TESTING AN HYPOTHESIS ON THE LOAD DISTRIBUTION OF A PARALLEL-TYPE STRUCTURAL CONNECTION EMPLOYING SPOT WELDS

Thesis for the Degree of Master of Science
in Mechanical Engineering
MICHIGAN STATE UNIVERSITY

Ernest Robert Johnson

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This is to certify that the

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TESTING AN HYPOTHESIS ON THE LOAD DISTRIBUTION OF A PARALLEL-TYPE STRUCTURAL CONNECTION EMPLOYING SPOT WELDS

presented by

ERNEST ROBERT JOHNSON

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Major professor

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By

Ernest Robert Johnson

A THESIS

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TESTING AN HYPOTHESIS ON THE LOAD DISTRIBUTION
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Abstract

This Master's Thesis consists of an experiment to determine the distribution of a tensile load over a structural connection employing five spot welds equally spaced in a line parallel to the direction of loading. The welds were centered in a lap joint which joined two identical low carbon steel plates.

The experiment was designed to test a theory proposed by Dr. Charles O. Harris in an unpublished paper. His theory presented an equation which could be used to determine the load distribution of a parallel-type structural connection as described in the previous paragraph providing the stiffness factors of the plates and connectors were known.

The experiment was performed in a Riehle Tensile Test machine. SR-4 strain gages were mounted on the outside surface of one of the plates to measure the strain distribution. Five rows of five gages were used on each

of seven connection designs to determine the change in load distribution as these three connection dimensions were varied: (1) plate width, (2) spot weld spacing, and (3) spot weld diameter.

The experiment was not successful in determining the load distribution in the connection because the load eccentricity at the position of the gages caused a significant strain at the gages so that the gages did not measure the average strain in the plate. Furthermore, the eccentricity could not be determined to allow the average load to be calculated.

References

1. Harris, C. O., The Analysis of a Parallel-Type Structural Connection by Means of a Difference Equation, Unpublished Paper.
2. Hrennikoff, A., "Work of Rivets in Riveted Joints," ASCE Proc., v. 58, n. 9, Nov. 1932, p. 1507-19.
3. Muckle, W., "Distribution of Load in Riveted Joints," Shipbldr. and Marine Engr.-Bldr., v.56, n. 484, April 1949, p. 225-8.

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TESTING AN HYPOTHESIS ON THE LOAD DISTRIBUTION
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I. Introduction

A parallel-type structural connection will be defined as a connection between two structural members joined by connectors located in lines parallel to the applied load which may be either tension or compression. The connectors may be rivets, bolts or welds. When there are more than two connectors in parallel to the load, the load distribution becomes statically indeterminate, and the load-carrying ability of the joint becomes difficult to predict. See Figure 1 on page 2 for an example of this type of connection.

Hrennikoff (1)* has solved this problem theoretically by developing simultaneous equations relating force to deformation. Discussions following his paper pointed out that the same problem had been solved by the principle of least work. Muckle (2) also has treated the problem

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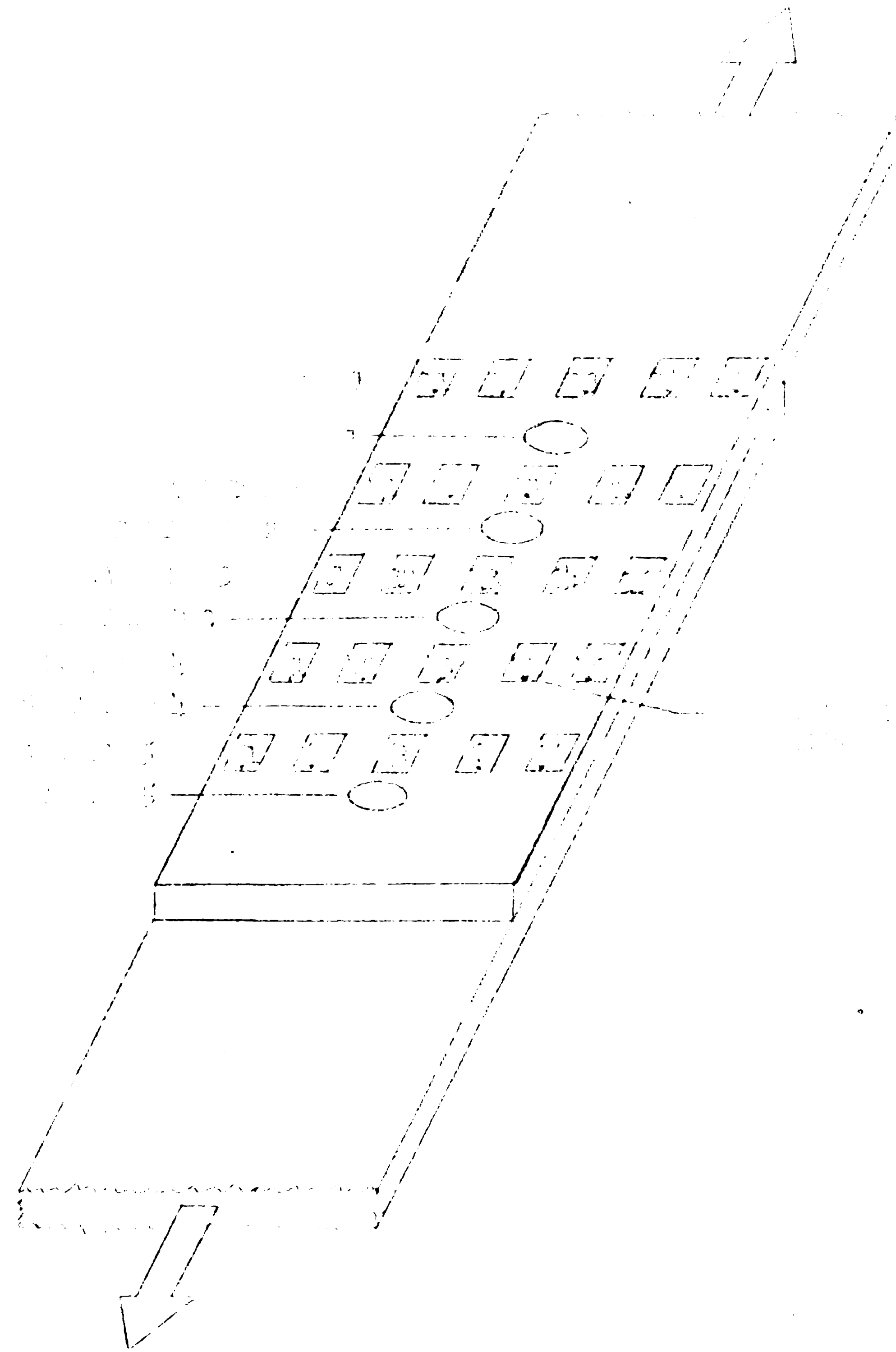
* Numbers in parentheses refer to references in the Bibliography.



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for a riveted connection using the principle of minimum strain energy.

Dr. Charles O. Harris (3) has dealt with this problem in an unpublished paper in which he relates force differences and the ratio of the connector stiffness factor to the member stiffness factor in a difference equation. This equation is then solved to arrive at a relationship which is an expression for the ratio of the force at any given point in one of the members to the applied load. Given the dimensions of the connection, the stiffness factor of the members and the stiffness factor of the connectors, it is possible to solve for the load distribution across the connectors for any parallel-type structural connection. Using Dr. Harris' theory to determine the load distribution for the connectors of a parallel structural connection similar to that shown in Figure 1, page 2, would result in a load distribution pattern as shown in Figure 2, page 4. This connection was assumed to have a plate stiffness factor equal to the connector stiffness factor.

The thesis project was designed to be an experimental test of Dr. Harris' theory to determine the actual distribution of the load in this type of connection and solve for the stiffness factor of the connectors. This

