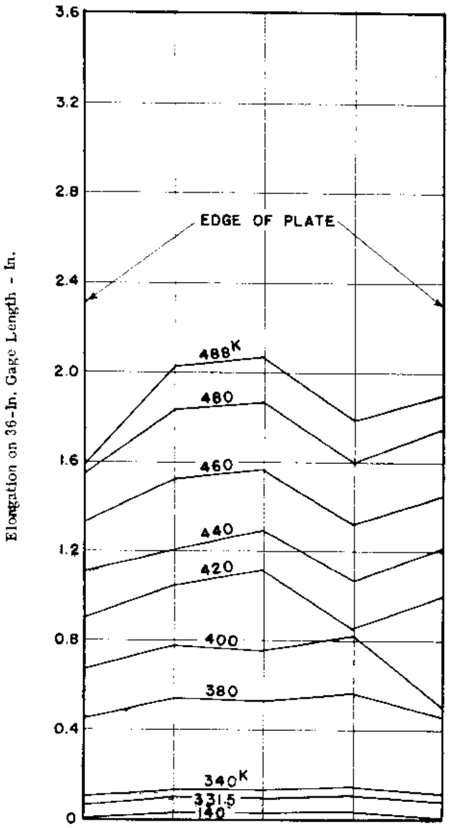


Fig. 23. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 12. Circular Opening. Single Doubler Plate Reinforcement.

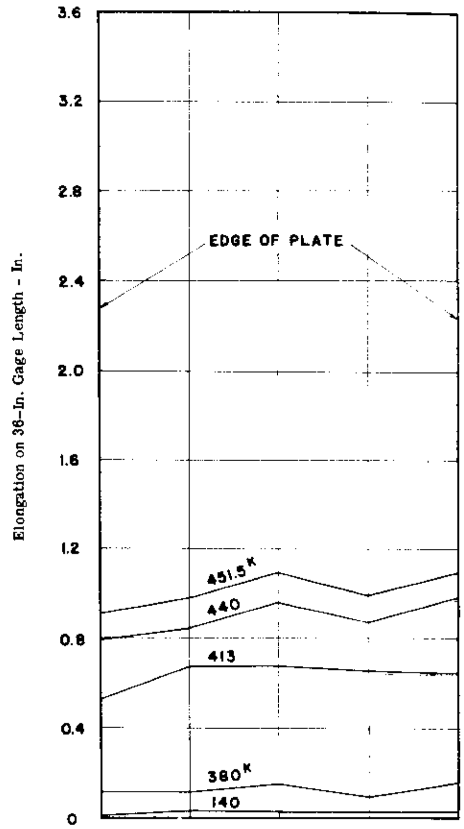


Fig. 24. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 13. Square Opening. Single Doubler Plate Reinforcement.

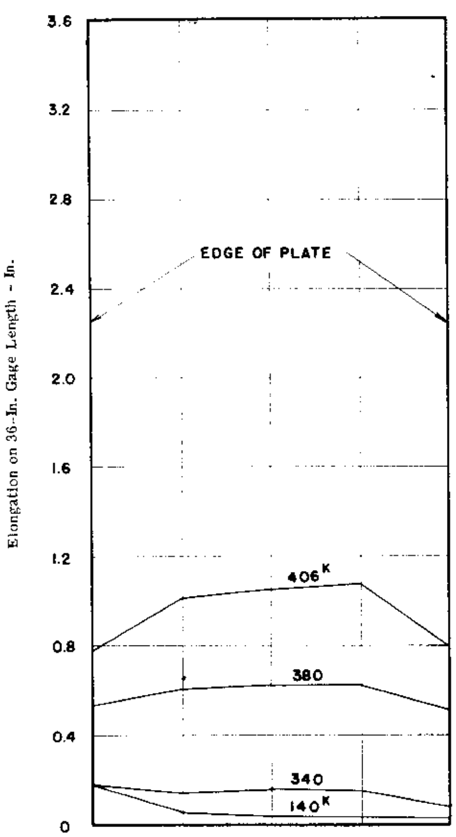


Fig. 25. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 14. Square Opening. Single Doubler Plate Reinforcement.

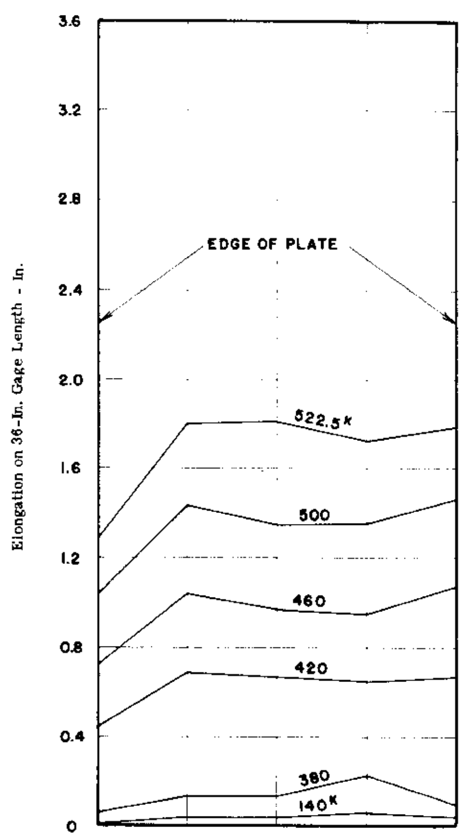


Fig. 26. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 15. Square Opening with Rounded Corners. Single Doubler Plate Reinforcement.

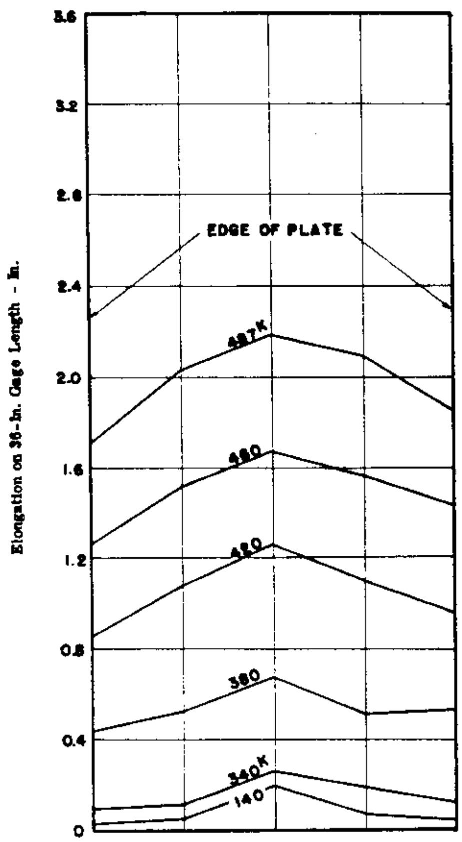


Fig. 27. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 16. Square Opening with Rounded Corners. Single Doubler Plate Reinforcement.

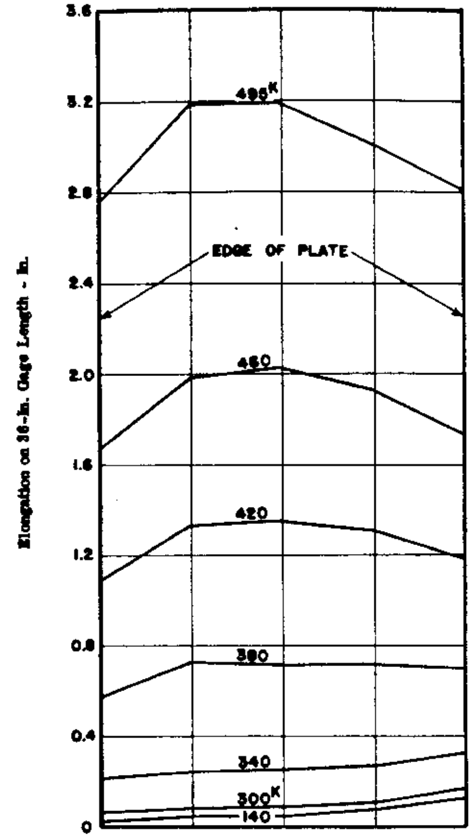


Fig. 28. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 17. Circular Opening. Insert Plate Reinforcement.

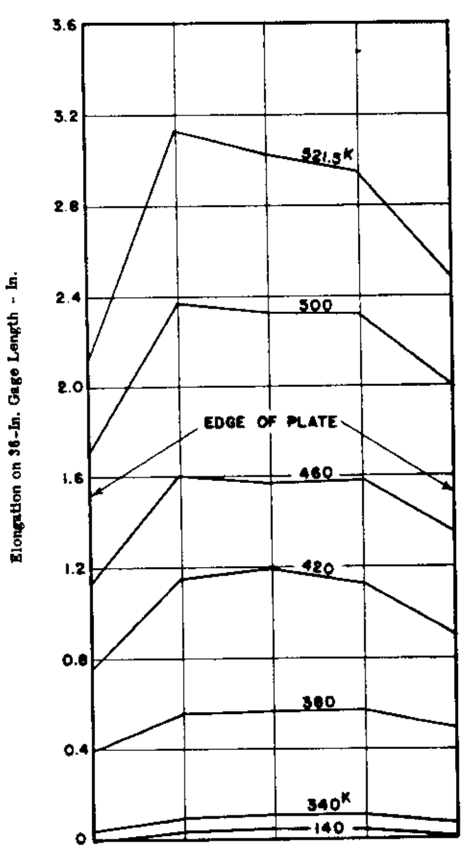


Fig. 29. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 18. Circular Opening. Insert Plate Reinforcement.

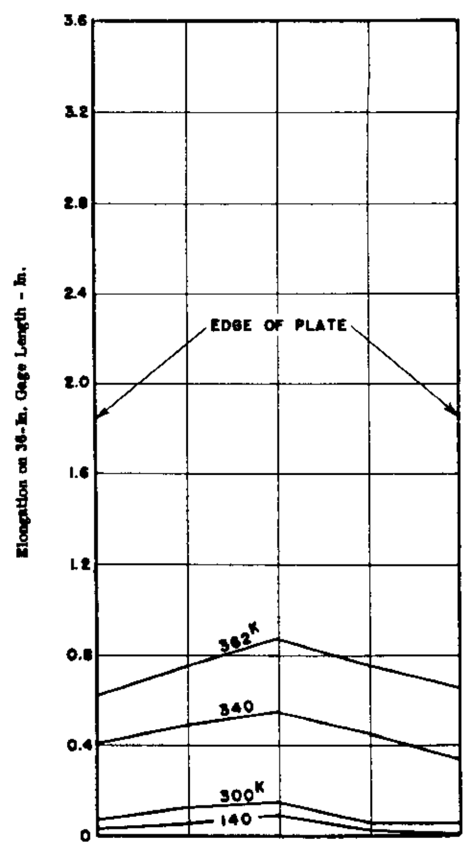


Fig. 30. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 19. Square Opening. Insert Plate Reinforcement.

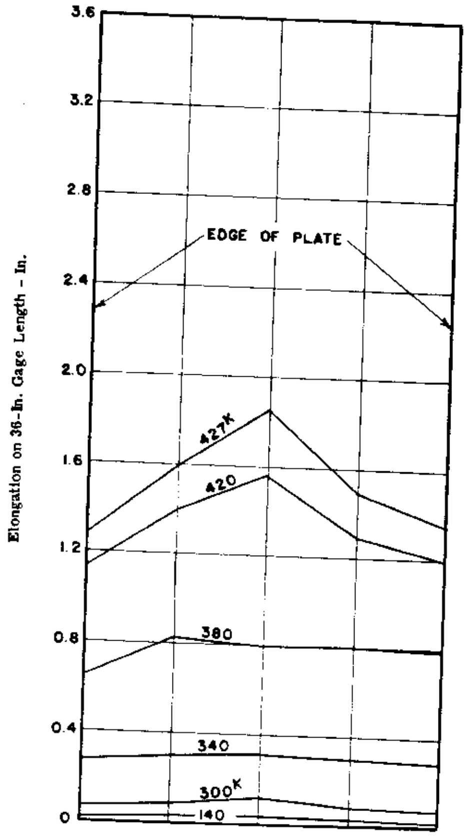


Fig. 31. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 20. Square Opening. Insert Plate Reinforcement.

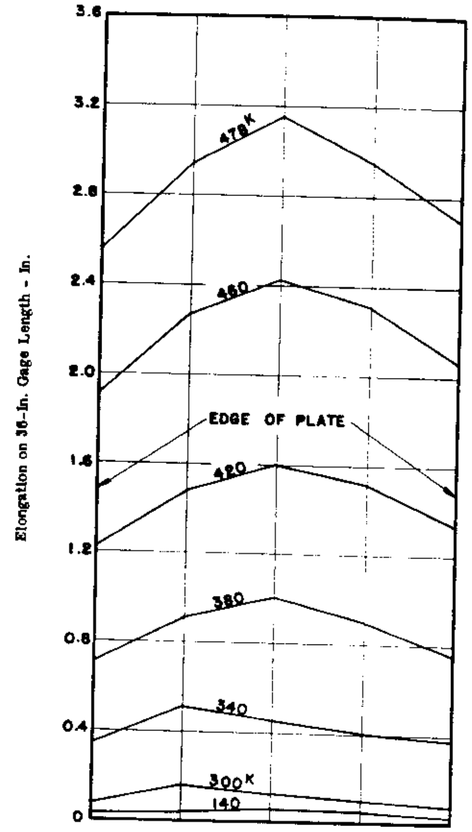


Fig. 32. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 21. Square Opening with Rounded Corners. Insert Plate Reinforcement.

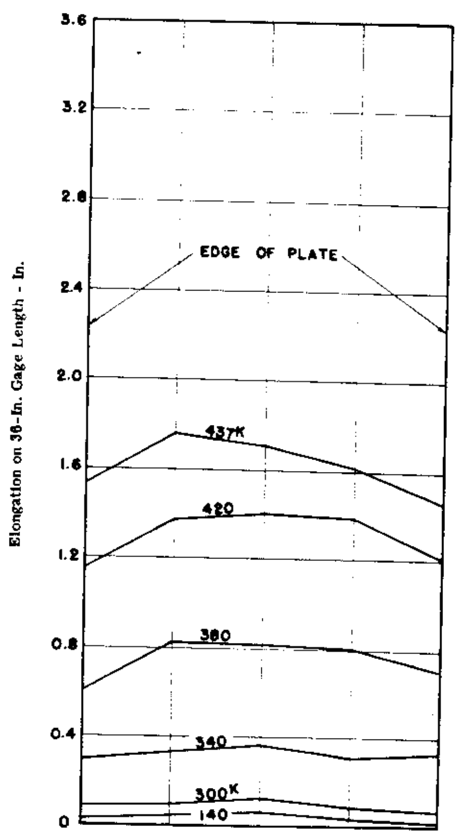


Fig. 33. Distribution across Plate of Elongation on 36-In. Gage Length. Spec. No. 22. Square Opening with Rounded Corners. Insert Plate Reinforcement.

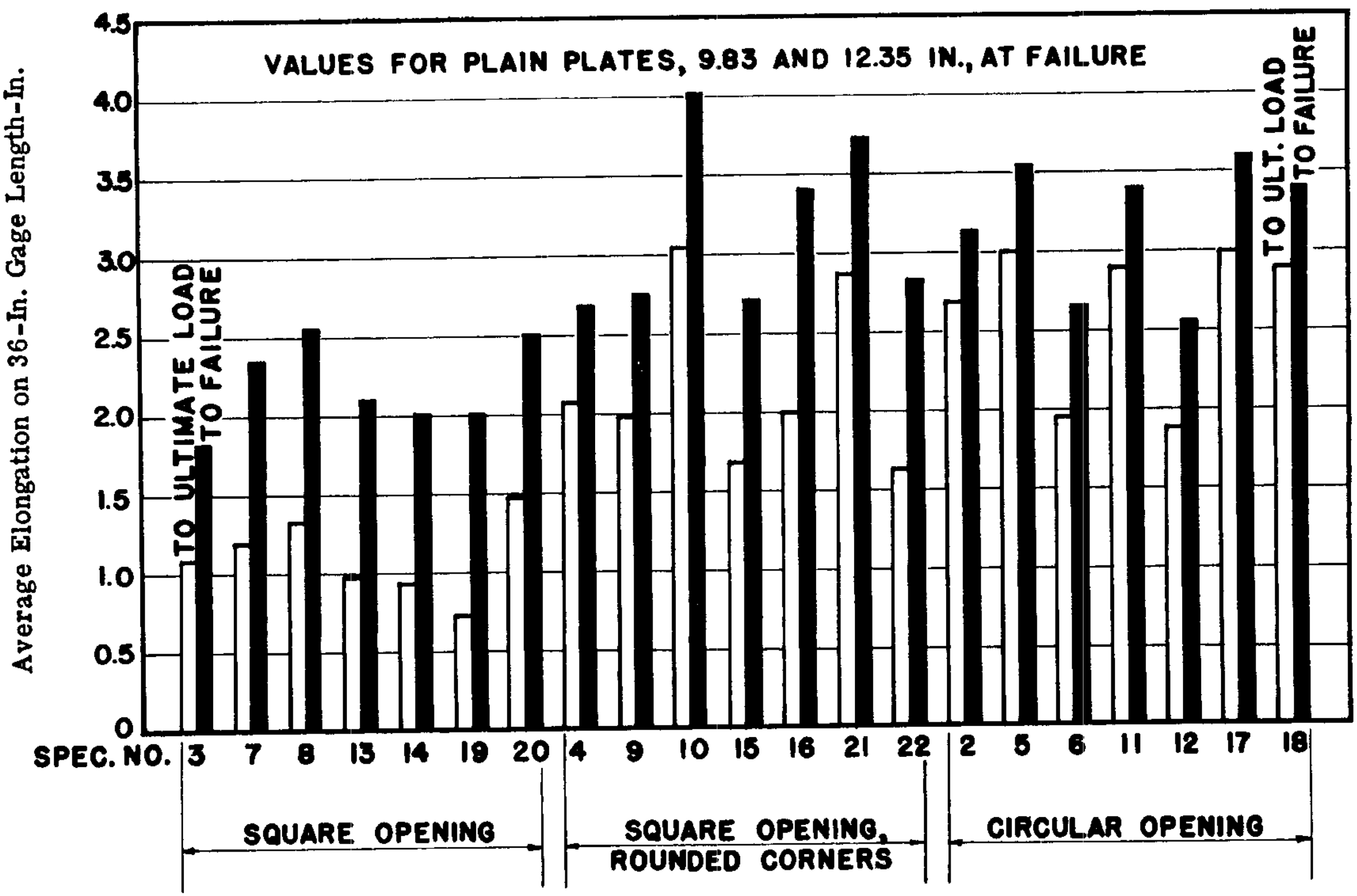


Fig. 34. Average Elongation to Ultimate Load and to Failure on 36-In. Gage Length for Plain Plates and Plates with Openings.

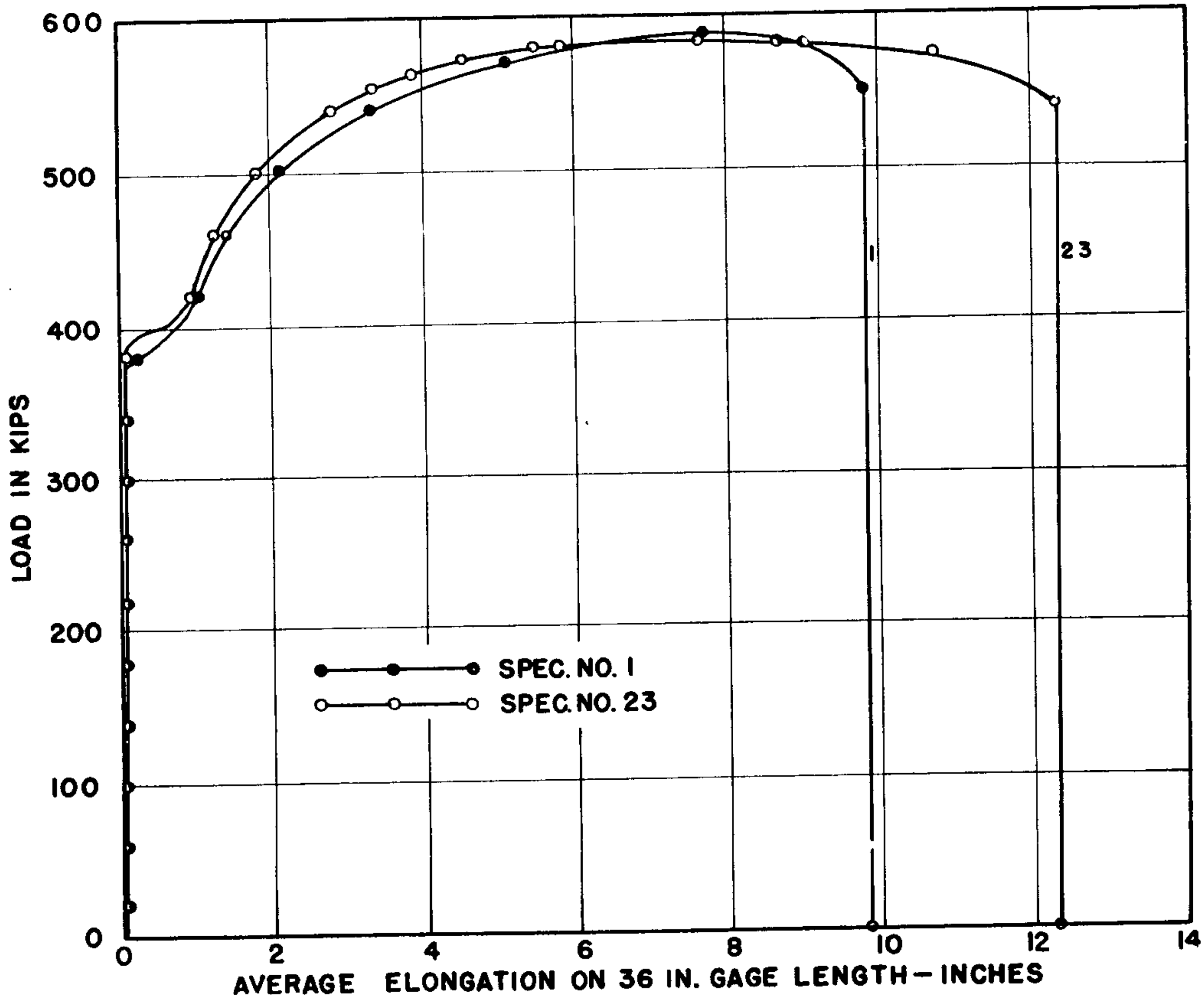


Fig. 35. Comparison of Load and Average Elongation on 36-In. Gage Length for Plain Plates

