A STUDY OF THE EFFECT OF VARIABLE CLEARANCES ON THE BOLT LOAD DISTRIBUTION IN A MULTI-FASTENER LAP JOINT

By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

CHAPTER I

INTRODUCTION

Joint design in recent years has become very important, especially in the aircraft industry. The increase in aircraft weight is probably on the order of ten percent due to the additional material and fasteners required for the joint. Thus, any significant savings in joint weight would result in considerable decrease in weight of the entire aircraft. With the recent increase in airplane production costs, any savings in weight results in a substantial saving in costs, therefore, it becomes paramount that all the joining devices in aircraft be as light as possible.

Joint design in earlier times was, and still is rather inexact. The first approach which was used assumed that each bolt carried an equal amount of load. Later it was suspected that this was not true and actually the bolts at the edges of a lap joint carried more load than the interior bolts. Recently, this suspicion has been substantiated and the variation has been shown to be, in some instances, (end bolt of a three bolt joint) approximately fifteen percent. (1). Currently, joints must be designed such that the extreme bolts will carry this additional fifteen percent load and, as is usual in joint design at present, all of the bolts are made the same size. Consequently, the interior bolts are not loaded to their full capacity and thus result in excess weight.

It is possible that equal loading of the bolts, or at least full loading of each bolt, could be accomplished by varying the clearances across the lap joint. This would allow smaller bolts (thus a decrease in weight) to be used, since each fastener would be loaded to its full capacity.

It is the purpose of this report to arrive at a means of predicting the clearances necessary for equal bolt load distribution and to present the results of an experimental check of this prediction. A relationship between necessary clearances, the number of bolts in a joint, the bolt spacing, the properties of the plate material, and the joint load is derived. The clearances predicted by this relation were experimentally checked for a specific joint configuration and the results are presented.

CHAPTER II

DERIVATION

In order to arrive at the relationship for predicting clearances, certain simplifying assumptions must be made to overcome inherent indeterminancies. The assumptions made are as follows:

(1) The stress strain relationship for the material is linear.

(2) The load-deflection characteristic of the bolts is linear and is independent of clearances.

(3) The relative motion of the plate and straps may be defined in terms of bolt deflection, hole clearances, and strap strain.

(4) Stress in a strap and plate can be approximated by an average stress $\frac{P}{A}$.

(5) That the load carried by friction between the plates and the straps is negligible.

The first assumption is necessary because some means must be available for determining the total strain in the straps between two adjacent bolts. The strain relationship for Young's modulus holds only when this assumption is made.

The second assumption of linear bolt deflection characteristic has been shown by other investigators to be substantially true under certain circumstances. (1). These include a loading below the yield point of the bolt material, zero clearances, and considering the bolt as a beam with clamped ends. Some of these conditions are not satisfied in the present study. Consequently, the behavior of the load-deflection characteristic of a bolt under a loading similar to that of the present study was determined. Joints similar to the one in the present study except having only one bolt per lap and having various clearances were studied in a preliminary investigation. Deflections were measured directly by mechanical strain gages and the load-deflection curves are presented in Appendix B. The results show that with considerable clearance the bolt load-deflection characteristic is not linear and that with clearances on the order of three percent of the bolt diameter, bolts show an increased change in deflection with load under higher loadings; however, the increase is rather small and it is believed that with a normal working load for a joint the non-linearity would be insignificant.

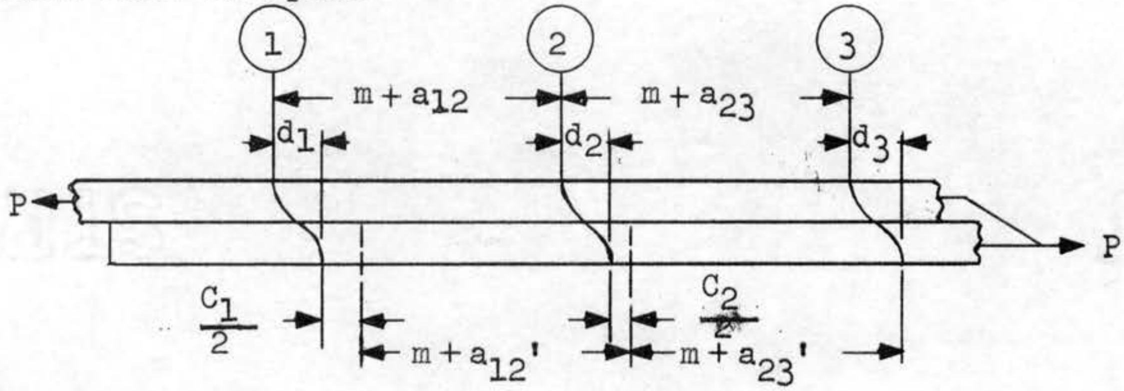
The third assumption takes care of the difficulty in determining or describing the bearing action of the bolt on the plate and straps.

The bearing action is very complex. Little work has been done to determine what actual deflections take place due to compression in the plate and bolt itself. Actually the third assumption implies that there is no compression of the bolt or plate, and that all relative motion between adjacent bolts is the sum of the total strain of the material between the bolts (as obtained from Young's modulus and an average stress mid-way between the bolts) and the clearances between the bolts and holes. Thus, the assumption absorbs the bearing action problem.

The fourth assumption, while not absolutely true as indicated by other investigations, can again be considered sufficiently accurate for this investigation. (1).

Tate and Rosenfield (1) indicate that assumption five is substantially correct though many other investigations have indicated that it plays a significant part in the load carrying capacity of many lap joints. However, experience gained during the tests of Appendix B indicates that the assumption is correct, especially when the materials have high hardness. The test specimens described in Appendix B, being made of 7075-T6 aluminum, could not be gripped in the jaws of the testing machine, apparently because of their extreme hardness. To stop the slippage, extensions of C1010 steel were attached to the ends of the specimens and the load applied through these extensions. Thus, it appears that a normal force (clamping action) of several times the joint load would be necessary to produce a friction force capable of carrying a significant load. Toward this end the bolts on installation were tightened snuggly with a wrench, loosened, and then retightened by hand.

Based on these five assumptions, a derivation of the proposed relationship for predicting clearances can be made. From the second assumption it is seen that in order to have equal distribution along the joint, the deflection of each bolt must be the same. Thus in Figure 1, $d_1 = d_2 = d_3$, and the center to center distances of the ends of two adjacent bolts must be equal.



P = Joint load.
C (Clearance) = Diameter of hole - Diameter of bolt.
d = Deflection of bolt.
m = Center to center distance of holes at zero load.
a = Elongation of section between bolts due to load.

Figure 1. Portion of a Five Bolt Lap Joint Showing Three Bolts

The equality of distances requires that

$$a_{23}' + m = a_{23} + m - \frac{C_2}{2} - d_2 + d_3,$$

or $$C_2 = 2\,(a_{23} - a_{23}').$$ Eq. (1)

Between bolts 1 and 2, the relation is:

$$a_{12}' + m = a_{12} + m - \frac{C_1}{2} + \frac{C_2}{2} + d_2 - d_1,$$

or $$C_1 = C_2 + 2(a_{12} - a_{12}').$$ Eq. (2)

The elongation of the strap segment between bolts is obtained by observing the relation between the elongation of the strap and plate between the same two bolts. This relation depends on the loads in the plate and strap segments. These loads are shown in Figure 2 in terms of the total joint load P.

