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THE FATIGUE CHARACTERISTICS OF BOLTED LAP JOINTS OF 24S-T ALCLAD SHEET MATERIALS

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SUMMARY

Fatigue tests have been conducted to determine the effect of bolt fit upon the lifetime of lap joints of 24S-T Alclad sheet of various thicknesses joined by steel bolts and designed for sheet failure under repeated loading.

Tests have been run in tension-tension and in tension-compression on specimens joined by one bolt and on specimens joined by several bolts having, for any one specimen, uniform fit. Bolt fit has been varied from a "press fit" to a "sloppy fit." Other variables have been examined briefly to determine their possible importance.

The most outstanding result is the relative unimportance of bolt fit. It appears that bolt fit has no pronounced influence on joint lifetime under unidirectional loading. The direct influence of bolt fit on lifetime under reversed loading also seems to be slight. While, from these tests, bolt fit does not appear to influence fatigue strength, it should be emphasized that loose-fitting bolts permit objectionable slip and joint deflection and are undesirable, especially for joints under reversed loading.

It has been observed that the use of two or more bolts in line with the load increases the fatigue strength, but not in proportion to the number of bolts used.

It has been observed that, for a given bolt diameter and a given bolt pattern, the fatigue strength of bolted lap joints does not increase in proportion to the sheet gage used.

These conclusions should be limited, for multibolt specimens, to cases where all bolts in any specimen have the same fit.

INTRODUCTION

Data have been reported on the fatigue properties of steel plates joined by steel rivets and on the properties of sheets of light-metal alloys joined by aluminum-alloy rivets. (See, for example, references 1 and 2.) However, little information is available concerning the fatigue properties of sheets of light-metal alloys joined by hard steel bolts. This report presents the results of an investigation on the behavior, under repeated loading, of bolted lap joints of 24S-T Alclad sheet materials.

The main objectives of the investigation have been to find out to what extent the fatigue strength of bolted lap joints is affected by such factors as: bolt fit, number and arrangement of bolts, and sheet gage (for a given bolt diameter). "Fatigue strength" here means the load sustained to complete fracture at some lifetime under tension-tension (at R = minimum/maximum load = +0.25) or under tension-compression (at R = 0.50).

The important factor of bolt fit has been examined by testing otherwise similar specimens with bolt holes of different clearances. Nominal clearances of -0.001, +0.002, +0.010, and +0.025 inch have been used. It has been a major objective to learn whether extremely close bolt fits are needed to obtain maximum life of bolt joints under repeated stresses.

Several types of bolt patterns have been tested: single-bolt specimens, specimens with two bolts in line with the load, specimens with three bolts in line with the load, specimens with a single row of three bolts, specimens with two rows of three bolts each, and specimens with three rows of three bolts each. In general, all bolts, in any multi-bolt joint, had the same fit. Nearly all test pieces were joined with 3/8-inch-diameter steel bolts of aircraft quality (AN6). The unthreaded length of the bolts was such that the bearing was on the smooth shank of the bolt.

Specimens of 0.102-, and 0.250-inch sheet have been tested both at the Battelle Memorial Institute and at the

University of Illinois and, thus, permit comparison of results obtained on different machines and in different laboratories. Specimens of intermediate sheet thicknesses (0.125, 0.156, and 0.187 in.) have been tested only at the Battelle Memorial Institute; while specimens of 0.375-inch sheet have been tested only at the University of Illinois.

About 950 specimens were used in the investigation. The greatest number for any one sheet gage was 400 for the 0.102-inch sheet. Fairly extensive tests were made for two other sheet gages (0.187 and 0.375 in.), and fewer tests for sheets of the other thickness.

This investigation, performed jointly by the Battelle Memorial Institute and by the University of Illinois, was sponsored by, and conducted with the financial assistance of, the National Advisory Committee for Aeronautics.

MATERIALS AND TEST METHODS

Materials

Sheets of 24S-T Alclad, each 4 by 12 feet, were obtained from the Aluminum Company of America. Table 1 gives some measured mechanical properties of the sheet materials and indicates that these were within standard values. In all cases, pieces used for the bolted lap-joint test specimens were cut in the direction of rolling.

For the most part, the bolts used were hexagonal-headed 3/8-inch-diameter steel bolts of aircraft quality (AN6-6, AN6-7, and AN6-11). One lot (of AN6-11) had notably less taper in the unthreaded shank (about 0.0002-in. change in diameter to within 1/32 in. of the bolt head), and these bolts were used rather extensively. Further details of bolts used in special cases are given in the text.

Test Pieces

Figure 1 shows the specifications of the test sections of specimens with various bolt patterns. Test pieces used at both laboratories had identical test sections, and differed only in the length of the reduced section and in details of grip ends. These details are described in the appendixes.

Table 2 shows typical tolerances used in fitting the bolts. The values quoted represent measurements on about 150 actual test pieces.

Except in a few instances, specifically noted in the text, the initial bolt torque was from 105 to 110 inch-pounds on each bolt. This value is within the range recommended for these bolts. (See reference 3.)

Table 3 gives values of static-failure loads for test pieces of the type used in the fatigue tests. It may be noted that:

1. There is no certain evidence of an effect of bolt fit upon static strength.
2. Increasing the number of bolts in the direction of loading increases the joint strength (up to three bolts) but decreases the load per bolt.
3. The static-failure load for a given type of specimen increases with increasing sheet gage.

Figure 2 shows typical sheet failures of single-bolt specimens broken in static tests. These are similar to failures reported for pin-bearing tests of aluminum-alloy sheets (reference 4). Figure 3 shows static failures of some multibolt specimens.

Machines and Testing Methods

Details of the testing machines and methods used in this investigation are given in the appendixes. Only brief summaries are included here.

Fatigue tests at the Battelle Memorial Institute were made on Krouse, Direct Repeated-Stress Machines of two capacities: (1) 4000-pound machines running at 1500 cycles per minute, and (2) 10,000-pound machines running at 1200 cycles per minute (occasionally at 600 cpm). Loads were corrected for dynamic inertial effects and were set and maintained to about ±3 percent.

For the 0.102-inch sheet specimens tested at the University of Illinois, three Moore-Krouse tension-compression machines were used. Each had a load capacity of 3200 pounds. Some tests were run at 1000 cycles per minute, but most tests at 600 cycles per minute.

Two types of machines were used in the tests of joints in 0.250-inch sheet and joints in 0.375-inch sheet. One is a direct-acting machine of 15,000-pound capacity and was operated at about 600 cycles per minute. The other is a lever-type machine and ran at approximately 300 cycles per minute. Special precautions were taken to minimize flexure of the test piece.

Details of gripping and loading specimens are also given in the appendixes. There were no particular difficulties concerned in tension-tension test. In reversed-loading tests, precautions were taken to minimize bending stresses during the compression part of the cycle. Two general schemes were used:

1. All specimens of 0.102-inch sheet tested at the University of Illinois were constrained from bending by guide plates. Most of the 0.102-inch sheet specimens, and some specimens of thicker gage, tested at the Battelle Memorial Institute, were similarly constrained.

2. Specimens of thicker sheet were generally tested with short unsupported lengths, or were supported laterally with rods normal to specimen and containing a plate fulcrum at each end, as shown in figures 60 and 61.

The guide-plate method was adapted from that developed at the National Bureau of Standards (reference 5). Some data, taken on similar specimens by both methods, agree within the precision of testing. (See Appendix 1.)

FATIGUE TEST RESULTS FOR BOLTED LAP JOINTS IN UNIDIRECTIONAL LOADING

Joints in 0.102-Inch Sheet

Tables 4, 5, 6, and 7 and figures 4 and 5 show the results of fatigue tests (at R = minimum load/maximum load = +0.25) made at the Battelle Memorial Institute on specimens of 0.102-inch sheet. In particular, figure 4 shows, on a load-life diagram, results of tests on single-bolt specimens and of tests on specimens with three bolts in the line of loading. Figure 5 shows results of tests on specimens with two bolts in the line of loading and of tests on wide specimens having three bolts in a row transverse to the direction of loading.

Tables 8 and 9 give the results of tests at the University of Illinois on single-bolt specimens. Tables 10 and 11 give results of tests, made at the University of Illinois, on specimens having two bolts in the direction of loading and on a few wide specimens having three bolts in a row transverse to the direction of loading. These data are plotted on load-life diagrams in figure 6 (single-bolt specimens) and figure 7 (two-bolt specimens). The few results of tests on three-bolt specimens have not been plotted; these results conform closely to those obtained at the Battelle Memorial Institute. (See fig. 5.)

In each figure, actual test values are indicated by points with different symbols to designate different bolt fits. A full-line curve, drawn through each set of points, represents an "average" load-life curve for the corresponding type of joint. Comparison of strength of joints of different bolt patterns and, later, of joints in different thicknesses of sheet will be made from these average curves.

Within the scatter of points for any one type of joint, the results plotted in figures 4, 5, 6, and 7 show little evidence of an effect of bolt fit upon fatigue strength.

Figure 8 shows fatigue failures for specimens of 0.102-inch sheet tested at the Battelle Memorial Institute. A fatigue crack always started either at the edge of a bolt hole (fig. 8A) or near a bolt hole in some region showing abrasion (fig. 8B) due to the bolt head or washer pressing against the sheet. These two types of failure appeared about equally often, and there seemed to be no correlation of lifetime with the position of the inception of the fatigue crack. Figure 8C shows typical progression of cracks between bolt holes and from bolt hole to edge of specimen. Similar failures were obtained in the tests made at the University of Illinois.

Joints in 0.125-Inch Sheet and Joints in 0.156-Inch Sheet

Results of tests at $R = +0.25$ on specimens of 0.125-inch sheet are given in tables 12 and 13 and are plotted on load-life diagrams in figure 9. Two specimen types were used: single-bolt specimens and specimens having three bolts in the line of loading.

Table 14 gives results and figure 10 shows a load-life curve for single-bolt specimens of 0.156-inch sheet.

These results show no definite effect of varying the bolt clearance from +0.002 to +0.010 inch. Fatigue failures were like those shown (in fig. 8) for specimens of 0.102-inch sheet.

Joints in 0.187-Inch Sheet

Tables 15, 16, and 17 give the results of tests on bolted joints of 0.187-inch sheet. Figure 11 shows the results of tests on single-bolt joints. Figure 12 shows results of tests on specimens having two bolts in the direction of loading and of tests on wide specimens having a transverse row of three bolts. The results indicate little effect of bolt fit upon fatigue strength. Failures were similar to those already described for thinner sheet.

Joints in 0.250-Inch Sheet

Tables 18 and 19 and figure 13 show results of tests on lap joints of 0.250-inch sheet fastened by single bolts. It may be noted that the few values obtained at the Battelle Memorial Institute show higher strength for lifetimes around 10^5 cycles than values obtained at the University of Illinois. Careful examination of testing records gives no explanation, and further tests would be needed to resolve the discrepancy.

The two bolts fits used for the 0.250-inch sheet caused no significant difference in fatigue strength.

Joints in 0.375-Inch Sheet

Tables 20, 21, 22, 23, and 24 and figures 14, 15, 16, 17, and 18 show results of fatigue tests at $R = +0.25$ on specimens of 0.375-inch sheet having, respectively, one bolt, two bolts in line with the load, three bolts in line with the load, two transverse rows of three bolts each, and three transverse rows of three bolts each. These results indicate little evidence of an effect of bolt fit upon fatigue strength under unidirectional loading.

Figures 19 and 20 show typical fatigue failures of bolted joints of 0.375-inch sheet. All fatigue failures were in the sheet (in contrast to some static failure by shearing bolts), and fatigue cracks started either at the edge of a bolt hole or at a region, near a bolt hole, showing evidence of abrasion by bolt head or washer.

FATIGUE TEST RESULTS FOR BOLTED LAP JOINTS

IN REVERSED LOADING

Joints in 0.102-Inch Sheet

Table 25 gives the results of tests at $R = -0.50$ made at the Battelle Memorial Institute on single-bolt specimens of 0.102-inch sheet. Figure 21 shows these results on a load-life diagram. Joints having loosely fitting bolts do not appear significantly stronger in these tests than joints with snugly fitting bolts. However, it should be noted that there are relatively few points in figure 21 for joints with loosely fitting bolts tested at relatively high load values. This reflects difficulties (discussed in a later section) of running reversed-load tests on joints with loosely fitting bolts.

Tables 26 and 27 and figure 22 show results of the Battelle Memorial Institute tests at $R = -0.50$ on specimens with two bolts in line with the load and on wide specimens having a transverse row of three bolts.

Figures 23 and 24 are load-life diagrams containing results of tests at the University of Illinois on single-bolt specimens and on two-bolt specimens. Data, from which these graphs are plotted, are given in tables 28 and 29.

None of the test results indicates any direct influence of bolt fit upon fatigue strength at $R = -0.50$. In most cases, however, the absence of many points for specimens with loosely fitting bolts is significant of indirect influence of bolt fit.

Fatigue failures for specimens tested at $R = -0.50$ were generally similar to those already described for tests at $R = +0.25$.

Joints in 0.125-Inch Sheet and Joints in 0.156-Inch Sheet

Tables 30 and 31 and figure 25 show results of tests on single-bolt specimens of 0.125-inch sheet and of 0.156-inch sheet. These tests were made at the Battelle Memorial Institute.

Joints in 0.187-Inch Sheet

Tables 32 and 33 give results of tests made at the Battelle Memorial Institute on bolted joints of 0.187-inch sheet.

Figure 26 is a load-life diagram for single-bolt specimens. Only specimens with tightly fitting bolts were able to be tested at high loads (causing failure in less than 10^5 cycles). A few specimens with loosely fitting bolts were tested at low loads and showed no significant difference in lifetimes under low loads.

Figure 27 shows results of tests on specimens having two bolts in the line of loading. Note that several specimens with bolt clearances of 0.050 inch were tested and showed lifetimes as long as those for specimens with good-fitting bolts.

Limitations of the testing machines made it impracticable to test specimens of 0.187-inch sheet with more than two bolts.

Joints in 0.250-Inch Sheet

Table 34 and figure 28 show results of fatigue tests (at the Battelle Memorial Institute) at $R = -0.50$ on single-bolt specimens of 0.250-inch sheet. Only two bolt fits were used: a "tight" fit (0.000- to 0.001-in. clearance) and a "drill" fit (+0.002-in. clearance). No difference in fatigue strengths resulted.

Joints in 0.375-Inch Sheet

Tables 35, 36, 37, and 38 give results of tests at $R = 0.50$ made at the University of Illinois on bolted joints of 0.375-inch sheet.

Figures 29, 30, 31, and 32 show the results of tests on specimens having, respectively, two bolts in line with the load, three bolts in line with the load, two transverse rows with three bolts in each row, and three transverse rows with three bolts in each row. For each specimen type, press-fit bolts (about 0.001-in. press) were used. For one pattern (three rows of three bolts each), specimens having bolt fits of 0.025 inch also were tested. Figure 32 indicates that these specimens with loosely fitting bolts were as strong in fatigue as specimens with tightly fitting bolts. However, the absence of other tests with loosely fitting bolts is significant. Attempts to test specimens having two bolts or three bolts (Types B and C, fig. 1) with "loose" fits were unsuccessful. Bolt slip caused difficulty in maintaining the range of load and, in some cases, led to failure of bolts.

Fatigue failures for the tests indicated in figures 29, 30, 31, and 32 were all sheet failures and were like those for unidirectional tests. (See figs. 8, 19, and 20.)

RESULTS OF AUXILIARY TESTS

The preceding sections of this report contain the experimental results of tests planned in the original program of research. As the investigation proceeded, it appeared desirable to make certain auxiliary tests. The results of such additional experiments are given in this section.

Some of the auxiliary tests were planned to examine very briefly possible effects of factors (such as type of bolt, bolt torque, and bolt size) which had been intentionally held constant during major portion of the investigation. Other tests (fatigue tests of unnotched and of notched sheet material, measurements of friction in bolted lap joints, and measurements of bolt slip during fatigue testing) sought more complete understanding of the fatigue properties of bolted lap joints.

Each of these auxiliary tests was brief; so the resulting data are sufficient only to outline possible trends. Nevertheless, certain of the results suggest important limitations that should be kept in mind in applying any conclusions from this investigation to practical aircraft design problems.

Joints with Countersunk Bolts

The original program for this investigation included several tests with countersunk steel bolts. However, it was found difficult to obtain such bolts with smooth shanks. A very few, obtained through the courtesy of the Curtiss-Wright Corporation, were used to make some single-bolt specimens of 0.156-inch sheet.

Figure 33 indicates the types of specimens (with bolts countersunk entirely through the top sheet so as to give a flush surface, and with bolts countersunk half as deeply), and shows the results of fatigue tests in unidirectional loading (at R = +0.25). The test data are given also in table 39. These tests indicate that countersunk bolts may produce joints considerably weaker in fatigue than joints made with hexagonal-headed bolts.

Joints with Bolts Drawn to High Initial Torques

For all tests described so far, each bolt was initially tightened by a torque wrench to 105 to 110 inch-pounds. Several specimens assembled with higher bolt torques have been tested in fatigue to determine, briefly, possible effects on fatigue strength.

Several single-bolt specimens of 0.102-inch sheet were assembled with 180 inch-pound initial bolt torque and tested in unidirectional loading (at R = +0.25) with the following results:

Bolt clearance	Load	Life[1] 180-in.-lb torque	Life[1] of similar specimen with 108-in.-lb torque
(in.)	(lb)	(cycles)	(cycles)
-0.001 to 0.000	2500	64,700	40,000 to 120,000
+.002	2500	94,100	70,000 to 160,000
+.002	1150	1,638,100	700,000 to 1,600,000
+.010	2900	41,000	40,000 to 100,000
+.025	2700	77,100	60,000 to 120,000
+.025	950	1,057,400	1,000,000 to 4,000,000

[1] Life estimated from scatter bands of data given in table 4.

Thus, within the precision of testing, there appeared to be no effect of increasing the bolt torque. Measurements, described later, showed the increased bolt torque did increase the static frictional force between the lapped sections.

In reversed-load testing (at $R = -0.50$), higher torques decreased difficulties of testing single-bolt specimens with loosely fitting bolts. This is illustrated in figure 34, which shows data from table 40 and a load-life diagram. Single-bolt ("loose fit") specimens could be run at successively higher maximum load values, provided higher initial torques were used. Comparison with the curve in figure 21 (showing high load values for specimens with tight-fitting bolts) shows no increase in lifetime due to the increased torque.

Joints with Bolts of Different Diameters

The tests so far described have included specimens of several sheet gages, but joined only by 3/8-inch-diameter bolts. Single-bolt specimens of 0.125-inch sheet were made using two additional bolt sizes: (1) 7/16-inch-diameter bolts machined from cold-rolled hexagonal steel bars, and (2) 1/4-inch-diameter commercially hardened steel bolts. These specimens were tested in fatigue at $R = +0.25$, and the results are given in table 41 and indicated on the load-life diagram of figure 35.

Fatigue strengths, at $R = +0.25$ and at various lifetimes, are tabulated in table 42 in terms of D/t (ratio of diameter of bolt to thickness of sheet). From these few tests, it appears that the fatigue strength of a bolted lap joint varies both with the D/t ratio and with the sheet thickness. These results are, however, insufficient for definite conclusions.

Multibolt Joints with Nonuniform Bolt Fit

Table 43 gives the results of fatigue tests at $R = +0.25$ made at the Battelle Memorial Institute on specimens of 0.102-inch sheet having two bolts (one tight fit and one loose fit) in the direction of loading. Comparison with the values given in table 5, and plotted in figure 5, shows that the specimens with nonuniformly fitting bolts had about the same fatigue strength as similar specimens with uniformly fitting bolts.

Table 44 shows the results of tests at the University of Illinois on specimens having three bolts in a transverse row (the center bolt being tight fit and the outer bolts sloppy fit). Figure 36 shows these results in comparison with results for specimens containing all tight-fit bolts. It appears that the joints having nonuniformly fitted bolts were weaker in fatigue than joints with uniformly fitted bolts.

Fatigue Strength of the Sheet Material

Table 45 gives the results of fatigue tests made at the Battelle Memorial Institute on specimens of 0.102-inch sheet both unnotched and notched by a single 3/8-inch hole. Tables 46 and 47 give the results of tests made at the University of Illinois on unnotched sheet specimens and on sheet specimens notched by bolt holes. Details of the specimens used are given in the appendixes. No unusual failures occurred in these tests.

Figure 37 shows the results of the tests on unnotched sheets, and figure 38 shows results of tests on notched sheet specimens.

Some pin-bearing fatigue tests were made at the Battelle Memorial Institute on specimens of 0.102-inch sheet. Results of these tests are tabulated in table 48 and plotted on a load-life diagram in figure 39.

These tests on the sheet material were made in consideration of the possibility of treating bolted joints as stress raisers in a material of known notched-fatigure characteristics. The results are discussed from this point of view in a later section of this report.

Friction in Bolted Lap Joints

The friction between the lapped sections of bolted-joint specimens was evaluated roughly by a simple test. Specimens, made with slightly elongated bolt holes, were loaded in static tension. The load values at which bolt slip appeared are recorded in table 49.

It should be noted that such values correspond to a "static" friction which is probably not often realized under repeated loading. However, the values noted in table 49 indicate that frictional forces of appreciable magnitudes, with respect to fracture load values, may exist.

Bolt Slip during Testing

Table 50 shows some measurements of the elongation of bolt holes due to stresses during fatigue testing. These values are the increase in longitudinal diameters of the bolt holes measured after failure on the bolt hole of the uncracked half of each test piece.

An extensometer, using SR-4 electrical resistance gages, was designed to measure joint slip during testing. Results of such measurements are shown in table 51. This measurement included several factors: strain in the metal, play due to initial looseness of bolt fit, and elongation of bolt holes. The "computed" values for bolt-hole elongation neglected the strain in the metal and allowed only roughly for play due to initial bolt-looseness. An indication that these computed values are reasonable is the close agreement of final computed elongations and elongations measured after failure. The results suggest that most of the elongation of the bolt hole takes place during the first few (1 to 10) cycles of loading.

Incidentally, the strain-gage extensometer in combination with a dynamic load-measuring device on the testing machine afforded means of making load-deflection measurements during testing. Figure 40 shows the result of such a measurement. This nonlinear load-deflection characteristic sometimes contributed to severe vibration of the testing machine. Table 52 indicates conditions under which vibration of one machine became so severe that tests were stopped. These observations pertain to the reaction on a particular testing machine. Nevertheless, it is believed they indicate a possible danger of bolted joints under reversed loading. The danger appears to be not so much premature failure of the joint in question as undue load reaction on other joints and parts attached to that joint.

Another characteristic result of bolt-hole wear and bolt slip in reversed-load testing was the difficulty of maintaining load values desired. Figure 41 shows the load values measured for single-bolt specimens purposely run to 1,000,000 cycles at constant deflection. Apparently, the joint with the loosely fitting bolt showed a marked tendency for falling off of load. Figure 42 shows photographs of these specimens after 1,000,000 cycles. The increase of abrasion with increasing initial bolt clearance is obvious.

DISCUSSION OF RESULTS

Comparison of Results from the Two Laboratories

Detailed examination of the results of all fatigue tests on bolted lap-joint specimens shows that both laboratories found no significant direct effect of bolt fit upon lifetime of a given joint under a given load.

Figures 43, 44, 45, and 46 show results from the two sources on specimens of 0.102-inch sheet. In each of these load-life diagrams, test results for all specimens of a given type (regardless of bolt fit) are designated by one symbol for tests made at the Battelle Memorial Institute, and by another symbol for tests made at the University of Illinois. In general, the test results from the University of Illinois show shorter lifetimes for high loads than those from Battelle Memorial Institute. However, in tests for which lifetimes approach 1,000,000 cycles, the differences become much smaller. Throughout the whole range of tests, the "scatter bands" of the load-cycle diagrams from the two laboratories overlap by a considerable amount. The discrepancies between the results from the two laboratories, if they are real, may be due to differences in unsupported lengths of test pieces and to slight departures from axiality of loading.

The only other sheet gage for which specimens were tested at both laboratories was 0.250 inch. Results of these tests have been shown in figure 13. Results from the two laboratories agree well at the ends of the curve (10,000 and 1,000,000 cycles), but the few Battelle Memorial Institute results available show high loads for failure near 100,000 cycles.

In a later section of this part of the report are graphs of fatigue strength versus sheet gage. The smoothness of these curves implies that test results for intermediate gages fit well into a general picture, and this adds confidence that there were no major discrepancies between tests at the two laboratories.

The Effect of Bolt Fit on Fatigue Strength

Most test results found in this investigation have shown no pronounced effect of bolt fit upon fatigue strength, as indicated by load-life values. This conclusion must not be extended beyond the limitations of the test conditions.

In the first place, tests have been made only upon lap joints of 24S-T sheets fastened by steel bolts. It has been noted that the hard steel bolts Brinelled the relatively soft sheet so as to cause elongation of the bolt hole within a very few cycles of the repeated load. Apparently, the bolt holes are deformed to an equilibrium condition dependent upon the loading, and the strength of this equilibrium condition seems independent of initial bolt fit. It should also be pointed out that the results show greater scatter for tight fits than for loose ones. It may well be questioned whether steel bolts in steel sheets or aluminum-alloy bolts in aluminum-alloy sheets would behave in a similar manner.

Secondly, the criterion of failure for the tests reported here has been visible cracking of the sheet material or complete fracture of the joint. No other seriously undesirable effect was noted in the unidirectional-loading tests. But, in reversed-loading tests, bolt slip caused considerable falling-off of load and severe vibration of testing machines. These effects were more serious for joints with loosely fitting bolts than for joints with snugly fitting bolts. It has been pointed out, in several cases, that it was impracticable to run single-bolt specimens with loosely fitting bolts under high reversed-load conditions. Such observations imply that loosely fitting bolts are definitely undesirable under reversed loading.

In general, multibolt specimens have had the same clearance for every bolt in a given specimen. Conclusions from such tests should not be extended without further considerations to a joint having a long row of differently fitting bolts.

It should be noted, further, that these tests have been limited to axial loading with precautions to avoid flexure. Service loadings are seldom this simple, and it is not certain how far conclusions from the axial-loading tests apply to more complex loading conditions.

Variation of Fatigue Strength with Sheet Gage

Figure 47 shows maximum loads, for several lifetimes at $R = +0.25$, plotted against sheet gage used for single-bolt lap joints. Figure 48 shows similar plots for joints having two bolts in line with the load, while figure 49 and 50 show results for loading at $R = -0.50$. In all cases, the "points" in figures 47 to 50 are obtained from the smooth curves drawn through experimental points on load-life diagrams previously shown.

Both fatigue strength and static strength of a bolted lap joint, with a given bolt pattern and bolts of given diameter, increased with increasing thickness of sheet used in making the joint. The rate of increase in fatigue strength at a given load ratio and for a given lifetime is less than the rate of increase in static strength. Thus, from figure 48, a two-bolt joint of 0.200-inch sheet would be nearly twice as strong in static tests as a single-bolt joint of 0.100-inch sheet. However, in fatigue (at 10^6 cycles at $R = +0.25$) the 0.200-inch-sheet joint would be only 45 percent stronger than the 0.100-inch-sheet joint.

Thus, increasing the sheet gage, for a bolted lap joint of a given type, apparently increases long-life fatigue strength considerably less than it increases static strength. It is probable that specimens of thicker sheet have higher stress concentrations than thin-sheet specimens, and it is commonly found that stress concentrations are more serious under dynamic loading than under static loading.

Effect of Number of Bolts on Fatigue Strength

In all of the tests described in this report, increasing the number of bolts in a lap joint between sheets of a given thickness increased both the static strength and the fatigue strength of that joint. Closer examination shows that the increase in strength was not usually proportional to the increase in the number of bolts.

Table 53 shows results obtained on increasing the number of bolts in line with the applied load. In every case, increasing the number of bolts (or the number of rows of bolts) for a given sheet gage decreased the strength per bolt. Thus, doubling the number of bolts in the direction of loading increased the fatigue strength only from 30 to 60 percent. Adding another bolt (or row of bolts) gave a further increase of only 10 to 30 percent. In general, the percent increase in fatigue strength due to adding bolts in the direction of loading was less for the thicker sheet specimens.

Table 54 compares the strengths of $1\frac{1}{2}$-inch-wide specimens having a single bolt (or line of bolts) with strengths of $4\frac{1}{2}$-inch-wide specimens having three bolts (or lines of bolts). Note (see fig. 1) that edge distances and bolt spacings were not varied. It might be expected that the ratio of strengths would be about 3:1, and it is clear that this was generally true. Detailed examination of the scatter shown in the load-life diagrams makes it seem questionable whether deviations from the average ratio of 3:1 are significant. The results suggest that a joint having a row of bolts may develop, under uniform loading, pretty nearly the strength predicted from tests of single-bolt joints.

It should be noted that this investigation has not included variation of bolt spacing, so that no statements concerning optimum bolt patterns are possible.

Fatigue Strength of Materials and Effective Stress Concentrations in Bolted Lap Joints

Figure 51 shows some values of "effective stress concentration," K, for specimens of 0.102-inch sheet tested at R = +0.25; K is here defined as the ratio of the maximum stress supported by a sheet specimen to a given lifetime divided by the nominal-gross-area stress supported by the specimen with stress raiser to the same lifetime at the same load ratio. Values of K were computed from the solid-line curves in figures 4, 37, 38, and 39.

An interesting observation from figure 51 is that the variation with lifetime of the effective stress concentration from the pin-bearing tests is much more like that for the bolted joint than is the variation of K for the sheets with drilled holes. It is well known that the stress concentration in a pin-loaded sheet differs from the stress concentration of a sheet with a central hole. (See, for example, figs. 9.17 and 7.32 in reference 6.)

However, factors other than stress concentration at the bolt holes are concerned in the fatigue behavior of a bolted lap joint. Friction between the overlapping sections (not necessarily identifiable with the static frictional loads previously noted), abrasion between the plates or between washers and plates, and bending stresses at the laps must all be included in any complete evaluation.

CONCLUSIONS

The data presented and discussed in the foregoing pages appear to warrant the following conclusions:

1. Bolt clearance (varied from −0.0005 to +0.050 in.) did not have a pronounced effect on the fatigue strength of bolted lap joints tested in tension-tension loading (R = +0.25).

2. Bolt fit did not affect directly the strength of such joints in tension-compression loading. Slip in joints with loose bolts did cause undesirable joint motion with resultant falling off of load under constant applied deflection. Under conditions of repeated reversal of load, the effect of an increase in bolt clearance may be detrimental both from the standpoint of increased wear at the joint faying surfaces and from the standpoint of possible sympathetic vibration effects caused by non-linear load-deflection characteristics.

3. The undesirable behavior of bolted joints under reversed loading may be mitigated by: using tight bolts (note that a bolt clearance of 0.002 in. gives much better characteristics than a clearance of 0.010 in.), by using bolt torques as high as allowed by other considerations, and by using joints with more than one bolt (or one row of bolts) along the direction of loading.

4. Increasing the number of bolts in line with the load increases the fatigue strength of the joint, but decreases the strength per bolt. In general, the increase in strength is less for dynamic loading than for static loading.

5. For a given bolt diameter and bolt pattern, joints made from thick sheet are stronger than joints from thin sheet. The increase in strength is not proportional to the increase in sheet gage, particularly for long-life fatigue loading in tension-compression.

In view of the testing conditions, these conclusions apply only to lap-joint test pieces, of 24S-T Alclad sheet and fastened by steel bolts with smooth shanks, within conditions under which failure occurs in the sheet. For multibolt specimens, these conclusions are valid only when all bolts in one joint have the same fit.

Battelle Memorial Institute,
Columbus, Ohio.

and

University of Illinois,
Urbana, Ill., December 15, 1945.

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APPENDIX I

DETAILS OF TEST METHODS USED AT THE BATTELLE MEMORIAL INSTITUTE

Fatigue Testing Machines

Tests at the Battelle Memorial Institute were run on Krouse, Direct Repeated-Stress Fatigue Testing Machines. Figure 52 shows one of the large load capacity (10,000 lb)) machines.

The variable load is applied by the lever A, which is actuated by the adjustable cam C. The average value of the load can be adjusted by the loading screw E. Static load values are obtained by measuring the bending of a fixed length of lever A by means of the dial gage on the "gage bar" F. The relation between dial readings and load is obtained from a calibration curve taken with dead-weight loading.

Tests showed the dynamic load range to be from 2 to 18 percent (on different machines) greater than the load range when the cam is slowly rotated for the static load measurement and adjustment. Detailed examination (made with SR-4 strain gages mounted on specimens, on the fulcrums D, and along the loading lever at N, O, P, . . .) showed this increase to be due to inertia of the loading lever and connecting rod. The throw increase is directly proportional to the load range, and is insensitive to specimen stiffness. Hence, specimens were loaded by static dial-bar measurements with calculated allowances for dynamic effects.

Each machine is equipped with mechanical counters G which record the number of hundreds of load cycles.

A cut-off H was designed to stop the machine upon specimen failure. The microswitch shown in figure 52 has been replaced by an adjustable contact and a thyratron relay. The present arrangement is sensitive to a load decrease of 15 pounds or more.

Test Pieces and Grips

Figure 53 shows sketches of typical bolted-joint test pieces used at the Battelle Memorial Institute. Note (for comparison with test pieces used at the University of Illinois – figs. 59, 62, and 63) the length of the specimens and the lack of widened grip sections. The length unsupported by grips was about 10 inches for specimens with a 1$\frac{1}{8}$-inch lap and greater by the additional lap for other specimens.

Figure 54 shows details of specimens used for tests of the sheet material (both unnotched and notched by a central hole).

The method of preparing and mounting specimens contributed toward equality of load across the width of each specimen. A specimen was mounted in the machine with only the center holding bolts inserted through the two holes drilled along a center line on the specimen. A nominal tension load (100 to 200 lb) was applied to insure adjustment. Then auxiliary bolts were inserted in the outer holes of the grip plates and tightened. These bolts either were outside the test piece (for 1$\frac{1}{2}$-in.-wide specimens) or (for wider ones) passed through holes 1/16 inch larger than the bolts. Thus, these additional bolts served only to squeeze the plates and afford increased frictional holding by the grips.

Reversed-Load Tests

Figure 55 shows a single-bolt specimen mounted for a tension-compression test with guide plates to prevent buckling.

Figure 56 shows parts of one pair of guide plates. The plates were made from 1/4-inch cold-rolled steel, cut approximately 3 by 8 inches. A 1-inch hole was drilled in the center of each plate to allow room for the specimen bolt. A piece of aluminum of the same thickness as the specimen to be tested was bolted to the upper half of one plate and a similar piece to the lower half of the other plate (A and B in fig. 56). Porous paper (from the National Bureau of Standards – see reference 5) was pasted on portions of the guide plates to be in contact with the test piece, and was saturated with oil. Spacers (C and D of fig. 56) were used to obtain suitable clearance to give the best balance between low friction and good "guidance." It was found necessary to adjust this clearance under maximum load to prevent binding due to bending at the lap. With care, this procedure gave uniform results.

A few specimens were run without guide plates. These were cut short so that the length unsupported by the machine grips was about $1\frac{1}{2}$ inches plus the overlap. Figure 57 shows a comparison of tests using the two methods and adds confidence that the guide-plate method was reasonably satisfactory.

APPENDIX II

TEST METHODS USED AT THE UNIVERSITY OF ILLINOIS

Tests on Specimens of 0.102-Inch Sheet

Machines.- The Moore-Krouse push-pull fatigue testing machine as fitted for tests of bolted joints is shown in figure 58. Cycles of repeated stress are applied to the specimen S by means of the variable-stroke cam C, the lever L, the fulcrum F, the slider M, and lower jaw J". The load on the specimen is carried by the upper jaw J' to the calibrated weighing ring R, the elastic deflection of which measures the load on the specimen. A pair of plate fulcra F" minimizes the lateral vibration of J' and of the upper end of the specimen. The micrometer dial gage D measures the elastic deflection of the weighing ring R.

The total throw of the variable-stroke cam C determined the total range of load applied to the specimen. The ratio of minimum load in a cycle of stress to maximum load is determined by the position of the nuts N' and N" on the screw T.

Unidirectional loading.- In starting a test under unidirectional load, the specimen is fastened in the upper and lower jaws. Then, with nut N" loose, nut N' is tightened until the desired maximum load for a cycle is indicated on the micrometer dial gage D. The nut N' is loosened until the minimum (tensile) load desired for the cycle is indicated on micrometer dial gage D. Then nut N" is tightened, the shaft of the testing machine is turned over by hand, and the stroke of the variable-throw cam C is adjusted by means of a spanner wrench to give the desired range of load from maximum to minimum. This adjustment usually changes the reading for the maximum load slightly, and readjustment is made by changing slightly the positions of nuts N' and N" along the screw T. The machine is then started and allowed to make about 100 revolutions, then stopped and readings of dial gage D taken, and any necessary adjustments in stroke of cam C and positions of nuts N' and N" to maintain the desired range of load are made. This process of stopping the machine and taking test readings at frequent intervals is kept up during the first 100,000 cycles, or until no adjustment is found necessary after three or four trials. After this, observations are taken of load at convenient intervals. When the specimen breaks or a crack opens up, the distance between J' and J" increases, and a microswitch K is set so that a very small increase in the distance between J' and J" will cause the switch to make contact, open the motor circuit through a relay, and stop the motor which drives the testing machine. Then the number of cycles of stress for fracture can be read directly from the revolution counter Q.

Reversed loading.- To apply cycles of partially reversed loading, nut N" is screwed upward so that there is compression on the specimen. The spring G is tightened sufficiently to insure contact throughout a stroke between cam C and the ball bearing at the end of lever L. After clamping the specimen in jaws J' and J", nut N" is screwed up until the desired maximum compression has been put on the specimen. Then nut N" is loosened and nut N' screwed down until the maximum desired tensile load is applied. Then the stroke of the cam C and the positions of nuts N' and N" are adjusted until the desired range is secured as the machine shaft is turned over by hand, after which the test is carried on in a manner similar to that used for tests under unidirectional stress. However, for reversed-load tests it is desirable to take observations of range of load at more frequent intervals of time than the intervals between observations in tests under unidirectional load.

Inertia effects in Moore-Krouse push-pull fatigue machine.- As the machine is in operation, the slider M, the lower jaw J", the upper jaw J', and the lower part of the ring R are in up-and-down motion, approximating harmonic motion. The inertial effects come mainly from the parts below the specimen S and, if the weighing ring R were equipped with a recording mirror deflectometer, the forces indicated would be those acting on the specimen, including the major inertial forces. The readings of the micrometer dial are not self-recording. They are taken at intervals during a test as the shaft of the machine is turned over by hand, and the effect of the inertial forces when the machine is running at normal speed (600 rpm) are not recorded.

To determine approximately the magnitudes of these inertial forces, the following procedure was followed: In its normal position, the lower point of the plunger of the micrometer dial gage does not touch the ring R, and a gage reading is obtained by pushing on the upper end of the plunger until contact between the lower point and the ring is made, when the reading is taken. Maximum and minimum readings of the dial gage are taken as the shaft of the machine is turned over by hand. Then the machine is started, and when running at normal speed, the upper end of the plunger of the dial gage is gently pushed down until contact is made between the lower point of the plunger and the ring R. This gives a reading of minimum load under running conditions, and it is assumed that the difference between the "hand turning" readings and "running" readings will be (numerically) the same for both maximum and minimum readings. Contact between lower point of the plunger of the dial gage and ring may be detected by the "feel" against the finger pressure on the upper end of the plunger, or by the dial reading for which violent vibration of the dial pointer begins.

This check has been made several times during each test made on the Moore-Krouse machine, and the difference between hand turning readings and running readings rarely indicated a difference greater than 25 pounds. The inertial effect does not seem to be serious in the tests herein reported.

Adjustment of results for actual values of R.- It is very difficult to adjust the length of throw of the cam and the position of nuts N' and N" in the Moore-Krouse machine to give the precise value of R (ratio of minimum to maximum load) desired in each individual test. In practice, it is more convenient to adjust the parts of the machine to give approximately the desired value of R, and then adjust the test results by the use of a correction factor.

Accordingly, the following empirical formula has been computed from tension-compression data reported in the Structural Aluminum Handbook (p. 26), published by Aluminum Company of America, 1945:

$$\left(P_{max}\right)' = \frac{1.25-R}{1.25-R'}\ P_{max}$$

where

P_{max} actual maximum load at the load ratio R

$P_{max'}$ "corrected maximum load" corresponding to the desired load ratio R'

In one or two cases, the correction of the maximum load was more than 10 percent. In the great majority of cases, the correction was from 0 to 2 percent. For such small corrections, it is believed that the procedure described is justifiable.

Test pieces.- Figure 59 shows diagrams of the 0.102-inch specimens used at the University of Illinois.

Tests on Specimens of 0.375-Inch Sheet

Testing machines.- Figure 60 shows a direct-acting 15,000-pound capacity testing machine used at the University of Illinois. This machine runs at approximately 600 cpm. The load is changed by adjusting the throw of the eccentric shown at the bottom.

Figure 61 shows a lever-type machine of 50,000-pound capacity, which is run at approximately 300 cpm. The load is changed by adjusting the eccentric shown at the left in the photograph.

For both machines, loads were measured by ring dynamometer. Load values were checked frequently, as experience dictated, and the eccentrics readjusted when the load varied appreciably. Records of these adjustments were kept and these data taken into account in arriving at reported load values.

In each machine, the lower corners of the upper pulling head and the upper corners of the lower pulling head are supported laterally by four horizontal steel bars. Each bar is machined to a thin ribbon at each end so that the heads are restrained laterally but are free to move vertically.

Both machines have roller bearings throughout.

Test pieces.- The details of typical test pieces are shown in figures 62 and 63. The unsupported lengths were:

5 inches for single-bolt and two-bolt specimens (fig. 62)

6 inches for three-bolt specimens (not shown)

5½ inches for six-bolt and nine-bolt specimens (fig. 63)

All joints had 3/8-inch bolts with washers under heads and nuts, and all nuts were tightened to a wrench torque of 110 inch-pounds.

