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LOAD DISTRIBUTION IN BOLTED JOINTS

by

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Submitted to Professor John L. Rumpf
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SYNOPSIS

This paper concerns load distribution among the bolts of a bolted structural joint at the maximum load. The test joints were fabricated with A7 steel and fastened with 7/8" A325 bolts. The deflections of each bolt in one line of the test joint were measured, and using these measurements a plot of the deformed profile of the bolt was made.

Another bolt from the same lot was subjected to increasing load increments in a shear jig, and the deformations of the bolt at various known loads were measured. Plots of the deformed profile of the bolt were made and these profiles were then matched with the profiles of the bolts from the test joints, the object being to determine the load that each bolt in the test joint was carrying. Additional data concerning hole deformations was also collected to determine the behavior of the plates.

1. INTRODUCTION

1.1 Background

Present design procedures are based on the assumption that each fastener in a structural joint carries an equal share of the load. This assumption is based on the fact that the more highly stressed fasteners in the joint deform, and in so doing, redistribute the load among the other fasteners. Ordinary rivets are ductile enough to permit an equal distribution of the load among each rivet when the load has reached its ultimate value. It is believed that high strength A325 bolts permit a fairly equal distribution of the load among each bolt when the load has reached its ultimate value. The length of the joint also affects the proportion of the load that each bolt carries.

The fact that the load distribution among the various bolts is not exactly equal was verified by the results obtained from static tension tests of long bolted joints. These tests were conducted at Fritz Engineering Laboratory, Lehigh University. From the results of these tests it was found that the deformations of the bolts varied depending on the location of the bolt in the joint. The purpose of this project was to find the value of the load carried by each bolt when the load reached its ultimate value.

1.2 Source of Information Concerning the Test Joints

The loading history of the test joints to be investigated was taken from the "Fritz Laboratory Report No. 271.8" titled "Static Tension Tests of Long Bolted Joints" by Robert A. Bendigo and John L. Rumpf. This report is dated February 1960.

2. DESCRIPTION OF TEST JOINTS

Four test joints were investigated. There were two lines of bolts in each joint. The number of bolts in each line were as follows: three bolts for joint D31; four bolts for joint D41; five bolts for joint D51; six bolts for joint D61.

The specimens had two one-inch plates combined to make the inner main plates and had outer lap plates of one-inch thickness. The specimens were actually half of a double shear butt joint. The fasteners were 7/8" A325 bolts, 5.1/2" under head, with a 2" thread. See Figs. 1, 2, 10, 11, 14, 17, 18, 21, and 22.

3. DESCRIPTION OF CALIBRATION SHEAR JIG

One joint was used for the bolt calibration. It had two one-inch plates combined to make the inner main plate and had outer lap plates of one-inch thickness. One fastener was used. It was a 7/8" A325 bolt, 5.1/2" under head, with a 2" thread. See Figs. 3 and 26.

4. MATERIAL PROPERTIES OF TEST JOINTS AND CALIBRATION SHEAR JIG

4.1 Plates

The plate material was ASTM-A7 structural steel. The plates were burned to a rough width and then machined to the finished dimension.

The average yield stress was 28,400 psi, while the average ultimate tensile stress was 60,000 psi.

4.2 Bolts

The bolts were 7/8" A325, 5.1/2" under head. The thread was the standard rolled thread, two inches in length. All the bolts were from the same lot, which was called the D-lot.

The average ultimate load on the bolts tested in tension was 56.7 kips. Based on this value the bolts were classified as being very nearly minimum strength bolts. Minimum strength bolts carry an ultimate load of 53.15 kips tested in tension.

5. FABRICATION OF TEST JOINTS

5.1 Shop Preparation

The plates used were gone over with a mechanical grinder to remove all mill scale. All holes were drilled to a 15/16" diamater.

5.2 Bolting-Up Procedure

The bolting-up operation was done at Fritz Laboratory by a Bethlehem Steel Company Erection Department field crew. The crew used the turn of the nut method to tighten the bolts. All bolts in these test joints were snugged with an impact wrench and then given a half turn.

6. FABRICATION OF CALIBRATION SHEAR JIG

6.1 Shop Preparation

The plates were free from mill scale. The hole was drilled to a 15/16" diameter.

6.2 Bolting-Up Procedure

The bolt was finger tightened, precautions being taken to make sure that the bolt was assembled in bearing. The reason for the deviation from the bolting-up procedure used in the test joints was that the ultimate shearing strength of the bolt is not affected by the degree of tightening up. This fact was proven in previous tests performed at Fritz Laboratory. From results obtained in these tests it was concluded that the degree of tightening the nut was not an influencing factor in determining the ultimate strength of the bolt.

7. TEST PROCEDURE FOR TEST JOINTS

Testing of the joints proceeded in even load increments until major slip occurred. At major slip the testing machine dropped load due to the sudden displacement, and stabilized at some lower load. Load was then applied until the joint failed. All of the joints considered failed due to yielding of the plates. See Figs. 11, 14, 18, and 22.

The joint was subjected to tension as shown in Fig. 2.

8. TEST PROCEDURE FOR CALIBRATION SHEAR JIG

The main difference between the testing procedures used for the calibration shear jig as against the test joints was the fact that the calibration shear jig was subjected to compression as shown in Fig. 3, whereas the test joint was subjected to tension as shown in Fig. 2.

The shear jig was loaded until the load reached a value of 60 kips. At this point the shear jig was unloaded and the bolt was removed. Measurements were taken to determine the deformed profile of the bolt. The shear jig was then reassembled, using the same bolt, making sure the bolt was in the exact position it occupied before the shear jig was disassembled. This procedure was repeated at load increments of 5 kips until a load of 80 kips was reached. Beyond that load the procedure was continued, using load increments of 2.5 kips until the bolt sheared. The maximum load at which bolt measurements were taken was 105 kips. Figure 25 shows bolt deformations corresponding to different loads.

The bolt deflections at various load increments were recorded with the aid of a dial gage. These deflection readings were taken each time the joint was loaded and unloaded. Loading and unloading curves were plotted to determine the deflection characteristics of the bolt when it is in the plastic range. See Fig. 7 for the curves mentioned.

9. PROCEDURE USED TO MEASURE BOLT DEFORMATIONS

A lathe was used to measure the deformation of the bolts used in the test joints and the calibration shear jig. Figures 28 and 29 show the main features of the setup.

Each bolt had a hole drilled in the center of the head and a hole drilled in the center of the shank. The depth of these holes was between 1/32" and 1/16". These holes were used to accommodate the tips of the live center and dead center; the live center being part of the spindle, and the dead center being part of the tailstock. This arrangement allowed measurements to be taken to determine the distance from the center of the bolt to the surface of the bolt. A pointed rod was inserted in the tool holder. Using the compound head it was possible to measure distances along the axis of the bolt. Through use of the cross head, which provided movement of the rod towards the bolt, it was possible to measure distances from the center of the bolt to the surface of the bolt.

The following procedure was used. Using the compound head, a desired distance was measured along the axis of the bolt. The underside of the bolt head was used as a reference point for this measurement. At this point, using the cross head, the pointed rod was moved toward the bolt until it came into contact with the surface of the bolt. These two measurements were recorded for a number of points along the bolt, making it possible to plot a profile of the deformed bolt. Distances were measured to an accuracy of one thousandth of an inch.

Figures 12, 15, 19, and 23 give an indication of the relative deflections of the bolts used in test joints D61, D51, D41, and D31.

10. LOADING HISTORY OF TEST JOINTS

All the joints were tested until a maximum load was reached. Test specimens D61 and D51 failed by tearing of the plate material. Joints D41 and D31 were not tested to complete failure although a maximum load had been reached prior to stopping the test.

The maximum load applied to joint D61 was 994 kips. At this load failure of the plates occurred.

Joint D51 also failed by tearing of the main plates. The load at failure was recorded at 850 kips.

The maximum load joint D41 was subjected to was 690 kips. When the load began to drop off the test was stopped before either the plate or bolts failed. Visual inspection of the joint showed that a plate failure was imminent.

The maximum load reach in joint D31 was 514 kips. The load started to fall off and the test was halted. Neither the plate nor the bolts failed, although failure in the plate was imminent.

In summarizing, the maximum loads attained and the types of failures that occurred were as follows: joint D61 - 994 kips - plate failure; joint D51 - 850 kips - plate failure; joint D41 - 690 kips - plate failure; joint D31 - 514 kips - plate failure.

11. TEST RESULTS

11.1 Joint D61

Only the bolt deformations in one line of bolts were measured. These bolts were numbered D37, D38, D39, D40, D41, and D42. The location of each of these bolts in the joint is shown in Fig. 1.

The bolt number; the load carried by each bolt; the percentage of the total load carried by each bolt (Fig. 5); and the percentage of uniform load distribution carried by each bolt (Fig. 6), as determined from comparisons of the deformed profiles of the bolts from the test joint and the calibration shear jig are as follows:

Bolt No.	Load Carried	% of Total Load	% of Uniform Load Distribution
D37	105.0^K	20.3	122
D38	85.0^K	16.5	99
D39	68.0^K	13.2	79
D40	68.0^K	13.2	79
D41	85.0^K	16.5	99
D42	105.0^K	20.3	122

The total load carried by these bolts as determined from the deformed profiles was 516.0 kips. The actual load carried by these bolts as recorded during the test was 497.0 kips. It was assummed that one line of bolts carried one half of the total load. The amount of error was + 3.82%.

11.2 Joint D51

The bolt deformations in one line of bolts were measured. These bolts were numbered D26, D27, D28, D29, and D30. The location of these bolts in the test joint is shown in Fig. 1.

The results were as follows:

Bolt No.	Load Carried	% of Total Load	% of Uniform Load Distribution
D26	105.0^K	23.7	118
D27	83.0^K	18.7	94
D28	75.0^K	17.0	85
D29	80.0^K	18.0	90
D30	100.0^K	22.6	113

The total load carried by these bolts as determined from the deformed profiles was 443.0 kips. The actual load carried by these bolts as determined by the test was 425.0 kips. The amount of error was + 4.24%.

11.3 Joint D41

The bolt deformations in one line of bolts were measured. These bolts were numbered D15, D16, D17, and D18. The location of these bolts in the joint is shown in Fig. 1.

The results were as follows:

Bolt No.	Load Carried	% of Total Load	% of Uniform Load Distribution
D15	99.0^K	27.3	109
D16	82.5^K	22.7	91
D17	82.5^K	22.7	91
D18	99.0^K	27.3	109

The total load carried by these bolts as determined from their deformed profiles was 363.0 kips. The actual load carried by these bolts as determined by testing was 345.0 kips. The amount of error was + 5.22%.

11.4 Joint D31

Only the bolt deformations in one line of bolts was measured. These bolts were numbered D179, D5 and D6. The location of these bolts in the test joint is shown in Fig. 1.

The results were as follows:

Bolt No.	Load Carried	% of Total Load	% of Uniform Load Distribution
D179	92.5^K	35.0	105
D5	80.0^K	30.0	90
D6	92.5^K	35.0	105

The total load carried by these joints as determined from their deformed profiles was 265.0 kips. The actual load carried by these bolts as determined by testing was 257.0 kips. The amount of error was + 3.11%.

11.5 Hole Elongations

Hole elongations were not symmetrical about the center of either the test joints or the calibration shear jig. At the interface of the lap plate and the main plate at the nut end of the bolt the hole elongations were greater than the hole elongations at the interface of the lap plate and the main plate at the head end of the bolt.

12. ANALYSIS OF RESULTS

12.1 Bolt Deformations

While plotting the bolt profiles it was noticed that the deformation of all bolts was greater at the bolt head end than at the nut end. From this observation it can be concluded that the load is not distributed evenly over the bearing surface of the bolt. This could possibly be caused by the unsimilar bearing conditions at the nut end and the head end. At the nut end part of the bearing surface is partially threaded while at the head end there are no threads.

12.2 Hole Elongations

There was a difference between the hole elongations of the lap plate at the interface of the lap plate and the main plate at the nut end of the bolt as compared to the hole elongations of the lap plate at the interface of the lap plate and the main plate at the nut end of the bolt. This could also be caused by the unsimilar bearing conditions at the nut end and the head end as mentioned in the previous paragraph. See Fig. 9.

12.3 Loading and Unloading Curves

The plotting of these curves showed that the deflection characteristics of the bolt from the calibration shear jig were not affected by the loading and unloading procedure used in this test. These curves are shown in Fig. 7.

A comparison of the load-deflection curve of a continuously loaded bolt with the load-deflection curve of the loaded and unloaded bolt showed close similarity. Both of these bolts were from the same D-lot. This comparison is illustrated in Fig. 8.

13. CONCLUSIONS

The following conclusions are based on the results obtained from the test.

1. In a connection there is an unequal distribution of load among the bolts that are on the same line. The bolts at the extremities of the connection carry the largest portion of the load, while the bolts near the center of the connection carry the smallest portion of the load.