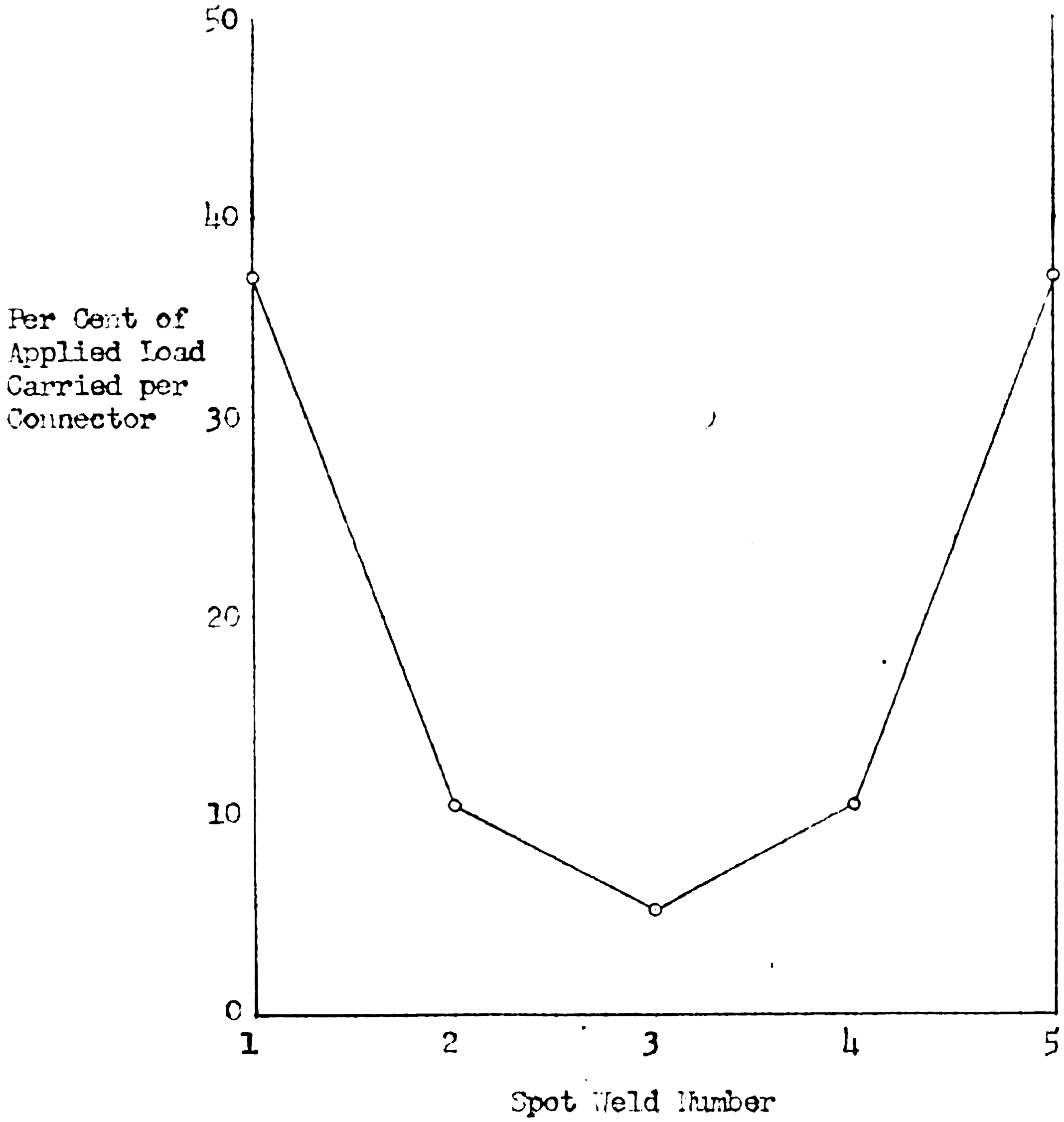


Fig. 2 Load distribution for the five connectors of a parallel-type structural connection as calculated using Dr. C. O. Harris' theory. The plates connected are assumed identical and the stiffness factor of the plate and the connectors are equal.

objective was unobtainable by the data taken during the experiment.

The experiment was designed to test the theory for a connection between two identical low carbon cold rolled steel plates joined by five equally spaced spot welds located in the center of the plates in a line parallel to a tensile force applied to the plates. Seven connection designs were tested to determine how three design dimensions affect the load distribution. These design dimensions were plate width, spot weld spacing and spot weld diameter. The strain distribution was measured by SR-4 strain gages mounted on one side of one plate and the load distribution was calculated from the strain distribution.

II. Analysis of Results

The load distribution across the plate and along the connection was determined by mounting five strain gages in a row across the plate and five rows of gages positioned as shown in Figure 1, page 2. The plate with the gage was labeled plate A, the other, plate B, and the welds and gages were referred to as numbered in Figure 1.

The seven sample connections were tested by applying a tensile load to the plates in regular increments until the proportional limit of the material was reached. At each load increment all twenty-five gage strains were measured and recorded. The resulting data was plotted as follows:

1. Measured strains for each gage were plotted against load. A straight line was drawn through the points thus plotted to give an indication of how each gage was functioning and how the plate was assuming the load in each position. All gages functioned well except gage 2.1 on sample 321. Strains for this gage were estimated as being the same as the gage nearest it for averaging purposes. The measured gage strains for sample 322 are shown in Figure 3, page 7. The plot of the gage readings for sample 312 indicated

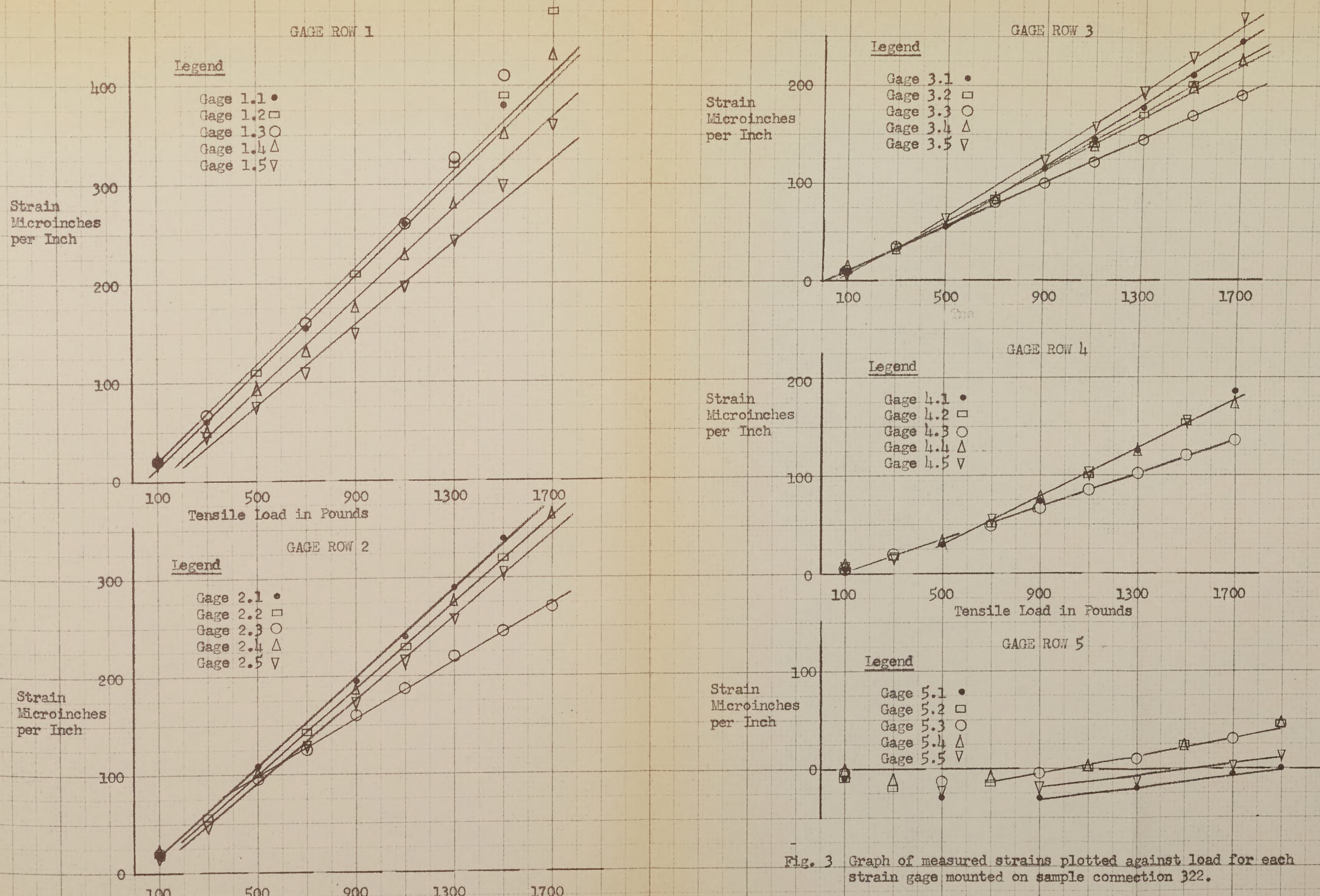
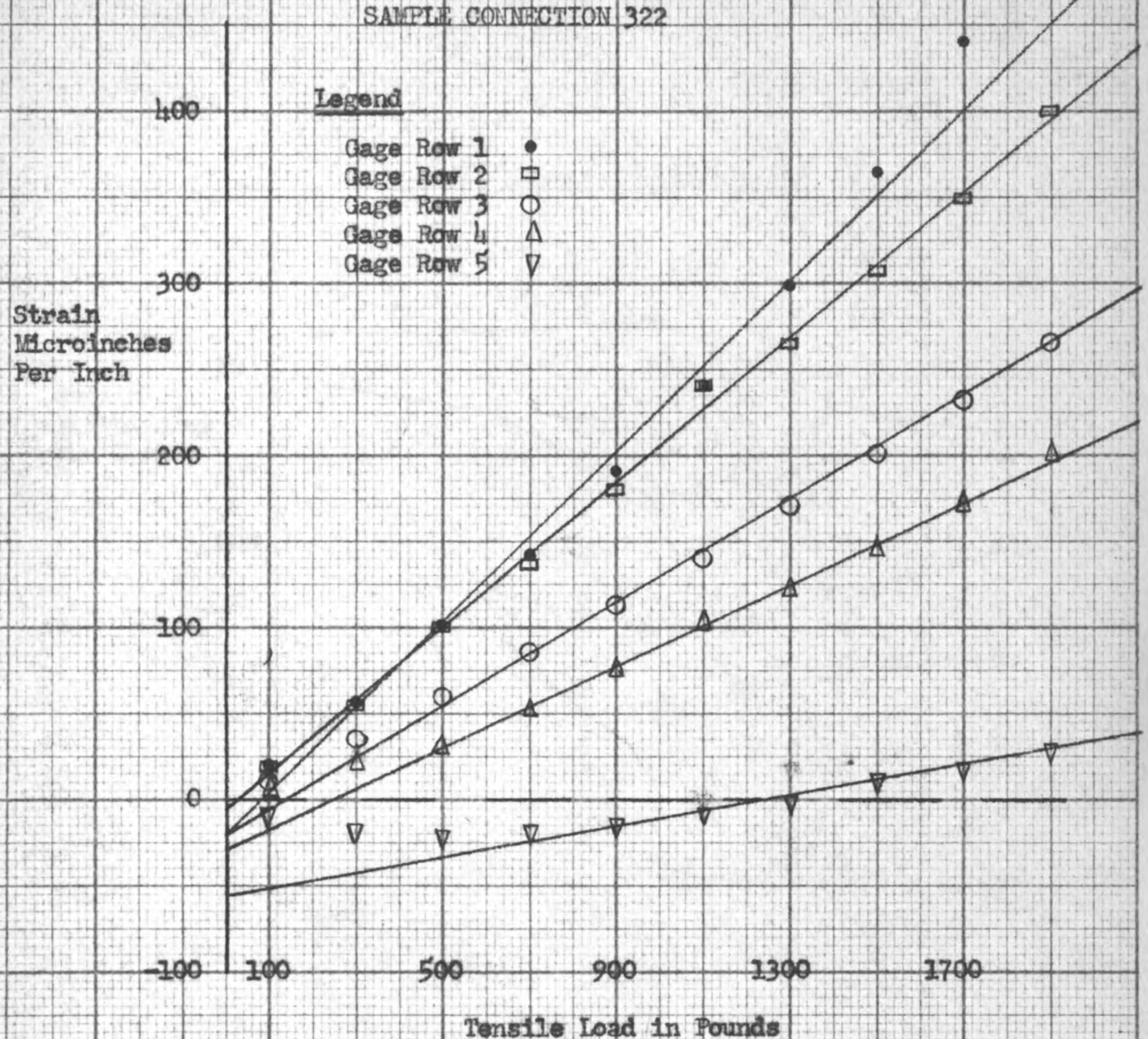


Fig. 3 Graph of measured strains plotted against load for each strain gage mounted on sample connection 322.

that the stress concentration around spot weld number 1 had a pronounced effect on the reading of gage 1.3, making it undesirable to consider the average strain employing this strain reading in its calculation. The center gages for this sample are located only one-half inch from the welds, which makes them sensitive to the stress concentrations around the welds; therefore, the data from this sample was not used in the analysis.