TABLE 1. MECHANICAL PROPERTIES OF SHEET MATERIALS

Sheet Gage (Inches)	Static Ultimate(1) (p.s.i.)	Yield Strength(2) (p.s.i.)	Per Cent Elongation(3)
0.102	69,700	49,920	16.0
0.125	70,450	51,200	17.9
0.156	70,000	51,000	19.3
0.187	69,000	50,650	19.1
0.250	69,800	51,675	16.3
0.375	67,050	49,450	18.8

(1) All values averages of results on two test pieces. Each piece 1" wide at center.
(2) Yield at 0.2% offset in 2" gage length.
(3) Elongation over 2" gage length.

TABLE 2. REPRESENTATIVE TOLERANCES IN BOLT HOLES

Bolt Fit	Nominal Bolt Clearance (Inch)	Measured Bolt Clearance (Inch)
"Tight"	-0.001 to 0.000	-0.0007 ± 0.0003
"Drill"	+0.002	0.0021 ± 0.0004
"Loose"	+0.010	0.0108 ± 0.0020
"Sloppy"	+0.025	0.0235 ± 0.0026

Note: A few tests, noted in the text, used larger clearances. (0.050 inch)

TABLE 3. STATIC STRENGTHS OF BOLTED-JOINT TEST PIECES

Sheet Gage (Inch)	Type of Specimen (1)	Bolt Fit (2)	Failure Loads, in Pounds		
			Specimen No. 1	Specimen No. 2	Average
0.102	A - Single bolt.	T	5420	5380	5400
		D	4920	4960	4940
		L	5220	5000	5110
		S	5060	5050	5055
		Q	4740	4860	4800
	B - Two bolts in line of load.	D	8160	8060	8110
		L	7020	7400	7210
		S	7520	7610	7565
		Q	7280	7260	7270
	C - Three bolts in line of load.	L	7720	7640	7680
	D - Three bolts in line transverse to load.	L	15980	15830	15905
		S	15640	15500	15570
0.125	A - Single bolt.	D	6150	6100	6125
		L	6300	6320	6310
	C - Three bolts in line of load.	L	9560	9440	9500
0.156	A - Single bolt.	D	7860	7980	7920
0.187	A - Single bolt.	T	9100	9160	9130
		D	7660	8480	8070
		L	8850	8640	8745
		S	8740	8740	8740
		Q	7820	7980	7900
	B - Two bolts in line of load.	D	14100	15400	15050
		S	13820	13600	13710
		Q	13920	13820	13870
0.187	D - Three bolts in line transverse to load.	L	26775	25425	26100
		Q	22750	26650	24700
0.250 (4)	A.- Single bolt.	T	10100	10260 (3)	10180

TABLE 3. (Continued)

Sheet Gage (Inch)	Type of Specimen(1)	Bolt Fit(2)	Failure Loads, in Pounds		
			Specimen No. 1	Specimen No. 2	Average
0.250(4)	B - Two bolts in line of load.		19220	18740	18980
0.375(4)	C - Three bolts in line of load		28630	27830	28230
	F - Three rows of three bolts each transverse to load		86680	86200	86440

(1) See Figure 1 for types of specimen.

(2) Bolt-fit clearances:
T = 0.0000 to -0.001 inch
D = 0.002 inch
L = 0.010 inch
S = 0.025 inch
Q = 0.050 inch

(3) Bolt sheared.

(4) Single-bolt joints of 0.250-inch sheet and of 0.375-inch sheet, and both two-bolt joints and three-bolt joints of 0.375-inch sheet failed in the bolts.

TABLE 4. FATIGUE TEST RESULTS FOR SINGLE-BOLT SPECIMENS OF 0.102-INCH SHEET, UNIDIRECTIONAL LOADING (BATTELLE)

(R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 1T1U (0.000" to -0.001" clearance)			
1	5000	3,300	A
27	4500	3,400	
6	4200	16,500	B
32	3600	62,900	
2	3000	30,500	B
16	2700	68,400	B
18	2700	45,000	B
30	2400	127,900	
26	2200	75,800	B
24	2100	122,000	B
35	2000	263,500	
23	1750	227,500	B
22	1750	76,900	A
14	1500	315,400	B
15	1500	533,500	B
13	1250	1,374,200	B
4	1200	229,100	A
17	1200	241,600	A
19	1200	716,700	B
25	1050	1,355,700	B
20	900	>48,845,000	
21	900	3,354,200	B
12	850	>11,078,900	
11	800	>11,172,500	
Group 1D1U (0.002" clearance)			
1	4800	3,200	A
15	4000	19,000	B
30	4000	43,900	A
34	3600	63,200	
23	3200	58,500	B
24	3200	75,000	B
29	3000	106,400	B
2	3000	32,000	B
31	3000	89,600	A
33	2400	141,900	
27	2400	161,700	B
3	2000	115,200	B
28	1500	429,800	B

TABLE 4. (Continued)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
4	1250	567,900	B
35	1200	1,316,000	B
25	1150	1,366,000	B
26	1150	1,354,700	B
20	1050	1,489,700	B
5	950	2,568,900	B
21	920	3,458,000	B
6	860	>13,861,800	
Group 1L1U (0.010" clearance)			
11	4800	6,400	A
5	4500	10,600	A
1	4000	13,700	A
29	3600	60,600	A
2	2500	79,500	B
14	2500	103,000	B
13	2200	185,200	B
3	1500	376,000	B
12	1200	790,500	B
28	1200	980,800	B
4	1000	793,300	B
6	850	6,935,600	B
Group 1S1U (0.025" clearance)			
6	4800	1,400	A
1	4200	12,800	A
22	3500	49,600	B
2	3000	41,600	A
21	2400	130,600	B
11	2000	147,500	B
3	1750	160,000	B
4	1200	560,400	B
12	1200	961,100	B
23	1000	2,922,400	B
5	800	8,779,500	B
Group 101U (0.050" clearance)			
7	4500	2,800	A
6	3800	6,300	A
4	3000	68,900	A
3	2100	183,700	B
13	2000	315,000	A
2	1500	470,500	A
12	1200	1,500,000	B
1	1000	1,399,000	B
5	850	2,648,000	B
10	700	3,589,000	B
	600	>110,382,900	

* A indicates fatigue crack through bolt hole. B indicates fatigue crack at edge of bolt hole. See Figure 8.

TABLE 5. FATIGUE TEST RESULTS FOR TWO-BOLT SPECIMENS OF 0.102-INCH SHEET WITH BOLTS IN LINE OF LOAD. UNIDIRECTIONAL LOADING (BATTELLE)

(R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 1D2U (0.002" clearance)			
9	6500	2,700	A
15	6000	37,700	B
10	5200	37,700	B
1	3800	92,500	B
5	2500	386,100	B
3	1500	1,438,800	B
14	1300	17,977,300	B
11	1200	917,300	A
12	1000	>13,852,900	
4	900	23,060,800	
Group 1L2U (0.010" clearance)			
6	6500	10,200	A
3	6000	22,800	A
1	4000	105,700	B
2	2400	499,300	B
4	1600	720,700	B
5	1600	1,496,900	B
7	1400	3,436,500	B
X 51	6000	46,400	
X 50	3100	137,900	B
X 52	1450	3,126,800	B
Group 1S2U (0.025" clearance)			
7	7000	6,300	A
4	6500	23,800	A
1	5200	41,600	A
2	3500	112,400	B
3	2200	335,100	B
5	1500	1,172,900	B
8	1250	>21,812,700	
6	1100	>22,198,700	

* A indicates fatigue crack through bolt hole; B indicates fatigue crack at edge of bolt hole. See Figure 8.

X Specimens made to give a tight fit in a loose hole by means of spacing between holes.

TABLE 6. FATIGUE TEST RESULTS FOR THREE-BOLT SPECIMENS OF 0.102-INCH SHEETS WITH BOLTS IN LINE OF LOAD. UNIDIRECTIONAL LOADING (BATTELLE)

(R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 114U (0.010" clearance)			
8	7200	1,900	A
5	6000	29,500	A
2	2800	204,500	B
3	2000	631,500	B
4	1600	937,100	B
6	1250	3,374,000	B
7	1100	>10,260,800	
(middle hole 1/8" off center)			
14	7200	18,600	A
13	6000	51,400	A
11	4000	149,800	B
12	2200	542,300	B
15	1300	2,235,000	B
(bottom hole 1/8" off center)			
19	6000	45,300	A
16	4000	124,800	B
17	2200	843,200	A
18	1600	1,354,000	A
12	1200	5,311,000	B

* A indicates fatigue crack through bolt hole; B indicates fatigue crack at edge of bolt hole. See Figure 8.

TABLE 7. FATIGUE-TEST RESULTS FOR THREE-BOLT SPECIMENS OF 0.102-INCH SHEET WITH BOLTS TRANSVERSE TO LOAD. UNIDIRECTIONAL LOADING (BATTELLE)

(R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 1D3U (0.002" clearance)			
9	9200	28,900	B
5	8000	44,000	B
7	6600	85,100	B
6	5500	162,600	B
1	3800	638,000	B
2	2800	2,011,800	B
10	2650	2,577,600	B
8	2500	>13,828,800	
3	1800	>9,525,200	
Group 1L3U (0.010" clearance)			
11	9200	37,900	
10	7500	65,600	B, A
1	6000	95,100	B, A
6	4800	229,000	B
2	4000	440,500	B
5	3500	488,800	B, A
3	3000	1,108,800	B
4	2500	2,367,600	B
7	2200	>9,319,000	
Group 1S3U (0.025" clearance)			
11	9400	24,900	A
6	8000	74,300	B
1	6000	126,500	B
3	4900	148,000	A
9	4000	332,600	B
2	3800	553,600	B
8	3000	939,800	B
7	2500	1,525,600	B
13	2300	3,426,100	A
12	2100	>15,726,200	
10	1800	>20,174,600	

* A indicates fatigue crack through bolt hole; B indicates fatigue crack at edge of bolt hole. See Figure 8.

TABLE 8. FATIGUE TEST RESULTS FOR SINGLE-BOLT SPECIMENS OF 0.102-INCH SHEET. UNIDIRECTIONAL LOADING (UNIVERSITY OF ILLINOIS)

(R = +0.25)*

Specimen No.	R_a*	Actual Max. Load (Lbs.)	Corrected** Max. Load (Lbs.)	Cycles to Failure
Tight Bolt fit (clearance 0.000" to -0.001")				
14	+0.19	2640	2800	37,500
47	+0.11	1870	2130	374,000
46	+0.23	1870	1910	150,300
3	+0.22	1820	1870	94,900
7	+0.27	1330	1300	392,100
10	+0.23	1040	1050	892,800
19	+0.22	970	1000	1,050,200
Sloppy bolt fit (clearance +0.031")				
37	+0.19	2120	2240	112,800
41	+0.22	2150	2220	31,800
50	+0.21	1670	1730	189,600
34	+0.19	1620	1720	150,600
39	+0.25	1370	1370	201,000
48	+0.22	1240	1300	366,500
26	+0.25	1210	1210	537,700
32	+0.24	980	990	1,280,000 No fracture
44	+0.33	760	700	1,009,900 No fracture

* Nominal ratio is +0.25, R_a is the actual test ratio.

** Maximum load corrected (see Appendix II) to correspond to the nominal load ratio R = +0.25.

TABLE 9. FATIGUE TEST RESULTS FOR SINGLE-BOLT SPECIMENS OF 0.102-INCH SHEET. UNIDIRECTIONAL LOADING (UNIVERSITY OF ILLINOIS)

(R = -0.67)*

Specimen No.	R_a*	Actual Max. Load (Lbs.)	Corrected** Max. Load (Lbs.)	Cycles to Failure
	Tight bolt fit (clearance 0.000" to -0.001")			
135	+0.64	3060	3220	224,400
138	+0.64	2450	2570	811,300
137	+0.66	2040	2080	1,371,500
136	+0.66	2780	2830	1,787,700

* Nominal ratio is -0.67, R_a is the actual test ratio.

** Maximum load corrected (See Appendix II) to correspond to the nominal load ratio R = +0.67.

TABLE 10. FATIGUE TEST RESULTS FOR TWO-BOLT SPECIMENS OF 0.102-INCH SHEET WITH BOLTS IN LINE OF LOAD. UNIDIRECTIONAL LOADING. UNIVERSITY OF ILLINOIS

(R = +0.25)*

Specimen No.	R_a*	Actual Max. Load (Lbs.)	Corrected** Max. Load (Lbs.)	Cycles to Failure
Tight bolt fit (clearance 0.000" to -0.001")				
20	+0.21	3740	3880	31,900
21	+0.23	3060	3120	69,900
24	+0.22	2540	2640	50,600
28	+0.23	1800	1850	497,700
46	+0.24	1720	1740	624,100
31	+0.19	1440	1530	389,500
54	+0.25	1420	1420	1,340,500
42	+0.25	1190	1190	1,109,000 No fracture
Drill fit (clearance +0.002")				
124	+0.23	3480	3540	46,200
125	+0.25	3280	3280	138,200
128	+0.25	2480	2480	233,800
126	+0.20	2240	2350	315,500
129	+0.25	1870	1870	662,300
127	+0.29	1630	1560	1,561,800
Loose bolt fit (clearance +0.016")				
133	+0.24	3120	3160	125,900
130	+0.23	2390	2430	231,000
131	+0.23	1960	2000	465,400
132	+0.21	1660	1730	1,532,200
Sloppy bolt fit (clearance +0.031")				
61	+0.25	3180	3180	22,400
36	+0.21	2750	2830	78,400
56	+0.26	2740	2710	61,200
71	+0.23	1880	1920	106,300
69	+0.26	1690	1670	760,600
58	+0.22	1380	1420	550,100
62	+0.24	1280	1290	1,078,300
60	+0.29	1110	1060	2,016,900 No fracture

* Nominal ratio is +0.25, R_a is the actual test ratio.

** Maximum load corrected (see Appendix II) to correspond to the nominal load ratio R = +0.25.

TABLE 11. FATIGUE TEST RESULTS FOR THREE-BOLT SPECIMENS OF 0.102-INCH SHEET WITH BOLTS TRANSVERSE TO LOAD. UNIDIRECTIONAL LOADING. (UNIVERSITY OF ILLINOIS)

(R = +0.25)*

Specimen No.	R_a*	Actual Max. Load (Lbs.)	Corrected** Max. Load (Lbs.)	Cycles to Failure
Tight bolt fit				
156	+0.125	4800	5390	162,500
154	+0.28	4350	4200	308,000
152	+0.21	3420	3560	557,500
157	+0.25	3000	3000	1,105,100

* The nominal ratio is +0.25, R_a is the actual test ratio

** Maximum load corrected (see Appendix II) to correspond to the nominal load ratio R = +0.25.

TABLE 12. FATIGUE TEST RESULTS FOR SINGLE-BOLT SPECIMENS OF 0.125-INCH SHEET. UNIDIRECTIONAL LOADING (BATTELLE)

(R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 2D1U (0.002" clearance)			
8	5400	8,400	A
9	5000	18,800	B
11	4500	7,900	A
1	4500	14,200	A
3	3000	52,100	A
13	2200	162,700	B
5	2000	222,200	B
12	1500	733,400	B
6	1200	1,831,400	B
7	1000	7,261,400	B
Group 2L1U (0.010" clearance)			
10	5000	8,100	A
11	5000	10,900	A
12	4000	42,800	B
1	3000	117,500	B
3	2200	180,200	B
4	1750	345,500	B
5	1250	1,177,100	B
14	1000	3,396,000	B
13	950	7,361,600	B
8	700	10,783,200	

* A indicates fatigue crack through bolt hole; B indicates fatigue crack at edge of bolt hole. See Figure 8.

TABLE 13. FATIGUE TEST RESULTS FOR THREE-BOLT SPECIMENS OF 0.125-INCH SHEET WITH BOLTS IN LINE OF LOAD. UNIDIRECTIONAL LOADING (BATTELLE)

(R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 2D4U (0.010" clearance)			
7	8000	26,700	B
6	6500	57,500	B
2	5000	122,100	B
5	3700	309,900	B
3	2700	638,800	B
1	2000	587,500	A
8	2000	1,991,900	A
11	1700	3,585,700	A
12	1500	4,512,300	B
4	1400	11,355,800	

* A indicates fatigue crack through bolt hole; B indicates fatigue crack at edge of bolt hole. See Figure 8.

TABLE 14. FATIGUE TEST RESULTS FOR SINGLE-BOLT SPECIMENS OF 0.156-INCH SHEET. UNIDIRECTIONAL LOADING (BATTELLE)

(R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycle to Failure	Position of Failure*
Group 3D1U (0.002" clearance)			
4	6000	4,800	A
14	5400	5,300	A
3	4000	39,000	A
15	3100	107,000	A
2	3000	107,500	B
9	2200	268,200	B
6	2200	343,900	B
1	1800	832,200	B
16	1600	991,900	B
5	1500	1,156,600	B
7	1150	3,361,600	B
13	1150	3,693,400	B
8	1050	>26,926,100	
Group 3L1U (0.010" clearance)			
8	6200	3,700	A
5	5500	18,900	A
2	4000	54,000	B
1	3000	157,500	B
3	2200	349,100	B
4	1750	704,400	B
14	1500	1,304,600	
6	1250	1,607,200	B
9	1120	>12,537,400	
10	1050	>9,846,600	
7	950	>11,104,500	

* A indicates fatigue crack through bolt hole; B indicates fatigue crack at edge of bolt hole. See Figure 8.

TABLE 15. FATIGUE TEST RESULTS FOR SINGLE-BOLT SPECIMENS OF 0.187-INCH SHEET. UNIDIRECTIONAL LOADING (BATTELLE)

($R = +0.25$)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 4T1U (0.000" to 0.001" clearance)			
7	6250	20,300	A
5	5200	51,600	A
1	3800	121,300	B
2	2800	238,400	B
3	1750	1,223,000	A
6	1400	3,296,100	B
8	1300	>30,572,000	
4	1200	>28,274,800	
Group 4D1U (0.002" clearance)			
4	6500	800	Bolt sheared
6	6000	8,900	A
1	5000	24,100	A
2	3000	140,900	A
3	2000	756,900	B
5	1400	5,173,800	B
7	1200	21,299,200	B
Group 4L1U (0.010" clearance)			
3	6500	6,200	A
1	5000	42,800	A
8	3500	101,400	A
2	3000	180,700	B
4	1750	2,282,100	B
5	1400	2,910,700	B
10	1300	>12,273,900	
9	1100	>35,736,000	
Group 4S1U (0.025" clearance)			
1	6500	4,800	A
2	5000	17,600	A
8	3700	114,800	B
3	3000	188,400	B
4	1800	913,600	B
5	1400	1,701,600	B
7	1250	>12,349,000	
6	1100	>14,229,600	
Group 4Q1U (0.050" clearance)			
7	5600	17,600	A
6	4700	19,600	A
5	3600	91,800	A
3	2700	377,300	B
2	2000	963,300	B
1	1500	2,627,900	B
4	1250	4,480,700	B
8	1100	>19,417,800	

* A indicates fatigue crack through bolt hole; B indicates fatigue crack at edge of hole. See Figure 8.

TABLE 16. FATIGUE TEST RESULTS FOR TWO-BOLT SPECIMENS OF 0.187-INCH SHEET. UNIDIRECTIONAL LOADING (BATTELLE)

(R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 4D2U (0.002" clearance)			
8	7000	17,500	A
5	6000	38,100	A
7	5000	185,600	B
1	3800	334,100	B
2	2800	588,600	B
3	2200	1,395,000	B
4	1750	8,385,000	B
Group 4S2U (0.025" clearance)			
7	8400	11,600	A
5	8000	10,700	A
3	6400	37,400	A
1	5000	65,700	B
4	3200	435,600	B
6	2400	927,700	B
2	1750	5,042,500	B
Group 4Q2U (0.050" clearance)			
5	6200	16,200	A
1	5000	73,400	A
2	3600	377,100	A
3	2500	828,400	B
4	1750	2,563,000	B
6	1500	>11,464,000	
7	1200	>7,709,600	

* A indicates fatigue crack through bolt hole.
B indicates fatigue crack at edge of hole.
See Figure 8.

TABLE 17. FATIGUE TEST RESULTS FOR THREE-BOLT SPECIMENS OF 0.187-INCH SHEET WITH BOLTS TRANSVERSE TO LOAD. UNIDIRECTIONAL LOADING (BATTELLE)

(R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 4L3U (0.010" clearance)			
4	9000	180,300	B
8	7500	374,800	A
2	6000	889,500	A
7	4500	1,681,200	B
3	2800	40,200,500	B
Group 4Q3U (0.050" clearance)			
3	9000	179,300	A
1	6000	763,400	B
2	3800	3,800,700	B
4	3200	>18,490,800	

* A indicates fatigue crack through bolt hole.
B indicates fatigue crack at edge of hole.
See Figure 8.

TABLE 18. FATIGUE TEST RESULTS FOR SINGLE-BOLT SPECIMENS OF 0.250-INCH SHEET. UNIDIRECTIONAL LOADING (BATTELLE)

(R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 5 T1U (0.00" to -0.001" clearance)			
1	6000	23,200	A
2	4000	196,300	B
3	3000	522,300	B
4	2000	1,700,800	A
5	1400	>28,838,400	

* A indicates fatigue crack through bolt hole. B indicates fatigue crack at edge of hole. See Figure 8.

TABLE 19. FATIGUE TEST RESULTS FOR SINGLE-BOLT SPECIMENS OF 0.250-INCH SHEET. UNIDIRECTIONAL LOADING (UNIVERSITY OF ILLINOIS)

(R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure
		Group Faa (Bolt clearance = +0.000")
1	2,360	185,200
2	2,940	69,300
3	3,380	127,700
4	3,760	42,600
5	4,340	34,800
6	4,960	26,100
7	5,940	19,800
8	6,360	10,200
9	6,630	19,500
10	3,980	44,300
11	3,590	97,700
12	2,490	97,600
13	2,300	518,500
14	2,210	187,500
15	2,980	169,300
16	2,970	114,300
17	3,000	100,000
18	2,120	360,700
19	1,990	467,200
20	1,820	1,420,000
		Group Fad (Bolt clearance = +0.025")
1	4,340	43,400
2	4,970	51,700
3	5,900	13,200
4	6,390	11,900
5	6,520	13,200
6	3,970	37,600
7	3,600	50,300
8	2,490	180,500
9	2,320	1,281,000
10	3,000	93,300
11	4,750	33,800
12	5,590	21,900
13	6,720	9,100

TABLE 20. FATIGUE TEST RESULTS FOR SINGLE-BOLT SPECIMENS OF 0.375-INCH SHEET. UNIDIRECTIONAL LOADING (UNIVERSITY OF ILLINOIS) (R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure
Group Aaa (Bolt clearance = +0.000")		
1	4,350	51,600
2	5,150	103,300
3	5,830	23,500
4	6,940	24,900
6	4,210	50,600
7	3,920	113,400
8	3,580	75,700
9	2,790	478,400
10	7,810	8,000
11	7,000	14,500
12	2,970	159,500
13	7,890	7,600
14	3,452	99,200
15	3,810	310,000
16	3,980	94,400
17	4,180	70,200
Group Aac (Bolt clearance = +0.010")		
1	5,100	80,200
2	6,890	20,400
3	3,830	73,400
4	3,000	54,700
5	3,140	117,000
7	5,170	50,400
	7,300	12,000
9	2,910	127,500
10	2,480	439,900
11	2,680	228,900
Group Aad (Bolt clearance = +0.025")		
1	7,490	12,000
2	4,790	34,600
3	4,000	76,300
4	3,610	71,700
5	3,110	281,500
6	2,490	371,800
8	6,170	19,600
9	3,230	104,700
10	5,550	26,200

TABLE 21. FATIGUE-TEST RESULTS FOR TWO-BOLT SPECIMENS OF 0.375-INCH SHEET WITH BOLTS IN LINE OF LOAD. UNIDIRECTIONAL LOADING (UNIVERSITY OF ILLINOIS)

(R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure
Group Baa (Bolt clearance = +0.000")		
1	5,160	59,100
2	10,260	6,300
3	4,370	431,900
4	6,460	34,800
5	3,920	224,200
6	3,020	452,400
7	4,400	188,500
8	4,820	125,200
9	7,620	34,200
10	9,330	18,700
Group Bab (Bolt clearance =+0.002")		
1	5,140	57,800
3	9,200	11,200
4	7,830	25,000
5	4,080	168,800
6	3,020	659,900
7	3,470	245,600
Group Bac (Bolt clearance = +0.010")		
1	5,910	62,900
2	6,820	36,600
3	7,200	26,300
4	8,250	22,800
5	9,340	18,300
6	11,770	4,800
7	5,040	103,200
8	4,560	130,000
9	3,980	257,200
10	2,950	568,700
11	11,970	6,100
Group Bad (Bolt clearance =+0.025")		
1	10,440	15,500
2	7,200	46,000
3	5,690	88,300
4	3,740	250,900
5	12,440	7,000
6	2,590	2,689,000 No failure
7	3,020	1,917,200
8	4,580	188,300
9	8,430	25,300
10	11,760	9,100

TABLE 22. FATIGUETEST RESULTS FOR THREE-BOLT SPECIMENS OF 0.375-INCH SHEET WITH BOLTS IN LINE OF LOAD. UNIDIRECTIONAL LOADING (UNIVERSITY OF ILLINOIS)

(R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure
Group Caa (Bolt clearance = +0.000")		
1	6,800	74,700
2	7,380	56,800
3	8,220	53,000
4	5,110	155,100
5	4,390	296,800
6	9,980	32,700
7	11,880	17,600
8	4,010	312,300
9	3,580	1,107,700
10	3,800	943,200
11	13,940	10,700
Group Cad (Bolt clearance = +0.025")		
1	6,010	131,900
2	8.030	63,700
3	5,210	178,400
4	4,190	736,600
5	4,120	416,600
6	10,090	28,600
7	6,990	92,700
8	12,100	22,700
9	14,010	10,000

TABLE 23. FATIGUE TEST RESULTS FOR SIX-BOLT SPECIMENS OF 0.375-INCH SHEET WITH TWO ROWS OF THREE BOLTS EACH. UNIDIRECTIONAL LOADING (UNIVERSITY OF ILLINOIS)

(R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure
	Group Daa (Bolt clearance = +0.000")	
2	17,960	60,600
3	13,940	554,600
4	16,960	72,500
5	15,710	304,000
6	19,990	51,800
8	15,970	237,900
9	20,970	64,300
10	21,793	44,700
11	24,910	26,100
12	12,010	469,700
13	29,620	16,200
14	11,990	211,900
15	12,000	191,100
16	10,910	320,200
17	10,030	413,800
	Group Dad (Bolt clearance = +0.025")	
1	16,090	305,400
2	18,060	110,900
3	14,200	644,200
4	19,920	61,300
5	21,670	47,200
6	23,990	54,200
7	26,140	26,500
8	17,410	135,100
9	29,660	20,500
10	30,720	14,300
11	31,660	12,600

TABLE 24. FATIGUE TEST RESULTS FOR NINE-BOLT SPECIMENS OF 0.375-INCH SHEET WITH THREE ROWS OF THREE BOLTS EACH. UNIDIRECTIONAL LOADING (UNIVERSITY OF ILLINOIS)

(R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure
Group Eaa (Bolt clearance = +0.000")		
1	20,000	107,900
2	16,970	134,100
3	14,940	274,800
4	24,970	57,800
5	30,050	33,300
6	35,940	19,700
7	42,010	8,600
8	13,070	1,048,300 No failure
9	13,840	313,600
Group Ead (Bolt clearance = +0.025")		
1	20,030	103,200
2	35,730	21,700
3	41,650	10,100
4	13,870	680,400
5	29,860	31,400
6	14,940	290,900
7	24,900	64,100
8	16,960	145,100

TABLE 25. FATIGUE TEST RESULTS FOR SINGLE-BOLT SPECIMENS OF 0.102-INCH SHEET. REVERSED LOADING (BATTELLE)
(R = -0.50)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 1T1R (0.000" to -0.001" clearance)			
21	3500	25,700	B
14	2600	24,100	A
9	2200	74,100	B
42	2200	54,500	A
20	2200	63,800	A
8	1900	56,300	A
41	1800	118,200	B
5	1600	209,500	B
18	1500	375,000	A
4	1400	225,700	
40	1300	405,000	B
7	1150	599,300	B
16	1090	1,843,400	
12	1000	1,866,800	B
43	1000	811,700	B
15	900	2,344,700	B
17	850	4,749,000	B
Group 1D1R (0.002" clearance)			
8	2600	73,900	B
6	2000	66,600	A
49	2000	111,300	B
4	1500	355,200	B
48	1500	186,900	B
7	1500	338,100	B
11	1400	294,600	B
47	1200	461,400	B
2	1000	599,900	B
3	800	2,218,500	B
Group 1L1R (0.010" clearance)			
13	800	1,609,100	A
Group 1S1R (0.025" clearance)			
38	1000	404,800	B
39	800	1,418,500	B

* A indicates fatigue crack through bolt hole.
B indicates fatigue crack at edge of hole. See Figure 8.

TABLE 26. FATIGUE TEST RESULTS FOR TWO-BOLT SPECIMENS OF 0.102-INCH SHEET WITH BOLTS IN LINE OF LOAD. REVERSED LOADING (BATTELLE)

(R = -0.50)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure
Group 1T2R (0.000" to -0.001" clearance)			
46	1900	362,000	B
41	1500	836,500	B
40	1000	1,740,000	B
Group 1D2R (0.002" clearance)			
7	4200	3,800	A
9	4000	49,000	
8	3800	53,700	
6	3400	35,000	
5	2700	44,700	
4	2100	227,100	B
42	2100	226,600	
41	1600	472,100	
1	1400	302,700	
40	1200	1,214,000	
3	1000	2,456,100	B
43	1000	3,049,200	
10	900	>8,430,700	
Group 1L2R (0.010" clearance)			
56	3000	86,900	A
45	2000	332,300	A
42	1750	472,000	B
40	1250	963,700	B
43	900	1,713,400	B
44	800	7,685,900	B
Group 1L2R (tight fit in a loose hole)			
55	2600	148,300	A
51	2000	312,500	B
52	1300	990,500	B
53	1000	3,226,200	B
54	860	2,757,800	B
Group 1Q2R (0.050" clearanse)			
6	2500	155,400	
3	1600	482,800	B
7	1200	2,253,200	B
1	1000	1,316,500	A
4	850	>8,168,000	

* A indicates fatigue crack through bolt hole.
B indicates fatigue crack at edge of hole.
See Figure 8.

TABLE 27. FATIGUE-TEST RESULTS FOR THREE-BOLT SPECIMENS OF 0.102-INCH SHEET WITH BOLTS TRANSVERSE TO LOAD. REVERSED LOADING (BATTELLE)

(R = -0.50)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 1D3R (0.002" clearance)			
1	4000	221,600	B
6	3200	729,200	B
2	2800	2,161,300	B
5	2600	2,155,700	B

* A indicates fatigue crack through bolt hole. B indicates fatigue crack at edge of hole. See Figure 8

TABLE 28. FATIGUE TEST RESULTS FOR SINGLE-BOLT SPECIMENS OF 0.102-INCH SHEET. REVERSED LOADING. (UNIVERSITY OF ILLINOIS)

(R = -0.50)*

Specimen No.	R_a*	Actual Max. Load (Lbs.)	Corrected** Max. Load (Lbs.)	Cycles to Failure	
Tight bolt fit. (clearance 0.000" to -0.001")					
92	-0.48	1590	1570	87,300	
99	-0.51	1610	1620	189,400	
93	-0.52	1380	1400	332,500	
87	-0.49	1130	1120	206,800	
89	-0.51	920	930	326,200	
100	-0.50	840	840	802,900	
91	-0.52	710	720	1,871,600	
B93	-0.49	1610	1600	319,200	Specimens machined at Battelle, tested at Univ. of Illinois
B92	-0.51	1220	1230	579,900	
B90	-0.56	1020	1050	352,800	
B91	-0.50	880	880	1,961,000	
Drill fit (clearance 0.002")					
98	-0.49	1520	1510	88,400	
94	-0.47	1680	1660	120,900	
95	-0.47	1170	1150	336,600	
96	-0.48	970	960	560,500	
97	-0.46	840	820	1,229,200	
Loose bolt fit (clearance 0.010")					
101	-0.52	950	960	214,700	

* Nominal ratio is -0.50, R_a is the actual test ratio.

** Maximum load corrected (see Appendix II) to correspond to the nominal load ratio R = -0.50.

TABLE 29. FATIGUE TEST RESULTS FOR TWO-BOLT SPECIMENS OF 0.102-INCH SHEET WITH BOLTS IN LINE OF LOAD. REVERSED LOADING. (UNIVERSITY OF ILLINOIS)

(R = -0.50)*

Specimen No.	R_a*	Actual Max. Load (Lbs.)	Corrected** Max. Load (Lbs.)	Cycles to Failure
Tight bolt fit. (clearance 0.000" to -0.001")				
106	-0.47	1710	1680	256,600
109	-0.51	1400	1410	383,600
110	-0.46	1350	1320	610,500
107	-0.51	1170	1180	869,000
108	-0.55	1030	1060	1,367,900
Drill fit. (clearance 0.002")				
119	-0.52	1840	1860	154,100
122	-0.48	1630	1610	220,700
120	-0.54	1330	1360	402,200
121	-0.47	1120	1100	840,100
123	-0.46	930	910	1,134,000
Loose bolt fit. (clearance 0.010")				
111	-0.53	1480	1500	148,500
112	-0.48	1350	1340	306,700
113	-0.52	1120	1130	893,300
114	-0.47	900	890	1,880,700

* The nominal ratio is -0.50, R_a is the actual load ratio.

** Maximum load corrected (see Appendix II) to correspond to the nominal load ratio R = -0.50.

TABLE 30. FATIGUE TEST RESULTS FOR SINGLE-BOLT SPECIMENS OF 0.125-INCH SHEET. REVERSED LOADING. (BATTELLE)

(R = -0.50)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 2T1R (0.000" to -0.001" clearance)			
47	4000	3,800	A
45	3600	19,700	A
41	3000	31,600	B
2	2500	95,100	B
40	2000	139,200	B
42	1400	413,900	B
43	1200	803,000	B
44	1000	1,584,300	B
46	850	1,565,900	B
48	800	2,630,900	B
Group 2D1R (0.002" clearance)			
3	2600	57,700	A
1	1500	361,800	B
5	1100	1,077,800	B
7	960	1,842,600	B
8	860	2,264,000	B
9	800	4,096,000	B
10	800	2,400,000	B

* A indicates fatigue crack through bolt hole; B indicates fatigue crack at edge of hole. See Figure 8.

TABLE 31. FATIGUE TEST RESULTS FOR SINGLE-BOLT SPECIMENS OF 0.156-INCH SHEET. REVERSED LOADING (BATTELLE)

(R = -0.50)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 3D1R (0.002" clearance)			
6	2200	231,900	A
8	1300	2,657,400	B

* A indicates fatigue crack through bolt hole; B indicates fatigue crack at edge of bolt hole. See Figure 8.

TABLE 32. FATIGUE TEST RESULTS FOR SINGLE-BOLT SPECIMENS OF 0.187-INCH SHEET. REVERSED LOADING. (BATTELLE)

(R = -0.50)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 4T1R (0.000" to -0.001" clearance)			
47	5000	2,600	B
8	3600	43,400	A
46	3600	43,600	A
5	3200	52,600	B
44	2800	92,700	B
2	2400	148,700	B
41	2200	285,700	B
6	1800	589,600	B
40	1500	777,700	A
4	1300	4,151,400	B
3	1100	1,069,400	A
42	1100	3,040,600	B
7	1000	8,823,400	B
45	1000	2,243,400	B
43	900	>8,511,000	
Group 4D1R (0.002" clearance)			
4	1300	1,449,200	B
6	1300	1,658,600	B
3	1000	6,258,600	
5	1000	1,658,600	B
Group 4L1R (0.010" clearance)			
1	2000	357,000	A
2	1400	992,900	B
5	1000	4,862,200	B

* A indicates fatigue crack through bolt hole; B indicates fatigue crack at edge of hole. See Figure 8.

TABLE 33. FATIGUE TEST RESULTS FOR TWO-BOLT SPECIMENS OF 0.187-INCH SHEET WITH BOLTS IN LINE OF LOAD. REVERSED LOADING. (BATTELLE)

(R = -0.50)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 4D2R (0.002" clearance)			
5	4500	25,900	A
3	3600	49,300	A
1	2800	125,600	A
2	2000	344,300	B
4	1500	1,134,800	B
6	1250	1,880,200	B
Group 4Q2R (0.050" clearance)			
6	4000	150,700	B
3	3000	125,600	B
1	2000	366,100	B
4	1500	966,800	B
5	1200	2,278,800	B

* A indicates fatigue crack through bolt hole; B indicates fatigue crack at edge of hole. See Figure 8.

TABLE 34. FATIGUE TEST RESULTS FOR SINGLE-BOLT SPECIMENS OF 0.250-INCH SHEET. REVERSED LOADING. (BATTELLE)

(R = -0.50)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 5T1R (0.000" to -0.001" clearance)			
8	4200	14,500	B
7	3000	90,600	B
6	2000	477,400	
9	1300	1,573,600	A
10	1000	> 10,419,700	
Group 5D1R (0.002" clearance)			
6	4200	18,200	A
4	3600	41,000	A
3	2700	222,500	A
2	2000	673,900	B
5	1500	1,195,000	B
1	1000	> 10,185,400	

* A indicates fatigue crack through bolt hole. B indicates fatigue crack at edge of hole. See Figure 8.

TABLE 35. FATIGUE TEST RESULTS FOR TWO-BOLT SPECIMENS OF 0.375-INCH SHEET WITH BOLTS IN LINE OF LOAD. REVERSED LOADING. (UNIVERSITY OF ILLINOIS)

(R = -0.50)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure
Group Bca (Bolt clearance = 0.000")		
1	4,910	90,900
2	7,940	10,200
3	5,430	51,000
4	3,980	212,200
5	3,520	458,100
6	2,990	245,500
7	3,230	372,200
8	6,990	18,200
10	3,210	527,100
11	6,010	54,800
12	6,010	30,900

TABLE 36. FATIGUE TEST RESULTS FOR THREE-BOLT SPECIMENS OF 0.375-INCH SHEET WITH BOLTS IN LINE OF LOAD. REVERSED LOADING (UNIV. OF ILLINOIS)

(R = -0.50)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure
Group Cca (Bolt clearance = 0.000")		
1	5,210	59,300
2	6,400	41,200
3	7,930	20,100
4	9,810	6,500
5	8,900	22,900
6	9,170	11,400
7	4,000	163,300
8	4,580	105,900
9	3,190	897,800
10	3,400	206,100

TABLE 37. FATIGUE TEST RESULTS FOR SIX-BOLT SPECIMENS OF 0.375-INCH SHEET WITH TWO ROWS OF THREE BOLTS EACH. REVERSED LOADING. (UNIV. OF ILLINOIS)

(R = -0.50)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure
Group Dca (Bolt clearance = 0.000^{+}		
1	12,030	73,400
2	10,010	385,700
3	10,970	160,600
4	12,910	73,000
5	13,930	59,100
6	14,840	49,600
7	17,920	24,000
8	19,960	28,300
9	21,690	12,100
10	9,590	144,100
11	8,990	287,800
12	8,010	287,400

TABLE 38. FATIGUE TEST RESULTS FOR NINE-BOLT SPECIMENS OF 0.375-INCH SHEET WITH THREE ROWS OF THREE BOLTS EACH. REVERSED LOADING. (UNIVERSITY OF ILLINOIS)

(R = -0.50)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure
Group Eca (Bolt clearance = 0.000")		
1	13,880	97,100
2	16,990	156,200
3	19,850	32,300
4	24,850	15,800
5	28,310	6,100
6	15,850	77,700
7	11,000	213,400
8	10,060	795,200
Group Ecd (Bolt clearance = +0.025")		
1	20,240	39,700
2	25,060	14,800
3	29,090	6,100
4	22,050	40,600
5	15,870	78,500
6	13,030	409,300
7	11,180	374,200
8	12,940	272,500

TABLE 39. FATIGUE TEST RESULTS FOR COUNTERSUNK SINGLE-BOLT SPECIMENS OF 0.156-INCH SHEET. (BATTELLE)

(R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 7D1U (0.002" clearance)			
Countersunk 1/2 way through sheet			
3	3600	37,300	A
4	2000	267,000	A
5	1200	2,219,500	B
6	1100	5,286,000	B
Countersunk all the way through top sheet			
9	3600	5,500	A
7	2000	17,200	A
11	1200	126,200	A
12	1000	1,062,700	A

* A indicates fatigue crack through bolt hole. B indicates fatigue crack at edge of bolt hole. See Figure 8.

TABLE 40. RESULTS OF FATIGUE TESTS ON BOLTED-JOINT SPECIMENS OF 0.102-INCH SHEET AND WITH HIGH VALUES OF BOLT TORQUE. REVERSED LOADING (BATTELLE)

(R = -0.50)

Specimen No.	Bolt Torque (Inch-Lbs.)	Maximum Load (Lbs.)	Cycles to Failure
50	300	3200	18,400
48	198	2600	33,300
42	108	2000	> 8,200
47	198	2000	84,000
41	108	1500	160,400
43	108	1200	311,800
40	108	1000	800,000

TABLE 41. FATIGUE TEST RESULTS FOR SPECIMENS OF 0.125-INCH SHEET WITH BOLTS OF 1/4" AND 15/32" DIAMETERS. UNIDIRECTIONAL LOADING. (BATTELLE)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group X2L1U (0.010" clearance - 1/4" bolts)			
7	4500	4000	A
5	3500	45,500	A
4	2600	72,700	B
3	2000	228,700	B
6	1500	345,000	B
8	1100	1,421,300	B
Group X2T1U (0.000" to-0.001" clearance - 1/4" bolts)			
3	3800	22,300	B
2	2800	124,600	B
1	2000	285,400	B
4	1500	640,000	B
5	1100	3,270,000	B
Group Y2T1U (0.000" to -0.001" clearance - 15/32" bolts)			
6	5200	18,500	A
4	4000	50,300	B
1	2800	197,300	B
2	2000	384,400	A
3	1500	1,569,400	A
9	1250	2,503,300	B
5	1100	3,334,600	B

* A indidates fatigue crack through bolt hole. B indicates fatigue crack at edge of bolt hole. See Figure 8.