   For example, in joint D41 the two outer bolts carried 54.6% of the total load while the two inner bolts carried 45.4% of the load. Each outer bolt carried 109% of the load it would have carried had the load been distributed uniformly, whereas each inner bolt carried 91% of the uniformly distributed load. Similar results were obtained from the other joints as illustrated in Figs. 4, 5, and 6.

2. The deformation of the bolt is not symmetrical about the center of its bearing surface. The bolt deformation is greater near the head end of the bolt than near the nut end of the bolt.

3. Hole elongations of the lap plate at the interface of the lap plate and the main plate are greater at the nut end of the bolt than at the head end of the bolt.

14. ACKNOWLEDGEMENTS

All work reported in this paper has been conducted at the Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvania. William J. Eney is Director of the Laboratory and Head of the Civil Engineering Department.

All data in this paper which is related to the loading history and the material properties of the test joints was extracted from the Fritz Laboratory Report No. 271.8 titled "Static Tension Tests of Long Bolted Joints" by Robert A. Bendigo and John L. Rumpf. All other data was collected from tests conducted by the author. These tests were part of the Large Bolted Joints Project at Lehigh. This project is sponsored financially by the Pennsylvania Department of Highways, the Bureau of Public Roads and the American Institute of Steel Construction, and is guided by the Research Council on Riveted and Bolted Structural Joints.

The author wishes to express his appreciation to John L. Rumpf, Robert A. Bendigo, and Roger M. Hansen for their guidances and advice; and to Mr. K.R. Harpel and his staff of technicians at the Fritz Engineering Laboratory.

TEST JOINTS

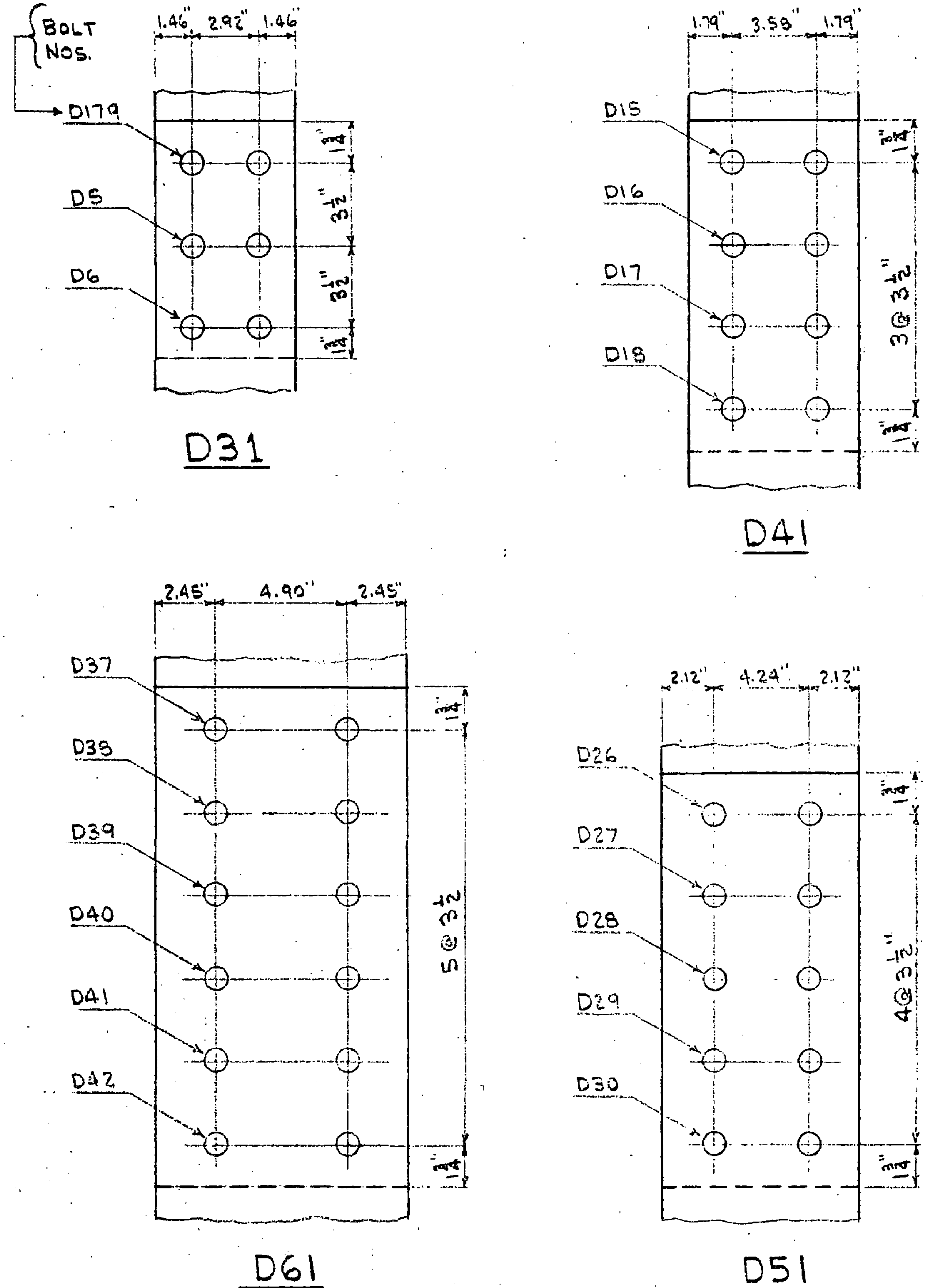


FIG. 1

TYPICAL EDGE VIEW OF TEST JOINTS

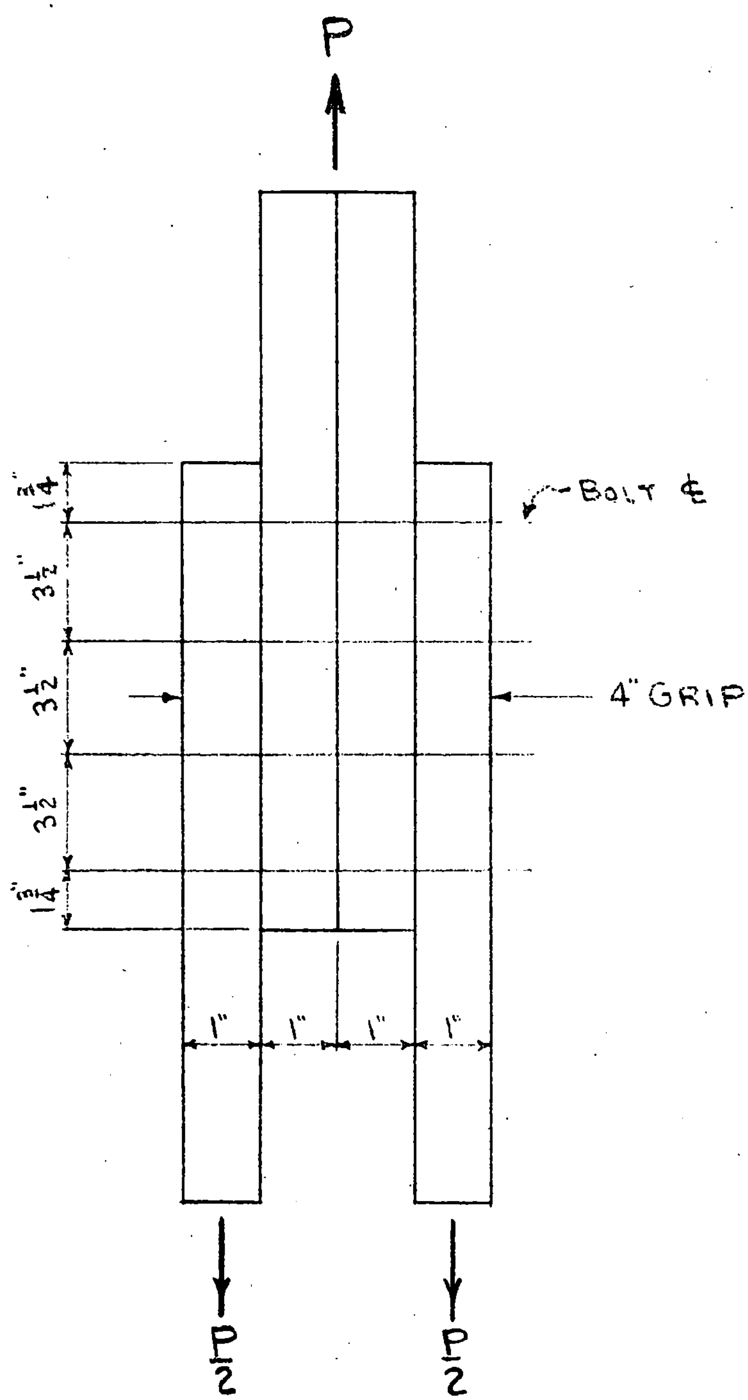


FIG. 2

CALIBRATION SHEAR JIG

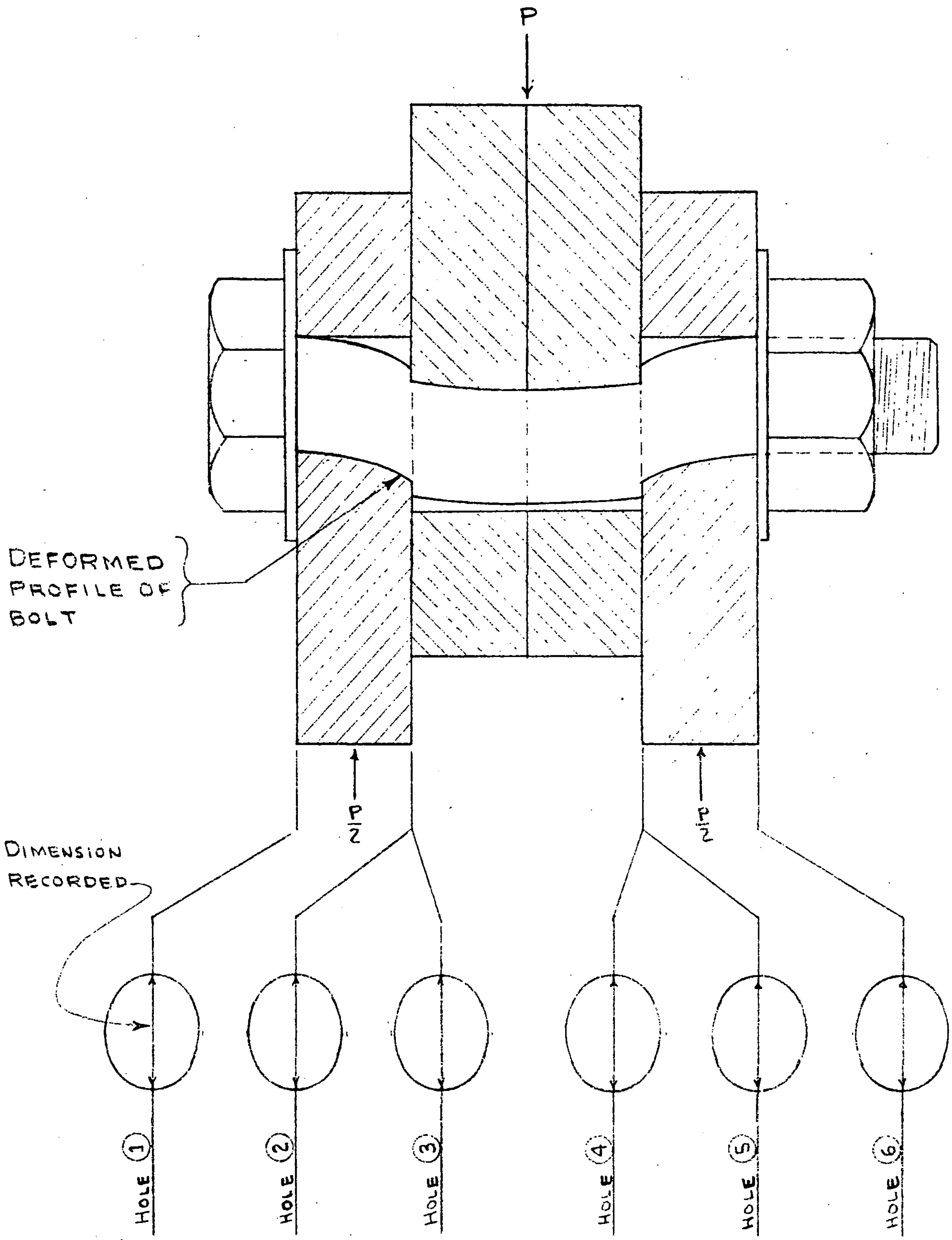
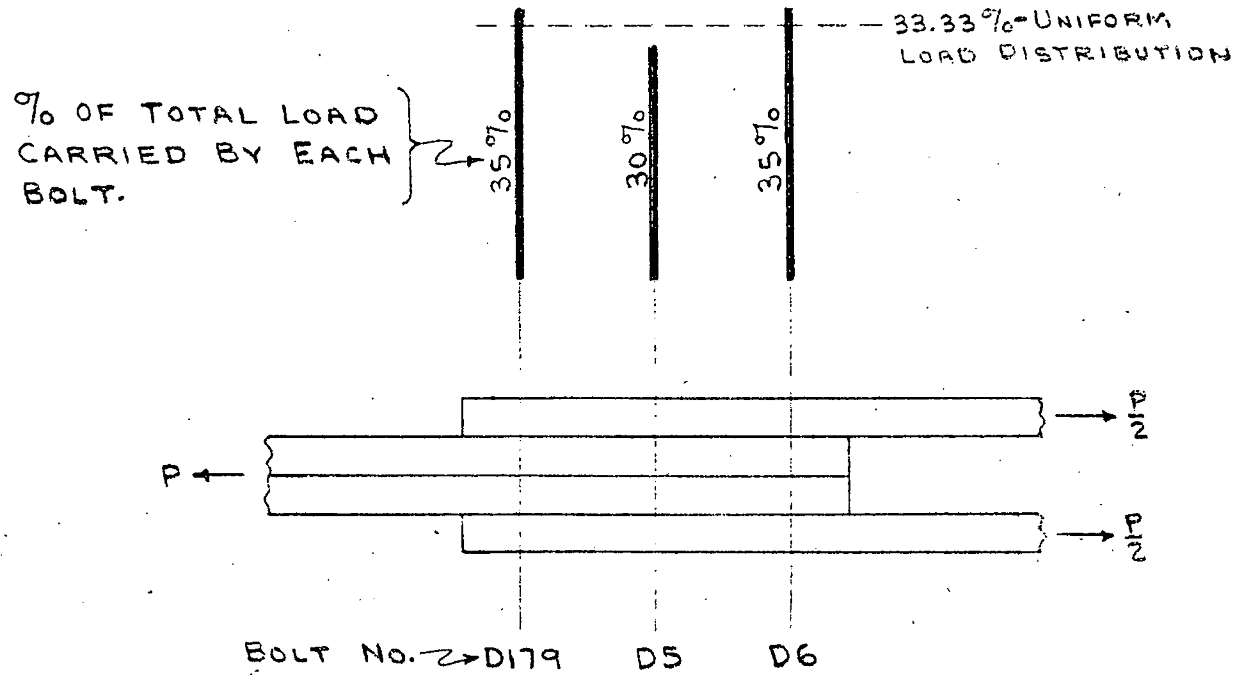


