ELECTRIC STRAIN GAGE ANALYSIS OF STRESS CONCENTRATION IN SHEAR PANEL WITH AN ACCESS HOLE

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ELECTRIC STRAIN GAGE ANALYSIS OF STRESS CONCENTRATION IN SHEAR PANEL WITH AN ACCESS HOLE

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PREFACE

MEANING OF SYMBOLS USED

b = Distance between bolt center lines, inches

B.S.F. = Bridge sensitivity factor of the SR-4 Wheatstone Bridge Control Box

C_e = Experimental stress concentration factor

C_r = Rivet factor

C_t = Theoretical stress concentration factor

D = Diameter of access hole, inches

ϵ = Strain in web, inches per inch

G.S.F. = Gage sensitivity factor of the SR-4 strain gages

ΔM = Change in the micrometer reading of the SR-4 Wheatstone Bridge Control Box

P = Applied tensile load, pounds

t = Nominal panel thickness, inches

τ = Nominal shear stress in web, pounds per square inch

$\frac{1}{R}$ = Stress concentration factor

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ELECTRIC STRAIN GAGE ANALYSIS OF STRESS CONCENTRATION IN SHEAR PANEL WITH AN ACCESS HOLE

SUMMARY

Pure shear tests were made on a number of 10 inch square panels of 24ST sheet and 24ST Alclad sheet aluminum alloy having various gage thicknesses and hole diameters to determine the stress concentration at static rupture and the strain characteristics around the hole. Primary axial and secondary bending strains were measured by means of electric strain gages.

The diagonal tension and the secondary bending strain perpendicular to the direction of diagonal tension buckles were measured on .032 panels at the hole edges. The access hole diameter was varied in increments of one inch from a 2 inch hole to a 7 inch hole. The diagonal compressive strain and the secondary bending strain parallel to the diagonal tension buckles were measured on an .032 panel with a 2 inch diameter access hole.

Panels with 3 inch diameter access holes and having nominal gage thicknesses of .020, .025, .032, .040, .051, and .064 were tested to determine the effect of gage thickness on the stress concentration factor, on the diagonal tension strain, and on the secondary bending strain perpendicular to the diagonal tension buckles. The stress concentration factors were determined for panels with 6 inch diameter access holes of the same gage thicknesses as above and for an .032 panel with

an 8 inch diameter access hole.

Solid panels were tested in pure shear, in the same manner as panels with access holes were tested, to determine the ultimate strength of each gage. The stress concentration factors were the ratio of ultimate load in the solid panel to the ultimate load in the panels with an access hole.

A family of curves was plotted of diagonal tension strain for various access hole diameters in .032 panels and for various gage thicknesses with a 3 inch diameter access hole. The same relationships were shown for the secondary bending strain perpendicular to the diagonal tension buckles.

The theoretical and experimental stress concentration factors were plotted for the .032 panels tested and for the constant access hole diameter panels tested.

INTRODUCTION

It is very often necessary to cut access holes in shear panels to facilitate assembly and inspection and to permit the installation of plumbing and control cables, but little has been done to determine the stress pattern and values of the stresses in these shear panels until recently.

Kuhn and Levin[1] made limited tests on panels with $1\frac{1}{2}$ inch diameter access holes of various types and determined the stress concentration

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[1]Kuhn, Paul and Levin, Ross L.: "Tests of 10-Inch Aluminum-Alloy Shear Panels with $1\frac{1}{2}$-Inch Holes." Wartime Report No. 1-500, N.A.C.A., June 1943.

factors. Ruffner and Schmidt[2] have investigated shear resistant webs with cut-outs by the photoelastic method. McKee[3], with the use of Stresscoat, determined the stress distribution patterns and stress concentration factors in incomplete tension field webs in the elastic range.

The purpose of this report was to determine more precisely the quantitative values of the stress concentration factors and the primary axial and secondary bending strain induced in the panels by access holes.

From the work done by McKee with Stresscoat, the areas of maximum stress were found to be at the edge of the hole parallel to and perpendicular to the diagonal tension buckles. The points of maximum stress were the ones of interest; hence, the strain gages were located at the edge of the hole in these areas.

Strain gages permit the evaluation of strain beyond the yield point of the material if the strain does not exceed the yield point of the gage wire or the elastic quality of the adhesive attaching the gage to the panel.

TEST EQUIPMENT

Material: The material was 24ST sheet and 24ST Alclad sheet aluminum alloy. The panels having a nominal thickness of .020, .025, and .032 inch were of 24ST sheet. The 24ST Alclad sheet panels had a nominal

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[2]Ruffner, Benjamin F. and Schmidt, Calvin L.: "Stresses At Cut-Outs in Shear Resistant Webs as Determined by the Photoelastic Method." Technical Note No. 984, N.A.C.A., October 1945.

[3]McKee, William H.: "An Investigation of Stresses in a Shear Panel with Access Hole by the Use of Stresscoat." Thesis, Georgia School of Technology, June 1947.

thickness of .040, .051, and .064 inch. All panels of the same thickness were taken from a single sheet. Tests were made using solid panels, and panels having 3 and 6 inch diameter access holes for all gage thicknesses. In addition to the above, tests were made on .032 inch panels having 2, 4, 5, 7, and 8 inch diameter access holes.

Jig: The jig, Figure 1, was a square picture-frame type like that used by Kuhn[4] at N.A.C.A. in several of his investigations of incomplete tension field panels. The sides were made of two $2 \times 2\frac{1}{4}$ steel angles placed back to back. The clear width of the panel was $8\frac{1}{4}$ inches; the distance between the center lines of the hinge points and bolt attachments was 10 inches. The edges of the specimen were clamped between the angles with 10-32 bolts one inch on center in staggered rows. The link arrangement used in applying the load eliminated the possibility of bending moments being induced at the corners of the jig and gave a pure shear loading on the 10 inch square panel, Figure 2.

Specimen: The specimens consisted of sheets $12\frac{1}{4}$ inches square and were bolted into the square picture-frame jig so diagonal tension buckles would form at 45 degrees to the direction of rolling.

Strain Gage System: Standard SR-4 type A-5 strain gages manufactured by the Baldwin Locomotive Works, Baldwin Southwark Division, were used in all tests which required strain gages. All the strain gages were from the same group and had a gage sensitivity factor of $2.01 \pm 1\%$.

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[4]op. cit., p. 1.
Kuhn, Paul: "Ultimate Stresses Developed by 24S-T Sheet in Incomplete Diagonal Tension." Technical Note No. 833, N.A.C.A., December 1941.

A Baldwin Southwark SR-4 Wheatstone Bridge Control Box[5] was used to measure the change in resistance of the strain gages. The circuit used in this control box is shown schematically in Figure 3. The four terminals on the box, A, C, C, and B, correspond to the notation on the figure. The balancing arms of the bridge consist of two variable resistors, "D" and "E", which are shunted by a fixed and a decade resistance. Approximate balance of the d'Arsonval galvanometer, built into the bridge case, is achieved by the decade resistance. Fine balance and strain readings are obtained by adjusting the variable arms "D" and "E", which are modified forms of the SR-4 strain gage so arranged that their resistance is varied by turning a micrometer screw located on the control panel of the bridge. The change in resistance of the arms "D" and "E" is a linear function of the motion of the micrometer screw over its entire range.

To measure the diagonal tension strain, the gages on the front and the back of the panel are connected in series and are connected in one arm of the bridge at "A" and "C". Two temperature compensating gages in series are connected in the other arm, at "C" and "B". With no test load applied to the panel, the galvanometer is balanced exactly to zero by means of the shunt decade resistance and micrometer screw. A test load is then applied and the galvanometer again adjusted to zero by the micrometer screw. The average strain in the gage is measured by the difference between the micrometer screw reading at balance and the zero

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[5]Anonymous: "SR-4 Bonded Metalectric Strain Gage." Bulletin 164-X, The Baldwin Locomotive Works, Baldwin Southwark Division, Philadelphia, Penna., 1941.

reading. See Figure 3.

To measure the secondary bending strains, one of these arms is connected to the terminals of the strain gage which is installed on the front of the panel at the point where strain is to be measured. The other is connected to the opposite gage on the back of the panel. As before, with no test load applied to the panel, the galvanometer is balanced exactly to zero by means of the shunt decade and the micrometer screw. The strain in the gage is then measured by the difference between the micrometer screw reading at balance and the zero reading. Since the gages are mounted in adjacent arms of the Wheatstone Bridge circuit, the micrometer reading is a measure of the difference in the resistance of the two gages. See Figure 3.

Each Wheatstone Bridge control box is calibrated at the factory. The bridge sensitivity factor is determined for all decade resistance settings and is plotted on a chart which is furnished with each control box.

Balancing units, Figure 4, were made so that all gages on the panel could be adjusted to the same zero. The balancing units consisted essentially of a cantilever strip of metal, the end of which could be deflected by an adjusting screw. Strain gages were mounted on either side of the strip and by adjusting the bar deflection, the resistance in the circuit was changed, since these gages were in parallel with the active gages in the bridge circuit. There was a balance gage for each of the four circuits, and the resistance of each circuit was adjusted so that all circuits had the same zero reading on the control box.

Strain gages mounted on both sides of a 1/8 inch thick strip of

24ST aluminum alloy served as temperature compensating gages. This strip was placed on the jig and rested against the panel during tests, Figure 5. It was, therefore, subjected to the same temperature changes as the panel undergoing tests. To save time in moving from one gage circuit to another, a Mallory four gang switch, type 1335L, with heavy silver plated contact members was used. Current for the electrical system was supplied by a 3 cell, 6 volt Firestone storage battery.

Testing Machine: The Universal Testing machine in the structures laboratory of the Daniel Guggenheim School of Aeronautics at the Georgia School of Technology was used to apply the tensile test load to the shear panel.

TEST PROCEDURE

A series of square panels were cut from different gage sheets. The 10-32 holes were back drilled from the jig angles to assure alignment on assembly. All panels were drilled so that when mounted in the jig the diagonal tension buckles would form at 45 degrees to the direction of rolling of the sheet.

The panels having an access hole were mounted in the jig before the access hole was cut. The center of the panel was determined, and the access hole of the desired diameter was cut with a fly-cutter. All sharp edges and burrs were removed with fine emery cloth.

Strain gages were mounted on the panel after it had been cleaned with thinner and roughened with fine emery cloth perpendicular to the longitudinal axis of the strain gage. The gages were mounted tangent to the hole, and the strains measured were those around the edge of the hole. The longitudinal axis of the strain gage was parallel to the direction of the strain to be measured, Figure 6.

The gages were bonded to the panel with Duco cement, and a 3/4 pound weight was applied to the gage until the cement became tacky. The adhesive was allowed to dry overnight before the test load was applied.[6] The gage terminals were attached to the switch leads with rosin core solder to eliminate contact resistance variations. Scotch tape was placed between the panel and the gage terminals, and each lead was taped to the panel separately to insure proper insulation.

The jig was suspended from the upper jaws of the testing machine, and the temperature compensating gage bar was placed on the jig adjacent to the panel. The test load indicator was adjusted to zero, and all strain gage circuits were adjusted to the same zero on the control box. When all zeros had been determined, the lower jaws of the testing machine were clamped to the jig and the test load applied.

Load was applied to the panel through the link arrangement at diagonally opposite corners. The load was applied in increments of 500 to 1000 pounds in the initial runs, but this was later changed to 250 pounds to permit a more accurate estimation of when to change decade readings. The test load was held constant and the galvanometer adjusted to zero by the micrometer screw. This was done for each strain gage circuit, after which the load was increased. When it was thought the resistance of the bridge could not be adjusted to zero at the next higher load by the micrometer screw, new decade resistance readings were taken.

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[6] Anonymous: "The SR-4 Bonded Resistance Wire Strain Gage." Bulletin No. 179, The Baldwin Locomotive Works, Baldwin Southwark Division, Philadelphia, Penna., 1945

The test load was held constant, and the micrometer reading at the old decade setting was taken; then the shunt decade was changed and the galvanometer adjusted to zero by the micrometer screw and this new reading recorded for the same load.

The first panels tested were .032 inch gage with 2, 3, 4, and 5 inch diameter access holes. These runs had zero readings taken after 3000 pounds had been applied to the panel and again after 5000 or 6000 pounds had been applied. It was found that some permanent set existed in these panels at these loads, but this practice was discontinued in later tests, since it contributed no other information.

The strains were read until the resistances could not be adjusted to the zero point on the control box scale, the strain gage failed, or the adhesive attaching the gage to the panel failed. After one or the other of these conditions had been reached for all strain gage circuits, the test load was increased without interruption until the panel failed by rupture.

The solid panels and those panels having an access hole but no strain gages were mounted in the jig in the same manner. The zero reading of the load indicator on the testing machine was taken with the jig suspended from the upper jaws. The lower jaws were then clamped and the test load increased without interruption until the panel ruptured. After the panels had failed by rupture, a zero reading was taken for the test load indicator with the lower jaws open to see if any change in zero setting had occurred. The jig was removed from the testing machine and the ruptured panel replaced.

DISCUSSION

The stress analyst is most interested in the sum of the diagonal tension strain and the secondary bending strain parallel to the diagonal tension buckles, Figure 10. Both these strains increase as the panel is loaded to rupture, and both of these strains add together to produce the critical stress in the panel if the panel fails at the minimum cross sectional area and not at the rivet line. The seriousness of this condition was not fully appreciated until the test program had been completed. It was originally thought the diagonal tension strain and the secondary bending strain perpendicular to the buckles would be the causes of panel failure, hence, the tests were run to determine the values of these strains.

The effect of the diameter of the access hole on the diagonal tension strain and secondary bending strain perpendicular to the diagonal tension buckles was determined from panels of .032 inch gage. These strains were measured on panels having 2, 3, 4, 5, 6, and 7 inch diameter access holes. The ultimate strength of the sheet was determined by applying the test load to a solid panel at two diagonally opposite corners of the jig in the same manner as test specimens with holes were loaded. An .032 panel with and 8 inch diameter access hole and having no strain gages was tested to determine how much load the flanges were carrying as the hole size approached the panel width.

The effect on the diagonal tension strain and the secondary bending strain perpendicular to the diagonal tension buckles of changes in gage thickness were determined from panels having a 3 inch diameter access hole. In this series of tests, the access hole diameter was held constant at 3 inches, and the gage thickness of the panel varied, using .020, .025, .032, .040, .051, and .064 inch. A series of tests to determine the ultimate strength of panels having a 6 inch diameter access hole was run on the same gages. This series of tests did not have strain gages mounted on the panels. The final series of tests consisted of determining the ultimate strength of the different gage thicknesses used. This was done by applying the test load to a solid panel at two diagonally opposite corners of the jig in the same manner as test specimens with holes were loaded.

The diagonal tension and compressive strains are determined from the following formula:

$$\epsilon = \frac{1}{.223} \Delta M \times \frac{B.S.F.}{G.S.F.}$$

The value of the constant, .223, is determined from the resistances in the circuit, and its evaluation is shown in Figure 7.

The equation for determining the secondary bending strains is

$$\epsilon = \frac{1}{.25} \frac{\Delta M}{2} \times \frac{B.S.F.}{G.S.F.}$$

The calculations for determining the constant, .25, are shown in Figure 9.

A measurement of the strain to rupture could not be determined for several reasons. As the panel approached its ultimate strength, the strain increments became too large to be covered by the bridge, and the galvanometer could not be adjusted to zero. The strains in the panel became so large the strain gage failed. The more frequent cause of not being able to determine the strain to rupture, however, was failure of the bond attaching the gage to the panel. The adhesive and elastic properties of the glue were exceeded, and the bond between the gage and the panel was destroyed as the strain increased in the panel.

The initial tests had intermediate zero readings taken after 3000 pounds had been applied to the panel and again after 5000 or 6000 pounds had been applied. It is to be noted in the .032 panels with 2, 3, 4, and 5 inch diameter access holes, Figures 11 through 14, that the curves show an irregularity in the slope after each zero reading. When the test load is relieved and then applied again, the strain increases for the same applied load.[7] This is very noticeable in the .051 panel with a 3 inch diameter access hole, Figure 20. With the test load of 5750 pounds applied to the panel, it was intended to increase this load to 6000 pounds. However, the load was unintentionally increased to 7300 pounds. The galvanometer could not be adjusted to zero with the micrometer screw, and the load was reduced to 5000 pounds again and a new decade reading for secondary bending strain taken. Starting at this point, the load was increased in increments of 250 pounds. It is to be noted that the strains of the repeat loading are considerably larger than the strains of the original loading.

In Tables I through IV, are sample calculations for the diagonal tensile and diagonal compressive strains and the secondary bending strains parallel and perpendicular to the diagonal tension buckles for an .032 panel with a 2 inch diameter access hole. These values are plotted in Figures 9, 10, and 11.

Figures 11 through 16 represent the diagonal tension strain and the secondary bending strain perpendicular to the diagonal tension

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[7]Timoshenko, S. and MacCullough, Gleason H.: Elements of Strength of Materials, pp. 309-313, D. Van Nostrand Co., Inc., New York, Second Edition, May 1940.

buckles for .032 panels with various diameter access holes.

The diagonal tension strain becomes greater as the access hole diameter increases for a constant gage thickness, Figure 22. This is in agreement with theory, since the stress is increasing in the panels. In the elastic range when the strain is compared with the area of the net section, it is found that as the access hole diameter is increased the strain decreases less rapidly than the net area. When the stress in the panel passes from the elastic into the plastic range and the panel approaches its ultimate load, the converse exists. That is, the diagonal tension strain decreases faster than the net area. This is to be expected, since the stress concentration factor, based on the rupture load of the panel, is below the theoretical stress concentration factor, based on the net area of the panel, Figures 26 and 27.

The diagonal tension strain for panels of various gage thicknesses, having a 3 inch diameter access hole, increases as the gage thickness is reduced, due to the reduction in net area, Figure 24. A comparison of the strains in these panels with the net section shows an increase in the strain as the gage thickness is reduced for both the elastic and plastic ranges.

The secondary bending strain perpendicular to the diagonal tension buckles increases as the access hole diameter increases for panels of constant gage thickness, Figure 23. The strain produced by the shear deformation of panels with large diameter access holes before rupture is great enough to offset the reduction in strain produced by the delay in the formation of the diagonal tension buckles due to the boundary of the hole approaching the clamped edges.

A study of the relationship of the secondary bending strain perpendicular to buckles to the net area for panels of constant gage thickness shows the strain decreases more rapidly than the net section as the access hole diameter is increased. Comparison of strain with the moment of inertia for panels of constant hole diameter and varying gage thicknesses indicates the strain decreases faster than the moment of inertia as the gage thickness becomes thinner.

Permanent set, indicated by the secondary bending strain perpendicular to the buckles, occurs at low loads but has little effect on the failing load at rupture. The crest of the diagonal tension buckle at the edge of the hole is the first point in the panel to reach the yield point. Evidence of fatique failure may first be noted at this point if the panel is subjected to stress reversals at high loads.

Figures 17 through 21, 24, and 25 show the effect of gage thickness on the secondary bending strain perpendicular to the diagonal tension buckles and diagonal tension strain for a 3 inch diameter access hole. The diagonal tension buckles are delayed in forming by increasing the gage thickness. This is very evident in the .064 panel, Figure 21; the test load is quite large before the bending curve begins to knee over. This is to be expected, since the thicker the gage the stiffer the panel becomes, and the more resistance it has to buckling. The diagonal tension strain decreases for the same test load as the gage increases and the stress in the panel decreases.

The diagonal compressive strain, Figure 9, although numerically small, increases very rapidly as the load is first applied. As the load is increased, the strain increments decrease gradually to zero. If the load is increased beyond this point, the increments of strain become negative, and the diagonal compressive strain decreases. This condition is not serious, for Wagner[8] assumes in his theories that the diagonal compressive stress goes to zero as soon as the web buckles. At the same time the buckles in the panel become deeper and more pronounced as the load increases. Diagonal compressive strain may be compared with the secondary bending or diagonal tension strain from Figure 11. It may be shown that the diagonal compressive strain reached its maximum value and had started to decrease before either of the others had reached its maximum.