TABLE 42. VARIATION OF FATIGUE STRENGTH AND RATIO OF BOLT DIAMETER TO SHEET THICKNESS

Sheet Thickness(t) (Inch)	Bolt Diameter(D) (Inch)	D/t	Fatigue Strength (Lbs.) of Single-bolt Specimen at R = +0.25		
			10^4 cycles	10^5 cycles	10^6 cycles
0.102	3/8	3.66	4200	2300	1150
0.125	7/16	3.50	5550	3300	1600
0.125	3/8	3.00	4950	2800	1350
0.187	3/8	2.00	6000	3700	1810
0.125	1/4	2.00	4200	2700	1220

TABLE 43. FATIGUE TEST RESULTS FOR TWO-BOLT SPECIMENS OF 0.102-INCH SHEET WITH BOLTS HAVING DIFFERENT FITS. (BATTELLE)

(R = +0.25)

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure	Position of Failure*
Group 1TL2U (one bolt, 0.000 to 0.001" clearance; other bolt, 0.010" clearance)			
2	6000	27,900	A
1	4000	83,500	B
3	2800	267,400	A
4	1500	947,000	A

* A indicates fatigue crack through bolt hole. B indicates fatigue crack at edge of hole. See Figure 8.

TABLE 44. FATIGUE TEST RESULTS FOR THREE-BOLT SPECIMENS OF 0.102-INCH SHEET WITH BOLTS HAVING DIFFERENT FITS. (UNIVERSITY OF ILLINOIS)

(R = +0.25)*

Specimen No.	R_a*	Actual Max. Load (Lbs.)	Corrected Max. Load** (Lbs.)	Cycles to Failure
151	+0.26	3060	3020	104,200
153	+0.27	2650	2600	159,100
155	+0.125	2450	2750	630,500
158	+0.25	2040	2040	2,254,000

* Nominal ratio is +0.25, R_a is the actual test ratio.

** Maximum load corrected (see Appendix II) to correspond to the nominal load ratio R = +0.25.

TABLE 45. UNIDIRECTIONAL FATIGUE TEST RESULTS ON 0.102-INCH SHEET MATERIAL

(R = +0.25)

Test	Specimen No.	Maximum Load Lbs.	Maximum Load p.s.i.	Cycles to Failure	Remarks
Unnotched sheet	3	6540	64,000	34,700	
	4	5120	50,000	98,500	
	1	3830	38,000	276,000	
	2	3050	30,000	902,100	
	6	2772	27,000	>5,335,200	Removed but later reloaded
		2772	27,000	+ 1,704,900	
	5	2560	25,000	>16,555,500	Did not fail
Sheet notched by bolt hole	8	5500	36,000	12,900	
	1	3475	30,000	63,400	
	4	3410	30,000	53,500	
	6	2720	24,000	100,500	
	2	2314	20,000	269,800	
	3	2316	20,000	266,500	
	5	2280	20,000	174,700	
	7	2050	18,000	235,400	
	10	1901	16,500	319,300	
	9	1724	15,000	6,751,500	
Sheet notched by bolt hole with "tight" fitting bolt	3	5240	45,000	133,900	Bolts drawn to 108-inch pounds
	2	2896	25,000	14,203,800	
	5	3999	35,000	25,000	Bolt not tightened
	7	2982	26,000	412,900	
Sheet notched by bolt hole with "loose" fitting Bolt	2	3800	33,000	306,500	Bolts drawn to 108-inch pounds
	3	2427	21,000	1,121,000	
	6	2995	26,000	73,500	Bolt not tightened

TABLE 46. UNIDIRECTIONAL FATIGUE TEST RESULTS FOR 0.102-INCH SHEET (UNIVERSITY OF ILLINOIS)

(R = +0.25)*

Specimen No.	R_a*	Actual Max. Load (Lbs.)	Corrected** Max. Load (Lbs.)	Cycles to Failure
01	+0.24	5950	6010	202,000
02	+0.24	4750	4800	455,300
03	+0.23	3770	3840	880,600
05	+0.25	3980	3980	1,282,600
04	+0.25	3460	3460	3,440,500 No fracture
		(R = +0.67)*		
011	+0.63	10,500	11,200	112,800
09	+0.58	9,700	11,100	171,000
019	+0.63	8,050	8,600	585,400
018	+0.64	6,750	7,100	2,031,400
		(R = -0.50)		
08	-0.55	6,000	6,160	31,900
06	-0.45	5,020	4,910	119,200
012	-0.50	4,050	4,050	200,600
010	-0.50	3,060	3,060	339,600
07	-0.47	3,040	3,000	1,256,300

* The nominal ratio is +0.25. R_a is the actual test ratio.

** Maximum load corrected (see Appendix II) to correspond to the nominal load ratio R = +0.25.

TABLE 47. UNIDIRECTIONAL FATIGUE TEST RESULTS FOR 0.102-INCH SHEET. SPECIMENS 1.5-INCHES WIDE WITH-3/8-INCH - D. HOLE. (UNIVERSITY OF ILLINOIS)

(R = +0.25)*

Specimen No.	R_a*	Actual Max. Load (Lbs.)	Corrected* Max. Load (Lbs.)	Cycles to Failure
008	+0.25	2920	2920	145,300
001	+0.25	2520	2520	184,900
006	+0.25	2110	2110	277,200
007	+0.26	1760	1740	1,114,600

* The nominal ratio is +0.25. R_a is the actual test ratio.

** Maximum load corrected (See appendix II) to correspond to the nominal load ratio R = +0.25.

TABLE 48. UNIDIRECTIONAL FATIGUE TEST RESULTS FOR 0.102-INCH SHEET. SPECIMENS LOADED THROUGH PIN BEARINGS. (BATTELLE)

$(R = +0.25)$

Specimen No.	Maximum Load (Lbs.)	Cycles to Failure
Specimens loaded through a single 3/8" pin		
26A	3000	10,400
29B	2500	35,100
1D1R30L	2000	54,300
1D1R30U	1500	131,800
27A	1000	374,500
30A	800	571,300
29A	600	>3,499,500
Specimens loaded through two 3/8" pins		
36B	3800	24,400
37B	3000	41,300
41A	2800	103,500
35B	2000	341,600
35A	1500	1,077,600
37A	1200	2,900,000

TABLE 49. LOADS SUPPORTED BY STATIC FRICTION OF LAP JOINTS

Type of Specimen	Sheet Gage (Inch)	Bolt Torque (Inch-Pounds)	Frictional Load (Lbs.)*
Single-Bolt	0.102	108	580
	0.102	180	900
	0.187	108	580
	0.187	198	860
	0.187	300	1190
Two bolts in line with load	0.102	108	790
	0.187	108	800
	0.187	198	1460
	0.187	300	1840

* The frictional loads recorded are tensile loads at which bolt slip (in a slightly elongated bolt hole) was first apparent. The values were reproducible, for a given specimen or for two similar specimens, to about ±10 per cent.

TABLE 50. ELONGATIONS OF BOLT HOLES IN SINGLE-BOLT TEST PIECES (BATTELLE)

Bolt Fit	Specimen Number	Maximum Load, Pounds	Cycles to Failure	Final Elongation, Inch*
Unidirectional Testing (R = +0.25)				
"Tight" (-0.0005" tolerance)	27	4,500	3,400	0.026
	6	4,200	16,500	0.011
	2	3,000	30,500	0.003
	26	2,200	75,800	0.003
	28	2,200	138,200	0.002
	2	2,100	122,000	0.000
	29	1,300	1,233,100	0.001
"Drill" (+0.002" tolerance)	—	3,600	—	0.009
"Loose" (+0.010" tolerance)	5	4,500	10,600	0.034
	1	4,000	13,100	0.016
	2	2,500	79,500	0.003
Reversed Loading (R = -0.50)				
"Tight" (-0.0005" tolerance)	22	3,500	>4,000	>0.007
	14	2,600	24,100	0.003
	8	1,900	56,300	0.002
"Drill" (+0.002" tolerance)	1	3,000	>3,100	>0.037
	5	1,500	94,500	0.011
	—	1,200	—	0.001
	2	1,000	599,900	0.000+

* Increase in longitudinal direction of diameter of bolt hole - measured after failure on bolt hole of uncracked half of test piece.

TABLE 51. DEFLECTION OF JOINT DURING TESTING (BATTELLE)

Time of Measurement	Measured Deflection, Inch(1)		Elongation of Bolt Hole, Inch	
			Computed(2)	Measured(3)
Specimen 34. Unidirectional Loading(4)				
1st Cycle	Min. Load	0.0070	0.002	
	Max. Load	0.0302		
10th Cycle	Min. Load	0.0207	0.008	
	Max. Load	0.0306		
1000th Cycle	Min. Load	0.0226	0.009	
	Max. Load	0.0293		
62,300 Cycles	(Failure)			0.0086
Specimen 47. Reversed Loading(5)				
1st Cycle	Min. Load	0.0038	0.002	
	Max. Load	0.0072		
1000th Cycle	Min. Load	0.0016	0.001	
	Max. Load	0.0057		
After 1.6 x 10^5 Cycles	Min. Load	0.0018	0.001	
	Max. Load	0.0056		
461,400 Cycles	(Failure)			0.0005

(1) Measured slip of the joint starting from a "zero" under mild compressive load.

(2) Computed as one-half deflection minus bolt tolerance (0.002 inch).

(3) Measured after failure on uncracked half of specimen.

(4) Specimen 34: Single-bolt test piece, "drill" fit, loaded at 3600 pounds max. at R = +0.25.

(5) Specimen 47: Single-bolt test piece, "drill" fit, loaded at 1200 pounds max. at R = -0.50.

TABLE 52. SPECIMENS REMOVED DUE TO EXCESSIVE VIBRATION OF TESTING MACHINE*

(Single-Bolt Specimens of 0.102-Inch Sheet, at R = -0.50)

Bolt Fit	Maximum Load, Pounds	Number of Cycles at Which Specimen Was Removed
"Tight"	3500	3300
"Drill"	3000	3100
"Loose"	1000	5000

* Recorded at Battelle for one particular testing machine.

TABLE 53. EFFECT ON FATIGUE STRENGTHS OF INCREASING THE NUMBER OF BOLTS IN THE DIRECTION OF LOADING

Sheet Gage (Inch)	Specimen		Static Strength (Lbs./Bolt)	Maximum Loads** (Lbs./Bolt) for Various Lifetimes at R = +0.25		
	Type*	Number of Bolts		10^4 Cycles	10^5 Cycles	10^6 Cycles
A. Unidirectional Loading						
0.102 Battelle Tests	A	1	5200	4400	2300	1180
	B	2	3800	3200	1900	850
	C	3	2330	2330	1530	600
Illinois Tests	A	1	(5200)		2050	1050
	B	2	(3800)		1275	650
0.125	A	1	6200	5000	2800	1320
	C	3	3200	3000	1830	830
0.187	A	1	8500	6000	3750	1800
	B	2	7200	4100	2530	1250
0.375	A	1		7700	4000	2400
	B	2		5050	2500	1600
	C	3		4670	2170	1200
	E	6 (2 rows)		5500	2910	1830
	F	9 (3 rows)		4670	2220	1470
B. Reversed Loading				Maximum Load (Lbs./Bolt) for Various Lifetimes at R = -0.50		
0.102 Battelle Tests	A	1	5200	3700	2000	980
	B	2	3800		1500	630
Illinois Tests	A	1	(5200)		1700	850
	B	2	(3800)		1000	550
0.187	A	1	8500	4800	3000	1450
	B	2	7200		1580	750
0.375	B	2		4000	2400	1450
	C	3		3070	1500	1070
	E	6 (2 rows)		4000	1910	1250
	F	9 (2 rows)		3000	1830	1000

* See Figure 1 for details of various specimen types.

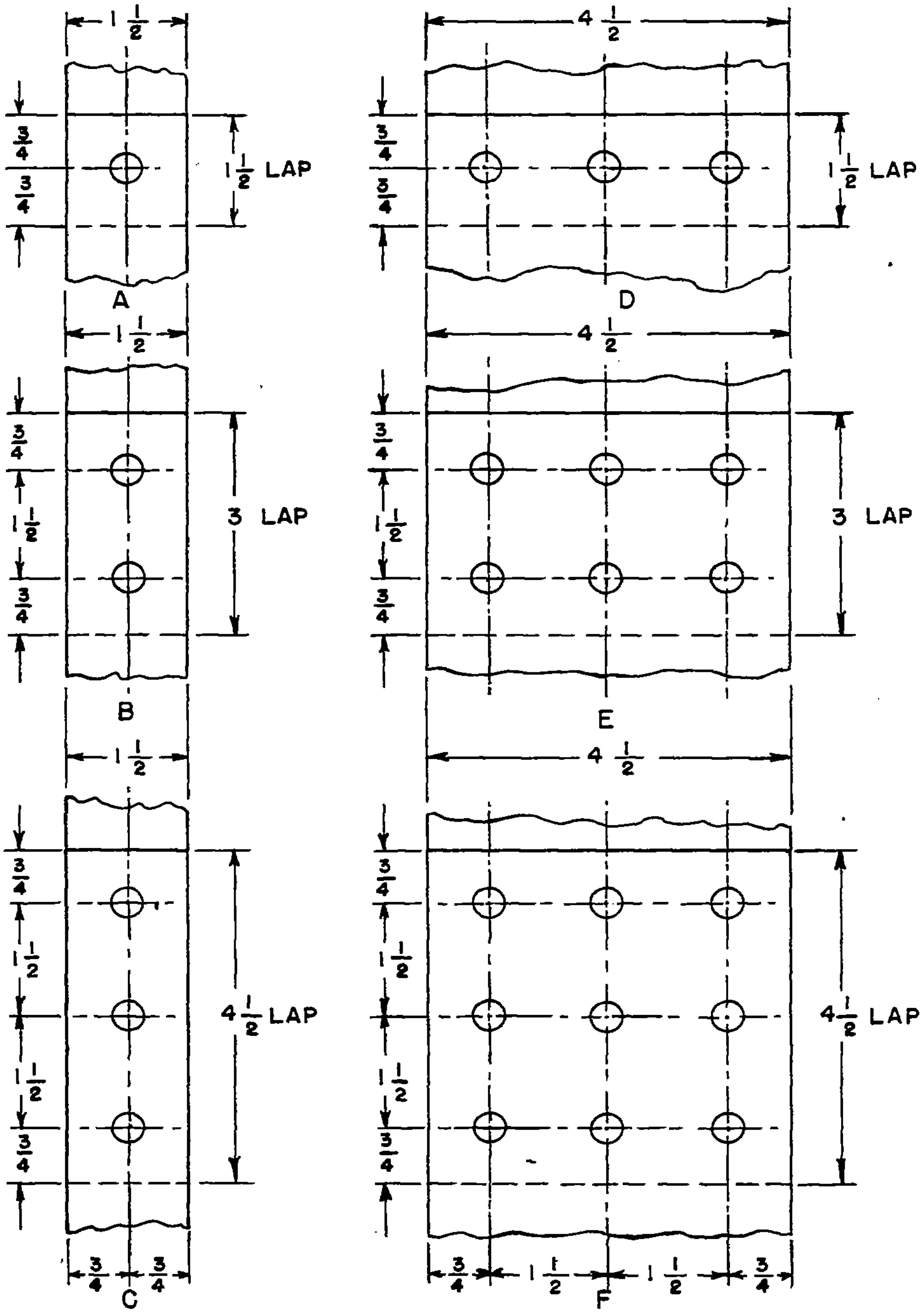
** Values read from solid line curves in load-life diagrams.

TABLE 54. FATIGUE STRENGTHS OF SINGLE-BOLT SPECIMENS AND OF SPECIMENS WITH A ROW OF 3 BOLTS

Test Condition	Sheet Gage (Inch)	Specimen 1			Specimen 2			Ratio Strengths
		Type[1]	No. Bolts	Load[2] (Lbs.)	Type[1]	No. Bolts	Load[2] (Lbs.)	
Static	0.102	A	1	5200	C	3	15,700	3.0
R = +0.25, 10^5 cycles		A	1	2300	C	3	6,500	2.8
R = -0.50, 10^5 cycles		A	1	2000	C	3	5,000	2.5
Static	0.187	A	1	8500	C	3	25,400	3.0
R = +0.25, 10^6 cycles		A	1	1800	C	3	5,600	3.3
R = +0.25, 10^5 cycles	0.375	B	2	5000	E	6	17,500	3.5
Ditto		C	3	6500	F	9	20,000	3.1
R = -0.50, 10^5 cycles		B	2	4800	E	6	11,500	2.4
Ditto		C	3	4600	F	9	16,500	3.6

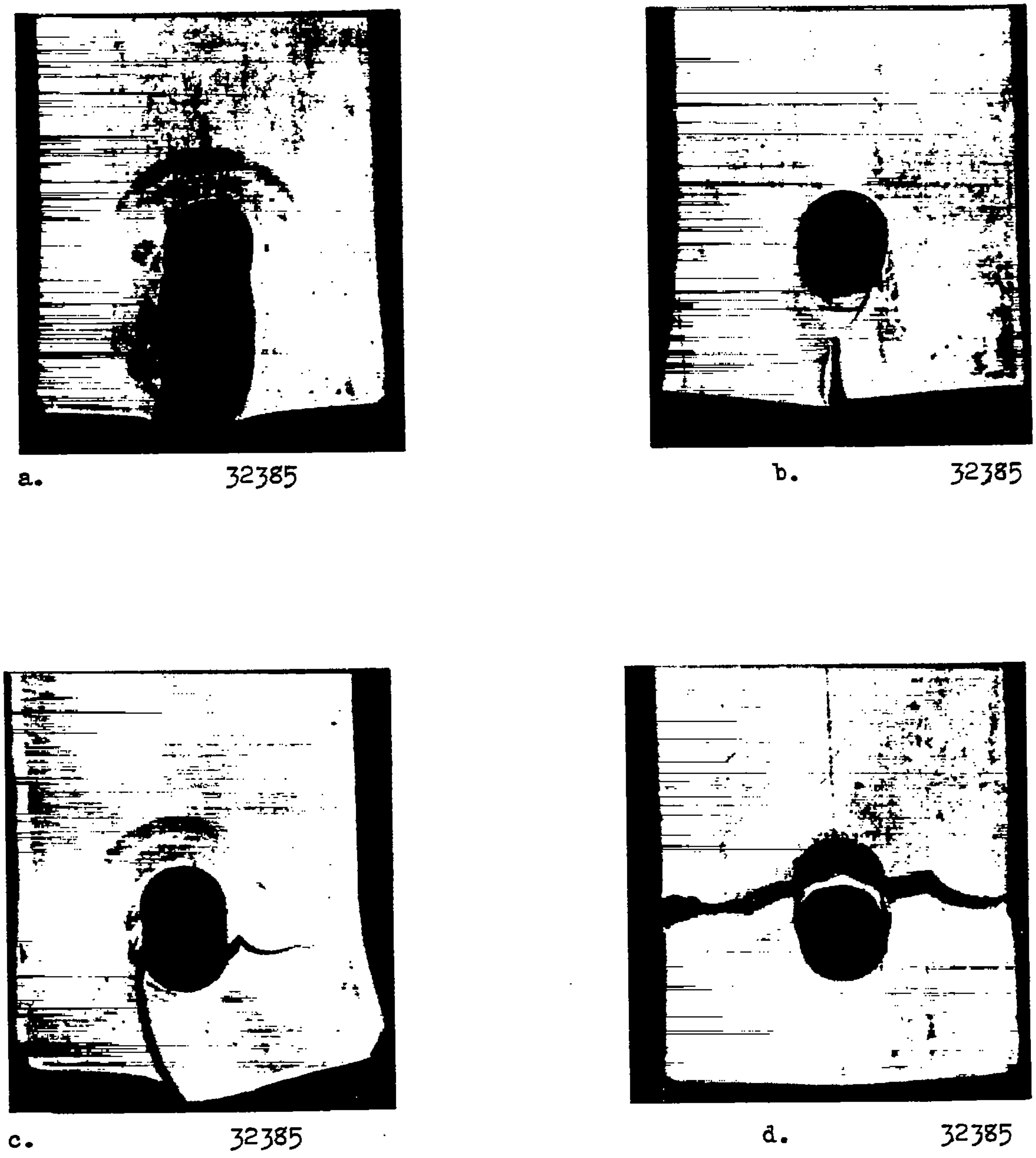
1. Details of specimen types are given in Figure 1.

2. Load values for fatigue tests are read from solid-line curves in preceding load-life diagrams.



ALL DIMENSIONS IN INCHES.

FIG. 1 – BOLT PATTERNS USED IN FATIGUE TEST SPECIMENS (TYPES E AND F USED ONLY FOR 0.375" SHEET).



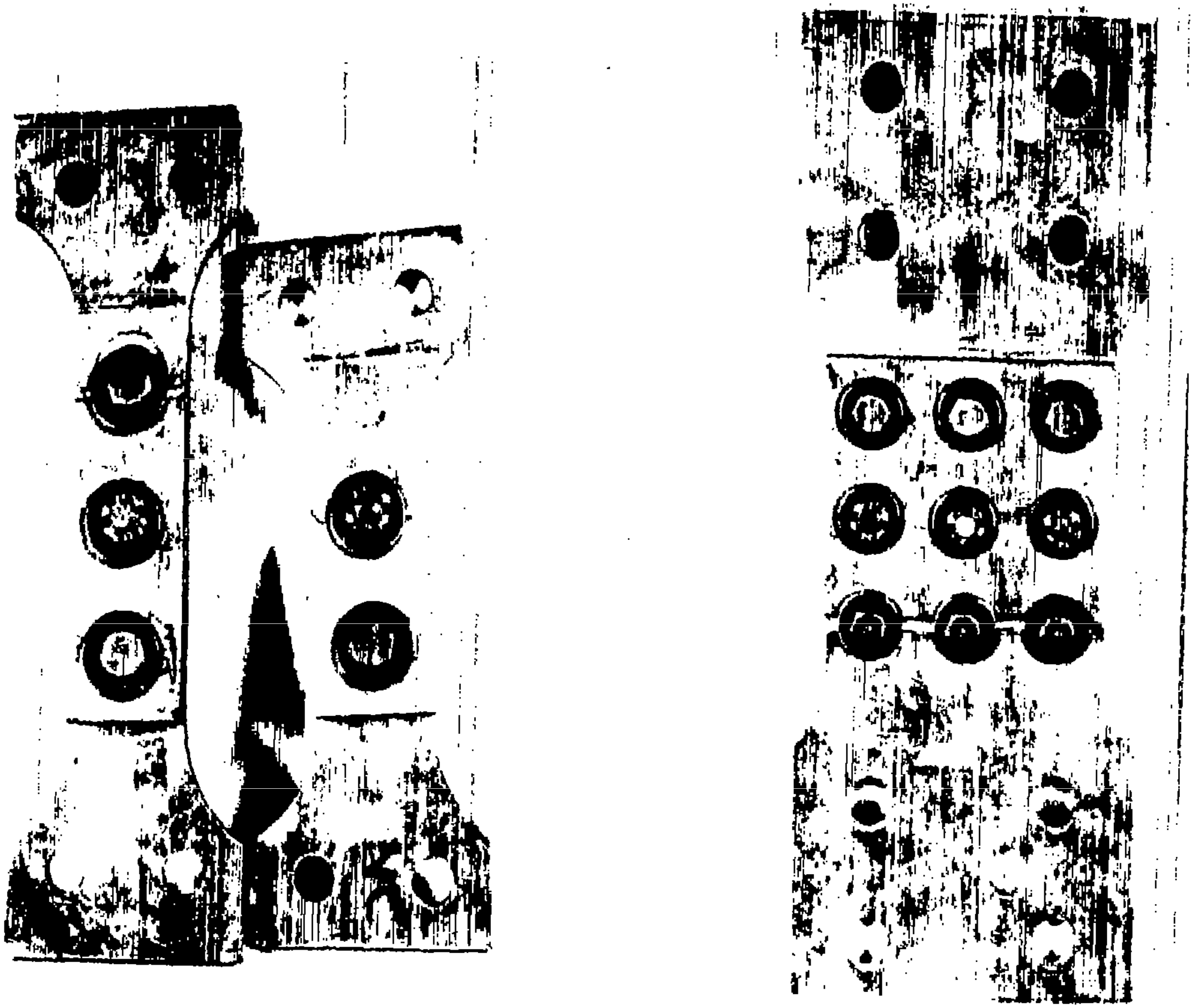
a. 32385

b. 32385

c. 32385

d. 32385

Figure 2. Typical static failure of single-bolt test pieces. (Battelle)



a. 36582

b. 36579

Figure 3. Typical static failures of multibolt test pieces.

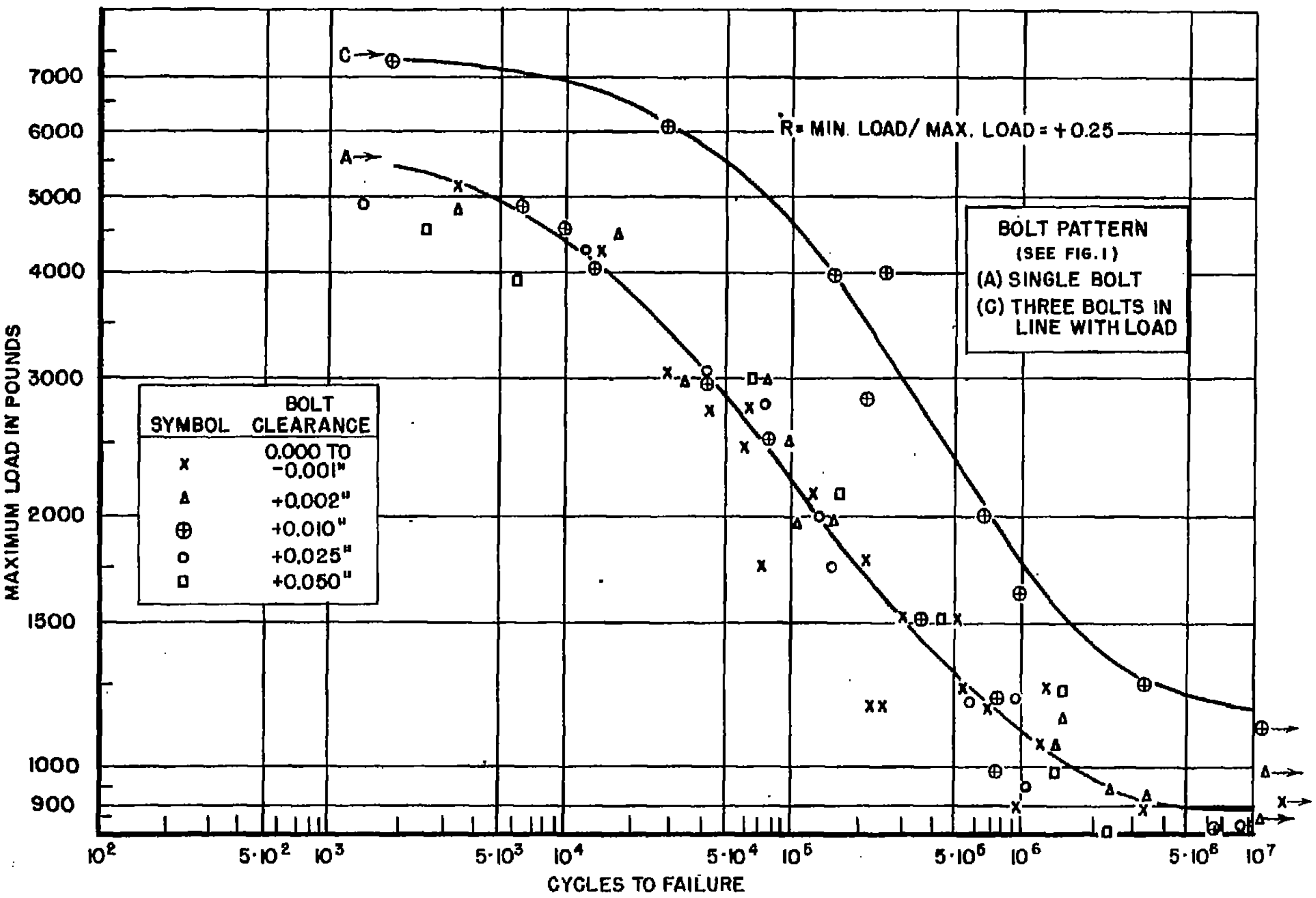


FIGURE 4 – FATIGUE CURVES, UNIDIRECTIONAL LOADING, SPECIMENS OF 0.102" SHEET. (BATTELLE)

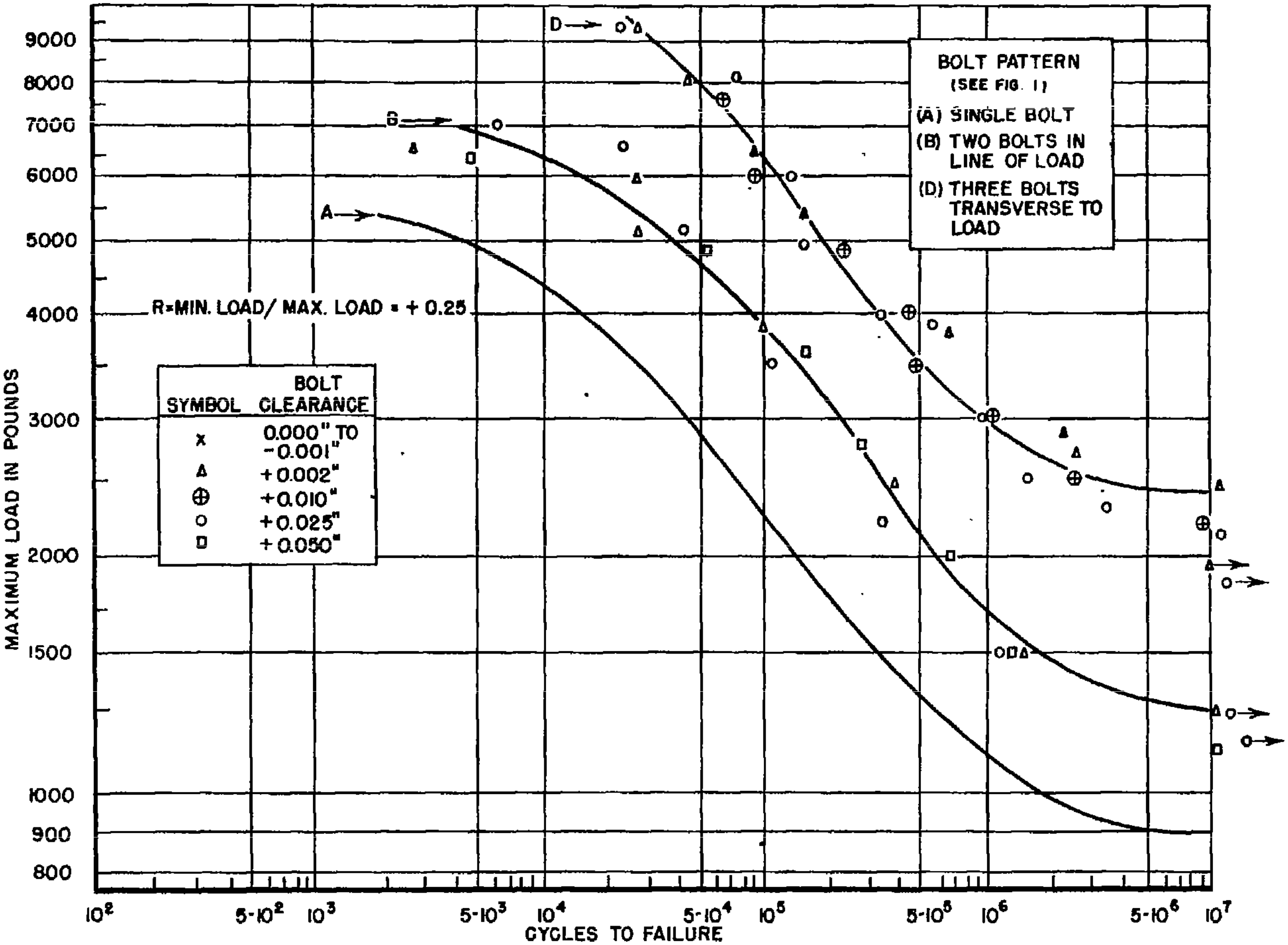


FIGURE 5 - FATIGUE CURVES, UNIDIRECTIONAL LOADING, SPECIMENS OF 0.102" SHEET. (BATTELLE)

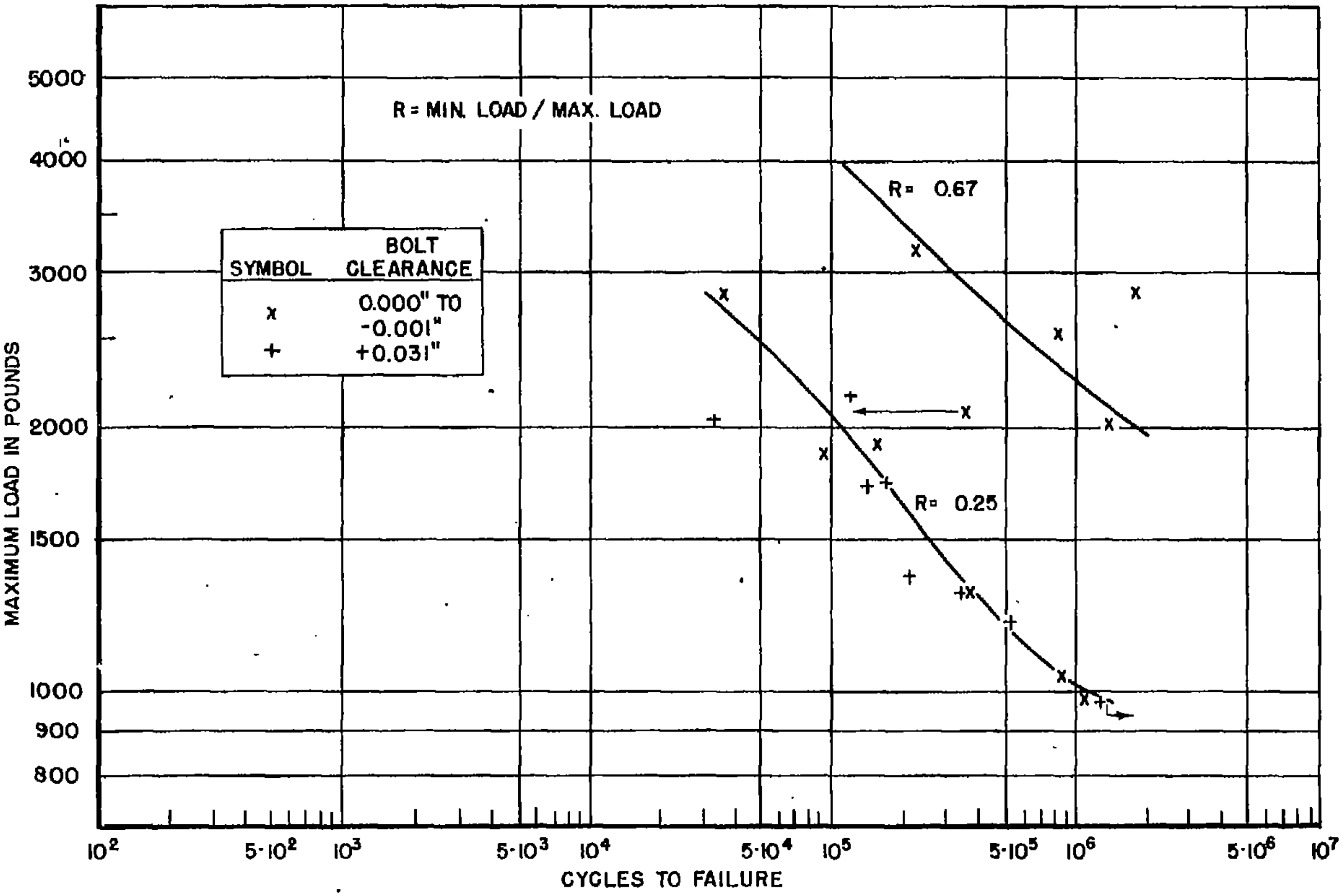


FIGURE 6 – FATIGUE CURVES, UNIDIRECTIONAL LOADING, SINGLE-BOLT SPECIMENS OF 0.102" SHEET. (UNIV. OF ILLINOIS)

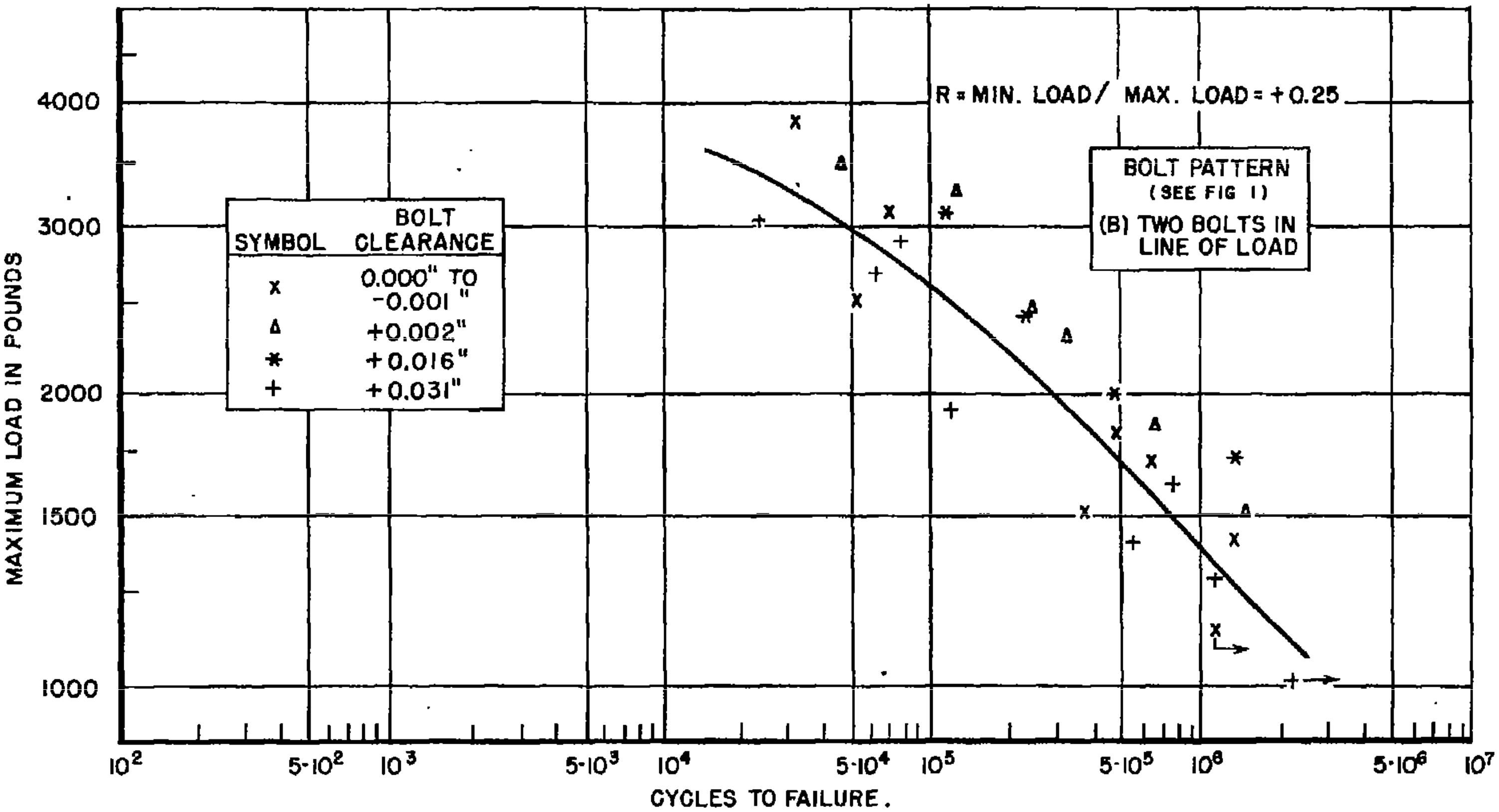


FIGURE 7 - FATIGUE CURVE, UNIDIRECTIONAL LOADING, TWO-BOLT SPECIMENS OF 0.102" SHEET (UNIV. OF ILLINOIS.)