FIG. 3

PERCENT OF TOTAL LOAD CARRIED BY EACH BOLT

JOINT D31



JOINT D41

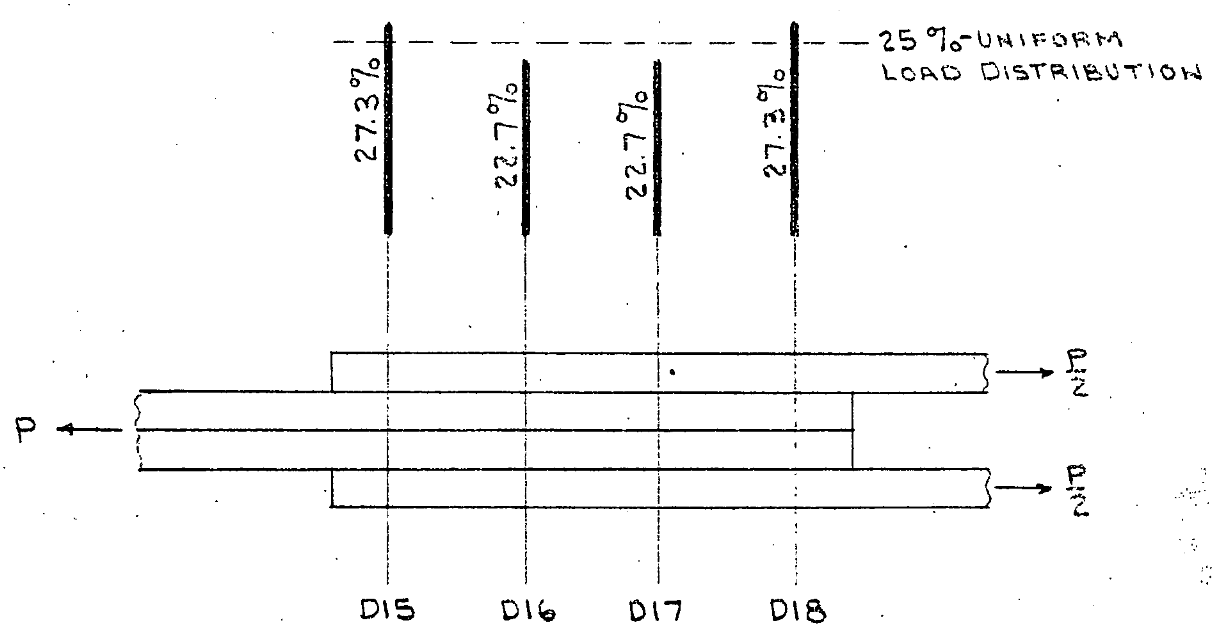
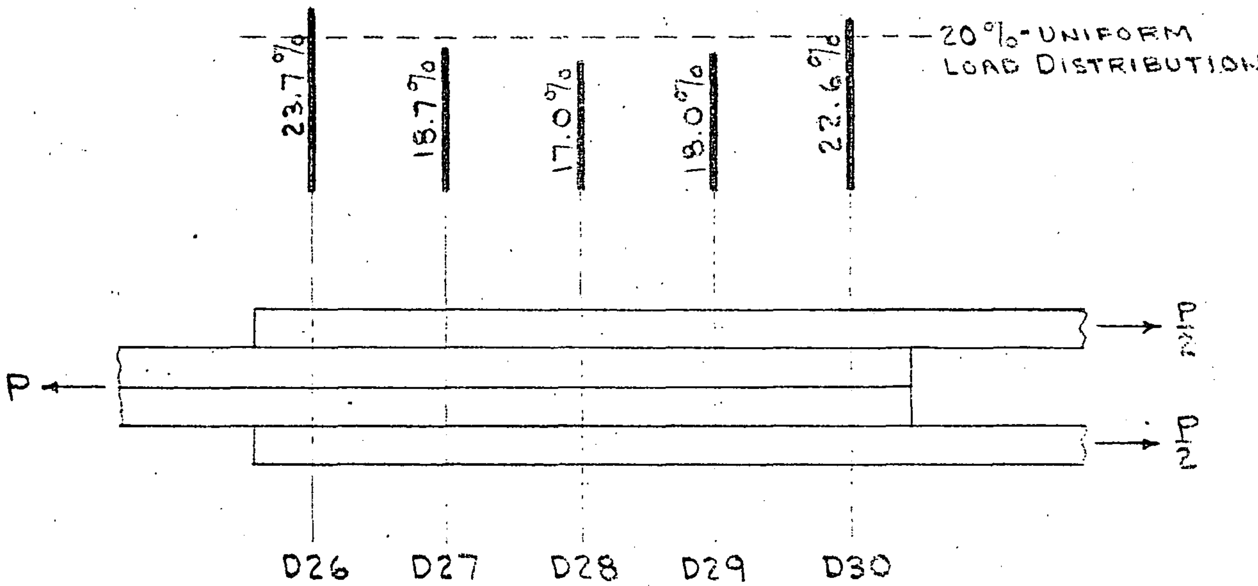


FIG. 4

PERCENT OF TOTAL LOAD CARRIED BY EACH BOLT

JOINT D51



JOINT D61

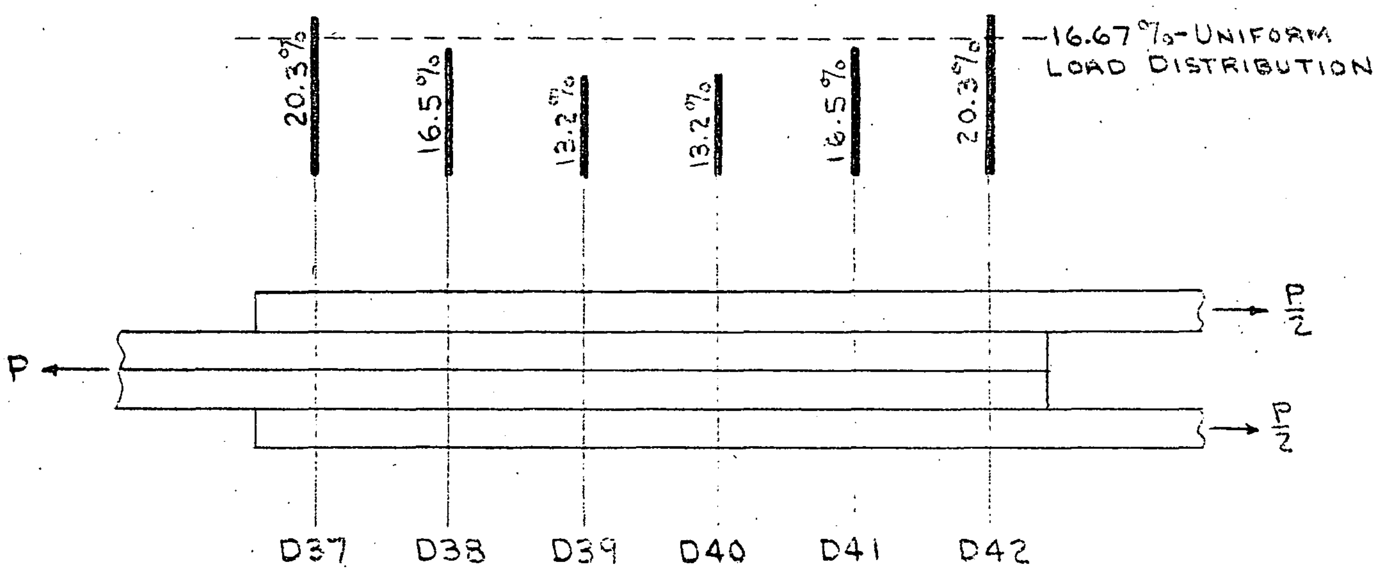


FIG. 5

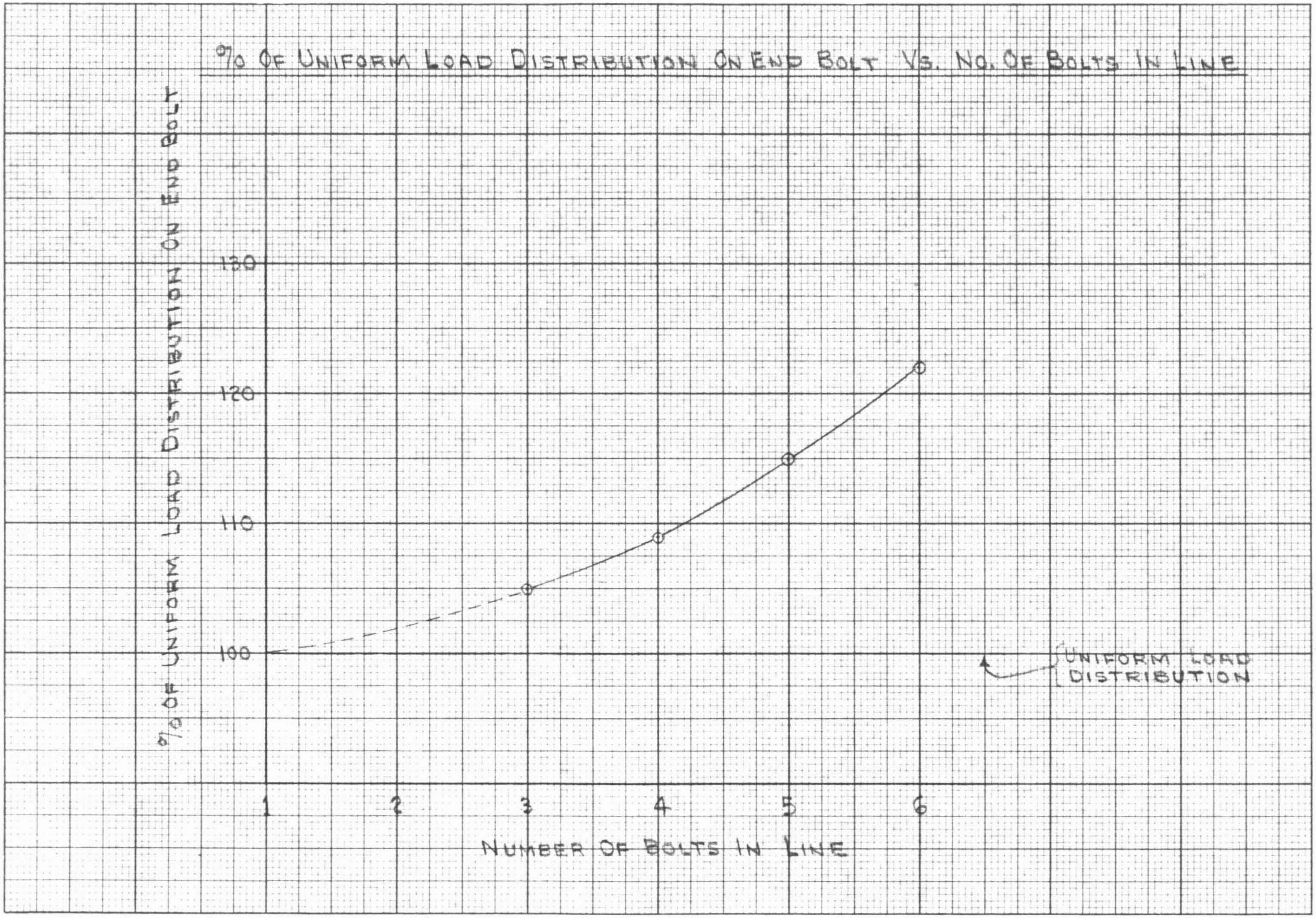

% OF UNIFORM LOAD DISTRIBUTION ON END BOLT VS. NO. OF BOLTS IN LINE
% OF UNIFORM LOAD DISTRIBUTION ON END BOLT
130
120
110
100
UNIFORM LOAD DISTRIBUTION
1
2
3
4
5
6
NUMBER OF BOLTS IN LINE

FIG. 6

K+E 10 X 10 TO THE ½ INCH 359-11
KEUFFEL & ESSER CO. MADE IN U.S.A.