2. All strains for each row of gages were averaged and this average was plotted against load for each sample. A straight line was drawn through the points thus plotted to measure the average rate at which the plate cross-section for each row of gages was assuming the load. This data for sample 322 is plotted in Figure 4, page 9. Graphs for the other six samples are presented in the Appendix.
3. The load distribution across the plate was investigated by selecting typical loads and plotting gage measurements against position across the plate for each row of gages on each sample. This graph for sample 322 is shown in Figure 5, page 10.

Since this experiment was carried on below the proportional limit of the material, the change in strain of the plate can be interpreted as the relative change in



Calculations

Gage Row	Strain Difference for 2100 and 300 Pounds	Strain Difference Between Gage Rows
1	500 - 55 = 445	
		68
2	435 - 58 = 377	
		107
3	295 - 25 = 270	
		57
4	218 - 5 = 213	
		132
5	38 -(-43) = 81	

Fig. 4 Graph of average strain for each row of gages plotted against tensile load for sample connection 322. Calculations for relative load distribution are also shown.

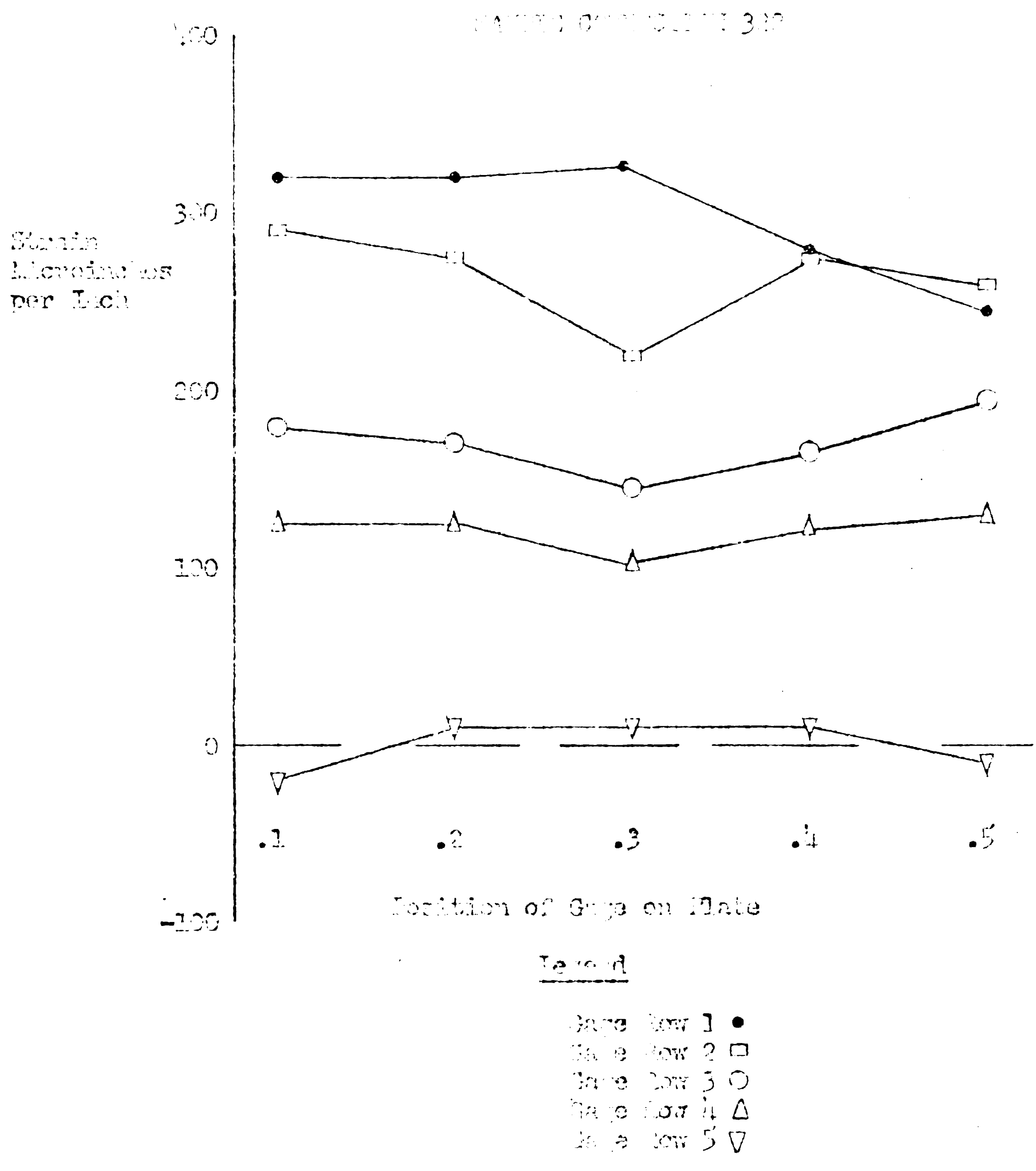


Fig. 5 Graph showing strain gage measurements across sample on connection 322 when loaded to 1100 pounds.

force at each row of gages resulting from the change in applied load. Therefore, the change in average strain for a given change in applied load was determined for each row of gages on each sample. Sample calculations are shown in Figure 4, page 9. A relative measure of the load taken by each spot weld equals the average strain difference between the row of gages before and following the weld considered. This data is shown on Table I, page 12.

Calculating the per cent load carried by each spot weld, assuming the strain in gage row 1 is proportional to the applied load, it is possible to plot a relative load distribution curve for the spot welds which can be compared with the load distribution curve computed using Dr. Harris' theory. A graph showing these curves for each sample is shown in Figure 6, page 13. It is easily noted that the curves for the samples do not compare well with the theoretical curves.

A check can be imposed on the data in Table I by applying the conditions of equilibrium and symmetry. The average strain at a point in plate A plus the average strain in plate B directly opposite must equal the average strain measured by gages in row 1 to satisfy the condition of equilibrium. Also, since plates A and B are identical, it is logical to state that corresponding points in plate B would have the same average strains as in plate A.

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Table [illegible] [illegible] of [illegible] distribution [illegible] the six [illegible] conditions [illegible] this report. [illegible] [illegible] the [illegible] in parentheses are the [illegible] differences [illegible] and are proportional to [illegible] by the [illegible].

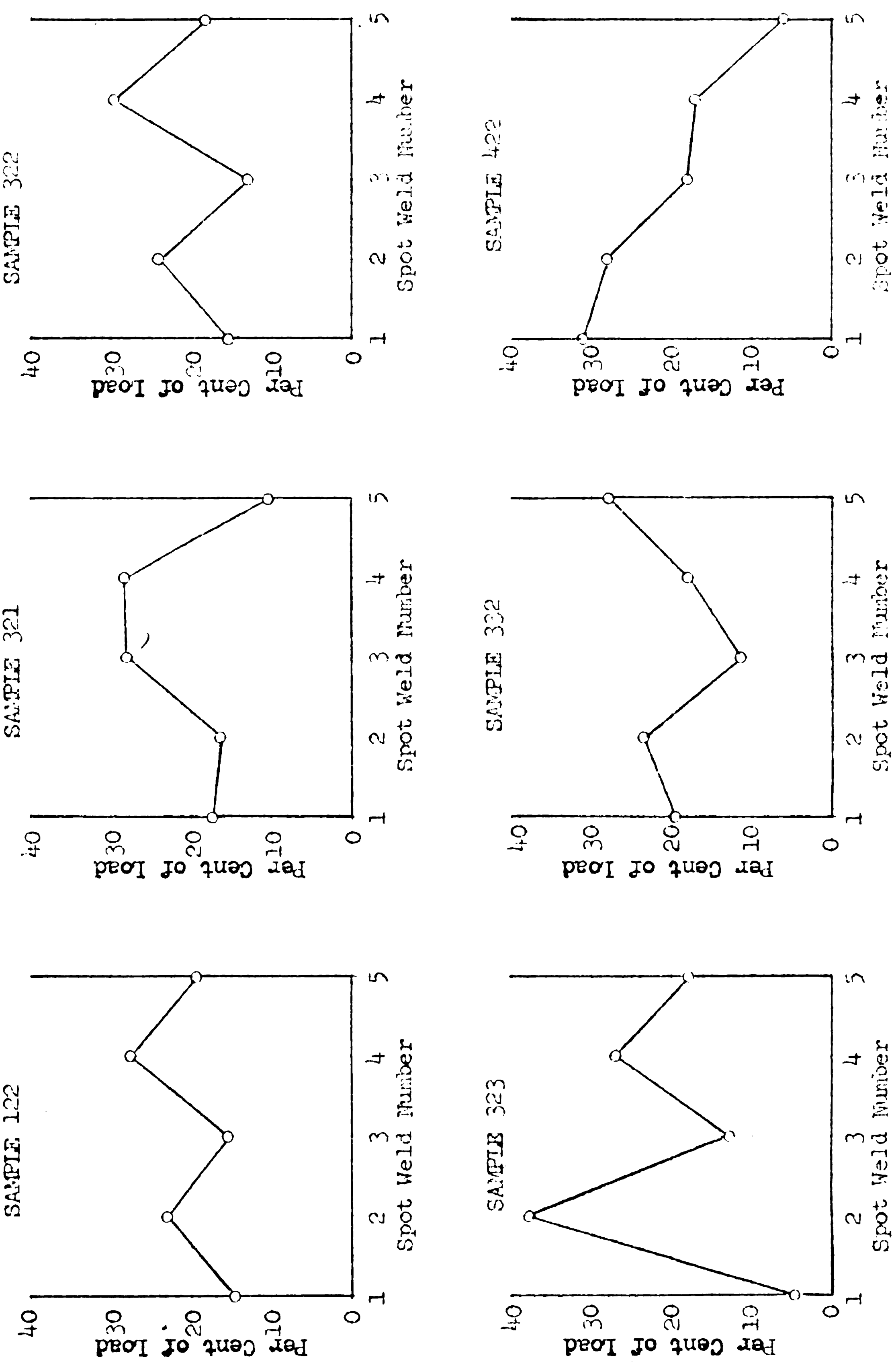


Fig. 6 Graphs showing per cent load calculated for each spot weld in six sample connections.