The decrease in the diagonal compressive strain is analogous to the decrease in the axial load of a long slender column as its load approaches the critical load. There is very little deflection of the column until the test load becomes a large percentage of the critical load. As this percentage approaches 100, the column deflection becomes very large for small increases in the applied load; and the critical load for the column is approached as an asymptote. The deflection of the column becomes so great that the yield point of the material is exceeded in bending, and the column is permanently buckled when the critical load is approached even closer. When this condition exists, the critical buckling load of the column decreases rapidly.

In like manner, the diagonal compressive strain in the panel decreased after the yield point had been passed at the crest of the buckle at the edge of the hole. The decrease of load carried as diagonal compression strain is offset by an increase in diagonal tension load after the yield point has been reached.

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[8]Wagner, Herbert: "Flat Sheet Metal Girder with Very Thin Metal Web." Technical Memorandum No. 604, N.A.C.A., February 1931.

The secondary bending strain parallel to the diagonal tension buckles is due to the center of the panel buckling out of the plane of the clamped edges. As the tensile test load is increased to rupture, the secondary bending strain parallel to the diagonal tension buckles increases, Figure 10.

It should be mentioned that the mode of panel failure can not always be predicted, Figures 29 through 32. On the thin panels with an access hole and the heavier gage panels with a 6 inch diameter access hole, failure occurred along the section of minimum area, starting at the access hole. As the diameter of the access hole decreased or the gage became thicker, failure frequently occurred at the attaching bolts at the panel edge. In all the solid panels tested, regardless of the gage thickness, the panels ruptured along a zigzag line between bolts, and in the heavier panels there was some evidence of bearing failure around the bolt holes. Since the edge supports were clamped as tight as the bolts would permit, the only remedy would be to increase the number of rows of bolts and increase the pitch of the bolts in the inner rows. Evidence of a shear and tension failure between the bolts was noticed by Kuhn[9] in some tests made on incomplete diagonal tension field webs, but he did not mention bearing failure at the bolt holes.

The nominal shear stress of the test panel is determined from the equation

$$\tau = \frac{.707P}{bt}$$

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[9] op. cit., p. 4.

The edge support given by the flanges was assumed to be the equivalent of fully clamped edges, as the flanges were more than three times the thickness of the panels and the faces touching the sheet were flat.[10]

The stress concentration factors given in Tables V and VI are the ratio of the ultimate shear stress in a solid panel to the shear stress of a panel with an access hole.

The theoretical stress concentration factor is the ratio of the ultimate shear stress in a panel with an access hole, given by the formula

$$\tau = \frac{.707P}{(b - D)t}$$

to the ultimate shear stress of a solid panel.

The rivet correction factor was not used to correct the calculated stresses in the heavier gage panels where failure occurred at the rivet line. This correction would have given a higher value for the ultimate stress, but the panel may have failed in some other manner before it developed this stress.

The stress concentration factor increases as the access hole diamter increases for .032 panels. Although it was assumed in the stress calculations that the flanges carried no load, it is evident from the rupture load of the .032 panel with an 8 inch diameter access hole that the flanges were carrying a large percent of the total load at rupture. The theoretical and experimental stress concentration factors

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[10]Kuhn, Paul and Chiartio, Patrick T.: "The Strength of Plane Web Systems in Incomplete Diagonal Tension." Wartime Report L-367, N.A.C.A., July 1943.

both approach infinity as the ratio of access hole diameter to panel width approaches 1. Figure 26.

An increase in stress concentration is evident with an increase in the ratio of access hole diameter to panel gage thickness in the .032 panels tested, Figure 27. As in the case of D/b ratios, the theoretical stress concentration factor is higher than the experimental value.

The stress concentration factors of the panels with 6 inch diameter access holes are approximately 1.80 times those of the panels with a 3 inch diameter access hole, Figure 28. This is in close agreement with the theoretical values.

The secondary bending strain gets less as the panel gage decreases. The diagonal tensile strain, being less for the thicker gages can carry more of the diagonal compressive load after the yield point has been passed at the crest of the buckle before failure will occur. The .032 panel may be the median gage for these conditions; thus, the stress concentration factors for the .032 panel are the greatest for all access hole diameters tested. Further tests on different size panels and/or additional strain measurements of secondary bending parallel to the buckles are needed to substantiate these deductions.

CONCLUSIONS

The tests indicate the diagonal tension strain in the elastic range, for panels of constant gage thickness, decreases less rapidly than the net area as the access hole diameter is increased. The converse is true in the plastic range, i.e., the diagonal tension strain decreases faster than the net area. This is indicated by the test results which show the theoretical stress concentration factors at rupture are greater than the experimental.

The relationship of the secondary bending strain perpendicular to buckles to the net area for panels of constant gage thickness shows the strain decreases more rapidly than the net section as the access hole diameter is increased. Comparison of the strain with the moment of inertia for panels of constant hole diameter and varying gage thickness indicates the strain decreases faster than the moment of inertia as the gage thickness becomes thinner.

Permanent set occurs at low loads but has little effect on the failing load at rupture. The yield point in secondary bending is first reached in the panel at the ridge of the diagonal tension buckle because of the very sharp curvature in the metal at that point. This area is subjected to early fatigue failure if the panel is subjected to stress reversal at high loading conditions.

The secondary bending strain parallel to the diagonal tension buckles increases as the test load is increased and combines with the diagonal tension strain to hasten failure starting at the hole edge. This was not too important in these tests, since many failures started at the rivet attachments due to the reduction in area at that point.

The diagonal compressive stress decreases after the yield point has been reached at the edge of the hole due to excessive secondary bending. The increase in the diagonal tension strain to offset the decrease in the diagonal compressive strain has little effect on the failing load.

The stress concentration factor increases as the access hole diameter increases for all gage thicknesses but not as rapidly as the reduction in net area. Since the theoretical stress concentration factor is based on the net area, the increase in the load carried by the flanges as the access hole diameter increases is probably the reason the theoretical stress concentration factor is so much larger than the experimental value. The maximum stress concentration factor occurs in the .032 panels for all hole diameters tested. Further tests should be made on panels with different dimensions to substantiate this conclusion. The stress concentration factor for panels with a 6 inch diameter access hole is approximately 1.80 times the value for panels with a 3 inch diameter access hole. This is in close agreement with the theoretical values.

The reduction in strength of the panels is approximately equal to the reduction in shear web area between the chord centroids. These deductions used in design would be conservative if based on the shear strength of a solid panel corrected for rivet holes and for non-uniformity of stress (i.e., if C_r and $1/R$ correction factors are applied).

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APPENDIX I, Tables

DIAGONAL TENSION STRAIN
.032 Panel with a 2 Inch Dia. Access Hole

LOAD	DECADE	MICRO. READ'G.	ΔM	B.S.F.	G.S.F.	ϵ	STRAIN
0	4800	7.00	.	2.497	2.01		
500	↓	6.57	.43	↓	↓	2.41	2.41
1000		4.76	2.24			12.57	12.57
1500		3.53	3.47			19.45	19.45
2000		2.51	4.49			25.18	25.18
2500		1.17	5.83			32.65	32.65
2700		0.17	6.83			38.30	38.30
2700	5400	11.07		2.500			
3000	↓	10.18	.89	↓		4.99	43.29
0	4800	5.48		2.497			
3000	5400	9.71	1.36	2.500		7.62	45.92
3250	↓	9.37	1.70	↓		9.53	47.83
3500		8.28	2.79			15.63	53.93
3750		7.18	3.89			21.80	60.10
4000		6.18	4.89			27.42	65.72
4250		4.16	6.91			38.70	77.00
4500		3.17	7.90			44.25	82.55
4750		1.66	9.41			52.75	91.05
5000		.16	10.91			61.20	99.50
5000	6300	12.06		2.504			
5300	↓	9.81	2.25	↓		12.61	112.11
5500		8.64	3.42			19.18	118.68
5750		5.72	6.34			35.80	125.30
5900		4.54	7.52			42.18	141.68
0	5000	0.36		2.498			
5900	6300	4.40	7.66	2.504		42.92	142.42
6250	↓	1.29	10.77	↓		60.40	159.90
6250	7400	12.12		2.509			
6500	↓	9.50	2.62	↓		14.70	174.60
6750		6.19	5.93			33.22	193.12
7000		3.80	8.32			46.62	206.52
7250		0.10	12.02			67.50	227.40
7250	9400	13.14		2.514			
7500	↓	7.10	6.04	↓	↓	34.02	261.42

.032 Panel with a 2 Inch Dia. Access Hole

LOAD	DECADE	MICRO. READ'G.	Δ	B.S.F.	G.S.F.	ϵ	STRAIN
0	4800	7.00		2.497	2.01		
500		7.53	0.53			2.97	2.97
1000		7.73	0.73			4.10	4.10
1500		7.90	0.90			5.05	5.05
2000		8.00	1.00			5.61	5.61
2500		8.08	1.08			6.05	6.05
3000		8.15	1.15			6.45	6.45
0		7.10	0.10				
3000		8.15	1.15			6.45	6.45
3250		8.18	1.18			6.62	6.62
3500		8.25	1.25			7.00	7.00
3750		8.26	1.26			7.07	7.07
4000		8.32	1.32			7.40	7.40
4250		8.37	1.37			7.69	7.69
4500		8.38	1.38			7.75	7.75
4750		8.48	1.48			8.30	8.30
5000		8.52	1.52			8.58	8.58
5300		8.56	1.56			8.76	8.76
5500		8.61	1.61			9.04	9.04
5750		8.63	1.63			9.14	9.14
5900		8.67	1.67			9.36	9.36
0		7.03	0.03				
5900		8.69	1.69			9.49	9.49
6250		8.72	1.72			9.65	9.65
6500		8.76	1.76			9.87	9.87
6750		8.78	1.78			9.99	9.99
7000		8.80	1.80			10.09	10.09
7250		8.82	1.82			10.20	10.20
7500		8.83	1.83			10.27	10.27
7700		8.83	1.83			10.27	10.27
8000		8.83	1.83			10.27	10.27
8250		8.83	1.83			10.27	10.27
8550		8.82	1.82			10.20	10.20
8750		8.81	1.81			10.15	10.15
9000		8.81	1.81			10.15	10.15
9250		8.75	1.75			9.80	9.80
9400		8.75	1.75			9.80	9.80
9700		8.67	1.67			9.36	9.36
10000		8.59	1.59			8.91	8.91
11000		8.24	1.24			6.96	6.96
11500		7.86	0.86			4.81	4.81
11750		7.57	0.57			3.20	3.20
0		6.83	-0.17				

... STRAIN PERPENDICULAR TO BUCKLES

.032 Panel with a 2 Inch Dia. Access Hole

LOAD	DECADE	MICRO. READ'G.	ΔM	$\frac{\Delta M}{2}$	B.S.F.	G.S.F.	ε	STRAIN
0	4800	7.00			2.497	2.01		
500		10.71	3.71	1.86			9.22	9.22
750		12.89	5.89	2.95			14.61	14.61
750	4300	1.04			2.493			
1000		3.81	2.77	1.39			6.90	21.51
1500		8.13	7.09	3.55			17.61	32.22
2000		12.37	11.43	5.72			28.40	43.01
2000	3900	1.35			2.489			
2500		5.71	4.36	2.18			10.80	53.81
3000		10.26	8.91	4.46			22.10	65.11
0	4800	8.74			2.497			
3000	3900	10.47	9.12	4.56	2.489		22.60	65.61
3250		12.30	10.95	5.48			27.17	70.18
3250	3600	2.58			2.487			
3500		4.43	1.85	0.98			4.90	75.08
3750		6.56	3.98	1.99			9.95	80.13
4000		9.97	7.39	3.70			18.50	86.68
4250		10.83	8.25	4.13			20.66	90.84
4500		13.13	10.55	5.23			26.13	96.31
4500	3300	2.24			2.482			
4750		3.37	1.13	0.57			2.85	99.16
5000		5.56	3.32	1.66			8.30	104.61
5300		8.01	5.77	2.89			14.42	110.73
5500		10.00	7.76	3.88			19.39	115.70
5750		11.79	9.55	4.78			23.88	120.19
5900		13.71	11.47	5.74			28.65	124.96
5900	3100	4.73			2.480			
0	4400	8.45			2.494			
5900	3100	4.91	0.18	0.09	2.480		0.45	125.41
6250		8.58	3.85	1.93			9.50	134.46
6500		10.24	5.51	2.76			13.78	138.74
6750		13.05	8.32	4.16			20.78	145.74
6750	2900	2.96			2.476			
7000		5.65	2.69	1.35			6.73	152.47
7250		8.50	5.54	2.77			13.80	159.54
7500		10.72	7.76	3.88			19.31	165.05
7700		12.90	9.94	4.97			24.75	170.49
7700	2700	1.80			2.471			
8000		5.38	3.58	1.79			8.90	179.39
8250		8.03	6.23	3.12			15.50	185.99
8550		13.46	11.66	5.83			29.00	199.49
8550	2600	7.11			2.469			
8750		8.22	1.11	0.56			2.78	202.27
9000		12.47	5.36	2.68			13.30	212.79

SECONDARY BENDING STRAIN PARALLEL TO BUCKLES
.032 Panel with a 2 Inch Dia. Access Hole

LOAD	DECADE	MICRO. READ'G.	ΔM	ΔM/2	B.S.F.	G.S.F.	ε	STRAIN
0	4800	7.00			2.497	2.01		
500		6.07	0.93	0.47			2.33	2.33
1000		5.56	1.44	0.72			3.57	3.57
1500		5.18	1.82	0.91			4.50	4.50
2000		4.39	2.61	1.31			6.51	6.51
2500		4.17	2.83	1.42			7.04	7.04
3000		3.57	3.43	1.72			8.52	8.52
0		5.80						
3000		3.42	3.58	1.79			8.87	8.87
3250		2.84	4.16	2.08			10.31	10.31
3500		2.50	4.50	2.25			11.16	11.16
3750		1.99	5.01	2.51			12.33	12.33
4000		1.63	5.36	2.68			13.29	13.29
4250		1.04	5.96	2.98			14.78	14.78
4250	5500	13.47			2.501			
4500		13.00	0.47	0.29			1.44	16.22
4750		12.12	1.35	0.68			3.38	18.16
5000		11.56	1.91	0.96			4.76	19.54
5250		10.79	2.68	1.34			6.66	21.44
5500		10.34	3.13	1.57			7.79	22.57
5750		9.99	3.48	1.74			8.64	23.42
5900		8.85	4.62	2.31			11.48	26.26
0	5000	9.57			2.498			
5900	5500	8.90	4.57	2.29	2.501		11.38	26.16
6250		7.70	5.77	2.89			14.34	29.12
6500		7.01	6.46	3.23			16.05	30.83
6750		5.92	7.55	3.78			18.78	33.56
7000		5.26	8.21	4.11			20.41	35.19
7250		4.16	9.32	4.66			23.18	37.96
7500		3.03	10.43	5.22			25.90	40.68
7700		1.40	12.07	6.04			30.00	44.78
7700	6400	13.35			2.505			
8000		12.56	0.79	0.40			1.99	46.77
8250		10.37	2.98	1.50			7.46	52.24

Solid Panels

t	b	tb	P	.707P	τ
.020	10	.20	9545	6745	33725
.025	↓	.25	11630	8230	32950
.032		.32	14800	10450	32700
.040		.40	17030	12030	30150
.051		.51	21618	15290	29930
.064		.64	29370	20790	32500

Panels with 3 and 6 Inch Diameter Access Hole

t	b	tb	P	.707P	τ	C_e	P	.707P	τ	C_e
			3 Inch Dia. Access Hole				6 Inch Dia. Access Hole			
.020	10	.20	7350	5200	26000	1.298	4070	2879	14395	2.342
.025	↓	.25	8750	6185	24750	1.331	4820	3405	13610	2.421
.032		.32	10900	7705	24080	1.360	6110	4320	13500	2.420
.040		.40	12900	9110	22800	1.321	7185	5087	12720	2.370
.051		.51	17300	12220	23980	1.250	9820	6950	13610	2.200
.064		.64	22680	16020	25030	1.297	13650	9650	15080	2.145

TABLE VI

STRESS CONCENTRATION FACTORS FOR .032 PANELS
Various Diameter Access Holes

Hole Dia.	b	tb	P	.707P	τ	C_e	(b-D)	t(b-D)	τ	C_t
0	10	.32	14800	10470	32700	1.000	10	.320	32700	1.000
2			12260	8660	27020	1.210	8	.256	40850	1.250
3			10900	7700	24010	1.361	7	.224	46750	1.428
4			9200	6500	20290	1.611	6	.192	54500	1.661
5			7750	5480	17110	1.911	5	.160	65400	2.000
6			6110	4320	13500	2.420	4	.128	81800	2.500
7			4950	3500	10910	2.992	3	.096	109000	3.350
8			3760	2658	8295	3.940	2	.064	163600	5.000

