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ADDITIONAL STATIC AND FATIGUE TESTS OF HIGH-STRENGTH ALUMINUM-ALLOY BOLTED JOINTS

By E. C. Hartmann, Marshall Holt, and I. D. Eaton

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SUMMARY

Additional static and fatigue tests were made on a few types of joints in 75S-T6, 24S-T4, and 14S-T6 high-strength aluminum-alloy extruded bar in order to supplement the data in NACA Technical Note 2276. Comparisons are made with the results of these earlier tests.

A joint of a new design, stepped double-shear joint, in 75S-T6 aluminum alloy was found to have an intermediate fatigue life when compared with the other joint designs used in this investigation. At like loading conditions, the stepped double-shear joint withstood fewer fatigue cycles than either the plain double-shear joint or the double-scarf joint, but its fatigue life exceeded that of all the other joint designs used. This new joint had the same net-section area as that of the other joints tested.

For three joint designs studied in 75S-T6, 24S-T4, and 14S-T6 aluminum alloys, no one alloy gave consistently greater fatigue life at the stress ranges studied. The plain-scarf joint in 24S-T4 gave consistently higher fatigue life than did the plain-scarf joint in 75S-T6 by ratios ranging from 1.4:1 to 18.5:1; there was no significant difference in the fatigue lives of the nonuniform-step joints in the three alloys; and the 75S-T6 aluminum-alloy double-shear joint gave a greater fatigue life than did either the 24S-T4 or 14S-T6 double-shear joints by ratios of 1.5:1 and 2.3:1, respectively.

When the load ranges of the plain-scarf joint in 24S-T4 and 75S-T6 are adjusted to take account of the difference in static strengths of the joints, the fatigue life of the 24S-T4 aluminum-alloy joint exceeds that of the 75S-T6 joint by ratios of about 5:1 and 12:1 for the 0 and 0.2 stress ratios, respectively. The adjustment leads to a mean load of 16,000 pounds for the 75S-T6 joint and 13,600 pounds for the 24S-T4 joint. If the comparisons are made on the basis of either the specified tensile strengths of the alloys or the actual tensile strengths of the materials rather than the static strengths of the joints, the ratios of fatigue lives are as high as 16.6:1.

No significant differences in fatigue lives were found when the 75S-T6 plain-scarf joint was assembled with a small clearance in the bolt holes rather than with a small interference.

When the 75S-T6 plain-scarf joint was statically preloaded in tension to halfway between the yield and ultimate strengths previous to fatigue testing, the fatigue life was increased by a ratio of 5.9:1. A double-shear joint of 75S-T6, preloaded in a like manner, gave a corresponding ratio of 1.4:1.

A limited study to determine the possibility of detecting fatigue cracks, without complete disassembly of a joint, before they reached catastrophic proportions, indicated that the use of penetrant inspection methods inside bolt holes did not give reliable indications of the presence of fatigue cracks.

Two double-shear joints, one each in 75S-T6 and 24S-T4 aluminum alloy, were subjected to static loading after cracks had been produced in fatigue tests. The ultimate loads were appreciably less (30 to 55 percent) than values estimated on the basis of net area obtained by correcting for the fatigue cracks.

INTRODUCTION

Early in 1951 the National Advisory Committee for Aeronautics published, as Technical Note 2276 (ref. 1), a report by the Aluminum Research Laboratories of the Aluminum Company of America on the results of static and fatigue tests of high-strength aluminum-alloy monobloc specimens and bolted joints. This publication has received widespread attention within the aircraft industry. In view of special interest shown by several aircraft companies, certain expansions of the test program were undertaken by the Aluminum Research Laboratories and are reported herein.

The limited expansions include the following:

(1) The determination of the static and fatigue strengths of a new type of joint, the stepped double-shear joint

(2) Additional tests on plain-scarf, double-shear, and nonuniform-step joints to obtain bases for further comparisons of the relative fatigue strengths of 75S-T6, 24S-T4, and 14S-T6 aluminum-alloy joints

(3) Additional tests to study the effects of bolt clearance rather than bolt interference

(4) Additional tests to determine the effects of static preload on the fatigue strength of bolted joints

(5) A determination of the feasibility of using penetrant inspection methods to locate fatigue cracks in a partially disassembled joint

(6) Determination of the reduction in static load-carrying capacity of two joints with fatigue cracks present

This work has been made available to the NACA for publication because of its general interest.