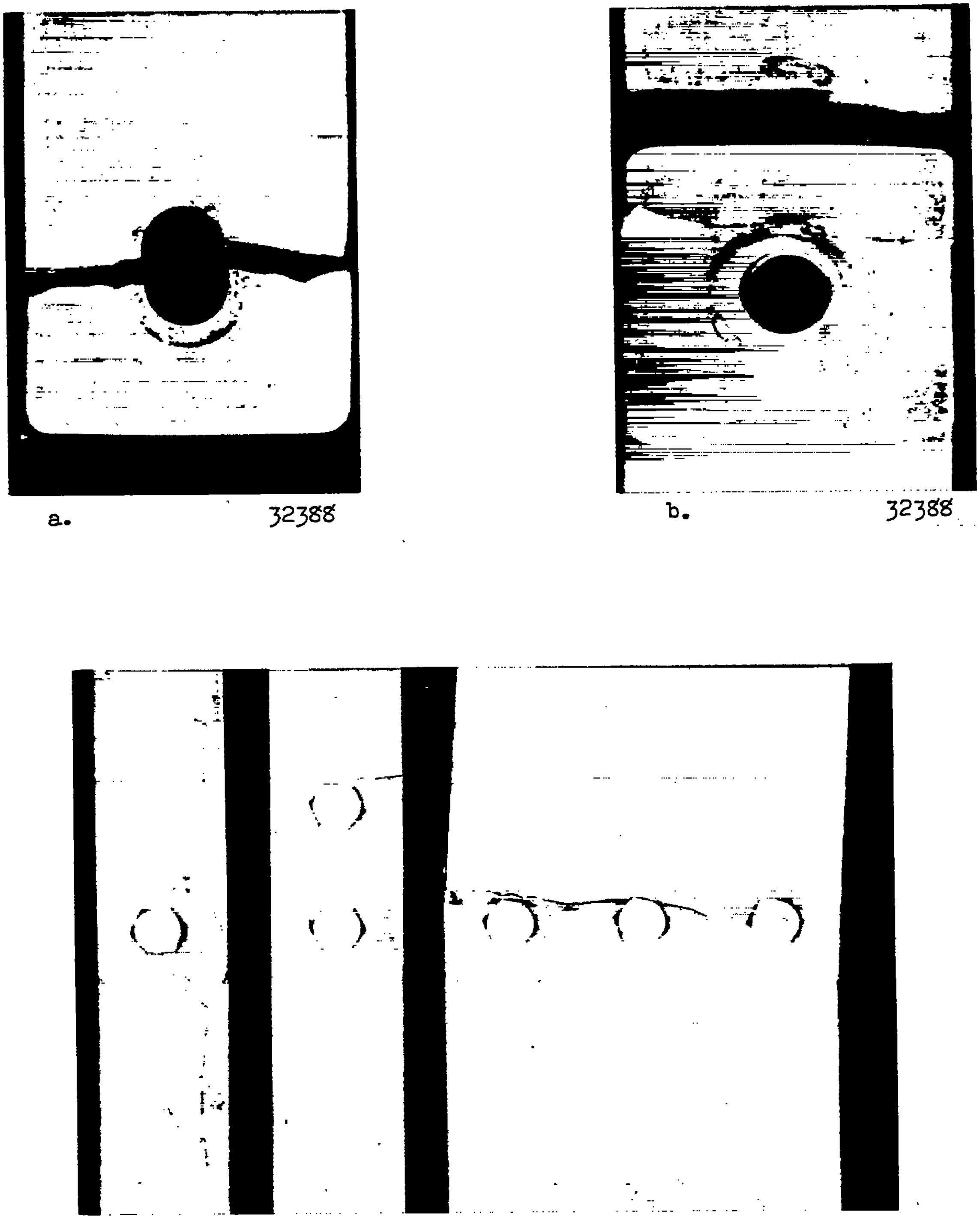


Figure 8. Typical fatigue failures in specimens of 0.102-inch sheet.

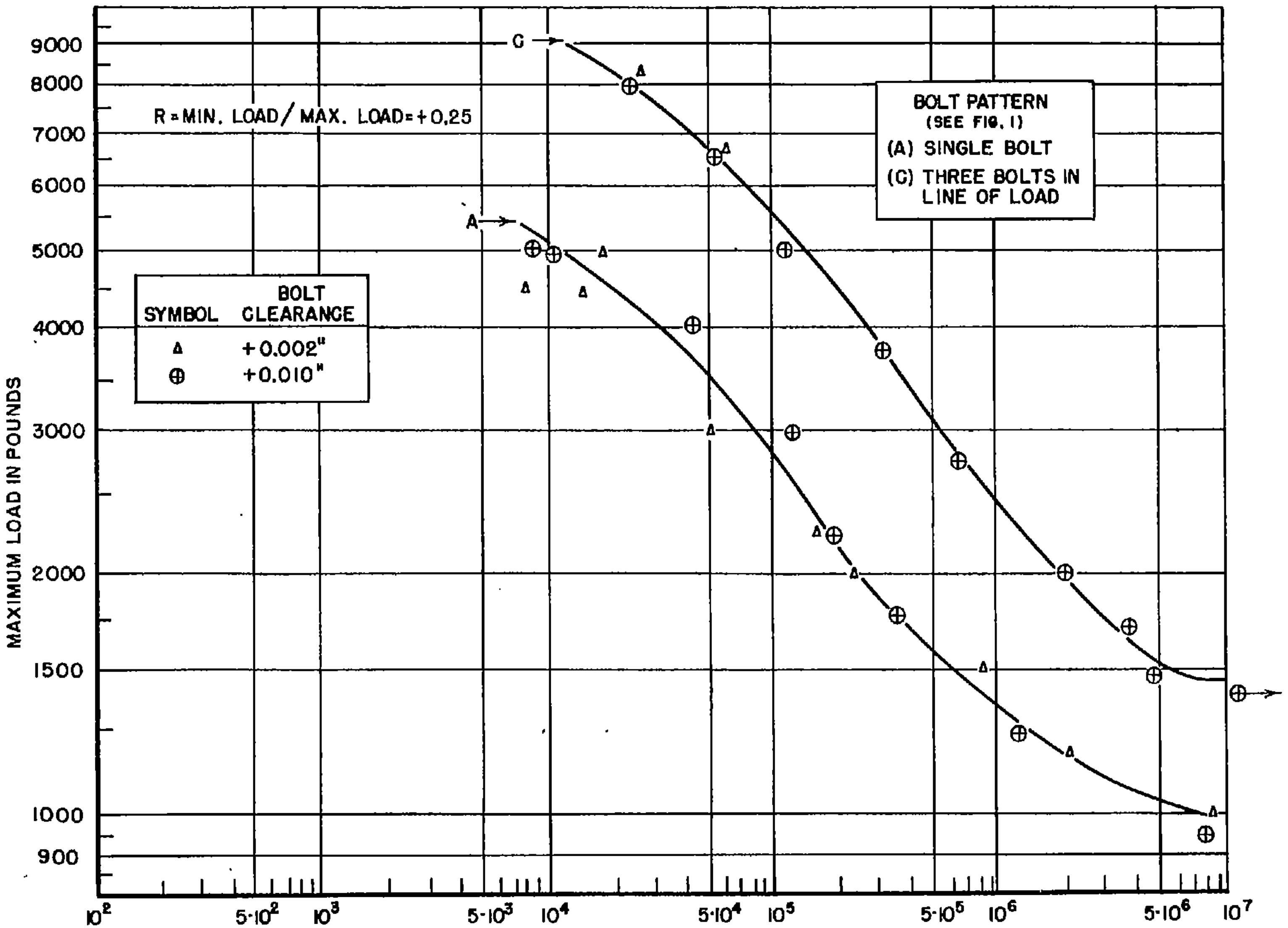


FIGURE 9 - FATIGUE CURVES, UNIDIRECTIONAL LOADING, SPECIMENS OF 0.125" SHEET. (BATTELLE)

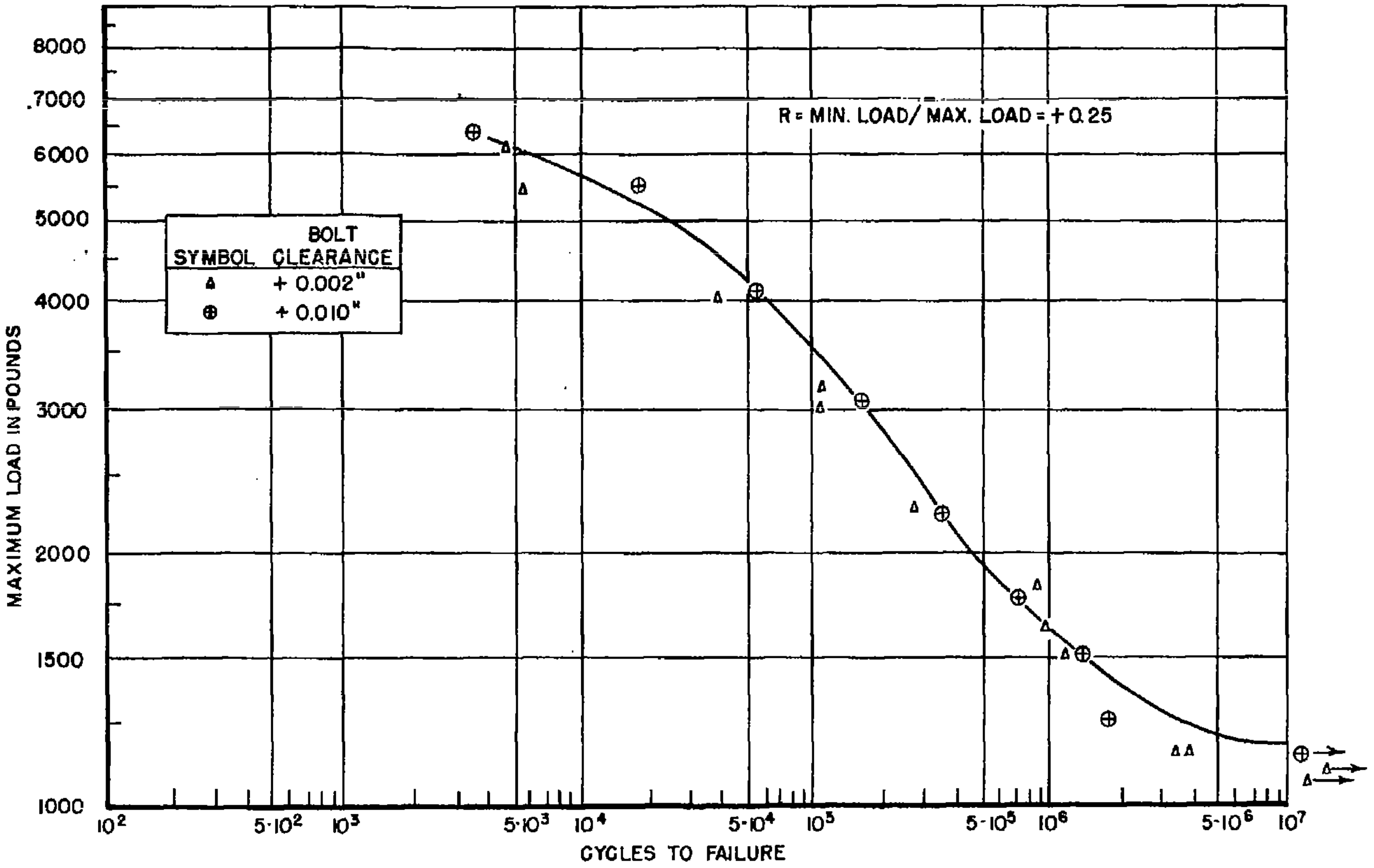


FIGURE 10 - FATIGUE CURVE, UNIDIRECTIONAL LOADING, SINGLE-BOLT SPECIMENS OF 0.156" SHEET.
(BATTELLE)

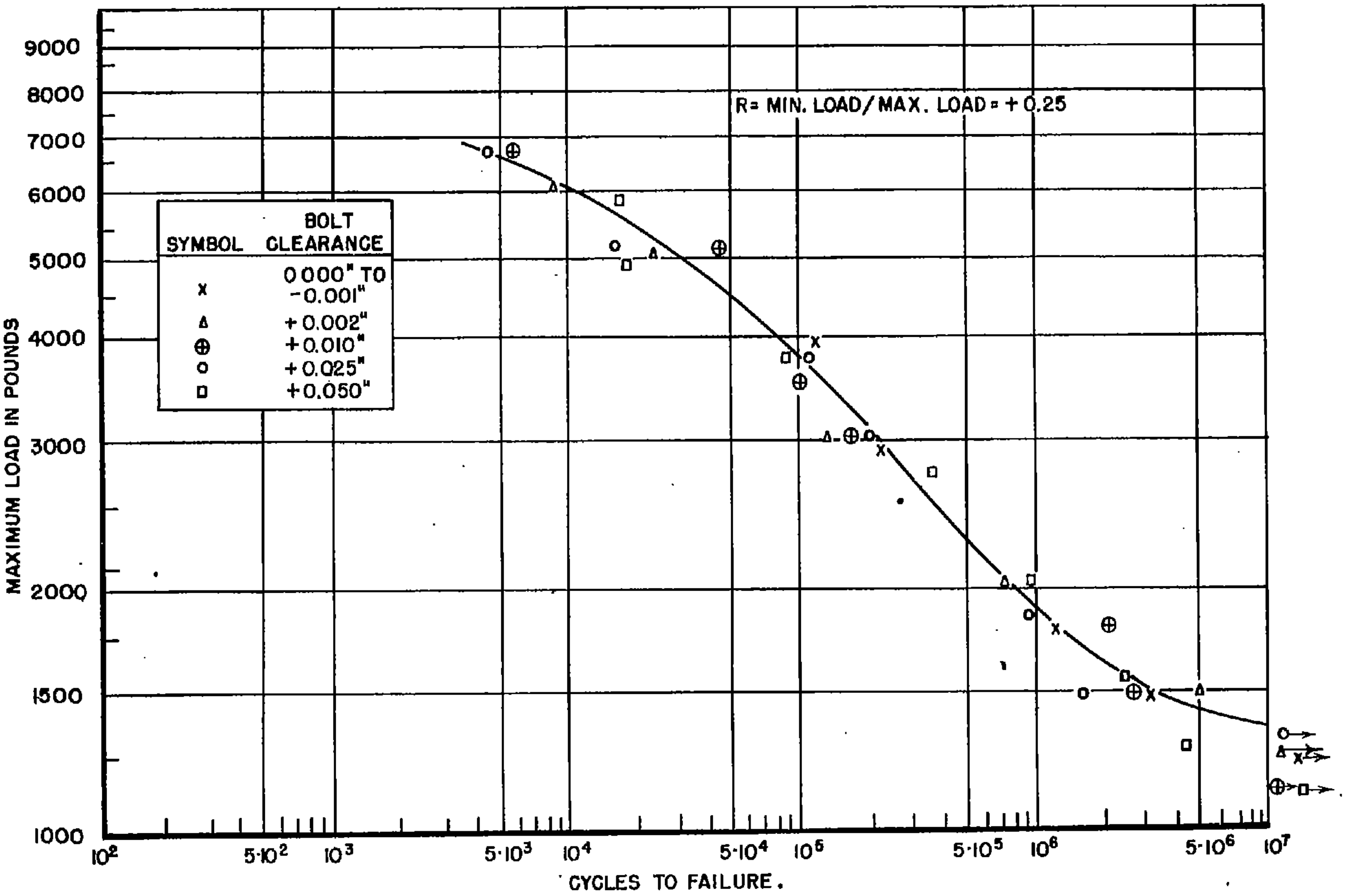


FIGURE 11–FATIGUE CURVE, UNIDIRECTIONAL LOADING, SINGLE-BOLT SPECIMENS OF 0.187" SHEET.
(BATTELLE)

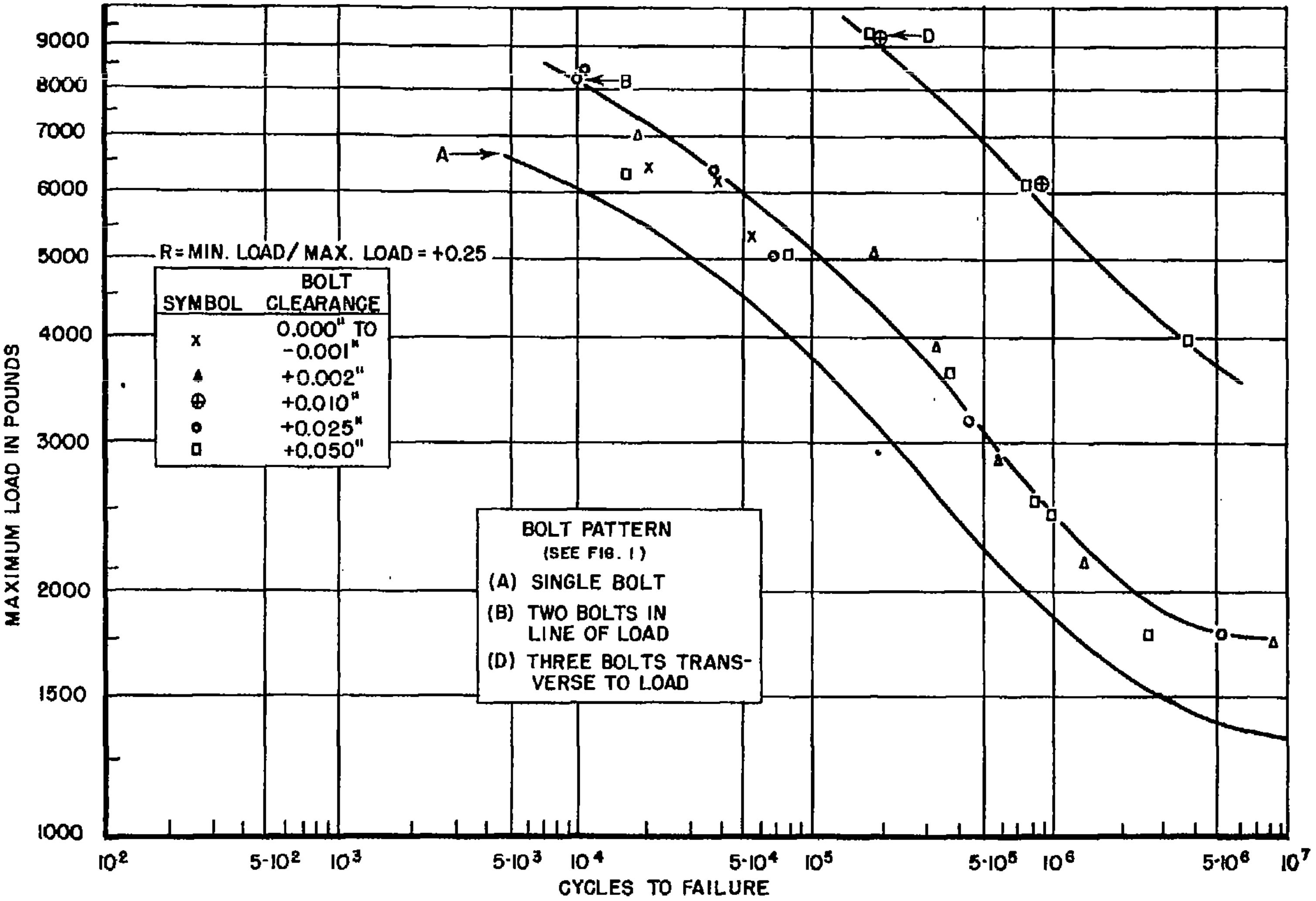


FIGURE 12 – FATIGUE CURVES, UNIDIRECTIONAL LOADING, SPECIMENS OF 0.187" SHEET. (BATTELLE)

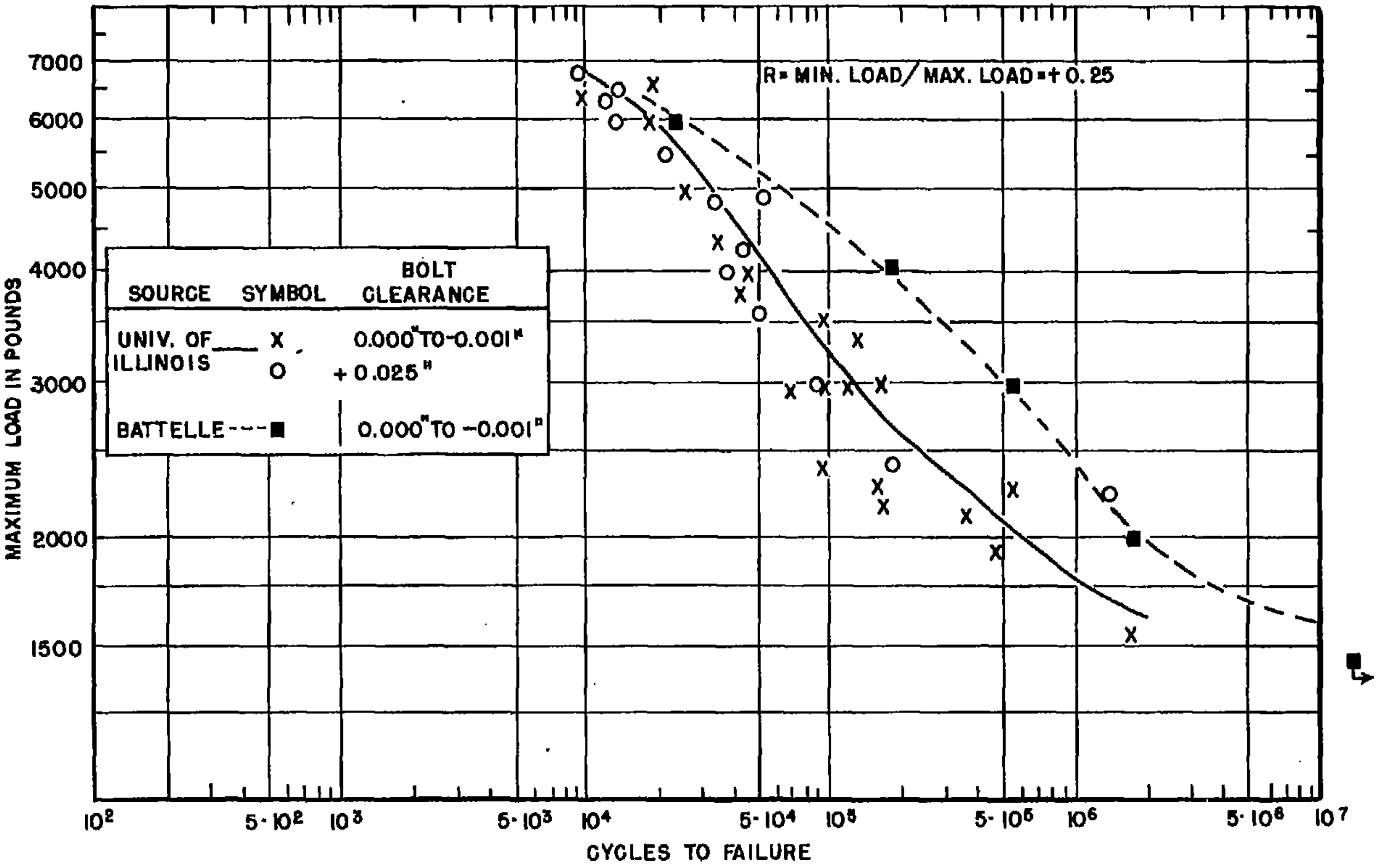


FIGURE 13- FATIGUE CURVES, UNIDIRECTIONAL LOADING, SINGLE-BOLT SPECIMENS OF 0.250" SHEET

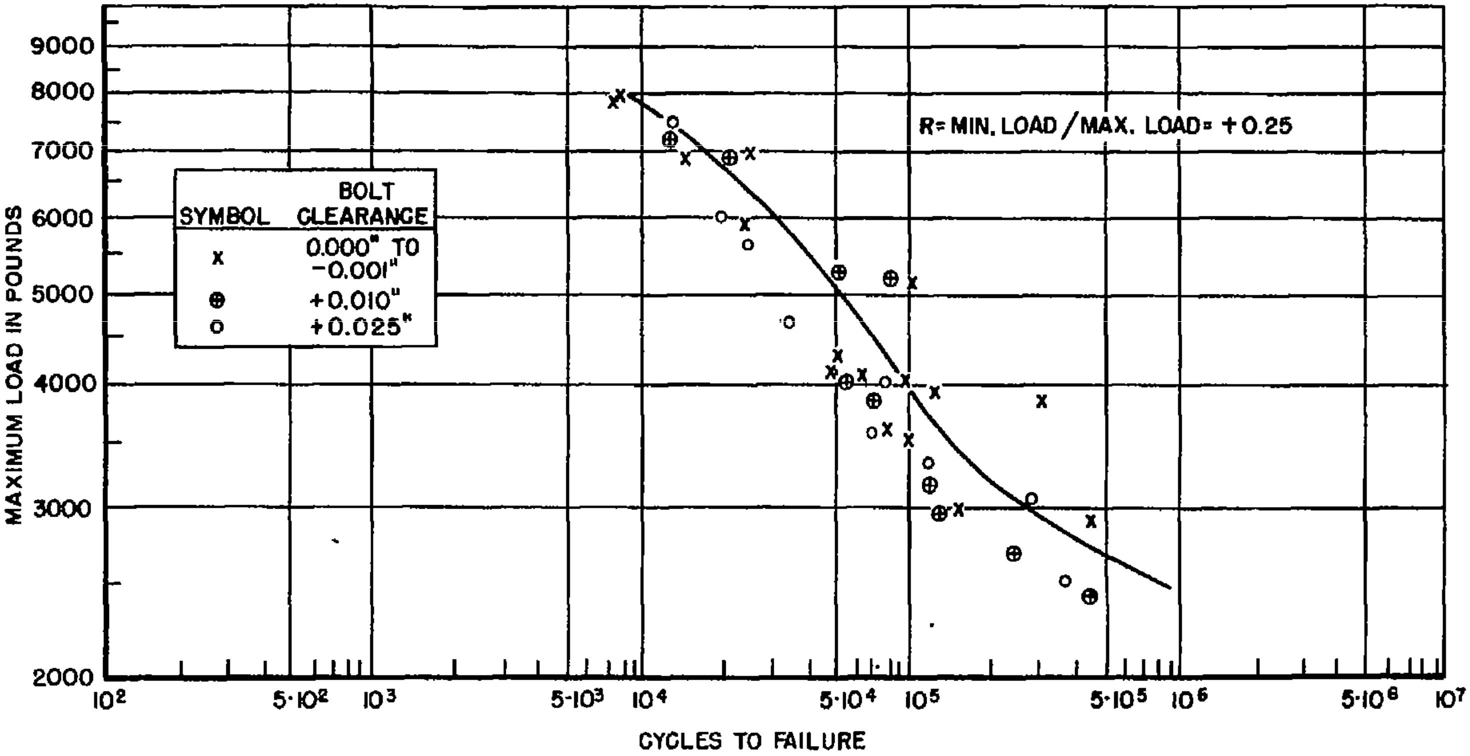


FIGURE 14 - FATIGUE CURVE, UNIDIRECTIONAL LOADING, SINGLE-BOLT SPECIMENS OF 0.375" SHEET. (UNIV. OF ILLINOIS)

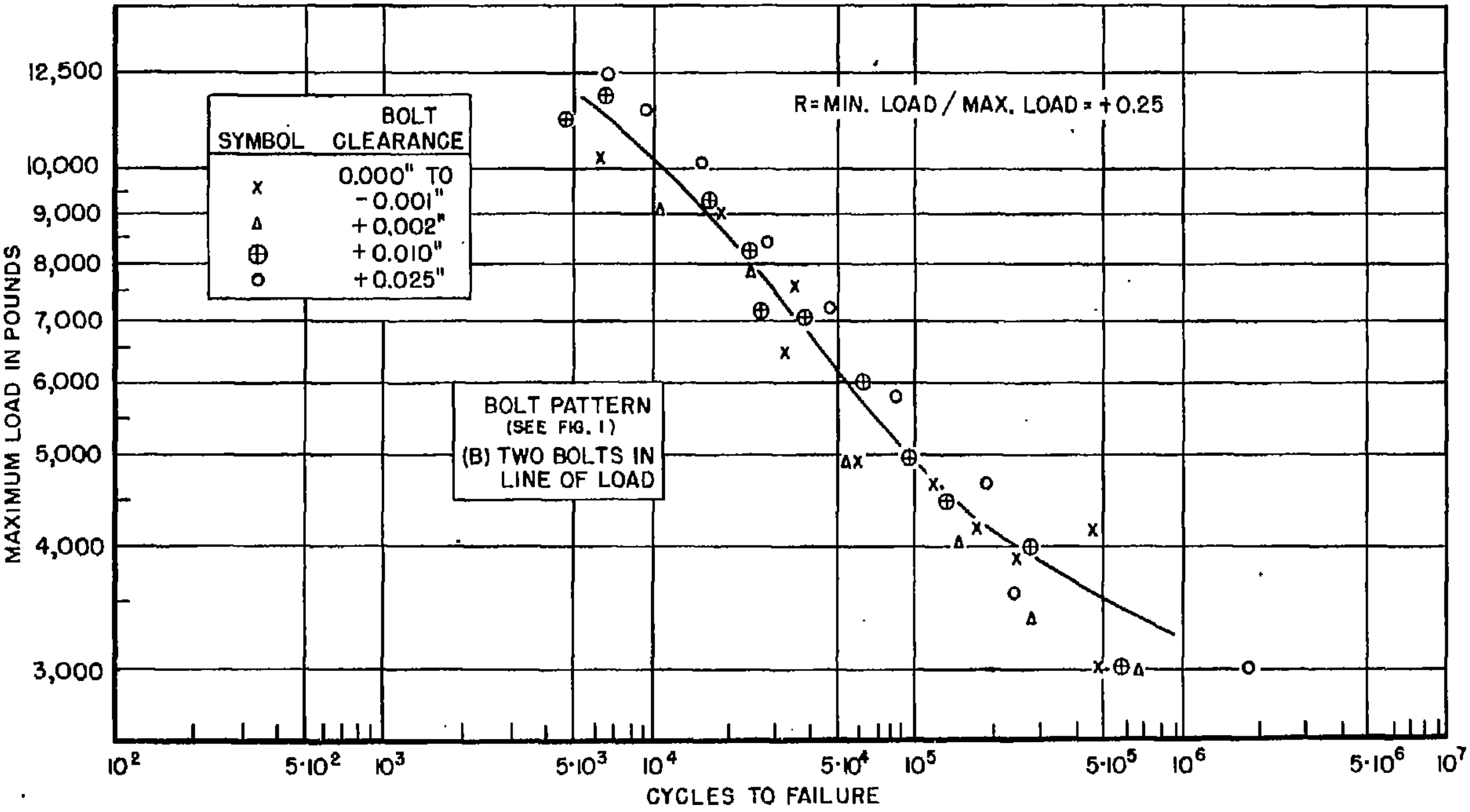


FIGURE 15 - FATIGUE CURVE, UNIDIRECTIONAL LOADING, TWO-BOLT SPECIMENS OF 0.375" SHEET. (UNIV. OF ILLINOIS)

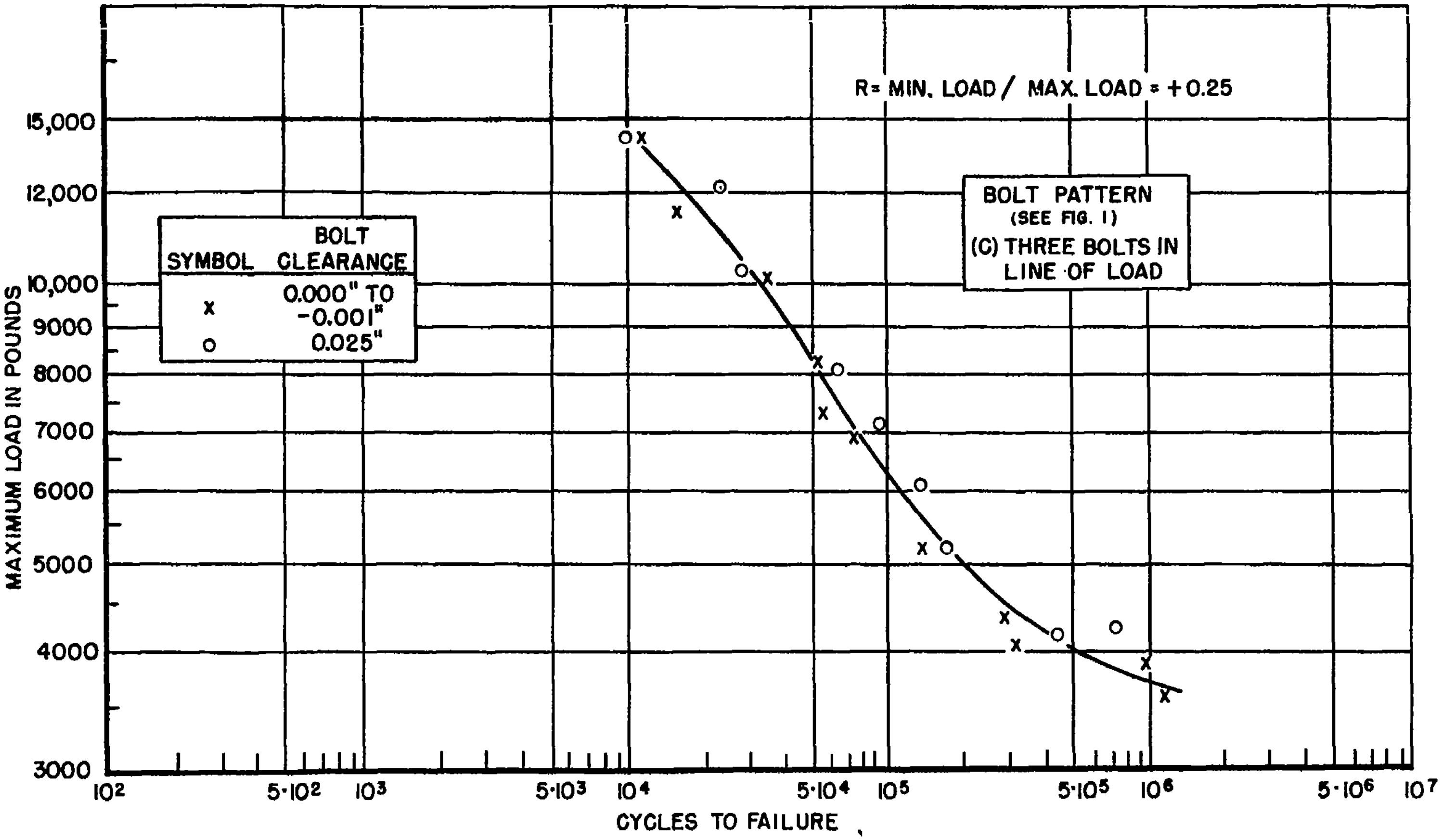


FIGURE 16 - FATIGUE CURVE, UNIDIRECTIONAL LOADING, THREE-BOLT SPECIMENS OF 0.375" SHEET. (UNIV. OF ILLINOIS)

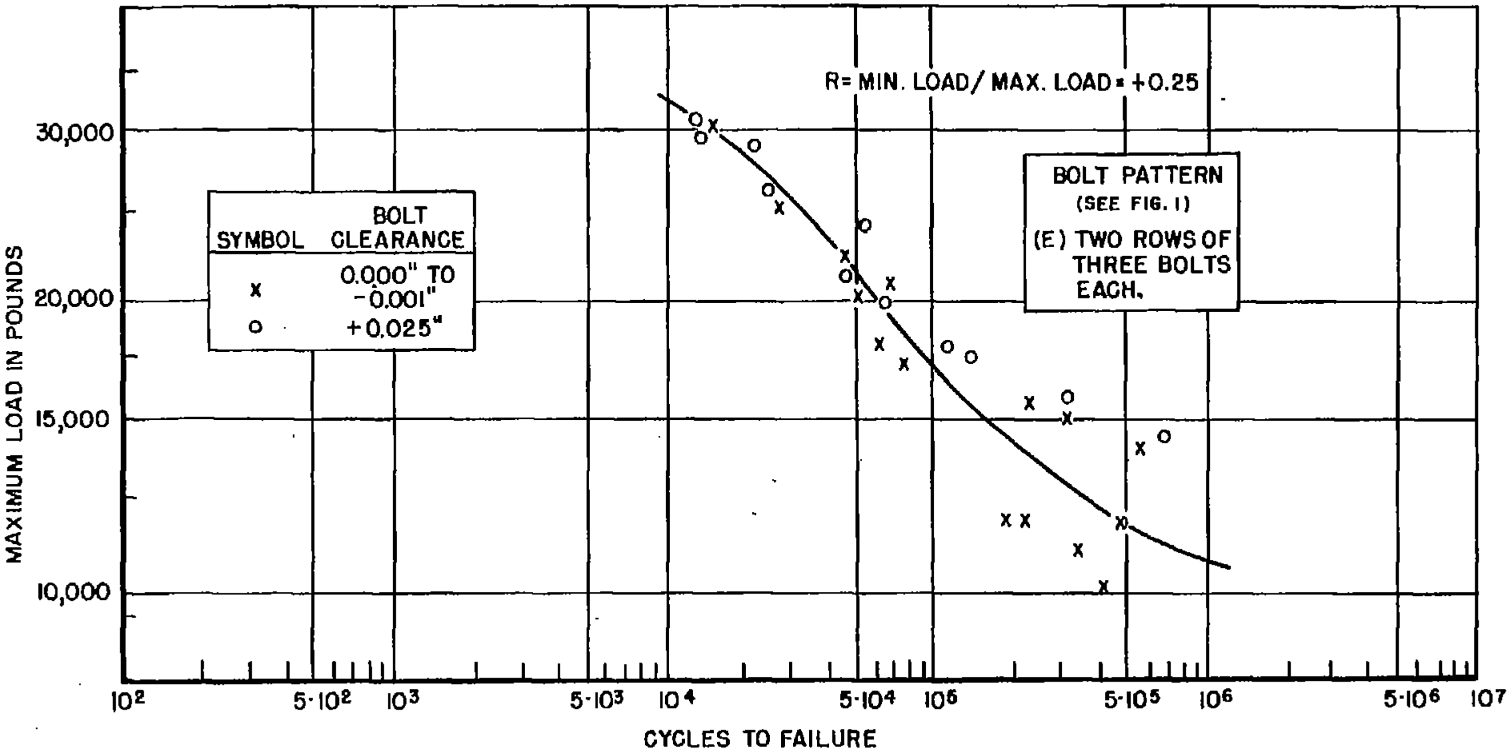


FIGURE 17 - FATIGUE CURVE, UNIDIRECTIONAL LOADING, SIX-BOLT SPECIMENS OF 0.375" SHEET. (UNIV. OF ILLINOIS)

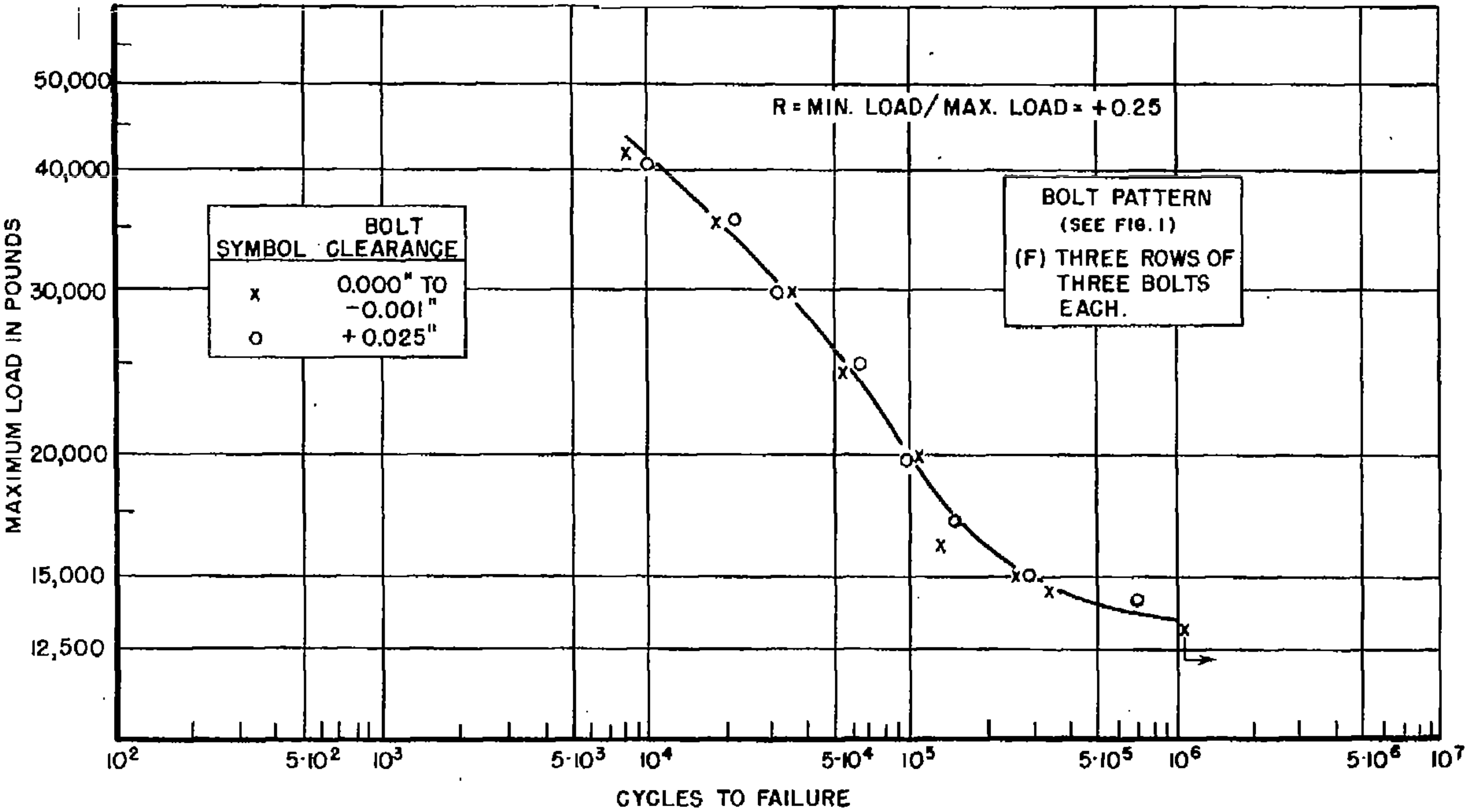
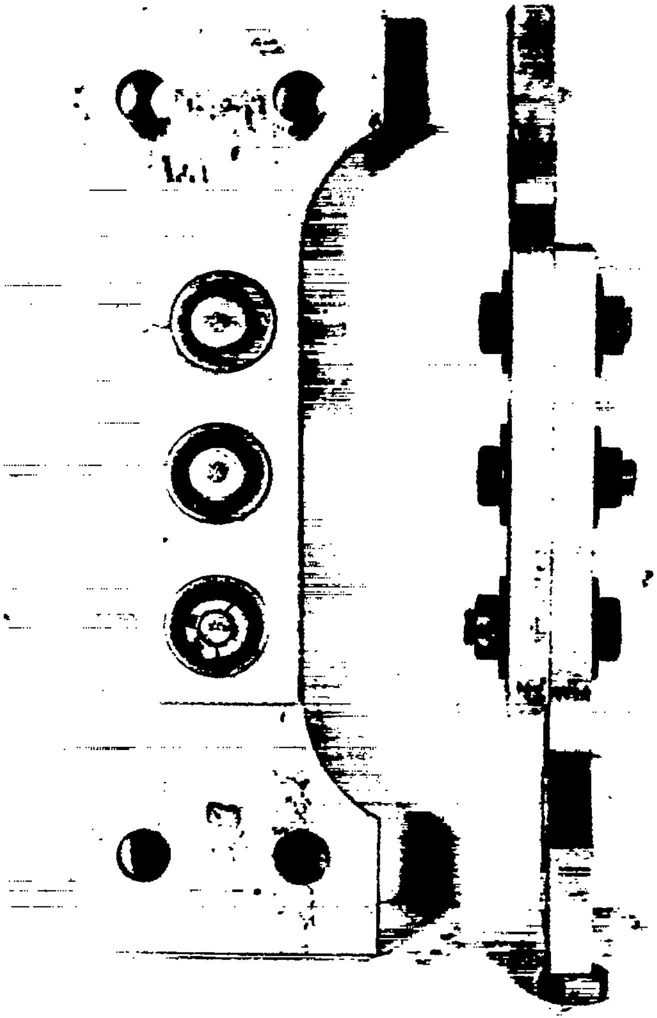


FIGURE 18 - FATIGUE CURVE, UNIDIRECTIONAL LOADING, NINE-BOLT SPECIMENS OF 0.375" SHEET. (UNIV. OF ILLINOIS)



36574

Figure 19. Fatigue failures of three-bolt joints in 0.375-inch sheet.