APPENDIX II, Figures

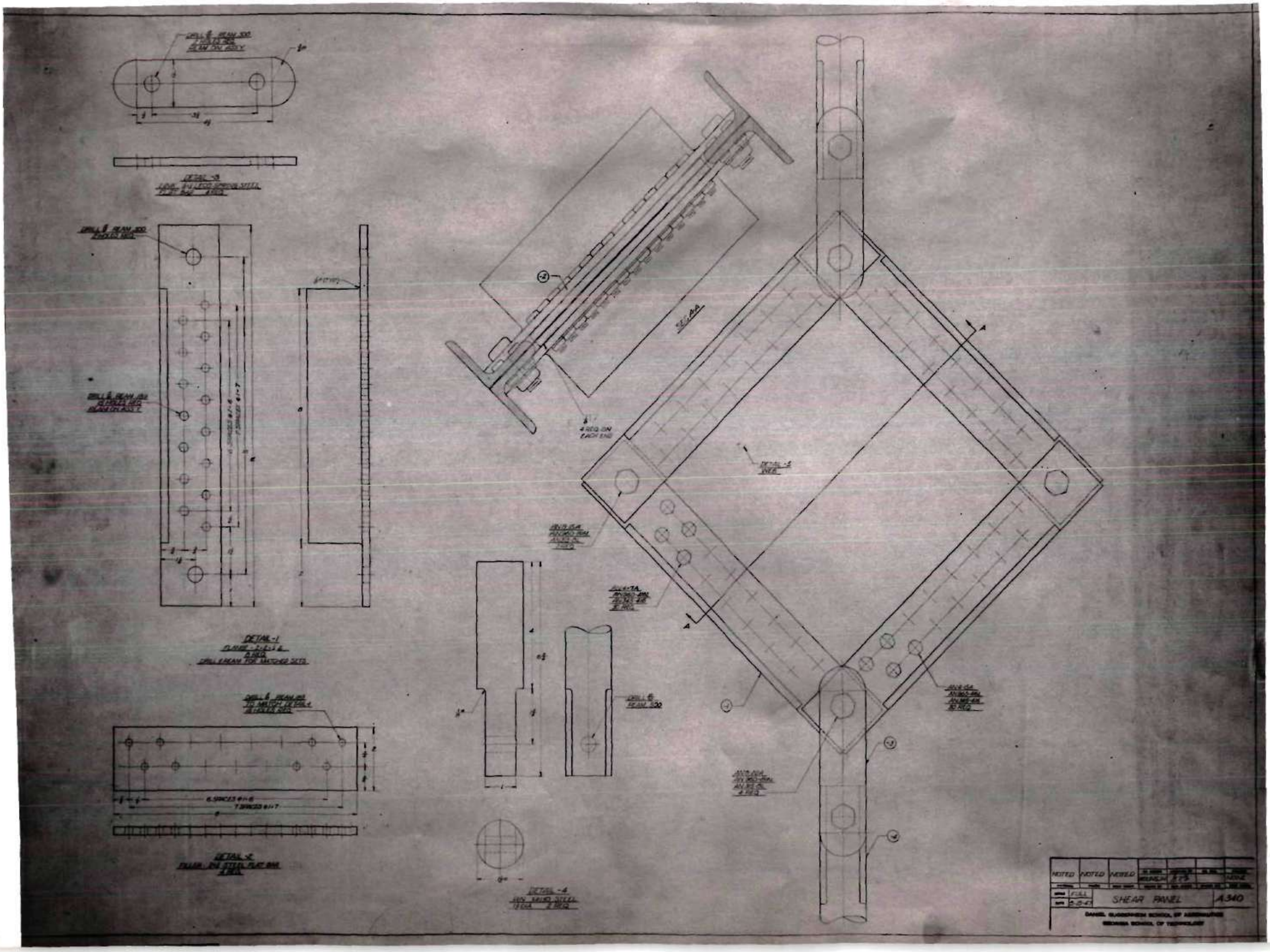


Figure 1

PANEL LOADING

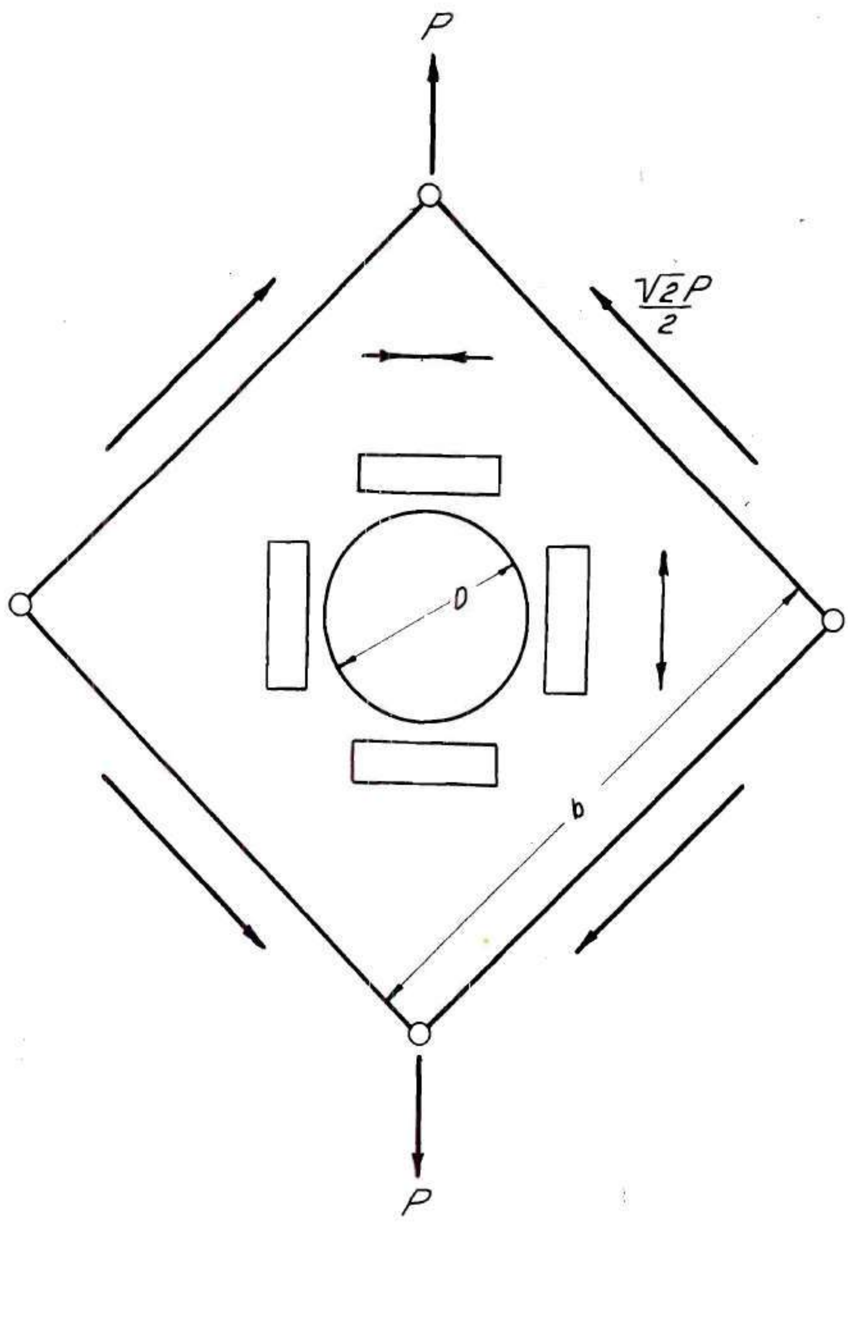


Figure 2

SCHEMATIC DIAGRAM OF

THE SR-4 WHEATSTONE BRIDGE CONTROL BOX

CIRCUIT

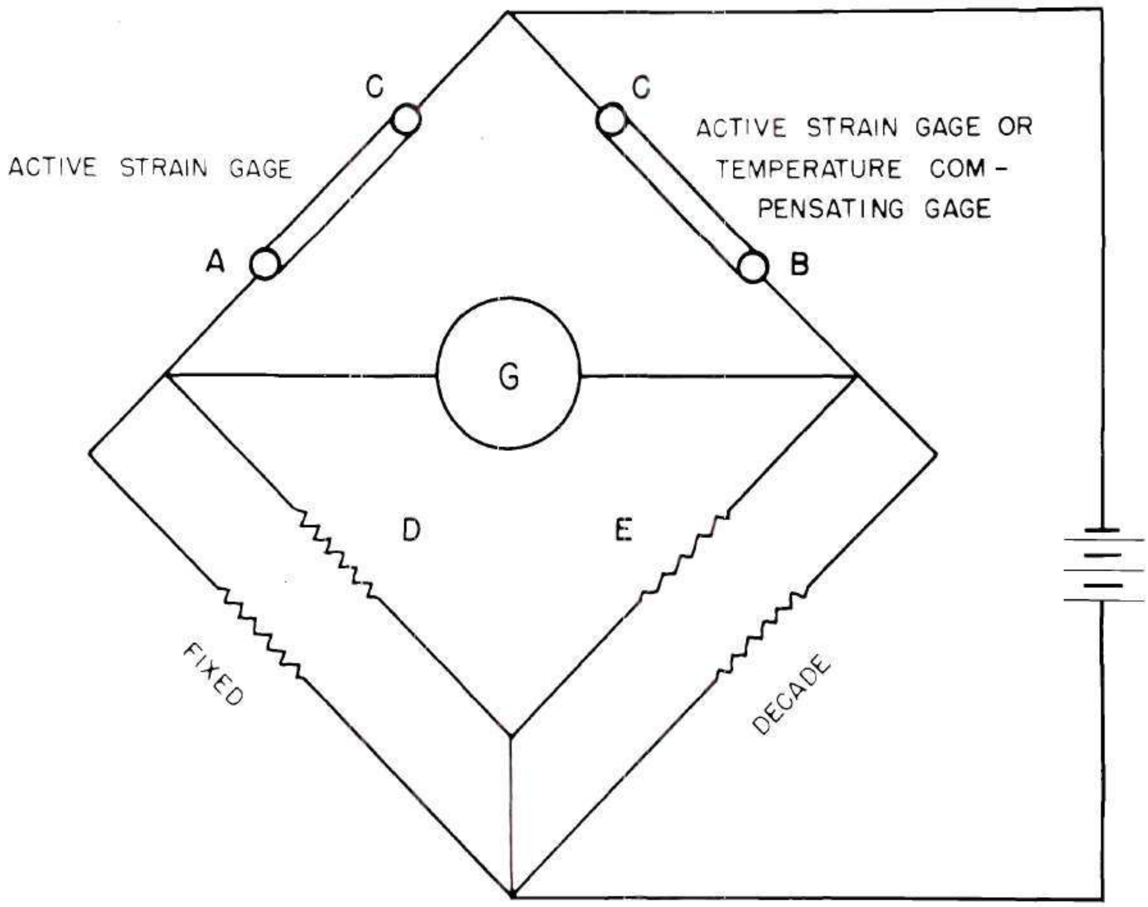


Figure 3

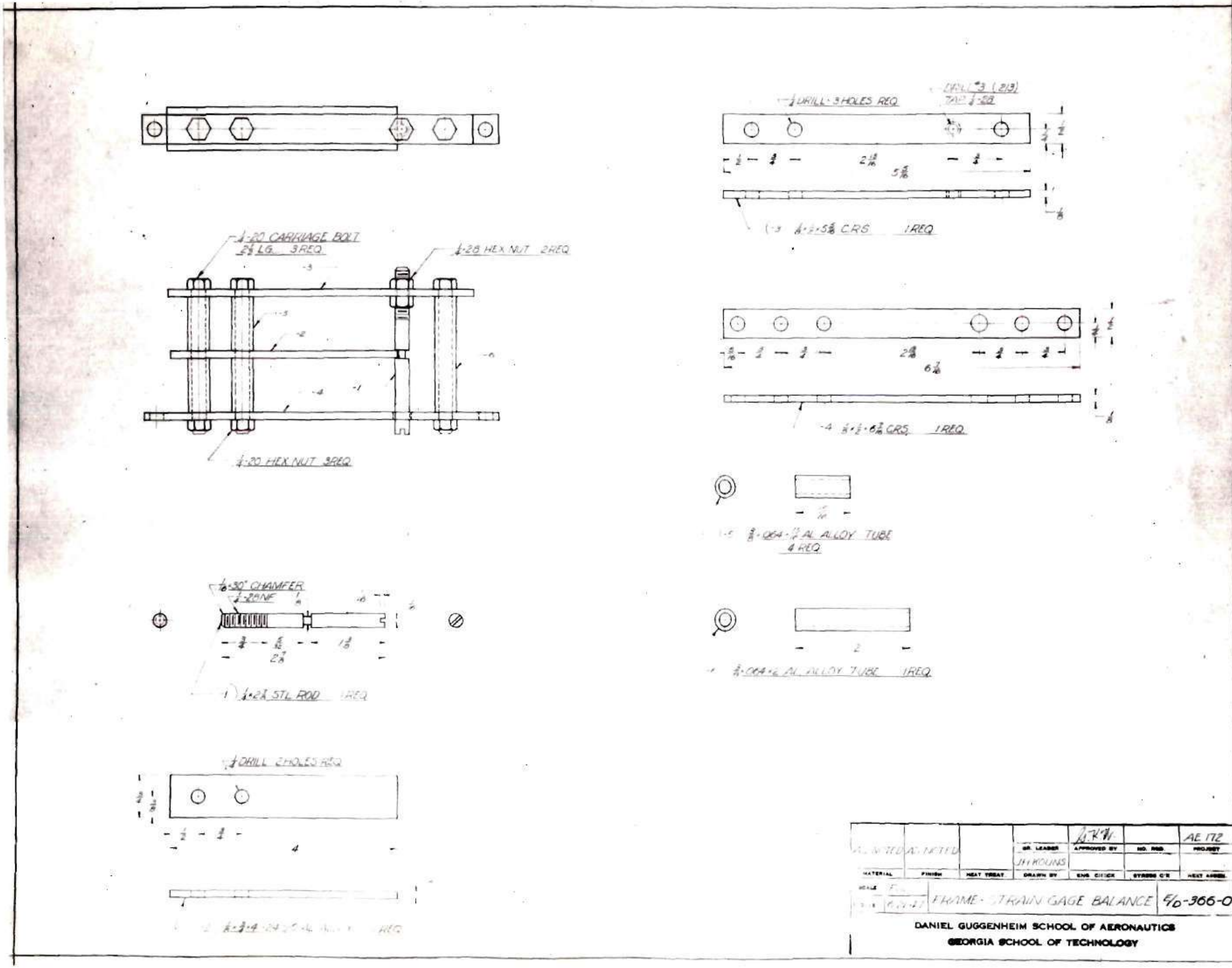

1/4-20 CARRIAGE BOLT 2 1/2 LG. 3 REQ
1/4-28 HEX NUT 2 REQ
1/4-20 HEX NUT 3 REQ
1/4 DRILL 3 HOLES REQ
-3 1/8 x 1/2 x 5 5/16 CRS 1 REQ
-4 1/8 x 1/2 x 6 7/16 CRS 1 REQ
3/8 x .064 x 11/16 AL ALLOY TUBE 4 REQ
3/8 x .064 x 2 AL ALLOY TUBE 1 REQ
1/16 x 30° CHAMFER
1/4-28 NF
1/4 x 2 7/8 STL ROD 1 REQ
1/4 DRILL 2 HOLES REQ
AS NOTED AS NOTED
J.H. KOUNS
AE 172
FRAME - STRAIN GAGE BALANCE
E/D-366-0
DANIEL GUGGENHEIM SCHOOL OF AERONAUTICS
GEORGIA SCHOOL OF TECHNOLOGY

Figure 4

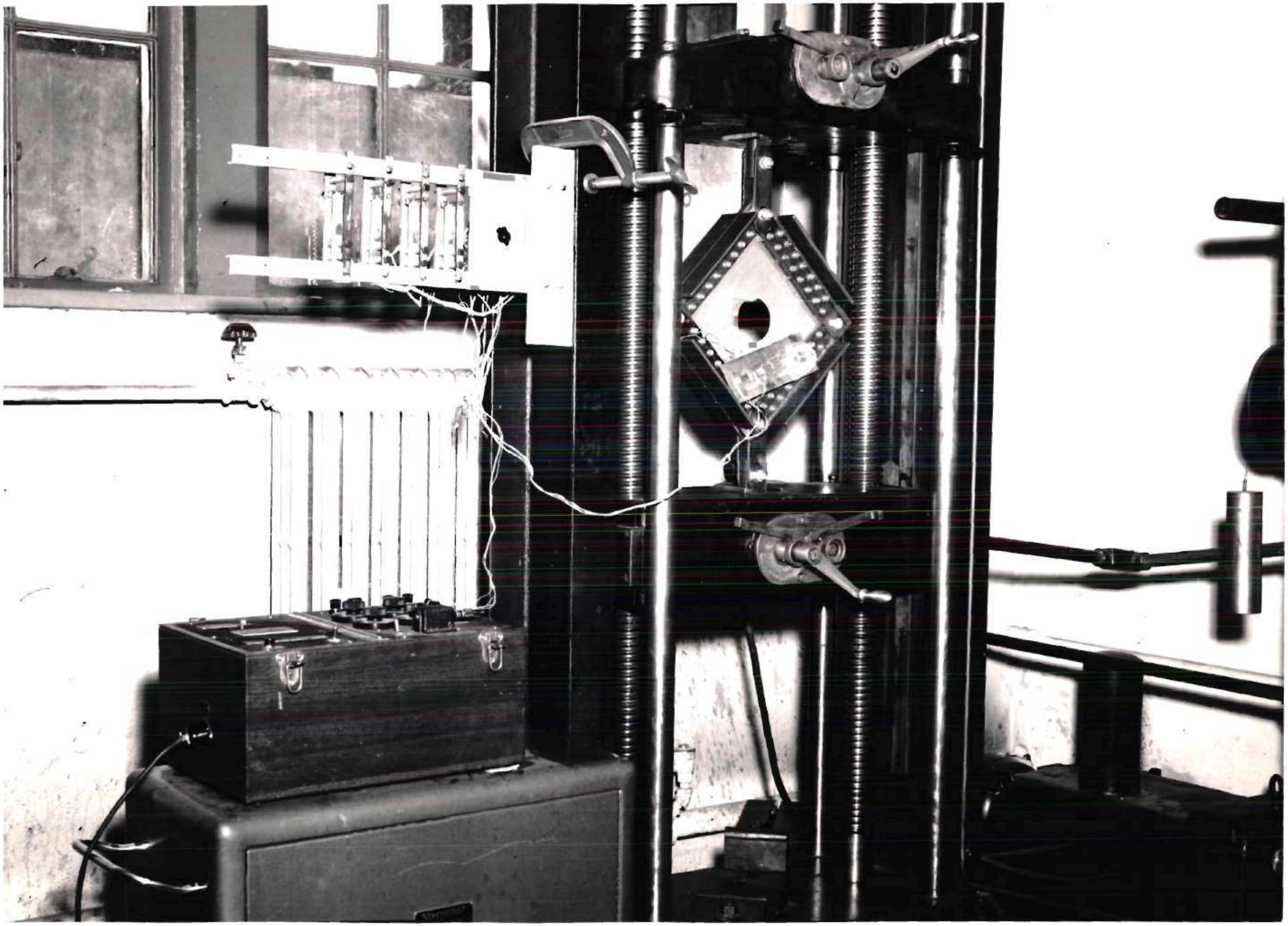


Figure 5. Shear Panel in Testing Machine

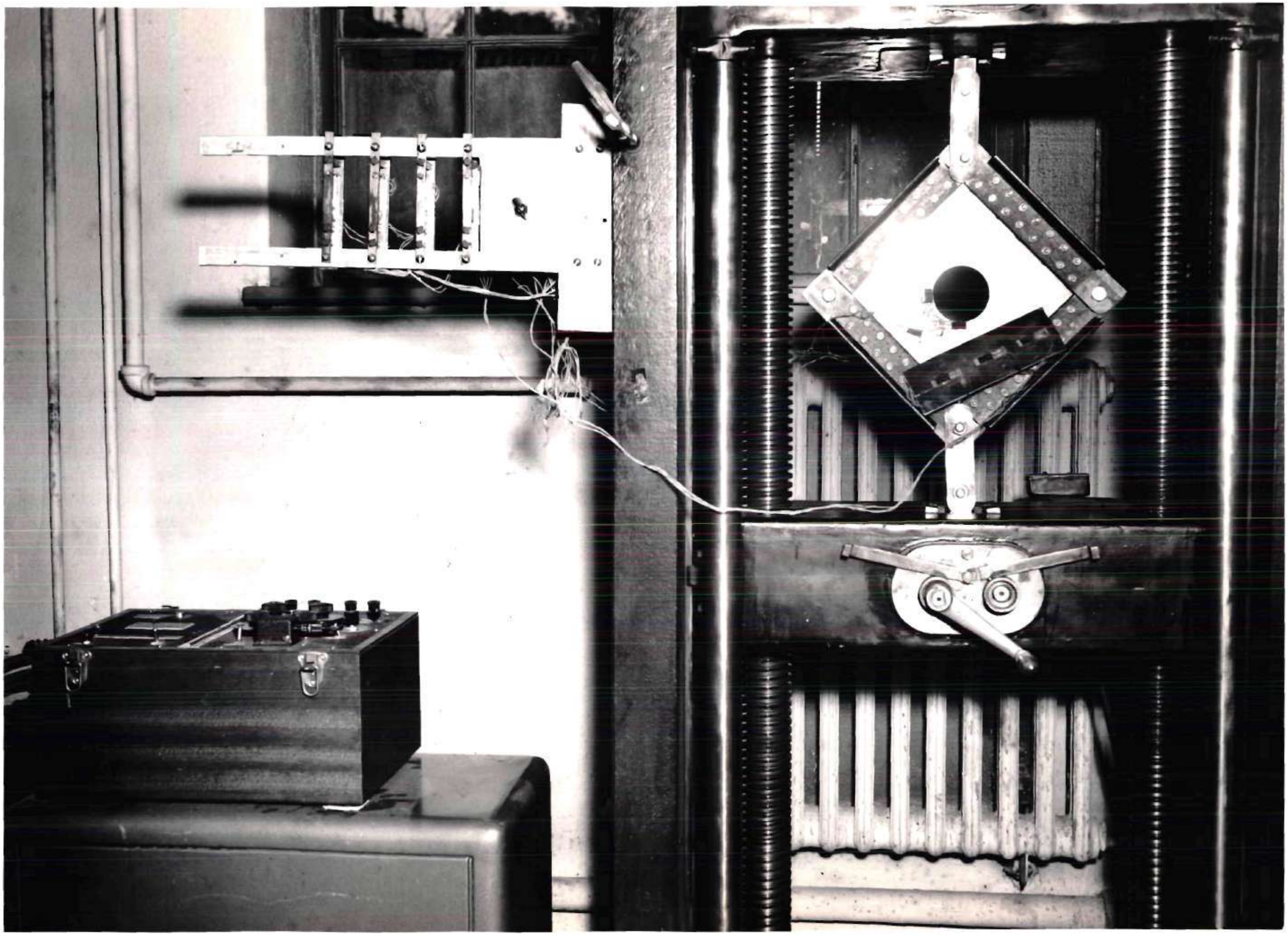
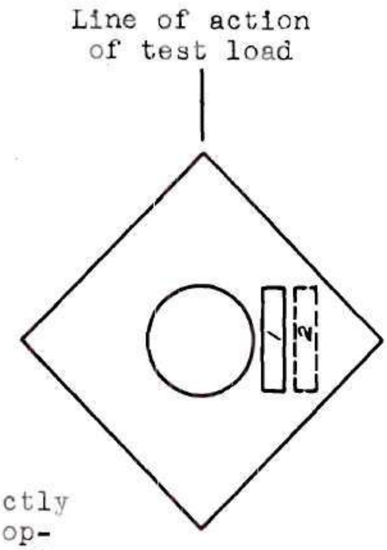
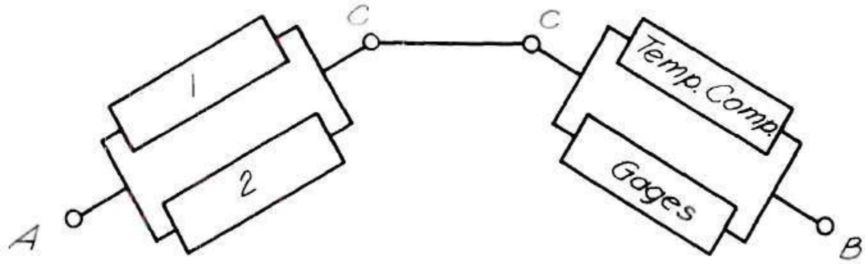