Therefore, the following equations can be written:

$$(1)\quad \epsilon_3 + \epsilon_4 = \epsilon_1$$

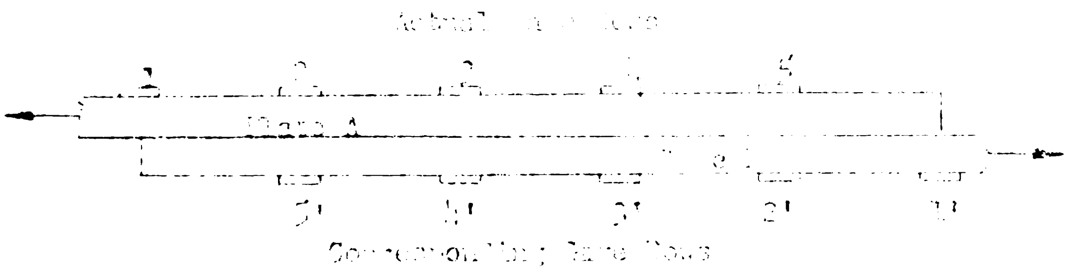
$$(2)\quad \epsilon_2 + \epsilon_5 = \epsilon_1$$

These relations are illustrated in Figure 7, page 15, and a table of data is also presented to compare the measured strains in the light of this analogy. The measured strains do not meet the conditions of equilibrium and symmetry.

Reviewing the data in the light of the preceding analysis it becomes evident that the strain measurements are not proportional to the average load in the plate, but they are proportional to the algebraic sum of the average load and a bending stress caused by the eccentricity of the force at that cross section of the plate. The strain at the outer surface of the plate adjacent to the strain gages is expressed by the following equation:

$$\epsilon(E) = \frac{P}{A} + \frac{(Pe)c}{I}$$

This equation can be solved for gage row 1 since the average load in the plate (P) is the applied load, the unit strain (ϵ) is measured by the gages, and all the other values are known except the eccentricity (e) which can be calculated. However, this is not true for gage rows 2, 3, 4, and 5, since the average load in the plate (P) is not known. Therefore, we have four equations with two



Let ϵ Equal Average Unit Strain in the Gauge Indicated.

Applying Condition of Equilibrium;

$$\epsilon_1 = \epsilon_2 + \epsilon_{5'} = \epsilon_3 + \epsilon_{4'} = \epsilon_4 + \epsilon_{3'} = \epsilon_5 + \epsilon_{2'}$$

However Because of Symmetry;

$$\epsilon_2 = \epsilon_{2'},\ \epsilon_3 = \epsilon_{3'},\ \epsilon_4 = \epsilon_{4'},\ \epsilon_5 = \epsilon_{5'}$$

Substituting; $\epsilon_1 = \epsilon_2 + \epsilon_5 = \epsilon_3 + \epsilon_4$

For an Applied Load of 1800 pounds:

Sample Number	ϵ_1	$\epsilon_2 + \epsilon_5$	$\epsilon_3 + \epsilon_4$
102*	280	307	310
301	417	416	409
302	415	423	413
303	430	417	421
202	427	419	407
402	320	290	285

* Sample 102 was loaded to 600 pounds.

Fig. 7 Drawing of sample connection and table of data comparing the average measured strain against the conditions of equilibrium and symmetry.

unknowns in each--the load (P) and the eccentricity (e).

$$\epsilon_2(E) = \frac{P2}{A} + \frac{P2\ e2\ c}{I}$$

$$\epsilon_3(E) = \frac{P_3}{A} + \frac{P_3\ e_3\ c}{I}$$

$$\epsilon_4(E) = \frac{P_4}{A} + \frac{P_4\ e_4\ c}{I}$$

$$\epsilon_5(E) = \frac{P_5}{A} + \frac{P_5\ e_5\ c}{I}$$

We can write two more equations relating the loads by applying the conditions of equilibrium and symmetry as shown in Figure 7, page 15.

$$P_2 + P_5 = P_1$$

$$P_3 + P_4 = P_1$$

However, this results in six equations with eight unknowns which cannot be solved.

Evidence of the eccentricity can be seen in the strain measurements for the gages in row 5 as the load is applied. Almost without exception these gage strains indicate compression during the early stages of loading. Further evidence of the eccentricity was noticed by the bending of the plates as shown by the photograph in Figure 8, page 17, showing two of these connections after they have been pulled to ultimate load. This illustration also shows that the plates do not bend the same in all of the positions, therefore the bending stress caused by the

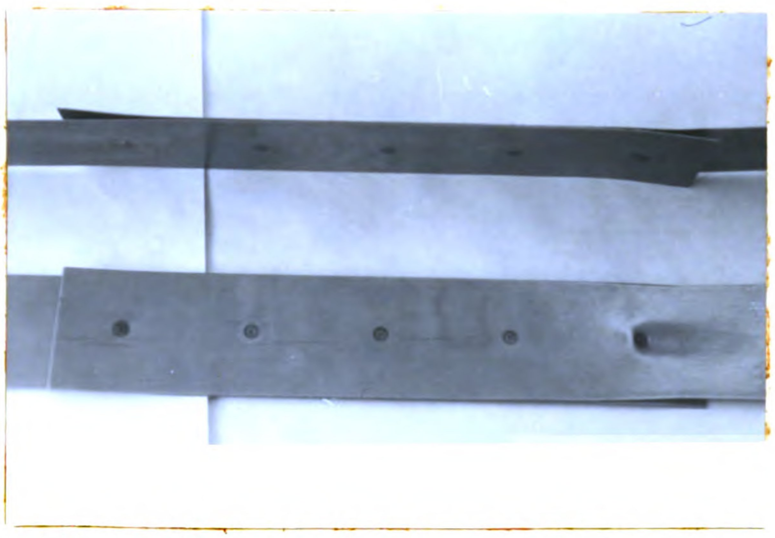


Fig. 8 Photograph of a sample connection pulled to ultimate load to show bending of the plate caused by the connection eccentricity.

eccentricity is not likely to be constant along the connection.

More evidence of the joint eccentricity was found when the measured strain in row 1 was compared to the calculated strain for the same load. This calculated strain was based on the modulus of elasticity of the material and assuming a central load. The average modulus of the material was determined by a tensile test which employed SR-4 type A-8 strain gages mounted on four samples taken from the original steel plate. For more details of the tensile test see sub-heading "Determining the Modulus of Elasticity" under section IV, "Experimental Procedure." In all cases (except sample 312 which was not considered in the analysis) the calculated value was higher than the average strain measured by the gages. Table II, page 19, presents this comparison and shows the extent of eccentricity at row 1 for each sample.

TABLE [illegible]

Sample Number	1[illegible]	301	302	303	332	[illegible]
Average Strain* Measured--Channel 1	[illegible]3	[illegible]	[illegible]5	[illegible]	[illegible]	310
Calculated Strain (No Eccentricity)	311	[illegible]	[illegible]	[illegible]	[illegible]	315
Strain Caused by Eccentricity	[illegible]	17	17	[illegible]	27	5
Per Cent Strain Due to Eccentricity	[illegible]	3.7	3.7	6.1	[illegible]	[illegible]
Calculated Eccentricity (Microinches)	[illegible]0	[illegible]	267	439	[illegible]	10[illegible]

* Strain given in microinches per inch.

Sample Calculations

$$\epsilon_{302} = \frac{P}{EA}(10^{6})$$

$$= \frac{1[illegible]00}{(30.[illegible] \times 10^{6})(3)(.0[illegible]3)}(10^{6})$$

$$= 4[illegible]2 \text{ microinches per inch}$$

A-- Cross-sectional Area
C-- One Half Plate Thickness
E-- Modulus of Elasticity
e-- Eccentricity (Microinches)
ϵ-- Unit Strain
I-- Area Moment of Inertia
P-- Load in Pounds

$$e = \left[\frac{P}{A} - \epsilon(E)\right]\frac{I}{PC}$$

$$= \left[\frac{1[illegible]00}{(.0[illegible]3)(3)} - \frac{([illegible])(3[illegible].[illegible] \times 10^{6})}{10^{6}}\right]\frac{(19.9 \times 10^{-[illegible]})(10^{[illegible]})}{(1[illegible]00)(.021[illegible])}$$

$$= 267 \text{ Microinches}$$

Table [illegible] This table presents a comparison between measured strain and calculated strain for a load of 1[illegible]00 pounds to illustrate the amount of eccentricity in the connection. (Sample 1[illegible] was loaded to [illegible] pounds.) The eccentricity is given for six sample connections and the calculation for sample connection 302 is shown.

III. Conclusions

The conclusions to be drawn from the thesis project are the following:

1. The load distribution for the parallel-type structural connection tested in this project can not be determined from strain measurements on the outer surface of the plate.
2. The eccentricity of the force at each point in the lap type parallel structural connection contributes significantly to the strain, as high as 9.0 per cent for position of gage row 1.
3. A successful experiment to determine the load distribution for this type of connection using strain gages must include some means of compensating for the bending in the plate.
4. In future experiments there should be a minimum distance of one inch between the connectors and the strain gages to minimize the effects of connector stress concentrations on the strain measurements.

IV. Experimental Procedure

The following experimental procedure and techniques were used in performing the thesis project.