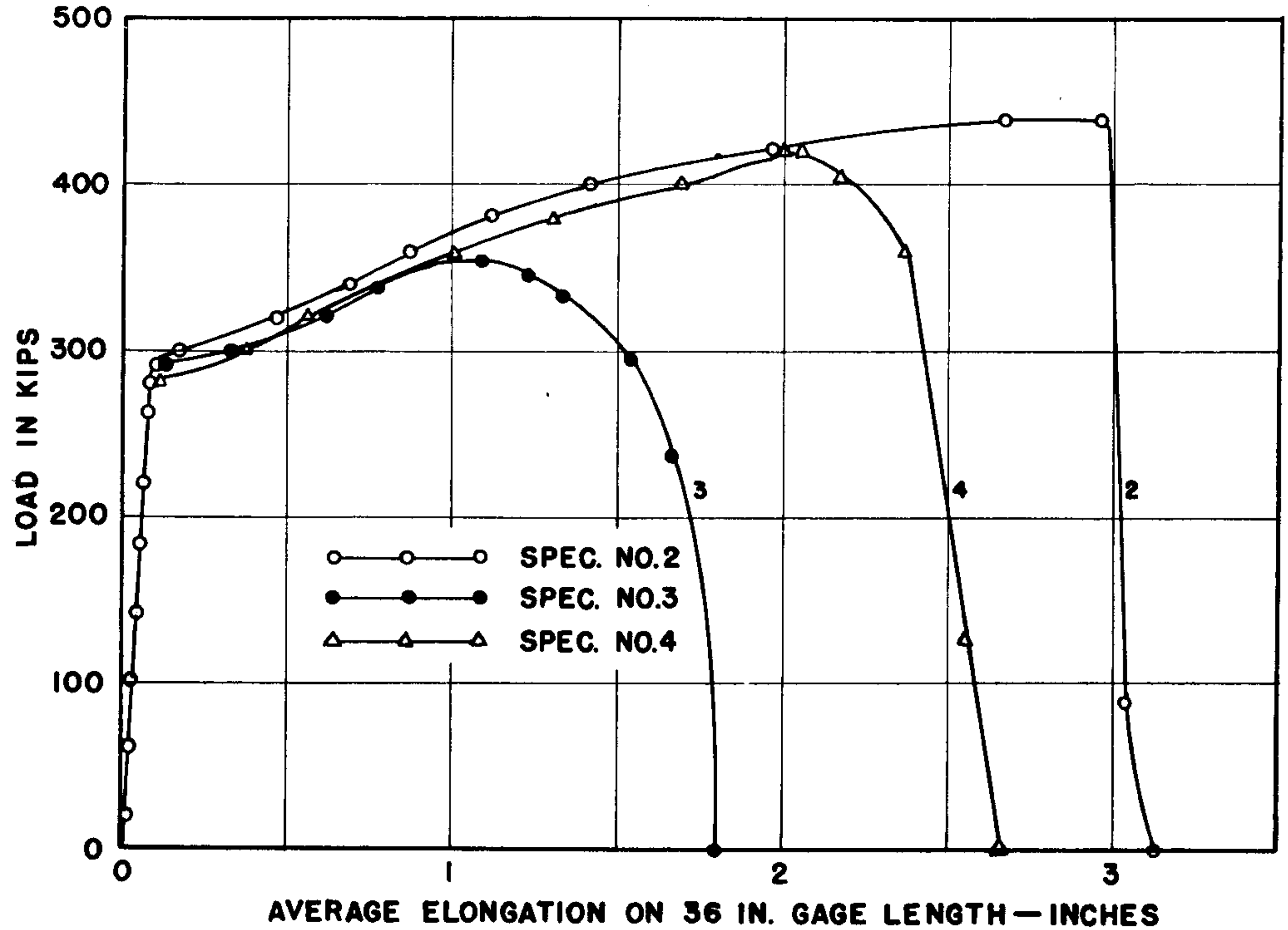


Fig. 36. Comparison of Load and Average Elongation on 36-In. Gage Length for Plates with an Unreinforced Opening.

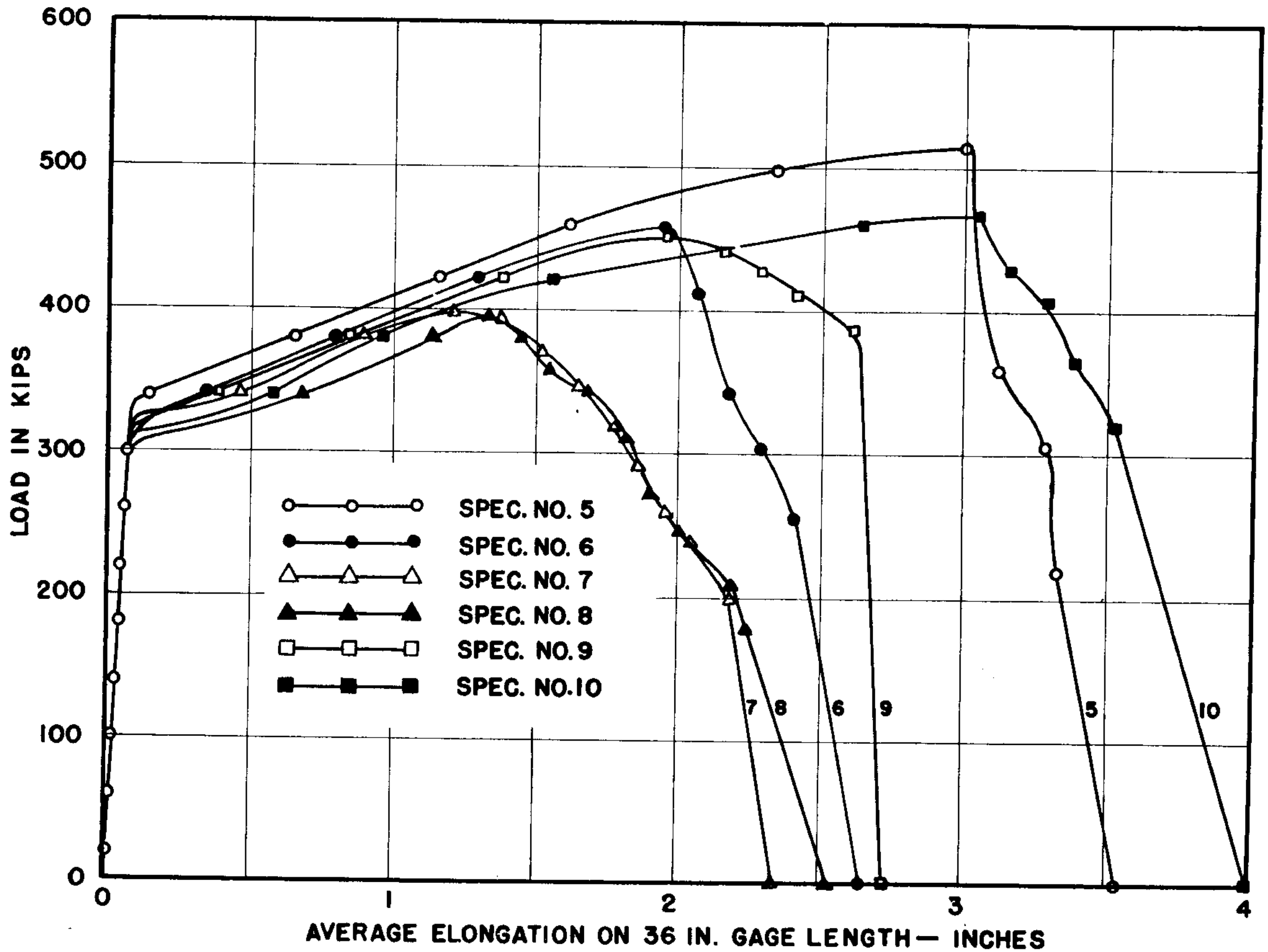


Fig. 37. Comparison of Load and Average Elongation on 36-in. Gage Length for Plates with Openings Reinforced by a Face Bar.

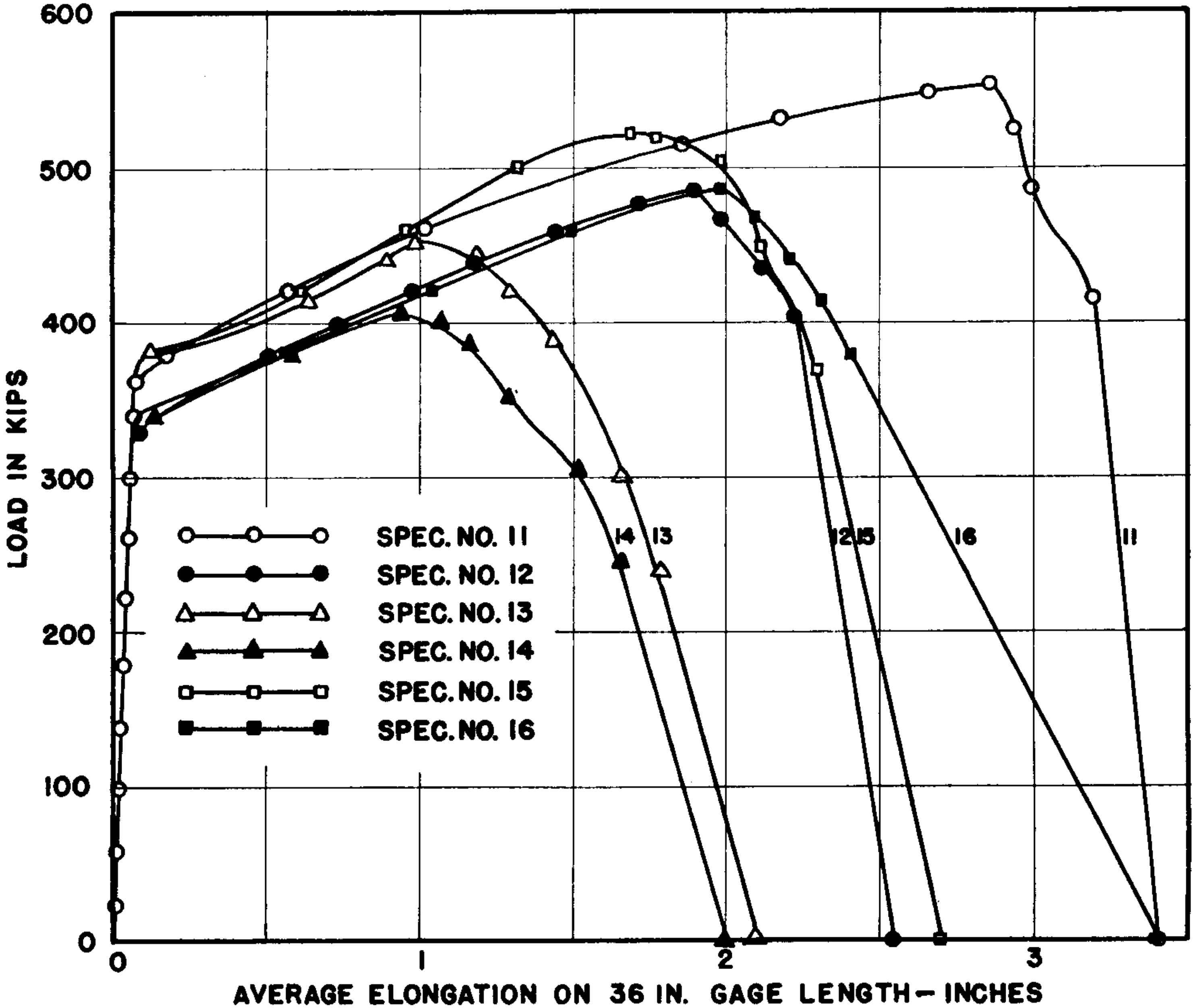


Fig. 38. Comparison of Load and Average Elongation on 36-In. Gage Length for Plates with Openings Reinforced by a Single Doubler Plate.

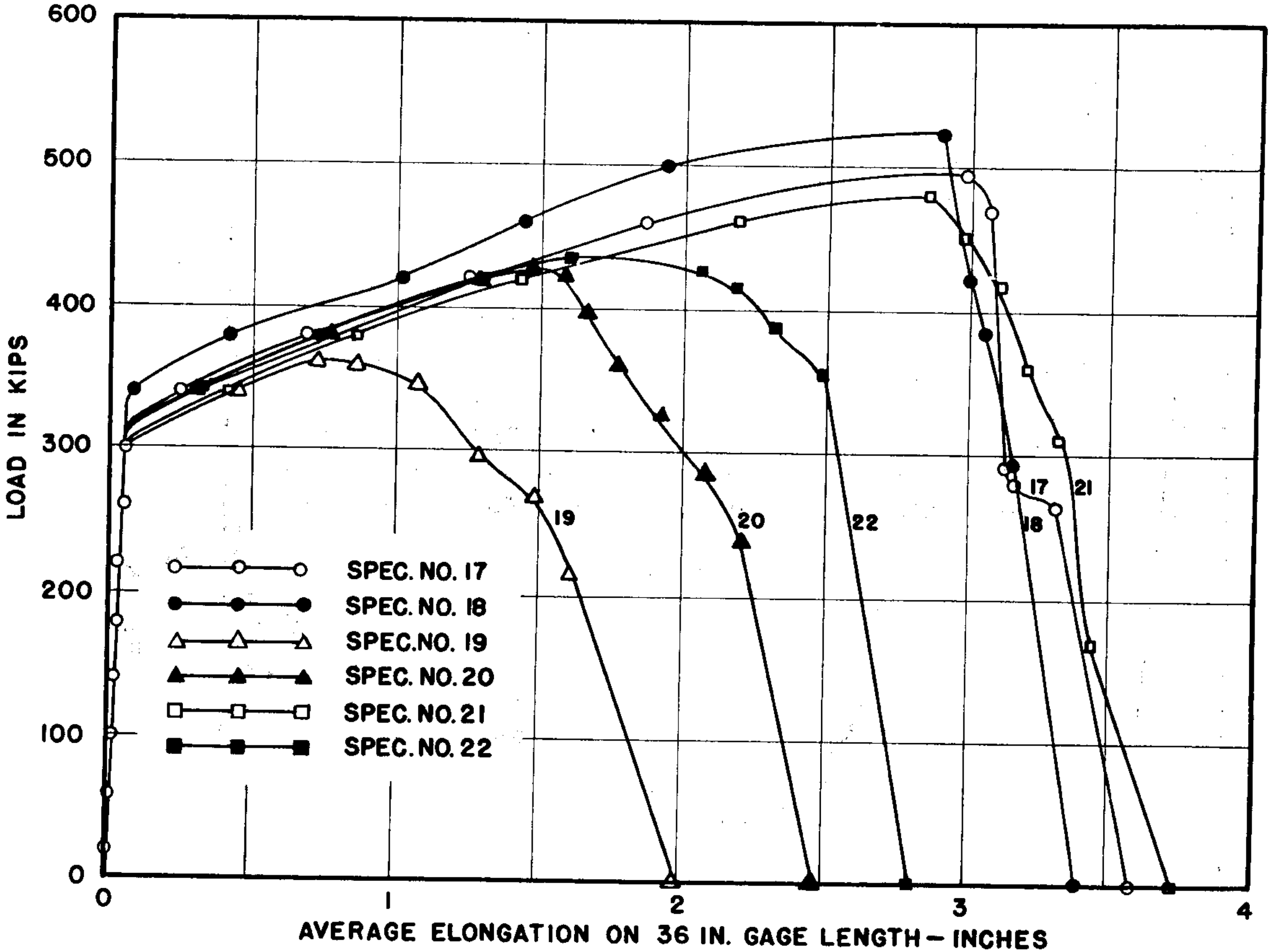


Fig. 39. Comparison of Load and Average Elongation on 36-In. Gage Length for Plates with Openings Reinforced by an Insert Plate.

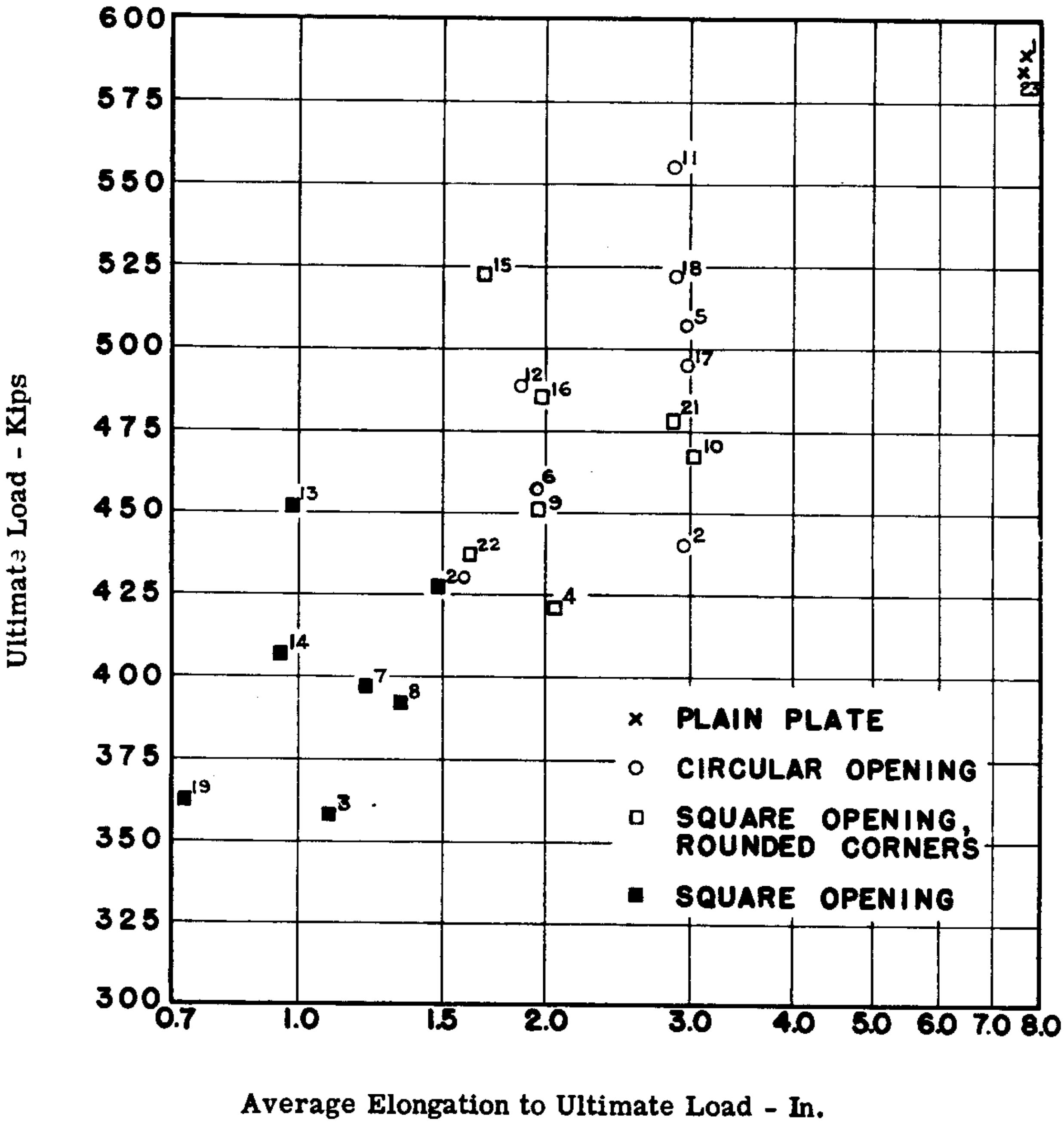


Fig. 40. Comparison of Ultimate Load and Average Elongation to Ultimate Load for Plain Plates and Plates with Openings.

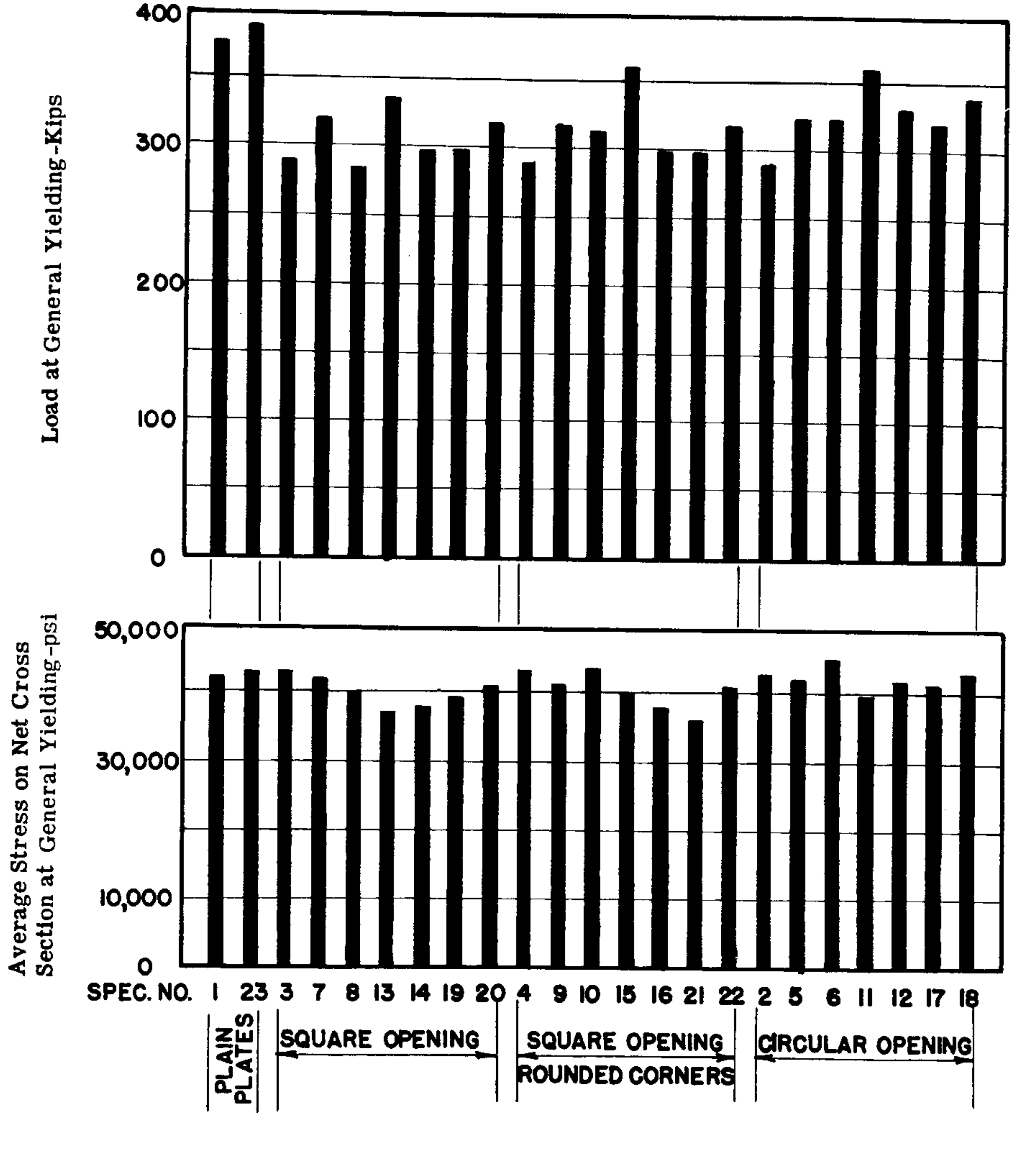


Fig. 41. Load and Average Stress on Net Cross Section at General Yielding of Plain Plates and Plates with Openings.