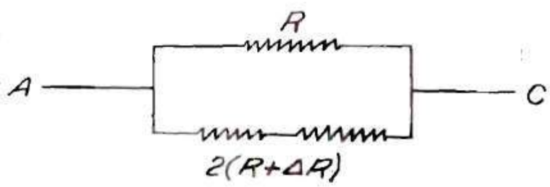
Figure 6. Location of Strain Gages on Shear Panel

CIRCUIT FOR MEASURING AXIAL AND DIAGONAL COMPRESSIVE STRAINS AND EVALUATION OF CONSTANT USED IN FORMULA FOR DETERMINING THESE STRAINS



Note: Gage 2 directly behind Gage 1 on opposite side of panel.





$$R_{AC} = \frac{1}{\frac{1}{2(R+\Delta R)} + \frac{1}{R}} = \frac{2R(R+\Delta R)}{R+2(R+\Delta R)}$$ Under strain

$$R_{AC} = \frac{R}{3}$$ No load value

$$\Delta R_{AC} = \frac{2R(R+\Delta R)}{R+2(R+\Delta R)} - .67R$$

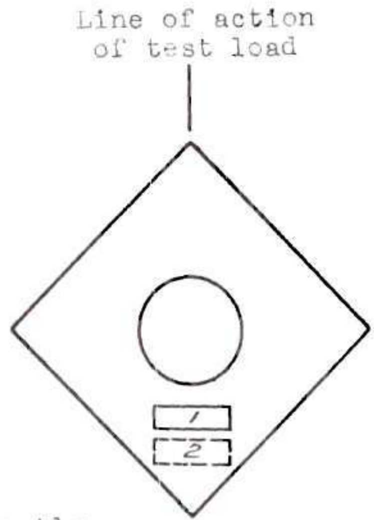
$$= \frac{.67R\Delta R}{R+2(R+\Delta R)}$$

If ΔR is small compared to R

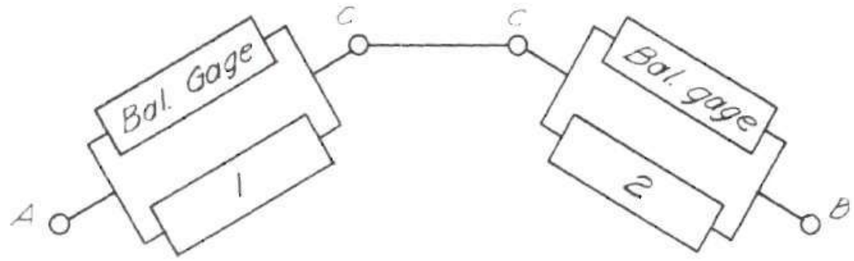
$$\Delta R_{AC} = \frac{.67R\Delta R}{3R} = .223\Delta R$$

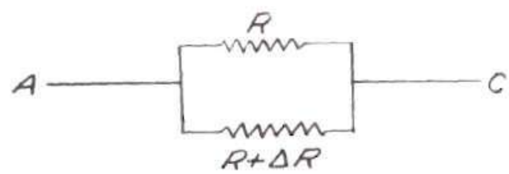
Figure 7

CIRCUIT FOR MEASURING SECONDARY BENDING STRAINS AND EVALUATION OF CONSTANT USED IN FORMULA FOR DETERMINING THESE STRAINS



Note: Gage 2 directly behind Gage 1 on opposite side of panel.





$$R_{AC} = \frac{1}{\frac{1}{R} + \frac{1}{R+\Delta R}} = \frac{R(R+\Delta R)}{(R+\Delta R)+R}$$ *Under strain*

$$R_{AC} = \frac{R}{2}$$ *No load value*

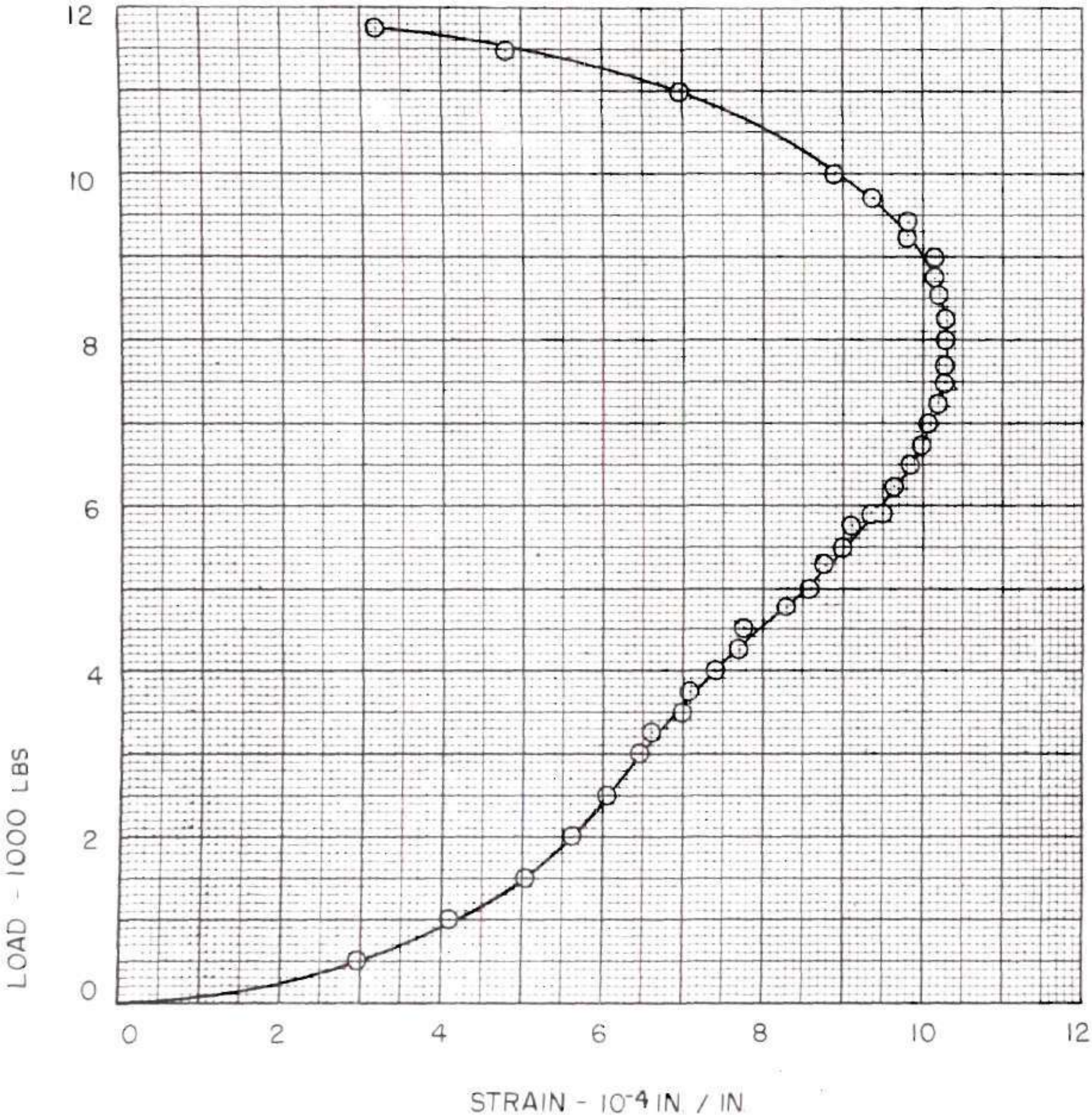
$$\Delta R_{AC} = \frac{R(R+\Delta R}{(R+\Delta R)+R} - \frac{R}{2}$$

$$= \frac{.5R\Delta R}{(R+\Delta R)+R}$$

If ΔR is small compared to R

$$\Delta R_{AC} = \frac{5R\Delta R}{2R} = .25\Delta R$$

Figure 8



DIAGONAL COMPRESSIVE STRAIN

.032 PANEL WITH A 3" DIAMETER ACCESS HOLE

Figure 9

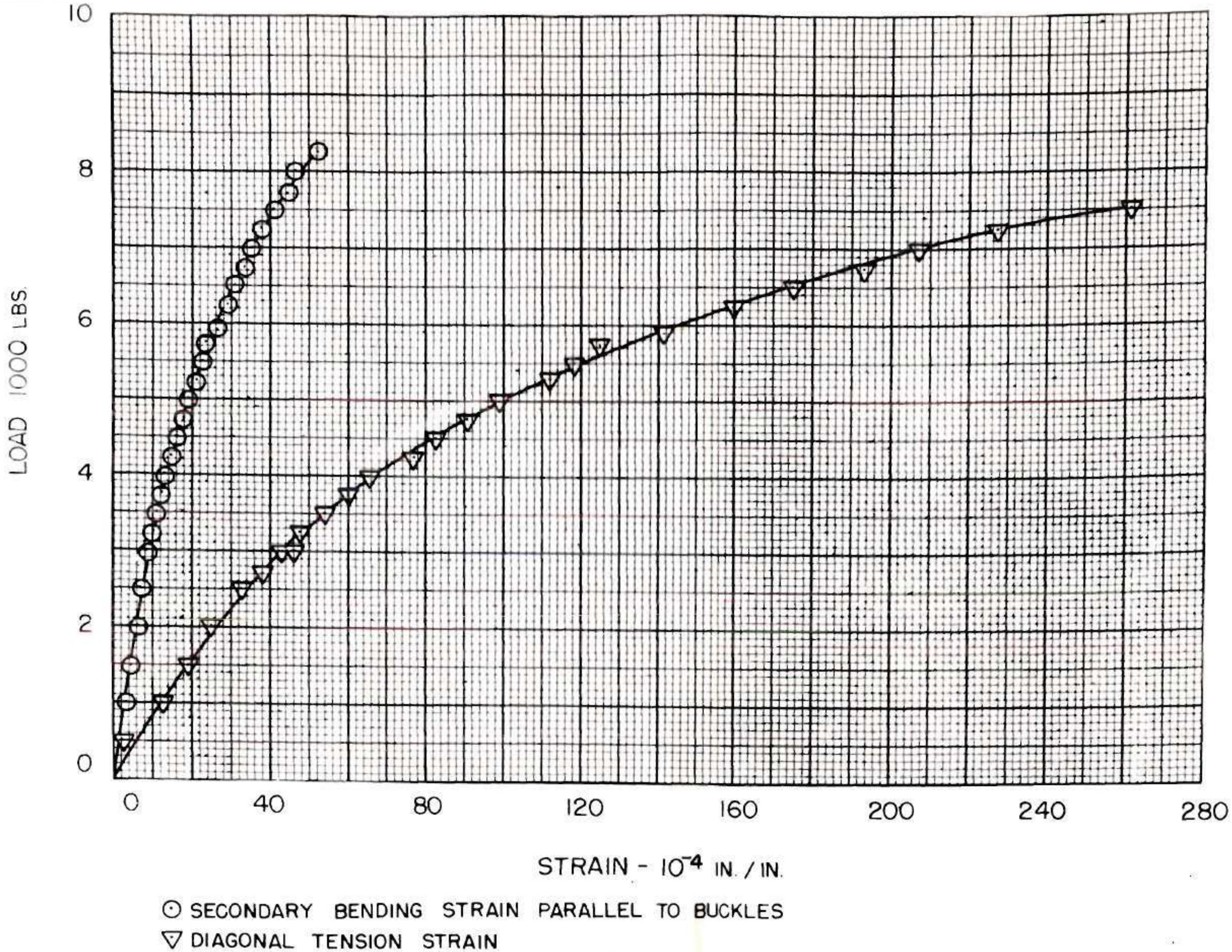


Figure 10

DIAGONAL TENSION STRAIN & SECONDARY BENDING STRAIN PARALLEL TO BUCKLES

.032 PANEL WITH 2" DIAMETER ACCESS HOLE

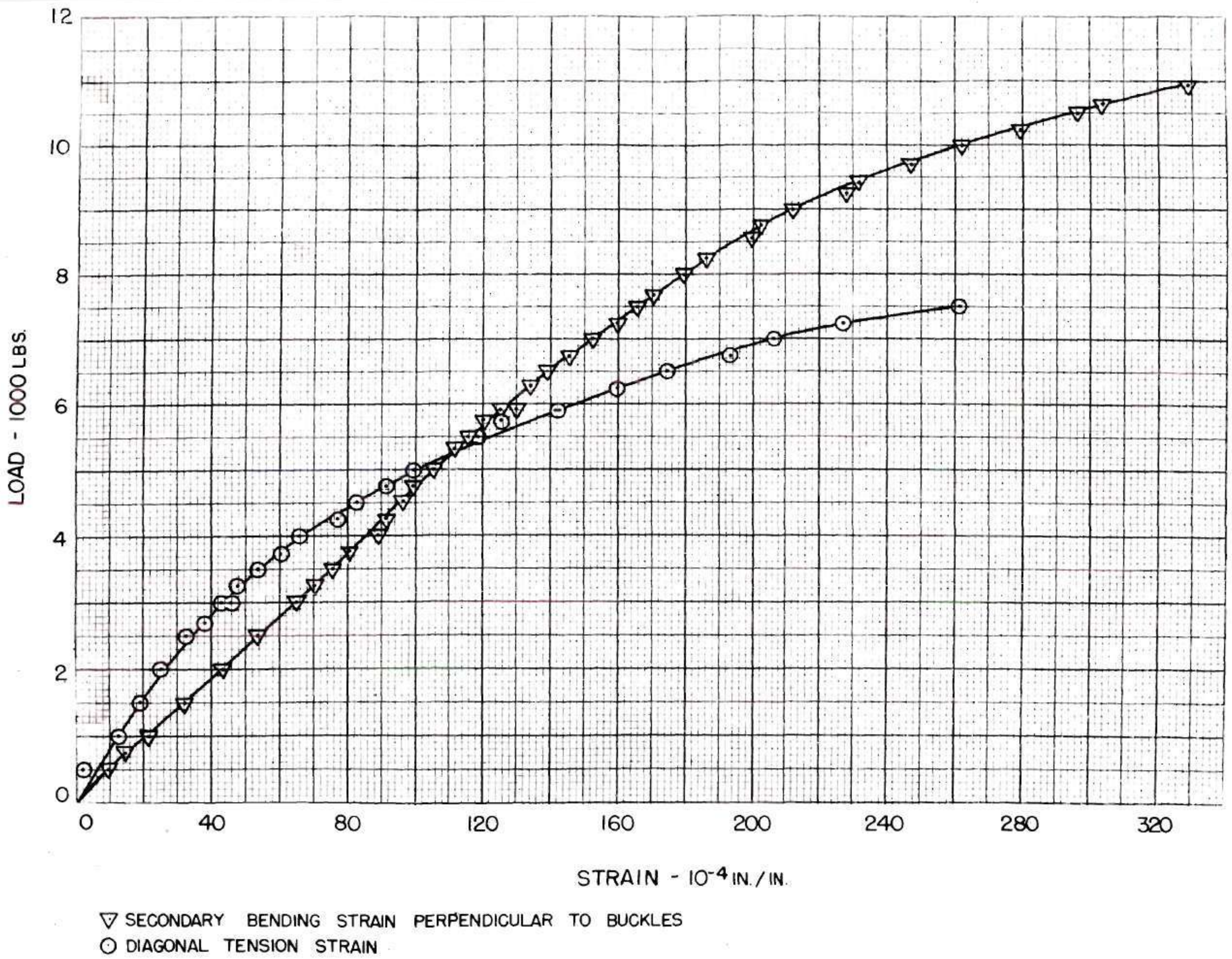
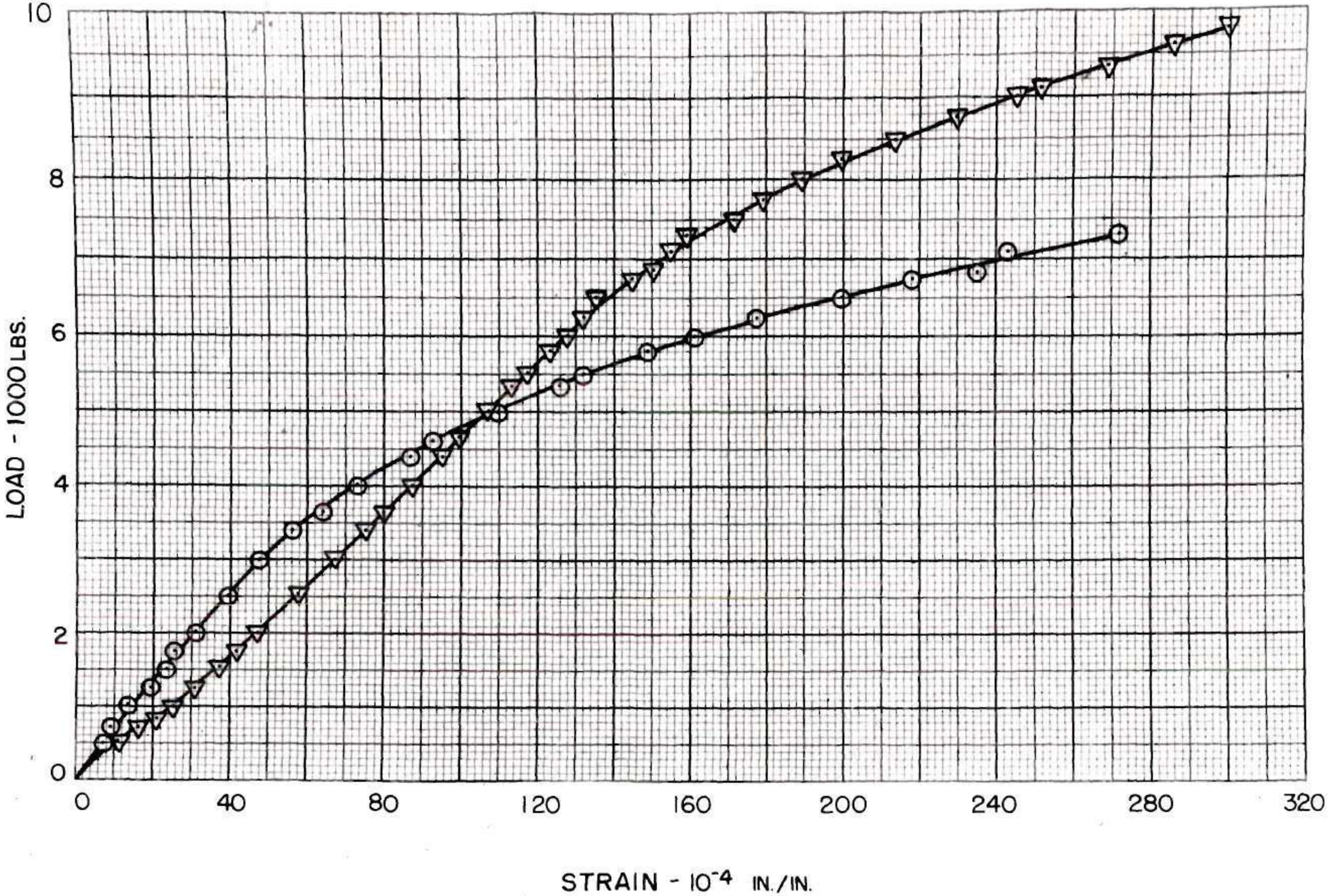