Making the Samples

The sample connections to be tested were made from one plate of deep drawing quality cold rolled steel, .043 inches thick. The connections were made by spot welds which were located accurately in the plates by the use of the wood fixture and clamps shown in the photographs in Figure 9, page 22, and Figure 10, page 23. The position of these welds could be reproduced within an accuracy of ± .005 inch. The resistance welding machine employed was equipped with an electronic Robotron control for accurate control of the weld quality. Before the samples were made, an investigation of the variation in weld diameters made in the material showed that weld diameters were consistent within ±.015 inch. The weld diameters were measured by sectioning the welds, etching the section with nitric acid and measuring the fused length of diameter with a pair of dividers and a steel rule.

The seven samples were designed to determine the effect of varying three connection dimensions, (1) plate

Fig. 9 Photograph of weld locating fixture mounted over welding electrode.

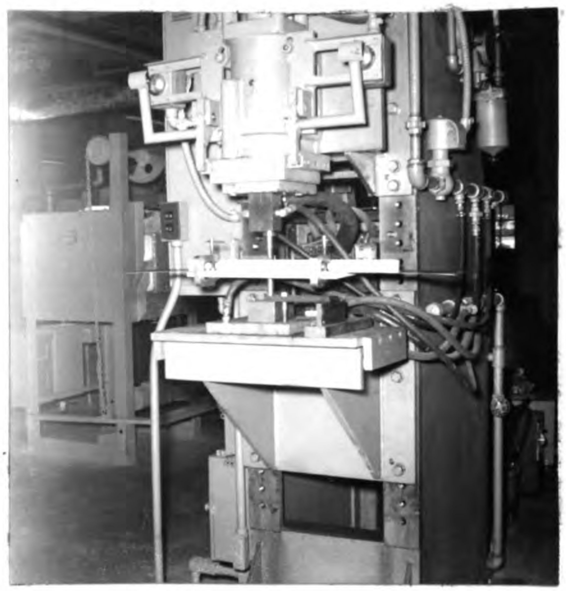


Fig. 10 Photograph of sample connection clamped to weld locating fixture and mounted in welding press ready for welding.

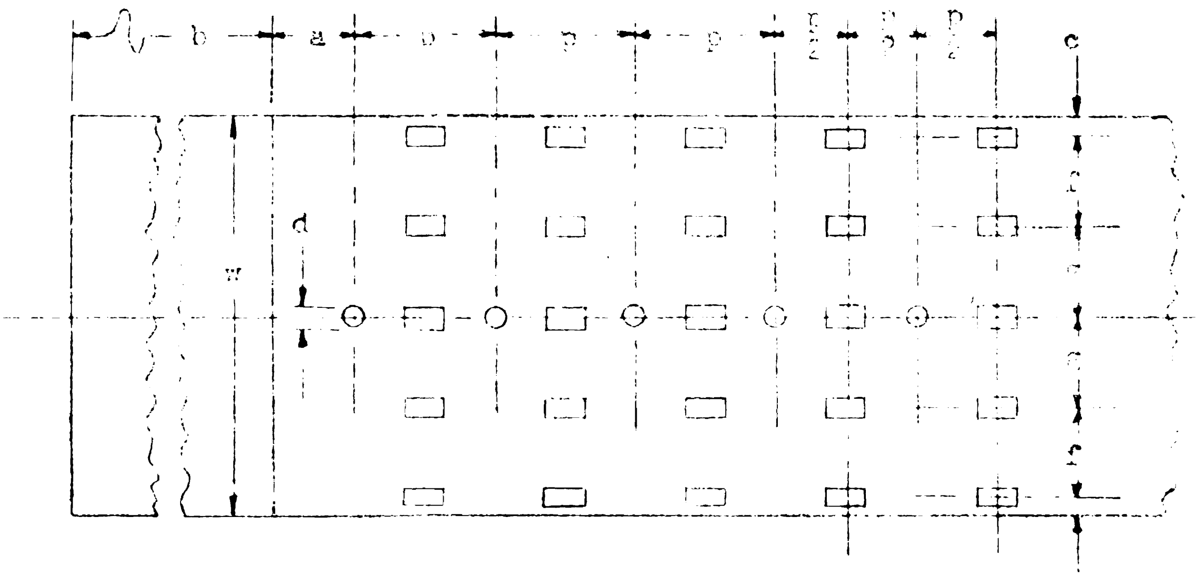
width, (2) spot weld spacing, and (3) diameter of spot weld. The dimensions of the seven samples are given in Figure 11, page 25.

The plate of steel from which all samples were made was sheared into fifteen equal sized pieces which were 6 inches x 26 inches x .043 inches. The orientation of each of these pieces in the original plate and the orientation of the samples cut from each piece is shown in Figure 12, page 26.

The gages were mounted on the samples exactly according to the recommended procedure by the gage manufacturer. They were located on the plates as shown in Figure 11, page 25. SR-4 type A-8 strain gages were used because of their convenient size and low costs. The gage grids were 1/8 inch in the direction of strain and 3/16 inches wide mounted on paper backs 1/2 inch by 5/16 inch.

<u>Testing the Samples</u>

The samples were tested in the Applied Mechanics Lab at Michigan State University. A Riehle Tensile Test Machine was used to apply the load while the gages were connected to a Type M Baldwin SR-4 strain indicator through five six-channel SR-4 bridge balancing units. All samples were tested by increasing the load in regular increments and measuring all the gage strains before increasing the load again. It was noted that the load relaxed



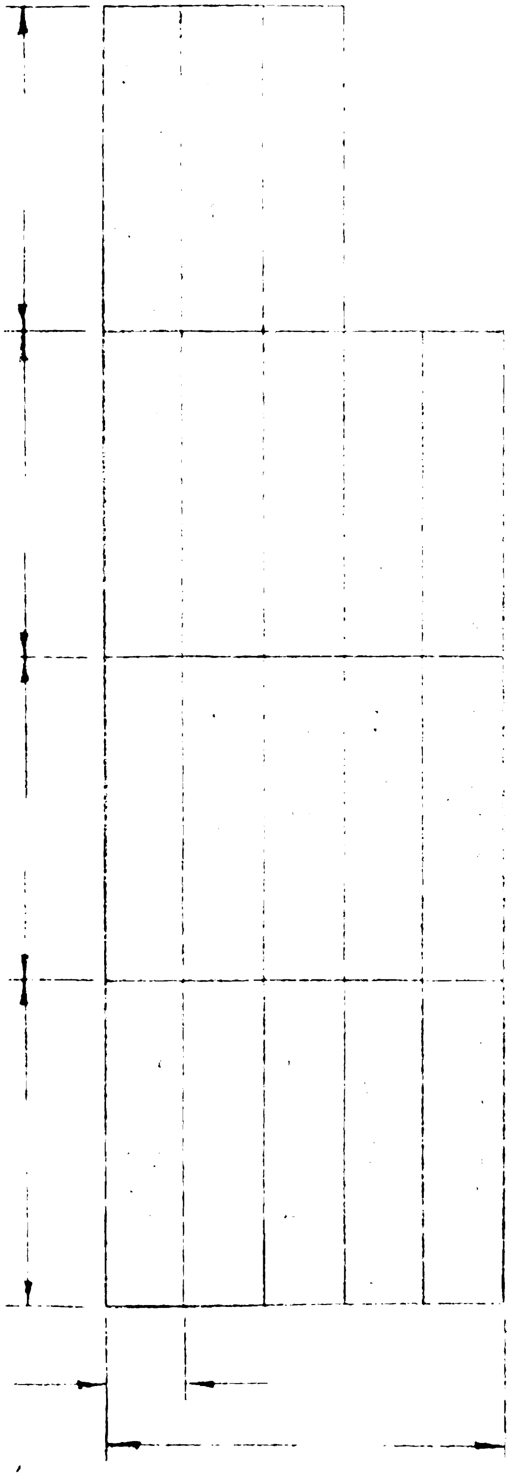
Material--Deep Drawing Quality Cold Rolled Steel

.043 ± .001 Inch Thickness.

Sample Number	Dimension in Inches							
	a	b	c	d	f	g	p	w
122*	1.0	11.0	.25	.25	.50	—	2.0	1.50
312	1.0	11.0	.25	.25	.62	.62	1.0	3.00
321	1.0	11.0	.25	.19	.62	.62	2.0	2.93
322	1.0	11.0	.25	.25	.62	.62	2.0	3.00
323	1.0	11.0	.25	.31	.62	.62	2.0	3.00
332	1.5	11.0	.25	.25	.62	.62	3.0	3.00
422	1.5	11.0	.25	.25	1.25	.75	2.0	4.50

* Sample 122 had only three gages in each row across the sample.

Fig. 11 Sketch and table of dimensions specifying the design of the seven sample connections tested in the experiment.



from fifteen to twenty pounds while the gages were being read. The load was brought to ten pounds over the value required and held there until it stabilized before the gage strains were measured. After reading and recording the gage strains, the load was noted again and in most cases the load was ten pounds under the nominal value desired. The average load value was used in processing the data. A photograph of the test equipment shown in Figure 13 is on page 28. The data was processed as described on page 6 in section II, "Analysis of Results."

Determining the Modulus of Elasticity

An accurate value of the modulus of elasticity was required to determine the extent of eccentricity in gage position 1. After several attempts failed to measure the modulus using mechanical and electronic extensometers, the modulus was finally determined by mounting SR-4 type A-8 strain gages to four tensile specimens taken from four different positions in the original steel plate, as shown in Figure 12, page 26. The tensile specimens were made to the specifications for testing this type of material by ASTM Standards 1955 Part I, "Tentative Methods of Tension Testing of Metallic Materials," ASTM Designation: E8-54T. A tensile specimen is shown in Figure 14, page 29.