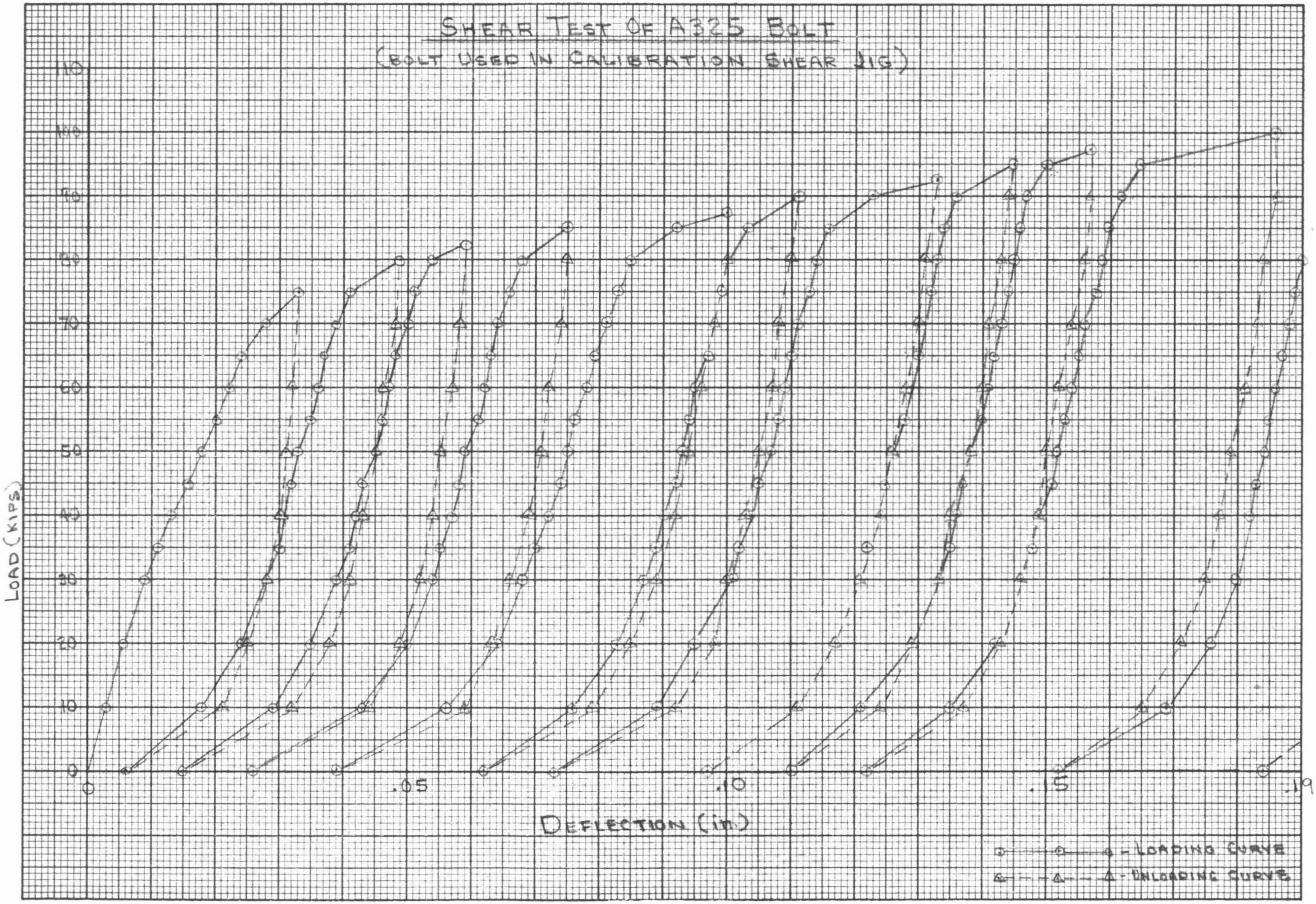


FIG. 7-A

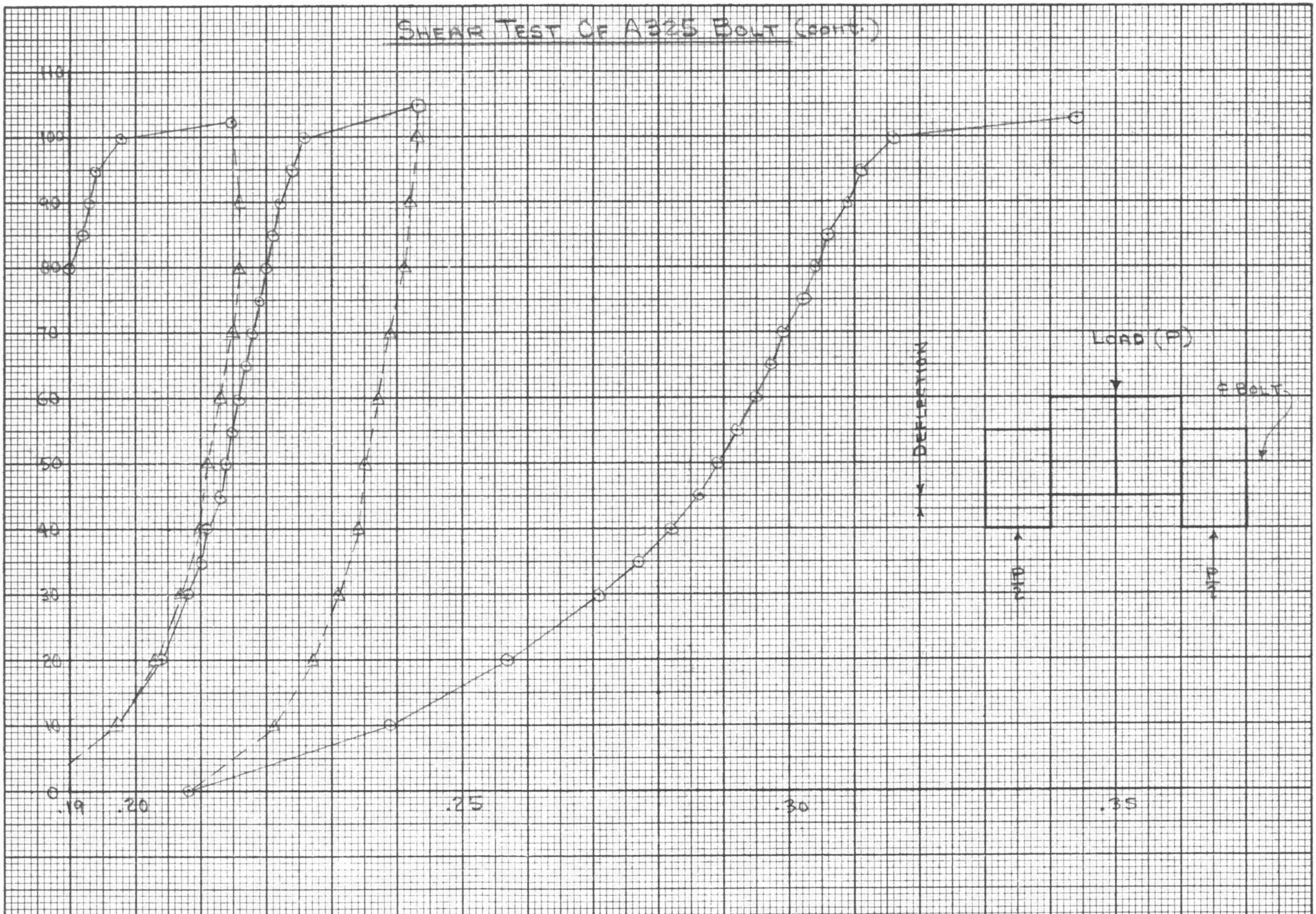

SHEAR TEST OF A325 BOLT (CONT.)
0
10
20
30
40
50
60
70
80
90
100
110
.19
.20
.25
.30
.35
DEFLECTION
LOAD (P)
℄ BOLT
P/2
P/2

FIG. 7-B

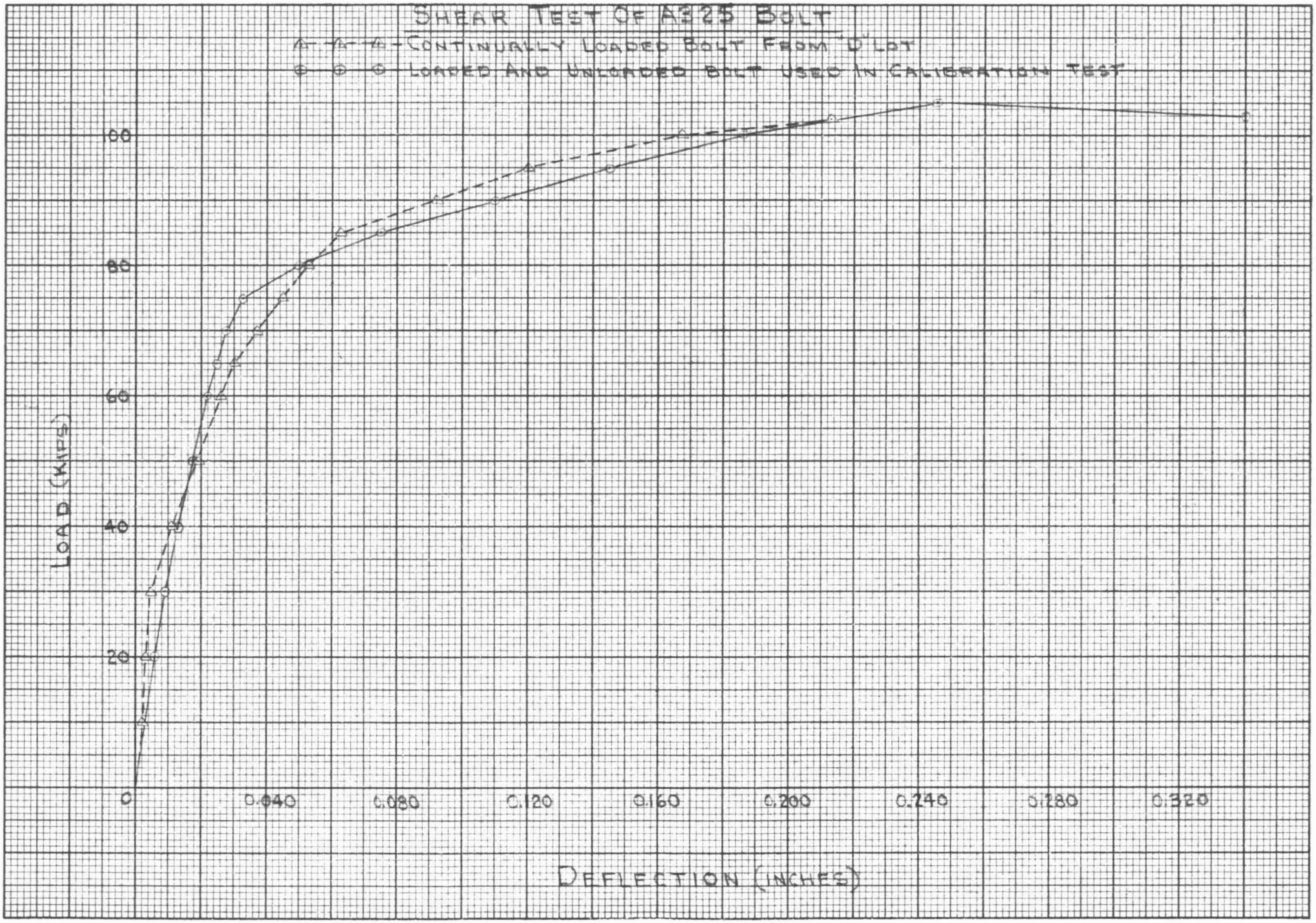

SHEAR TEST OF A325 BOLT
△—△—△ CONTINUALLY LOADED BOLT FROM "D" LOT
⊖—⊖—⊖ LOADED AND UNLOADED BOLT USED IN CALIBRATION TEST
100
80
60
40
20
0
0.040
0.080
0.120
0.160
0.200
0.240
0.280
0.320
LOAD (KIPS)
DEFLECTION (INCHES)