Figure 11

DIAGONAL TENSION STRAIN & SECONDARY BENDING STRAIN PERPENDICULAR TO BUCKLES

.032 PANEL WITH 2" DIAMETER ACCESS HOLE



▽ SECONDARY BENDING STRAIN PERPENDICULAR TO BUCKLES

⊙ DIAGONAL TENSION STRAIN

Figure 12

DIAGONAL TENSION STRAIN & SECONDARY BENDING STRAIN PERPENDICULAR TO BUCKLES

.032 PANEL WITH 3" DIAMETER ACCESS HOLE

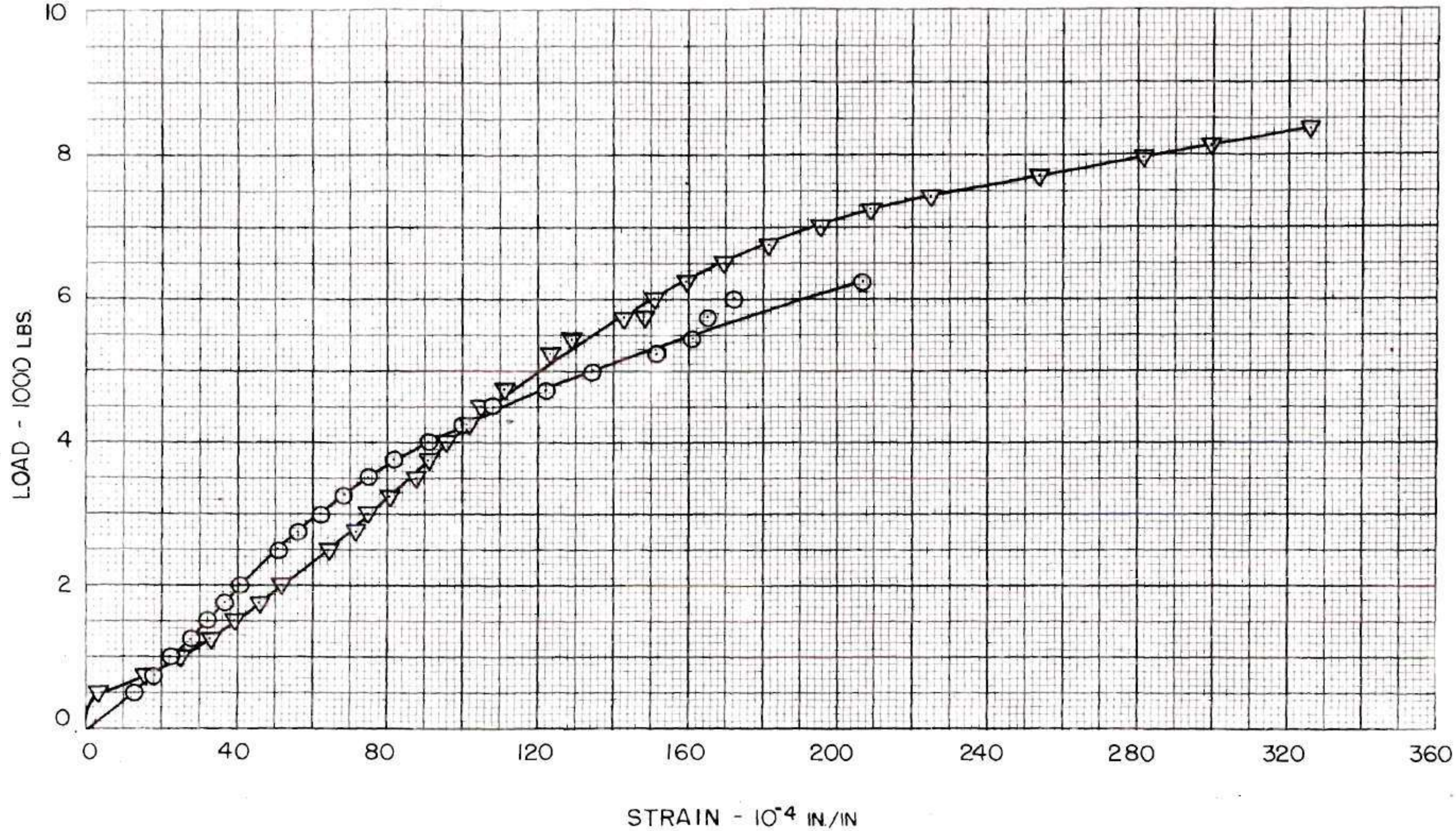


Figure 13

DIAGONAL TENSION STRAIN & SECONDARY BENDING STRAIN PERPENDICULAR TO BUCKLES

.032 PANEL WITH 4" DIAMETER ACCESS HOLE

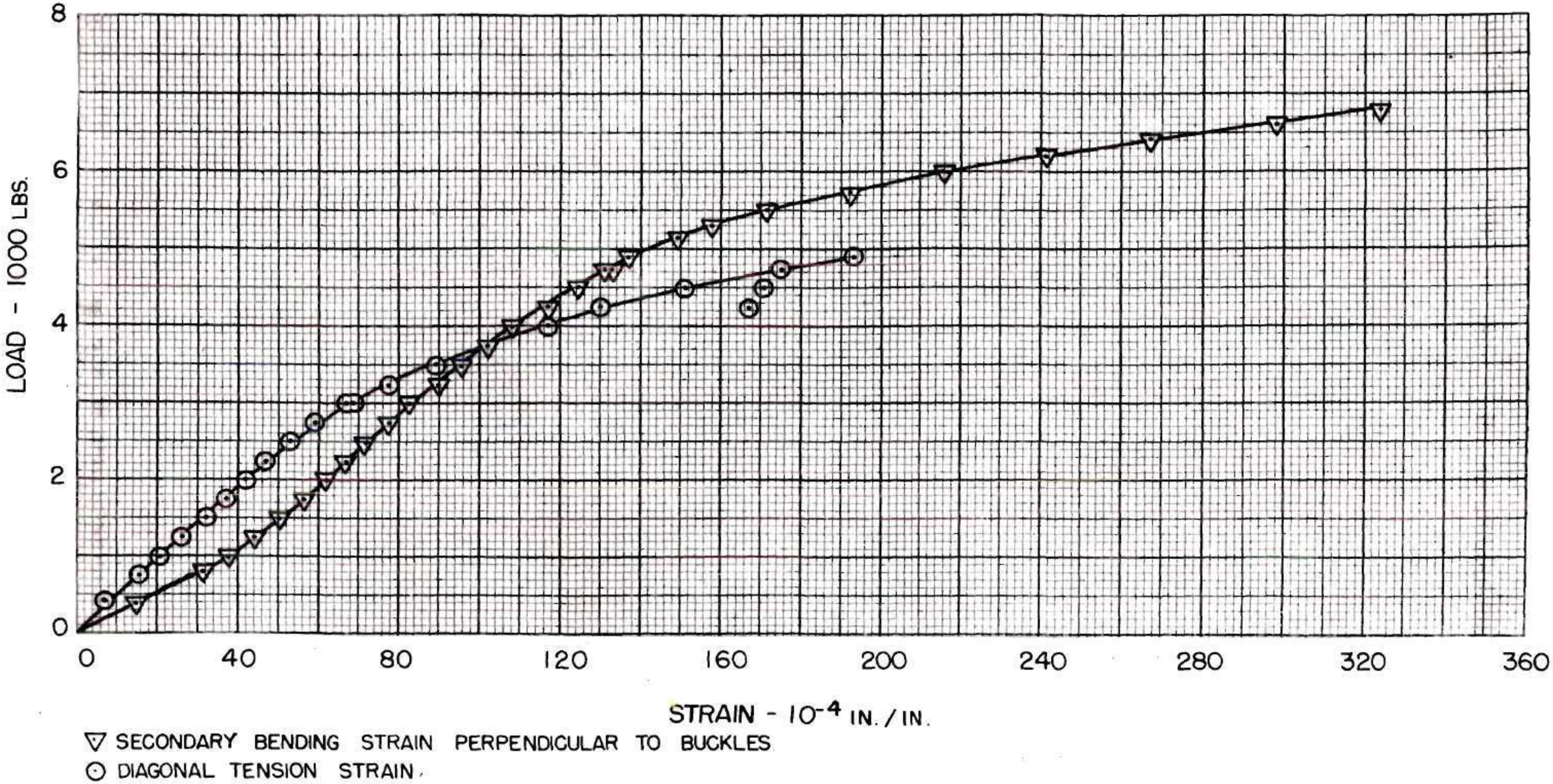


Figure 14

DIAGONAL TENSION STRAIN & SECONDARY BENDING STRAIN PERPENDICULAR TO BUCKLES

.032 PANEL WITH 5" DIAMETER ACCESS HOLE

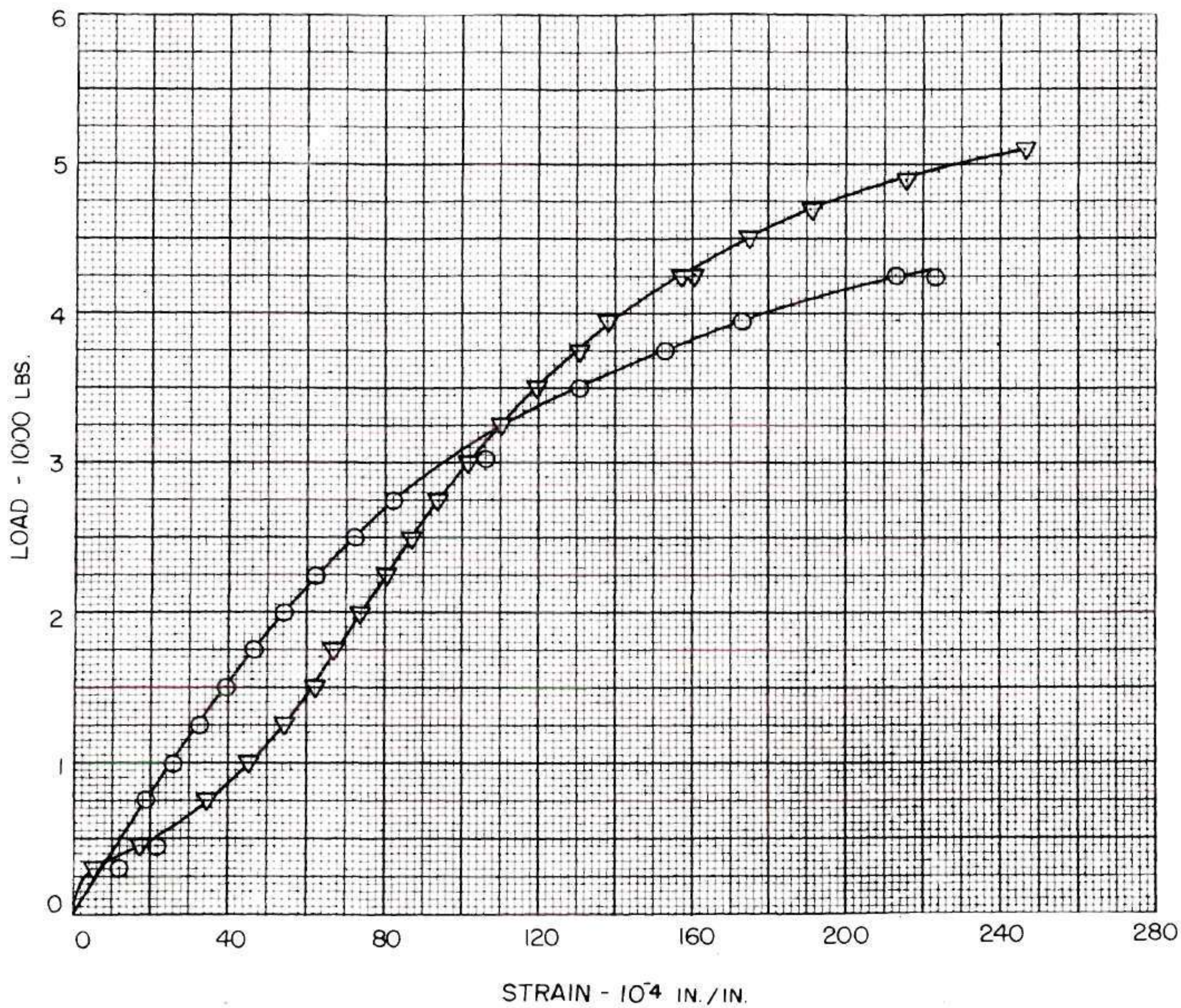


Figure 15

DIAGONAL TENSION STRAIN & SECONDARY BENDING STRAIN PERPENDICULAR TO BUCKLES

.032 PANEL WITH 6" DIAMETER ACCESS HOLE

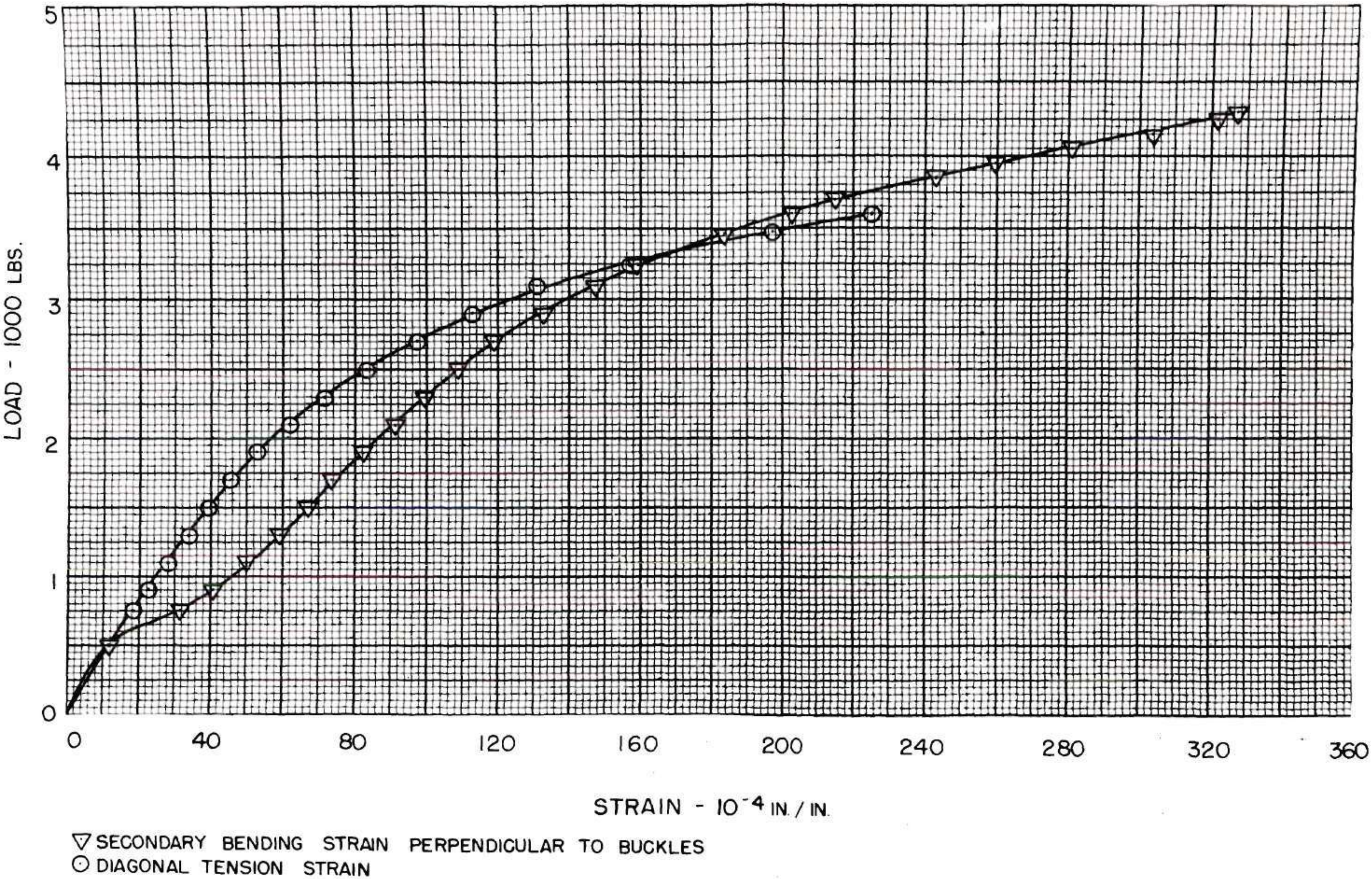


Figure 16