Strain gages were mounted on both sides of each specimen and the specimens were pulled in a Tinus Olsen

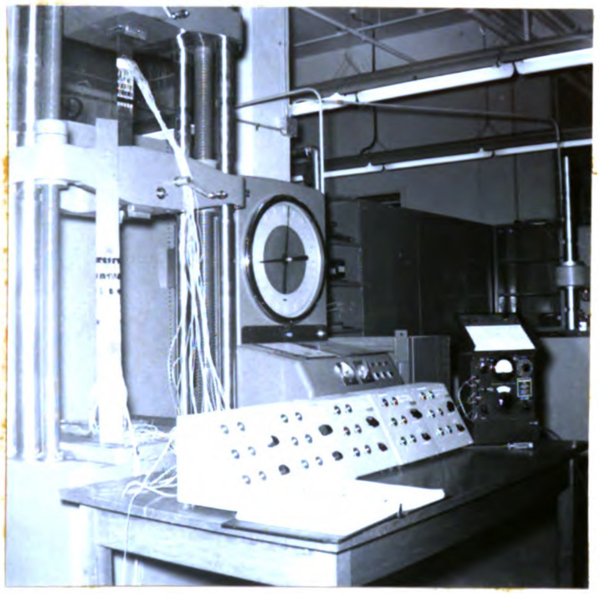
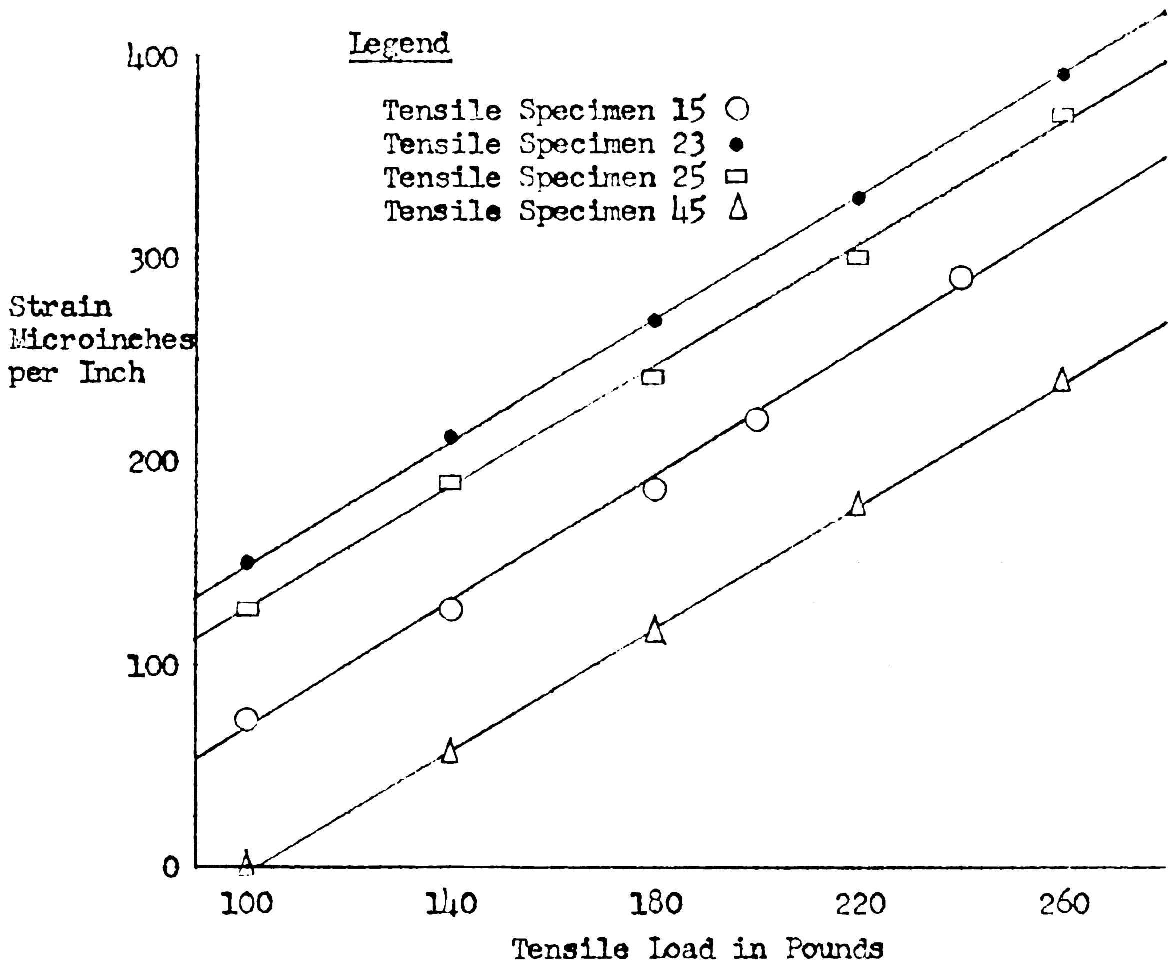


Fig. 13 Photograph of equipment employed in testing the sample connections showing a sample in position for testing.

Fig. 14 Photograph of tensile test specimen used to determine the modulus of elasticity for the steel used for the sample connections.

Tensile Test Machine using the lowest scale for which a scale division represented two pounds. The load was increased in forty-pound increments starting with a preload of fifty pounds, and both gage strains were measured. Each sample was tested twice and the gage readings for each load were averaged and plotted to determine the modulus. The plotted data is shown in the graphs in Figure 15, page 31. The average modulus from the four specimens was 30.2×10^6 pounds per square inch which was used in the calculations for Table II, page 19.



Test Specimen	Modulus of Elasticity in Pounds per Square Inch (E)
15	29,200,000
23	30,400,000
25	30,600,000
43	30,400,000
Average	30,200,000

Sample Calculation

$$E_{15} = \frac{P}{\epsilon\, t\, w}$$

$$= \frac{180}{(281)(.043)(.510)}$$

$$= 29,200,000$$

P—Load in Pounds
ϵ—Unit Strain in Inches per Inch
t—Specimen Thickness in Inches
w—Specimen Width in Inches

Fig. 15 Graph of average strain measurements taken in the tensile test to determine the modulus of elasticity.

V. Bibliography

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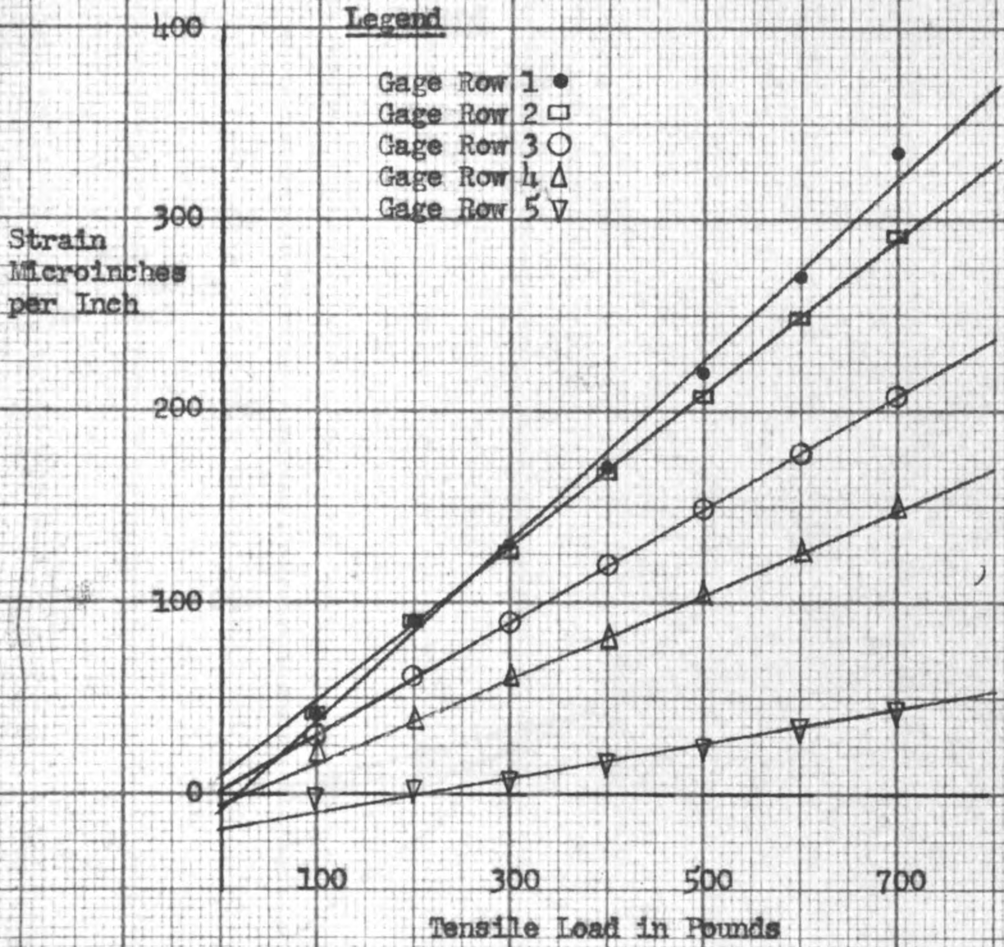
VI. Appendix