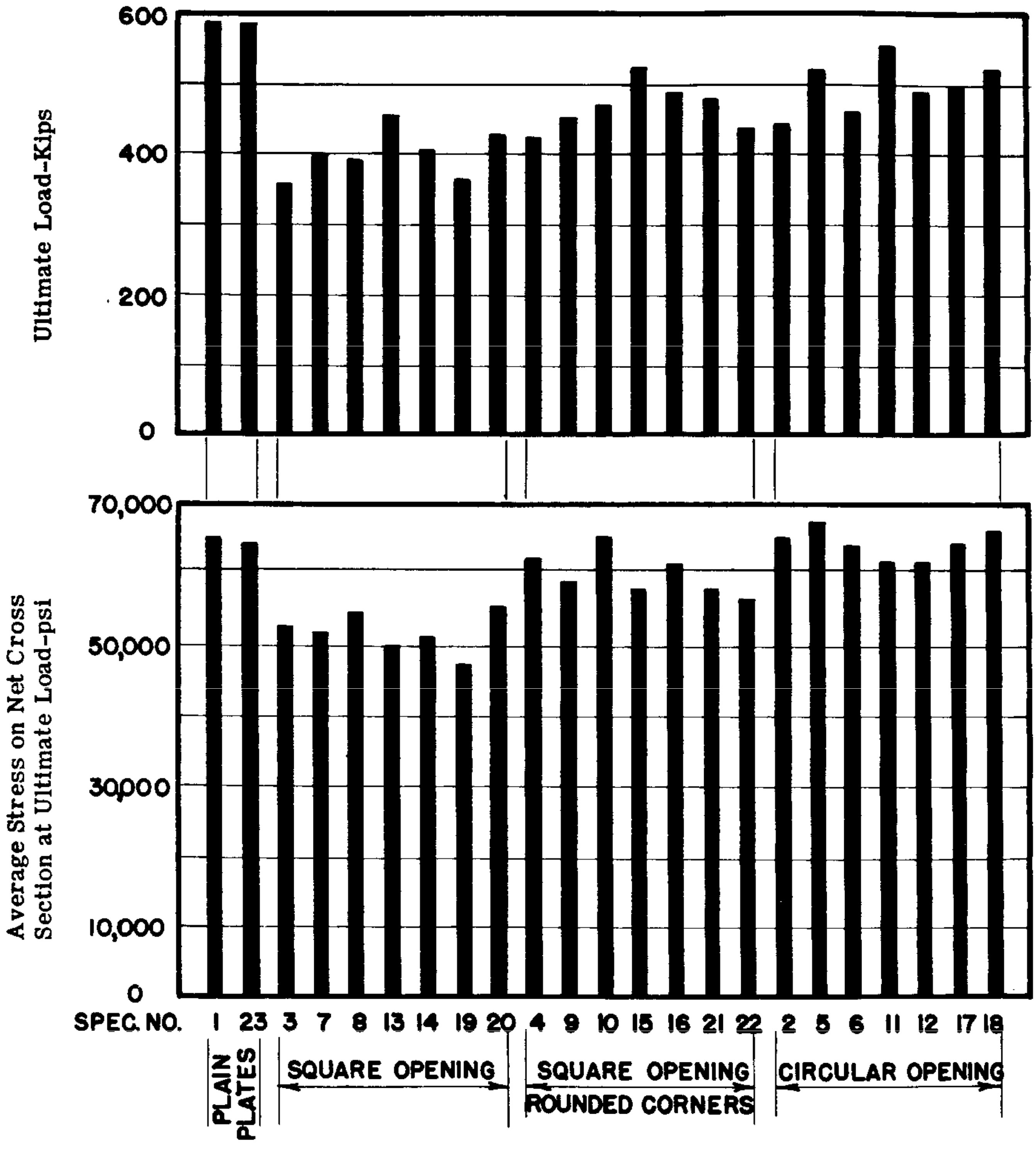


Fig. 42. Ultimate Strength of Plain Plates and Plates with Openings.

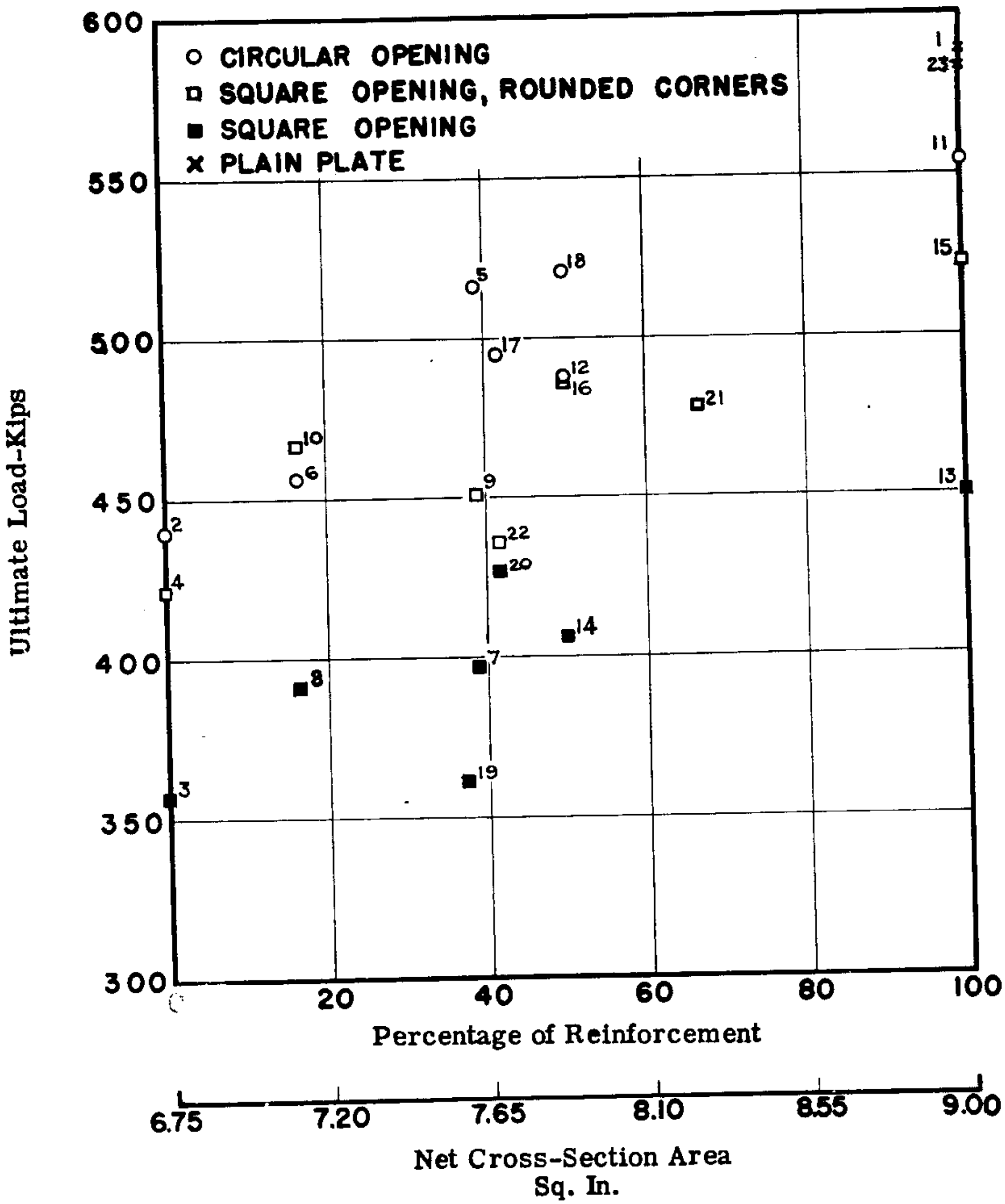


Fig. 43. Comparison of Ultimate Load and Percentage of Reinforcement for Plates with Openings.

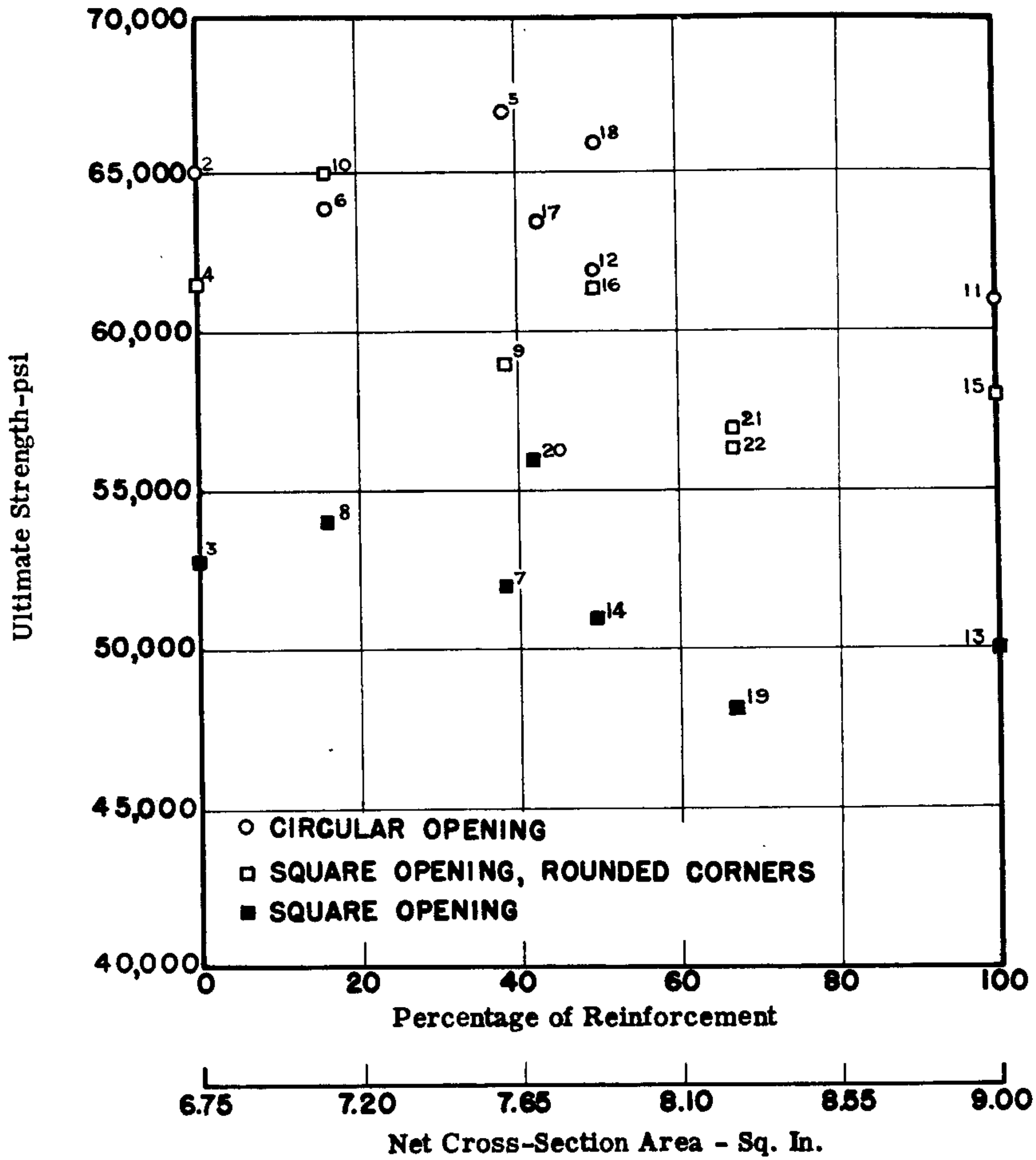


Fig. 44. Comparison of Ultimate Strength with Percentage of Reinforcement for Plates with Openings.

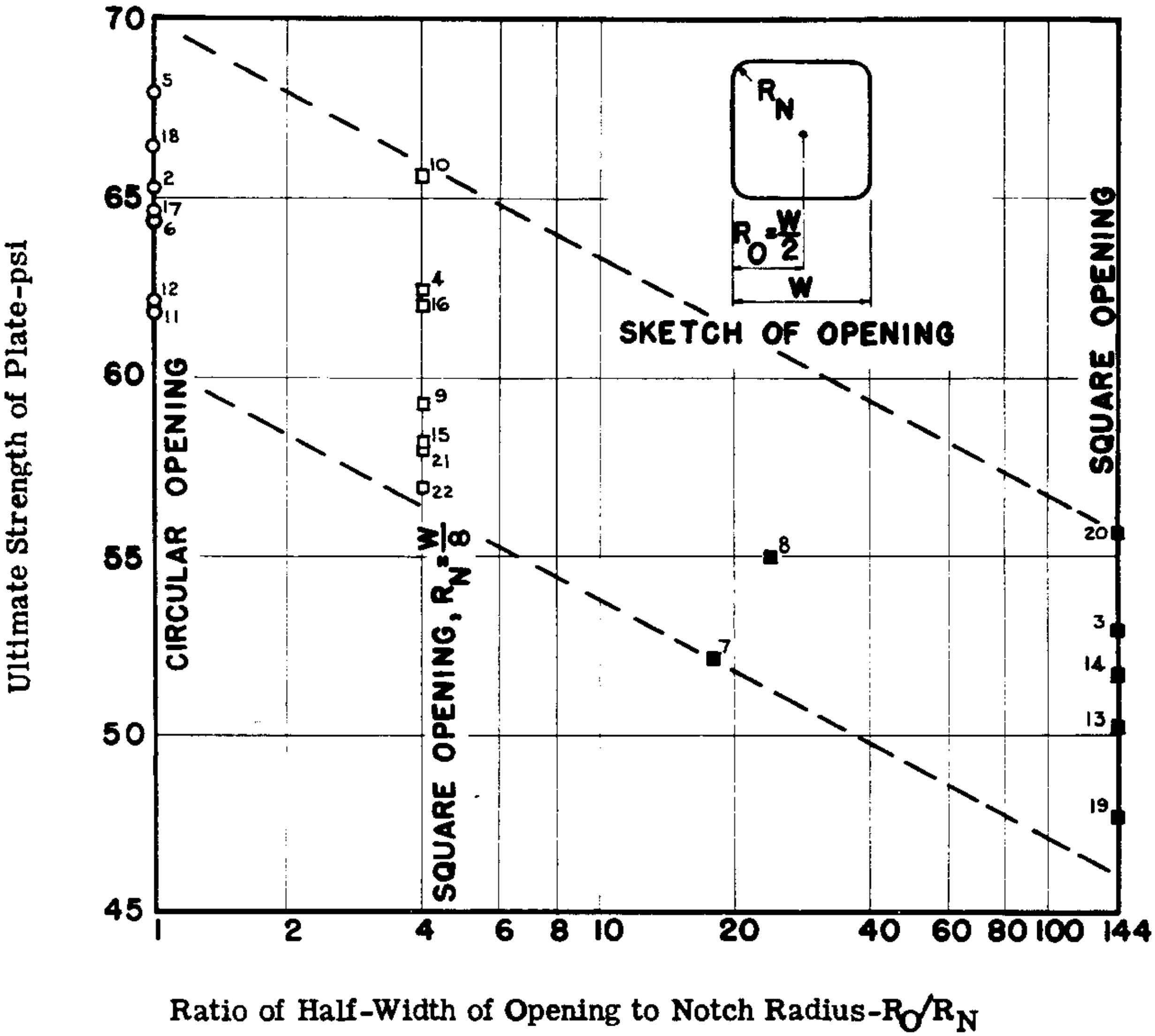


Fig. 45. Relation between the Ultimate Strength of Plates with Openings and the Notch Acuity of the Opening.

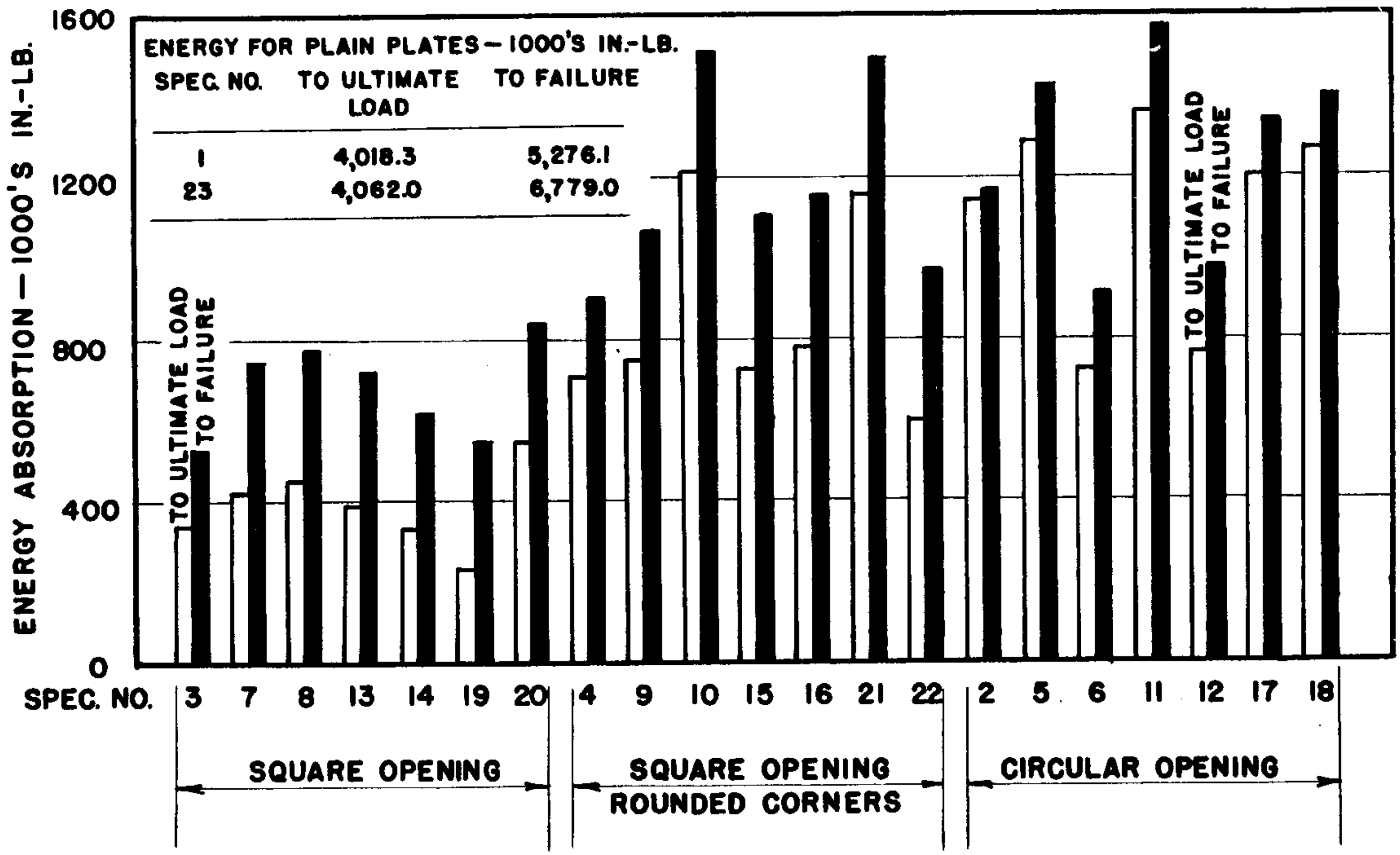


Fig. 46. Energy Absorption to Ultimate Load and to Failure for Plates with Openings.

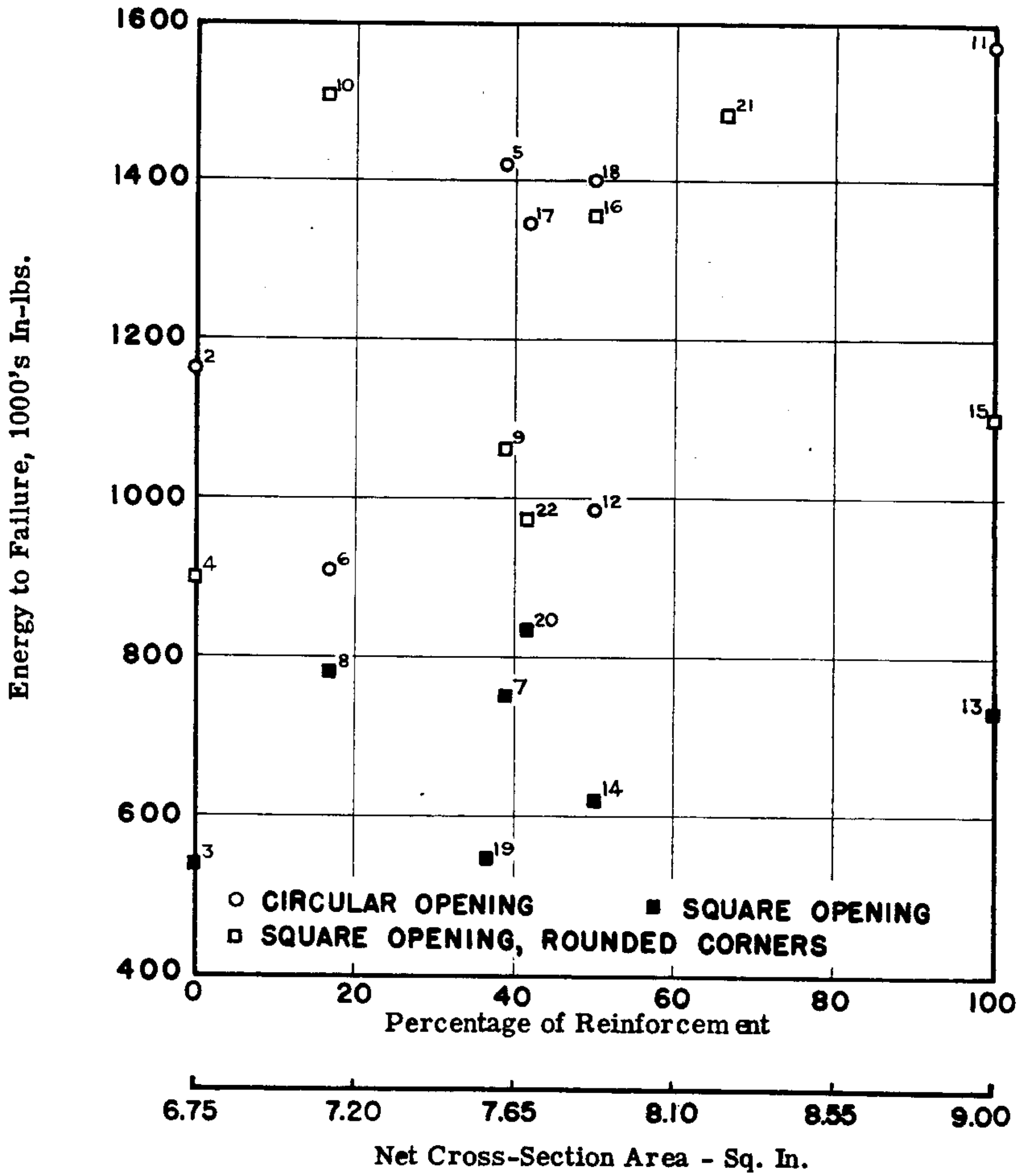


Fig. 47. Comparison of Energy Absorption to Failure and Percentage of Reinforcement for Plates with Openings.