DIAGONAL TENSION STRAIN & SECONDARY BENDING STRAIN PERPENDICULAR TO BUCKLES

.032 PANEL WITH 7" DIAMETER ACCESS HOLE

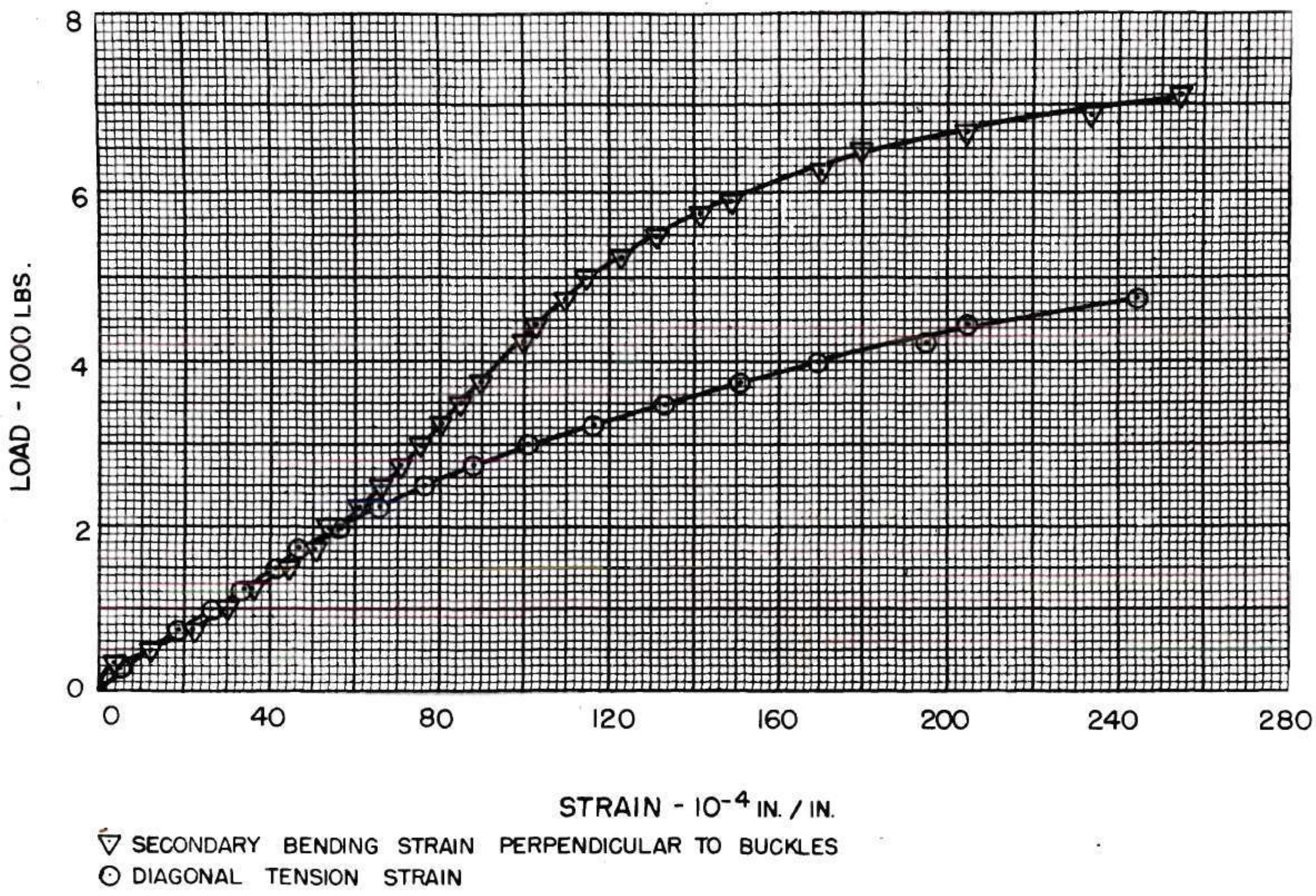


Figure 17

DIAGONAL TENSION STRAIN & SECONDARY BENDING STRAIN PERPENDICULAR TO BUCKLES

.020 PANEL WITH 3" DIAMETER ACCESS HOLE

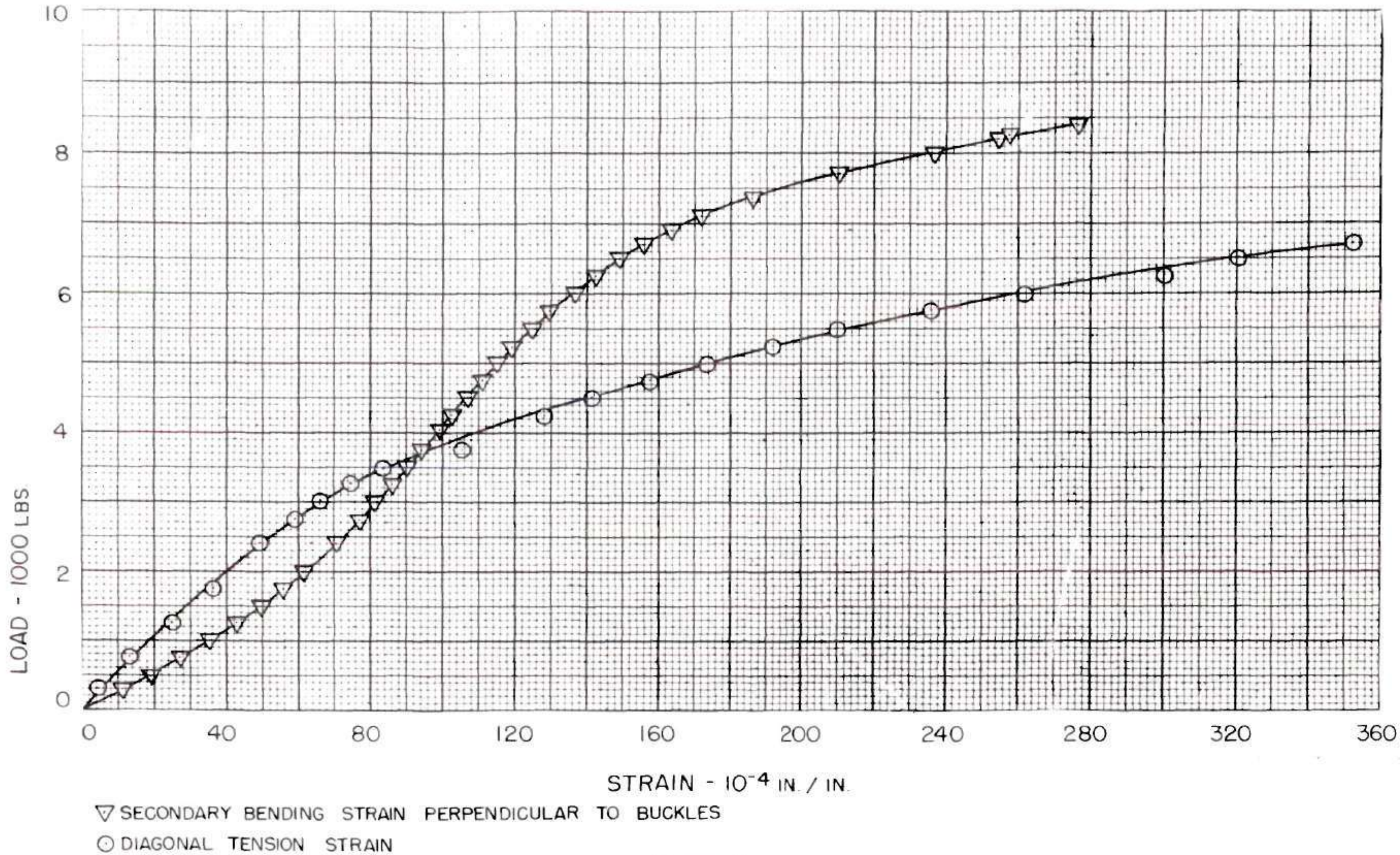


Figure 18

DIAGONAL TENSION STRAIN & SECONDARY BENDING STRAIN PERPENDICULAR TO BUCKLES

.025 PANEL WITH 3" DIAMETER ACCESS HOLE

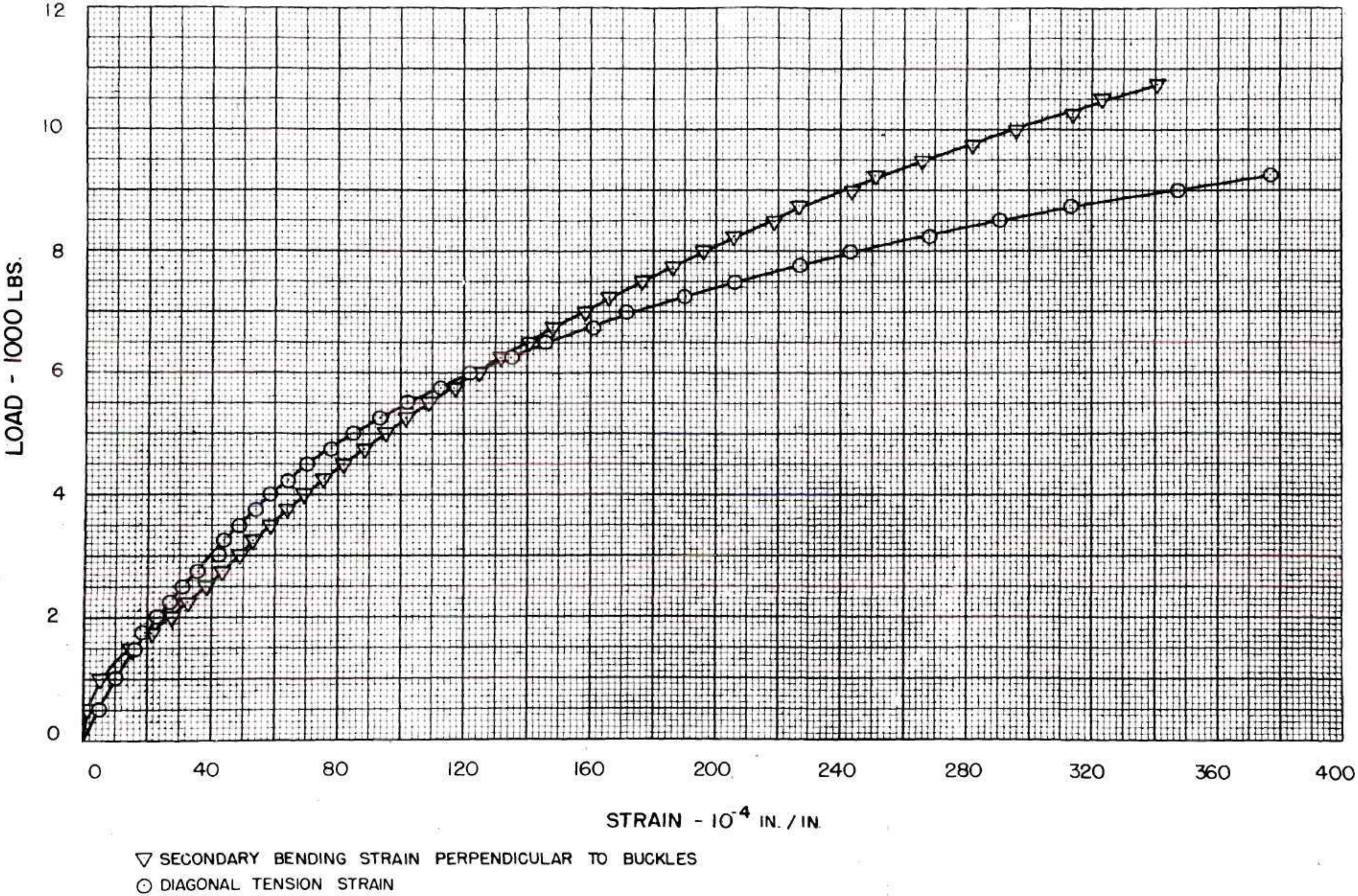
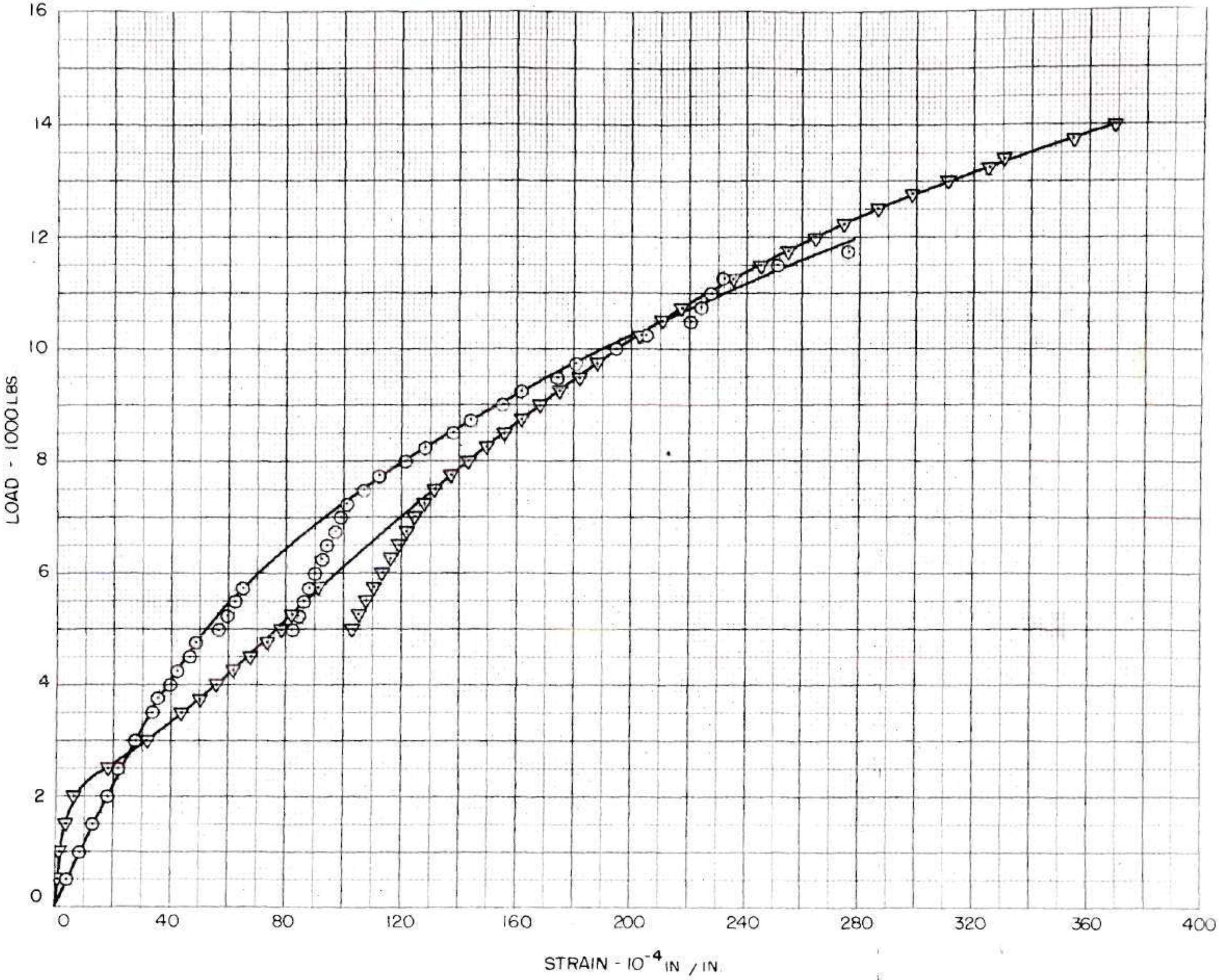


Figure 19

DIAGONAL TENSION STRAIN & SECONDARY BENDING STRAIN PERPENDICULAR TO BUCKLES

.040 PANEL WITH 3" DIAMETER ACCESS HOLE



▽ SECONDARY BENDING STRAIN PERPENDICULAR TO BUCKLES

⊙ DIAGONAL TENSION STRAIN

Figure 20

DIAGONAL TENSION STRAIN & SECONDARY BENDING STRAIN PERPENDICULAR TO BUCKLES

.051 PANEL WITH 3" DIAMETER ACCESS HOLE

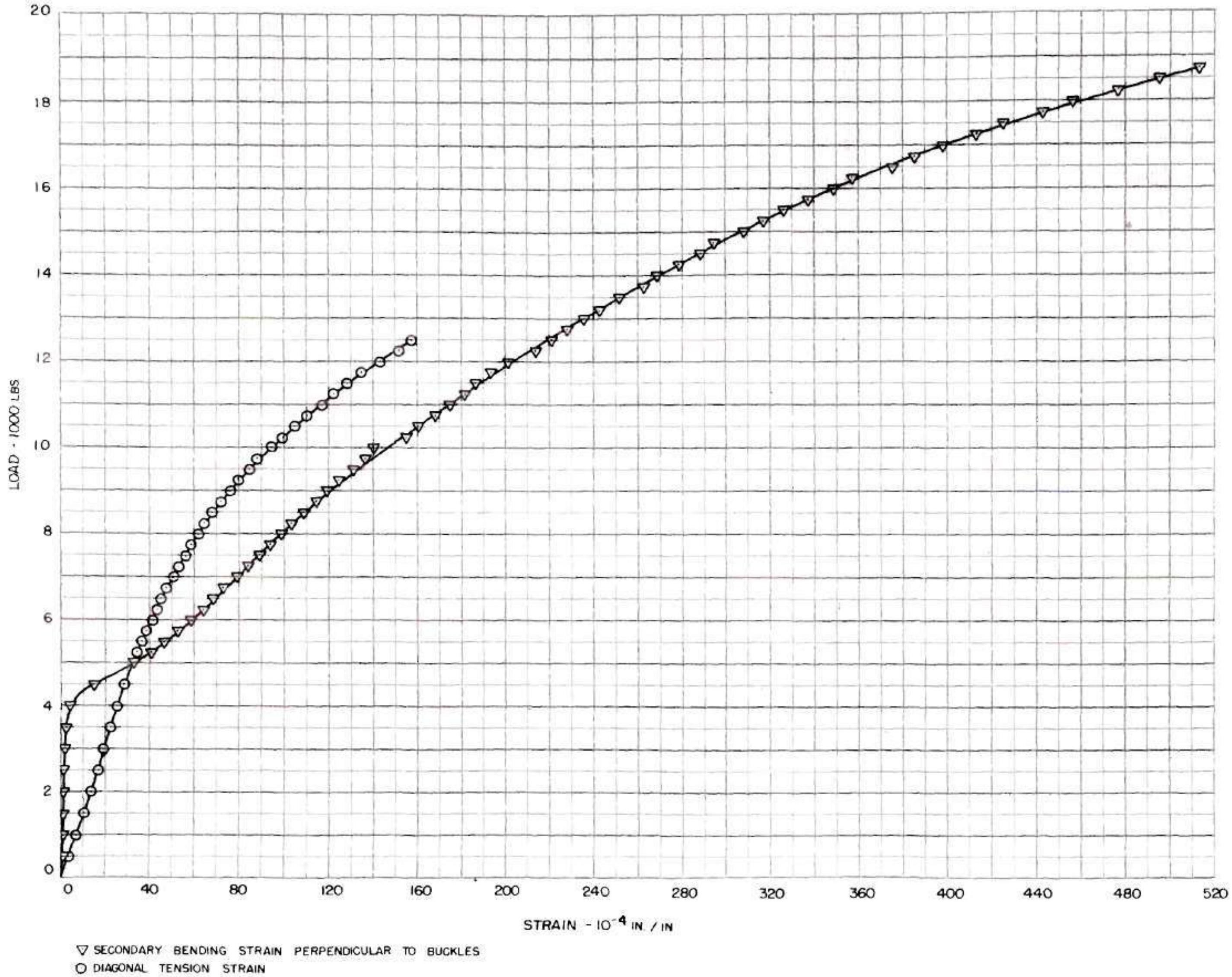
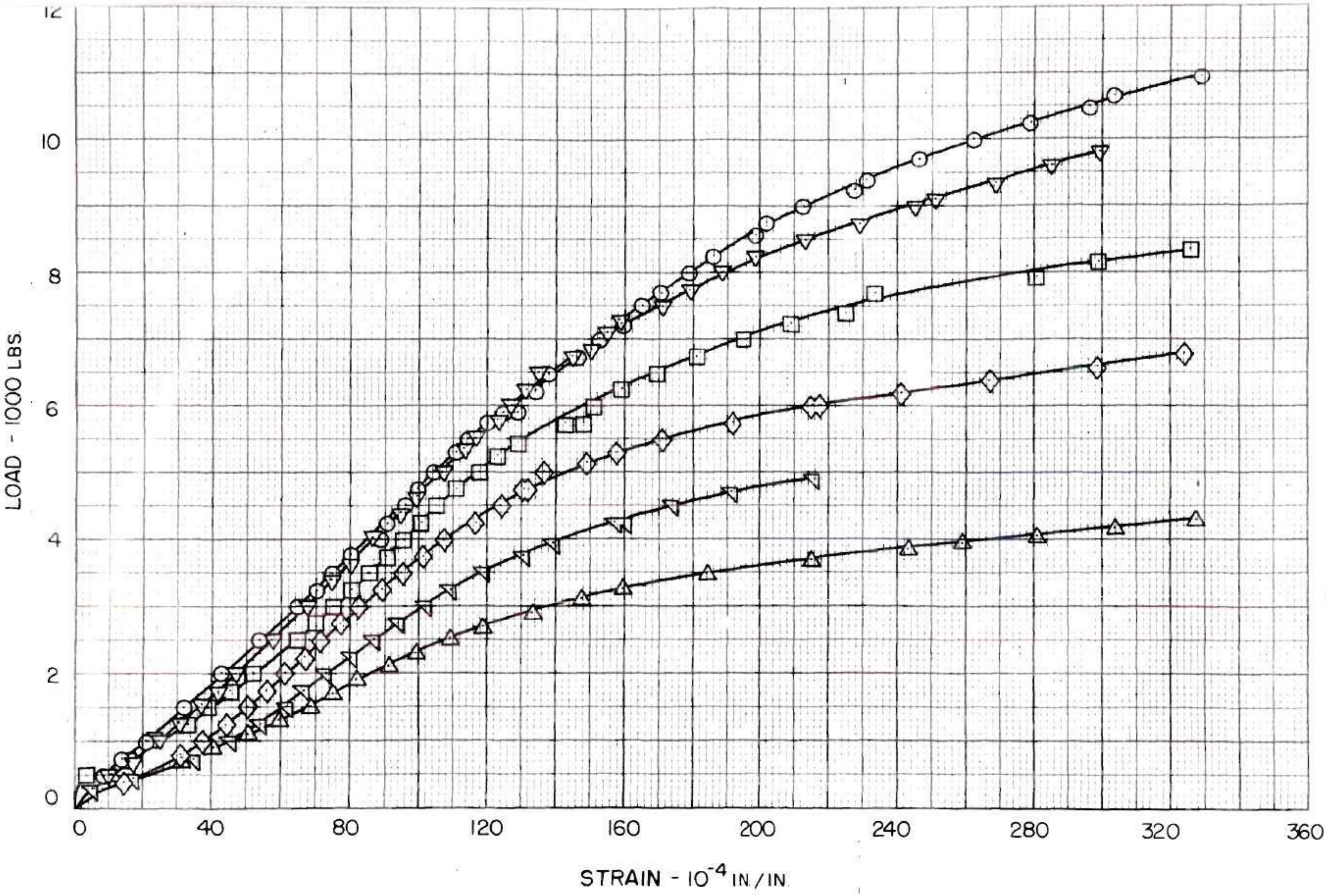