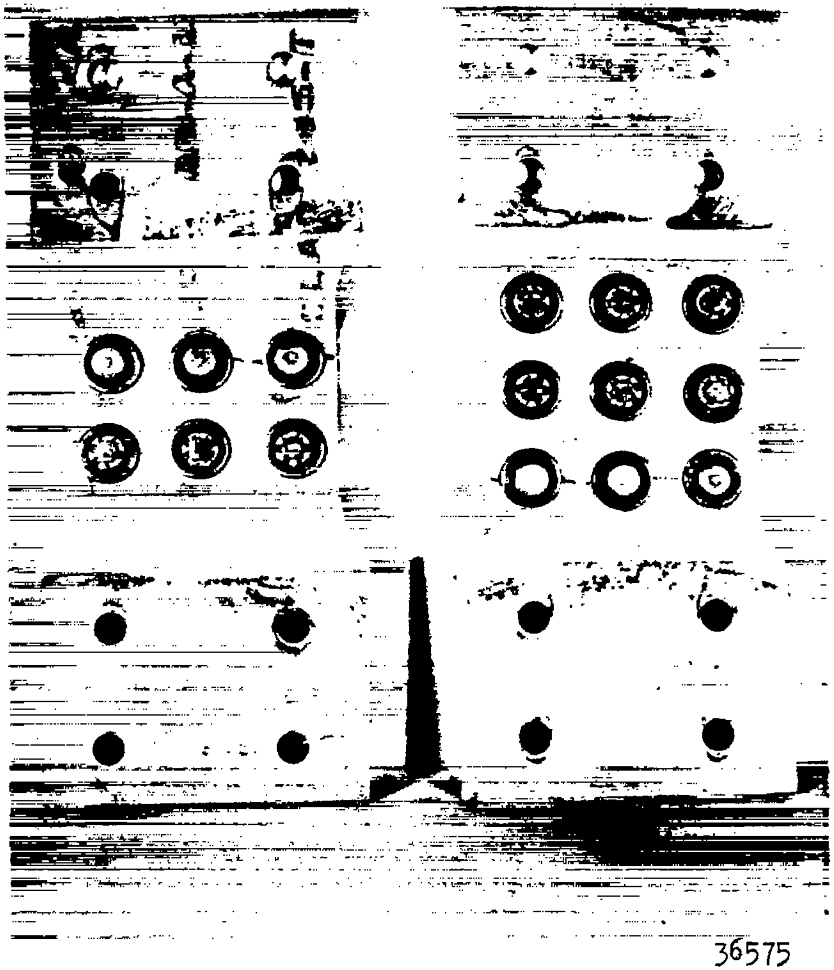


Figure 20. Character of fatigue failure for joints with three bolts in a transverse row connecting 0.375-inch sheet.

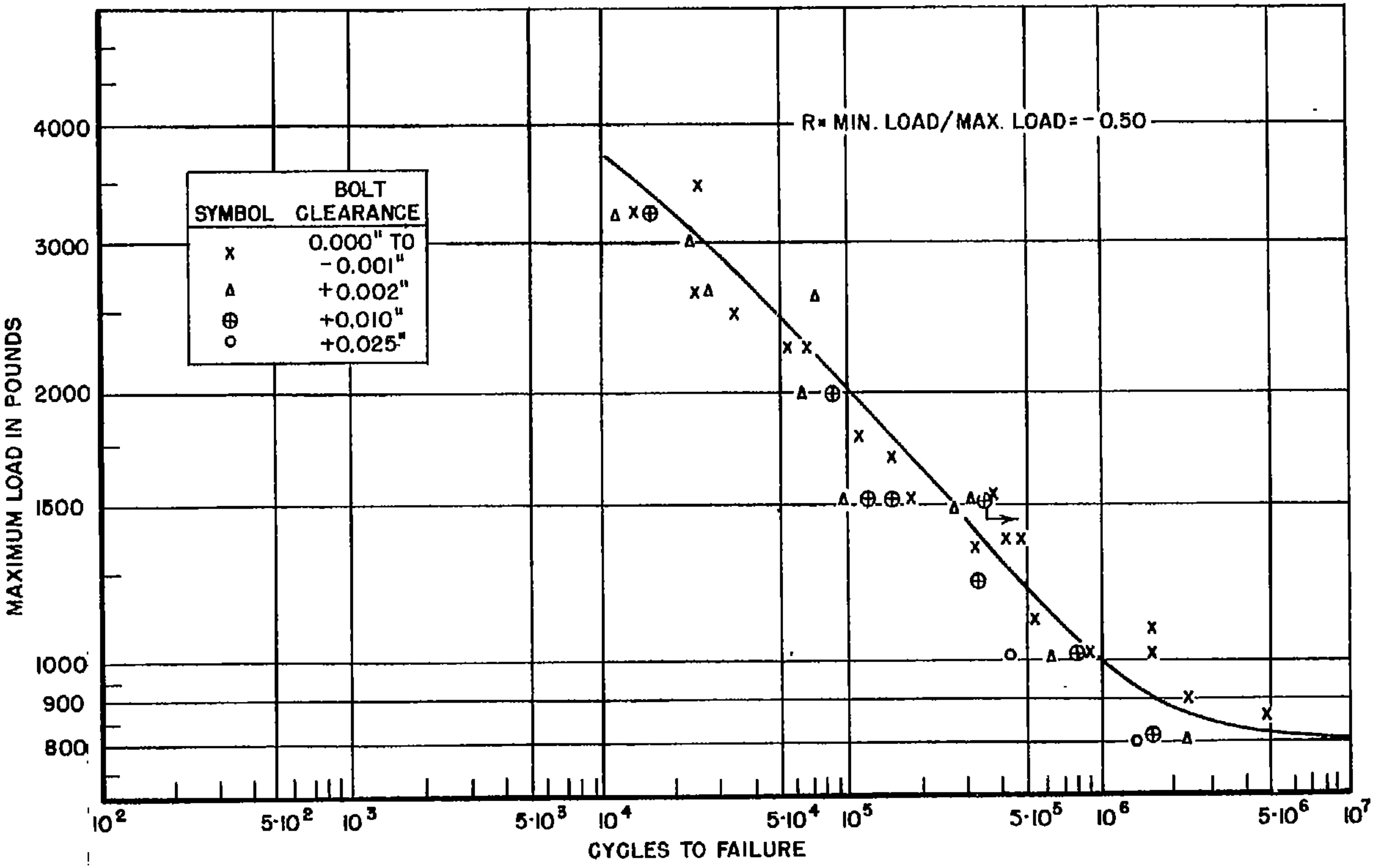


FIGURE 21 - FATIGUE CURVE, REVERSED LOADING, SINGLE-BOLT SPECIMENS OF 0.102" SHEET. (BATTELLE)

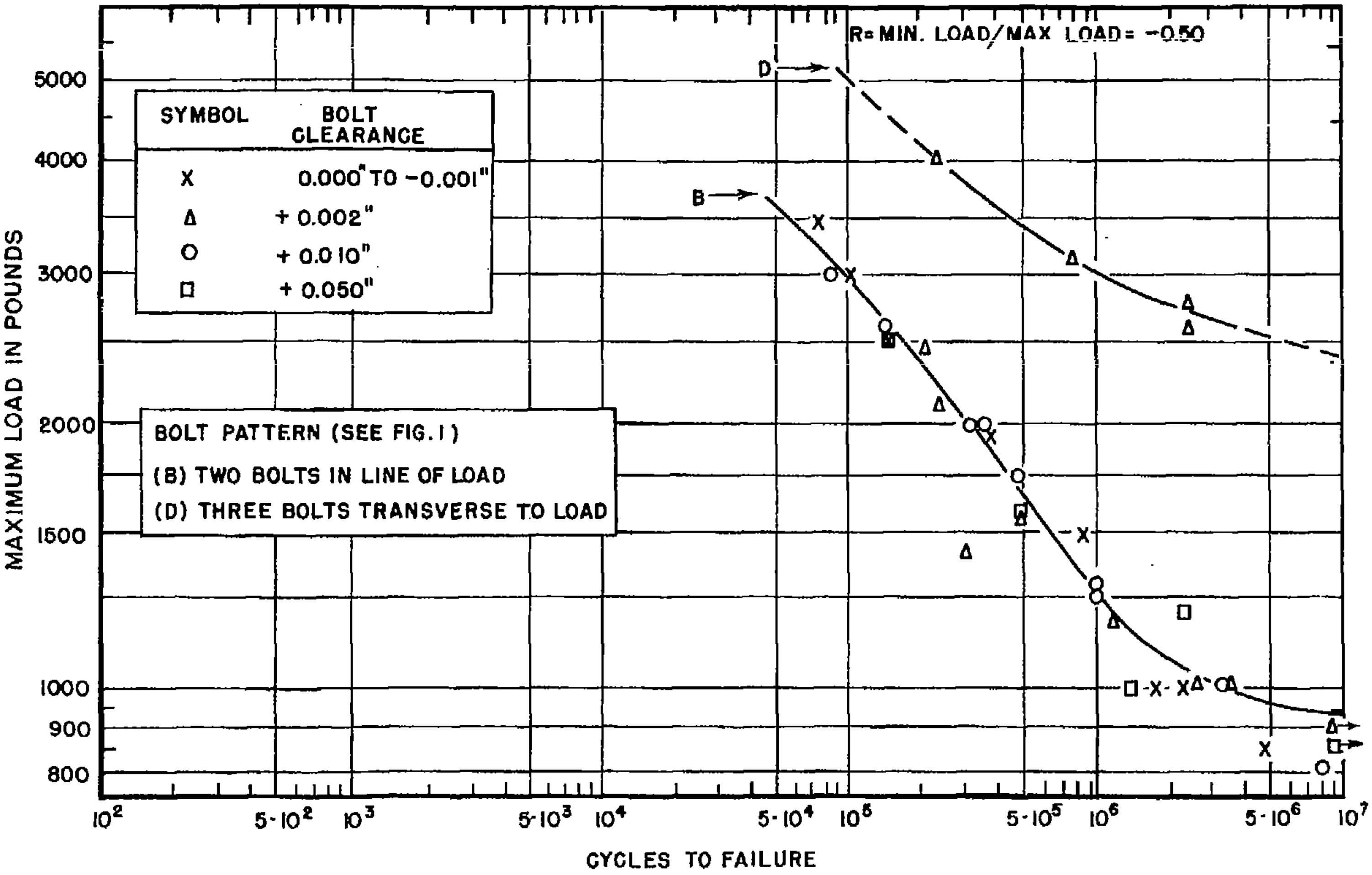


FIGURE 22 – FATIGUE CURVES, REVERSED LOADING, SPECIMENS OF 0.102" SHEET. (BATTELLE)

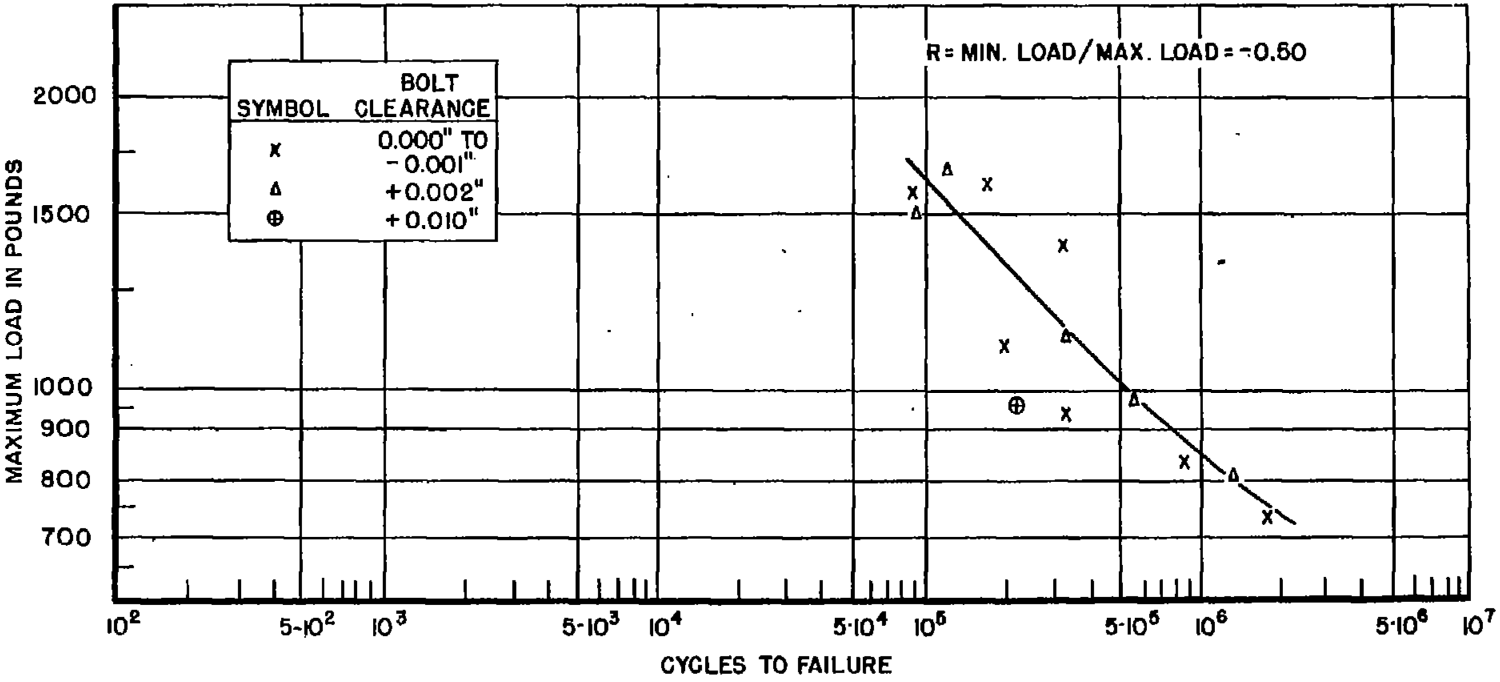


FIGURE 23 – FATIGUE CURVE, REVERSED LOADING, SINGLE-BOLT SPECIMENS OF 0.102" SHEET. (UNIV. OF ILLINOIS)

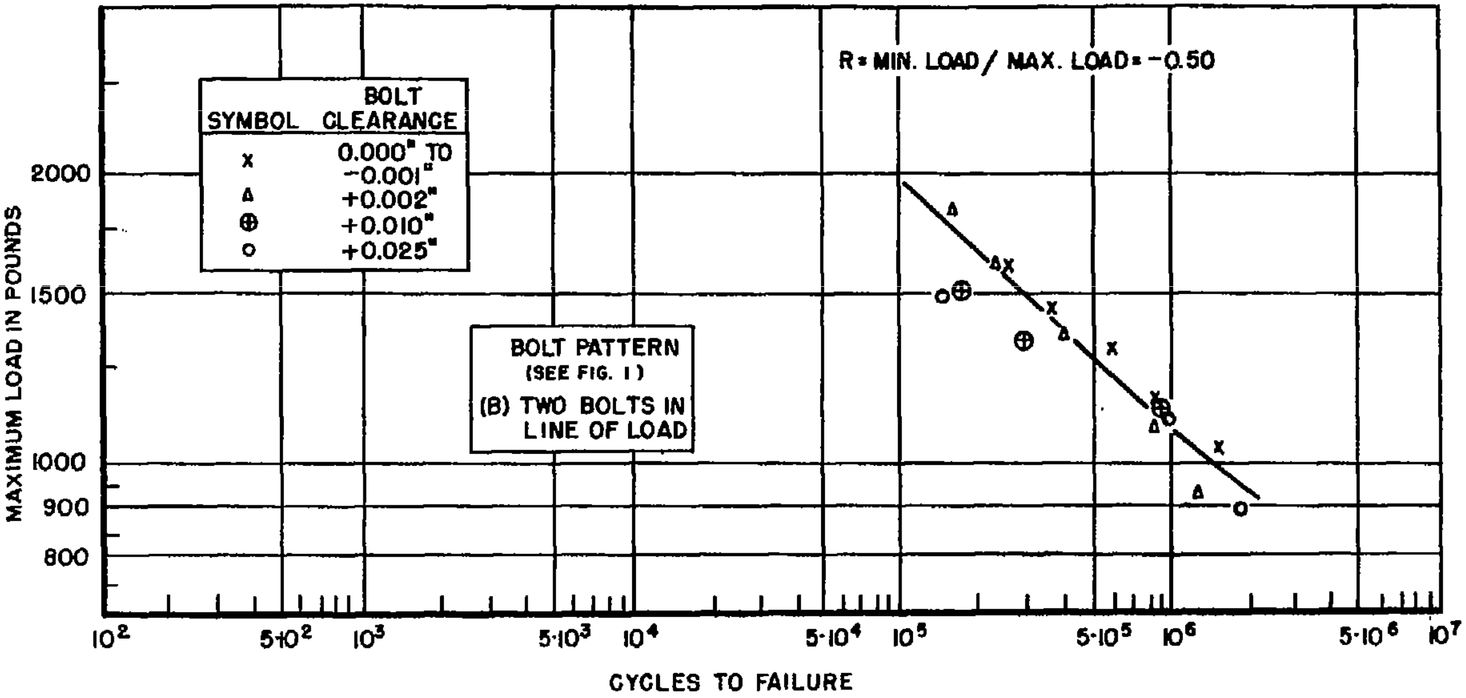


FIGURE 24 - FATIGUE CURVE, REVERSED LOADING, TWO-BOLT SPECIMENS OF 0.102" SHEET (UNIV. OF ILLINOIS)

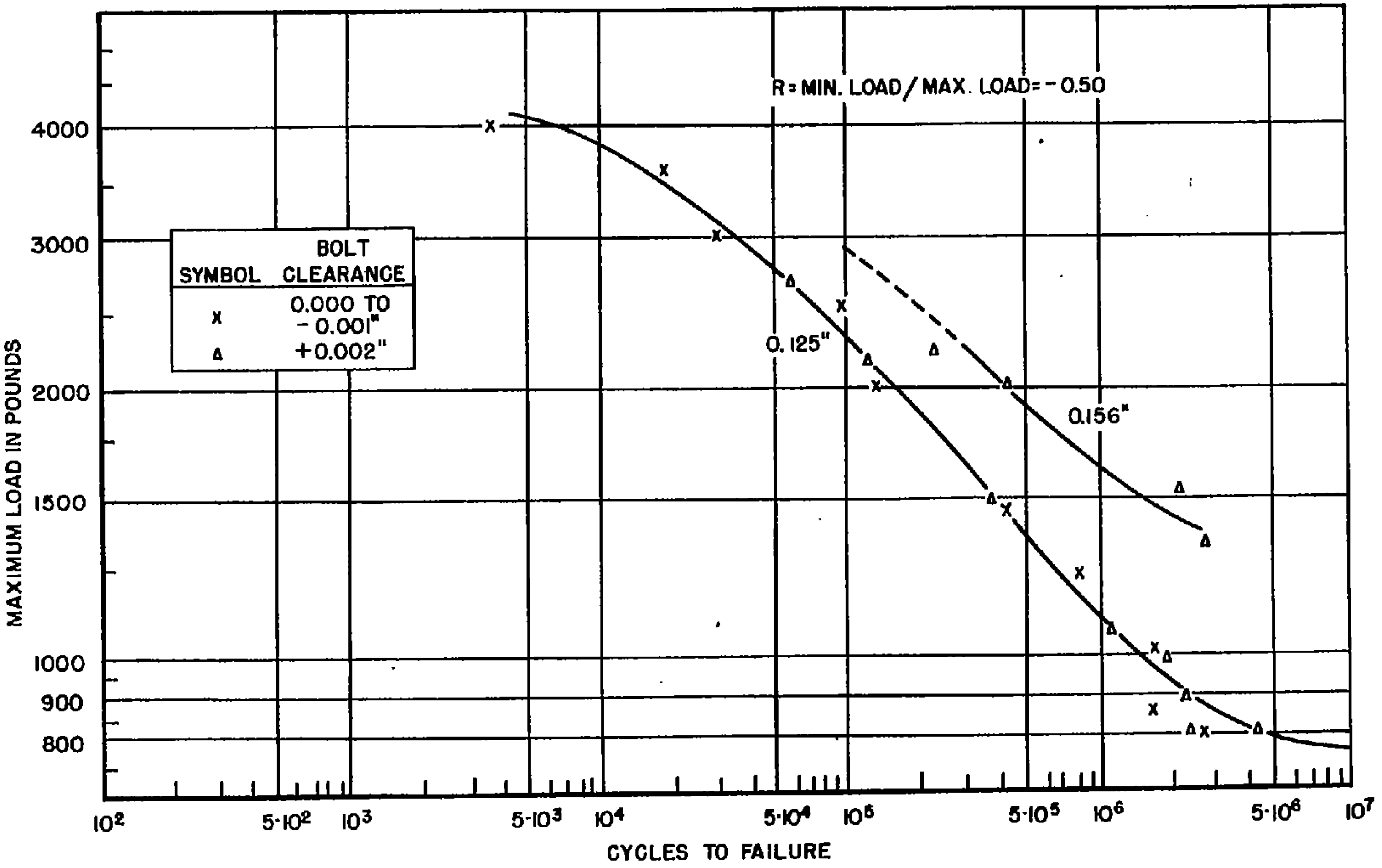


FIGURE 25 - FATIGUE CURVES, REVERSED LOADING, SINGLE-BOLT SPECIMENS OF 0.125" SHEET AND OF 0.156" SHEET. (BATTELLE)

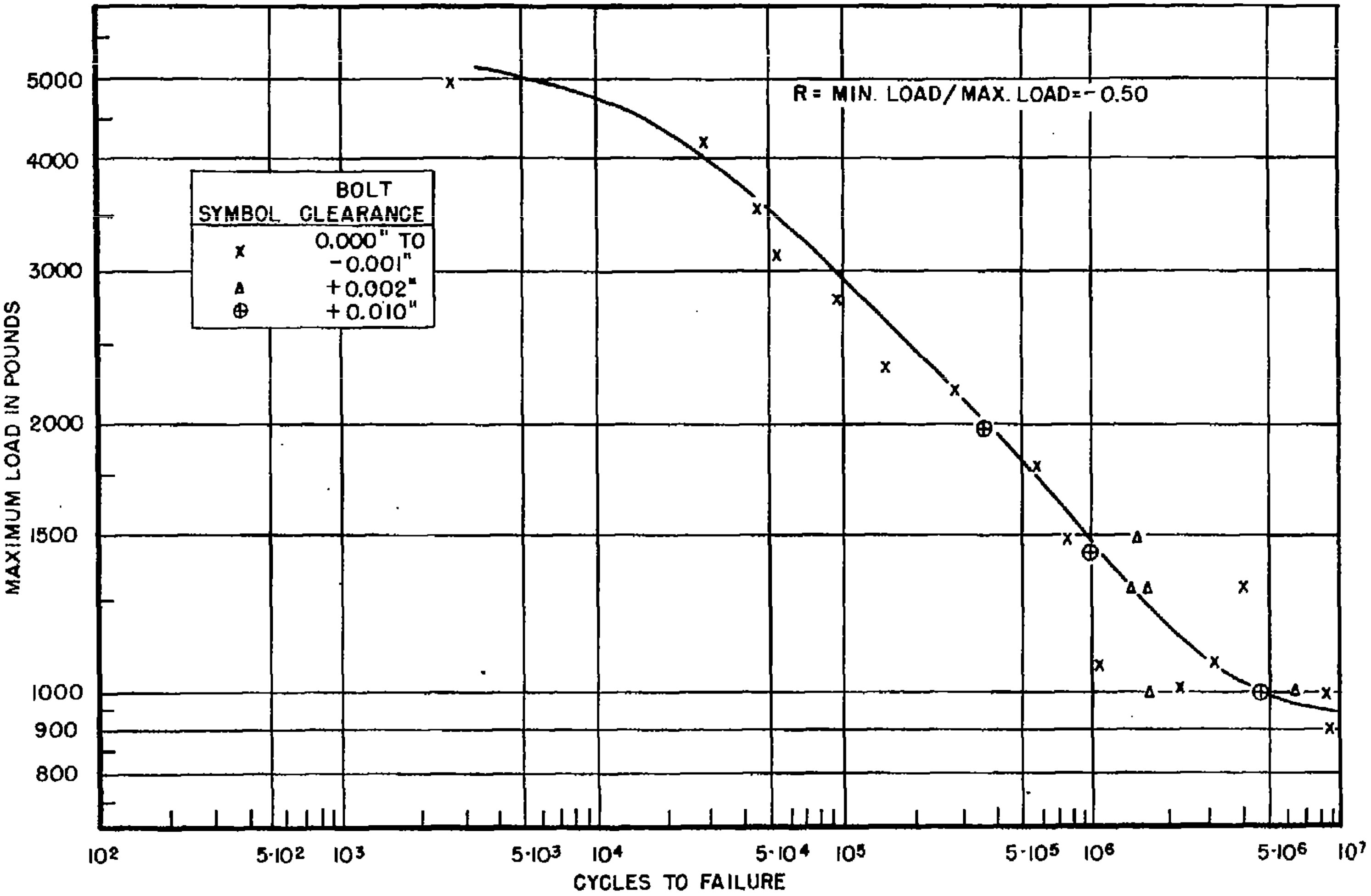


FIGURE 26 - FATIGUE CURVE, REVERSED LOADING, SINGLE-BOLT SPECIMENS OF 0.187" SHEET. (BATTELLE)

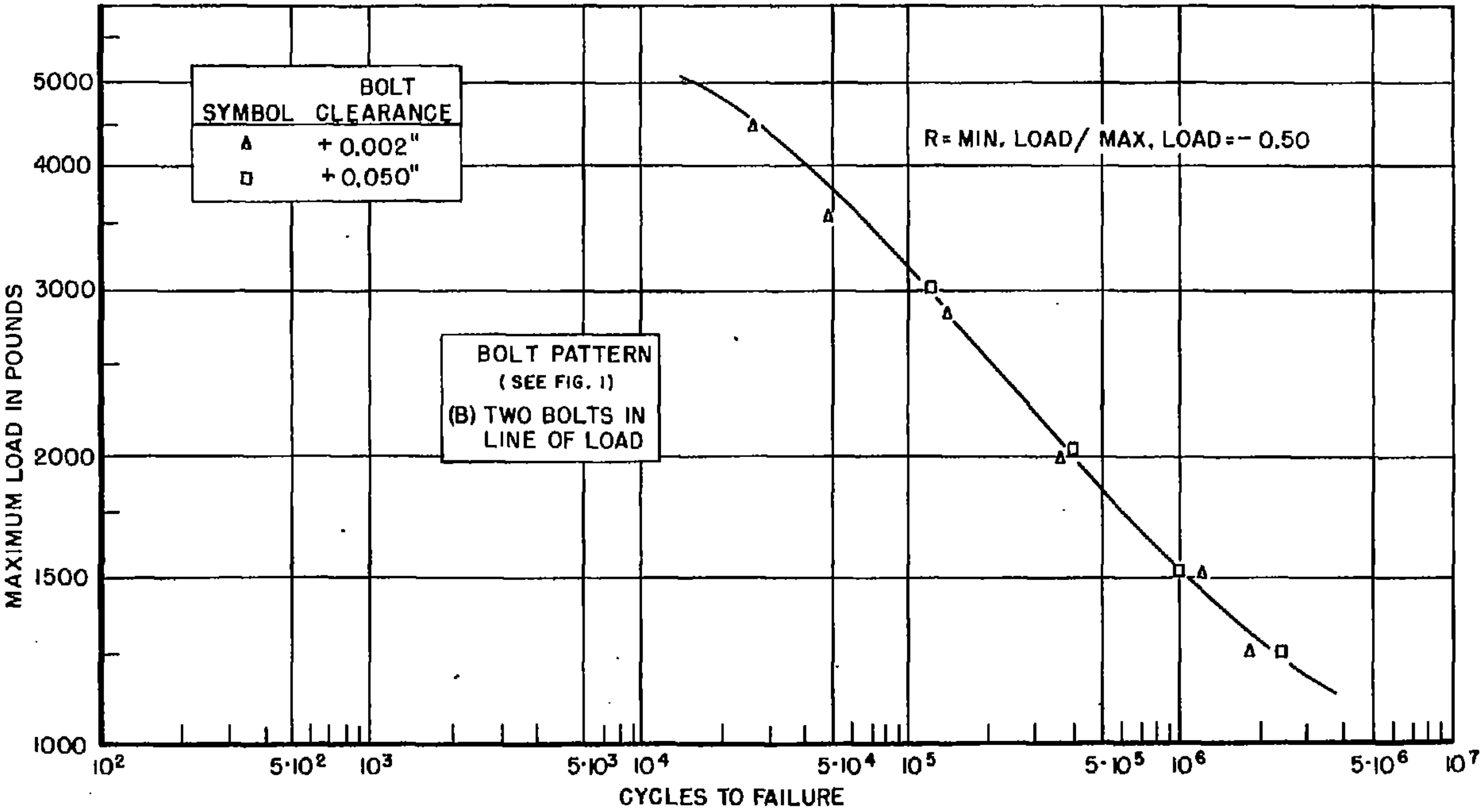


FIGURE 27 - FATIGUE CURVE, REVERSED LOADING, TWO-BOLT SPECIMENS OF 0.187" SHEET. (BATTELLE)

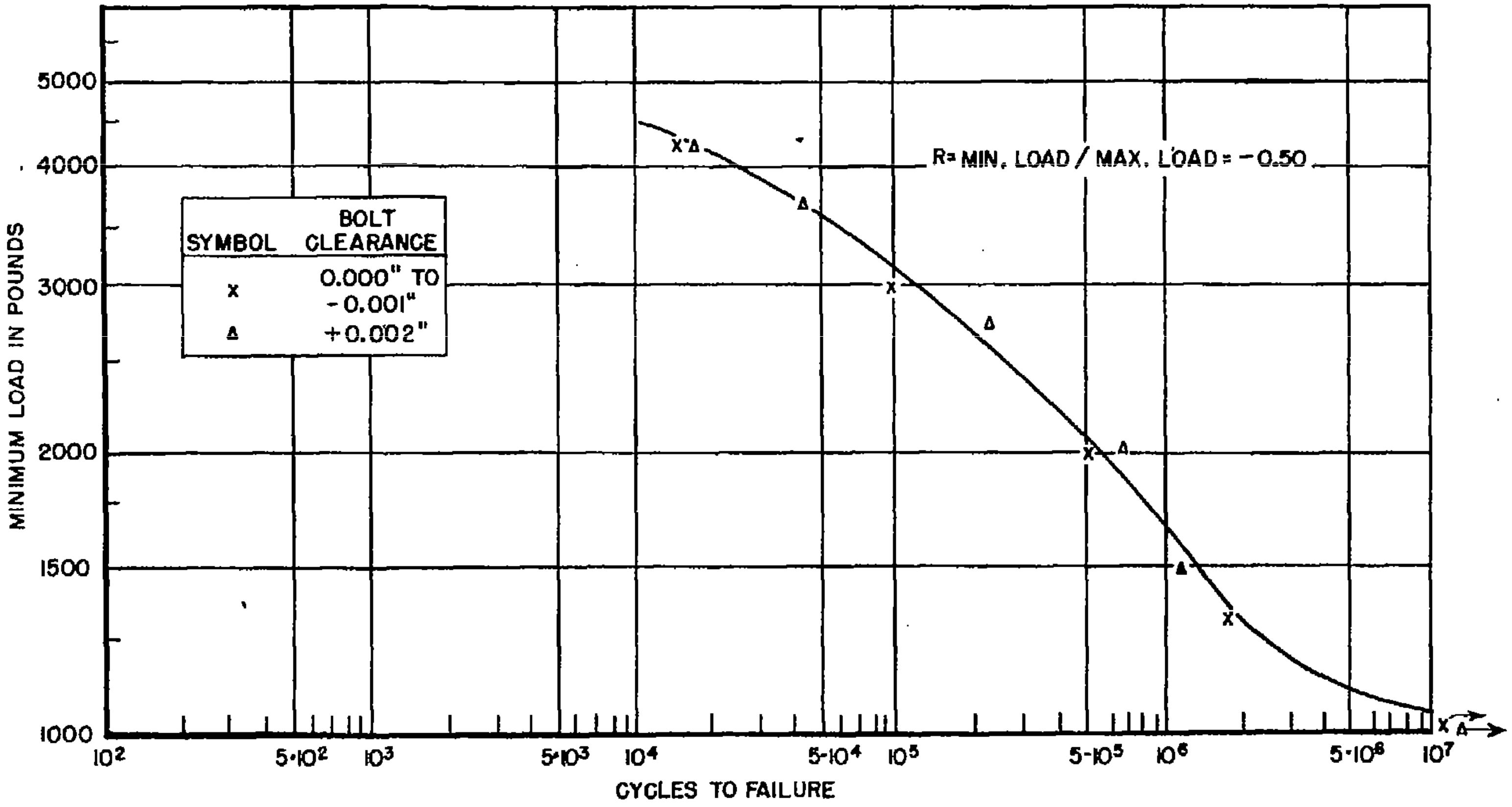


FIGURE 28 – FATIGUE CURVE, REVERSED LOADING, SINGLE-BOLT SPECIMENS OF 0.250" SHEET. (BATTELLE)

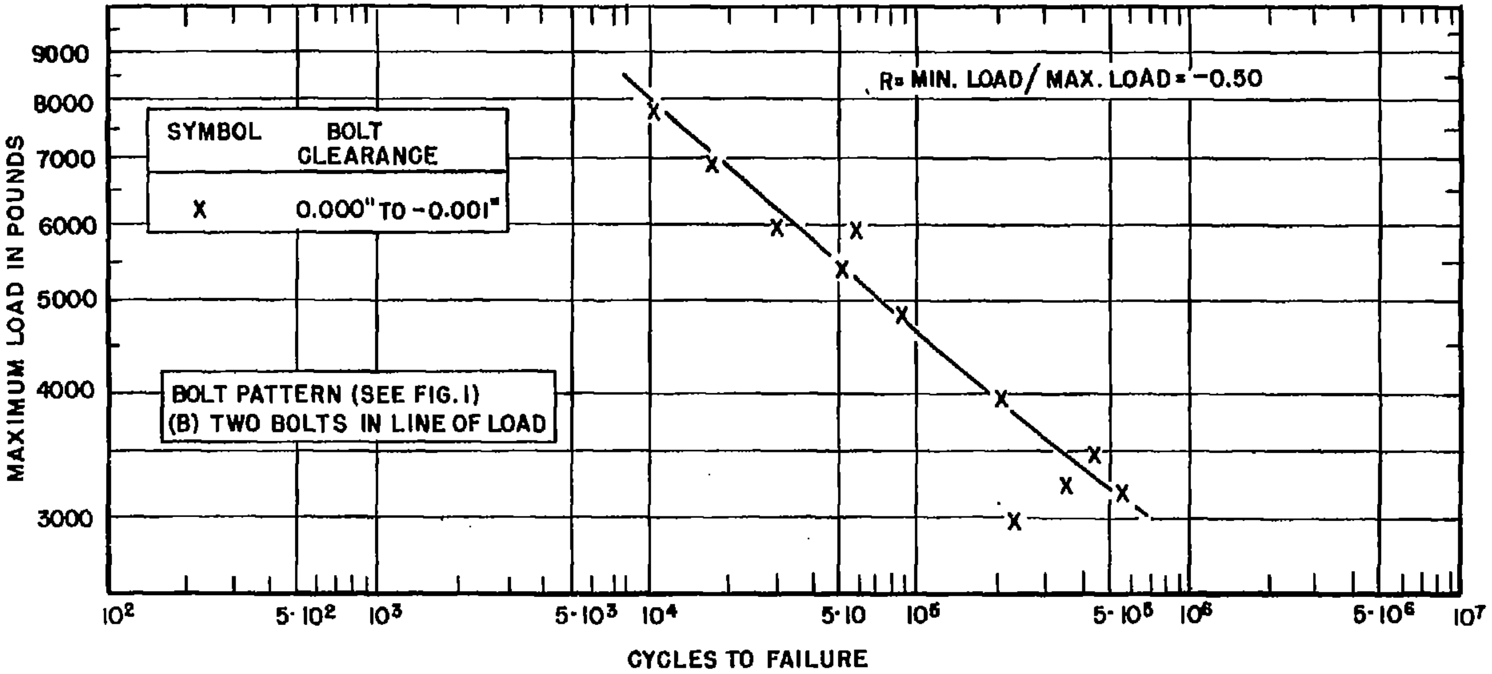


FIGURE 29 - FATIGUE CURVE, REVERSED LOADING, TWO-BOLT SPECIMENS OF 0.375" SHEET.
(UNIV. OF ILLINOIS)

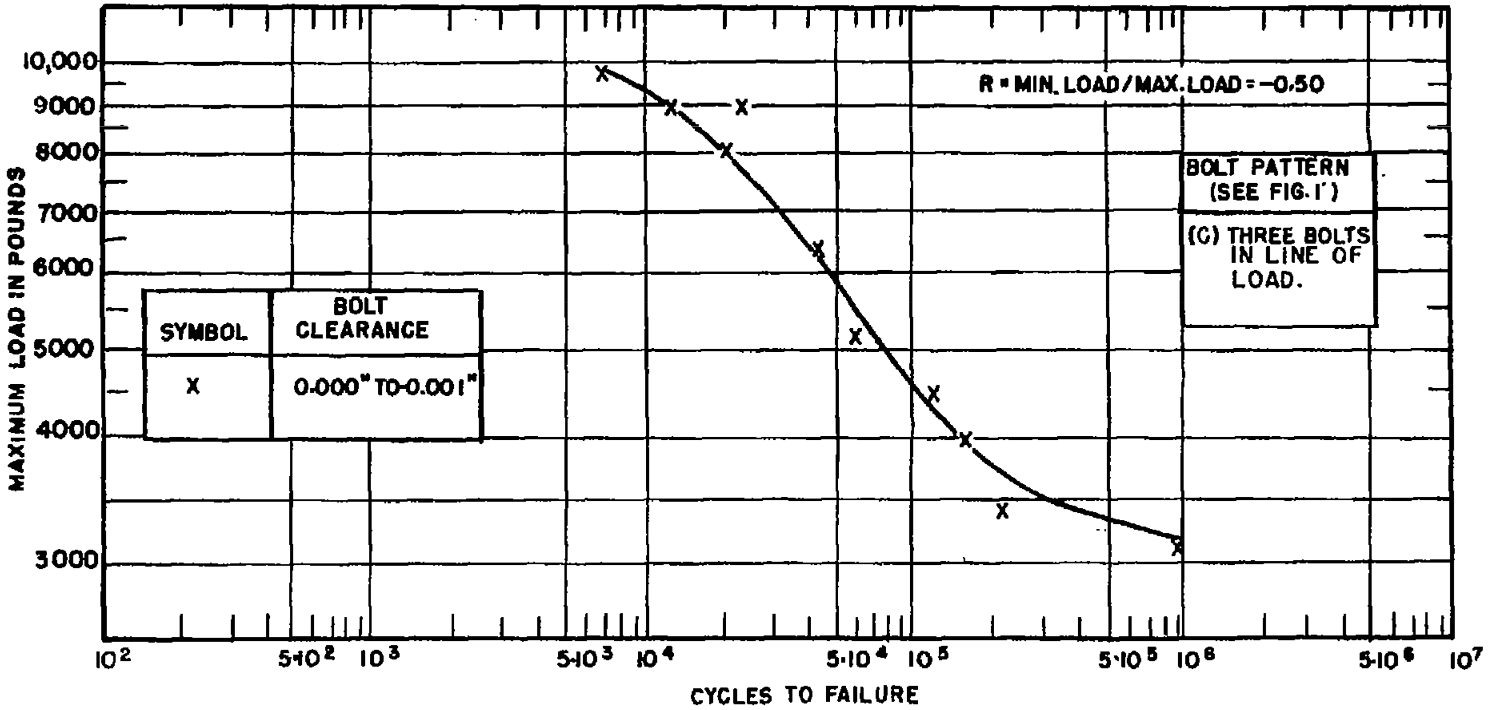


FIGURE 30 - FATIGUE CURVE, REVERSED LOADING, THREE-BOLT SPECIMENS OF 0.375" SHEET.
(UNIV. OF ILLINOIS)