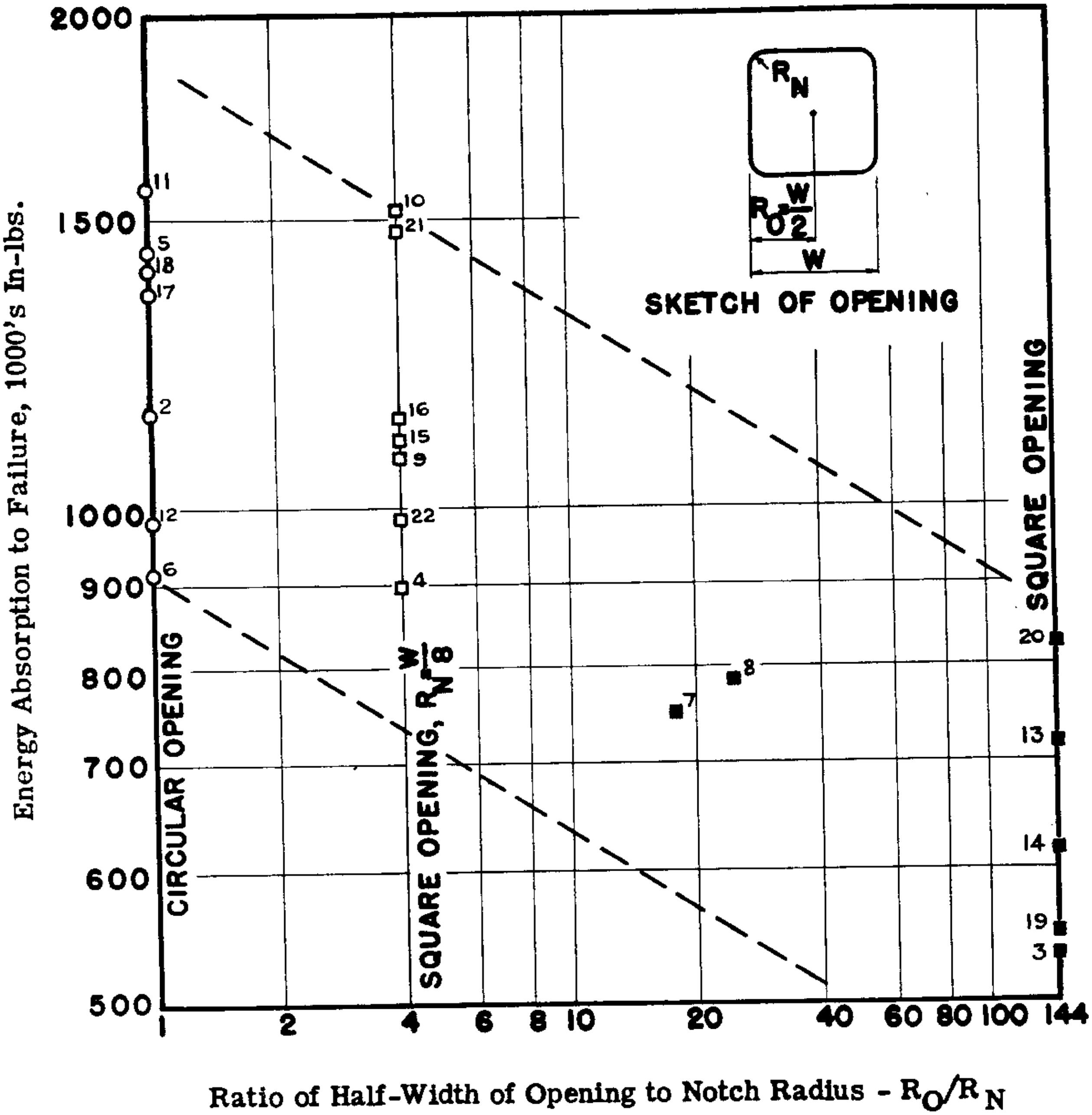


Fig. 48. Relation between the Energy Absorption to Failure of Plates with Openings and the Notch Acuity of the Opening.

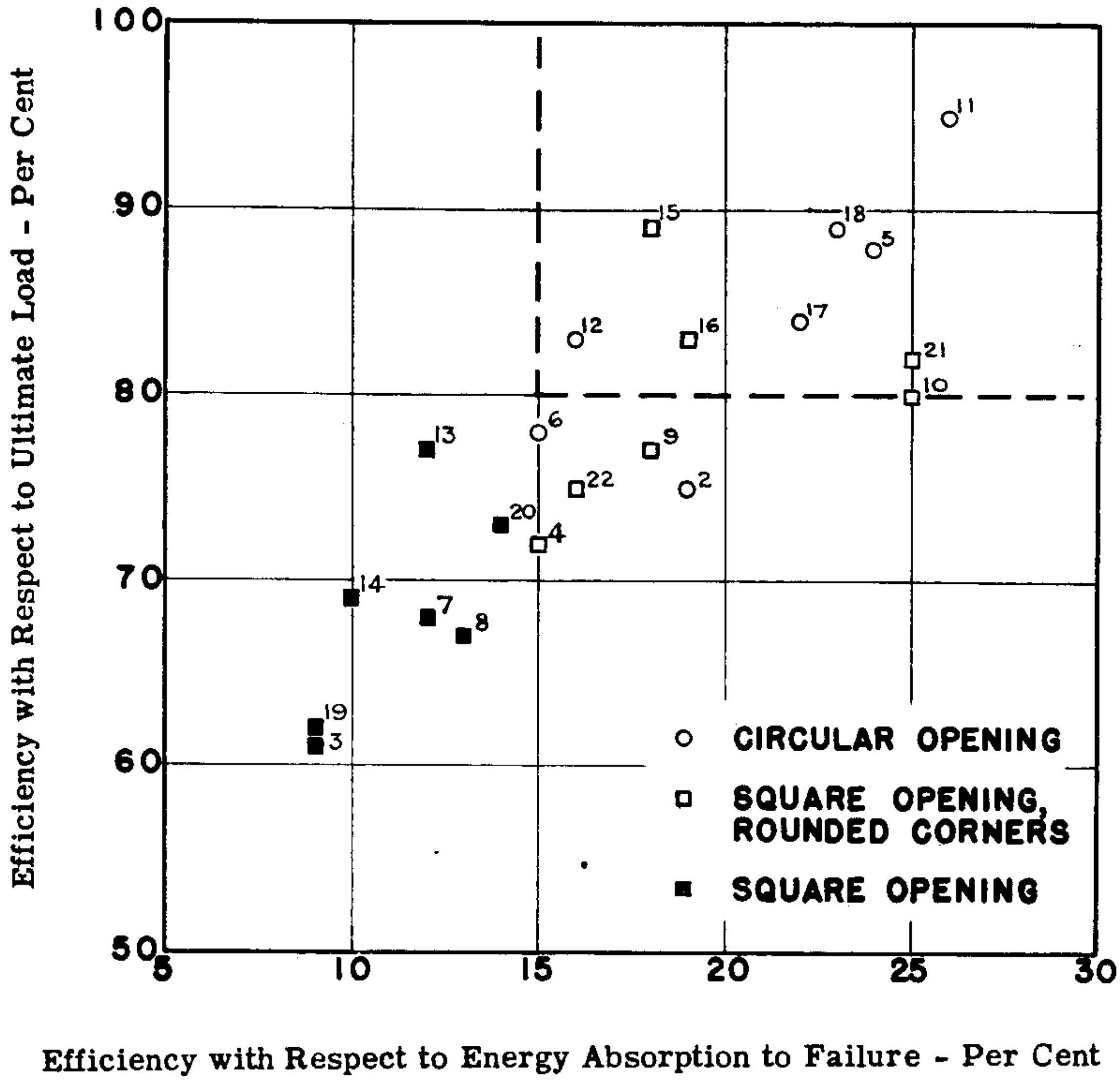


Fig. 49. Comparison of the Efficiencies with Respect to Ultimate Load and Energy Absorption to Failure for Plates with Openings.

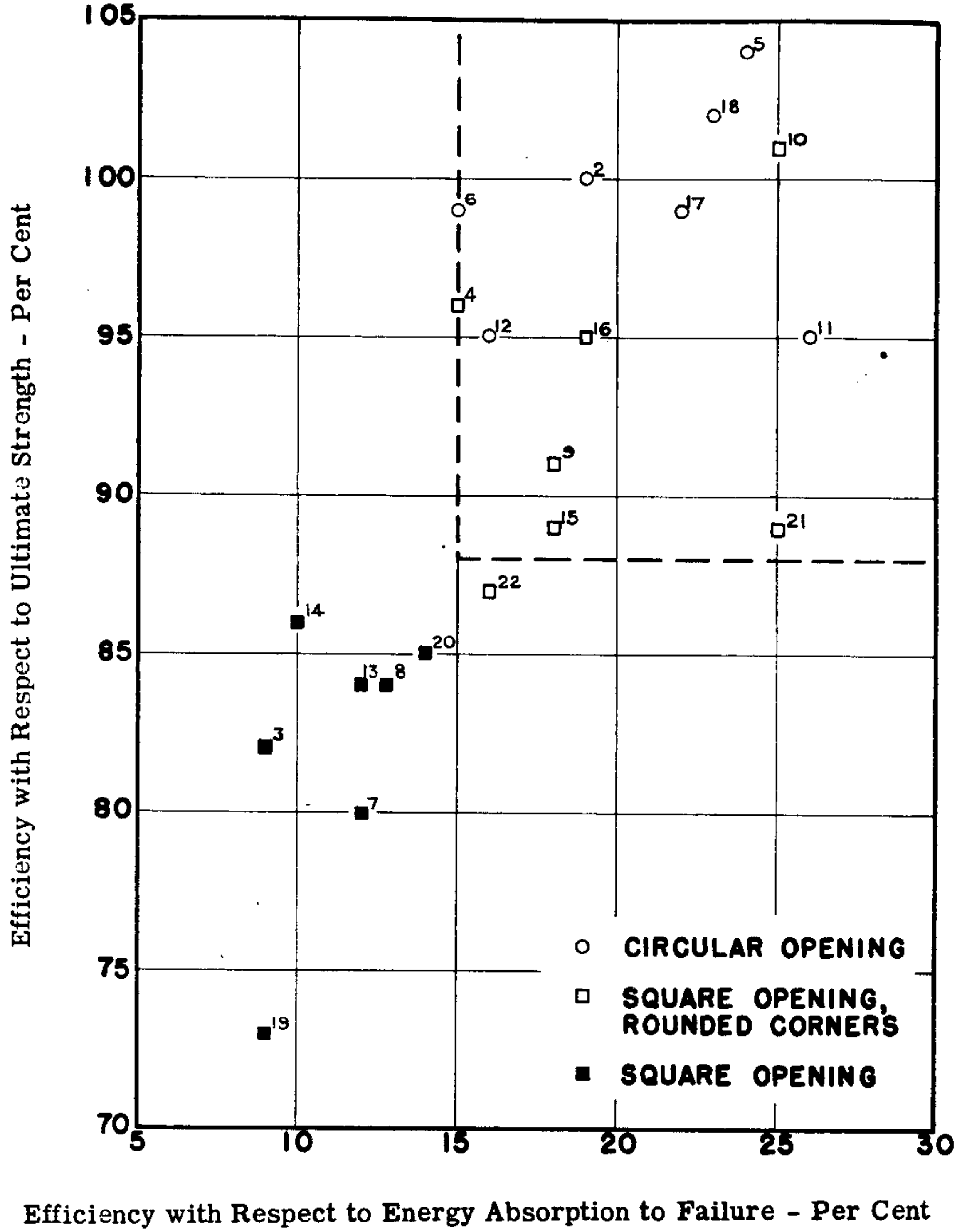


Fig. 50. Comparison of Efficiencies with Respect to Ultimate Strength and Energy Absorption to Failure for Plates with Openings.

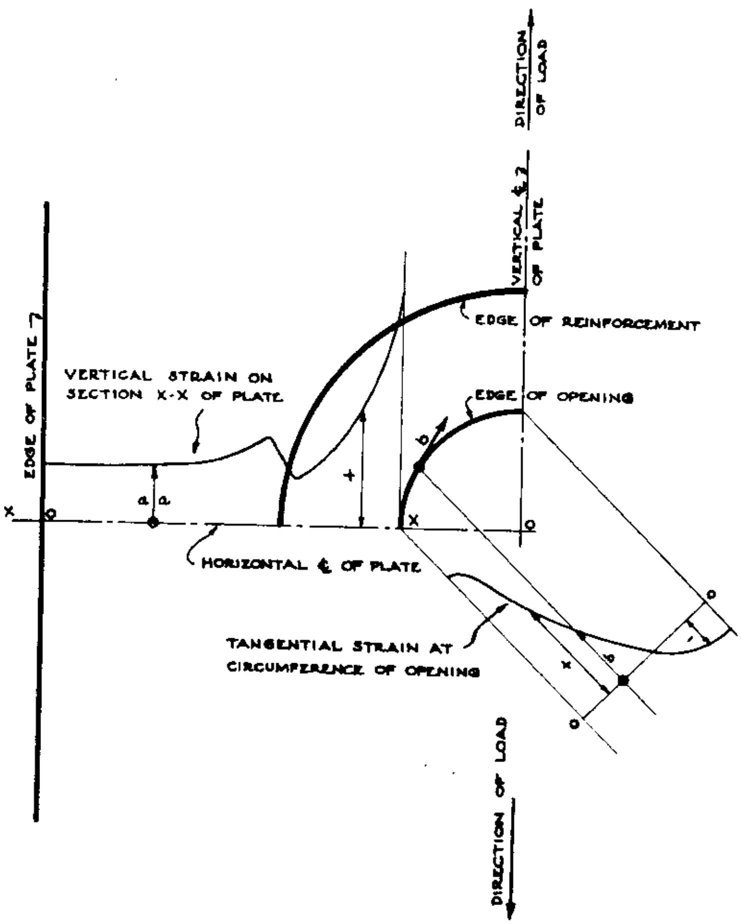


Fig. 51. Sketch Showing Method of Presentation of Unit Strain Concentration in Plates with Openings.

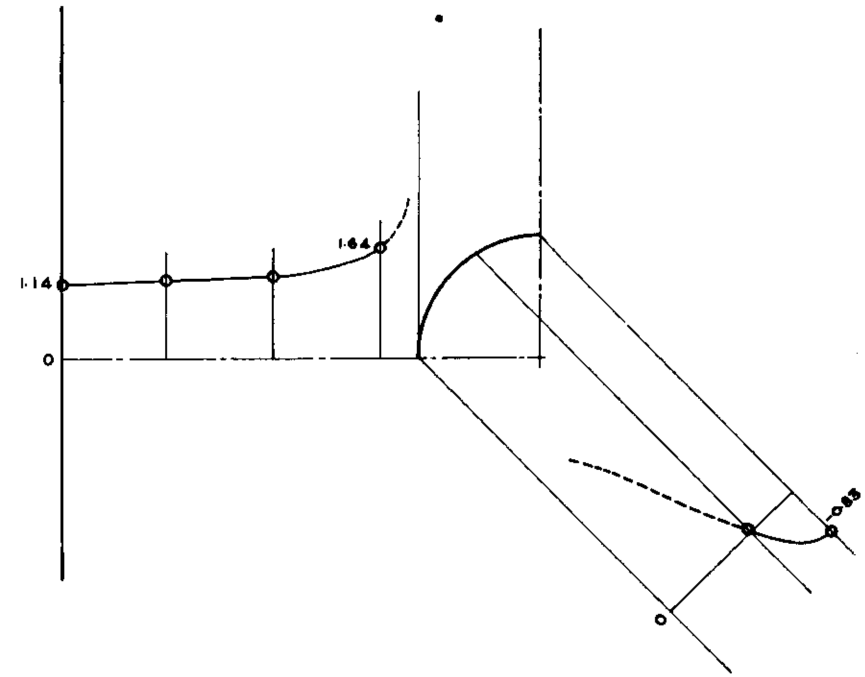


Fig. 52. Unit Strain Concentration in Region of Opening. Spec. No. 2. Circular Opening. No Reinforcement.

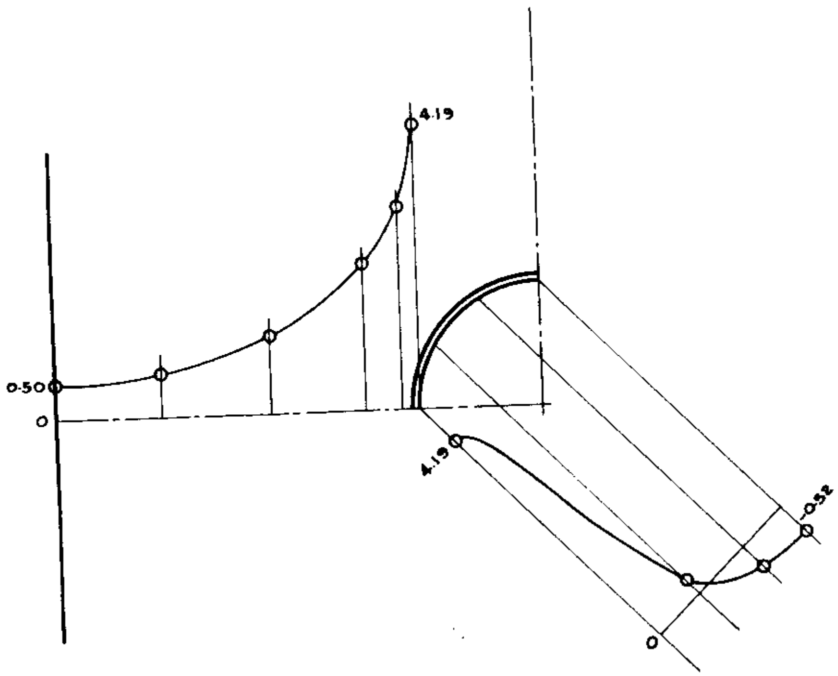


Fig. 53. Unit Strain Concentration in Region of Opening. Spec. No. 5. Circular Opening. Face Bar Reinforcement.

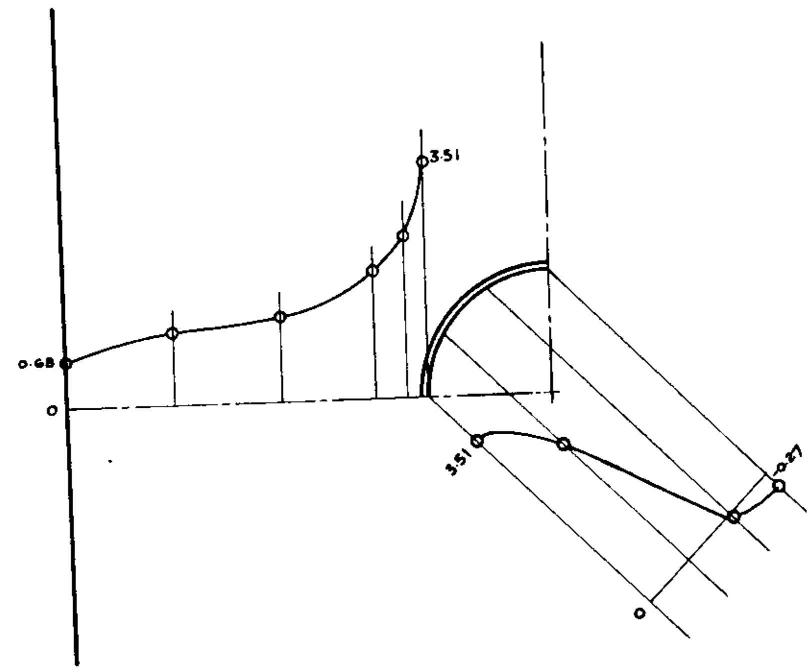


Fig. 54. Unit Strain Concentration in Region of Opening. Spec. No. 6. Circular Opening. Face Bar Reinforcement.

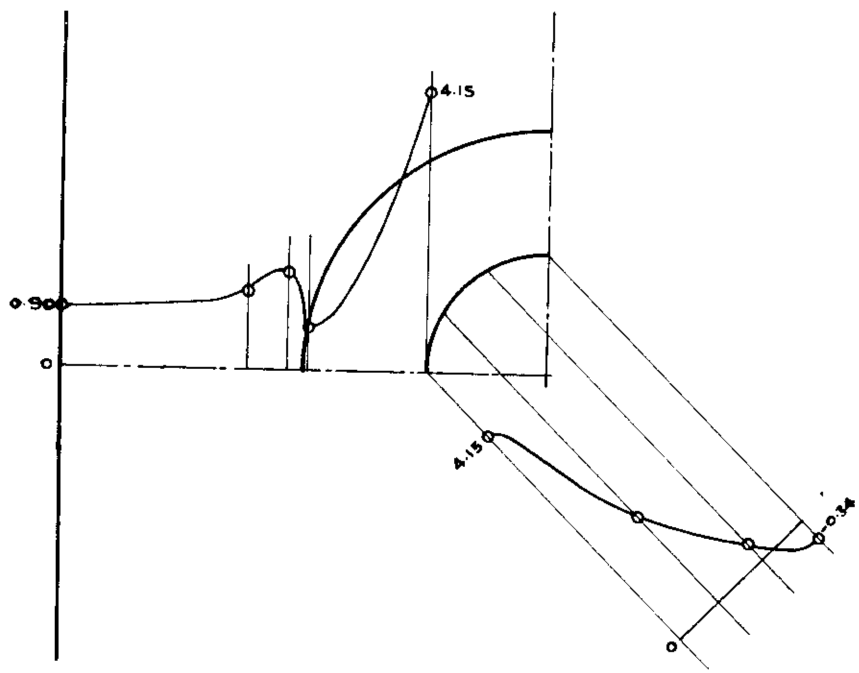


Fig. 55. Unit Strain Concentration in Region of Opening. Spec. No. 11. Circular Opening. Single Doubler Plate Reinforcement.