FIG. 8

HOLE ELONGATIONS VS. APPLIED LOADS

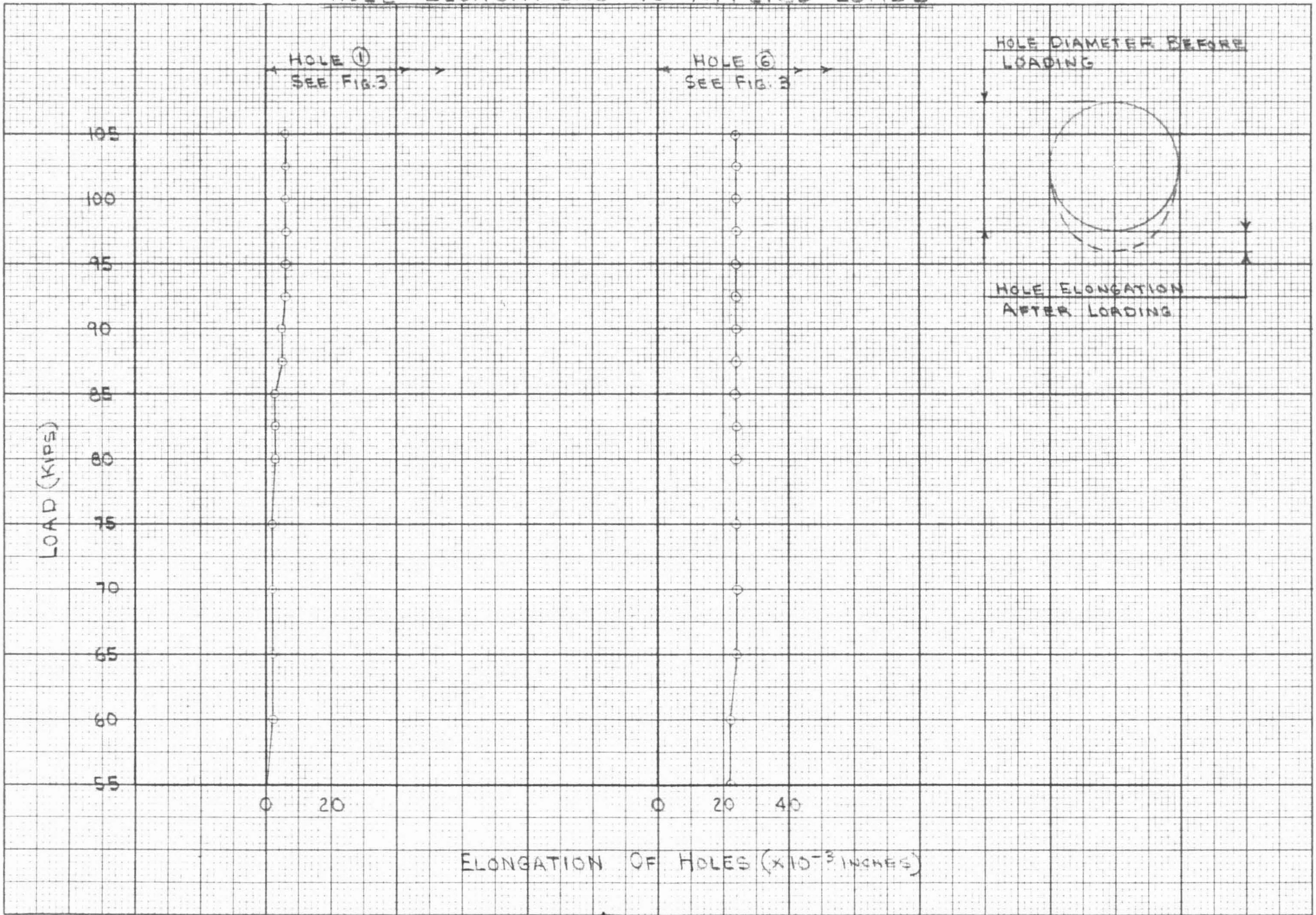


FIG. 9 — A

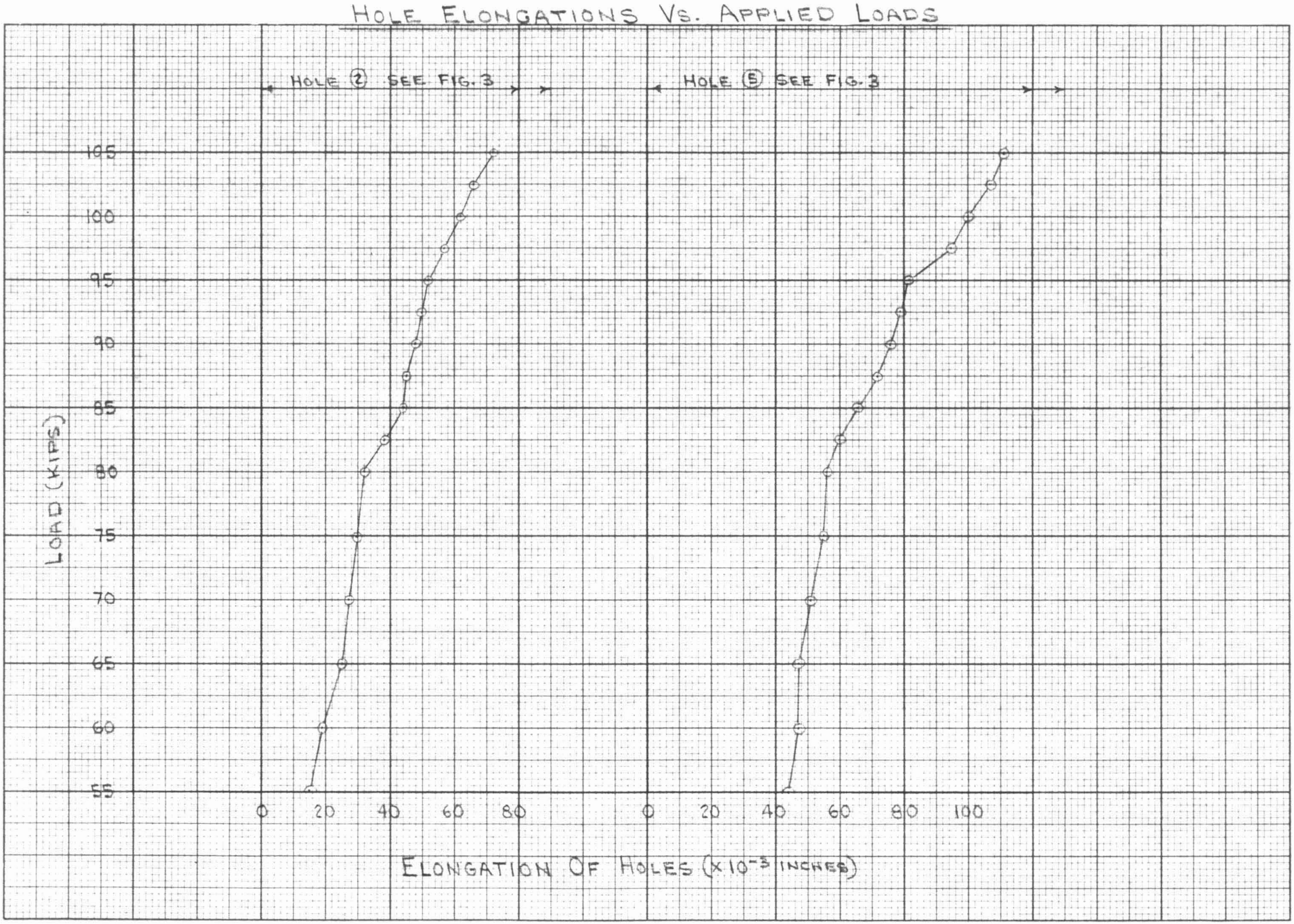

HOLE ELONGATIONS VS. APPLIED LOADS
HOLE ② SEE FIG. 3
HOLE ⑤ SEE FIG. 3
LOAD (KIPS)
105
100
95
90
85
80
75
70
65
60
55
0
20
40
60
80
0
20
40
60
80
100
ELONGATION OF HOLES (x 10^-3 INCHES)

FIG. 9 – B

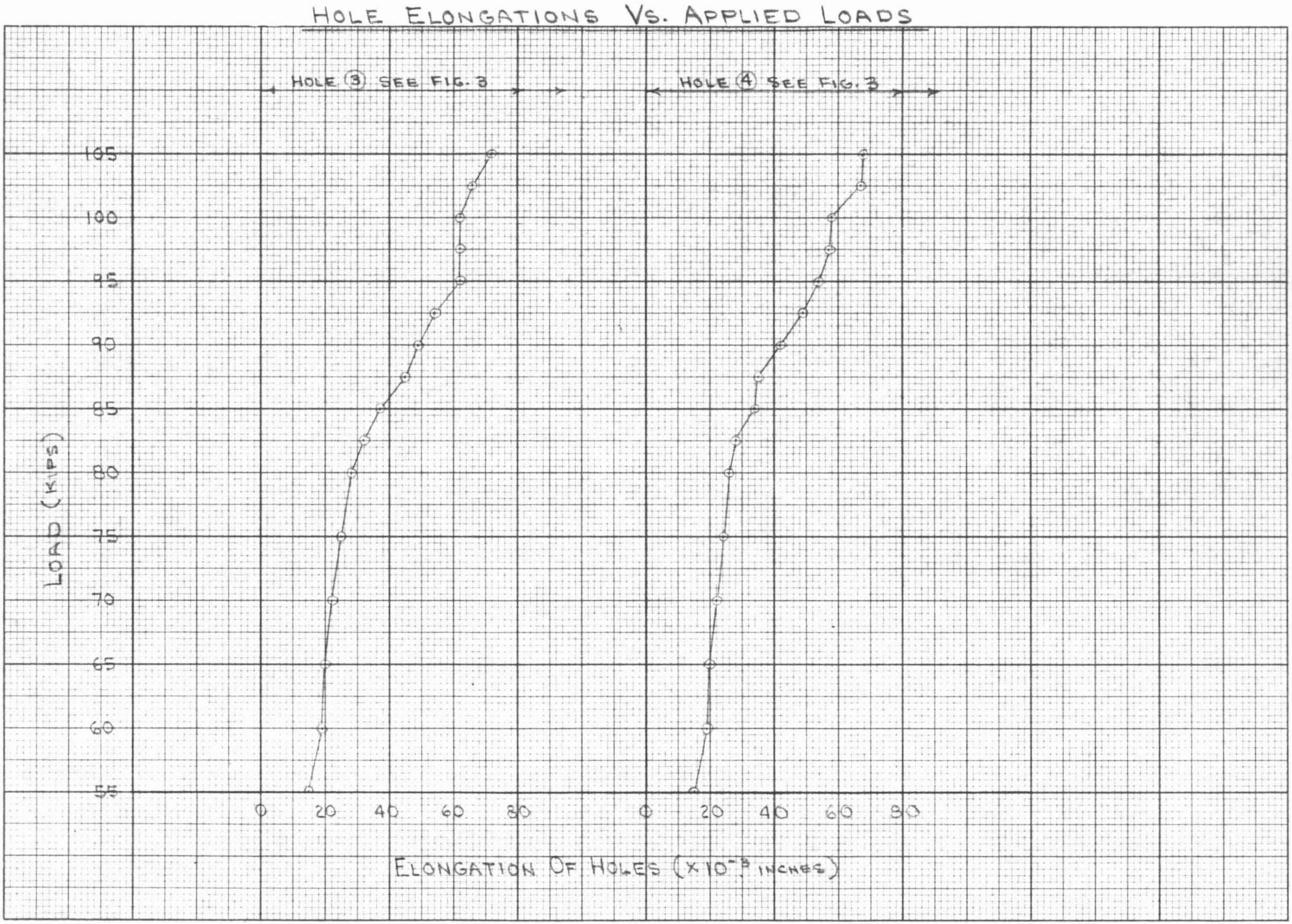

HOLE ELONGATIONS VS. APPLIED LOADS
HOLE ③ SEE FIG. 3
HOLE ④ SEE FIG. 3
105
100
95
90
85
80
75
70
65
60
55
LOAD (KIPS)
0
20
40
60
80
0
20
40
60
80
ELONGATION OF HOLES (X10⁻³ INCHES)