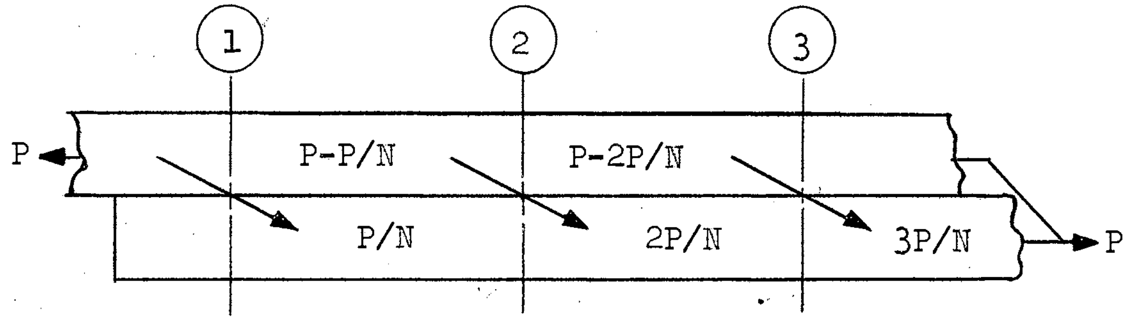


Figure 2. Lap Joint Showing the Loads in Segments Between Bolts

From Young's modulus, $a_{ij} = \frac{Fm}{AE}$, where $j = i + 1$ and both are bolt locations; F is the load in the section between i and j; A is the area of the section and E is the modulus of elasticity. The force corresponding to

a_{12} is, $F = P - \frac{P}{N}$;

a_{23} is, $F = P - \frac{2P}{N}$;

and to a_{ij}, $F = P - \frac{iP}{N}$.

It follows that

$$a_{ij} = \frac{(P-iP/N)m}{AE} = \frac{Pm}{AE}(1-i/N), \qquad \text{Eq. (3)}$$

and similarly, $$a_{ij}' = \frac{\frac{iPm}{N}}{AE}. \qquad \text{Eq. (4)}$$

Division of the last two equations yields,

$$\frac{a_{ij}}{a_{ij}'} = \frac{\frac{Pm}{AE}(1-i/N)}{\frac{Pm}{AE}(i/N)} = \frac{N - i}{i}. \qquad \text{Eq. (5)}$$

Substituting for a_{ij}' in Eqs. (1) and (2) gives:

$$C_2 = 2\left(a_{23} - 2\frac{a_{23}}{N-2}\right) = 2a_{23}\left(1 - \frac{2}{N-2}\right) = 2a_{23}\left(\frac{N-4}{N-2}\right). \qquad \text{Eq. (1a)}$$

$$C_1 = C_2 + 2\left(a_{12} - \frac{a_{12}}{N-1}\right) = C_2 + 2a_{12}\left(\frac{N-2}{N-1}\right) .$$ Eq. (2a)

$$\text{or } C_1 = 2a_{12}\left(\frac{N-2}{N-1}\right) + 2a_{23}\left(\frac{N-4}{N-2}\right).$$

In general induction leads to

$$C_i = \sum_{i}^{f(N)} 2a_{ij}\left(\frac{N-2i}{N-i}\right),$$

where $f(N) = \frac{N-1}{2}$ for odd values of N, and $f(N) = \frac{N-2}{2}$ for even values of N. Since,

$$2a_{ij}\left(\frac{N-2i}{N-i}\right) = \frac{2Pm}{AE}(1-i/N)\left(\frac{N-2i}{N-i}\right) = \frac{2Pm}{AE}\frac{(N-2i)}{N} ,$$

it follows that

$$C_i = \frac{2Pm}{NAE}\sum_{i}^{f(N)}(N-2i).$$ Eq. (6)

Equation (6) is the proposed relation for predicting the necessary clearances for equal bolt load distribution. It is based on a joint having an odd number of bolts, the center bolt having zero clearances in both plate and strap and the remaining bolts having zero clearances in one and the predicted clearance in the other. All clearances may be increased by an equal amount without disturbing the bolt load distribution. Also, since "m" may be inside the summation, it could be varied to provide some flexibility in joint configuration. The relationship can be applied to a joint with an even number of bolts by considering the two center bolts as one and calculating the clearances using a value for "N" of one less than the actual number of bolts. The predicted clearances are then applied to the remaining bolts.

The relationship is limited to the range of loadings that stress the bolts and plates to a value below their proportional limits. Beyond the load corresponding to the proportional limits of either or both, it has been found that yielding of one or the other, or both, tend to equalize the bolt load distribution. (1). In a joint designed for equal bolt load distribution with a given maximum load, the joint can be subjected to higher loadings and still maintain essentially an equal bolt load distribution, although local yielding would take place with such loadings. Also, the relationship is limited to joints with bolts made of the same material and having like diameters. Under a condition of loading with a fraction of the design load, the bolt loading is unequal, the bulk of the load being carried by the interior bolts. Intermediate bolt load distributions are shown in Figure 4.

CHAPTER III

EXPERIMENTAL VERIFICATION OF PREDICTED CLEARANCES

The lap joint used in the test was designed so that maximum deflection of the bolts and strain of the plate material would occur under a load that would not cause stresses above the proportional limits. Also, an attempt was made to duplicate the materials and configurations used in present day aircraft construction, in order that the results might be more easily applied to design in the aircraft industry.