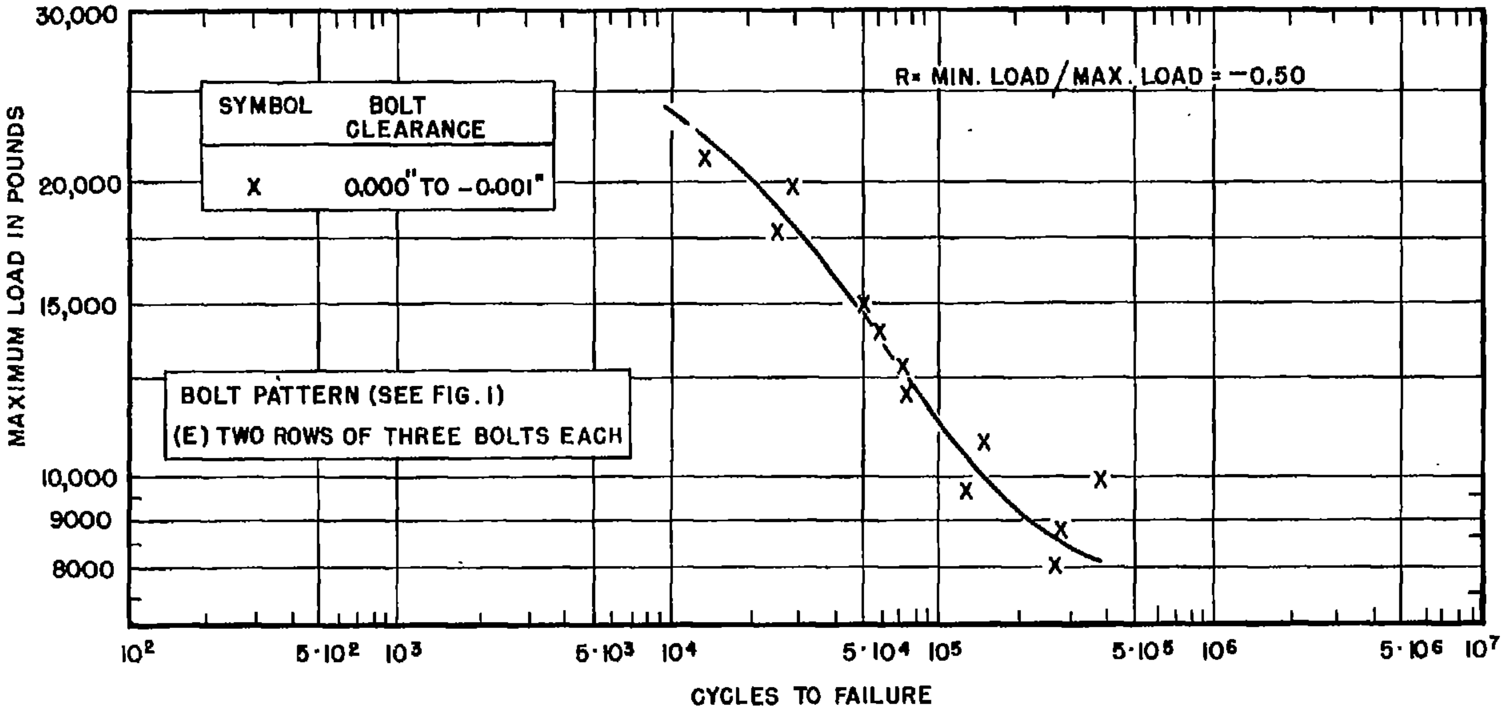


FIGURE 31 - FATIGUE CURVE, REVERSED LOADING, SIX-BOLT SPECIMENS OF 0.375" SHEET. (UNIV. OF ILLINOIS)

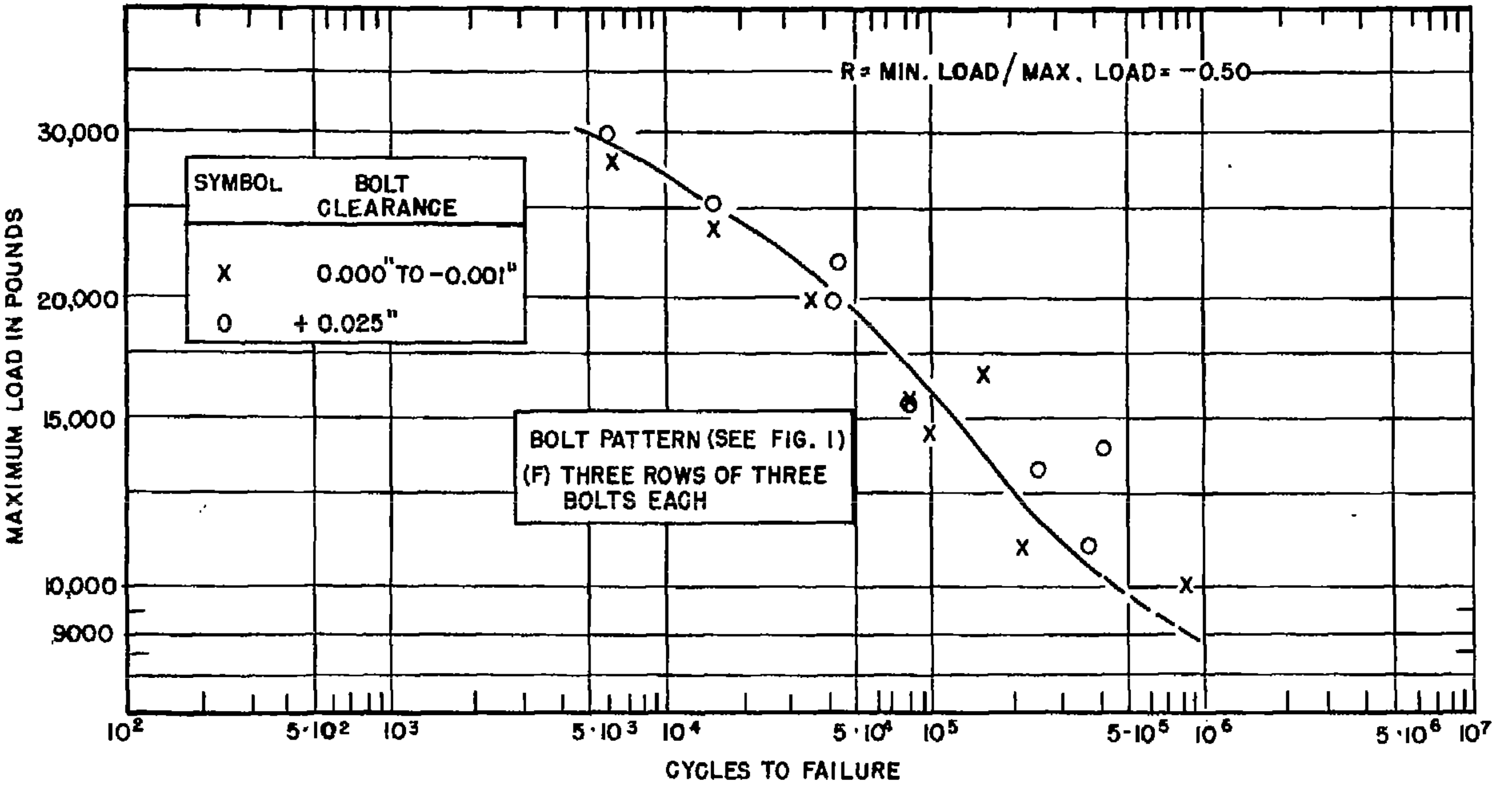


FIGURE 32 – FATIGUE CURVE, REVERSED LOADING, NINE-BOLT SPECIMEN OF 0.375" SHEET. (UNIV. OF ILLINOIS)

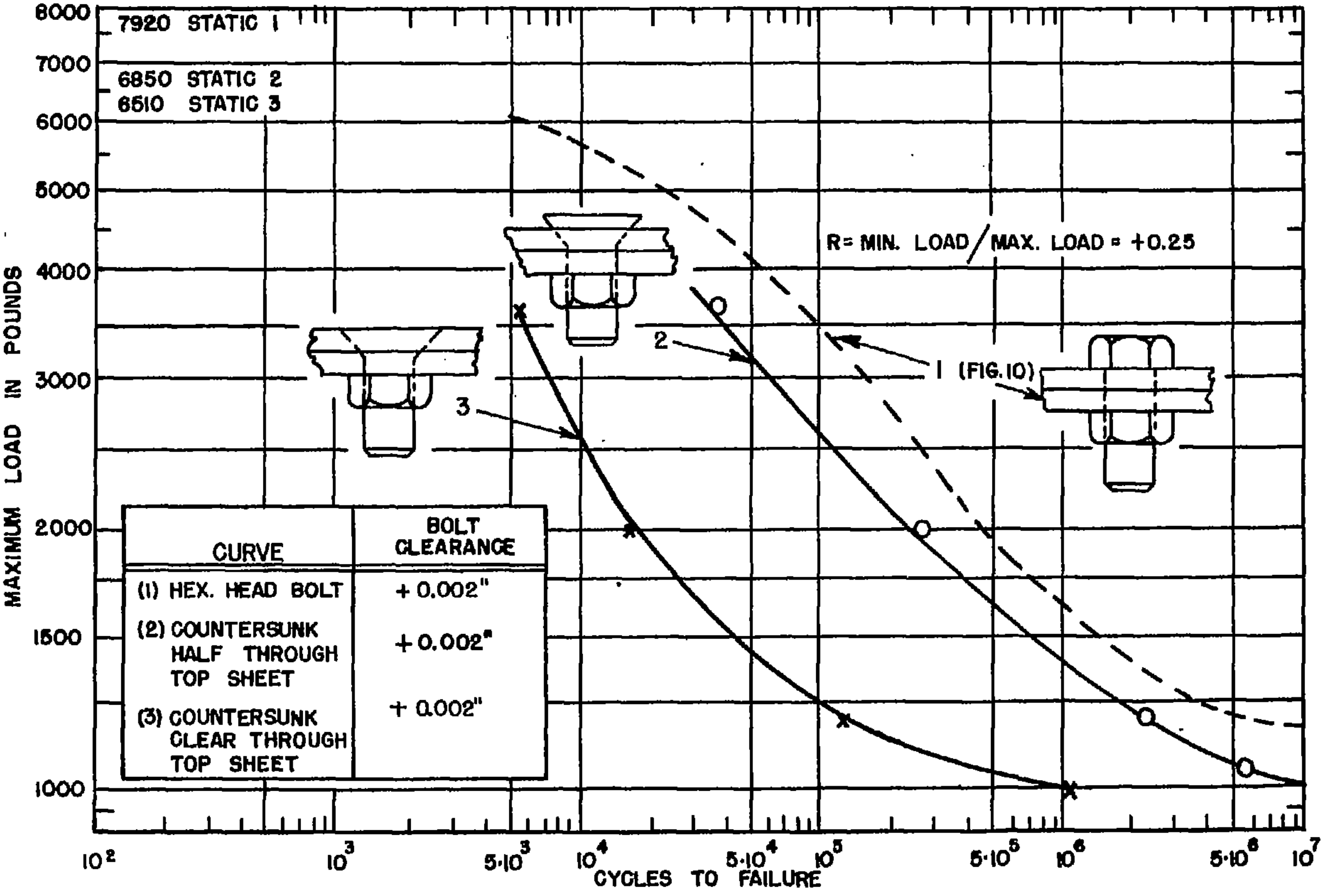


FIGURE33 – FATIGUE CURVES, UNIDIRECTIONAL LOADING, SINGLE-BOLT SPECIMENS OF 0.156" SHEET, 42° COUNTERSUNK BOLTS. (BATTELLE)

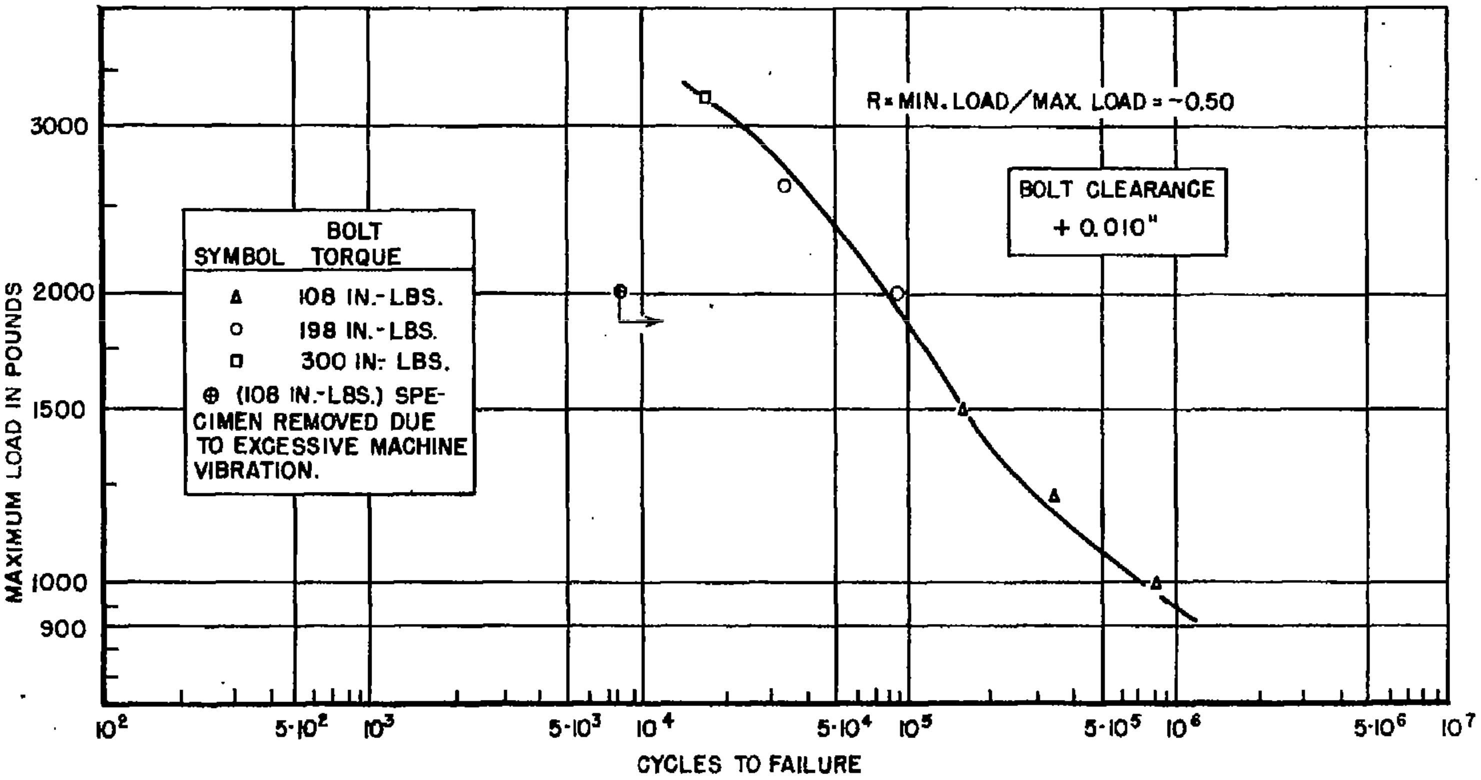


FIGURE 34 - EFFECT OF INCREASING BOLT TORQUE ON FATIGUE STRENGTH, SINGLE-BOLT SPECIMENS OF 0.102" SHEET. (BATTELLE)

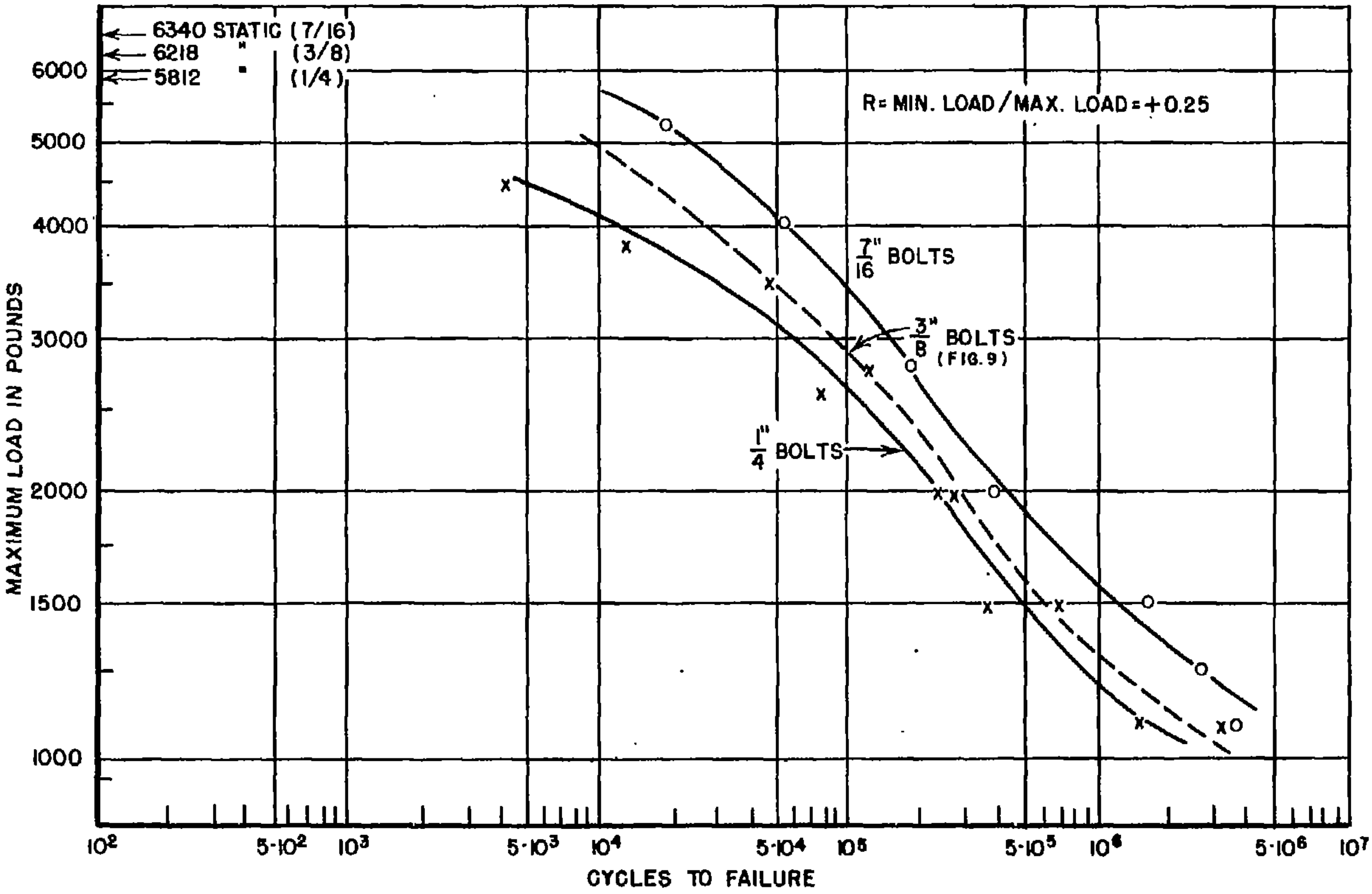


FIGURE 35 – FATIGUE CURVES, UNIDIRECTIONAL LOADING, SINGLE-BOLT SPECIMENS OF 0.125" SHEET, BOLTS OF VARIOUS DIAMETERS. (BATTELLE)

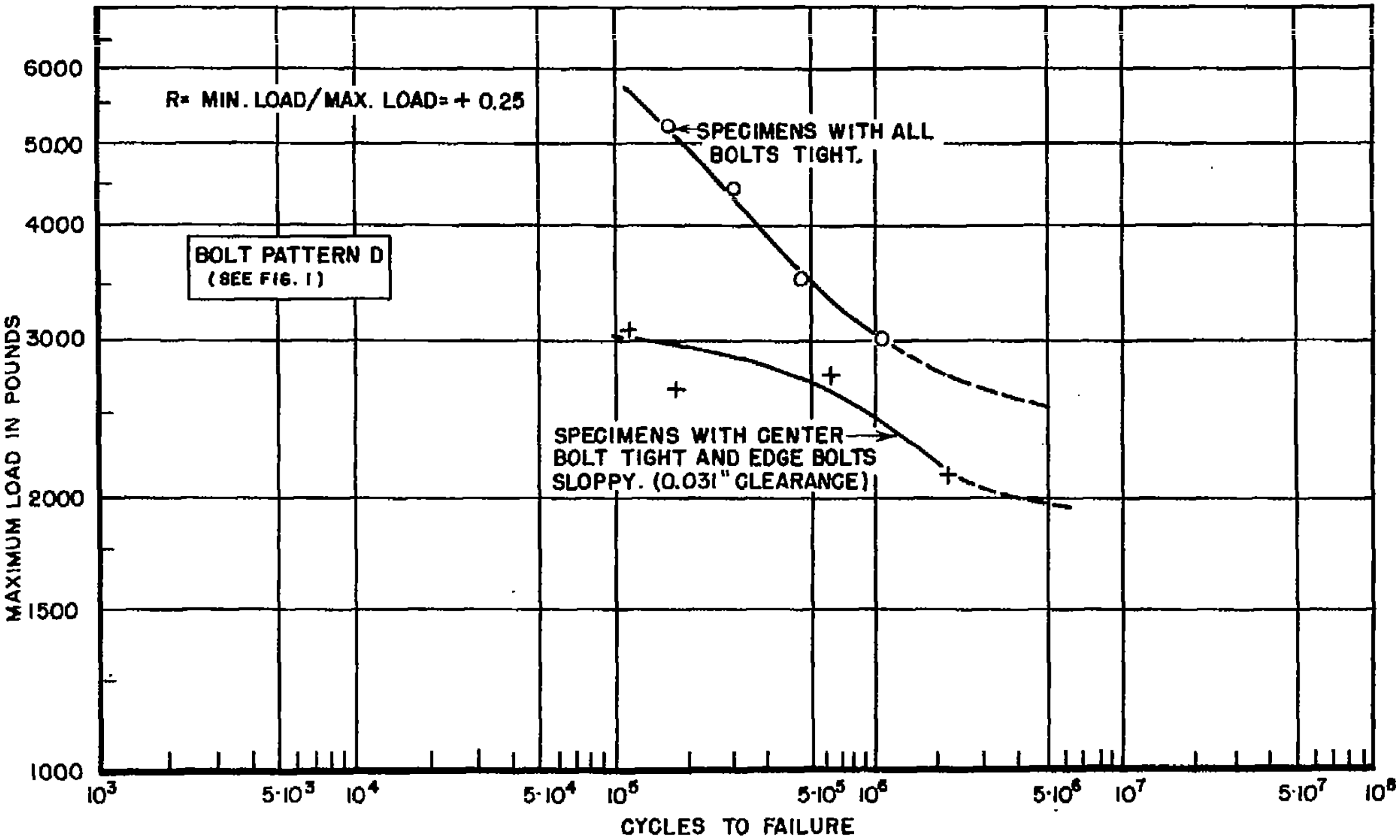


FIGURE 36 - FATIGUE CURVE, UNIDIRECTIONAL LOADING, THREE-BOLT SPECIMENS OF 0.102" SHEET OF NON UNIFORM BOLT. (UNIV. OF ILLINOIS)

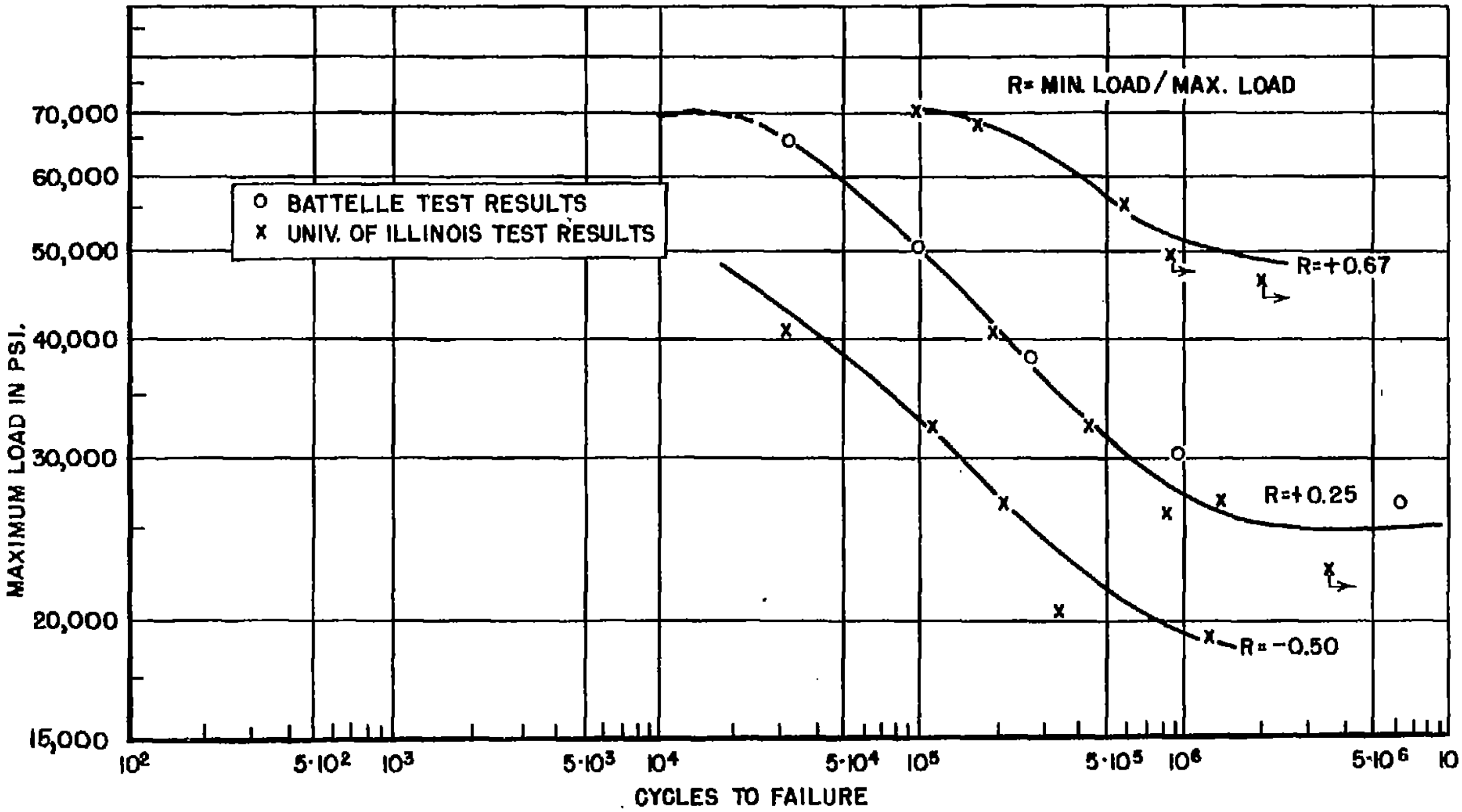


FIGURE 37-FATIGUE CURVES FOR 0.102" SHEET MATERIAL.

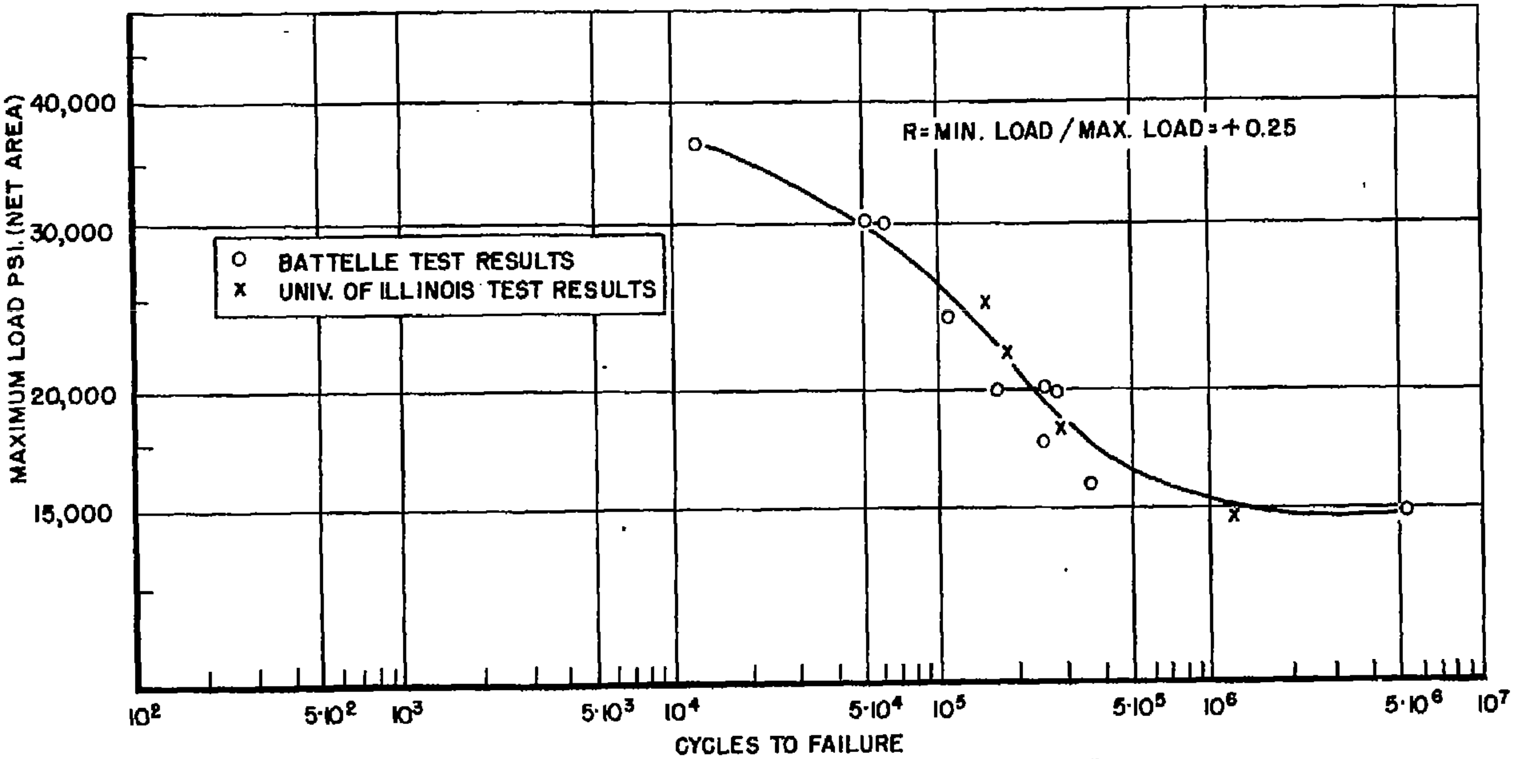


FIGURE 38—FATIGUE CURVE FOR 0.102" SHEET NOTCHED BY ONE $\frac{3"}{8}$ CENTRAL HOLE.

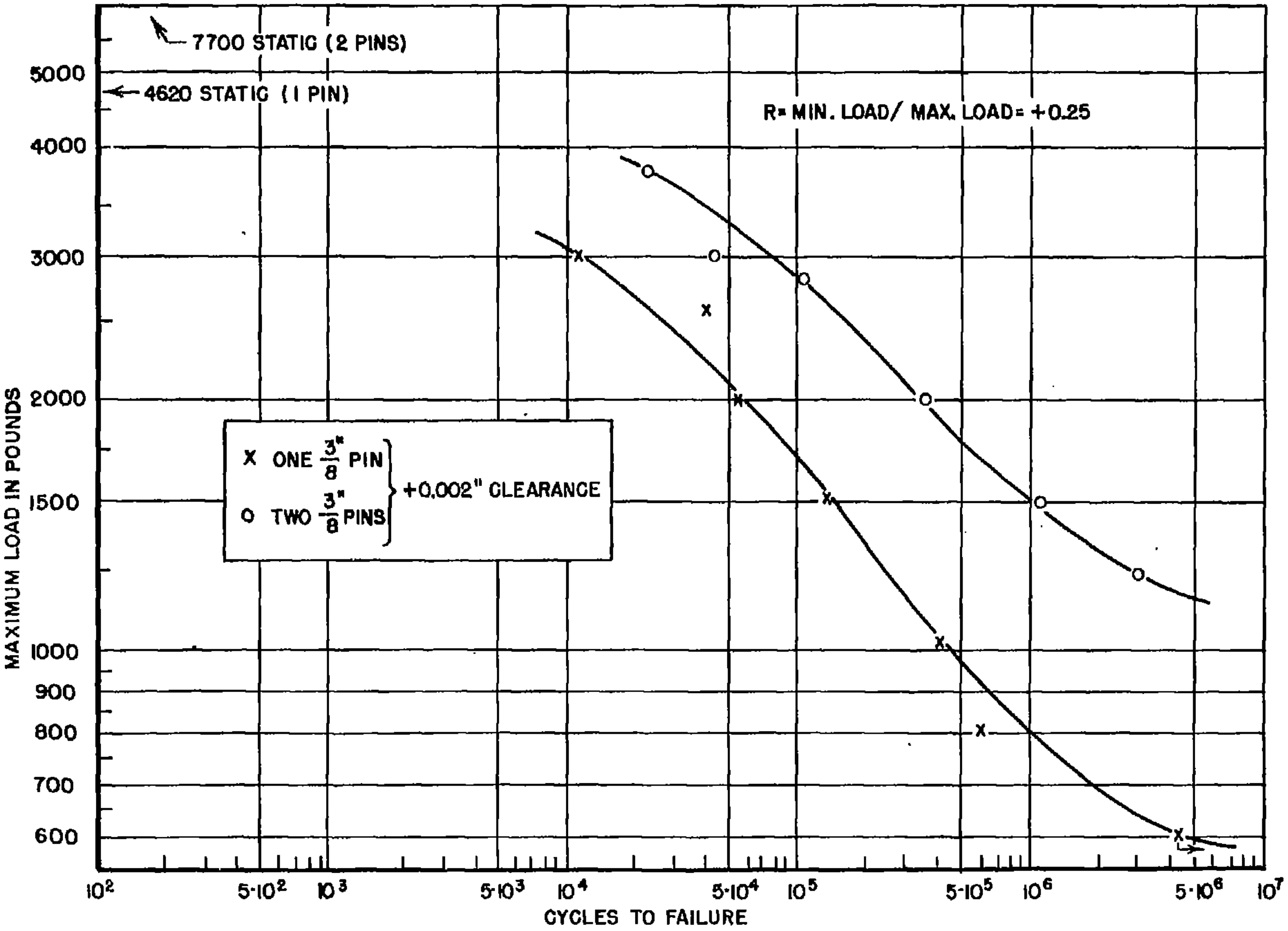


FIGURE 39 – FATIGUE CURVES FOR 0.102" SHEET LOADED THROUGH PIN BEARINGS. (BATTELLE)

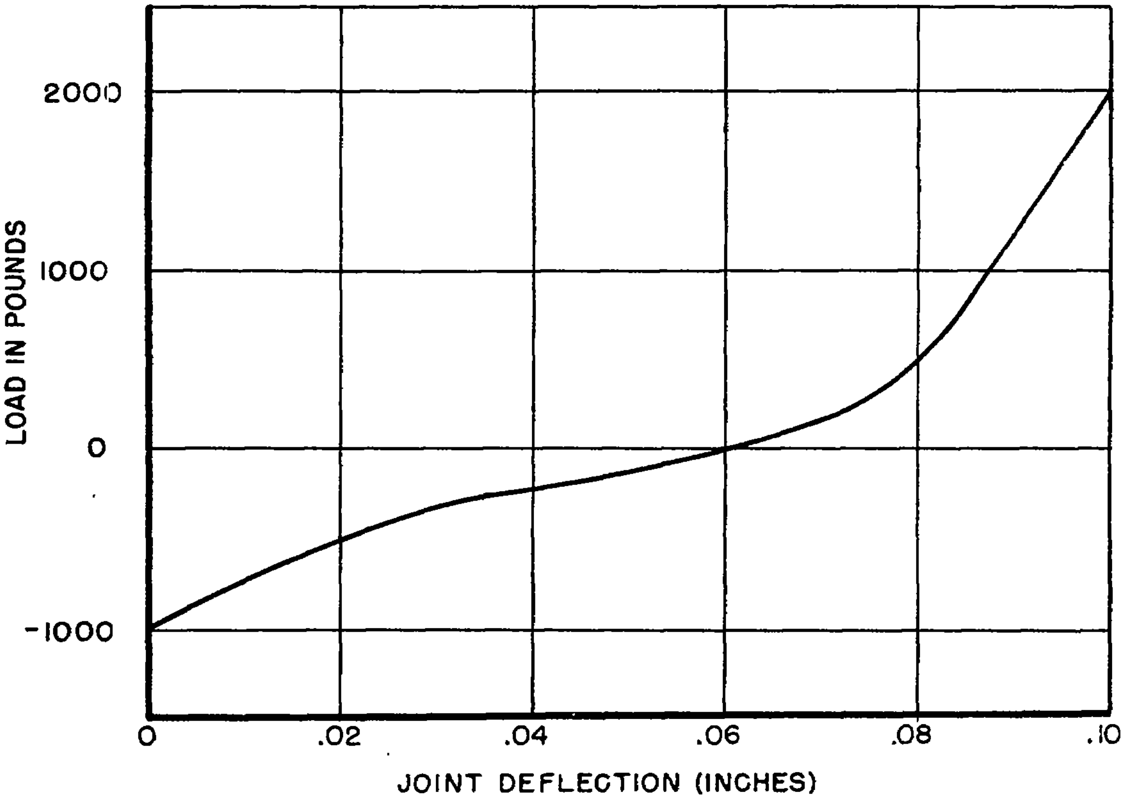


FIGURE 40 - DYNAMIC LOAD-DEFLECTION CURVE, SINGLE-BOLT SPECIMEN, "LOOSE" FIT, LOADED AT 2000 LBS. MAX. AT R= −0.50.

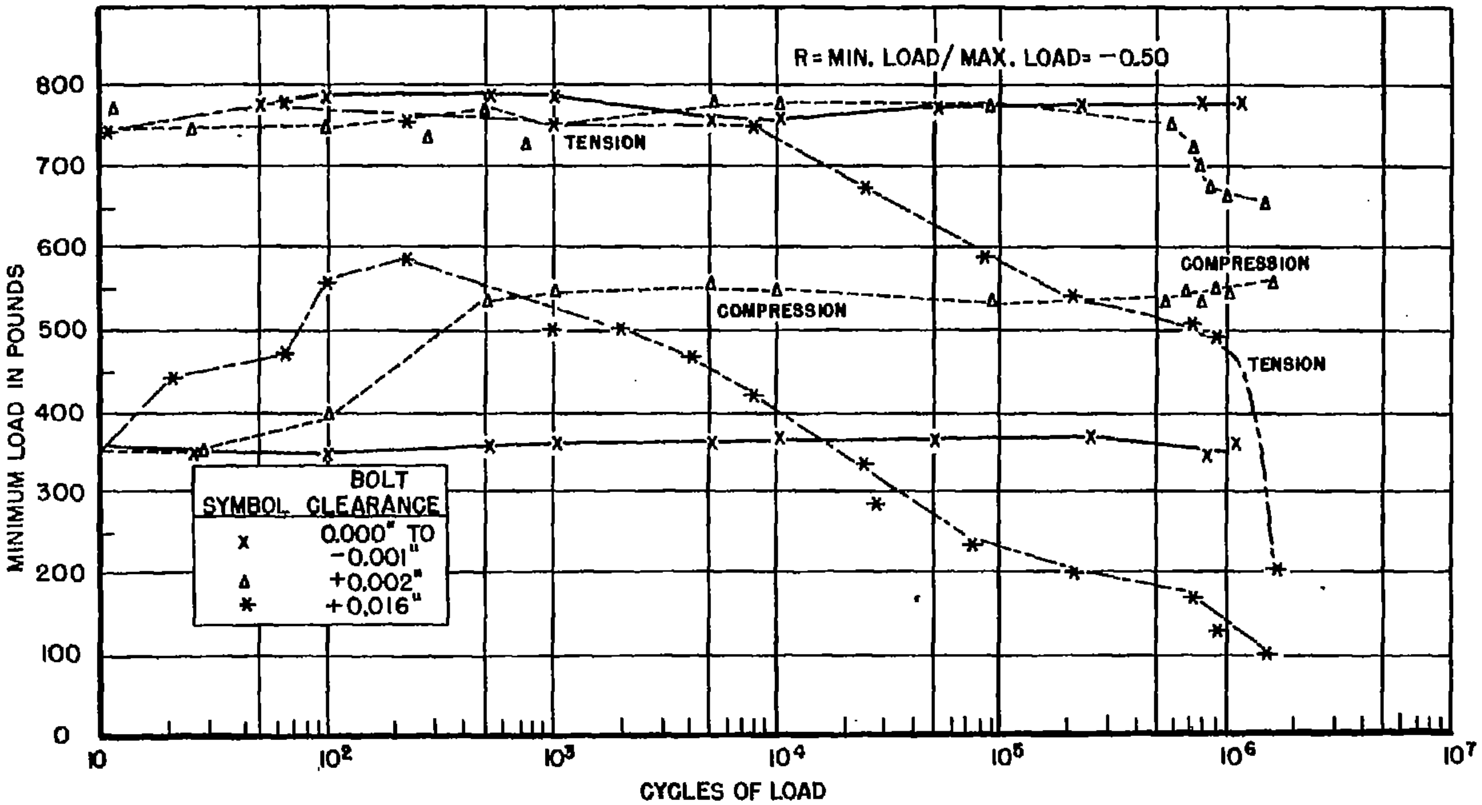


FIGURE 41 – TESTS FOR FALLING OFF OF LOAD.