FIG. 9 - C

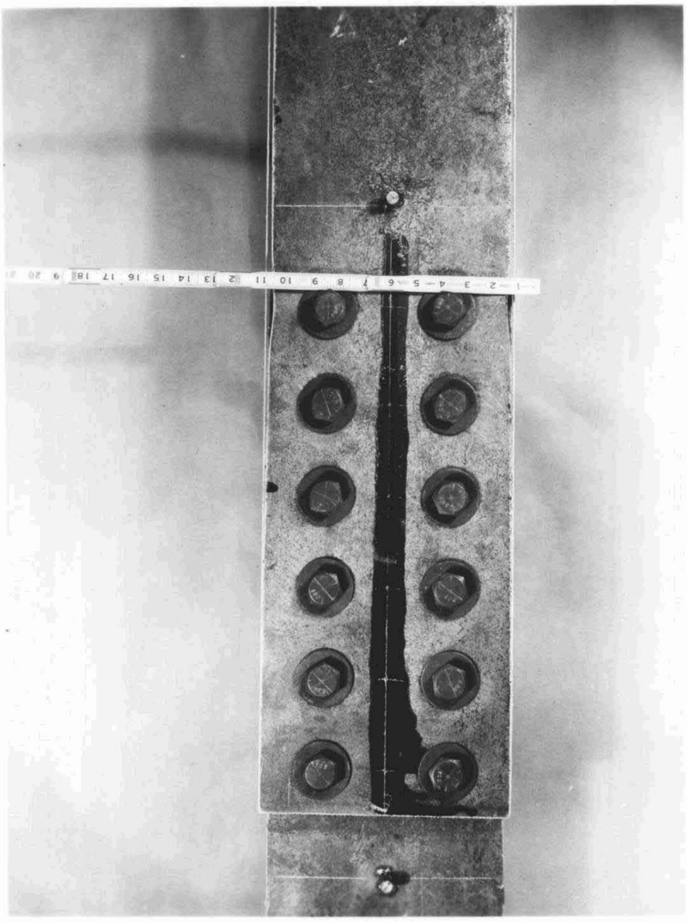


Fig. 10

JOINT D61 - PLAN VIEW

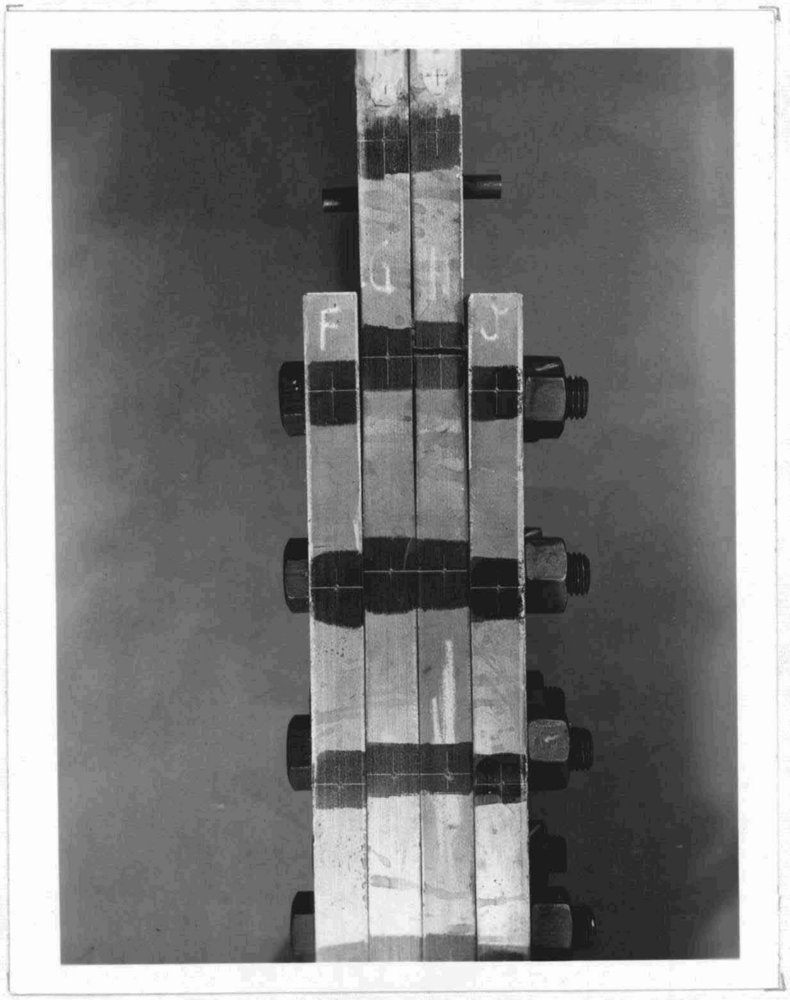


Fig. 11

JOINT D61 - SIDE VIEW

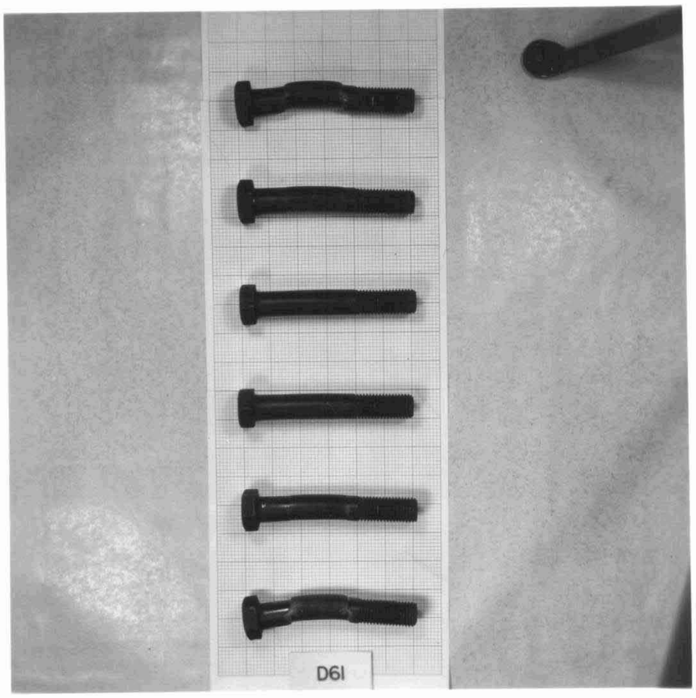


Fig. 12

JOINT D61 - BOLT DEFORMATIONS

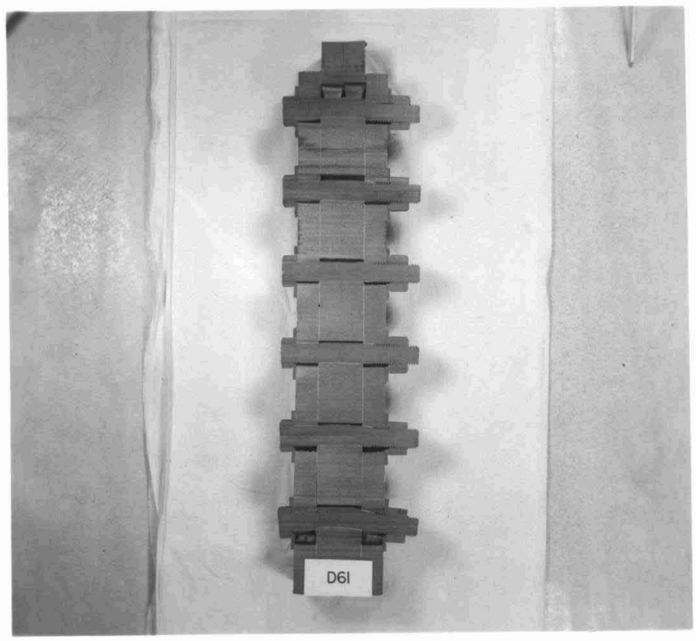


Fig. 13

JOINT D61 - SECTIONAL SIDE VIEW

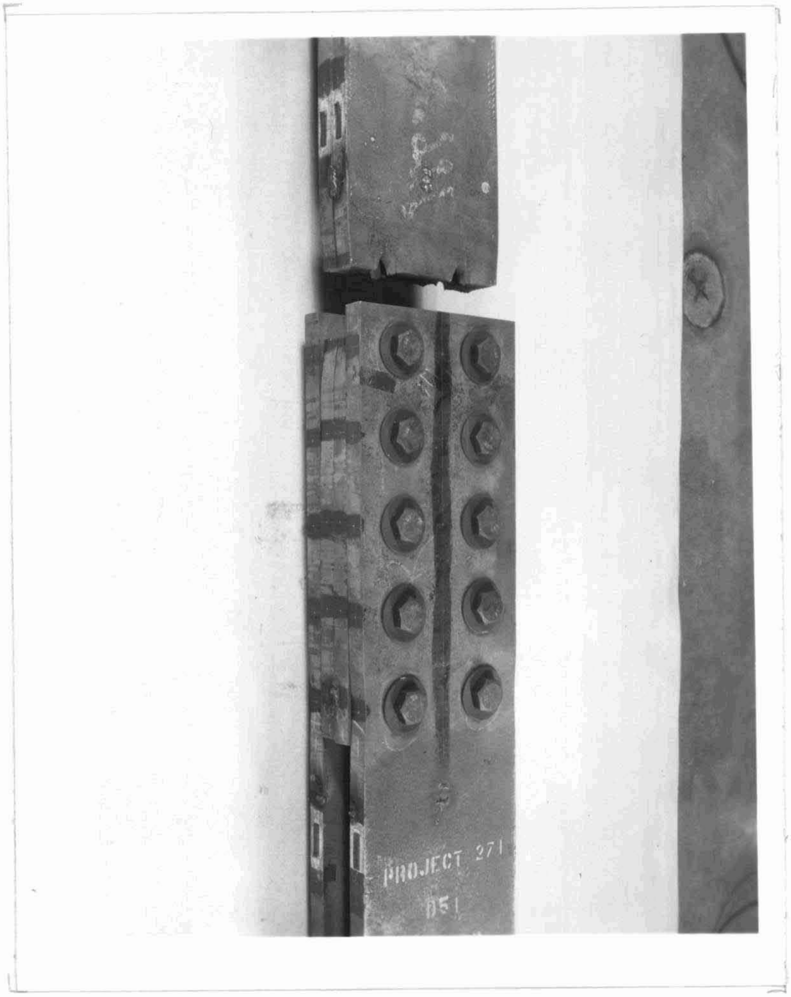


Fig. 14

JOINT D51 - PLAN VIEW

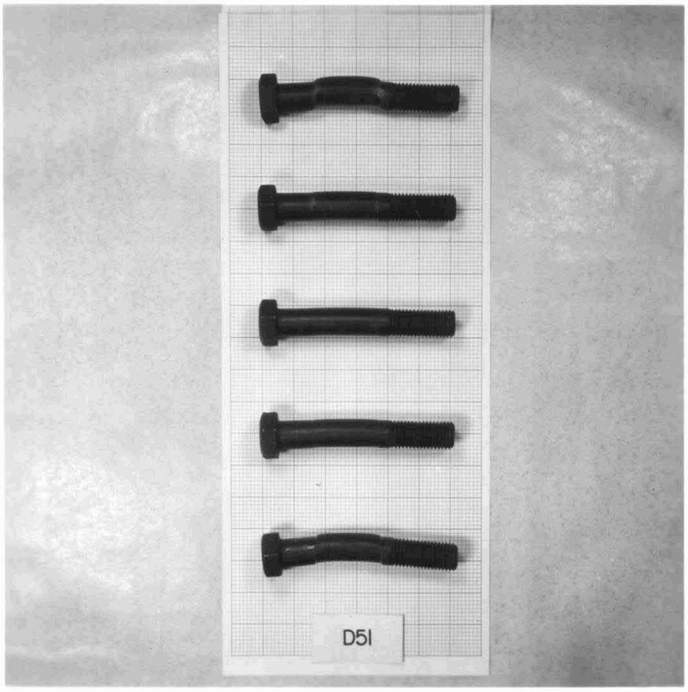


Fig. 15

JOINT D51 - BOLT DEFORMATIONS

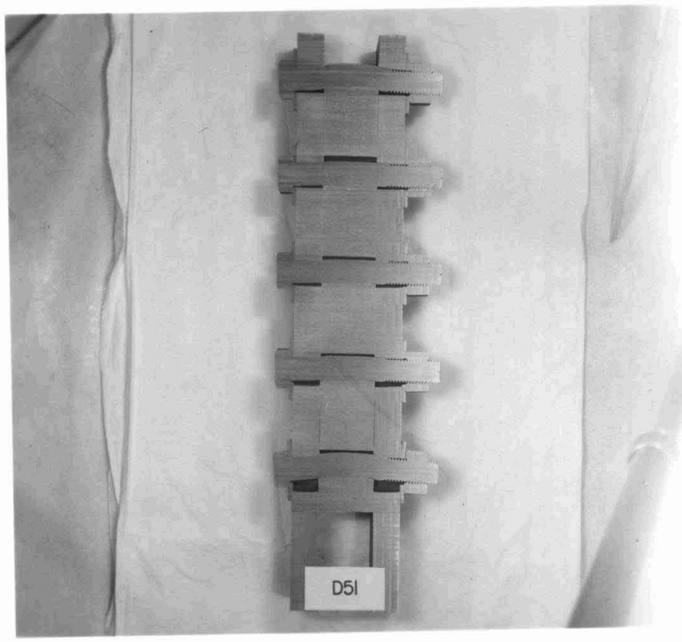


Fig. 16