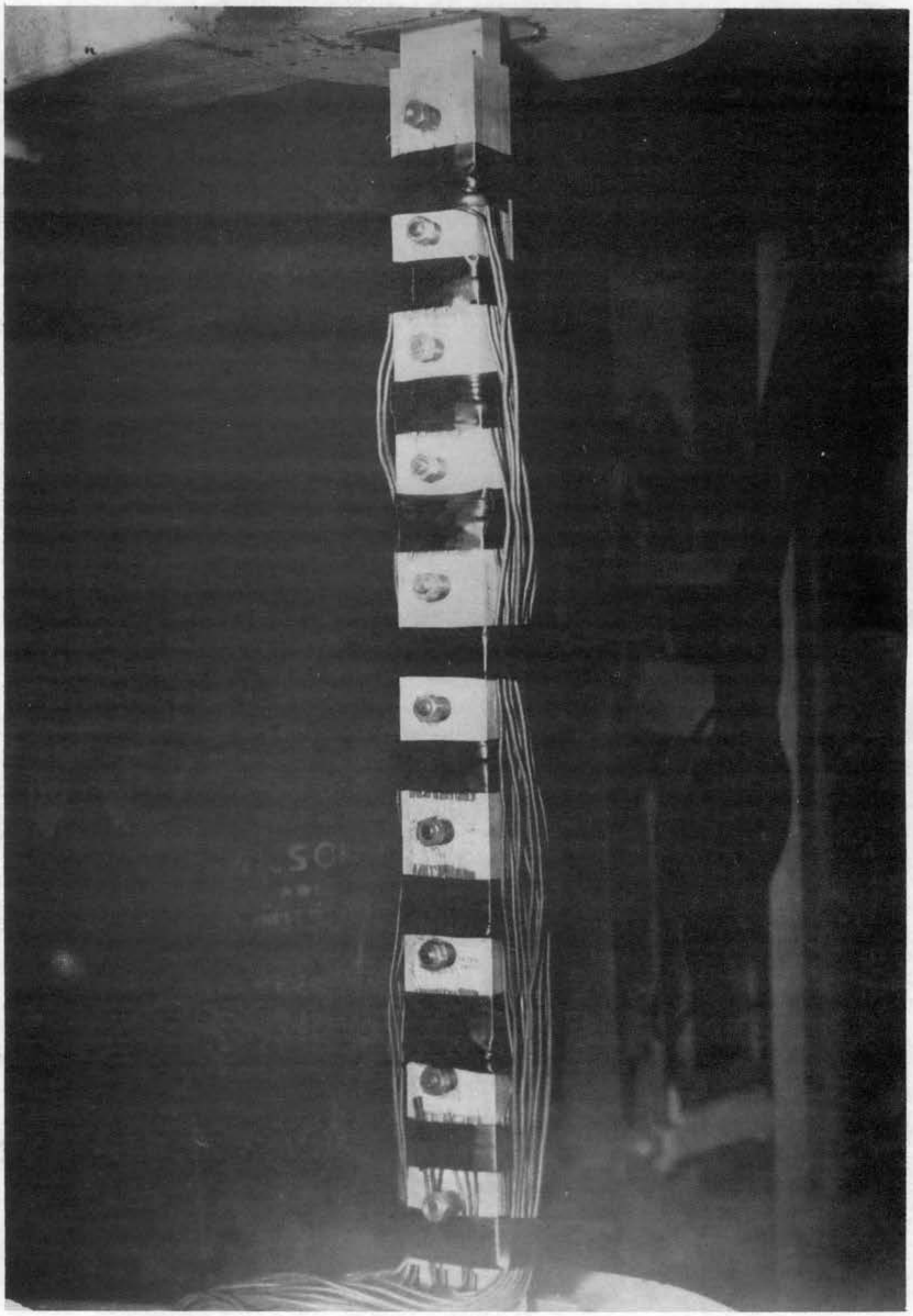
Test Model

The test model consisted of two double lap joints fastened by five fasteners each (Figure 3). The joint labeled "A" has clearances for equal bolt loading at a joint load of 23,000 pounds. The joint labeled "B" has the necessary clearances predicted for a 46,000 pound load. The two configurations were used in order to determine the bolt load distribution at loads above and below the design joint load.

The joints were doubled in order to avoid the bending moment inherent in a single lap joint due to eccentricity of load applications. The bending moment in the single lap

PIATE I

TEST MODEL



joint produced "waves" along the joint such that any strain measurement taken on the surface of one strap between two adjacent bolts would be considerably influenced. By doubling the joint, bending moments of opposite sign are introduced in the central plate and they cancel. Some "wave" shape is still present in the straps because of the bending moment introduced by the deflection of the bolts. However, no method was found for determining this effect. It appears that the amount of distortion in strain readings would be proportional to the load in the section. The actual bolt loads would then be proportional to the calculated loads. Thus, the bolt loads presented in the results need to be corrected by some small percentage. The lack of the correction does not, however, change the relative magnitudes of the bolt loads. Tate and Rosenfield (1) attempted to make this correction and found that at higher loadings, (near the yield point of the materials) the effect was considerable, as indicated by separation of the straps from the plate. In the present study no such separation was detected and it is concluded that the loadings were low enough that the bending effect was negligible.

The sizes of the straps and bolts were dictated by the availability of material, capacity of testing machine, and fabrication methods available. The straps were 0.250 inches thick by 1.750 inches in width. The plates were 0.500 inches thick by 1.750 inches in width. The bolts used were 0.250 inches in diameter by 2 inches in length. The bolts were threaded on both ends so that both ends would present the same deflection characteristics. A collar 3/8" long made of 1/4" black pipe was placed under each nut in order that sufficient threading was available for the nuts and that no threads would be in bearing contact with the straps.

The material of the plate and strap was 7075-T6 rolled aluminum plate. The specimens were cut from the plate so that the direction of the grain coincided with the load application. The edges of the straps and plates were milled to assure uniform width and straightness. The bolts were fabricated from commercial carbon steel of one percent carbon content. The bolts were then heat treated to gain hardness and strength. The heat treatment consisted of heating the bolts to 1440° F., quenching in oil, and tempering at 400° F. The heat treatment resulted in an average Rockwell hardness of 38.

All holes were drilled and all holes except those with 17 thousandths clearance were reamed to size. No reamer was available in the size necessary for the 17 thousandths clearances. In most cases, holes of the same size were aligned and finish reamed with one operation to assure uniformity.

Testing Procedure

In order to verify the predicted clearances, the bolt load distribution was determined. The load in the strap between adjacent bolts was determined by means of strain measurements and the load on each bolt was assumed to be the difference of the loads in the straps on either side of the bolt. The load in the free end of the strap was assumed to be zero and the load between the two joints was assumed to be the joint load.

Strain measurements were taken by means of electrical strain gages. Three gages were placed, as shown in Figure 3, half way between each pair of adjacent bolts. The gages were spaced at equal intervals across the plate. An attempt was made to determine the most advantageous placement of the gages - a line along which the three indicated strains would be nearly the same. Two tests were made on a steel lap joint similar to the test model, in which the strap surface stress levels and distribution was to be determined by brittle stress coating. The results were inconclusive; consequently, the placement used by Tate and Rosenfield (1) was used. They indicate that while this is not the best placement, the strains obtained should not vary more than twenty percent among the three gages. With variations in load of this amount or less, an average of the three loads (strains) should be representative of the section load.

The SR-4 strain gages were type A-5, 1/2" in length, and were applied according to manufacturers specifications.

An SR-4 bridge circuit was used in conjunction with a switching circuit to take the strain readings. The system indicates strain in microinches directly and from this and Young's modulus, the load in the section can be determined.