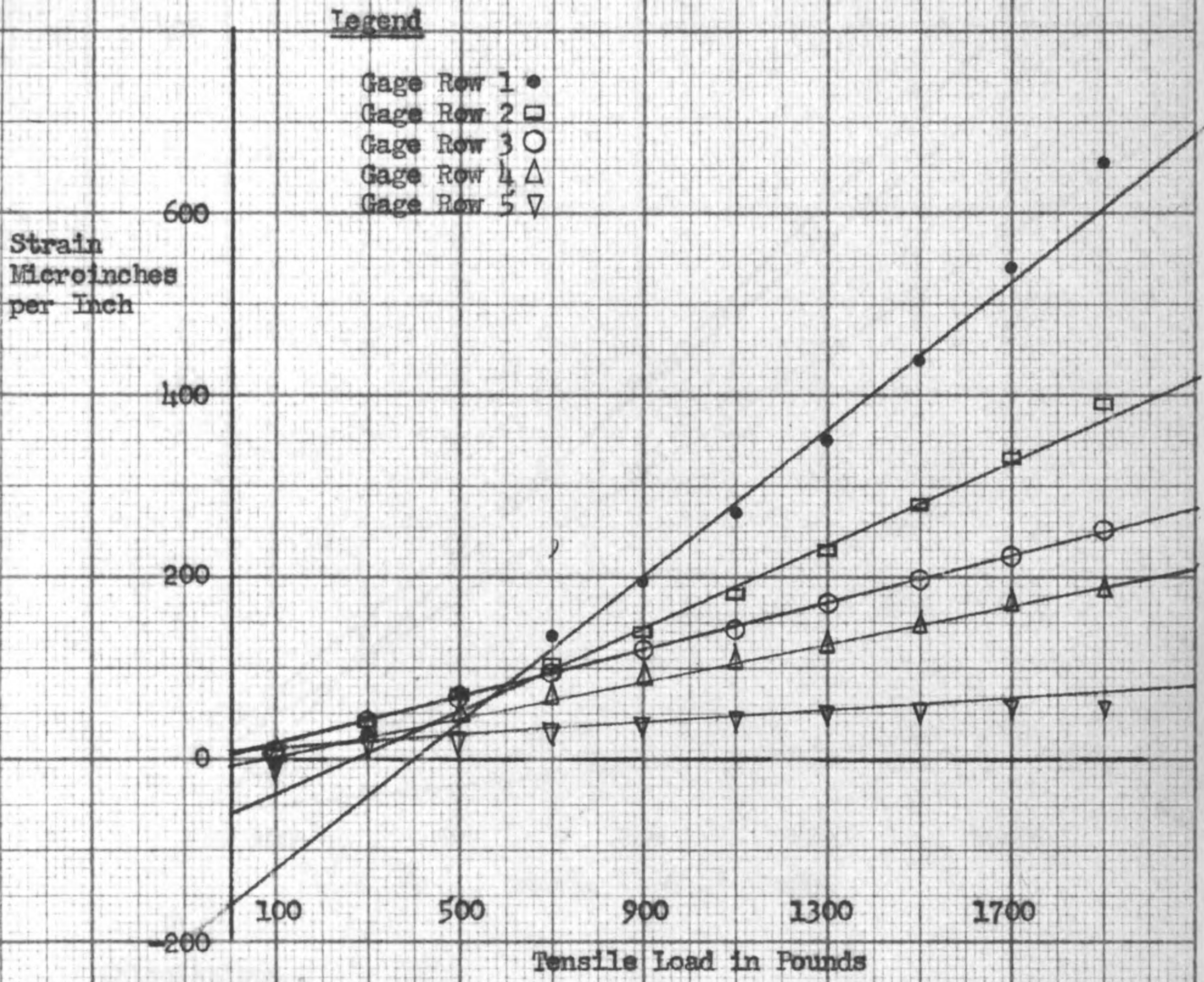
The Appendix contains the graphs of average strain for each row of gages plotted against tensile load for sample connections 122, 312, 321, 323, 332, and 422, in that order. They are presented as Figures 16 through 21 respectively. The graph for sample connection 322 is shown as Figure 4, page 9.



Calculations

Gage Row	Strain Difference for 700 and 100 Pounds	Strain Difference Between Gage Rows
1	320 - 37 = 283	
		41
2	290 - 48 = 242	
		65
3	207 - 30 = 177	
		44
4	148 - 15 = 133	
		78
5	45 -(-10) = 55	

Fig. 16 Graph of average strain for each row of gages plotted against load for sample connection 122.

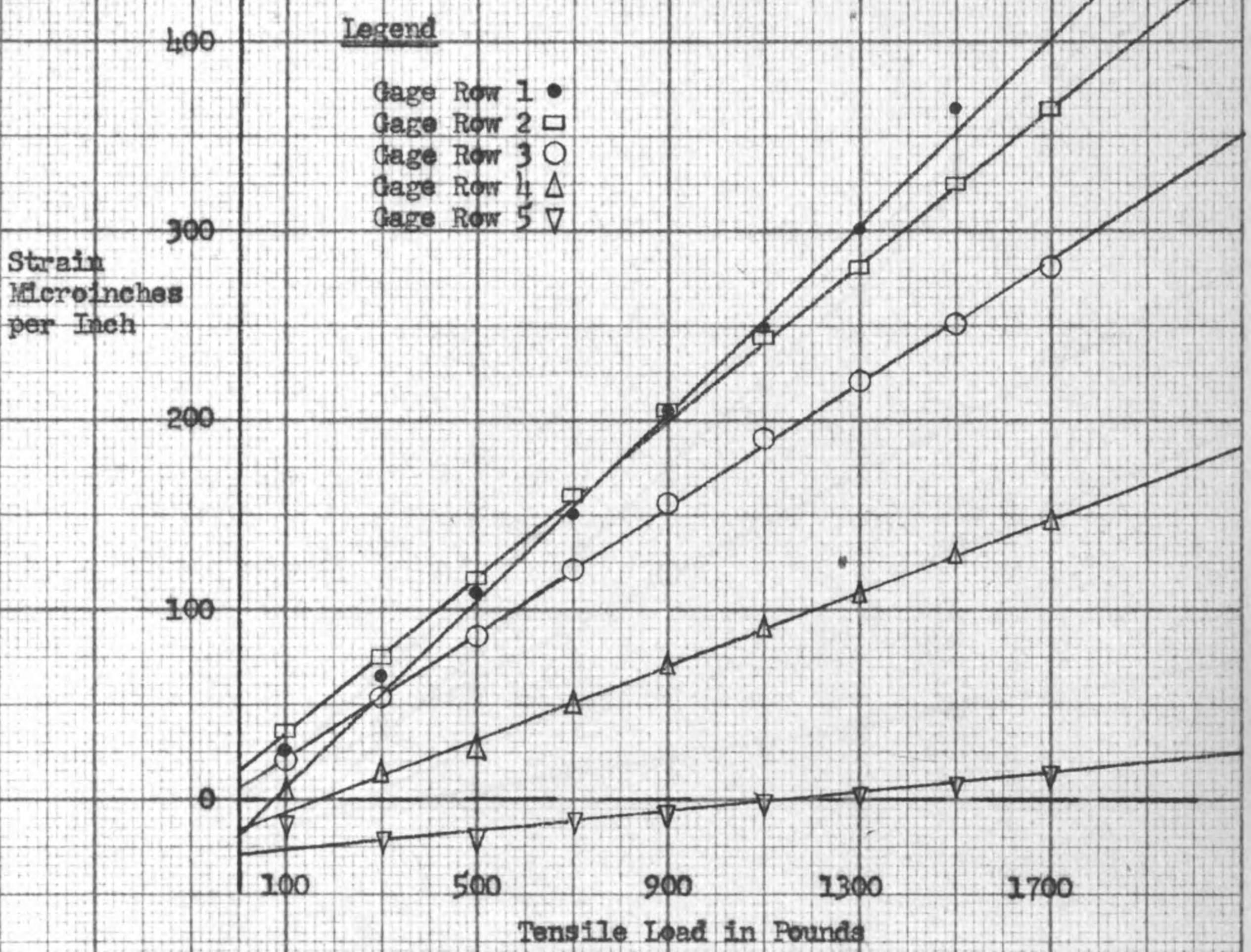


Calculations

Gage Row	Strain Difference for 2100 and 300 Pounds	Strain Difference Between Gage Rows
1	682 −(−40) = 722	
		311
2	418 − 7 = 411	
		181
3	275 − 45 = 230	
		50
4	205 − 25 = 180	
		120
5	80 − 20 = 60	

Fig. 17 Graph of average strain for each row of gages plotted against load for sample connection 312.

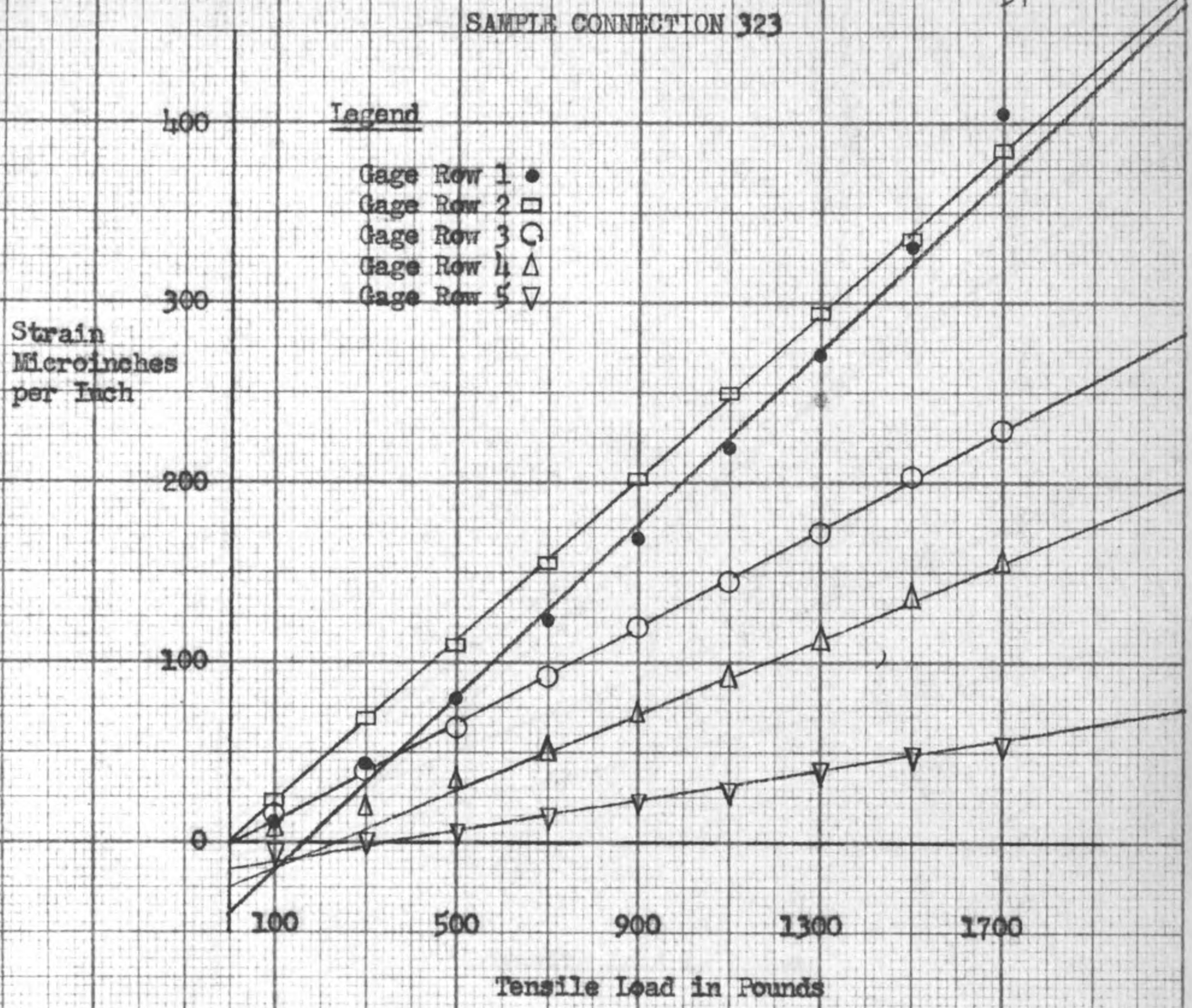
SAMPLE CONNECTION 321



Calculations

Gage Row	Strain Difference for 2100 and 300 Pounds	Strain Difference Between Gage Rows
1	500 - 53 = 447	
		77
2	445 - 75 = 370	
		73
3	352 - 55 = 297	
		125
4	185 - 13 = 172	
		126
5	25 -(-21) = 46	