Figure 21

DIAGONAL TENSION STRAIN & SECONDARY BENDING STRAIN
PERPENDICULAR TO BUCKLES
.064 PANEL WITH 3" DIAMETER ACCESS HOLE



⊙ .032 PANEL WITH 2" DIA. ACCESS HOLE
▽ .032 PANEL WITH 3" DIA. ACCESS HOLE
⊡ .032 PANEL WITH 4" DIA. ACCESS HOLE
◇ .032 PANEL WITH 5" DIA. ACCESS HOLE
◁ .032 PANEL WITH 6" DIA. ACCESS HOLE
△ .032 PANEL WITH 7" DIA. ACCESS HOLE

Figure 22

DIAGONAL TENSION STRAIN

.032 PANELS WITH AN ACCESS HOLE OF VARIOUS DIAMETERS

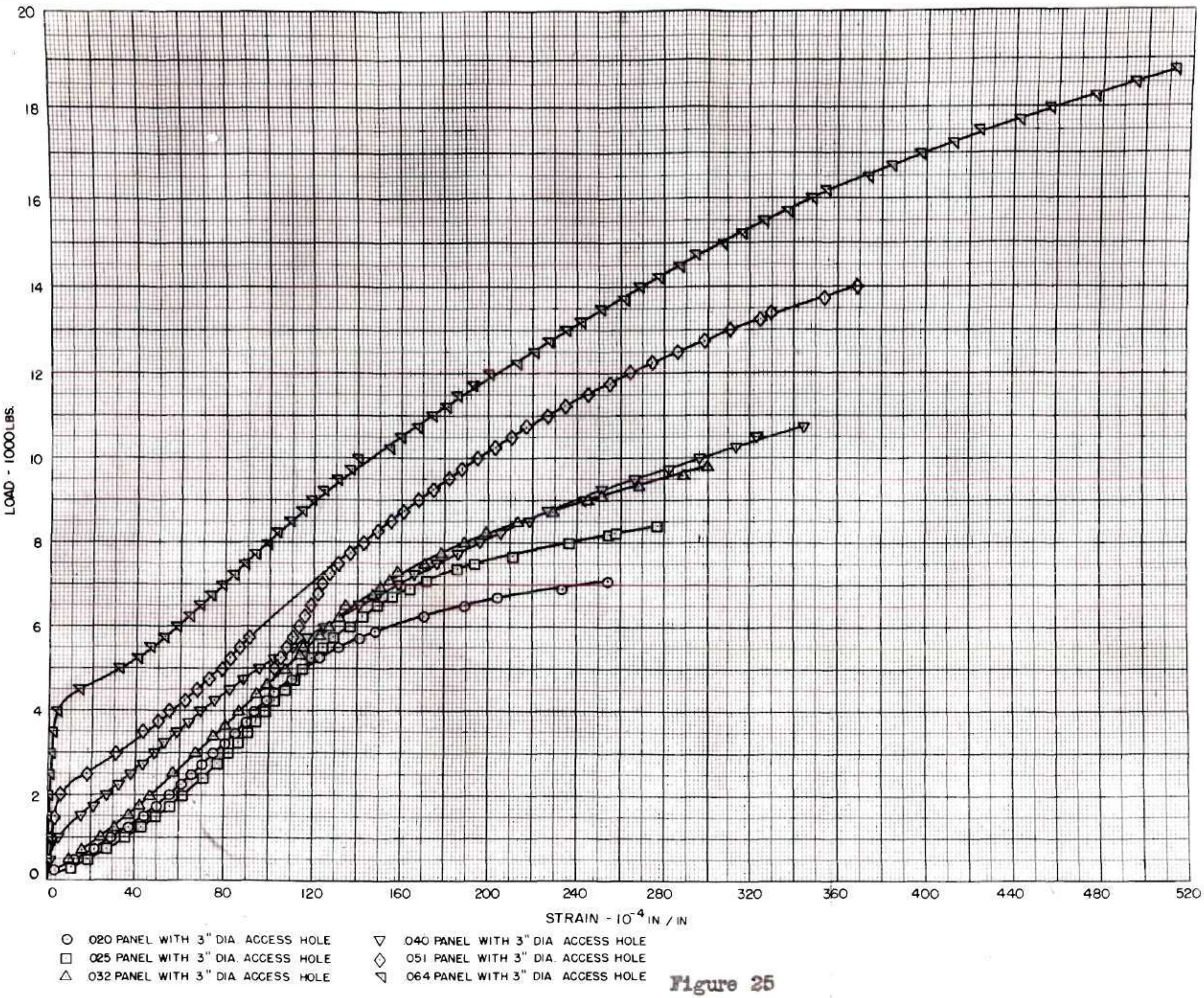
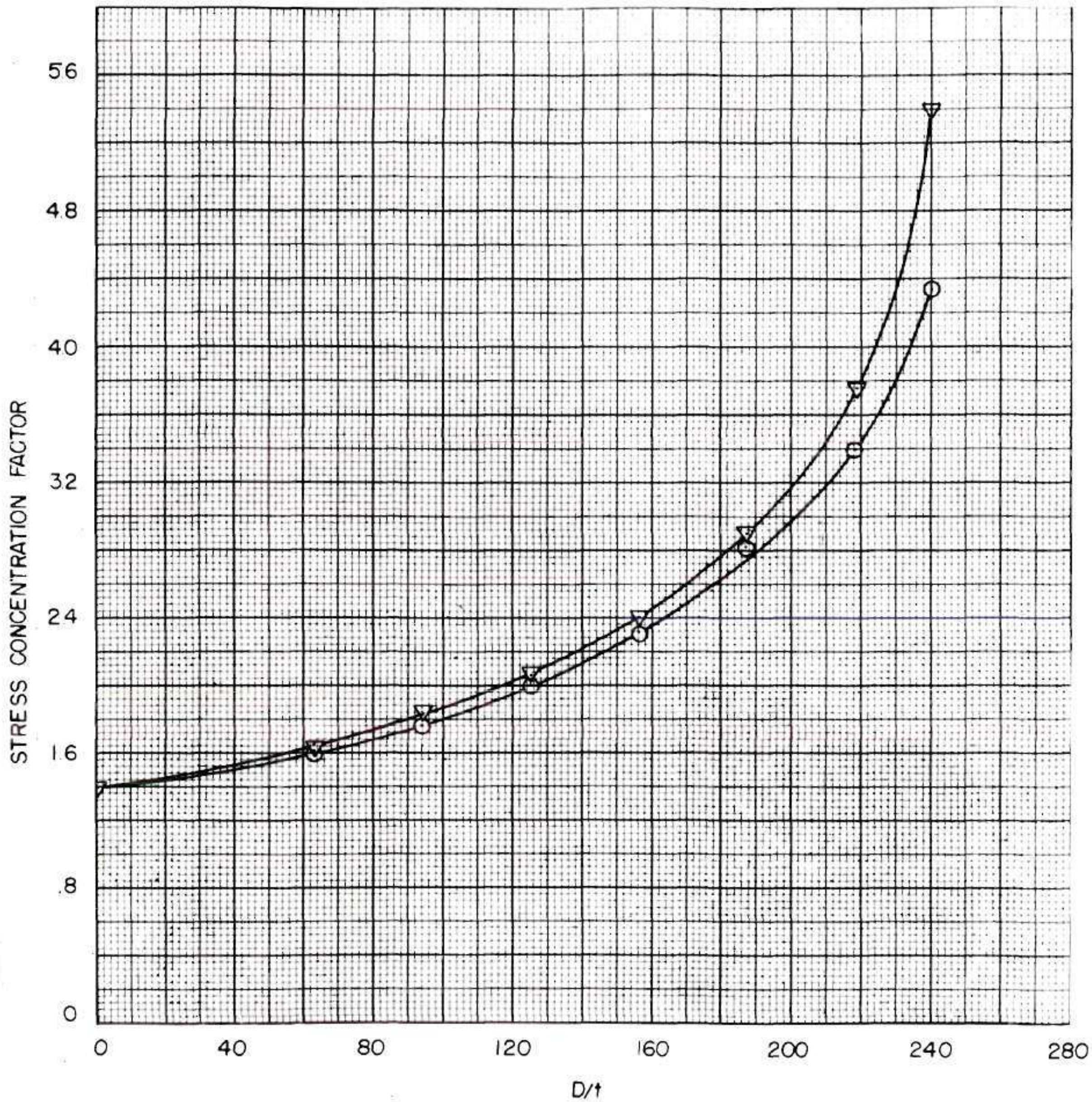


Figure 25

SECONDARY BENDING STRAIN PERPENDICULAR TO BUCKLES
VARIOUS GAGE PANELS WITH A 3" DIAMETER ACCESS HOLE



▽ THEORETICAL STRESS CONCENTRATION FACTOR
⊙ EXPERIMENTAL STRESS CONCENTRATION FACTOR

Figure 26
STRESS CONCENTRATION FACTORS
FOR VARIOUS RATIOS OF D/t FOR AN .032 PANEL

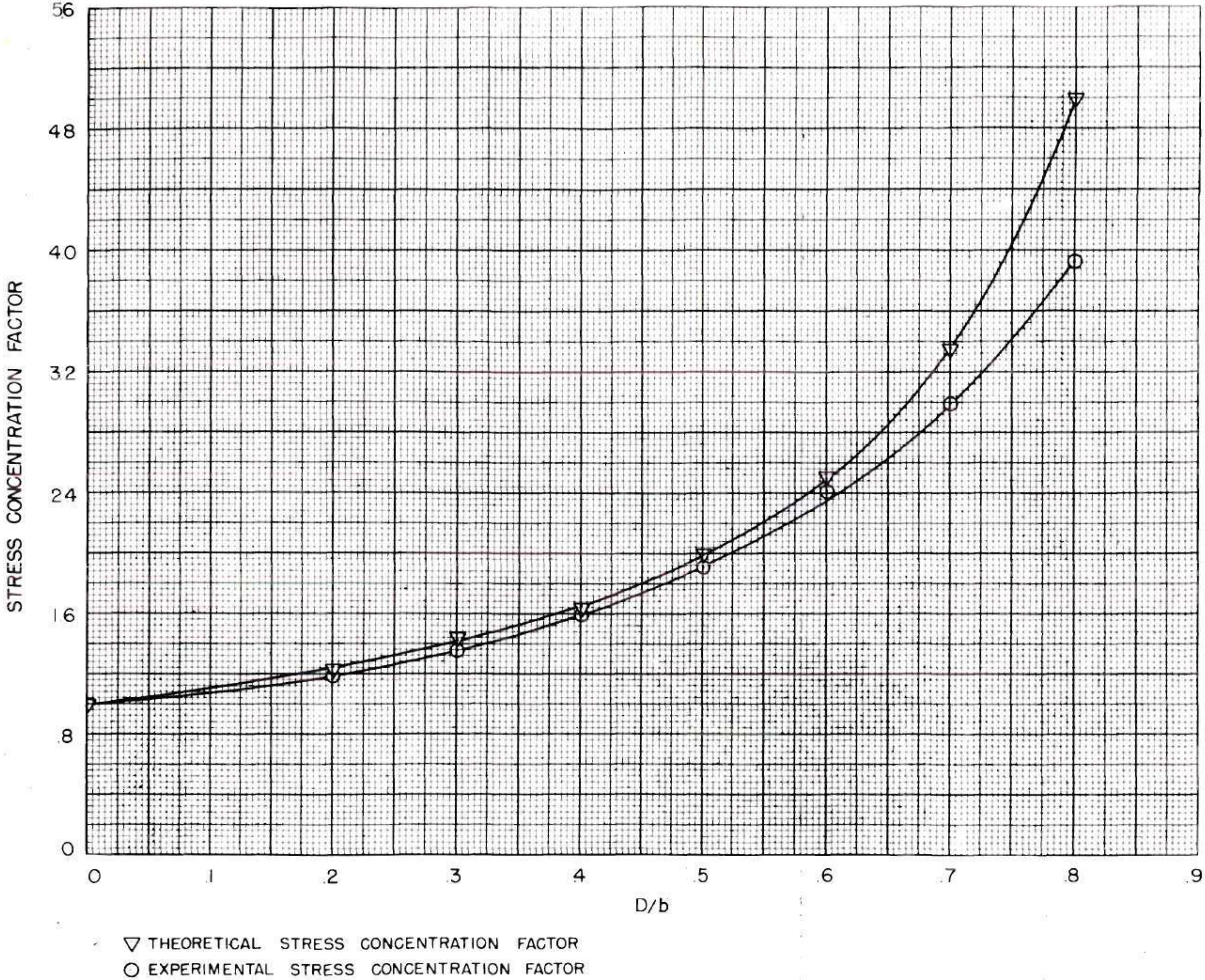
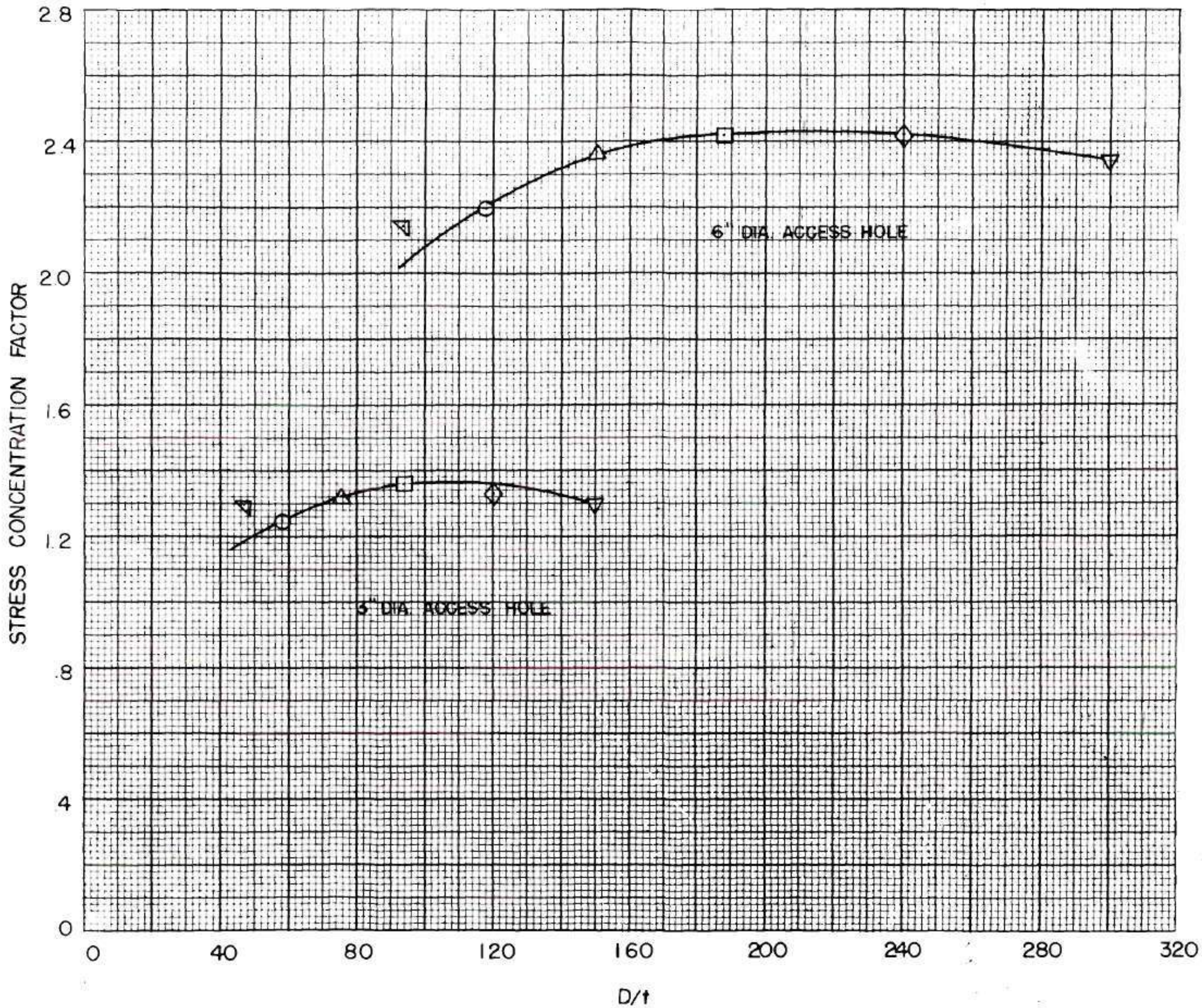