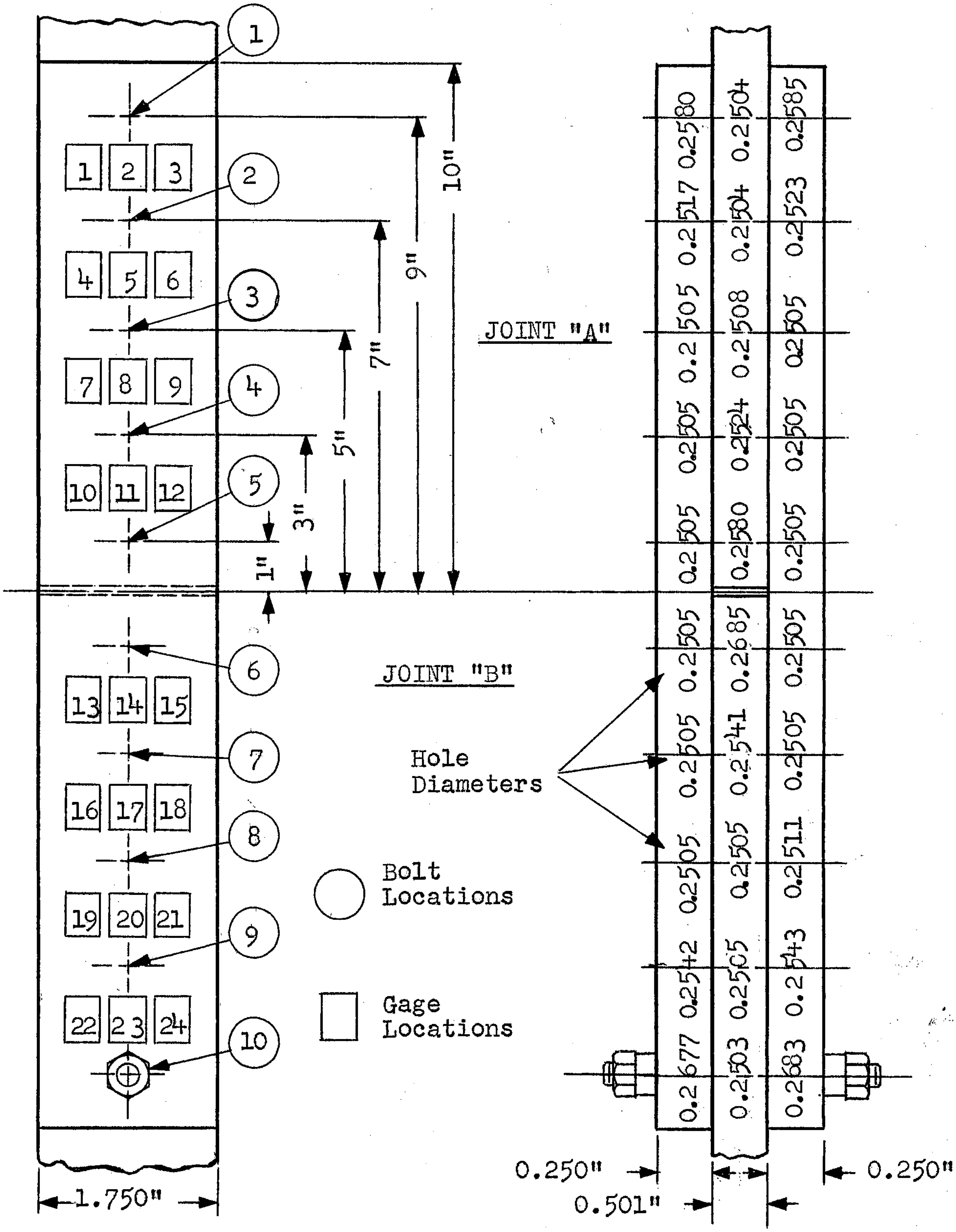


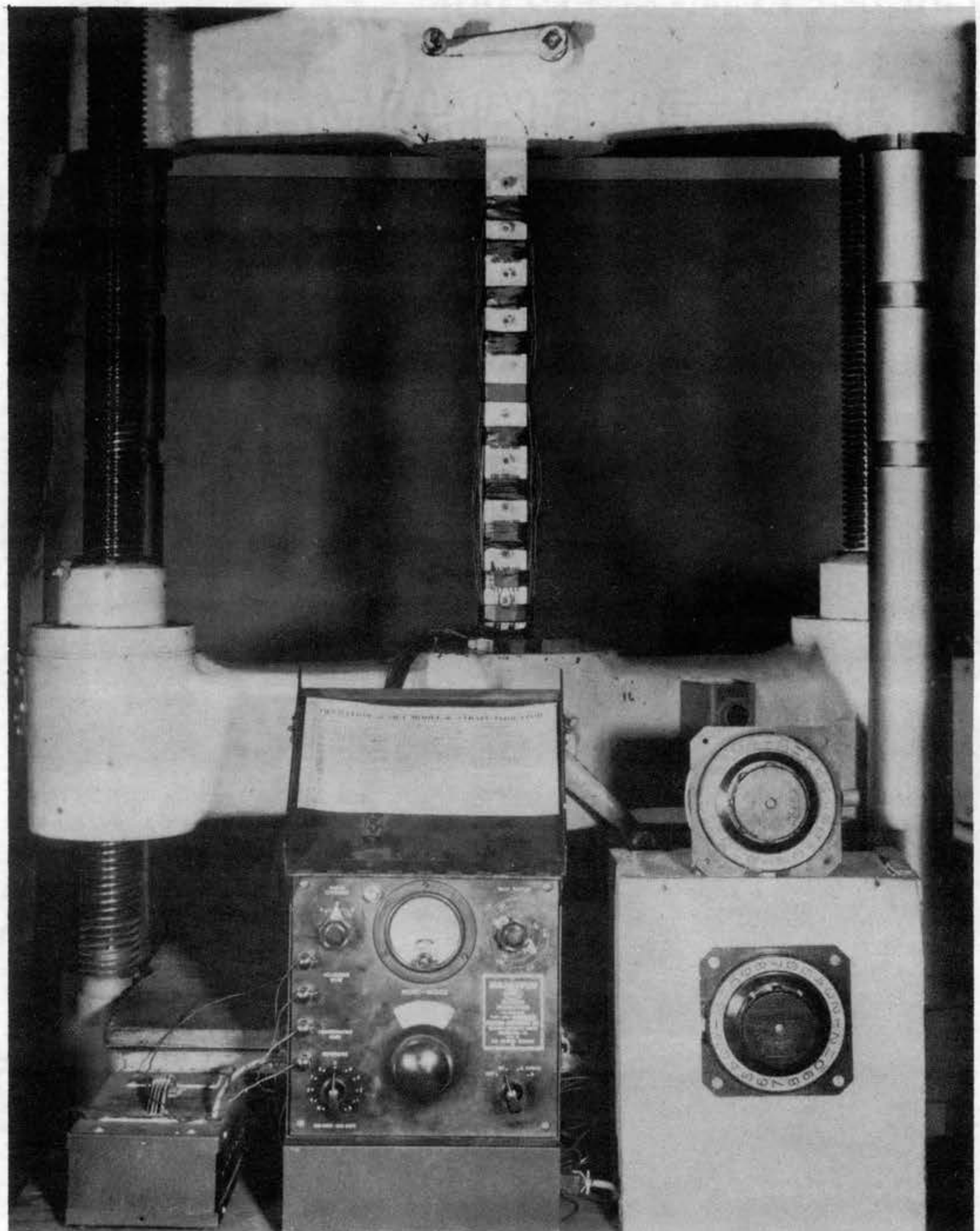
Figure 3. Test Specimen

The load was applied to the joint in a Baldwin Southwark hydraulic testing machine of 60,000 pounds capacity. The machine was calibrated in June, 1959 and the maximum error found was 0.38 percent. Plate II shows the test arrangement.