MATERIAL

Aluminum-alloy extruded bars $1\frac{1}{4}$ by 4 inches of 75S-T6, 24S-T4, and 14S-T6 were used for fabrication of the specimens tested in this investigation. Some bar stock was available from the lot of material used in the earlier part of this investigation, but additional bar stock was obtained for some of the joints of 75S-T6 and 24S-T4. The mechanical properties of the additional lots of material are given in table I. Table I also includes the average values of the mechanical properties for the original lots of material as reported in table I of reference 1. It can be seen that the tensile and yield strengths of the new lots of 75S-T6 and 24S-T4 slightly exceed the like properties for the original lots of material. The elongations obtained on the new lots of material are slightly lower than for the previous lots. The properties satisfy the applicable specifications given in reference 2.

Direct-stress fatigue tests were made on polished round specimens as described in reference 1 to determine the degree of agreement of basic fatigue strengths for the old and new lots of 75S-T6 and 24S-T4 aluminum alloys. The fatigue test results for the two lots of each alloy are plotted in figures 1 and 2 where it is seen that the direct-stress fatigue strengths for the two lots of 75S-T6 compare very well and that the fatigue strengths of the new lot of 24S-T4 are slightly higher than the results obtained on the original lot, but such small differences are not considered significant in light of the data in reference 3.

TEST SPECIMENS

The stepped double-shear joint, the new joint type used in this investigation, is shown in figure 3. It can be seen that the net-section area is 1.2 square inches at the first row of bolt holes and 0.6 square inch at the second row of bolt holes. The bolt holes were reamed to 0.0010 to 0.0020 inch under the measured bolt diameter.

Additional specimens of the nonuniform-step, plain-scarf, and double-shear joints, shown in figures 2(b), 2(c), and 2(g) of reference 1, were fabricated. Two of the plain-scarf joints were fabricated with the bolt holes reamed to 0.0015 to 0.0025 inch larger than the measured bolt diameter in order to introduce a bolt clearance of that amount, whereas the bolt holes in all the other specimens were reamed to 0.0010 to 0.0020 inch less than the measured bolt diameter as in the original part of the investigation.

Prior to the fatigue test, a plain-scarf joint and a double-shear joint, both assembled with interference bolt fits, were preloaded in static tension to a computed stress on the net section halfway between the yield and ultimate strengths. All other specimens were tested without preload.

As in the initial part of the investigation reported in reference 1, aircraft-type bolts 1/2 inch in diameter were used and a torque of 690 inch-pounds was applied to the nuts. The specimens were given a chromic-acid anodic treatment and one coat of zinc-chromate primer prior to assembly. The joints which were fabricated of 24S-T4 and/or 14S-T6 aluminum alloys were made identical in size with like 75S-T6 joints without regard to differences in the mechanical properties of the materials.

PROCEDURE

The procedures used for the static and fatigue tests of the bolted joints have been described in reference 1. As will be seen later, not all joints were tested to complete failure as was the case in the previous investigation.

As noted above, a plain-scarf joint and a double-shear joint each of 75S-T6 aluminum alloy were subjected to a static loading previous to fatigue testing. The fixtures and machine used in the static tests were used in applying the preload. The joints were preloaded to a load equivalent to the mean of: (1) the load corresponding to the nominal yield strength P/A of the material on the net section (1.2 square inches × 79,400 psi = 95,300 pounds) and (2) the ultimate tensile load of a like joint (107,250 pounds for the plain-scarf joint and 115,250 pounds for the double-shear joint). Thus the preloaded plain-scarf joint was subjected to a static load of 101,230 pounds and the preloaded double-shear joint, to a load of 105,250 pounds.

Upon completion of the fatigue tests, all joints were disassembled and auxiliary failures recorded. In conjunction with the disassembly of the joints, the least torque required to tighten the bolts further was measured in order to determine whether or not the fatigue loading had affected the original bolt tensions.