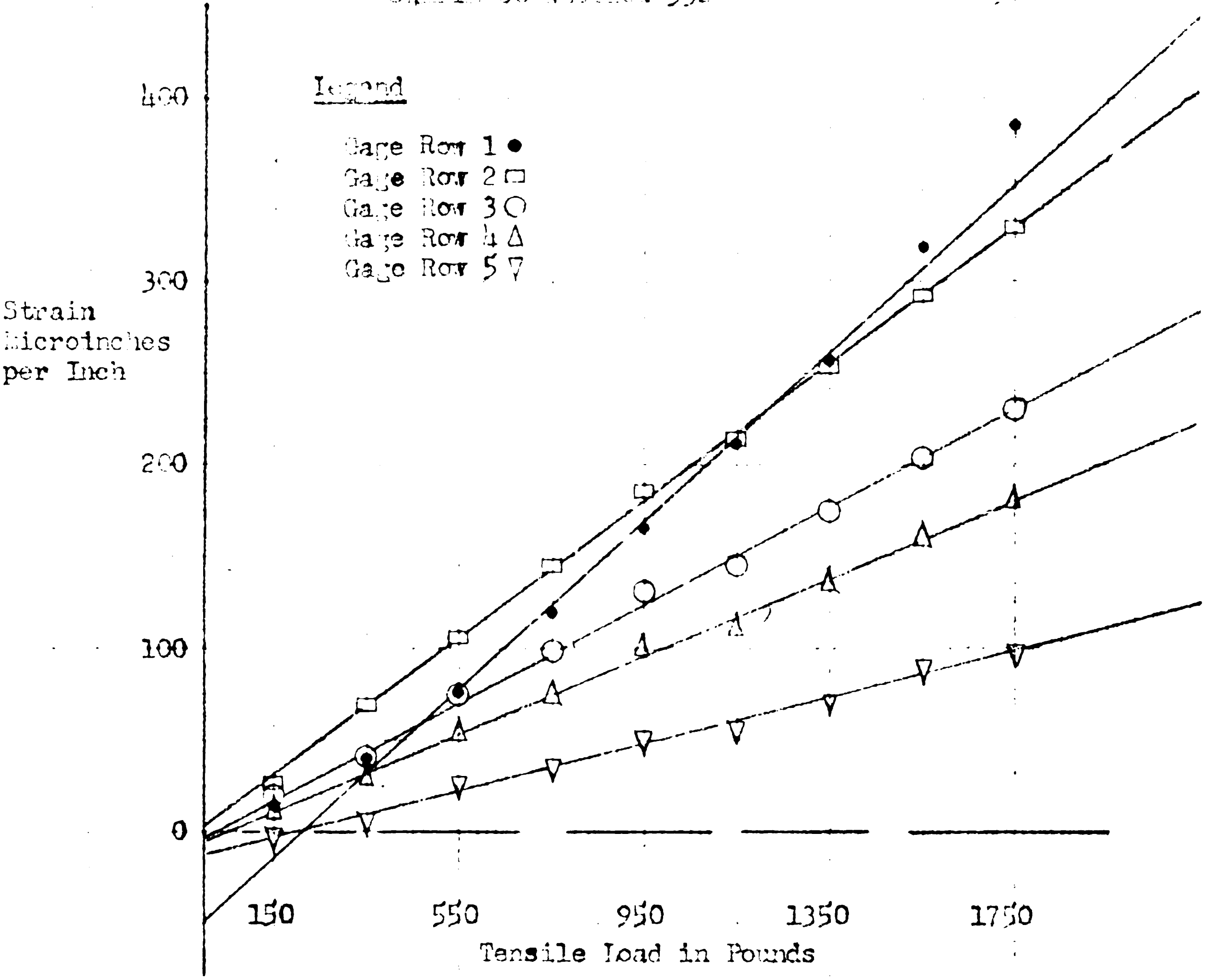
Fig. 18 Graph of average strain for each row of gages plotted against load for sample connection 321.



Calculations

Gage Row	Strain Difference for 2100 and 300 Pounds	Strain Difference Between Gage Rows
1	463 - 33 = 430	20
2	480 - 70 = 410	162
3	287 - 39 = 248	55
4	200 - 7 = 193	116
5	75 -(-2) = 77	

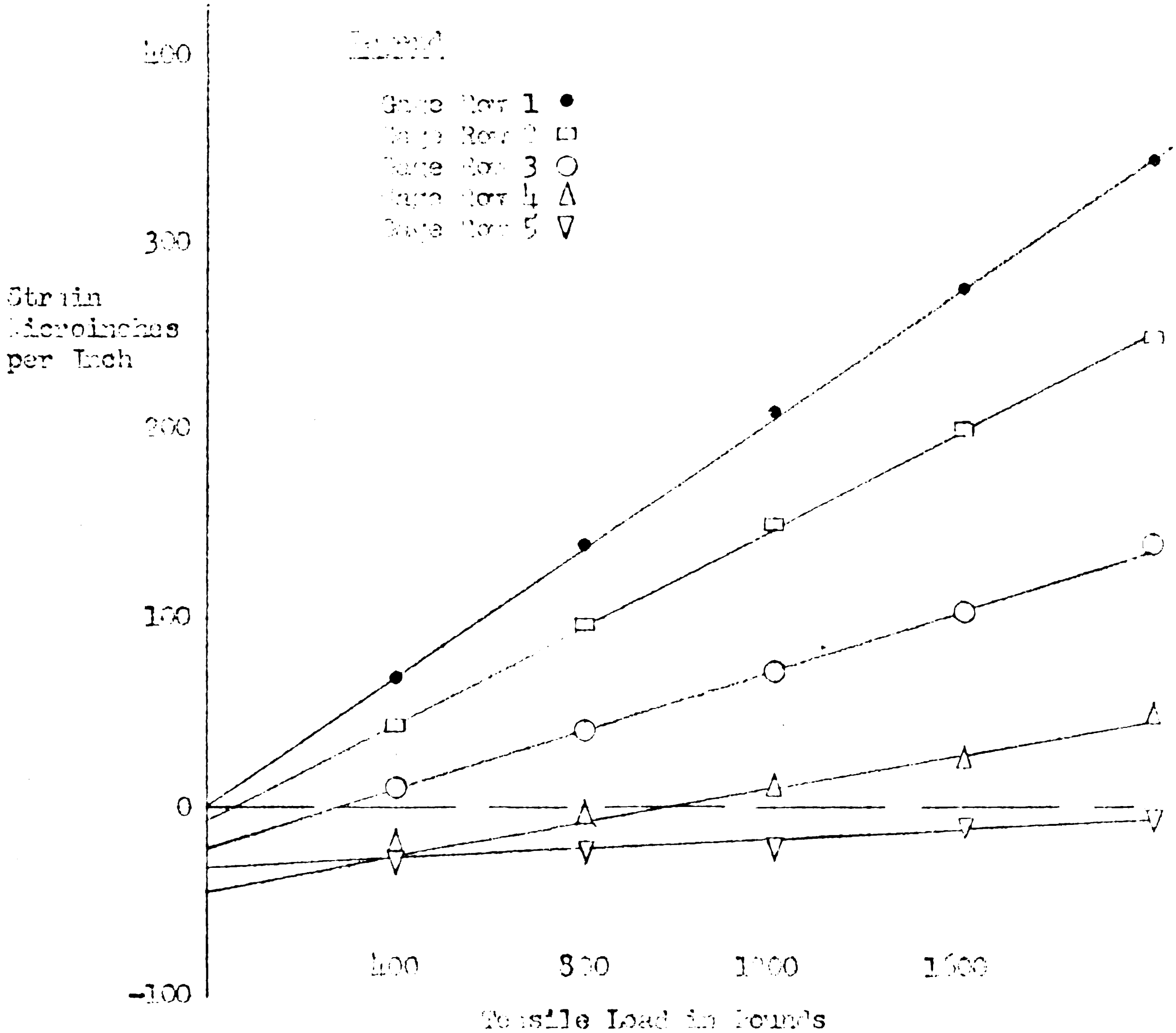
Fig. 19 Graph of average strain for each row of gages plotted against load for sample connection 323.



Calculations

Gage Row	Strain Difference for 2150 and 350 Pounds	Strain Difference Between Gage Rows
1	443 - 28 = 415	81
2	402 - 68 = 334	97
3	282 - 45 = 237	47
4	222 - 32 = 190	75
5	125 - 10 = 115	

Fig. 20 Graph of average strain for each row of gages plotted against load for sample connection 332.



<u>Calculations</u>

Gage Row	Strain Difference for 2100 and 300 Pounds	Strain Difference Between Gage Rows
1	360 - 50 = 310	
		80
2	262 - 32 = 230	
		87
3	145 - 2 = 143	
		61
4	50 -(-32) = 82	
		60
5	(-5) - (-27) = 22	

Fig. 21 Graph of average strain for each row of gages plotted against load for sample connection 4P2.

ROOM USE ONLY