The load was applied in increments of 2,000 pounds over a range of from zero to 14,000 on the first two runs and from zero to 23,000 pounds on the last run. Subsequently, the specimen was loaded to failure at approximately 32,000 pounds. Measurements during the test consisted solely of the strain readings at various loadings.

PLATE II

EQUIPMENT ARRANGEMENT



CHAPTER IV

RESULTS AND CONCLUSIONS

Results

The load distribution, as indicated in Figure 4, did not become equal at the design load in either lap joint. One bolt in each joint carried considerably more than the others. In joint "A" at the design load, bolt 4 carried a load fourty percent greater than the design load.

On the four remaining bolts in joint "A", the greatest percentage deviation was approximately eighteen percent. This occurred on bolts 1 and 5 and was below the design load. Bolts 2 and 3 were loaded to within five percent of the design load.

The distribution in joint "B" was similar to that in "A" except that the deviations were more pronounced. Since the design loading was not reached, no comparison can be given concerning the accuracy of the predicted clearances. However, at intermediate loads, the deviation from an average load (joint load divided by number of bolts) was as much as sixty percent. This was above the average load. The deviation below average was considerably less — on the order of thirty percent.

The results of the continuation of the third run were somewhat erratic. The specimen ruptured at approximately 32,000 pounds. Bolt 4 failed at that loading and subsequently all four remaining bolts failed, some in shear, some in bending and some in tension.

Conclusions

Zero or equal clearance along a multi-fastener lap joint require greatest load on the outer bolts and least load on the center bolt. From the results of this study it can be concluded that the loads on the bolts can be equalized by varying the clearances along the joint. The derived relationship however, over-corrects for the inequality. One possible reason for this is the dependence of the slope of the bolt load-deflection characteristic on clearance.

The curves in Figure 5, Appendix B show that while the characteristic is primarily linear, its slope depends on clearance. The greater the clearance the greater deflection and the greater the apparent yield under a given load. Thus, bolts with the greater clearance (as predicted by the presented relationship) must be deflected a greater amount to carry the same load. The modification of the relationship to include this effect could be a subject for further study.

The unusually high loading on bolts 4 and 9 suggest that some fabrication inequalities are present on the fasteners. To check this, the holes were inspected and remeasured to see if the correct clearance had been applied. Discrepancies of less than eight ten-thousandths were noted in all cases. In addition bolt diameters were rechecked and the Rockwell "C" hardness of each bolt was determined to insure that no extraneous bolts had been used. The checks uncovered no discrepancies. The possibility of misaligned holes remains as the only possible explanation. No means was available for checking the hole alignment.

It can be concluded from the preceding discussion that the load distribution is very sensitive to slight discrepancies in fabrication. This, plus the indication that correct clearances for equal load distribution must be even smaller than those used in this test, indicates that the usefulness of this method of load distribution control is small, except for joints under high loads with five or more fasteners.

TABLE I

STRAIN READINGS IN MICROINCHES

Joint Load	Gage Numbers 1	2	3	4	5	6	7	8	9
Run 1									
0	5920	6910	6290	6850	7000	6300	6740	7270	7810
2,000	5970	6900	6300	6920	7050	6350	6850	7340	7780
4,000	6030	6950	6370	7030	7130	6470	7010	7480	7930
6,000	6060	6960	6390	7110	7190	6530	7120	7580	8040
8,000	6080	6940	6380	7140	7200	6550	7220	7640	8160
10,000	6170	6990	6440	7230	7290	6630	7350	7750	8300
12,000	6210	7030	6490	7320	7380	6740	7480	7890	8430
14,000	6250	7040	6530	7370	7420	6810	7580	7970	8520
Run 2									
0	5960	6930	6290	6890	7050	6330	6790	7270	7710
2,000	5940	6890	6260	6920	7040	6350	6860	7330	7730
4,000	5970	6910	6330	7020	7110	6440	7000	7430	7870
6,000	6080	6940	6370	7110	7160	6500	7090	7540	8000
8,000	6090	6970	6400	7170	7210	6560	7240	7640	8110
10,000	6180	6990	6430	7240	7280	6640	7350	7730	8240
12,000	6200	7020	6490	7320	7350	6720	7500	7850	8340
14,000	6240	7050	6550	7390	7420	6810	7580	7960	8460
Run 3									
0	5940	6920	6280	6860	7000	6310	6780	7240	7640
2,000	5970	6900	6270	6930	7050	6350	6850	7310	7700
4,000	5980	6900	6310	7010	7080	6410	7010	7410	7820
6,000	6050	6930	6350	7080	7160	6480	7100	7510	7930
8,000	6110	6960	6390	7160	7210	6540	7220	7620	8050
10,000	6140	6990	6450	7250	7280	6620	7340	7740	8170
12,000	6180	7030	6510	7330	7360	6720	7490	7850	8350
14,000	6220	7050	6540	7380	7420	6800	7580	7940	8450
16,000	6260	7100	6590	7480	7500	6890	7700	8060	8600
18,000	6330	7130	6640	7550	7580	6990	7820	8170	8710
20,000	6370	7160	6680	7650	7660	7110	8000	8310	8890
23,000	6440	7200	6730	7800	7780	7250	8200	8500	9150
Run 4									
0	5980	6960	6300	6900	7030	6310	6970	7330	7820
24,500	6380	7250	6750	7910	7960	7430	8460	8650	9330
25,500	6420	7230	6790	7980	7990	7450	8600	8720	9450
30,000	6480	7290	6800	8200	8220	7700	8900	9060	9770

TABLE I (Continued)