TIGHT FIT DRILL FIT LOOSE FIT

36576

Figure 42. Rubbing surfaces of specimens after 1,000,000 cycles of partially reversed load. ($R = -0.50$)

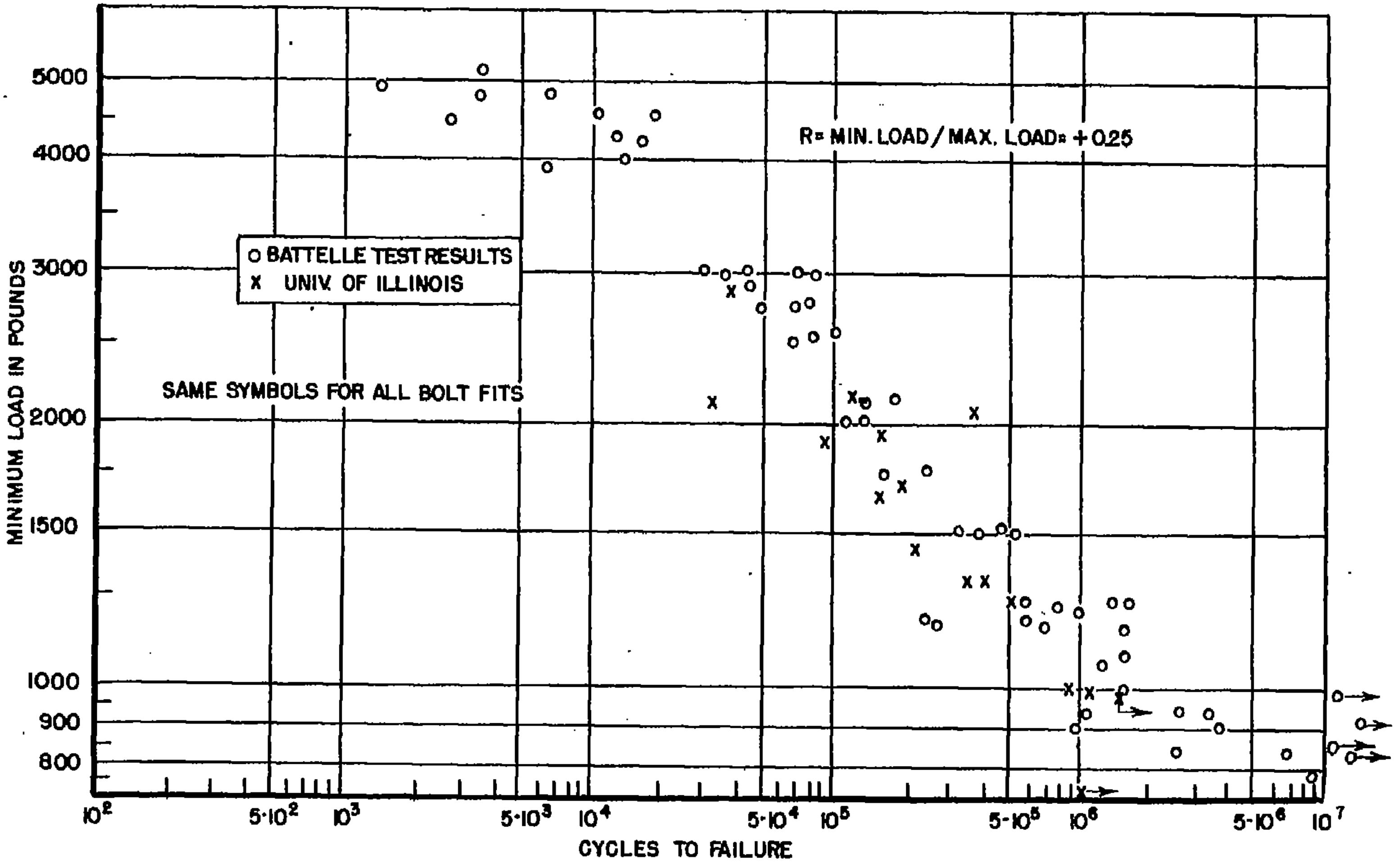


FIGURE 43 - COMPARISON OF RESULTS FROM THE TWO SOURCES (UNIDIRECTIONAL LOADING, SINGLE-BOLT SPECIMENS OF 0.102" SHEET)

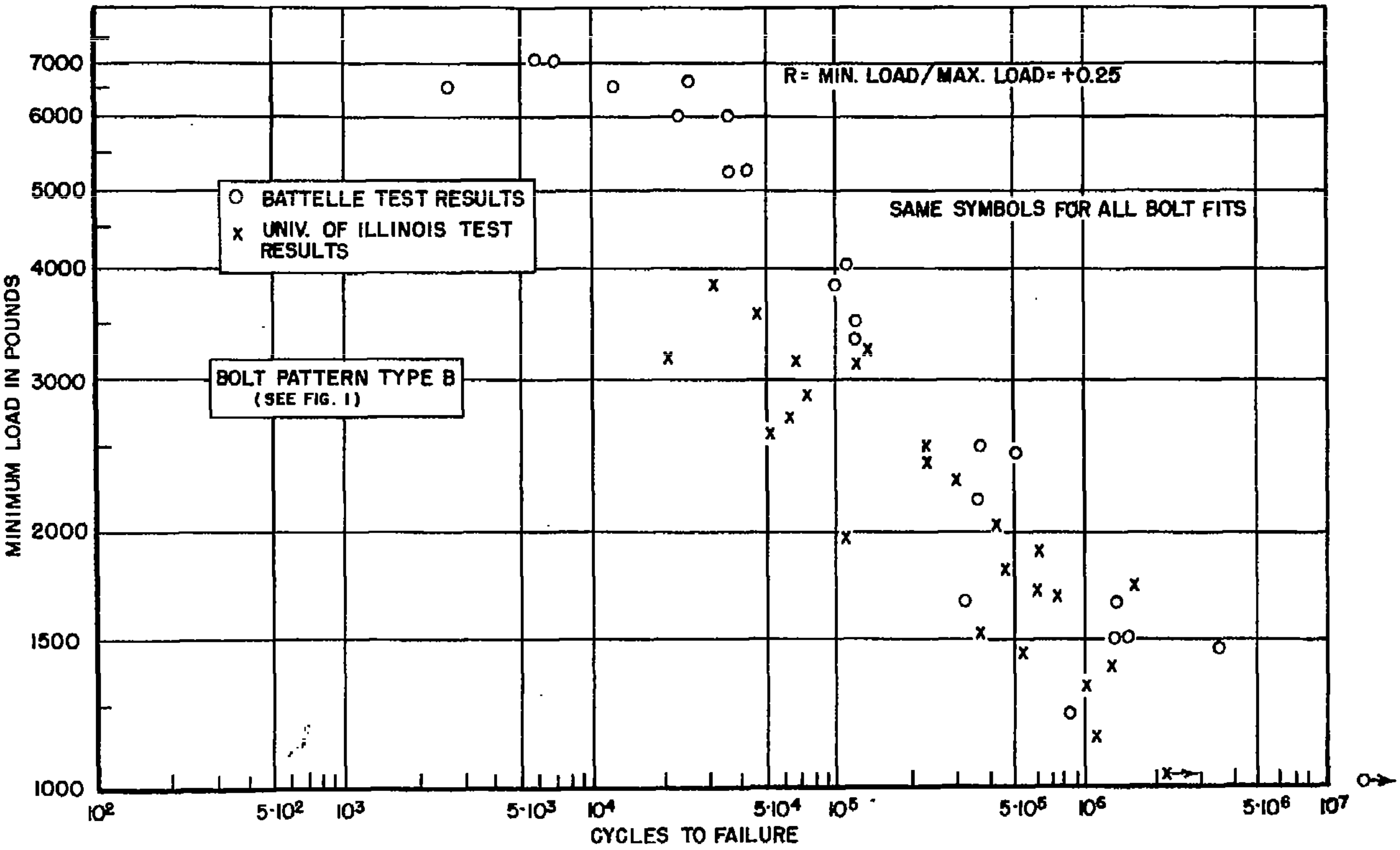


FIGURE 44 — COMPARISON OF RESULTS FROM THE TWO SOURCES (UNIDIRECTIONAL LOADING, TWO-BOLT SPECIMENS OF 0.102" SHEET)

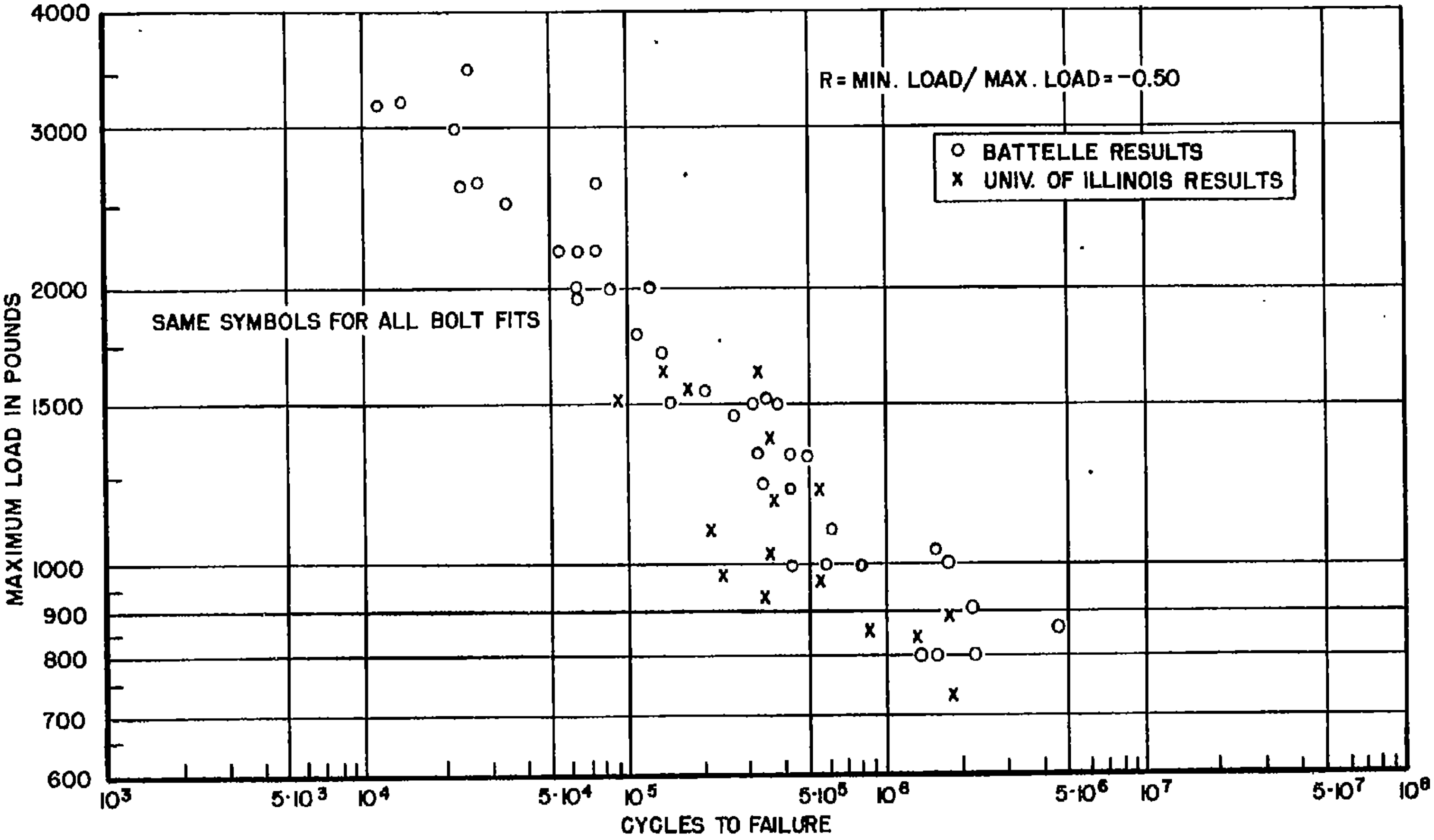


FIGURE 45 - COMPARISON OF RESULTS FROM THE TWO SOURCES. (REVERSED LOADING, SINGLE-BOLT SPECIMENS OF 0.102" SHEET)

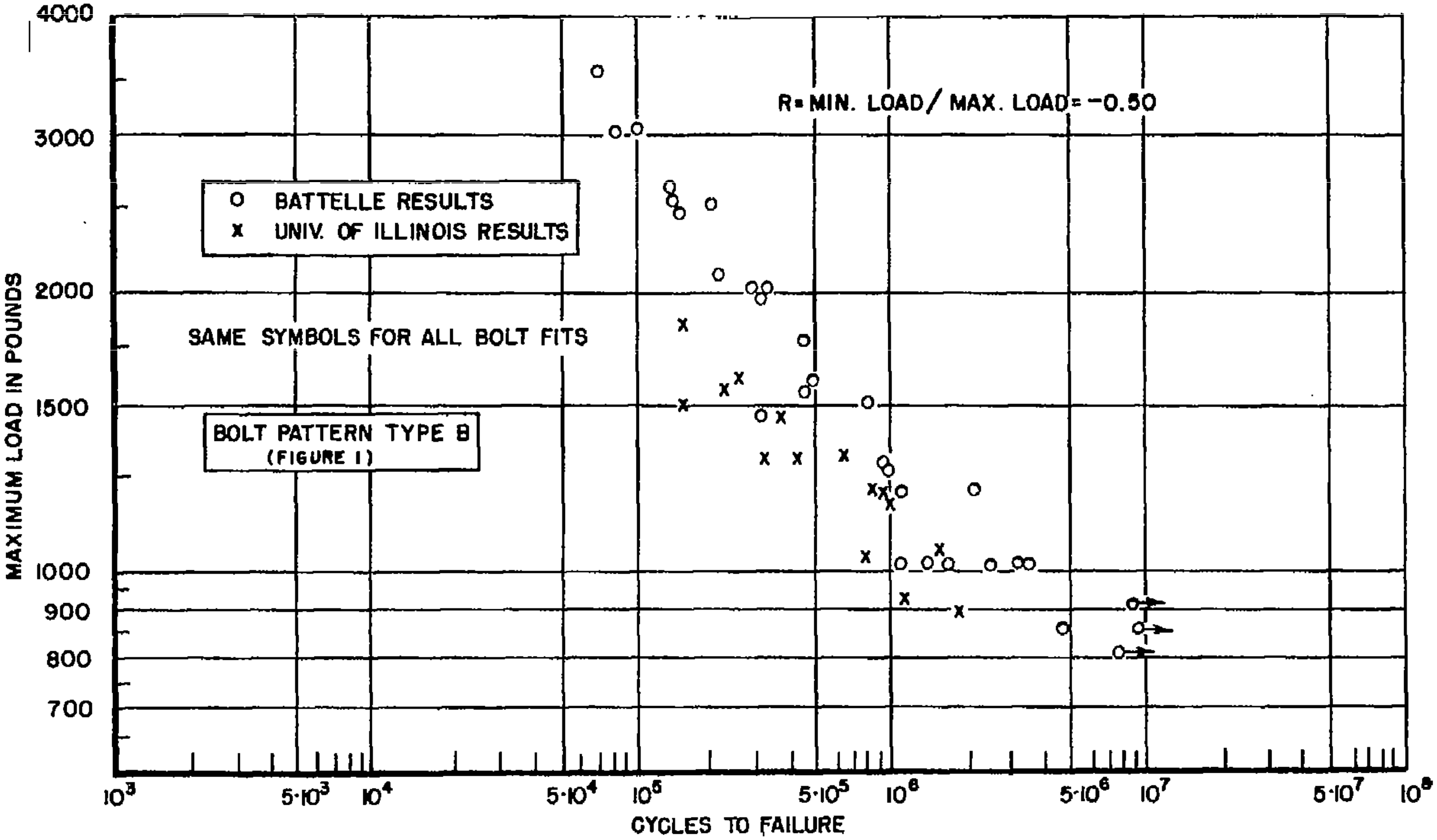


FIGURE 46 – COMPARISON OF RESULTS FROM THE TWO SOURCES (REVERSED LOADING, TWO-BOLT SPECIMENS OF 0.102" SHEET)

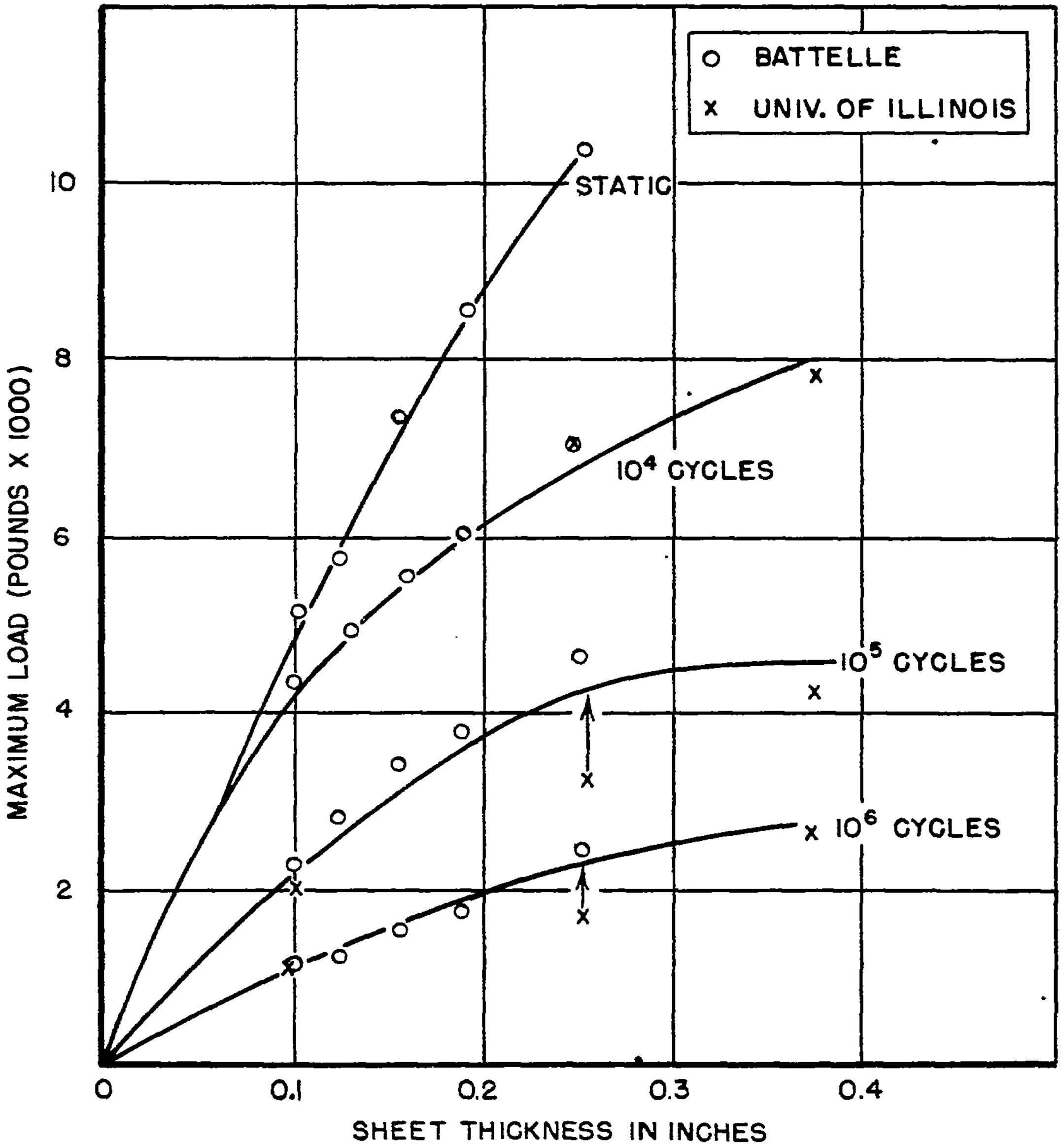


FIGURE 47 – FATIGUE STRENGTH IN UNIDIRECTIONAL LOADING VS. SHEET THICKNESS, SINGLE-BOLT SPECIMENS.

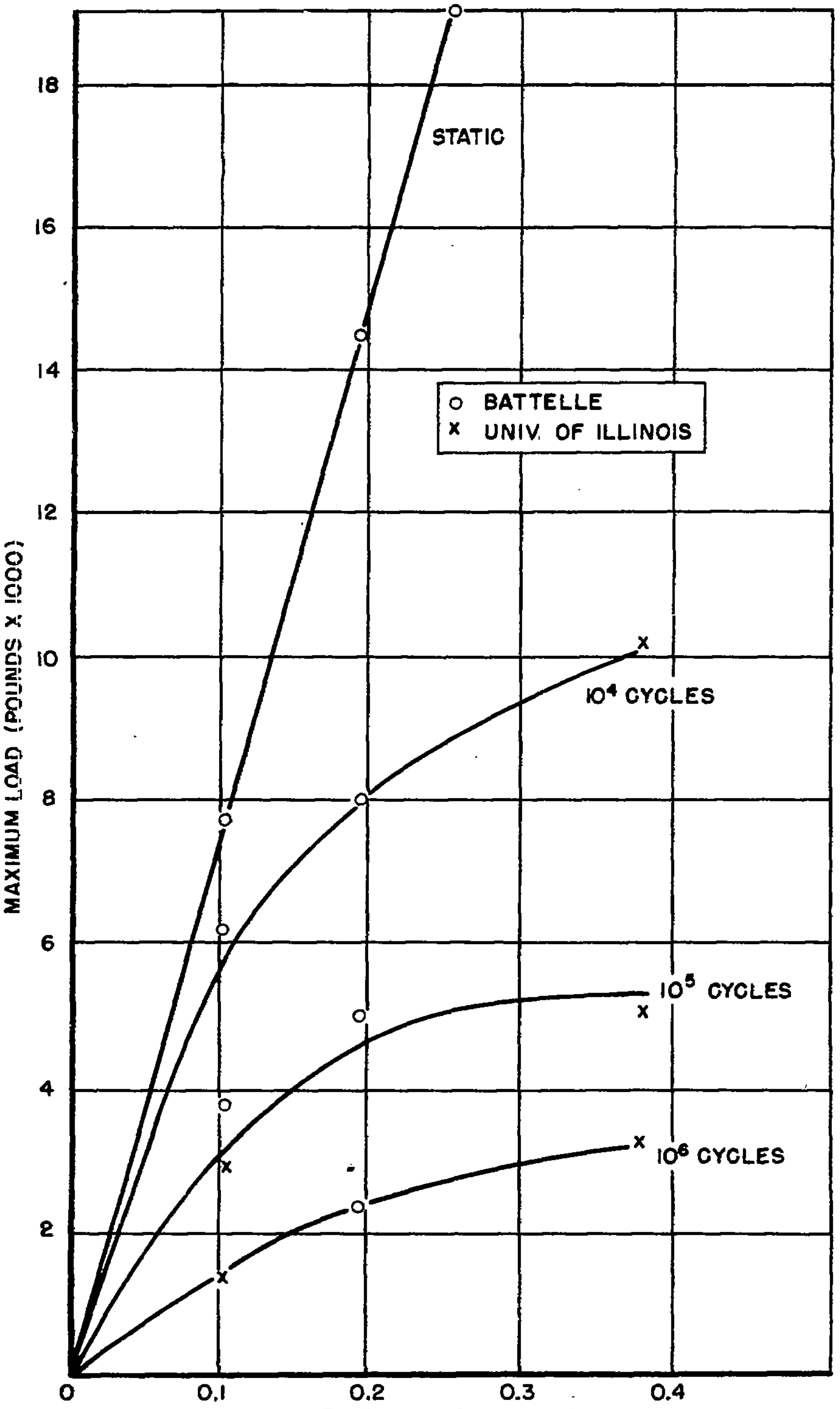


FIGURE 48 - FATIGUE STRENGTH IN UNIDIRECTIONAL LOADING VS. SHEET THICKNESS, TWO-BOLT SPECIMENS.

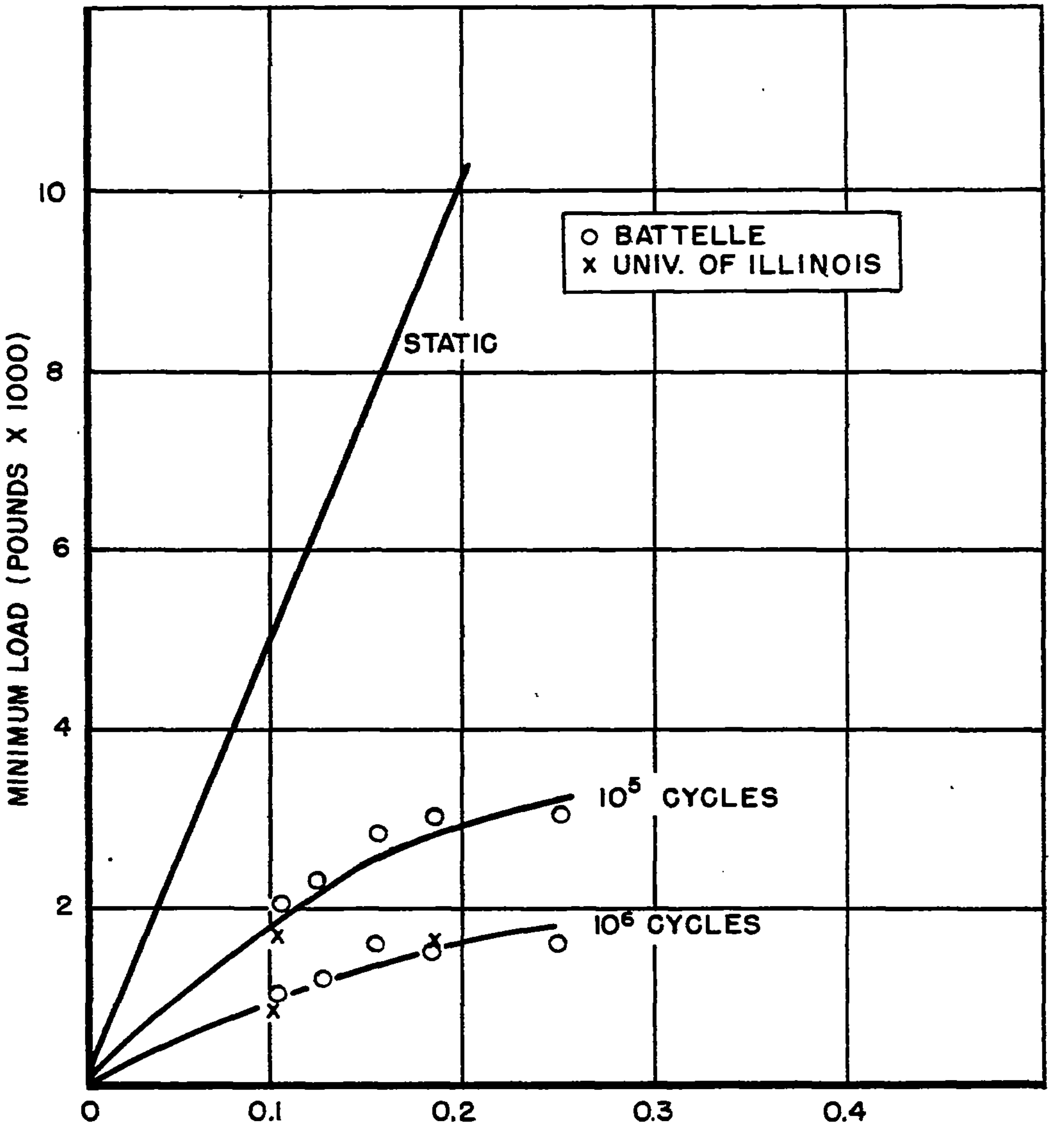


FIGURE 49 – FATIGUE STRENGTH IN REVERSED LOADING (AT R = −0.50) VS. SHEET THICKNESS, SINGLE-BOLT SPECIMENS.

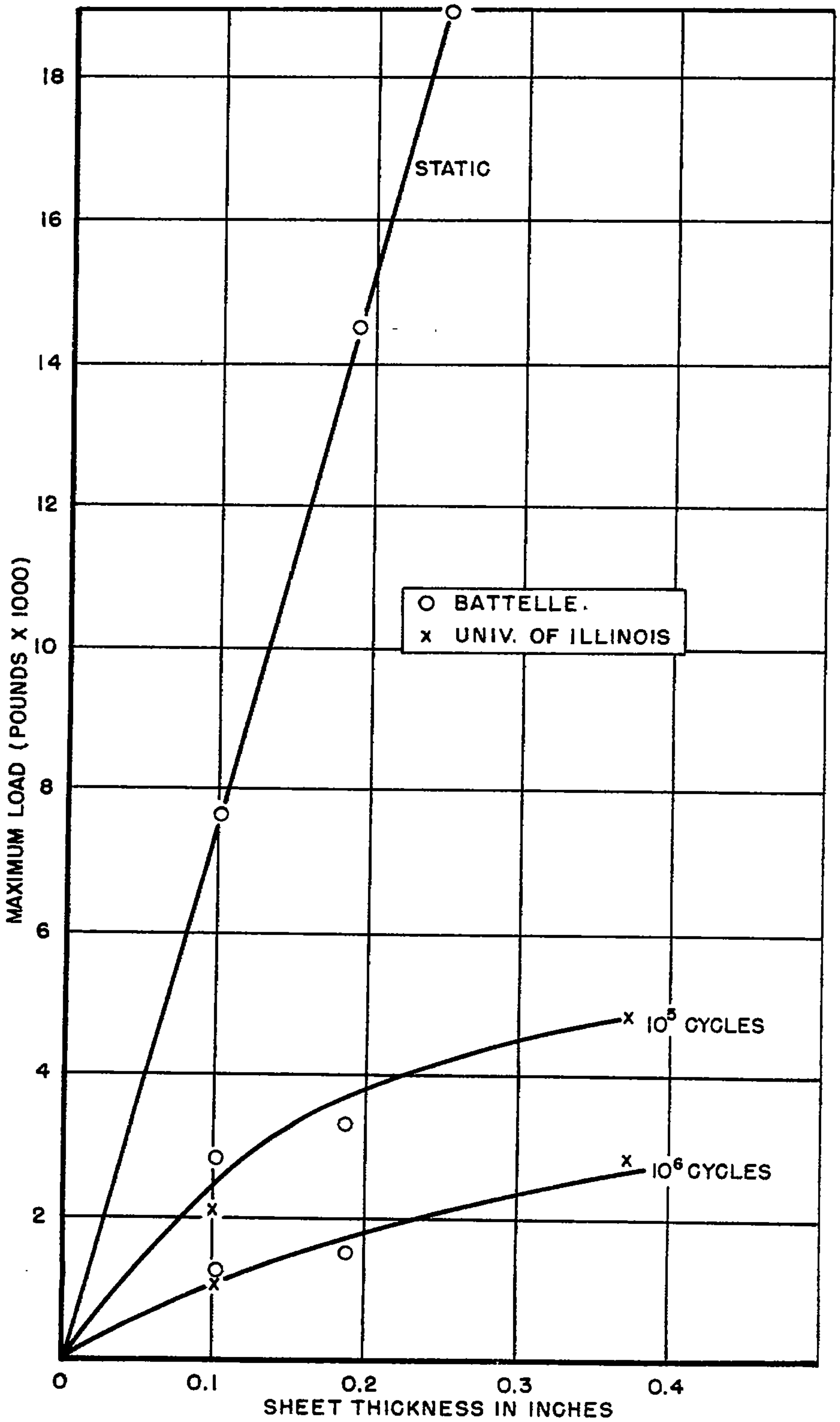


FIGURE 50–FATIGUE STRENGTH IN REVERSED LOADING (R= –0.50)
VS. SHEET THICKNESS, TWO-BOLT SPECIMENS.

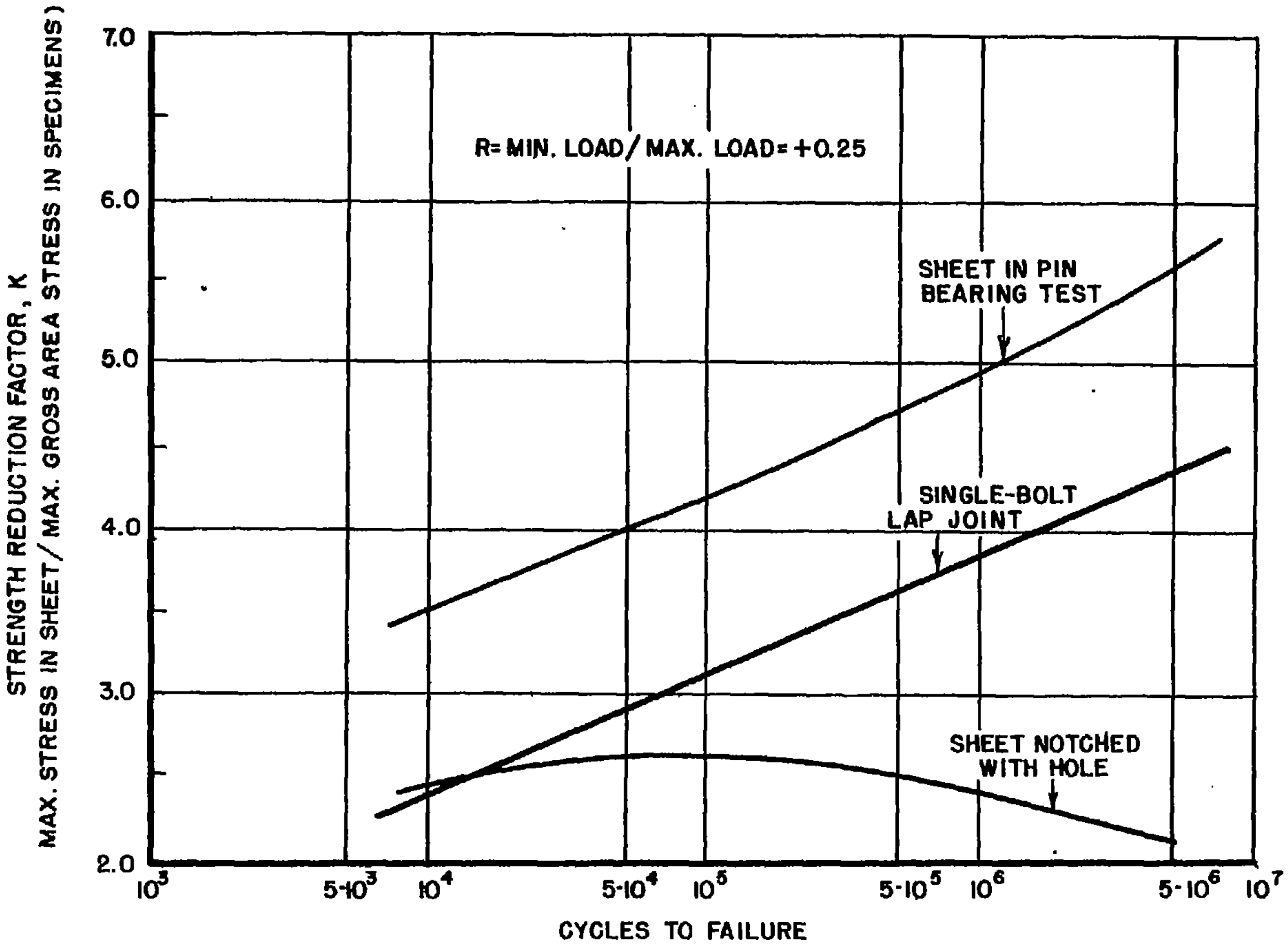
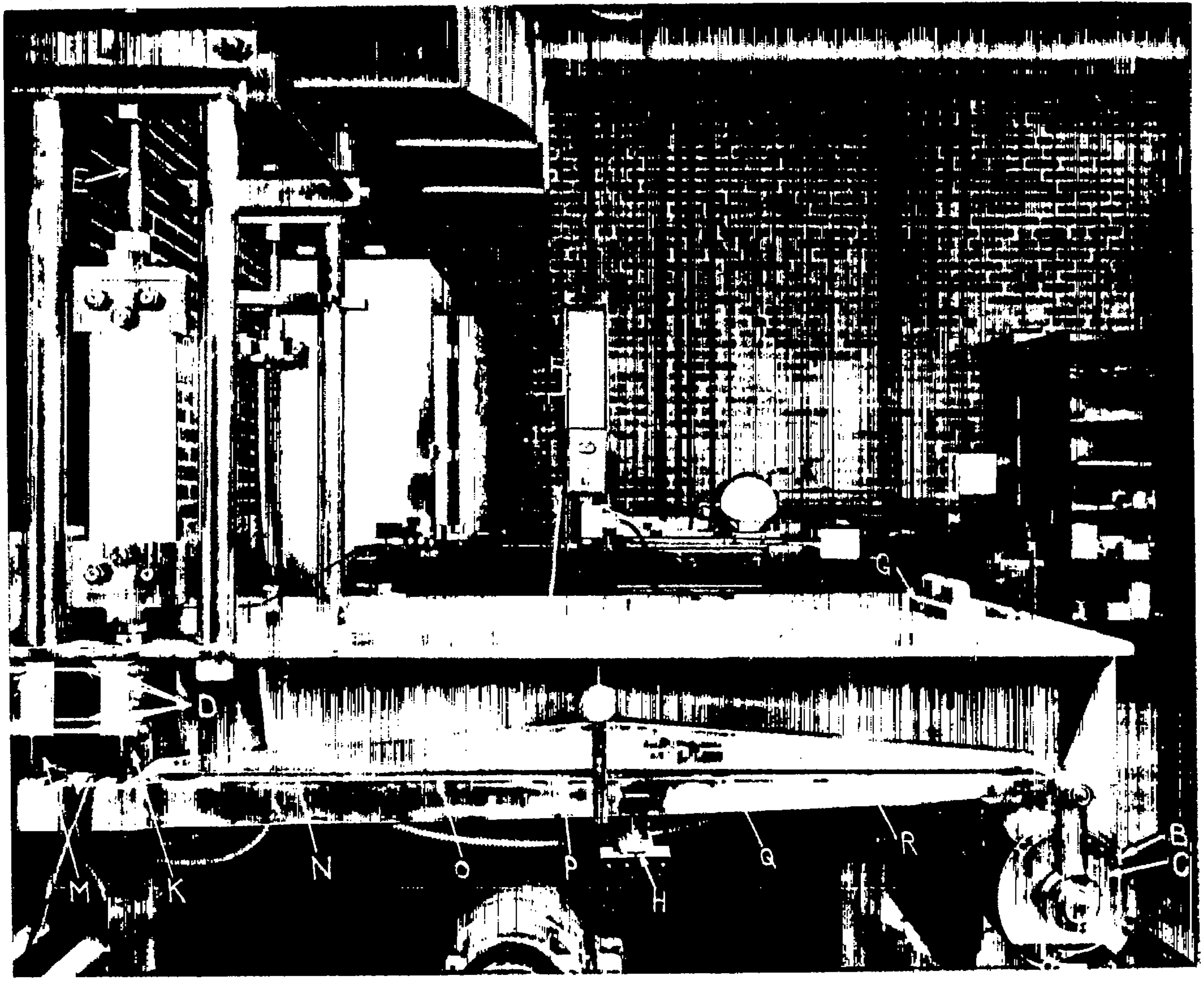


FIGURE 51 – FATIGUE STRENGTH REDUCTION FACTORS FOR VARIOUS STRESS RAISERS IN 0.102-INCH SHEET. (BATTELLE)



18221

Figure 52. Krouse fatigue testing machine (used at Battelle)

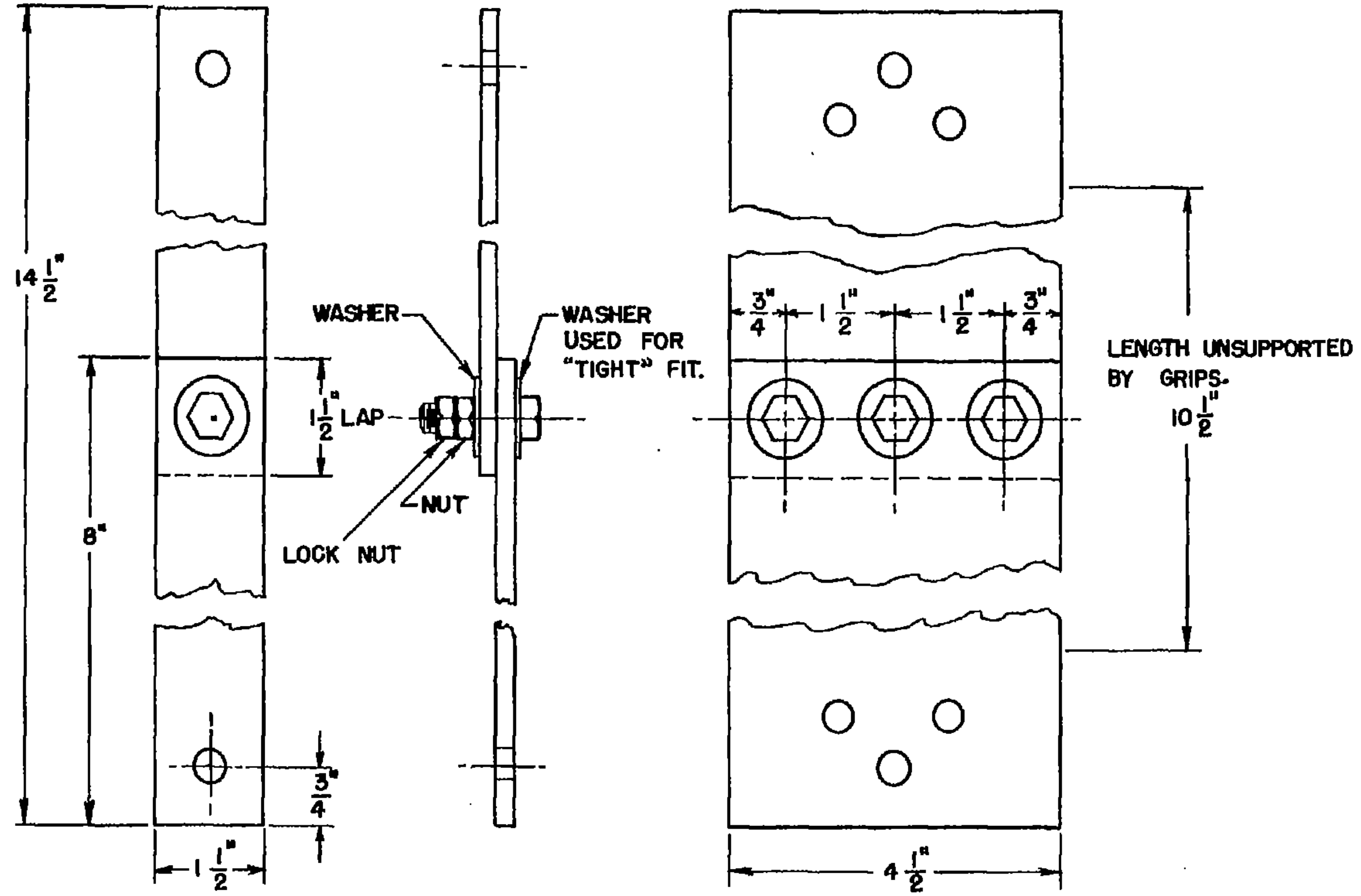


FIG. 53 - TYPICAL BOLTED - JOINT FATIGUE TEST SPECIMENS USED AT BATTELLE.