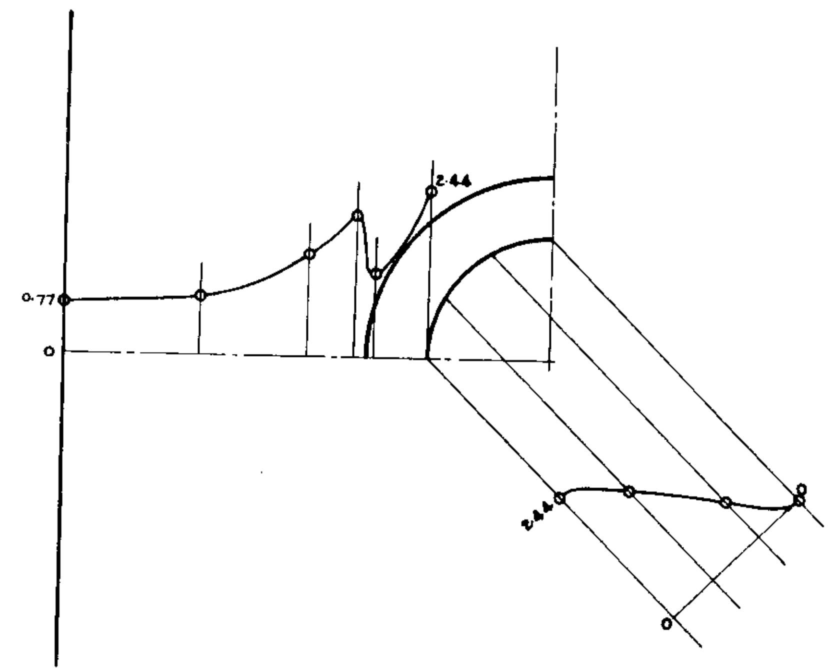


Fig. 56. Unit Strain Concentration in Region of Opening. Spec. No. 12. Circular Opening. Single Doubler Plate Reinforcement.

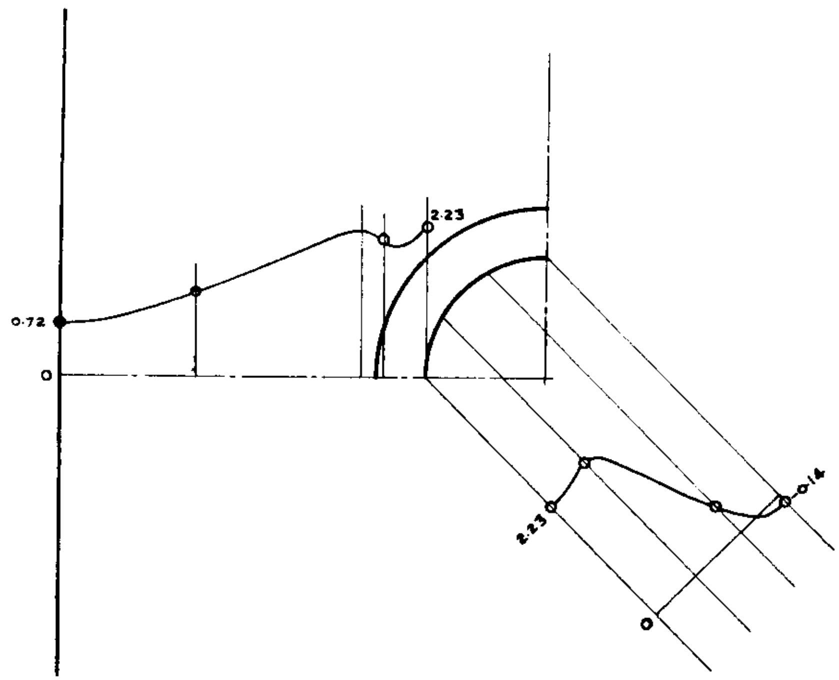


Fig. 57. Unit Strain Concentration in Region of Opening. Spec. No. 17. Circular Opening. Insert Plate Reinforcement.

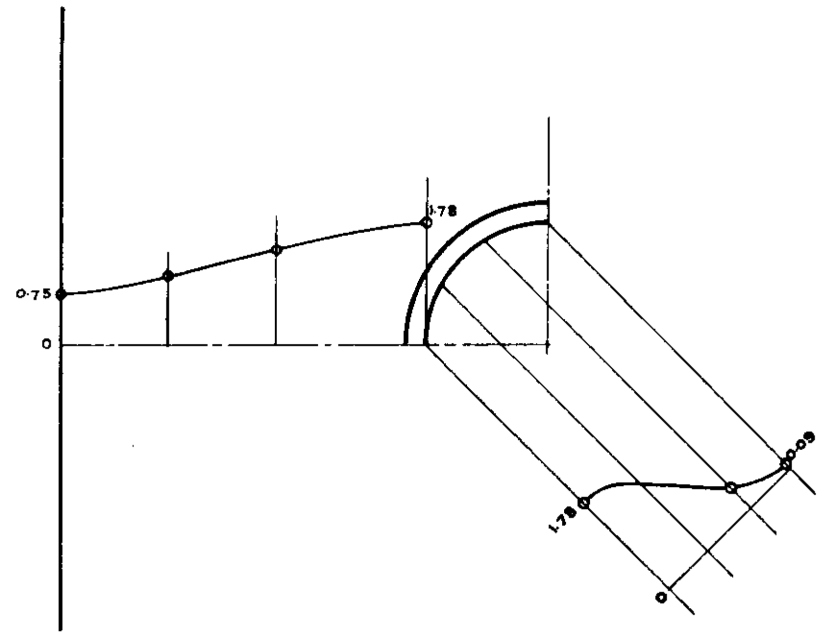


Fig. 58. Unit Strain Concentration in Region of Opening. Spec. No. 18. Circular Opening. Insert Plate Reinforcement.

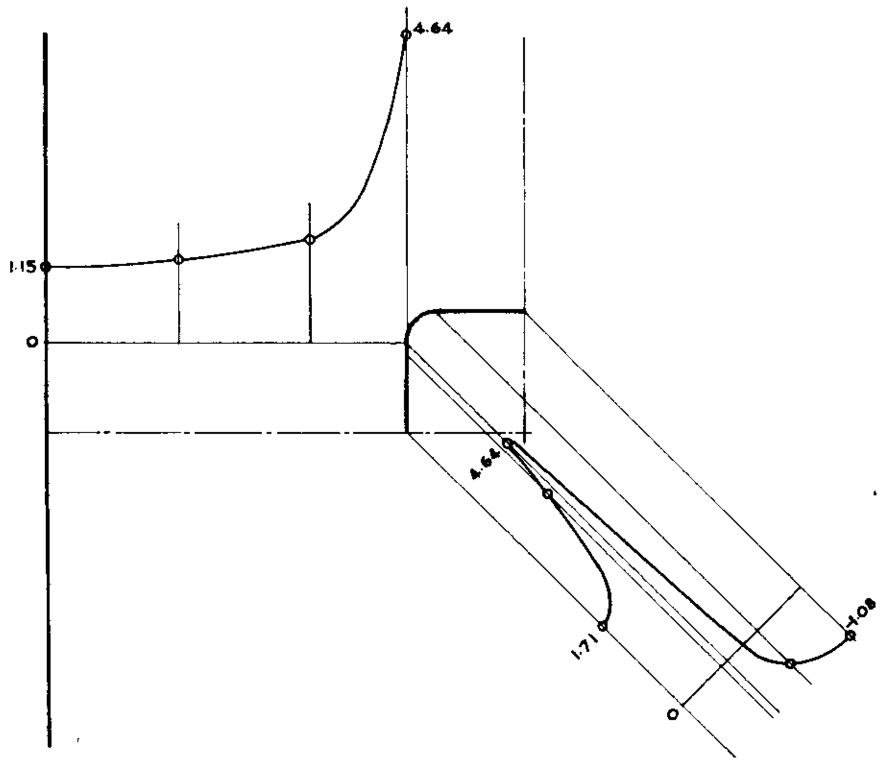


Fig. 59. Unit Strain Concentration in Region of Opening. Spec. No. 4.
Square Opening, Rounded Corners. No Reinforcement.

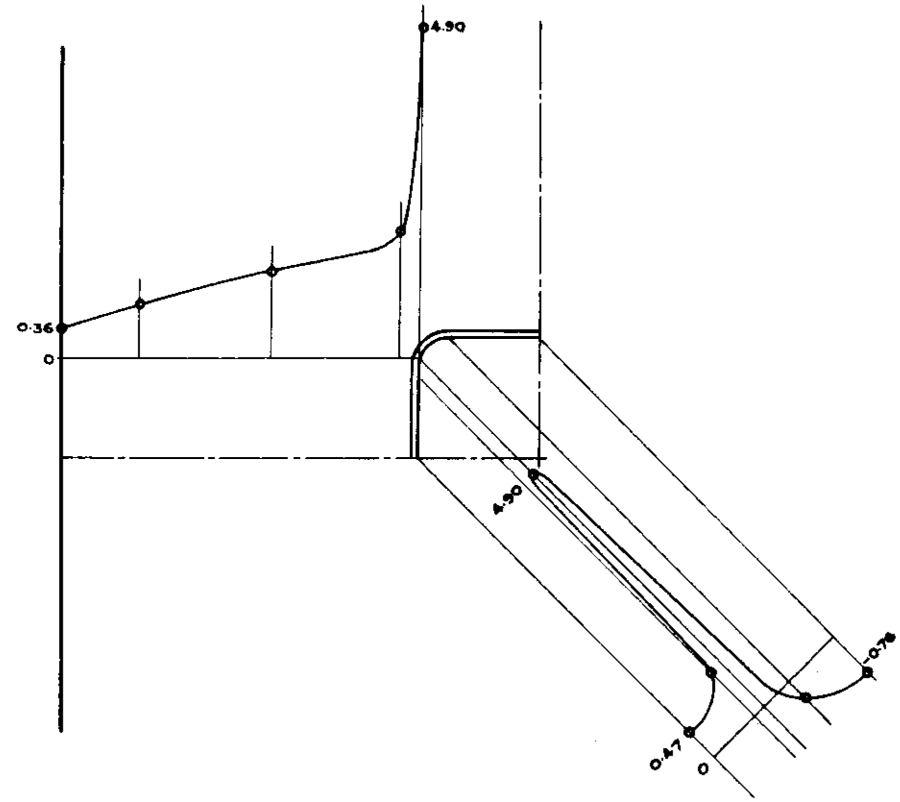


Fig. 60. Unit Strain Concentration in Region of Opening. Spec. No. 9.
Square Opening, Rounded Corners. Face Bar Reinforcement.

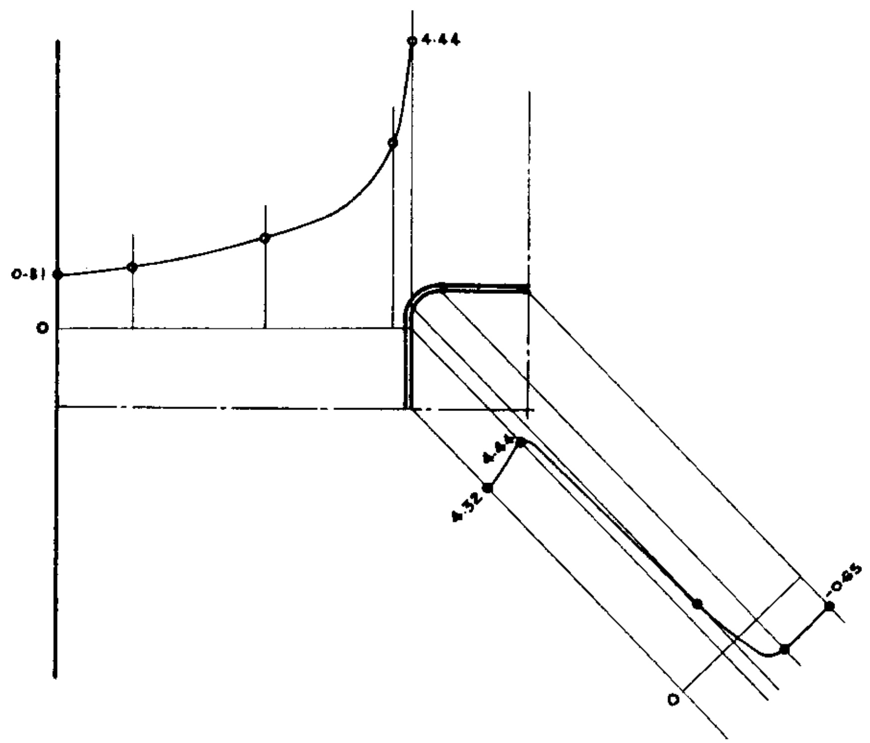


Fig. 61. Unit Strain Concentration in Region of Opening. Spec. No. 10. Square Opening, Rounded Corners. Face Bar Reinforcement.

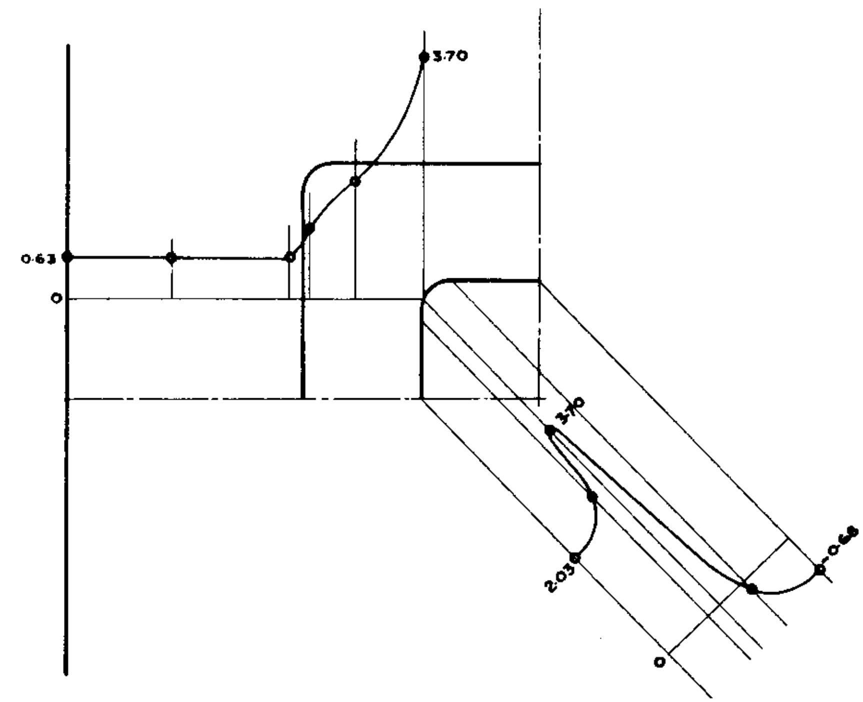


Fig. 62. Unit Strain Concentration in Region of Opening. Spec. No. 15. Square Opening, Rounded Corners. Single Doubler Plate Reinforcement.

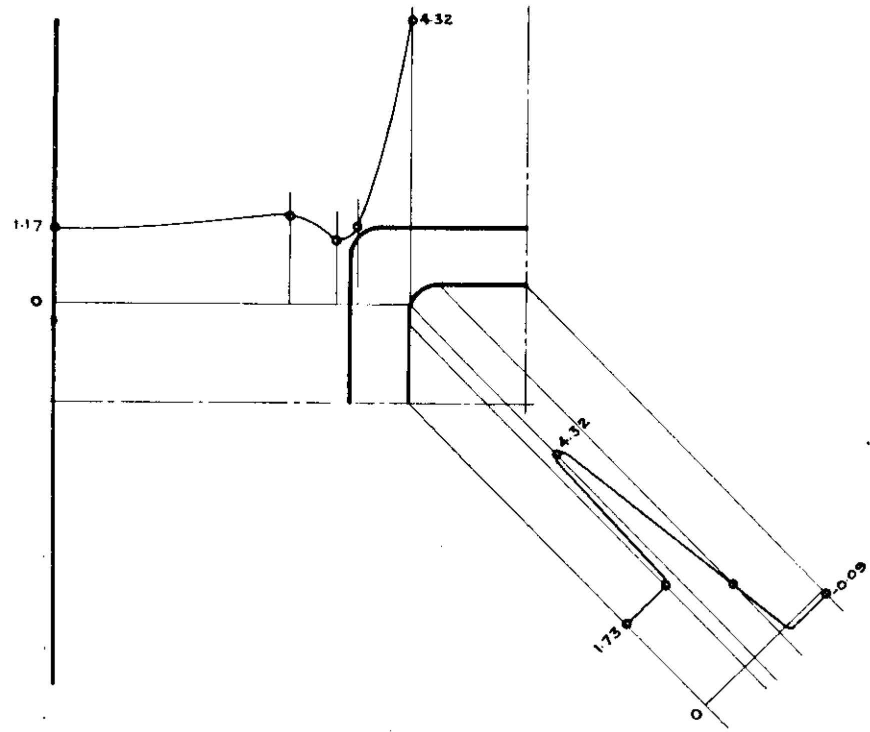


Fig. 63. Unit Strain Concentration in Region of Opening. Spec. No. 16. Square Opening, Rounded Corners. Single Doubler Plate Reinforcement.

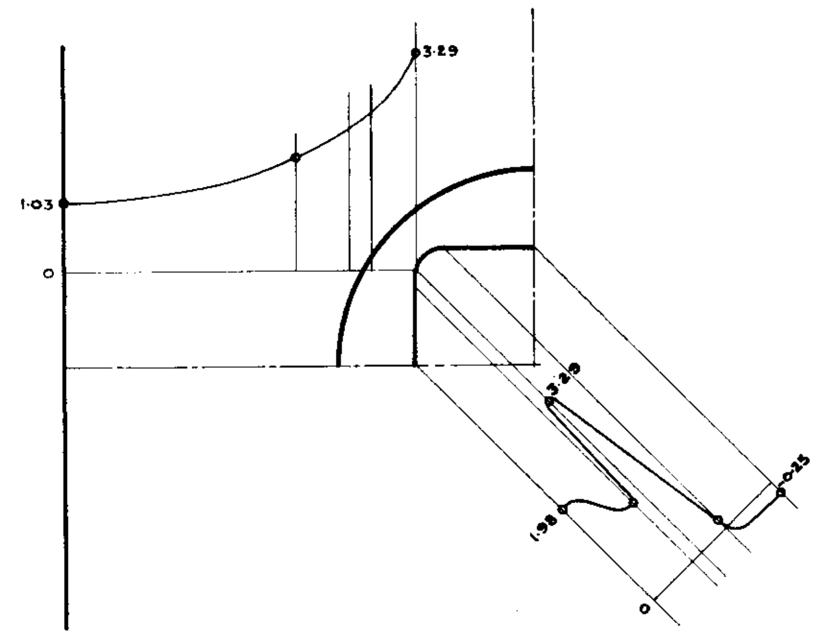


Fig. 64. Unit Strain Concentration in Region of Opening. Spec. No. 21. Square Opening, Rounded Corners. Insert Plate Reinforcement.

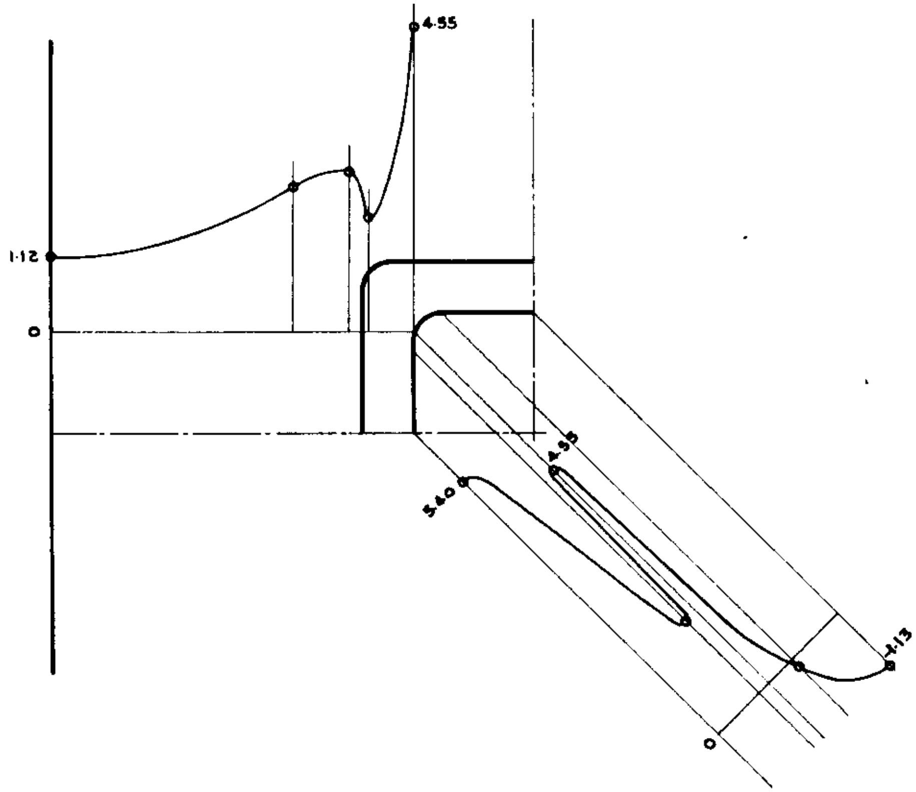


Fig. 65. Unit Strain Concentration in Region of Opening. Spec. No. 22. Square Opening, Rounded Corners. Insert Plate Reinforcement.