Joint: Load	Gage Numbers 10	11	12	13	14	15	16	17	18
Run 1									
0	7650	8130	7130	5840	6200	5820	6960	7760	8060
2,000	7870	8300	7350	5980	6450	6050	7130	7960	8200
4,000	8010	8520	7570	6200	6660	6290	7290	8100	8320
6,000	8300	8700	7770	6380	6840	6480	7460	8250	8490
8,000	8460	8840	7920	6600	7020	6650	7600	8400	8640
10,000	8650	9020	8120	6770	7200	6850	7740	8540	8760
12,000	8850	9200	8270	7000	7400	7010	7890	8700	8910
14,000	9100	9330	8450	7200	7520	7240	8030	8770	8990
Run 2									
0	7650	8130	7200	5730	6270	5890	7020	7820	8080
2,000	7870	8310	7350	5990	6490	6100	7190	8010	8230
4,000	8070	8490	7530	6200	6700	6280	7350	8150	8410
6,000	8290	8700	7740	6400	6860	6480	7510	8320	8570
8,000	8480	8860	7950	6600	7000	6630	7640	8430	8720
10,000	8660	9030	8110	6800	7230	6820	7780	8570	8810
12,000	8840	9200	8280	7020	7330	7020	7950	8700	8920
14,000	9030	9350	8500	7160	7570	7200	8070	8820	9060
Run 3									
0	7620	8090	7130	5790	6250	5850	7010	7830	8080
2,000	7890	8310	7330	6020	6480	6080	7200	8020	8250
4,000	8070	8480	7530	6290	6650	6280	7380	8170	8390
6,000	8290	8690	7750	6430	6880	6470	7550	8330	8580
8,000	8480	8830	7930	6630	7020	6620	7680	8490	8690
10,000	8660	9020	8100	6850	7180	6790	7820	8570	8840
12,000	8850	9190	8310	7030	7350	6990	7970	8700	8910
14,000	9030	9330	8460	7160	7520	7170	8100	8840	9070
16,000	9200	9500	8650	7380	7680	7350	8210	8970	9200
18,000	9400	9660	8850	7550	7830	7510	8350	9070	9320
20,000	9520	9830	9050	7720	8000	7700	8470	9190	9490
23,000	9870	10070	9260	8000	8230	7960	8670	9380	9600
Run 4									
0	7690	8160	7240	5560	6450	6030	7190	7970	8230
24,500	10100	9840	9580	8320	8580	8350	8960	9610	9890
25,500	10180	10350	9670	8490	8640	8330	9000	9610	9900
30,000	10630	10670	10020	8850	8940	8740	9260	9880	10160

TABLE I (Continued)

Joint Load	19	20	21	22	23	24
			Gage Numbers			
Run 1						
0	6230	5650	6210	5230	3910	5000
2,000	6300	5760	6240	5250	3940	4850
4,000	6500	5780	6330	5240	3930	4850
6,000	6610	5880	6440	5270	3930	4900
8,000	6730	5930	6530	5310	3980	4870
10,000	6850	6000	6580	5340	3960	4930
12,000	6930	6100	6670	5380	3960	4970
14,000	7030	6180	6700	5430	4010	4960
Run 2						
0	6290	5660	6150	5250	3950	5060
2,000	6390	5730	6240	5260	3950	4910
4,000	6530	5800	6350	5260	3930	4880
6,000	6640	5890	6430	5270	3920	4950
8,000	6720	5960	6530	5300	3930	4920
10,000	6850	6030	6580	5330	3950	4960
12,000	6980	6120	6630	5400	3980	5000
14,000	7070	6200	6750	5430	4000	5030
Run 3						
0	6280	5680	6130	5250	3950	4890
2,000	6400	5740	6230	5260	3950	4900
4,000	6550	5820	6330	5250	3940	4940
6,000	6650	5910	6440	5290	3930	4980
8,000	6770	5990	6540	5320	3950	4920
10,000	6850	6040	6570	5350	3960	4980
12,000	6960	6120	6650	5390	3970	4990
14,000	7070	6200	6730	5430	3990	5040
16,000	7190	6330	6860	5490	4030	5030
18,000	7280	6390	6930	5540	4070	5160
20,000	7390	6480	7000	5610	4120	5180
23,000	7550	6610	7150	5660	4160	5250
Run 4						
0	6450	5860	6280	5420	4130	5320
24,500	7770	6890	7370	5950	4460	5790
25,500	7760	6840	7330	5950	4420	5740
30,000	7970	7020	7520	6040	4500	5800

TABLE II

INDIVIDUAL BOLT LOADS

Joint Load	Bolt Locations 1	2	3	4	5	6	7	8	9	10
Run 1										
2,000	154	55	309	1338	144	117	336	910	937	-300
4,000	700	446	737	1729	388	90	1089	1247	1938	-364
6,000	882	874	1101	2785	368	422	1274	1756	2757	-209
8,000	846	1098	1765	3304	993	693	1665	2312	3267	63
10,000	1456	1274	2129	3877	1264	1019	2129	2794	3785	273
12,000	2093	1510	2466	4277	1654	1235	2512	3376	4359	518
14,000	2111	1984	2793	5160	1952	1561	3312	3613	4723	791
Run 2										
2,000	-336	372	419	1210	335	-93	546	728	1246	-427
4,000	91	819	700	1757	633	87	910	1183	2393	-573
6,000	637	882	1092	2694	695	390	1124	1847	3003	-364
8,000	846	1192	1665	3304	993	902	1429	2275	3758	-364
10,000	1327	1374	2002	3850	1446	1019	2193	2639	4231	-82
12,000	1665	1738	2421	4304	1872	1472	2493	3067	4604	364
14,000	2056	2039	2675	5060	2170	1743	3066	3340	5242	609
Run 3										
2,000	0	492	118	1390	0	-100	430	820	795	55
4,000	155	845	760	2000	240	-50	900	1250	1730	120
6,000	480	1200	700	3370	250	250	1070	1920	2332	328
8,000	975	1275	1490	3560	700	780	1320	2220	3380	300
10,000	1300	1680	1850	3990	1180	1100	1880	2860	3560	600
12,000	1760	2020	2400	4520	1300	1400	2500	3110	4105	785
14,000	2030	2301	2680	4980	2000	2000	2620	3580	4680	1120
16,000	2460	2800	2940	5600	2200	2300	3200	3050	5550	1400
18,000	2920	2990	3290	6200	2600	2800	3600	4210	5310	2080
20,000	3270	3570	4260	5600	3200	3200	3950	4400	5960	2490
23,000	3740	4360	4700	6500	3700	3850	4650	4700	7130	2670
Run 4										
24,500	3460	4990	4650	6500	4900	2600	6400	5050	6450	4000
25,500	3640	5180	5280	7700	3700	2900	7000	5400	6480	3720
30,000	4000	6800	6200	8000	5000	4300	7700	6100	7450	4450