Figure 27

STRESS CONCENTRATION FACTORS FOR VARIOUS RATIOS OF D/b FOR AN .032 PANEL



.020 PANEL .040 PANEL
.025 PANEL .051 PANEL
.032 PANEL .064 PANEL

Figure 28

STRESS CONCENTRATION FACTORS FOR VARIOUS RATIOS OF D/t

3" & 6" DIAMETER HOLES

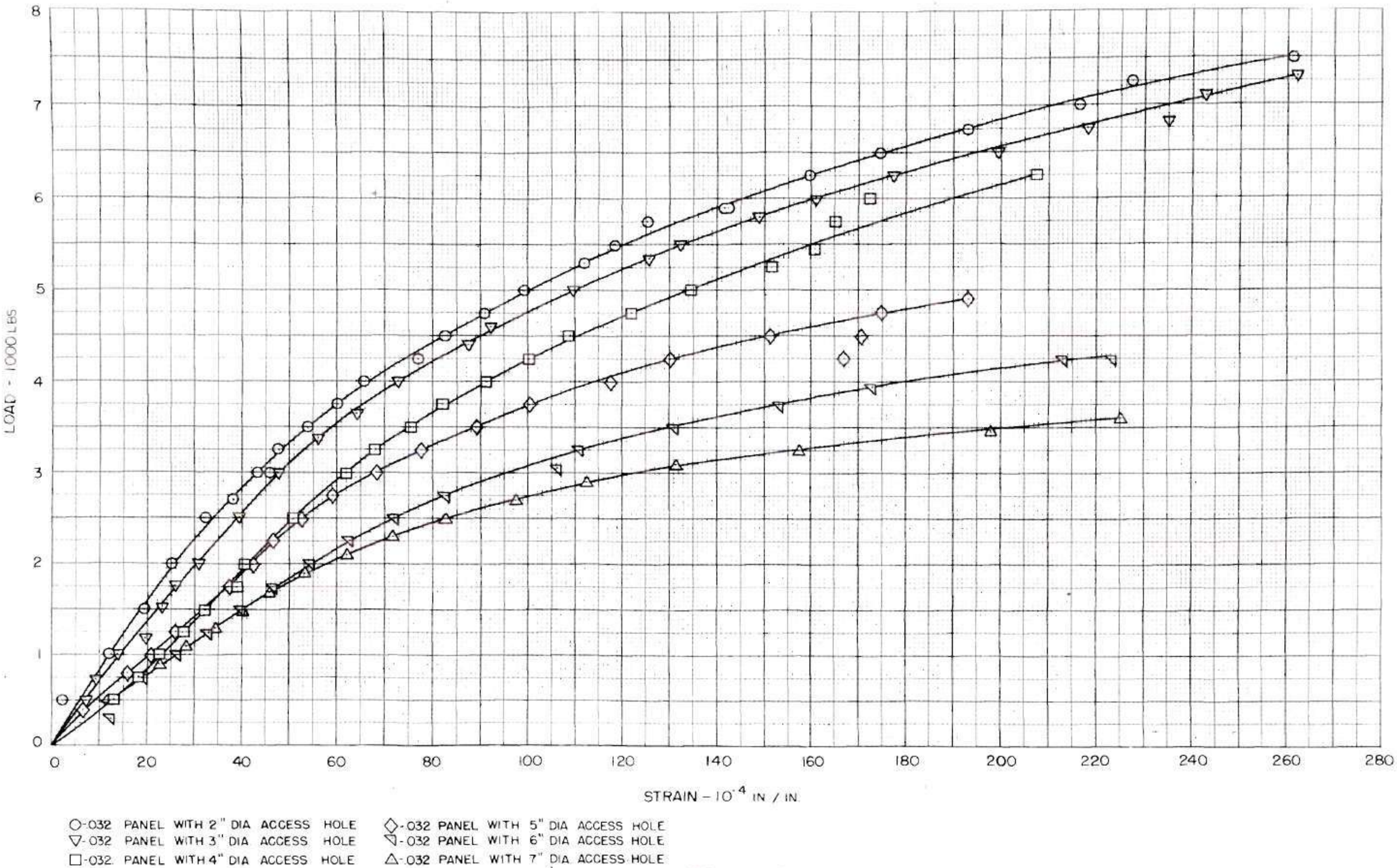


Figure 23

SECONDARY BENDING STRAIN PERPENDICULAR TO BUCKLES

.032 PANELS WITH AN ACCESS HOLE OF VARIOUS DIAMETERS

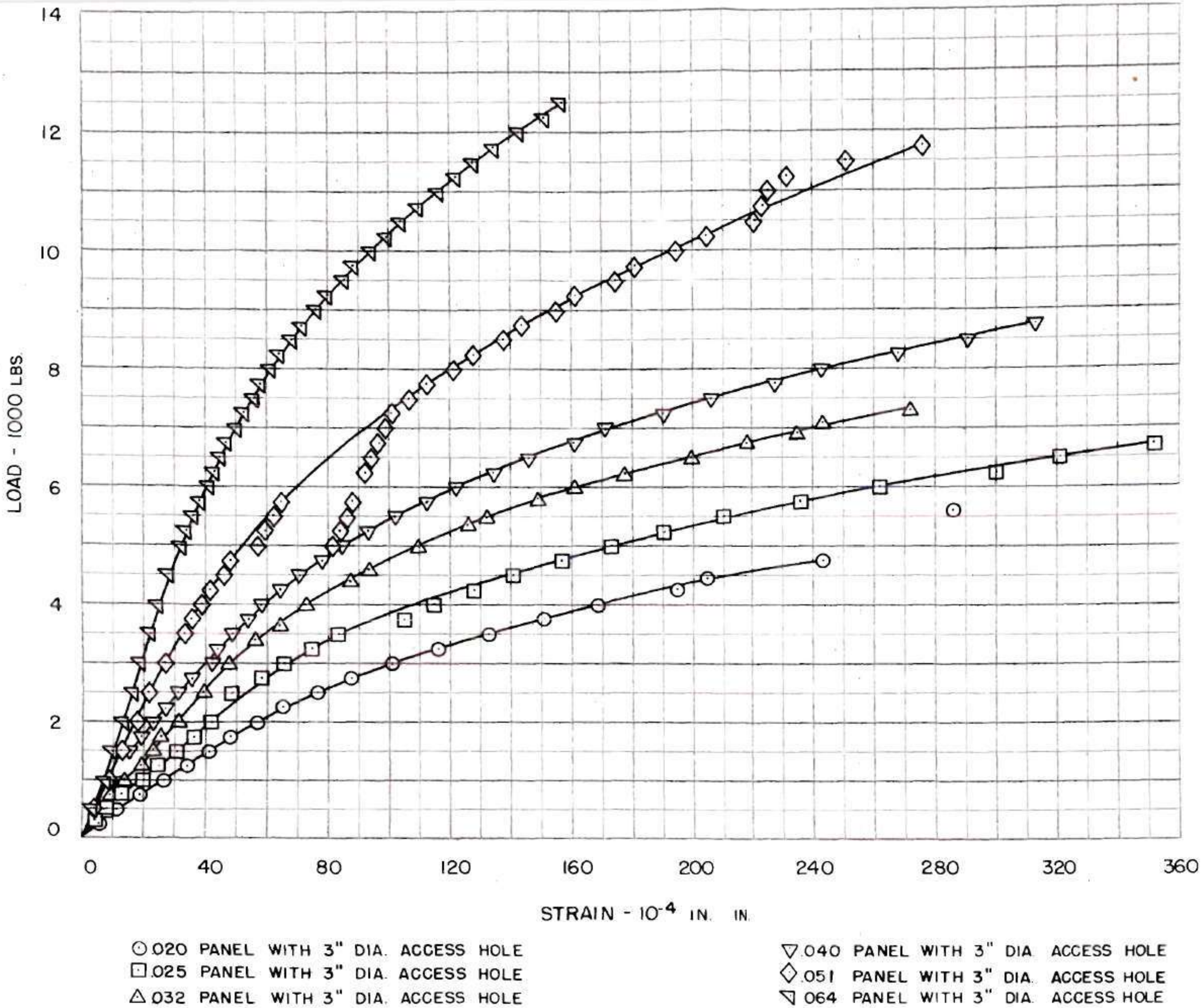


Figure 24

DIAGONAL TENSION STRAIN

VARIOUS GAGE PANELS WITH A 3" DIAMETER ACCESS HOLE

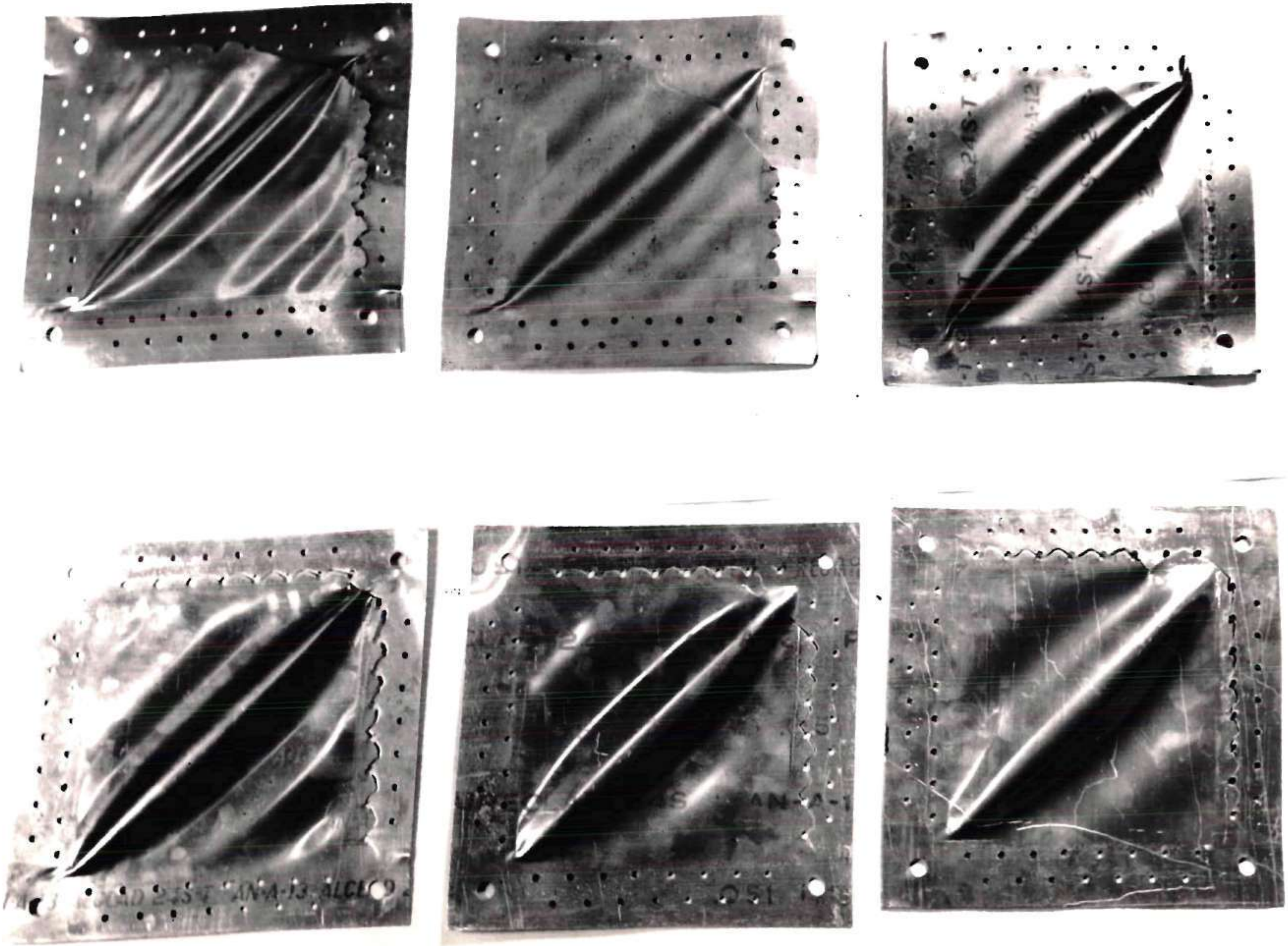


Figure 29. Solid Panels After Failure

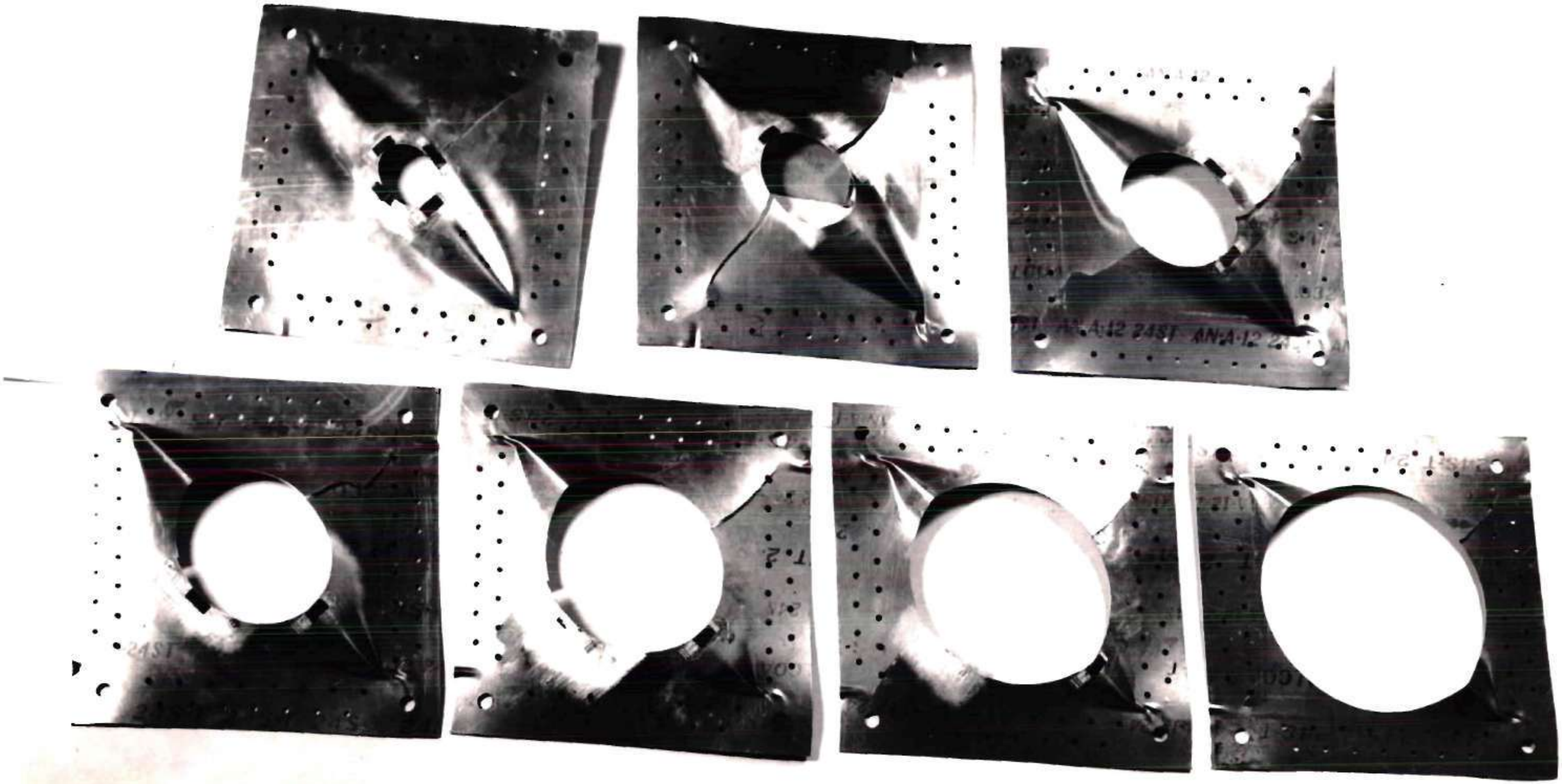


Figure 30. .032 Panels With Various Diameter Access Holes After Failure

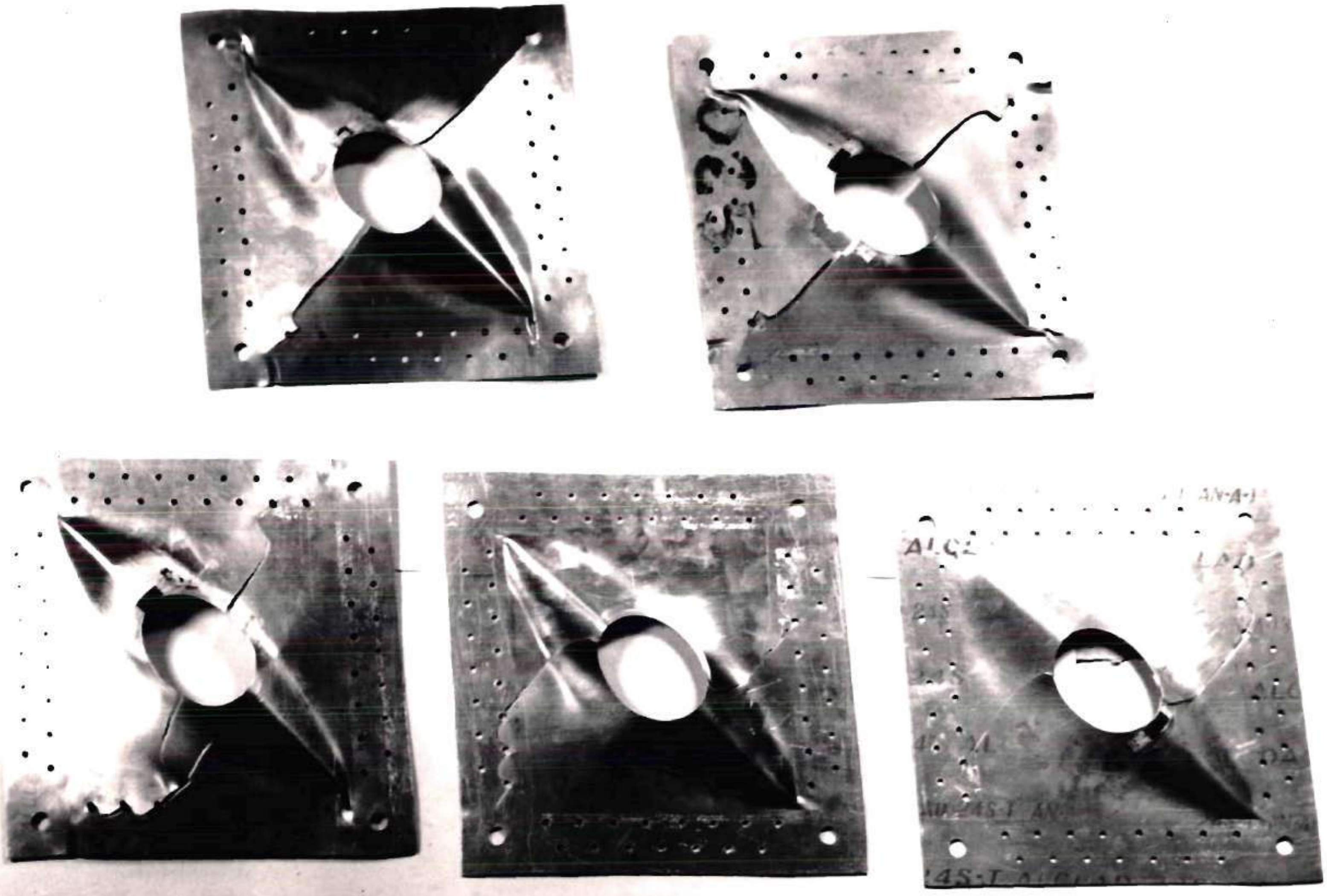


Figure 31. Various Gage Panels With a 3-Inch Diameter Access Hole After Rupture

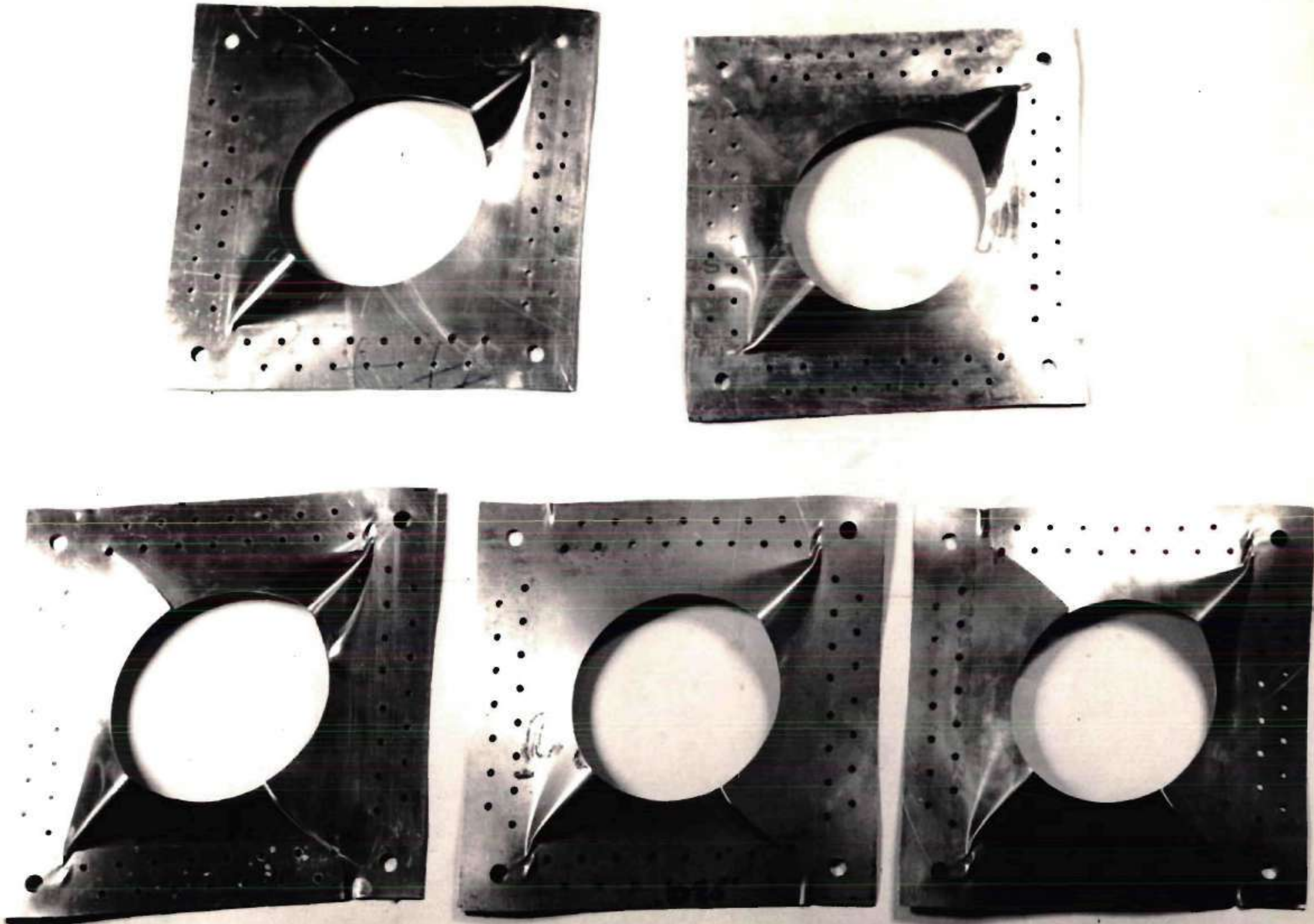


Figure 32. Various Gage Panels With a 6-Inch Diameter Access Hole After Failure