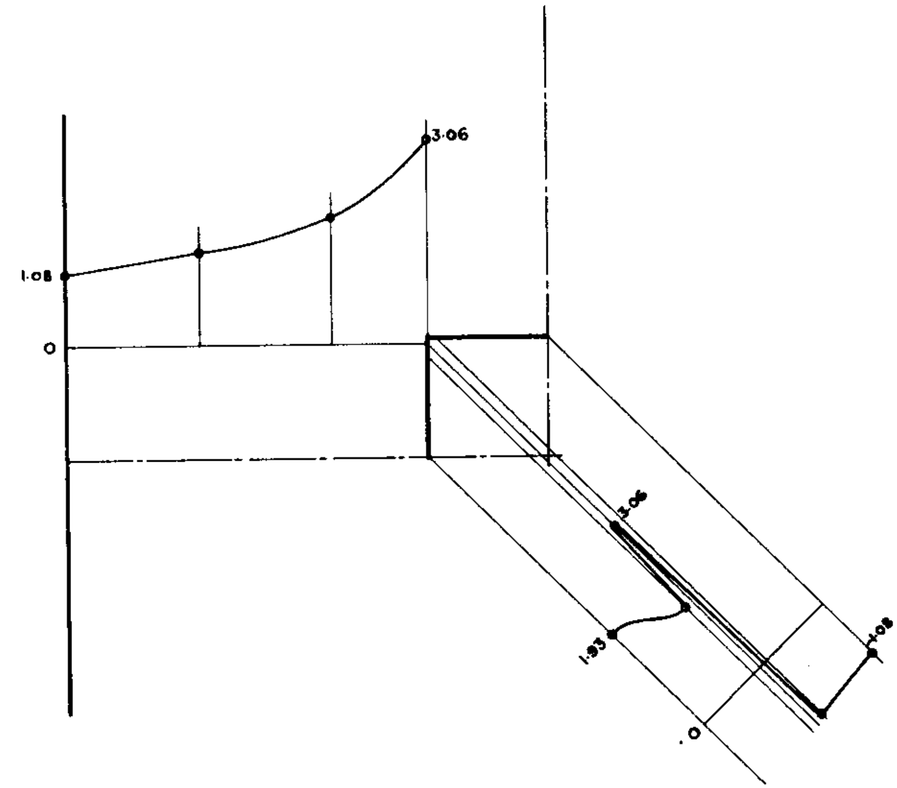


Fig. 66. Unit Strain Concentration in Region of Opening. Spec. No. 3. Square Opening. No Reinforcement.

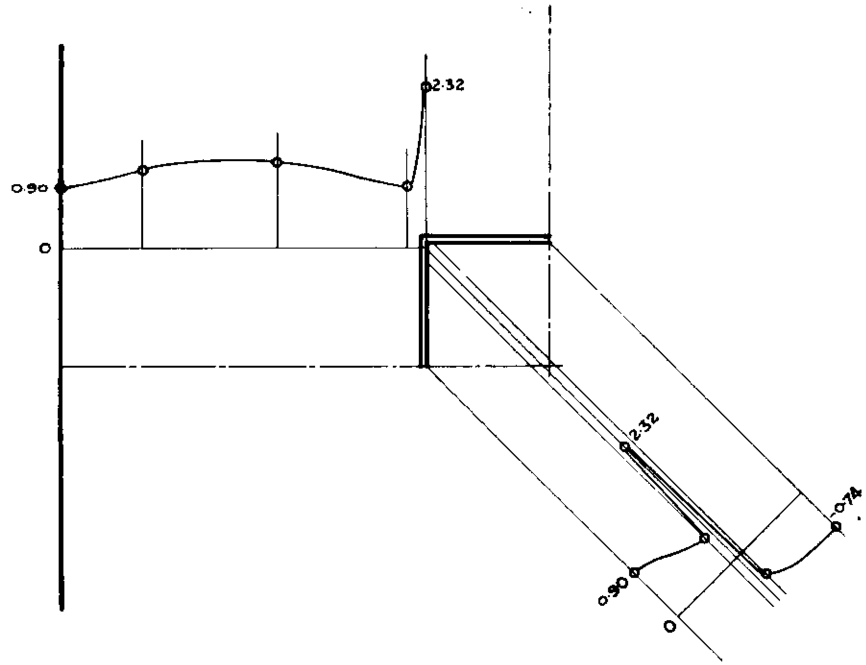


Fig. 67. Unit Strain Concentration in Region of Opening. Spec. No. 7. Square Opening. Face Bar Reinforcement.

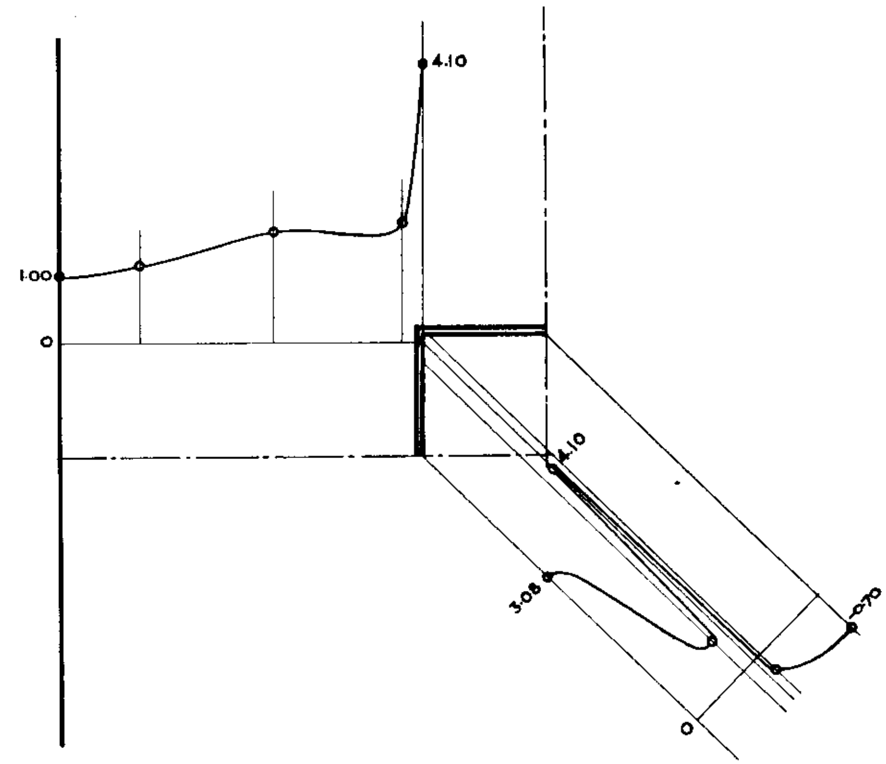


Fig. 68. Unit Strain Concentration in Region of Opening. Spec. No. 8. Square Opening. Face Bar Reinforcement.

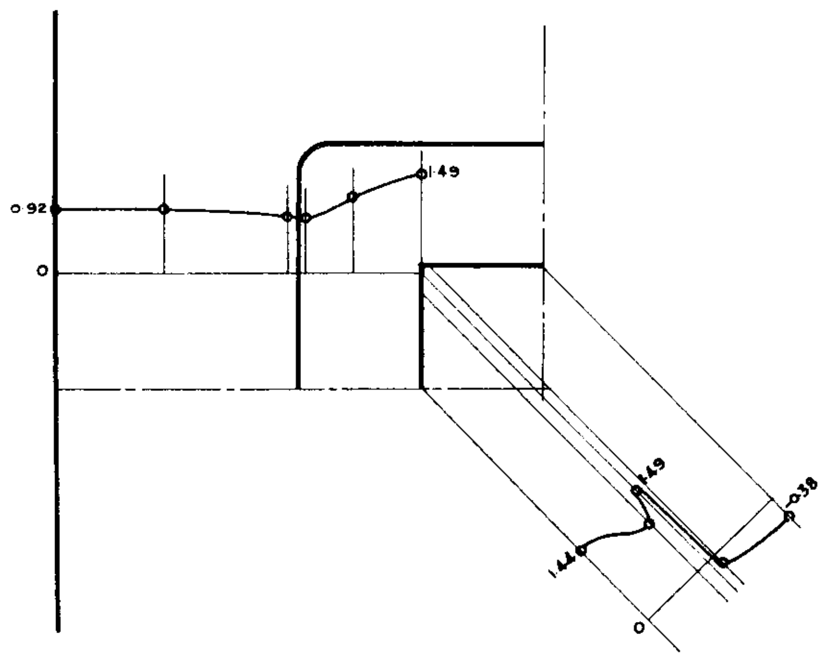


Fig. 69. Unit Strain Concentration in Region of Opening. Spec. No. 13. Square Opening. Single Doubler Plate Reinforcement.

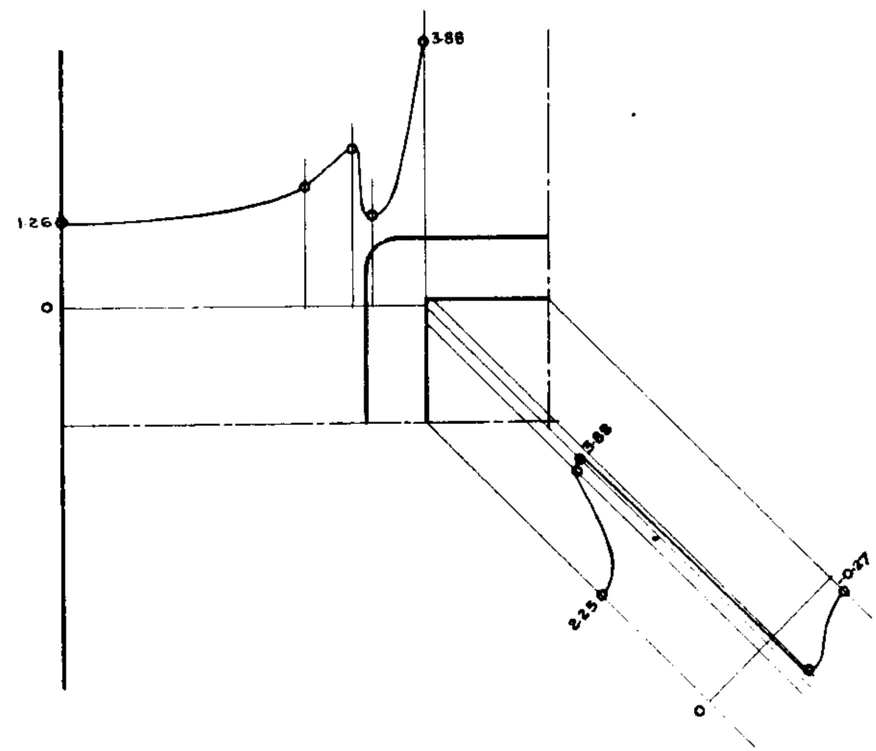


Fig. 70. Unit Strain Concentration in Region of Opening. Spec. No. 14. Square Opening. Single Doubler Plate Reinforcement.

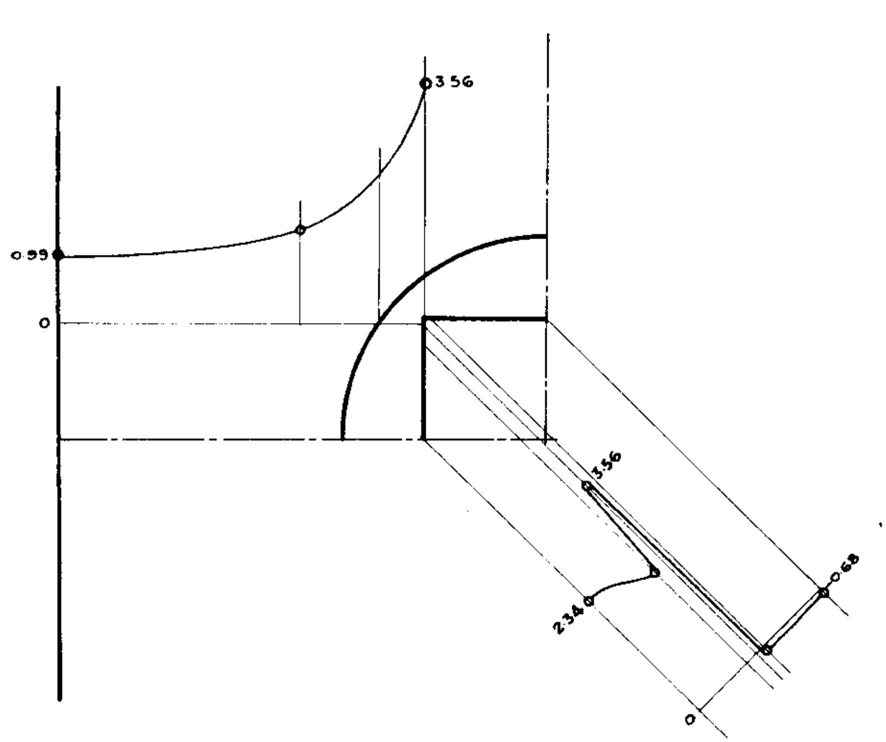


Fig. 71. Unit Strain Concentration in Region of Opening. Spec. No. 19. Square Opening. Insert Plate Reinforcement.

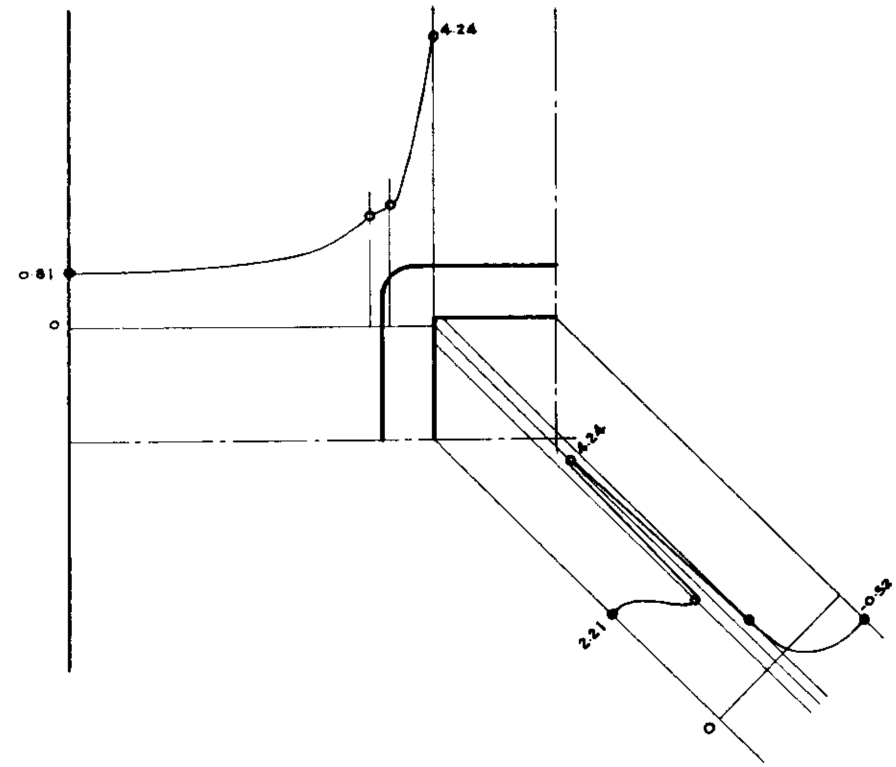
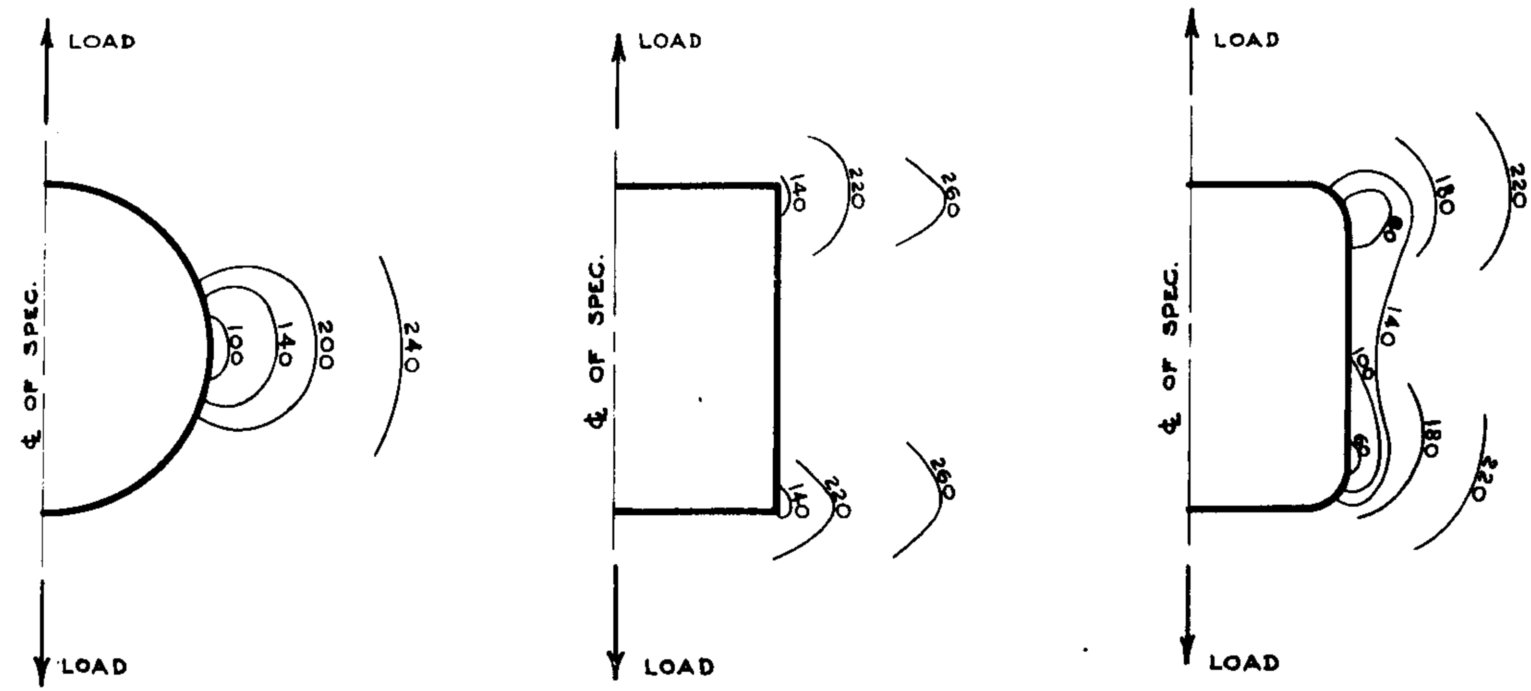


Fig. 72. Unit Strain Concentration in Region of Opening. Spec. No. 20. Square Opening. Insert Plate Reinforcement.

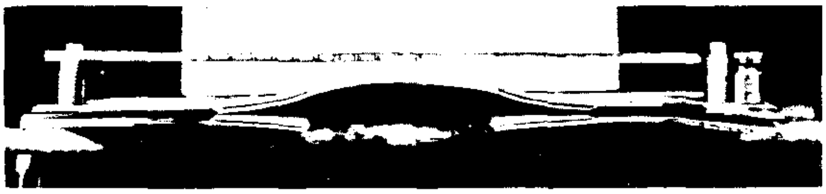


Spec. No. 2. Spec. No. 3. Spec. No. 4.

Fig. 73. Highly Stressed Regions around Openings of Unreinforced Plates as Indicated by Stresscoat Analysis. Three Shapes of Openings.

Spec. No. 11. 18"D x 1/4" Doubler Plate

Circular Opening.



Spec. No. 13. 18" x 18" x 1/4" Doubler Plate.

Square Opening.

Spec. No. 20. 12 3/4" x 12 3/4" x 1/2" Insert Plate

Square Opening

Fig. 74. Photograph of Rim of Opening which Buckled Laterally during Loading. Plates with Different Types of Reinforcement and Opening.

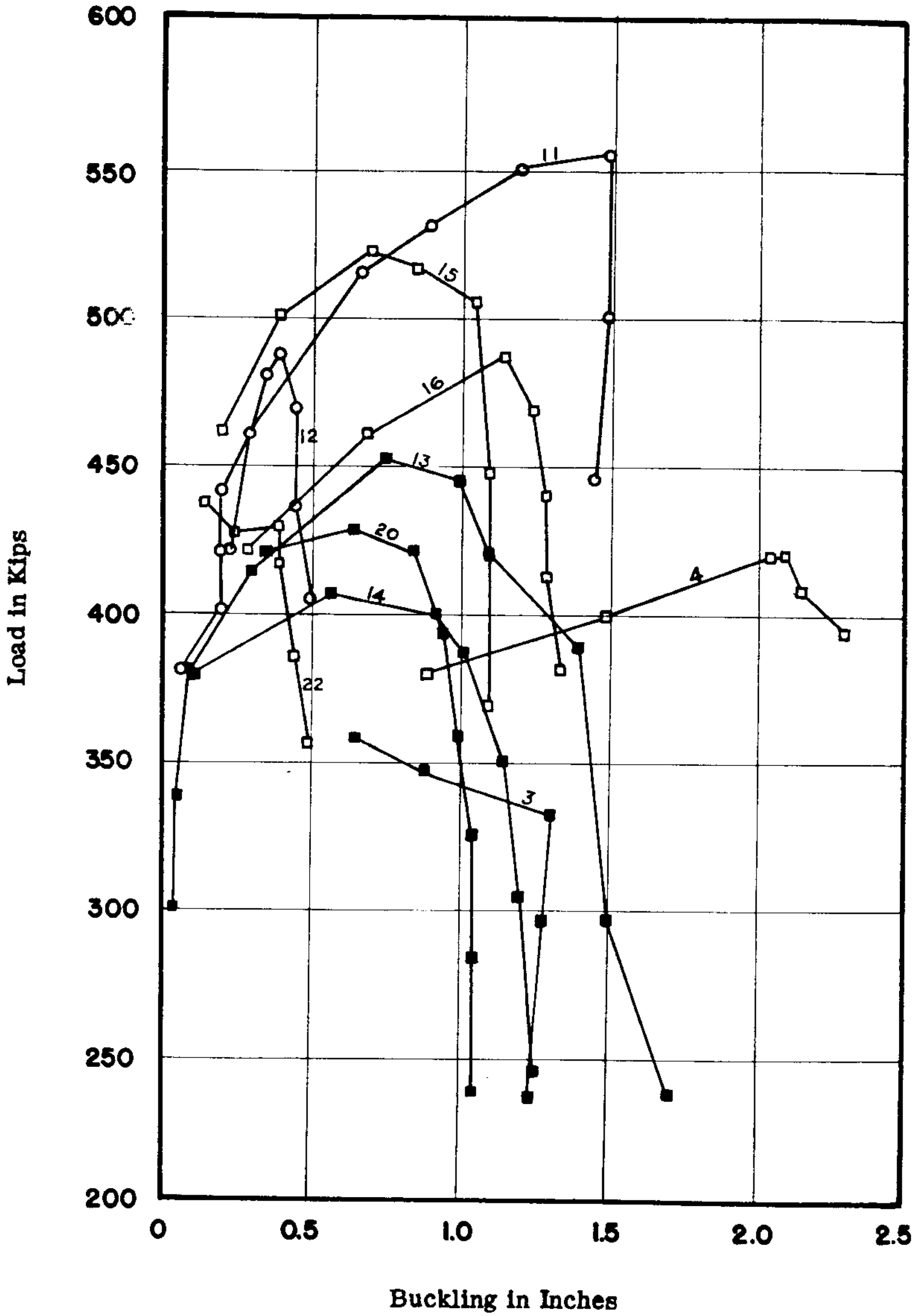
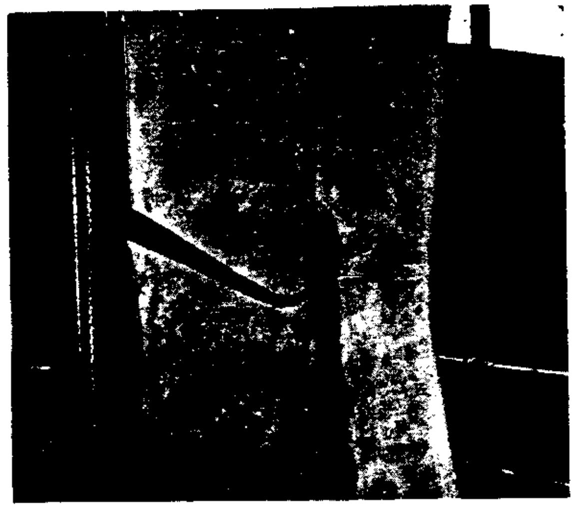
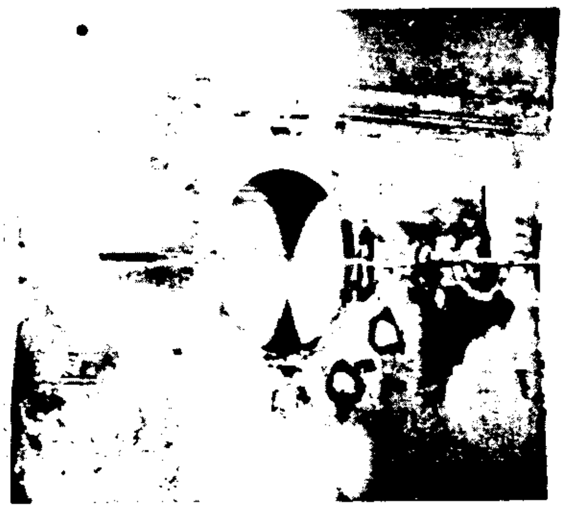


Fig. 75. Comparison of Load and the Maximum Lateral Deflection of the Buckled Edge of Opening in Plates with Openings.