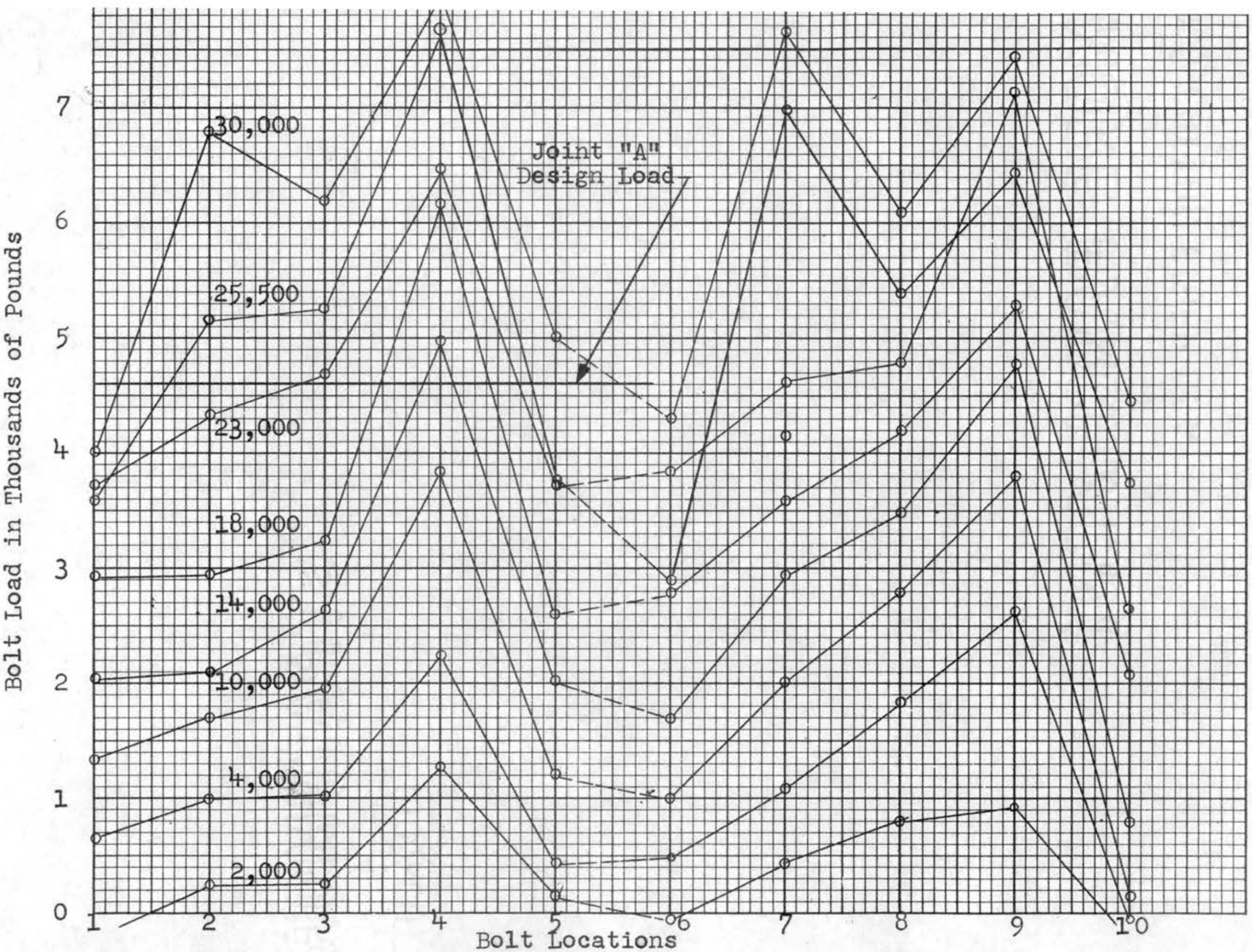


Figure 4. Bolt Load Distribution at Various Joint Loadings

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1. Tate, Manford B., and Samuel J. Rosenfield, "Preliminary Investigation of the Loads Carried by Individual Bolts in Bolted Joints," National Advisory Committee on Aeronautics, Technical Note 1051, May, 1946

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APPENDIX A

SAMPLE CALCULATION OF CLEARANCES

Given:
1. Joint load $P = 23,000$ pounds.
2. Stress area $A = (1.75)''(0.501)'' = 0.876$ sq. in.
3. Bolt spacing $m = 2$ in.
4. Number of bolts $N = 5$.
5. Modulus of elasticity $E = 10.4 \times 10^6$

$$C_i = \frac{2Pm}{NAE} \sum_{i}^{\frac{N-1}{2}} (N-2i) \qquad \frac{N-1}{2} = \frac{5-1}{2} = 2$$

Substitution of given values yields

$$C_i = \frac{(2)(23.000)(2)}{(5)(0.876)(10.4X10^6)} \sum_{i}^{2} (5-2i)$$

Bolt i	5-2i	$\sum_{i}^{2} (5-2i)$	C_i
1	3	4	0.00808
2	1	1	0.00202

APPENDIX B

DETERMINATION OF BOLT LOAD-DEFLECTION CHARACTERISTIC WITH CLEARANCE

To determine the effect of clearance on the bolt load-deflection characteristic, one bolt, butt joints were tested with various clearances. The clearances used were 0.0046", 0.018", and "infinite". The "infinite" clearance hole was obtained by removing material from the hole wall opposite the side in bearing contact. This allows unrestrained deflection of the bolt.

The configuration of the test models and the instrumentation of the test set-up is shown in Plate III. The models were made of 7075-T6 rolled aluminum plate and the bolts were fabricated from carbon steel drill rod and heat treated. The heat treatment consisted of heating to 1440° F., quenching in oil, and tempering at 400° F. The resulting Rockwell C hardness was approximately 38. The holes were drilled and the 0.0046" clearance hole was finish reamed. On assembly, 3/8" thick collars were placed under each nut to duplicate the bolt end action of an ordinary installation without collar, and allow the threaded portion of the bolt to be kept clear of the bearing area of the bolt.

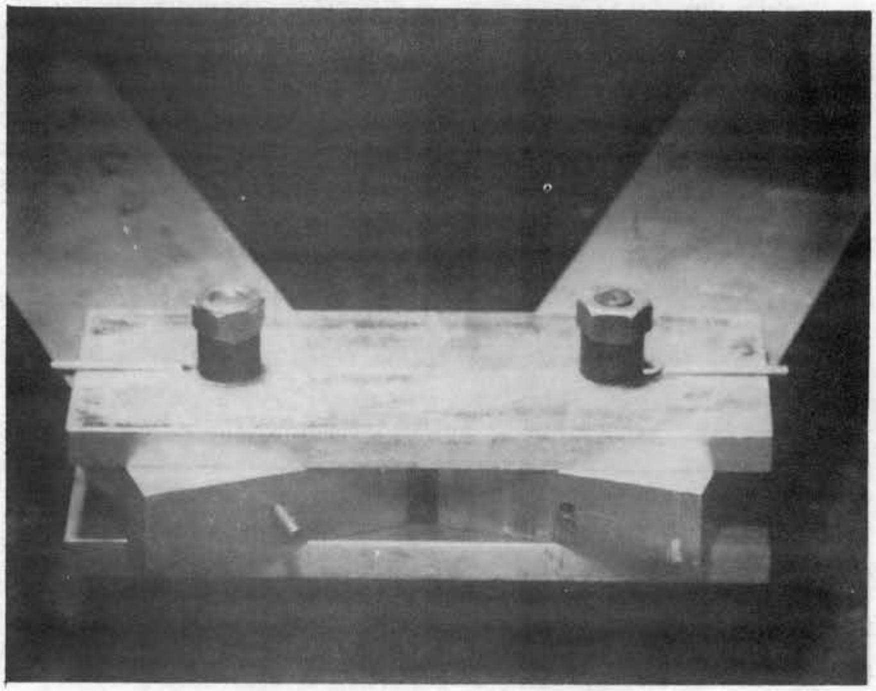
Slipping of the specimen in the jaws of the testing machine occurred during the first tests. Because of the method of measuring, absolutely no slippage between the specimen and the lower jaw could be allowed. Therefore, extensions of C 1010 commercial steel were attached to the ends of the specimen to provide a soft and positive gripping surface.