JOINT D51 - SECTIONAL SIDE VIEW

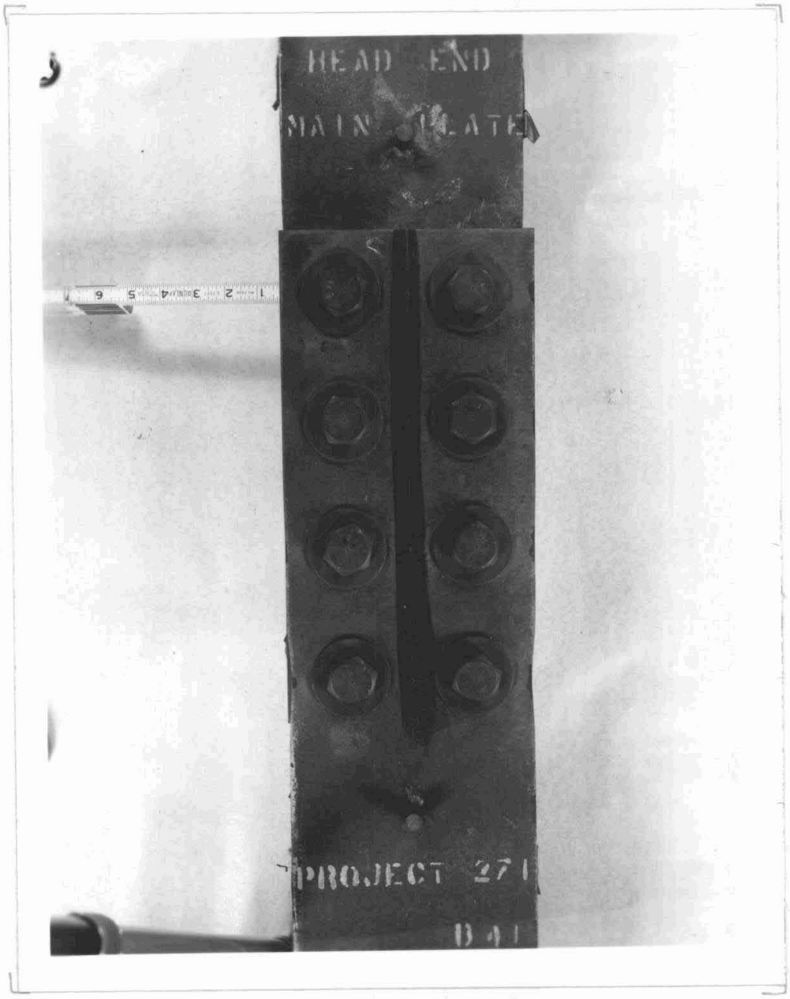


Fig. 17

JOINT D41 - PLAN VIEW

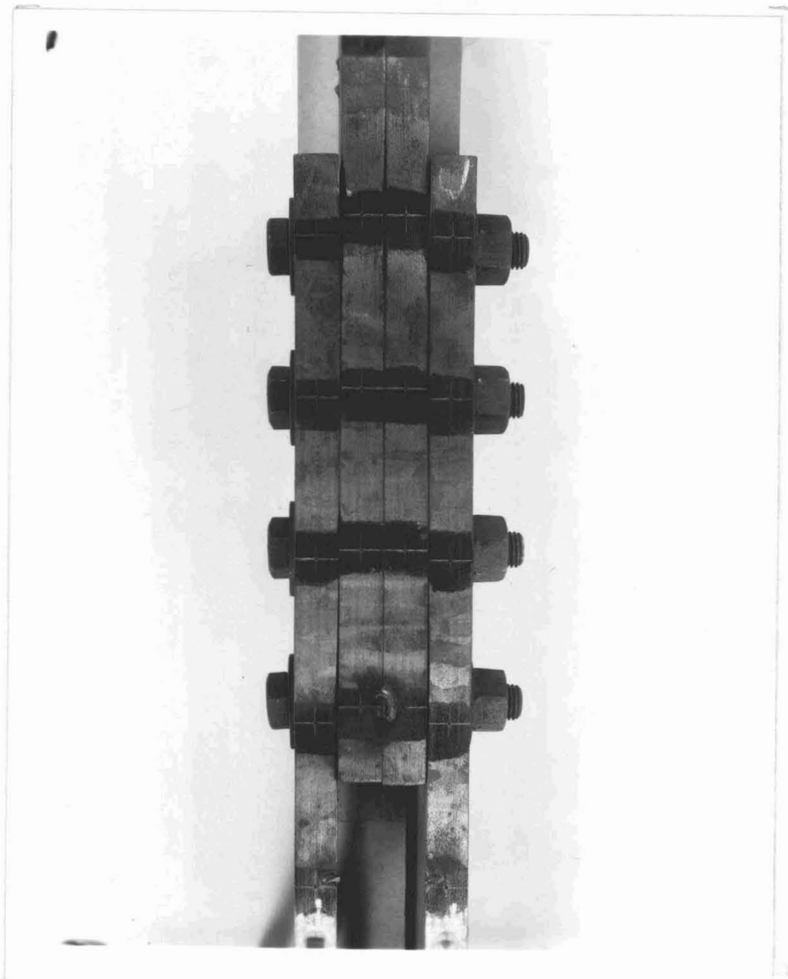


Fig. 18

JOINT D41 - SIDE VIEW

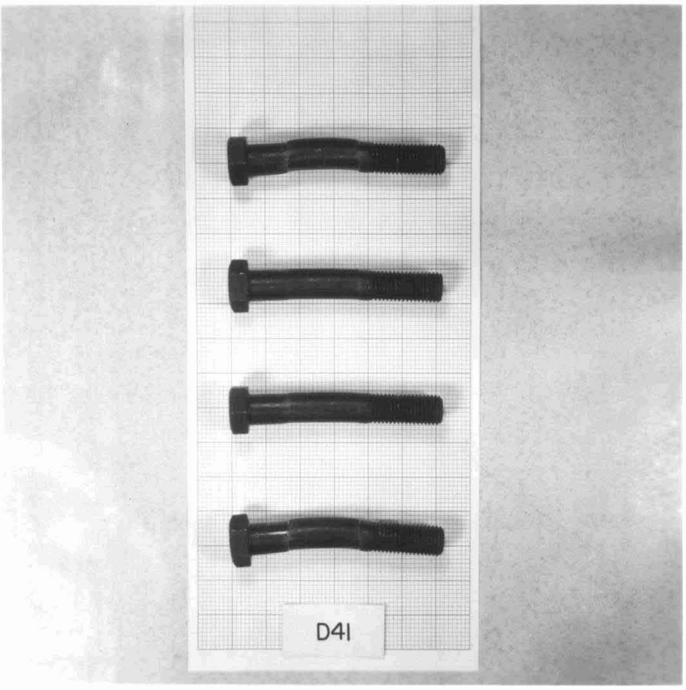


Fig. 19

JOINT D41 - BOLT DEFORMATIONS

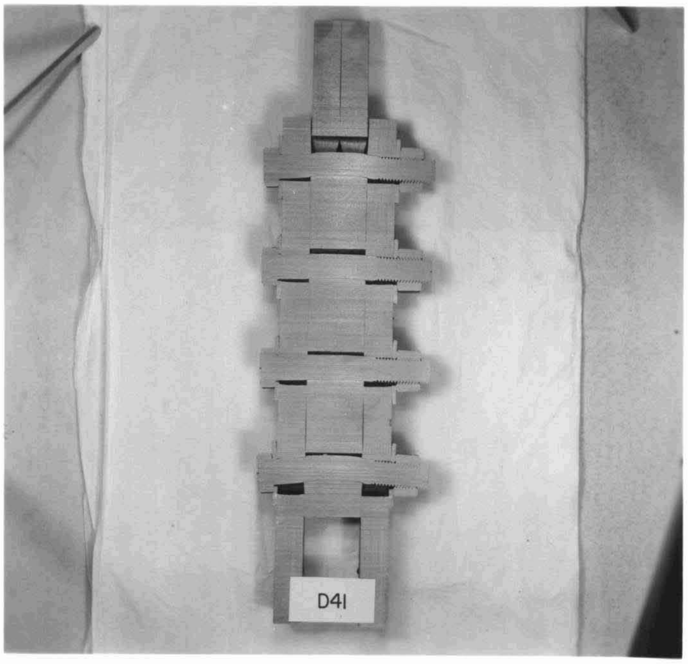


Fig. 20

JOINT D41 - SECTIONAL SIDE VIEW

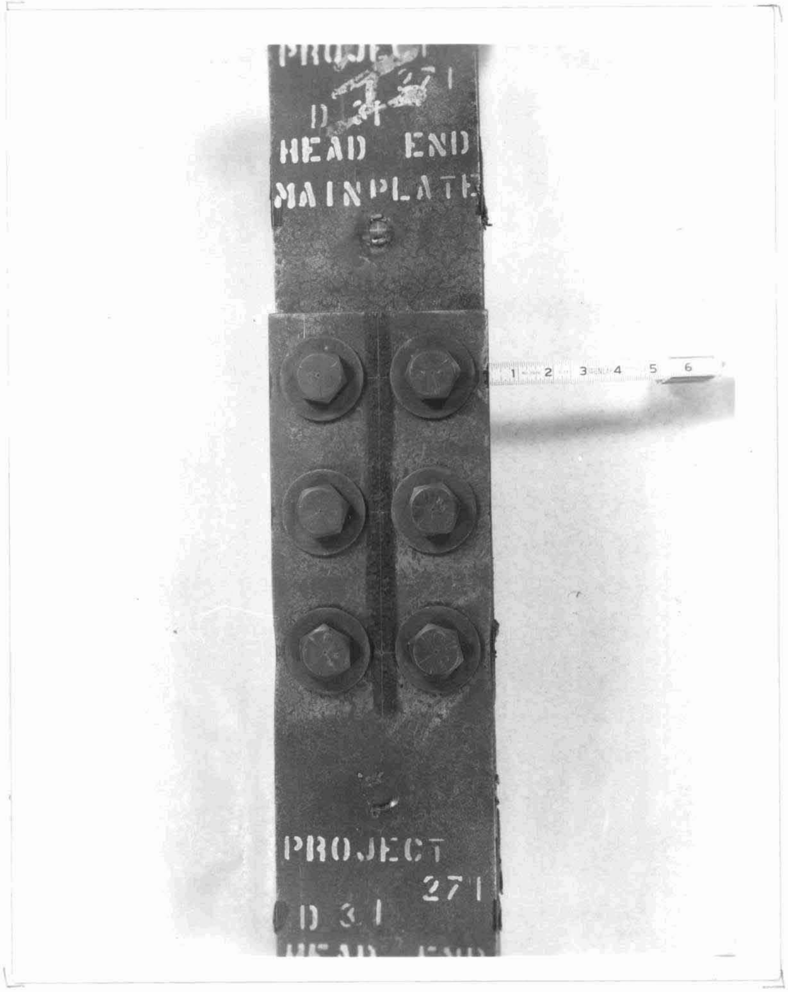


Fig. 21

JOINT D31 - PLAN VIEW

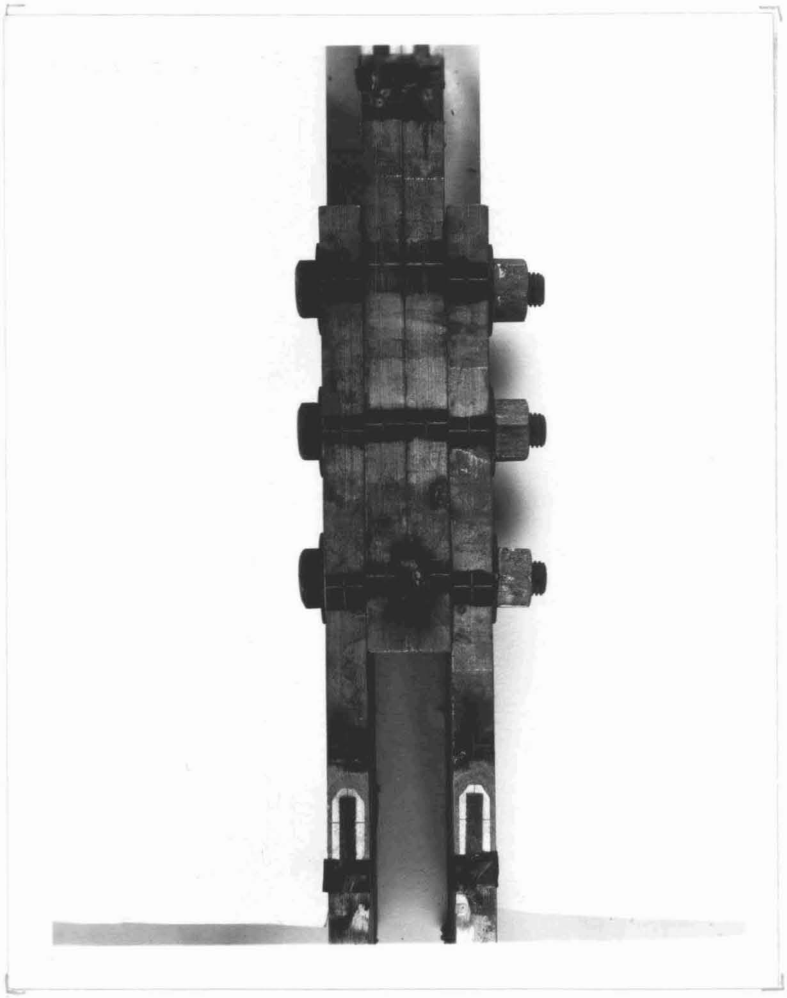


Fig. 22

JOINT D31 - SIDE VIEW

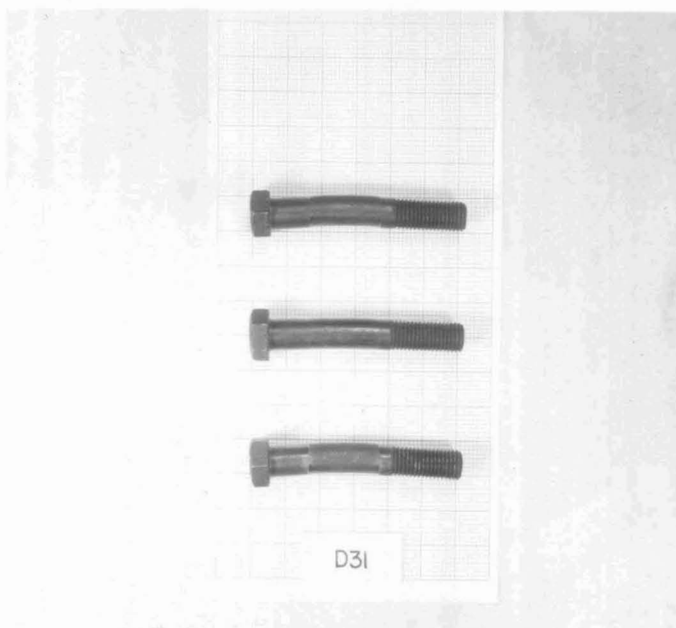


Fig. 23

JOINT D31 - BOLT DEFORMATIONS