Two joints which intentionally were not tested to complete fracture were studied to determine the possibility of locating small fatigue cracks without completely disassembling a joint. In order to assure that small fatigue cracks were present, however, the joints were first disassembled for a thorough examination and then reassembled. The bolts were removed from the bolt holes in which small fatigue cracks were known to exist and penetrant inspection methods were used to inspect for the known cracks. This inspection was made with specimens removed from the testing machines; so no inspection was made with the specimens under load.

In order to determine the reduction in static strength produced by small fatigue cracks, two specimens were subjected to static test conditions using the machine and adapters previously described. These specimens were loaded to fracture and the ultimate loads recorded.

RESULTS

Static Test Results

The results of the additional static tests are presented in figure 4 and are summarized in table II, together with the results for the 75S-T6 nonuniform-step and double-shear joints taken from table IV of reference 1.

The stepped double-shear joint, the new joint design tested in this investigation, withstood an ultimate load of 94,900 pounds, in other words, 29,200 pounds per pound of joint weight. The deformation in an 8-inch gage length under a load of 16,000 pounds was 0.0060 inch. When compared with the static test results of the other 75S-T6 aluminum-alloy joints given in reference 1, it is found that the ultimate load of the stepped double-shear joint is lower than that of the double-shear (115,250 pounds), the uniform-step (107,800 pounds), the plain-scarf (107,250 pounds), and the nonuniform-step (100,000 pounds) joints. The ultimate load of the new stepped double-shear joint exceeds the ultimate loads of the bolted-keyed, double-scarf, single-shear, serrated, and clamped-keyed joints. The load per pound of weight and deformation in 8 inches at 16,000-pound load are also intermediate to the values obtained for the other types of 75S-T6 joints.

The 75S-T6 aluminum-alloy nonuniform-step joint and double-shear joint withstood higher ultimate loads (17 to 29 percent) than did like joints in 24S-T4 or 14S-T6, as would be expected from the tensile strengths of the materials and as was obtained for the plain-scarf joints and monobloc specimens in the initial part of this investigation. It can be seen, however, that the order of ultimate loads for like joints in 24S-T4 and 14S-T6 aluminum alloys is not always consistent with the order of tensile properties of the materials.

The static failure of the stepped double-shear joint shown in figure 5 was by combined bearing and tension on the thin portions of both the tongue and outside members of the joint representing the main plate and splice plates, respectively, of an ordinary double-strap butt joint. It is reasonable to believe that the load-carrying capacity might be increased by minor changes in the proportions of the joint. The paths of the static fractures in the 24S-T4 and 14S-T6 nonuniform-step and double-shear joints were almost identical to the paths of the fractures in like 75S-T6 joints shown in figure 7(b) of reference 1 (specimens 1B and 6A, respectively).

Fatigue Test Results

The results of the additional fatigue tests are given in table III. None of the fatigue test results from the initial investigation (ref. 1) have been repeated in table III, but, in the discussion, curves, and tabulations that follow, rather extensive reference is made to the earlier tests.

The results of the fatigue tests at 16,000-pound mean load ±10,670 pounds (stress ratio, 0.2) are summarized in table IV. Ratios of fatigue life based on the life of the nonuniform-step joint of 75S-T6 are given. It can be seen that the new data obtained do not alter the conclusion of reference 1 that the double-scarf joint (75S-T6) has the highest fatigue strength of all the types of joints studied. Although the nonuniform-step joints show no significant difference attributable to the material, the double-shear joints place the materials in the following order of decreasing fatigue lives: 75S-T6, 24S-T4, and 14S-T6. As indicated in reference 1, the plain-scarf joint of 24S-T4 had a longer fatigue life than the corresponding joints of 75S-T6 or 14S-T6. It thus appears that no one alloy was consistently superior.