Spec. No. 1

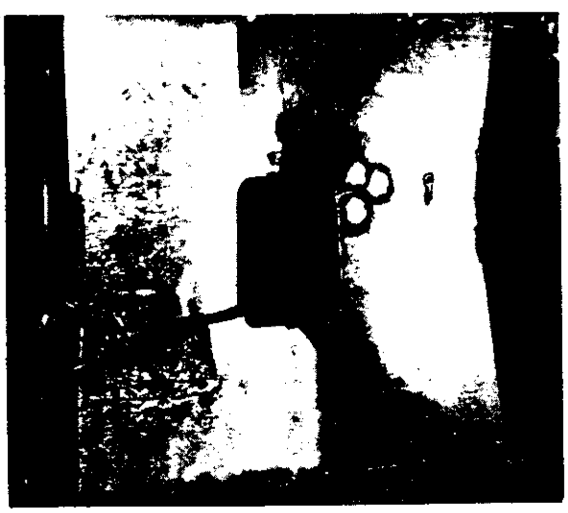


Spec. No. 23

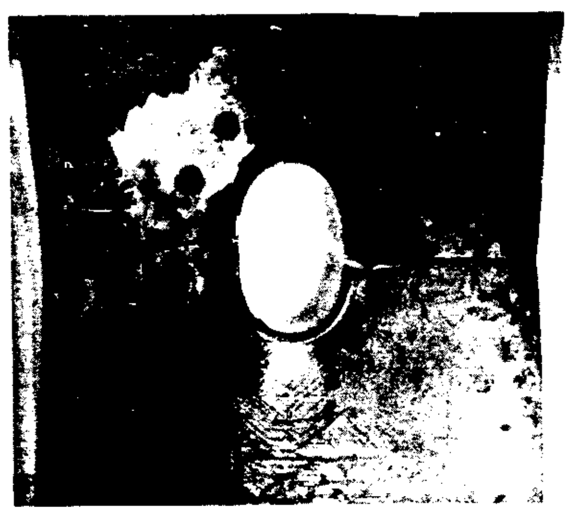


Spec. No. 2

Spec. No. 3

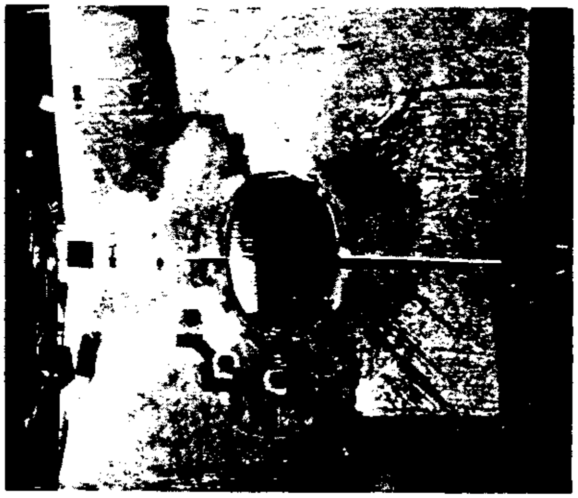


Spec. No. 4



Spec. No. 5

Fig. 76. Photographs of Plain Plates and Plates with Openings after Fracture



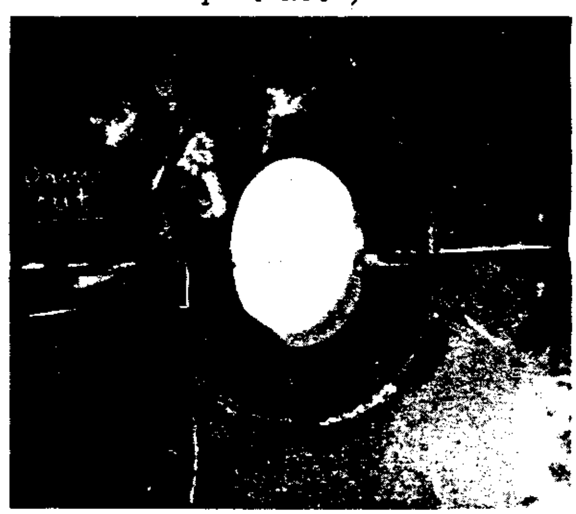
Spec. No. 6

Spec. No. 7

Spec. No. 8

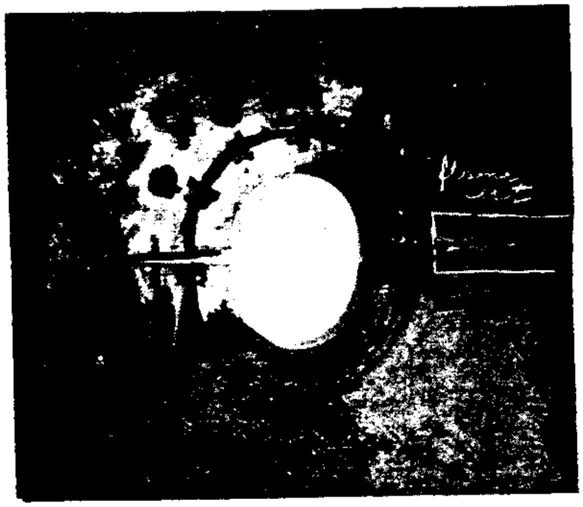
Spec. No. 9

Spec. No. 10

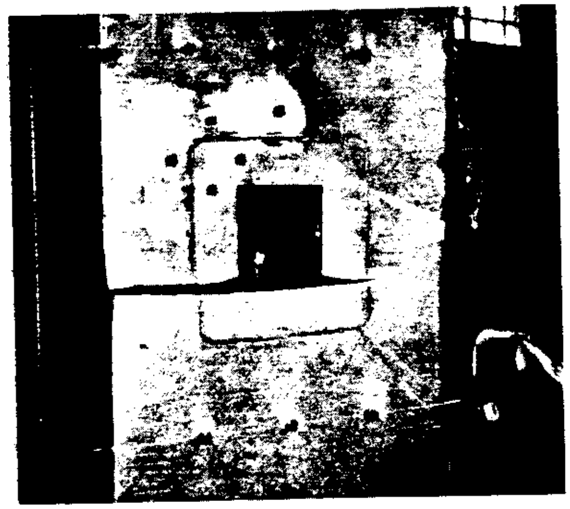


Spec. No. 11

Fig. 77. Photographs of Plates with Openings after Fracture



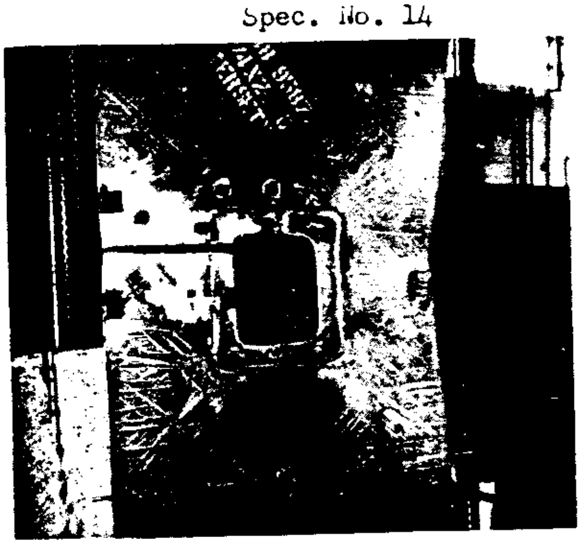
Spec. No. 12



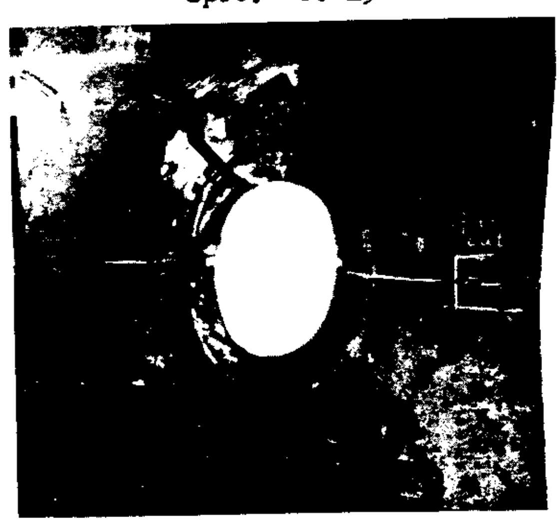
Spec. No. 13

Spec. No. 14

Spec. No. 15

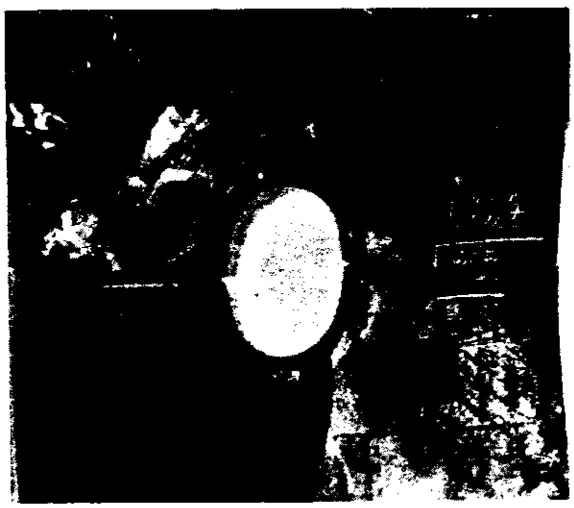


Spec. No. 16



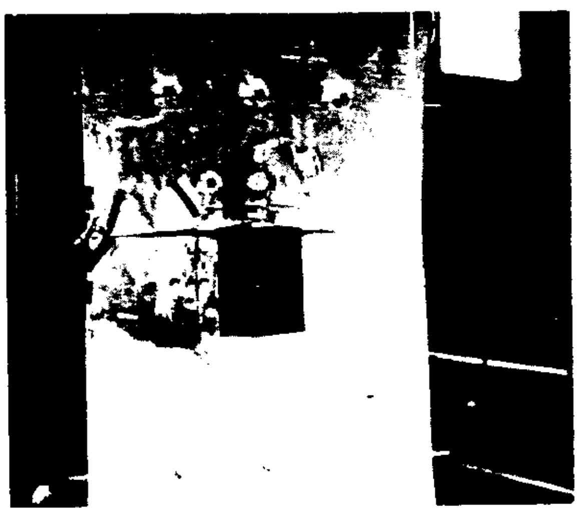
Spec. No. 17

Fig. 78. Photographs of Plates with Openings after Fracture.



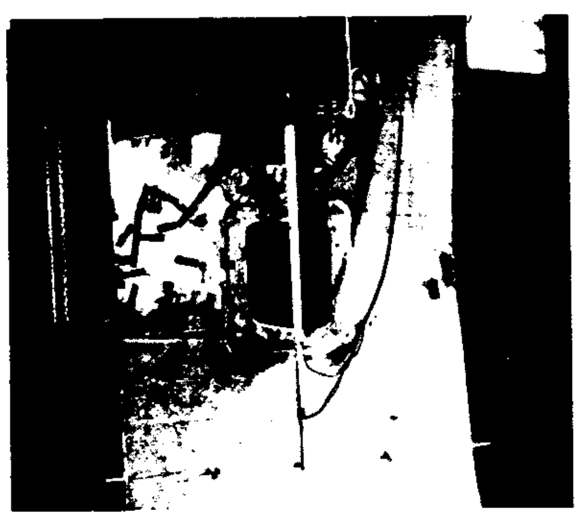
Spec. No. 18

Spec. No. 19



Spec. No. 20

Spec. No. 21



Spec. No. 22

Fig. 79. Photographs of Plates with Openings after Fracture

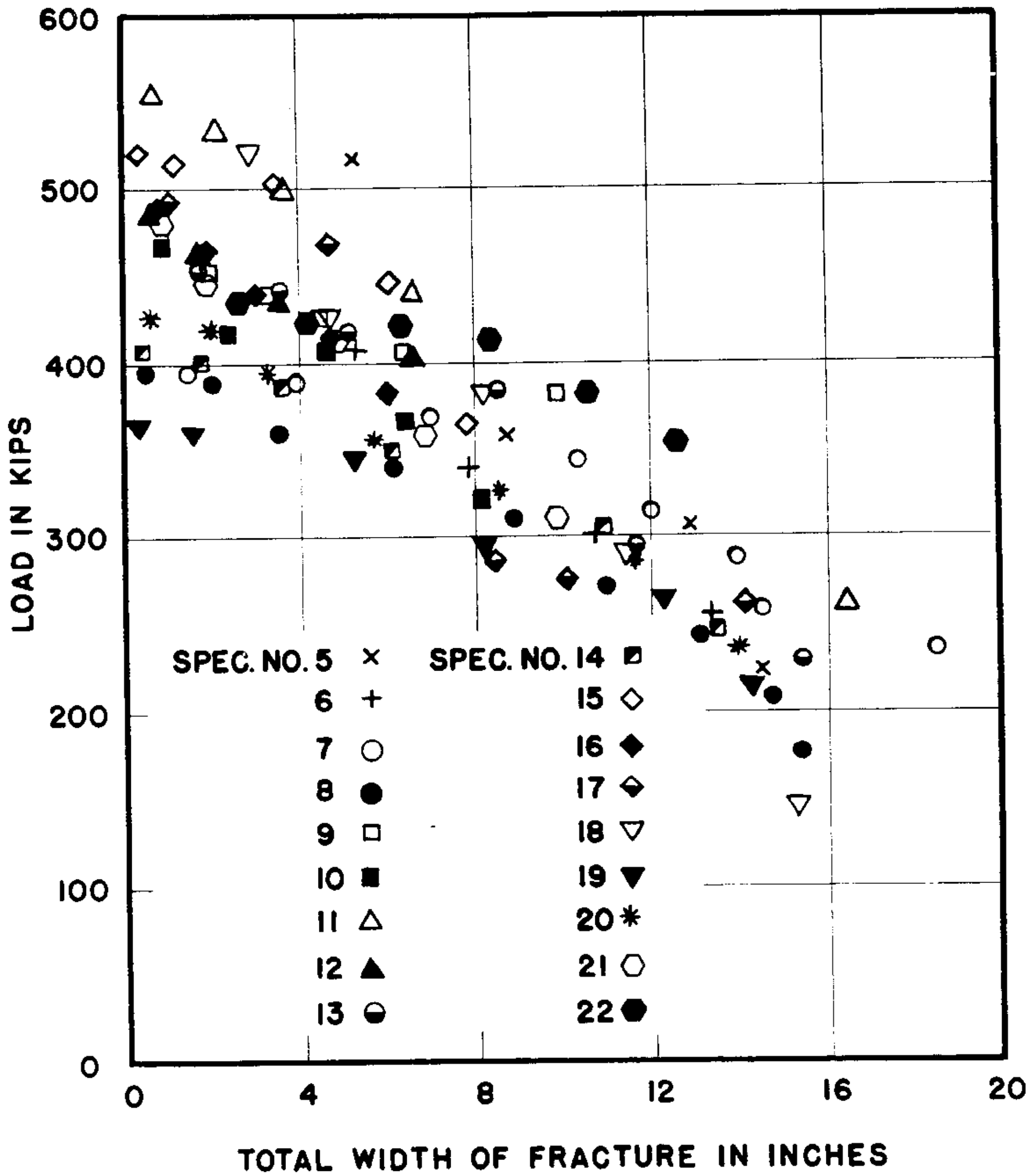


Fig. 80. Comparison of Total Load on Plate and Total Length of Fracture.

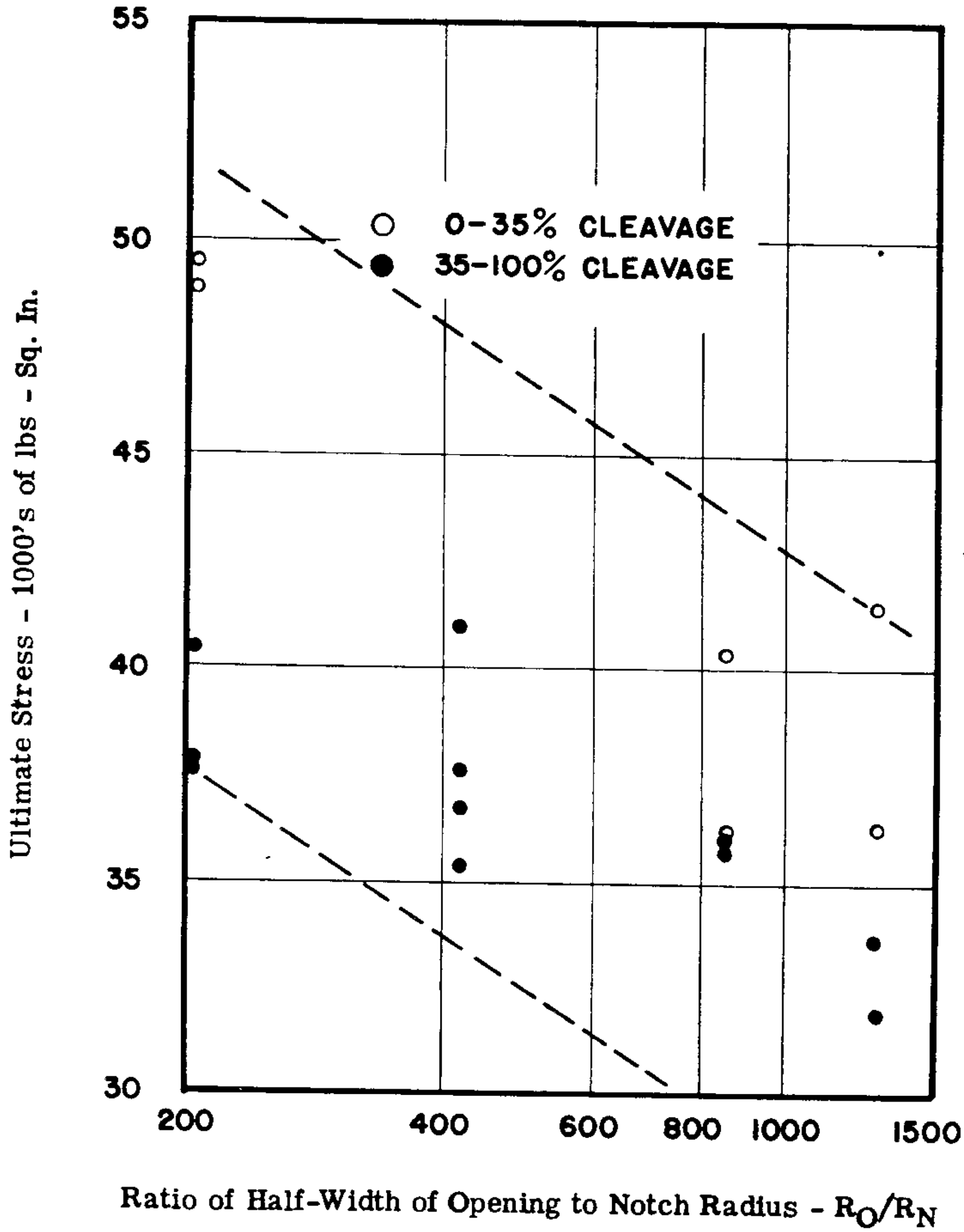


Fig. 81. Relation between the Ultimate Strength and the Notch Acuity of the Opening for Illinois Wide Plate Tests. Steel E as Rolled.