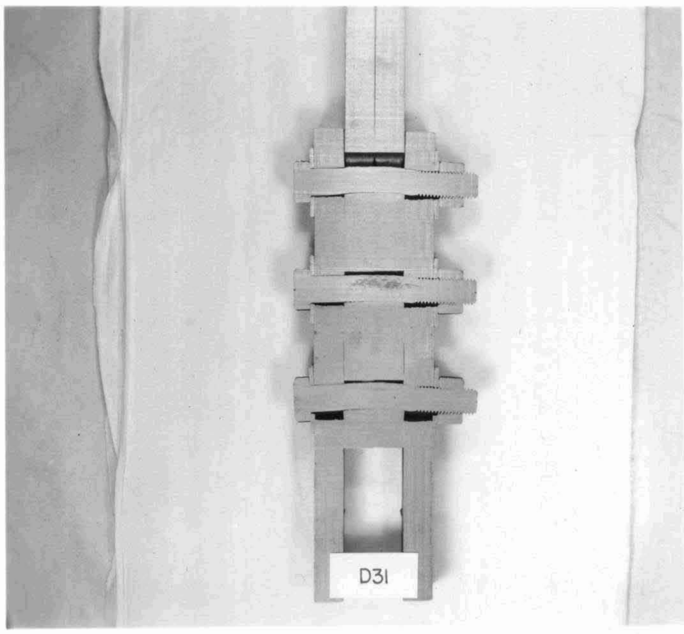


Fig. 24

JOINT D31 - SECTIONAL SIDE VIEW

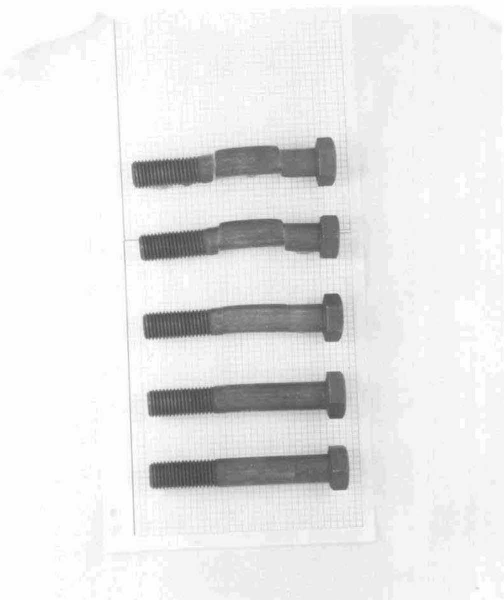


Fig. 25

PROGRESSIVE SHEAR DEFORMATION OF CALIBRATION BOLT

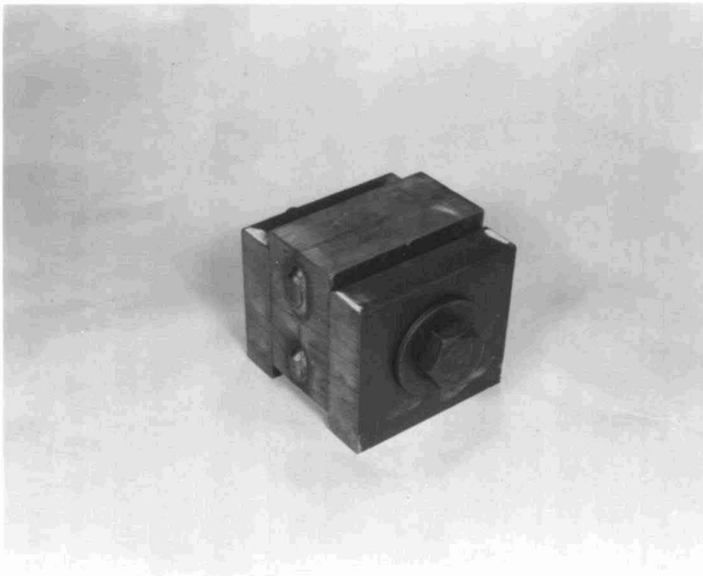


Fig. 26

CALIBRATION SHEAR JIG

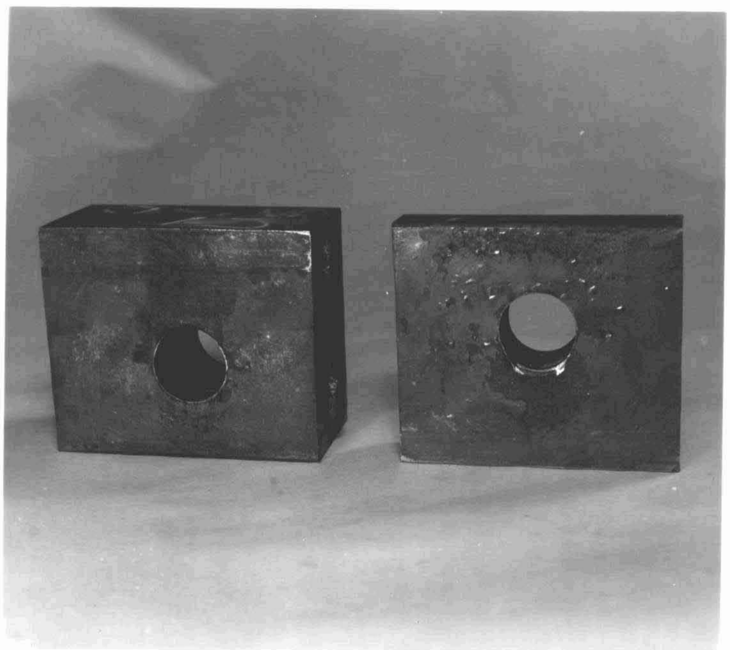


Fig. 27

HOLE DEFORMATIONS - SHEAR JIG

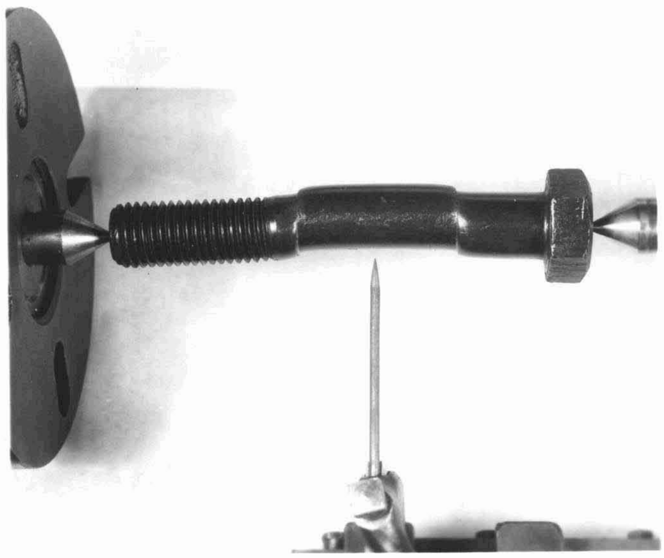


Fig. 28

LATHE SET-UP FOR MEASURING BOLT DEFORMATIONS

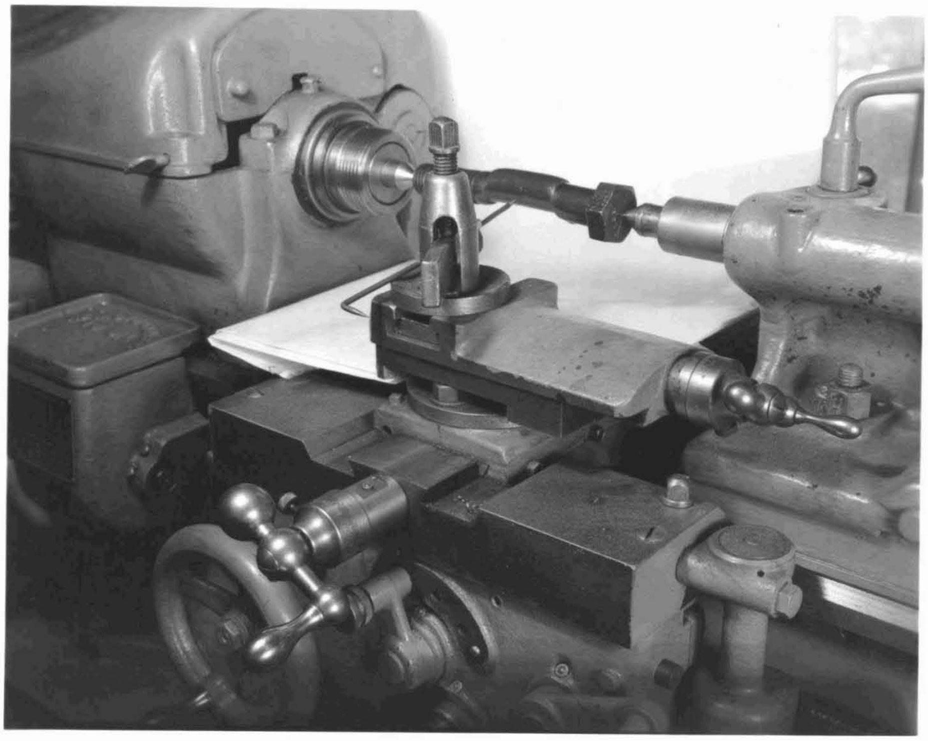


Fig. 29

LATHE SET-UP FOR MEASURING BOLT DEFORMATIONS