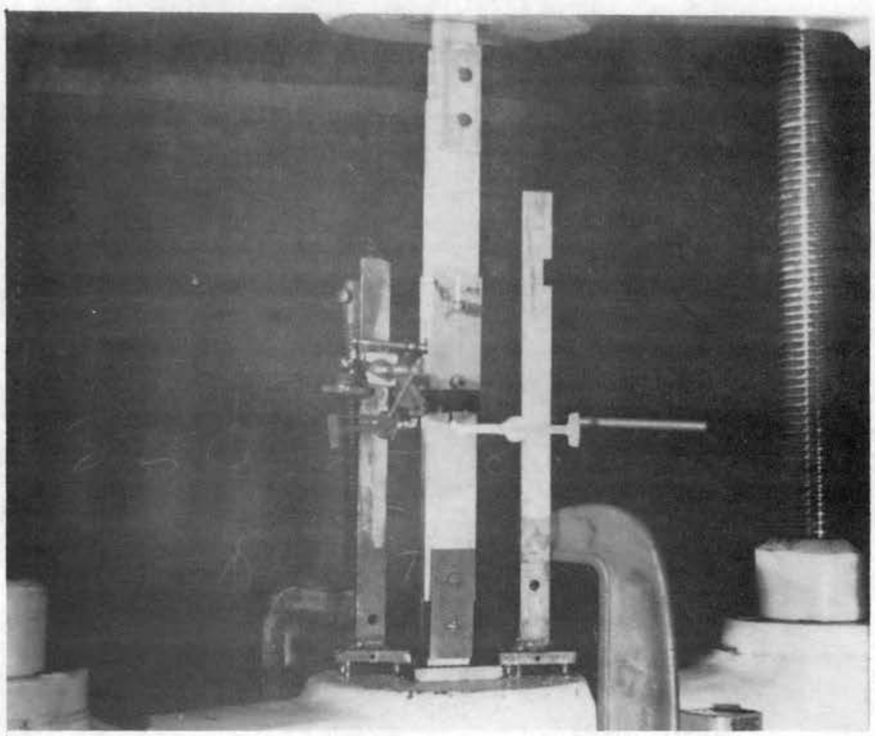
The deflections were measured directly with mechanical strain gages. Pins 3/32" in diameter were inserted in grooves in the straps and a hole in the plate in such a manner that they rested against the bolt. They were free to move so that any motion of the bolt would be transmitted through the pin to its free end. The strain gages were placed so as to indicate the axial movement of these pins. Caliper and dial gages as shown in Plate III were used. They were clamped to supports which were, in turn, clamped to the stationary bolster of the testing machine. Thus, the motion indicated by the gages was the motion of the three points on the bolt with respect to a common point — the bolster. By averaging the two bolt end movements and subtracting the bolt center movement, the deflection of the ends of the bolt with respect to the center was obtained.

Three runs were made on each specimen and the averaged results are shown in Figure 5. The load was applied in increments of 200 pounds over a range of 200 pounds to 3000 pounds. Readings at a load of 150 pounds were also taken and used as a zero reference since loadings of less than this allowed slippage of the specimen with resulting disruption of strain readings.

PLATE III

ONE BOLT TEST SPECIMEN AND TEST SET-UP





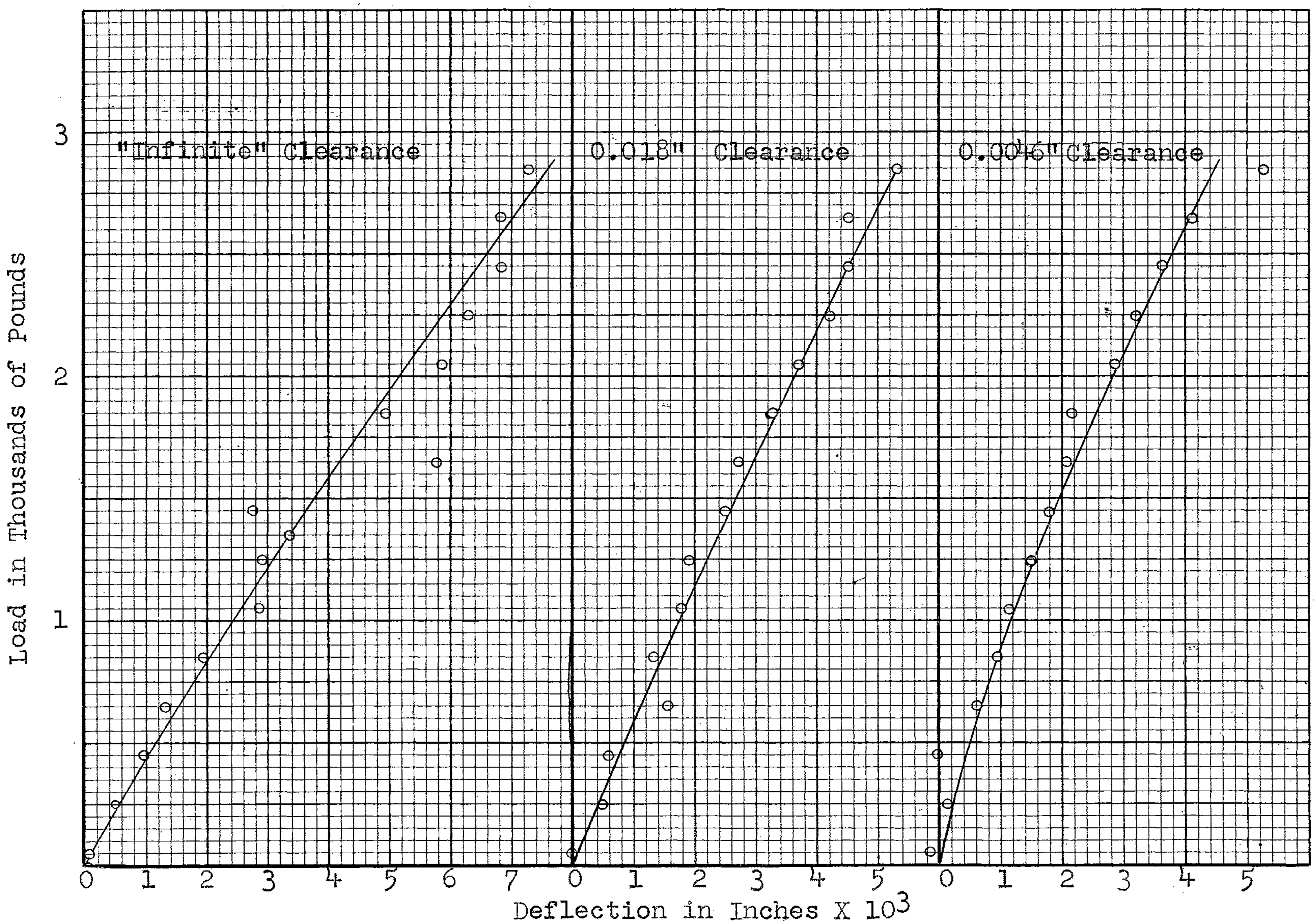


Figure 5. Load-Deflection Curves for 0.250" Diameter Bolt with Various Clearances

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