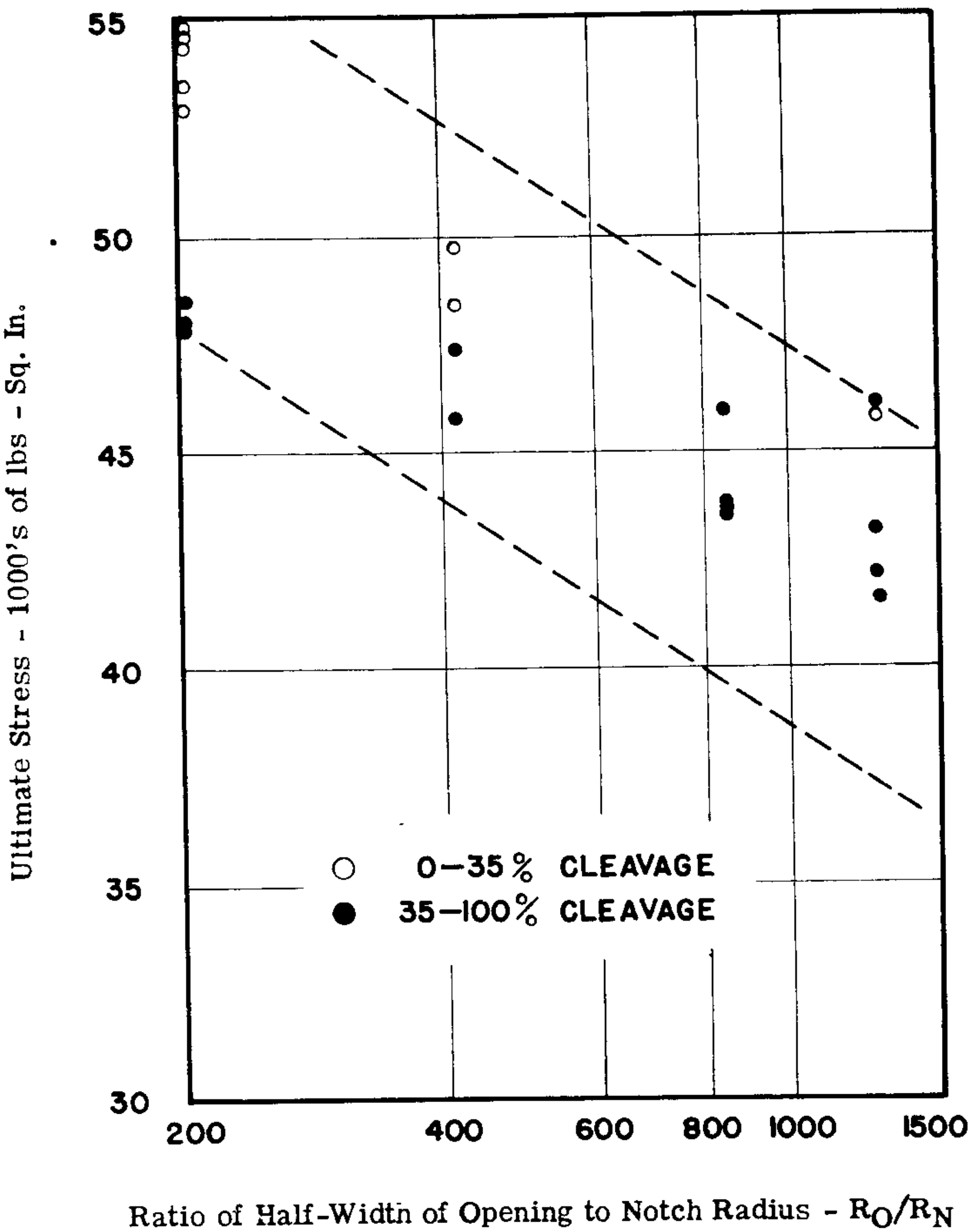


Fig. 82. Relation between the Ultimate Strength and the Notch Acuity of the Opening for Illinois Wide Plate Tests. Steel D as Rolled.

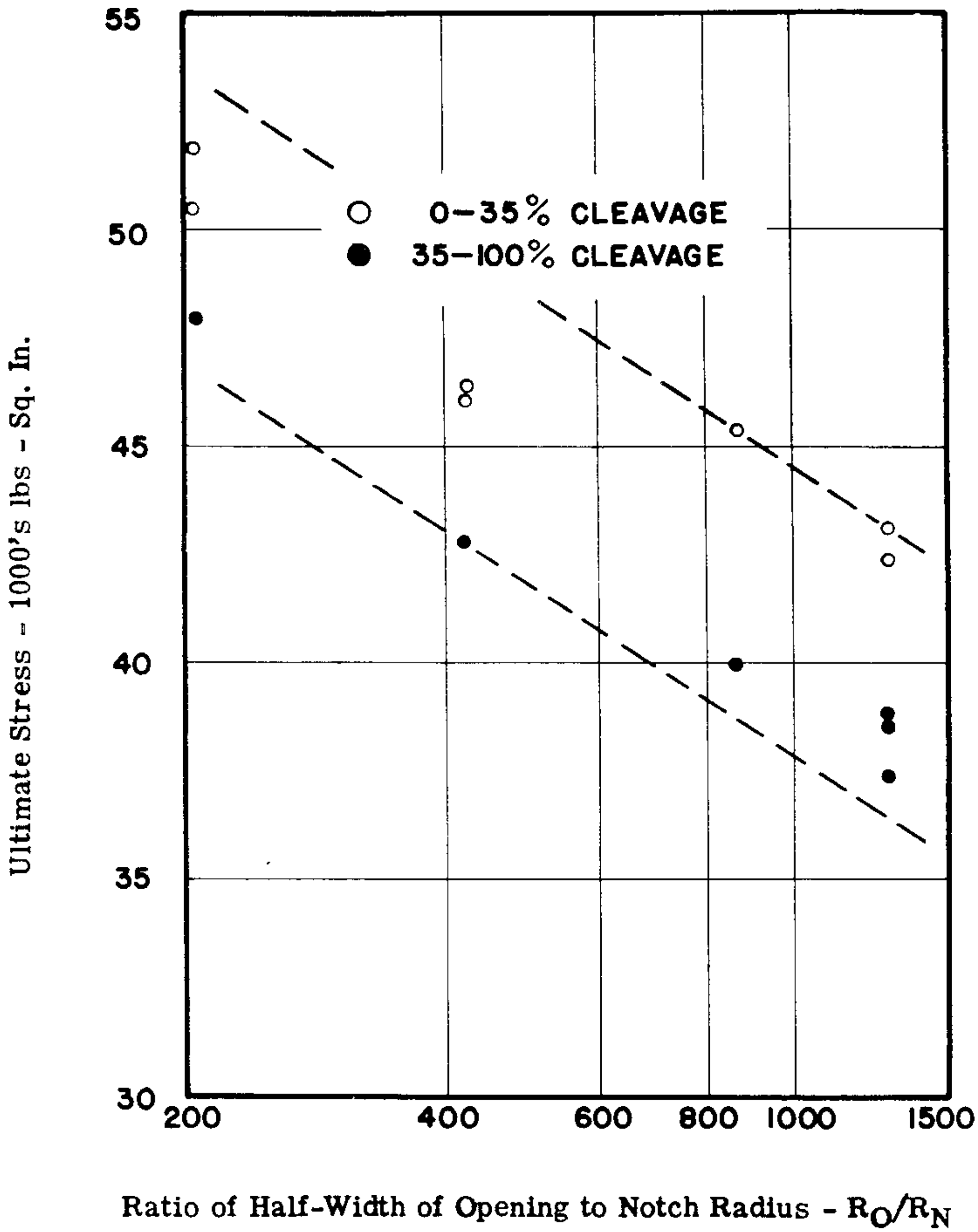


Fig. 83. Relation between the Ultimate Strength and the Notch Acuity of the Opening for Illinois Wide Plate Tests. Steel D Normalized.

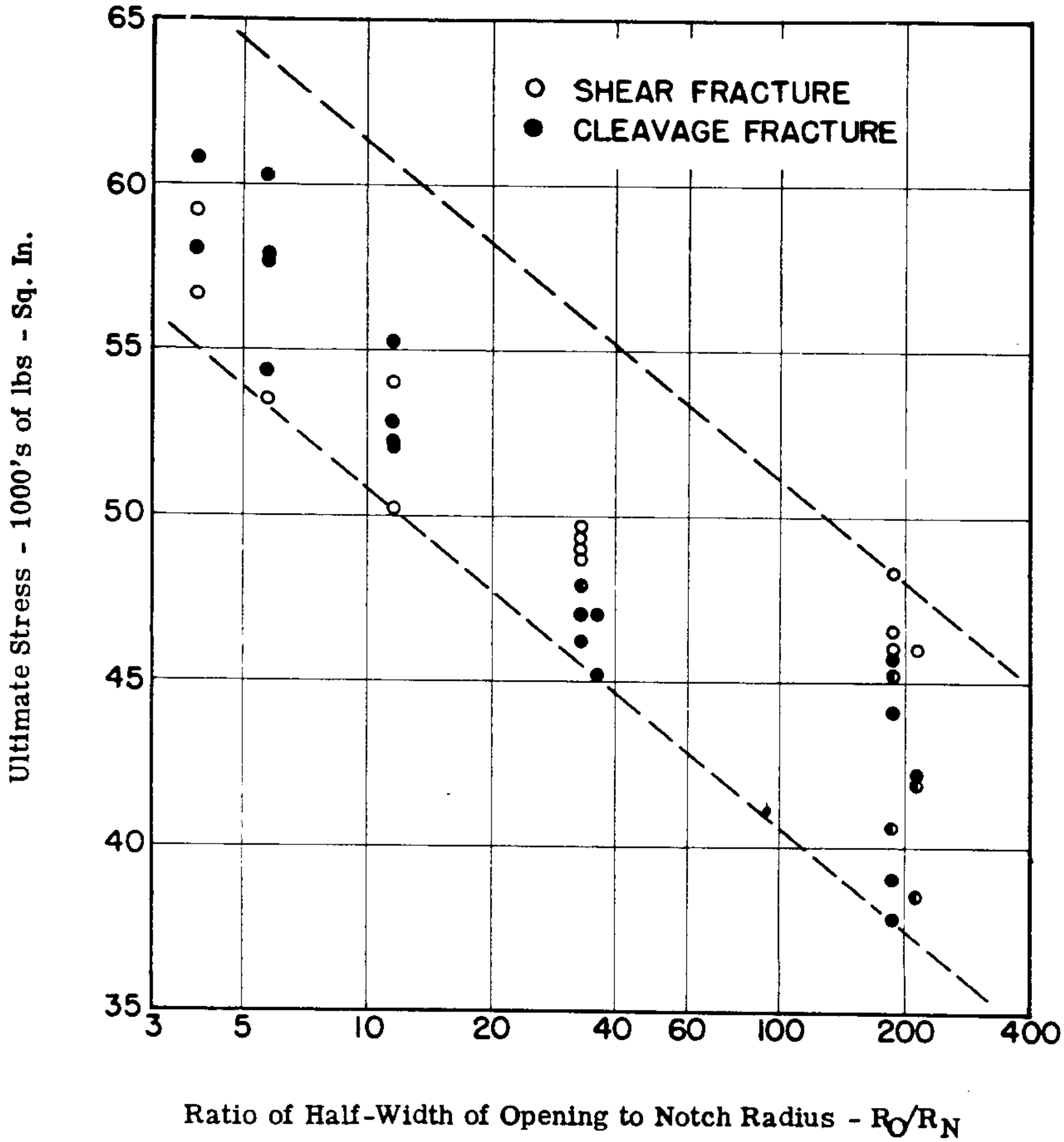


Fig. 84. Relation between the Ultimate Strength and the Notch Acuity of the Opening for Wide Plate Tests by Thomas and Windenburg. Steel E as Rolled.

APPENDIX A

REVIEW OF REFERENCES IN TECHNICAL LITERATURE ON OPENINGS IN PLATES

The analysis of the stress distribution and the stress concentration in the region of an opening in a plate is a common engineering problem encountered in the design of many types of structures. This problem has been the subject of many papers in the technical literature, and this section of the report will very briefly describe the scope of the more important papers. While this review of the technical literature has been rather extensive, it does not presume to have found all the available information of significance. A bibliography of the references is given at the end of this appendix.

1. Mathematical Analyses of Stresses in Plates with Openings.

The analysis of the elastic stresses in plates with openings by the methods of the theory of elasticity has been almost entirely limited to the solutions for plates of infinite dimensions and uniform thickness acted upon by uniform distributions of applied stress at the boundaries of the plate. These limitations have been imposed by the mathematical complexity of the procedure required to develop suitable stress functions for the problem.

The simplest case of an opening in a plate from the standpoint of mathematical complexity is that of the infinite plate of uniform thickness with a central circular opening, the plate being subjected to uniform uniaxial tension. Kirsch (3) published an approximate solution for this problem in 1898. The complete mathematical solution was given later by Föppl (4), Mesnager (5), and Wyss (6). These analyses lead to the well-known stress-concentration factor of three for the tension stress at the edge of the circular opening at the points on the centerline transverse to the direction of the applied stress. The factor of three is relative to the uniform tensile stress, which is applied to the plate along a section remote from the opening.

Inglis (7), Wolf (8), Durelli and Murray (9, 10) extended these solutions to the case of an elliptical opening located in an infinite plate of uniform thickness. For a uniformly applied uniaxial tensile stress on the plate, they found that the stress-concentration factor at the edge of the opening lying on the transverse centerline varied from one to three, if the major axis of the elliptical opening were parallel to the applied stress and from three to infinity, if the minor axis were parallel to the applied stress.

Many of these solutions also treat the cases where pure shear or combinations of pure shear and direct stress are applied to the boundaries of the plate.

The solutions for the case of a square opening in an infinite plate of uniform thickness are much more difficult. No "exact" solutions were found to have been made, principally because of the difficulty of expressing the shape of a square opening mathematically. By approximating a square opening by an ovaloid with a very small corner radius, Greenspan (11) found the points of maximum stress concentration in an infinite plate under uniformly applied uni-axial stress. If the two sides of the square opening were parallel to the applied stress, the four points of maximum stress concentration fell very close to the corners of the opening and on the sides of the opening parallel to the applied stress. If the diagonal of the square opening were parallel to the applied stress, the two points of maximum stress concentration were located at the corners of the square opening lying on the transverse centerline.

The problem of the triaxial stress concentration on the edge of a circular opening in an infinite plate of uniform thickness was investigated by Sternberg and Sadowsky (12), who found that triaxial stresses need to be considered only when the ratio of the diameter of the circular opening to the thickness of the plate is less than 30.

A very comprehensive coverage of the various theoretical analyses was published by Neuber (13).

The effect of strains in the plastic range of the material was investigated by Stowel (14). He found the stress and strain concentration factors to be a function of the secant modulus of the material.

The one solution for a plate of finite width and uniform thickness is that by Howland (15) for a centrally-located circular opening and a uniform uni-axial stress applied in the infinite direction of the plate. If r is the radius of the opening and b the half-width of the plate, the stress-concentration factor at the two points of the opening on the transverse centerline varies from 3 to 4.32 as the ratio r/b changes from zero (plate of infinite width) to 0.5. The stress at the outer edges of the plate on the transverse centerline varies from 0.99 to 0.73 as r/b changes from 0.1 to 0.5.

In all these analyses, the authors found zones of compressive stress adjacent to the edges of the opening which lay on each side of the transverse centerline, when the stress was applied in the longitudinal direction of the plate, and reported a stress in these regions almost as great as in the regions of tensile stress. No mention was found of the possibility of lateral buckling of the plate in the regions of compressive stress if the thickness of the plate became sufficiently small.

The effect of a simple type of reinforcmenet around a circular opening in a plate of infinite extent and of uniform thickness except for the reinforcement was investigated by Gurney (16), Beskin (17), Reissner and Morduchov (18). The applied stress on the plate could be uniform uniaxial or biaxial stress or uniform shear. Gurney analyzed the case of a ring around the opening, while Beskin solved the cases of reinforcement by a ring, by a rim and by the ring and the rim combined. Both authors supplied tables of values to be used for stress computation.

The mathematical analyses of the effect of reinforcement upon the elastic stresses in the region of the opening point to several important facts:

1. An increase in the amount of reinforcement decreases the circumferential stress, but this decrease is not proportional to the increase in the amount of reinforcement.
2. An incaease in the amount of reinforcement increases the maximum shear stress at the outer boundary of the reinforcement. Thus, it is not possible for reinforcement to develop in the plate with an opening the strength of a solid plate.

3. The cross-section area of the reinforcement on the transverse centerline is more effective upon the values of the stresses than the bending stiffness of the reinforcement at the same cross section.

2. Experimental Determination of Stresses in Plates with Openings.

Some experimental investigation of the stresses in plates with openings has been carried out. Most of this work was concerned with the verification of information obtained from the theoretical solutions.

Kirsch (3) and Preuss (19) investigated plates of finite width and uniform thickness with a centrally-located circular opening. For uniformly applied uni-axial stress, they found good correlation between the values derived from experiment and those from theory. Preuss determined the effect of varying the ratio of the diameter of the opening to the width of the plate and found values of the stresses which were in good agreement with those computed theoretically at a later date by Howland (15). Similar results were published by Hill and Barker (20) for plates of various aluminum alloys.

Analysis of the stresses around openings by the photo-elastic method was made by Durelli and Murray (9, 10), and Frocht (21) for the cases of the circular and the elliptical openings and by Coker and Kimball (22) and Heymans (23) for the case of the square opening with rounded corners, the two sides of the square opening being parallel to the applied tension. Uni-axial stress was used in these investigations.

The stresses in stiffened steel compression members under uni-axial stress were determined for square and rectangular openings by Stang and Greenspan (24, 25). Similar experiments on stiffened aluminum-alloy panels in tension and in bending with circular and rectangular openings were made by Farb (26) and Kuhn, Duberg, and Diskin (27).

Good correlation with theoretical analyses was found in experimental investigations of reinforcement around circular openings in aluminum-alloy specimens by Kroll and McPherson (28), Levy, Woolley, and Kroll (29), and Griffith (30). Griffith showed that the data for flat plates could be applied to curved plates if the ratio of the radius of curvature of the latter to the radius of the opening was not less than four. The other investigators reported the lower limit of this ratio as six, while Timoshenko (31) gives a value of five.

Because of the difficulty of measuring accurately the strains in the very small regions of high strain concentration, the maximum measured strains in the experimental reports were often not so large as those predicted by theory. Moreover, the plastic flow that occurred in these regions at low loads made satisfactory observations difficult.

One reference was found on the effectiveness of arc-welded reinforcement, an investigation of the strength developed by different types of reinforcement around circular and square openings by the David Taylor Model Basin (32).

3. Bibliography.

1. Wilson, W. M., Hechtman, R. A., Bruckner, W. H., Cleavage Fracture of Ship Plates as Influenced by Size Effect, Welding Journ., 1948, Vol. 27, p. 200-s.

2. Thomas, H. R., Widenburg, D. F., A Study of Slotted Tensile Specimens for Evaluating the Toughness of Structural Steel, Welding Journ., 1948, Vol. 27, p. 209-s.

3. Kirsch, G., Die Theorie des Elastizitaet und die Beduerfnisse der Festigkeit, Zeit. V.D.I., 1898, Vol. II, p. 797.

4. Foeppl, A., Vorlesungen ueber technischen Mechanik, 1907, Vol. 5, p. 352.

5. Mesnager, A., Determination experimentale des efforts interieurs dans les solides, Mem. des Sciences Physiques, F.X., 1929, Chap. 31.

6. Wyss, T., Die Kraftfelder in festen elastischen Koerpern, 1926, Springer, Berlin, p. 191.

7. Inglis, C., Stress in Plate due to the Presence of Cracks and Sharp Corners, Proc. Inst. Nav. Arch., 1913.

8. Wolf, R., Beitraege zu ebenen Elastizitaetstheorie, Zeit. Techn. Phys., 1921, 1922.

9. Durelli, A.J., Murray, W. M., Stress Distribution around a Circular Discontinuity in any Two-Dimensional System of Combined Stress, Eastern Photoel. Conference, Proc. 14, 1941, p. 21.

10. Durelli, A.J., Murray, W.M., Stress Distribution around an Elliptical Discontinuity in any Two-Dimensional Uniform and Axial System of Combined Stress, E.S.A., 1943, Vol. 1, No. 1.

11. Greenspan, M., Effect of a Small Hole on the Stresses in a Uniformly Loaded Plate, Quart. of Appl. Math., Apr. 1944, Vol. II, p. 60-71.

12. Sternberg, E., Sadowsky, M.A., Three-Dimensional Solution for the Stress Concentration Around a Circular Hole in a Plate of Arbitrary Thickness, ASME, June 1948.

13. Neuber, H., Kerbspannungslehre, Grundlagen fuer genaue Spannungsrechnung, Berling, J. Springer, 1937. (Translation 74, D.W. Taylor Model Basin, U. S. Navy).

14. Stowell, E.F., Stress and Strain Concentration at a Circular Hole in an Infinite Plate, NACA, April 1950, Tech. Note 2073.

15. Howland, R.C.J., Stresses in the Neighborhood of a Circular Hole in a Strip under Tension, Roy. Soc. London, Phil. Trans., 1930, Vol. 229, p. 49.

16. Gurney, C., An Analysis of the Stresses in a Flat Plate with Reinforced Circular Hole under Edge Forces, Brit. Res. Memo., 1938, No. 1834.

17. Beskin, L., Strengthening of Circular Holes in Plates under Edge Loads, Journ. Appl. Mech., 1944, p. A-140.

18. Reissner, H., Morduchov, M., Reinforced Circular Cutouts in Plane Sheets, NACA, Apr. 1949, Techn. Note 1852.

19. Preuss, E., Versuche ueber die Spannungsverteilung in Gelochten Zugstaebe., Zeit. V.D.I., 1912, Vol. II, p. 1780.

20. Hill, H.N. Barker, R. S., Effect of Open Circular Holes on Tensile Strength and Elongation of Sheet Specimens, NACA, Oct. 1949, Tech. Note 1974.

21. Frocht, M.M., Photoelasticity, J. Willey, N.Y., 1941-1948, Vol. I-II.

22. Coker, E.G., Kimball, A.L., The Effect of Holes, Cracks and Other Discontinuities in Ship's Plating, Trans. Inst. Naval Arch., 1920, Vol. LXII, p. 117.

23. Heymans, P., La determination par la photoelasticimetrie des surtensions, Academie Royale de Belgique. Classe des Sciences, Memo-in-8-o, 2me serie., Vol. VI, Fasc. 10.

24. Stang, A.H., Greenspan, M., Perforated Cover Plates for Steel Columns, Summary of Compressive Properties, Journ. of Res. N.B.S., Vol. 40, No. 5, p. 344-359.

25. Stang, H., Greenspan, M., Perforated Cover Plates for Steel Columns, Journ. of Res. Nat. Bureau of Standards, 1942-1944, Vol. 28, p. 669 and 687; Vol. 29, p. 279; Vol. 30, p. 177 and 411.

26. Farb, D., Experimental Investigation of the Stress Distribution around Reinforced Circular Cut-Outs in Skin-Stringer Panels under Axial Loads, NACA, March 1947, Tech. Note 1241.

27. Kuhn, P., Duberg, Y.E., Diskin, S. H., Stresses around Rectangular Cutouts in Skin-Stringer Panels under Axial Loads, NACA, Oct. 1943, Wartime Report, ARR 3T02.

28. Kroll, W.D., McPherson, A. E., Compression Test of Curved Panel with Circular Hole Reinforced with Circular Doubler Plates, Journ. of the Aeronautical Sciences, June 1949, Vol. 16, No. 6, p. 354.

29. Levy, S., Woolley, R.M., Kroll, W.D., Instability of Simply Supported Square Plate with Reinforced Circular Hole in Edge Compression, Journ. of Research, N.B.S., Vol. 39, No. 6, p. 571.

30. Griffith, G.E., Experimental Investigation of the Effects of Plastic Flow in a Tension Panel with a Circular Hole, NACA, Sept. 1948, Tech. Note 1705.

31. Timoshenko, S., Strength of Materials, D. Van Nostrand Co., N.Y., 2nd Ed., 1941, Part II, p. 315.

32. U. S. Exp. Model Basin, Navy Yard, Washington, D.C., The Effect of Openings on the Ultimate Tensile Strength of Flat Plates, Rpt. No. 446.