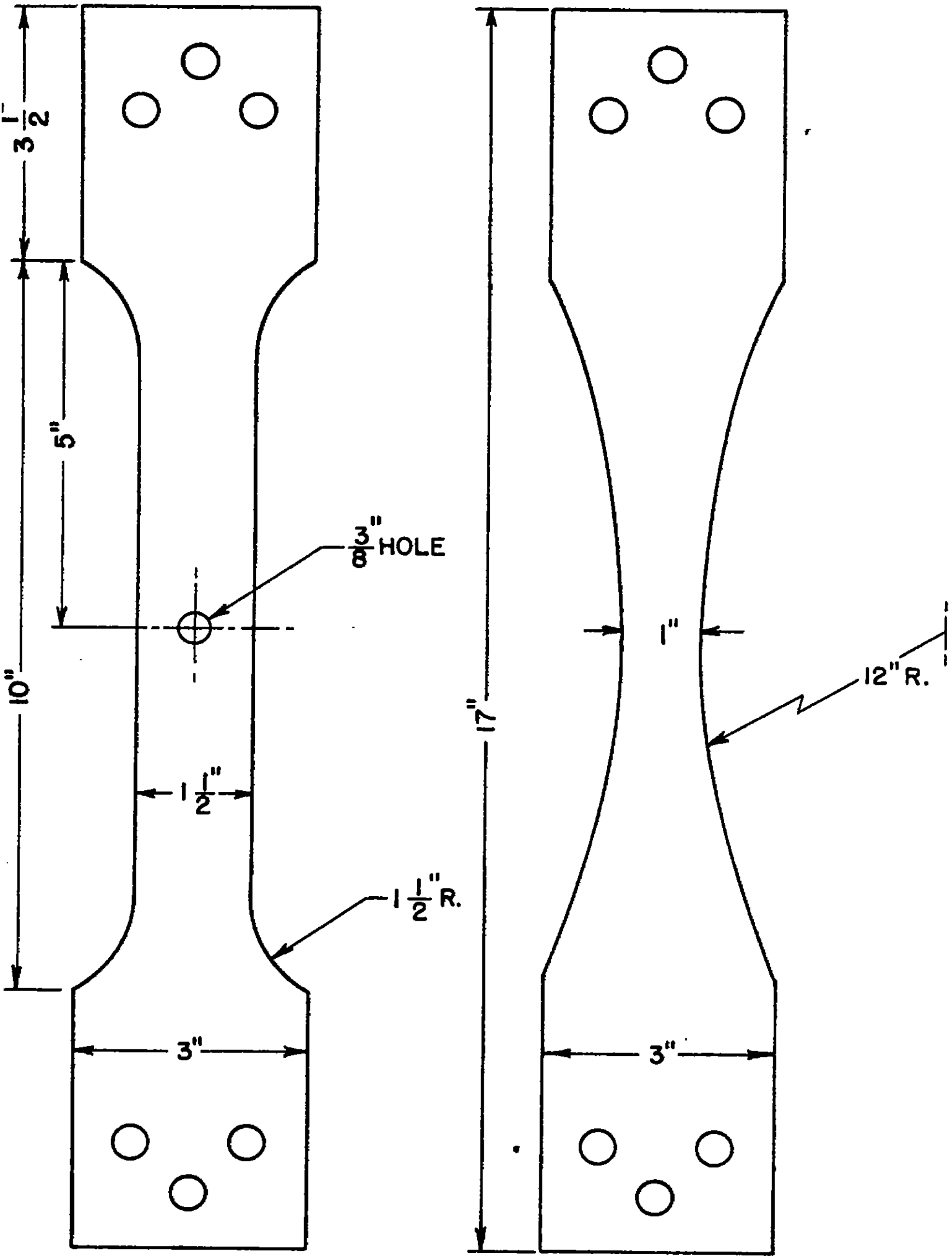
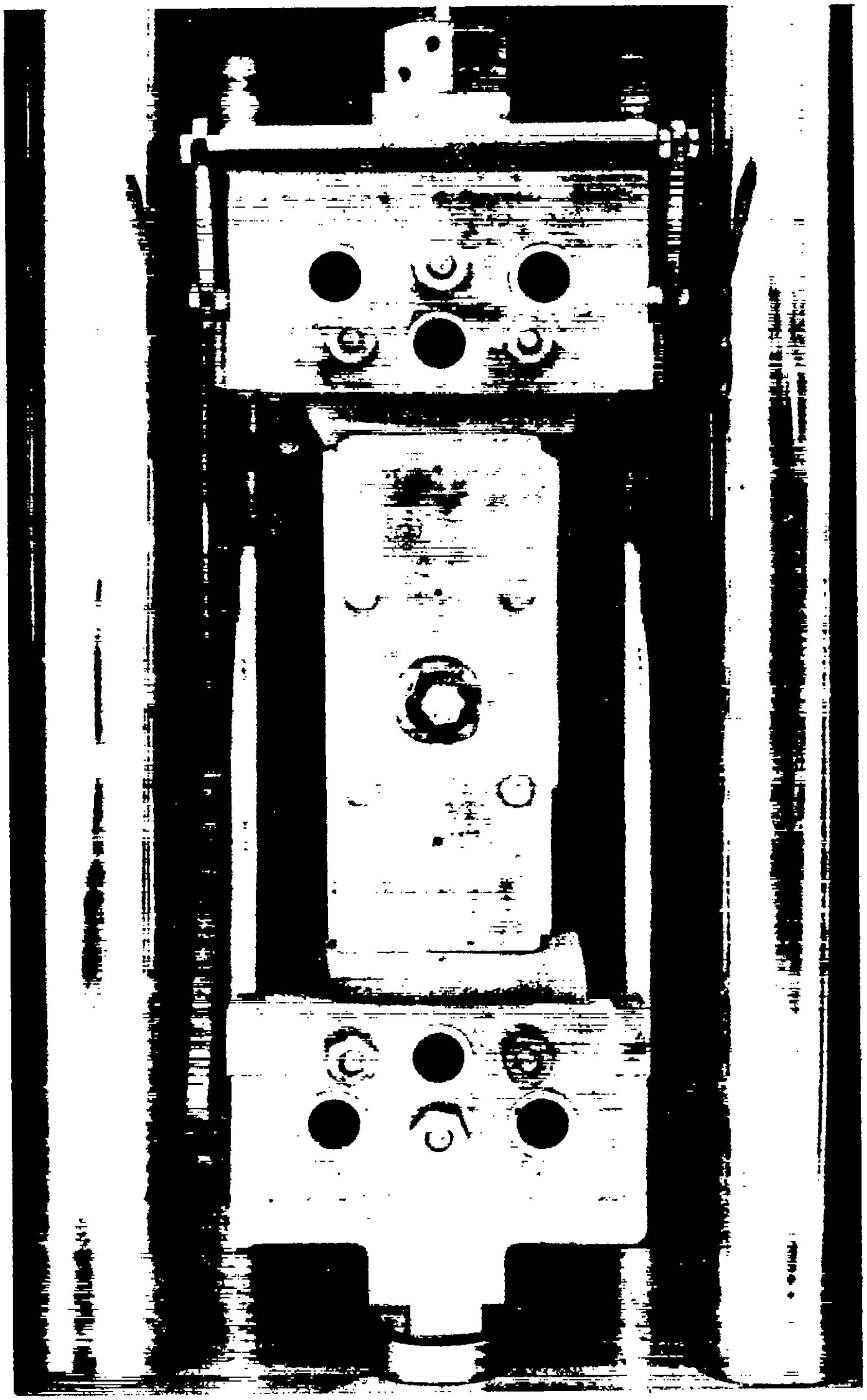
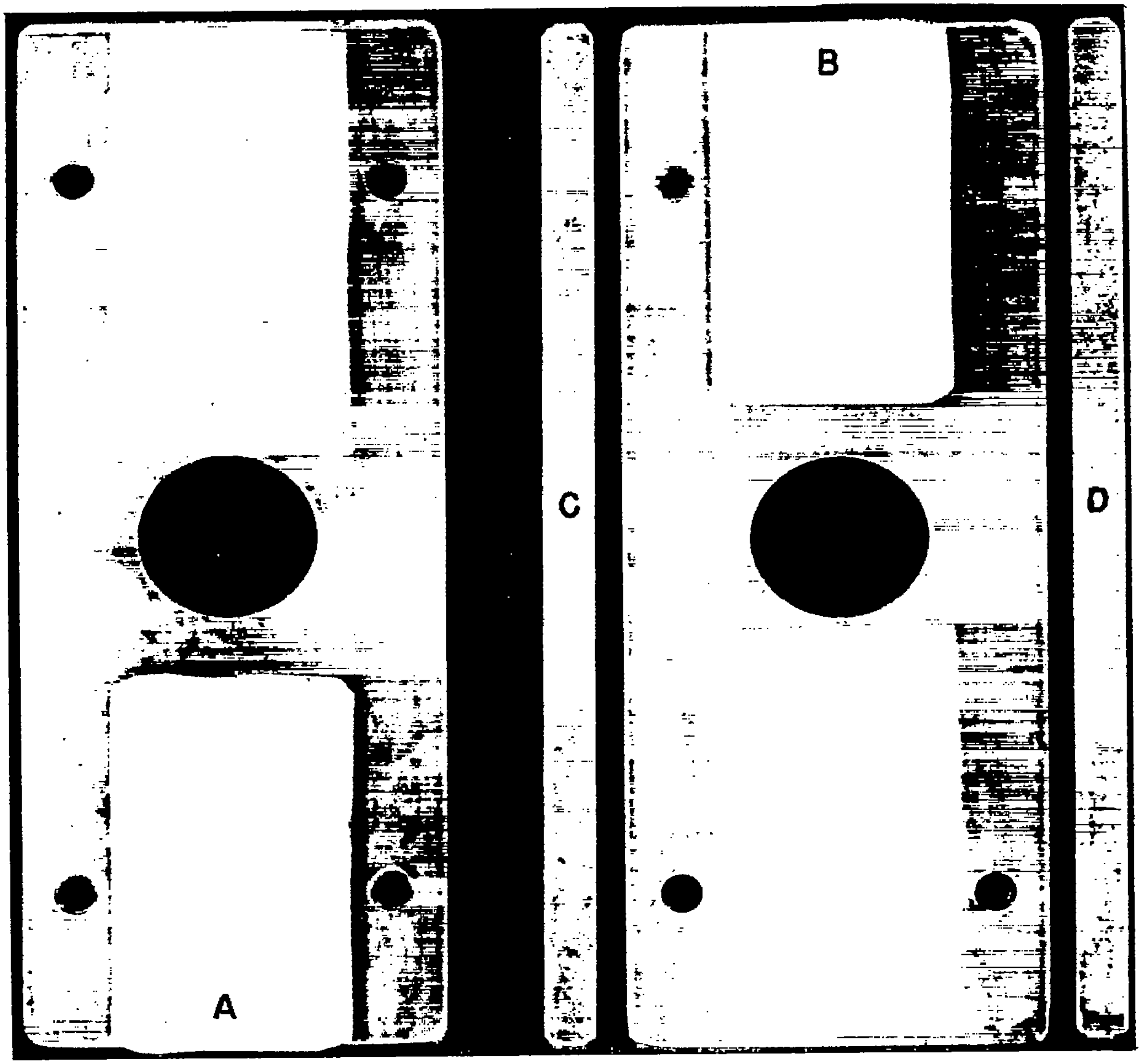


FIG. 54 – FATIGUE TEST SPECIMENS USED AT BATTELLE FOR AUXILIARY TESTS.



32384

Figure 55. Tension-compression specimens mounted in fatigue testing machine.



32386

A, B: Oiled paper raised from steel plate by the thickness of sheet used in test piece.

C, D: Spacers (cut for particular specimen thickness) to separate plates.

Figure 56. Guide plates for single-bolt test pieces in reversed loading. (Battelle).

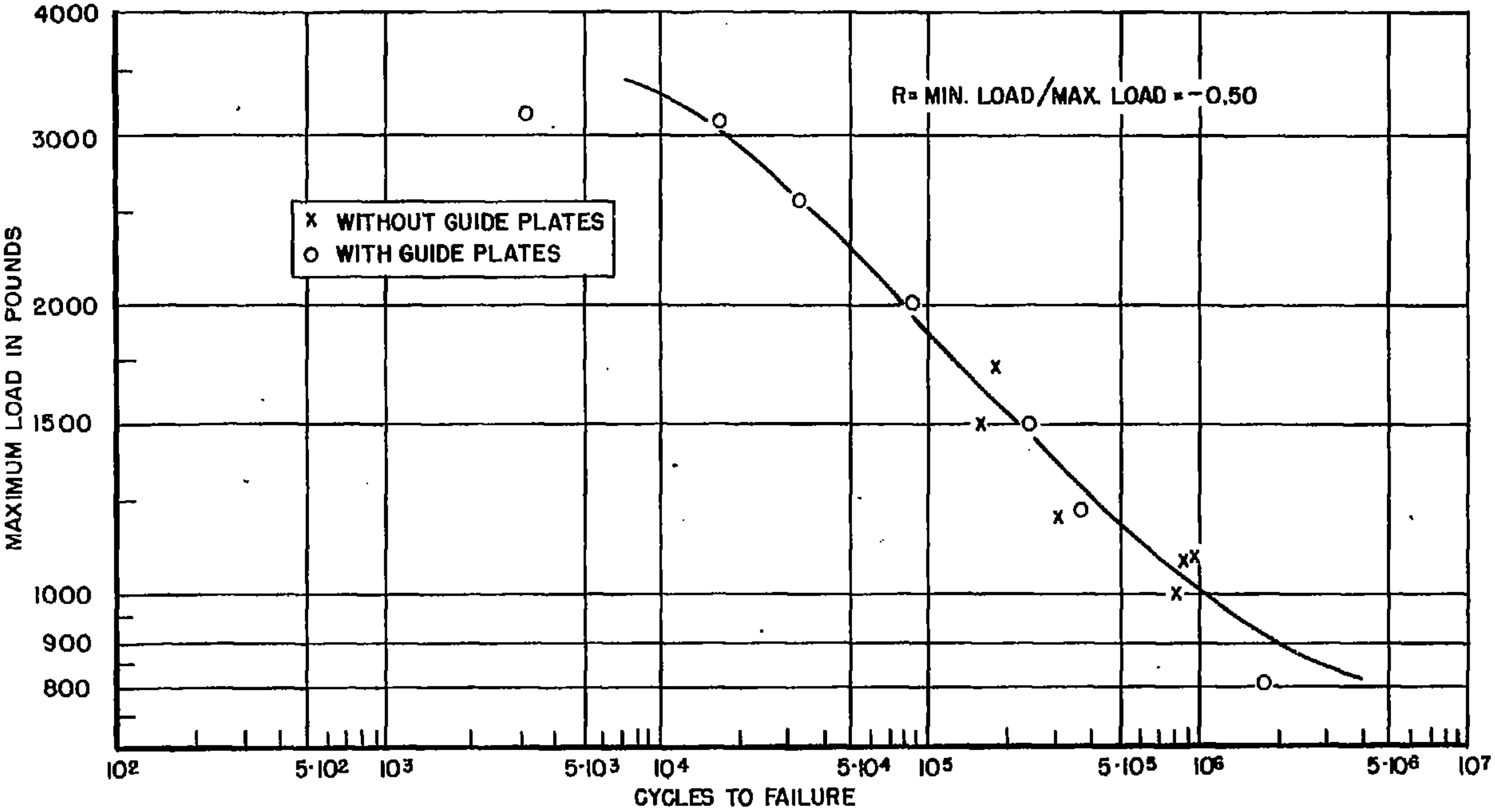
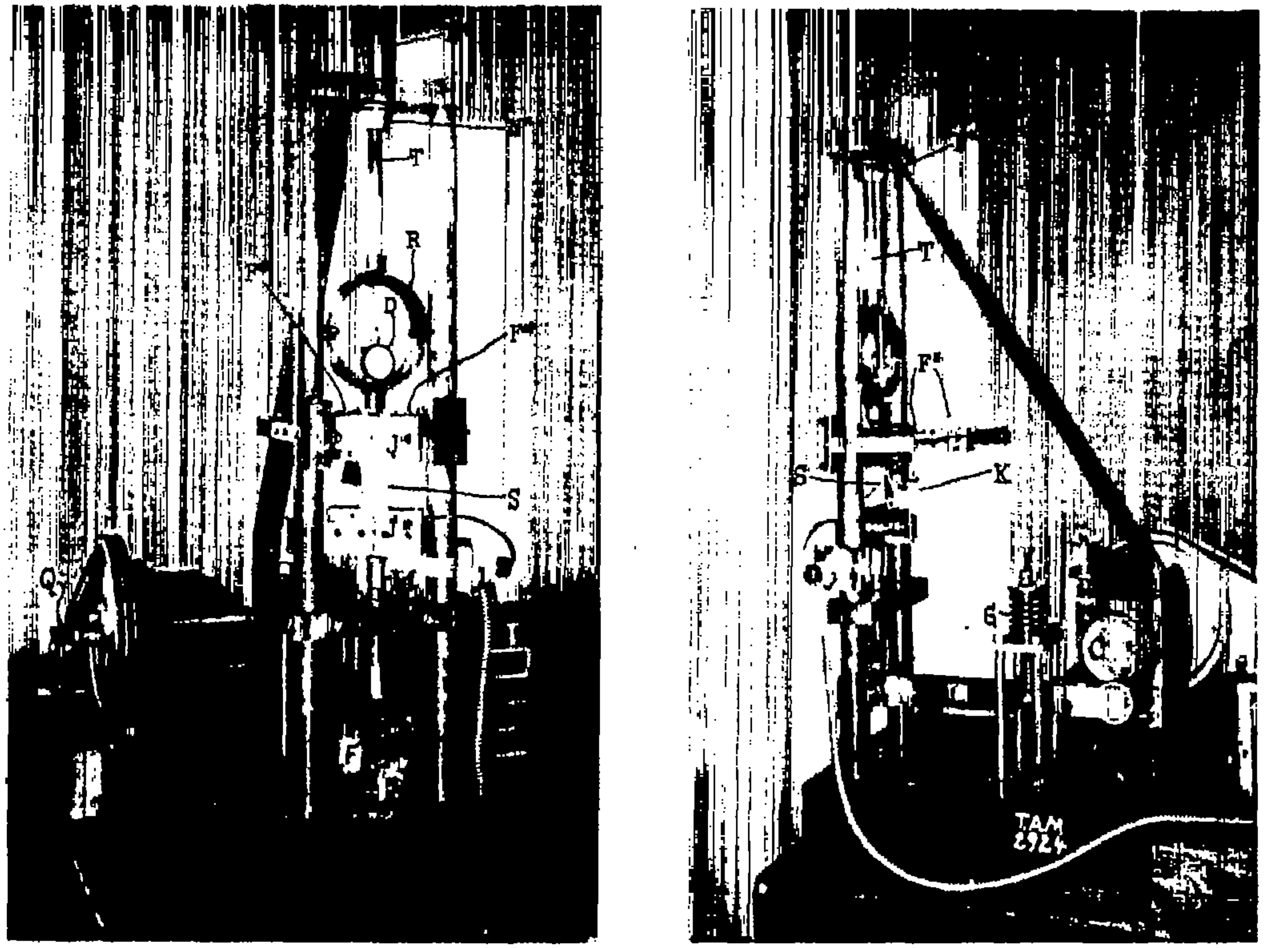


FIGURE 57–EFFECT OF GUIDE PLATES IN REVERSED LOADING, SINGLE-BOLT SPECIMENS OF 0.102" SHEET (0.010" CLEARANCE) (BATTELLE)



36578

36577

Figure 58. Moore-Krouse fatigue testing machine. (University of Illinois)

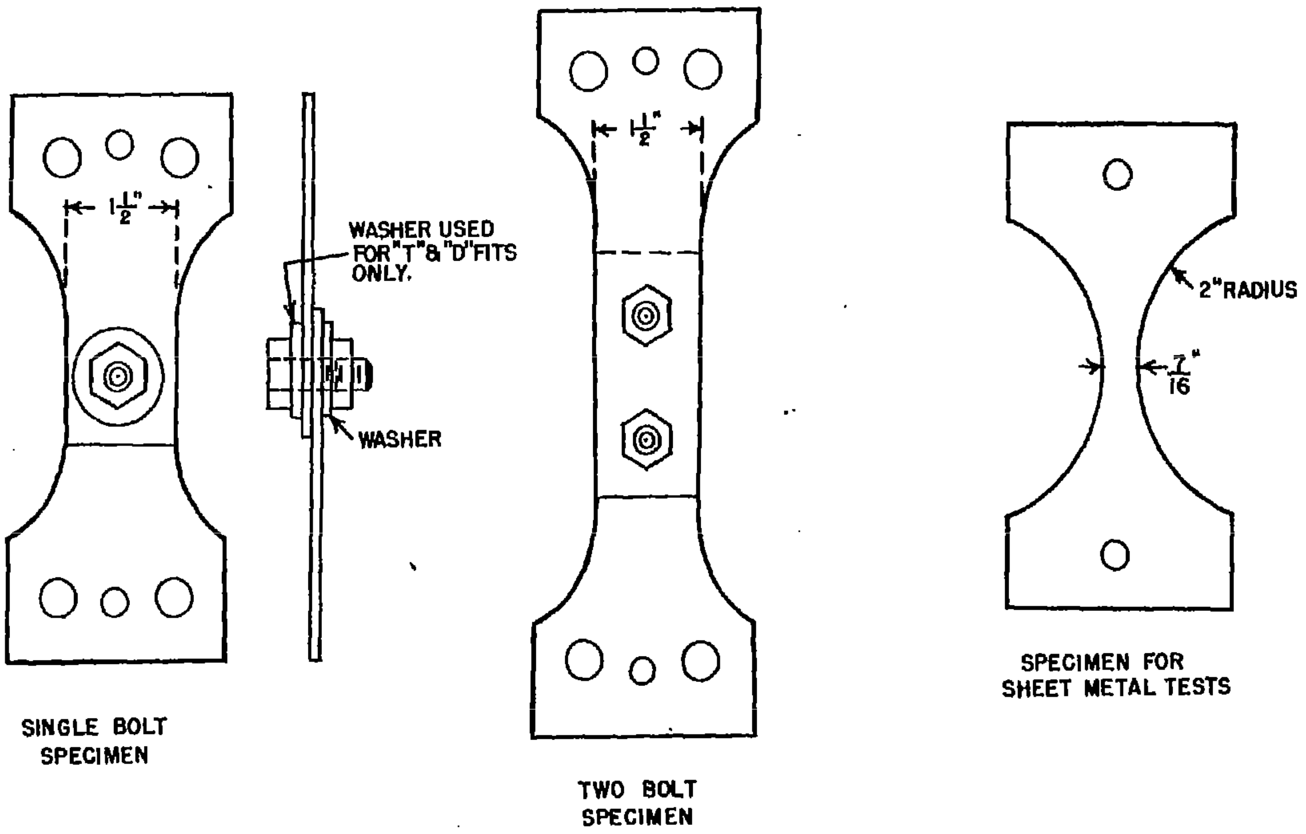
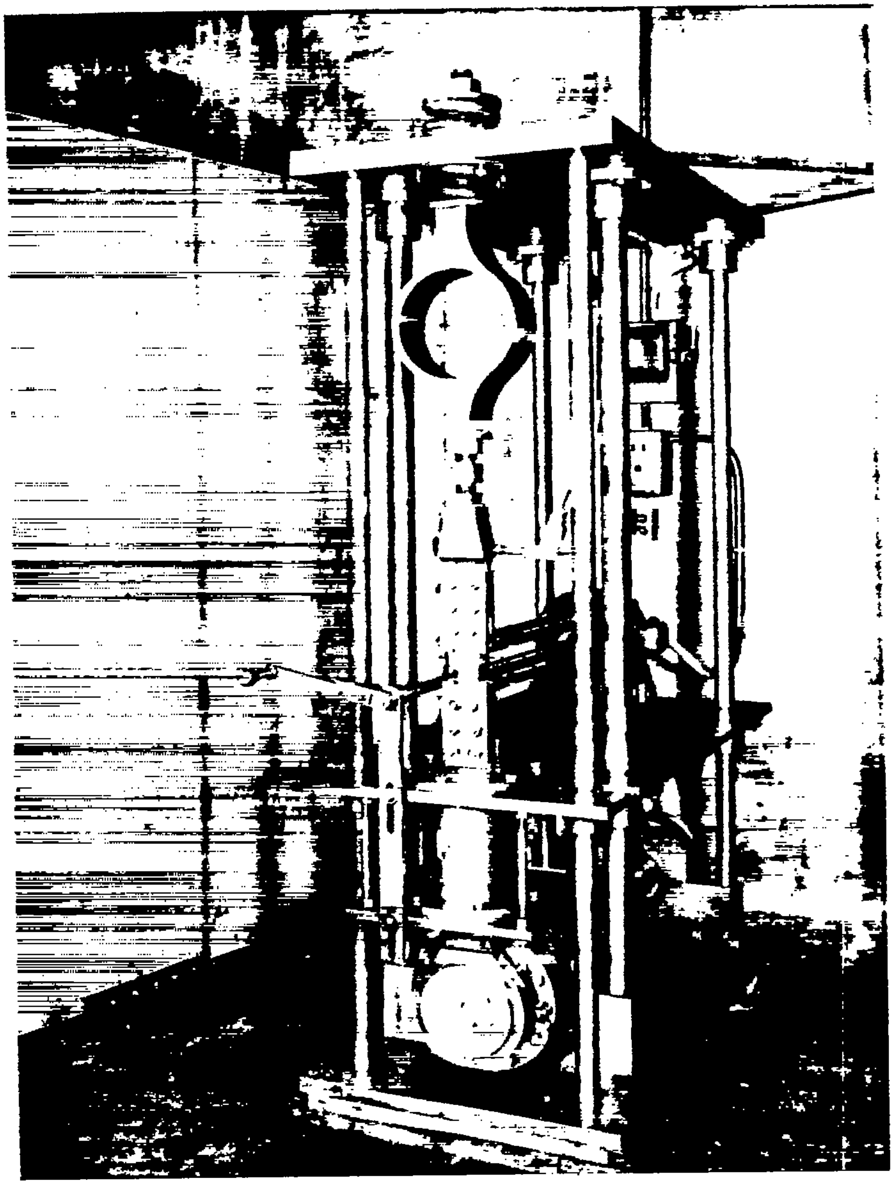
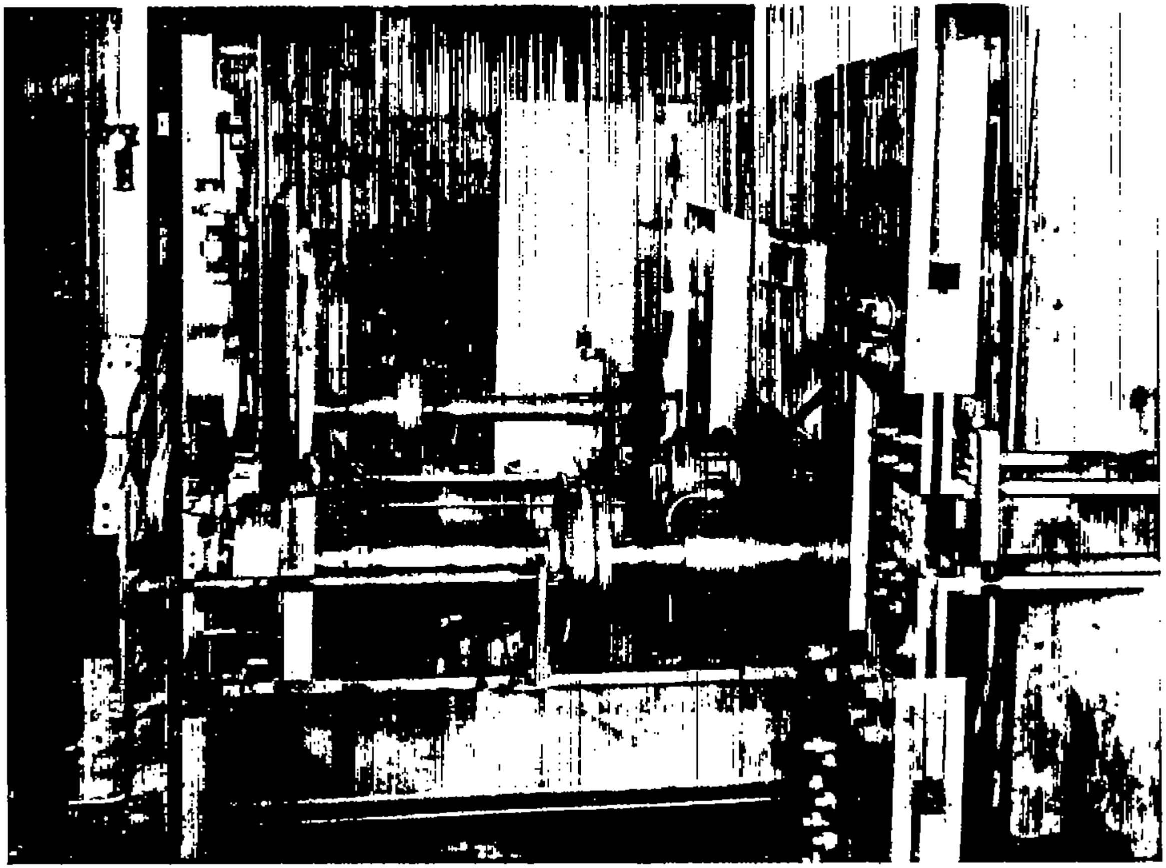


FIGURE 59 - FATIGUE SPECIMENS FOR 0.102" SHEET USED IN UNIVERSITY OF ILLINOIS TESTS.



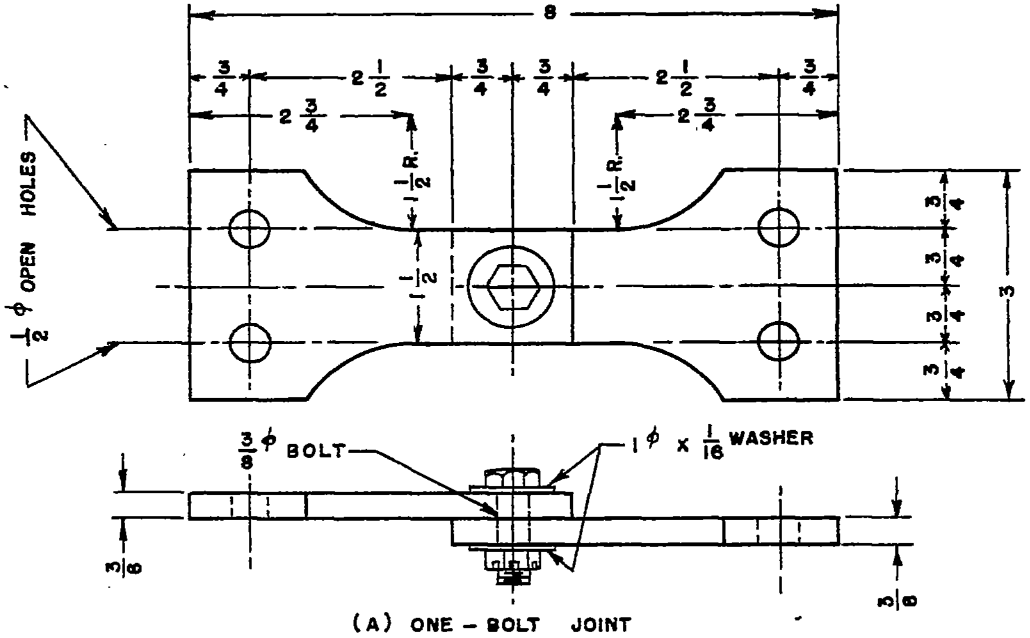
36581

Figure 60. 15,000 pound direct-acting fatigue testing machine. (University of Illinois)

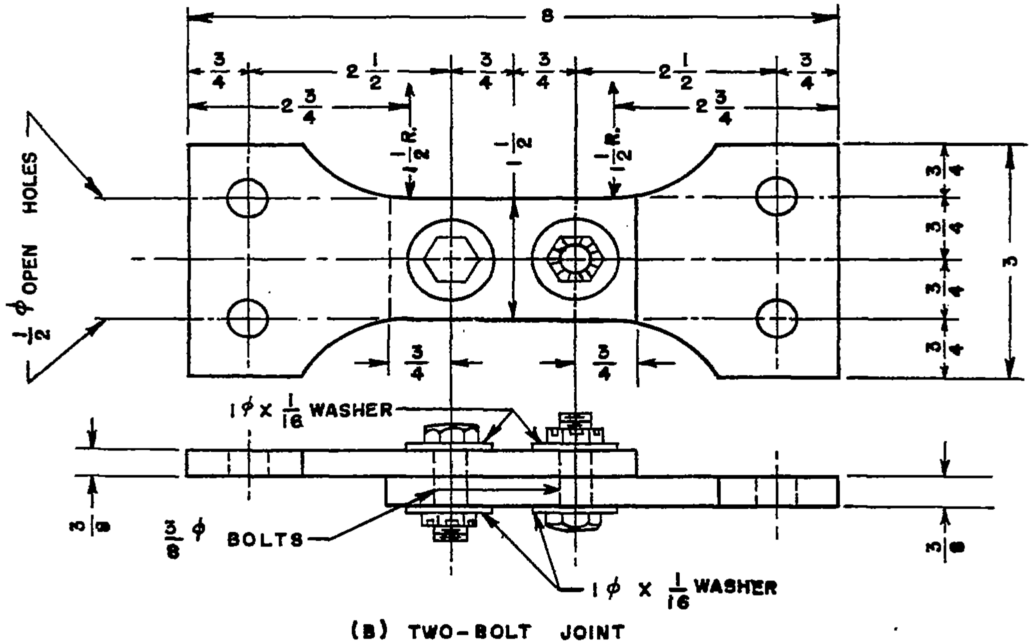


36580

Figure 61. 50,000 pound lever-type fatigue testing machine. (University of Illinois)



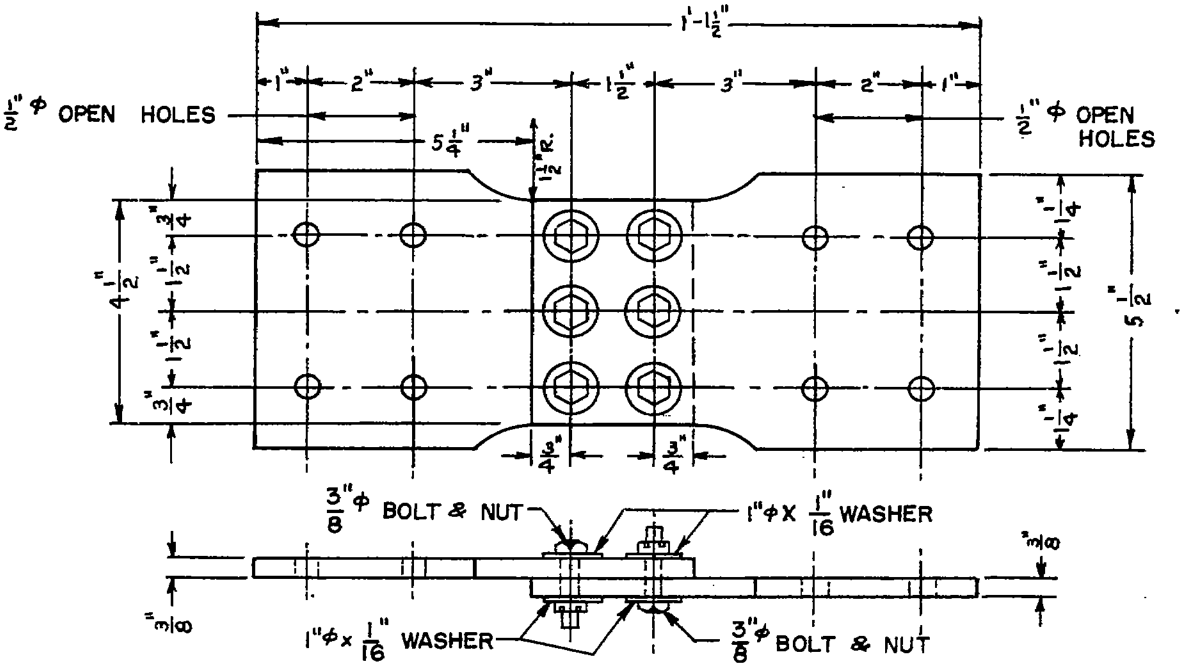
(A) ONE – BOLT JOINT



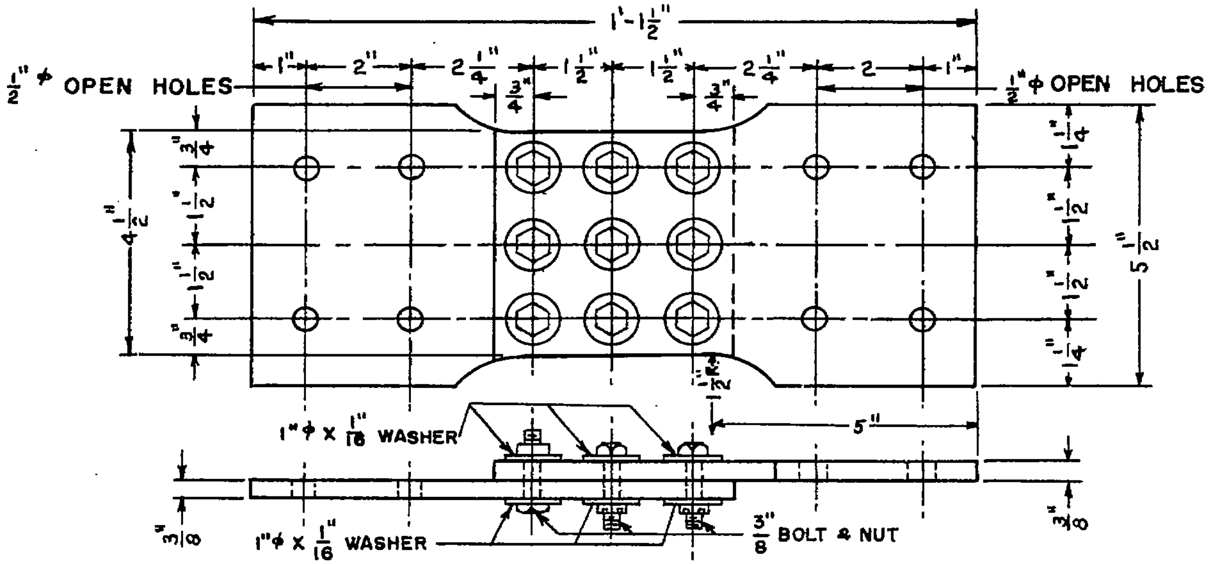
(B) TWO-BOLT JOINT

ALL DIMENSIONS IN INCHES

FIG. 62 - FATIGUE TEST SPECIMENS USED AT UNIVERSITY OF ILLINOIS FOR 0.375" SHEET.



(A) THREE BOLTS IN A ROW, TWO ROWS TRANVERSE TO DIRECTION OF STRESS



(B) THREE BOLTS IN A ROW, THREE ROWS TRANSVERSE TO DIRECTION OF STRESS

FIG. 63 - FATIGUE TEST SPECIMENS USED AT UNIVERSITY OF ILLINOIS FOR 0.375" SHEET.

TITLE: The Fatigue Characteristics of Bolted Lap Joints of 24S-T Alclad Sheet Materials	ATI- 7175
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ABSTRACT:

Fatigue tests on lap joints of 24S-T alclad sheet of various thicknesses joined by steel bolts showed that bolt fit has no influence on joint lifetime under unidirectional or reverse loading. Two or more bolts in line with load increase fatigue strength but not proportionally to number used. For given bolt diameter and pattern, fatigue strength of bolted lap joints does not increase proportionally to sheet gage used. Bolted joints under reverse loading were mitigated by using tight bolts and torques as high as allowed by other considerations.

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