The result of the fatigue test on the stepped double-shear joint is included in table IV and is plotted with other results from this and the initial part of the investigation in figure 6. It can be seen that, of the 75S-T6 joints tested, the fatigue life of the stepped double-shear joint (111,400 cycles) is exceeded by that of the double-scarf (418,000 cycles) and double-shear (187,400 cycles) joints. The fatigue fracture shown in figure 7 occurred at the bolt holes in the thin portion of the tongue. No additional fractures were found, either in the tongue or in the outside members.

Direct-stress fatigue test results for the double-shear and nonuniform-step joints of the three aluminum alloys under consideration are plotted in figure 8 and are included in the summary of table V. For the conditions of 16,000-pound mean load ±10,670 pounds, it can be seen that there is no significant difference in the fatigue lives of the nonuniform-step joint in any of the three alloys studied. At a load of 16,000 pounds ±10,670 pounds, the fatigue life of the 75S-T6 double-shear joint exceeds the fatigue lives of the 24S-T4 and 14S-T6 double-shear joints by ratios of 1.5:1 and 2.3:1, respectively.

The summary of results of direct-stress fatigue tests for the plain-scarf joints of 75S-T6, 24S-T4, and 14S-T6 at a mean load of 16,000 pounds and various variable loads, given in table X of reference 1, is extended in table V and figure 9 to include similar comparisons of 75S-T6 and 24S-T4 plain-scarf joints tested with a 12,000-pound mean load and various variable loads. It can be seen that the 24S-T4 plain-scarf joint gives consistently greater fatigue life than the 75S-T6 joint with the ratios of fatigue lives ranging from 1.4:1 to 18.5:1 for the mean loads and stress ratios used in these tests. For like stress ratios the fatigue-life ratios are larger in favor of 24S-T4 at the 12,000-pound mean load than at the 16,000-pound mean load.

The direct-stress fatigue test results for the 75S-T6 and 24S-T4 aluminum-alloy plain-scarf joints at 0 and 0.2 stress ratios have been replotted in figure 10. In order to take care of differences in the static properties of the 75S-T6 and 24S-T4, the fatigue results for the 75S-T6 and 24S-T4 joints should be compared at lower loading conditions for the 24S-T4 joint than for the 75S-T6 joint, that is, on the basis of mean loads of 13,600 pounds and 16,000 pounds, respectively, which are proportional to the ultimate static strengths of the joints. Thus it can be seen in figure 10 that at a mean load of 13,600 pounds the 24S-T4 plain-scarf joint would be expected to fail at 100,000 and 680,000 cycles for the 0 and 0.2 stress ratios, respectively. Included in table V are comparisons of these results with the results for the 75S-T6 plain-scarf joints at the higher mean load of 16,000 pounds and at like stress ratios. The ratio of fatigue lives for the 24S-T4 joint to that of the 75S-T6 joint, when the load on the 24S-T4 joint is adjusted to take account of differences in the static strengths of the joints, is 4.6:1 and 12.4:1 for the 0 and 0.2 stress ratios, respectively. Had the loading on the 24S-T4 joint been adjusted on the basis of the ratio of the ultimate tensile strengths of the materials the mean load would be 14,600 pounds and the ratios of the fatigue life of the 24S-T4 joint to the fatigue life of the 75S-T6 joint would have been 3.2:1 and 6.7:1 for stress ratios of 0 and 0.2, respectively. Further, had the adjustment been made on the basis of the applicable guaranteed minimum values given in reference 2, the adjusted load on the 24S-T4 would have been 13,000 pounds and ratios of fatigue lives of the 24S-T4 to the 75S-T6 joints would have been 6.0:1 and 16.6:1. On the other hand, it was shown in the original report that differences in design of 75S-T6 aluminum-alloy joints have been instrumental in producing increases in fatigue life, at a 0.2 stress ratio, of more than 18:1.

The fatigue test results for the two 75S-T6 plain-scarf joints which were fabricated with hole clearance (0.0020 ± 0.0005 inch) rather than hole interference (0.0015 ± 0.0005 inch) are plotted in figures 9 and 11 and are included in the summary of table VI. It can be seen that the bolt clearance, within the limits used, had no noticeable effect upon the fatigue strength of the joint, either when tested completely in a tensile load range or tested in a load range from compression to tension. Put another way, it can be said that the bolt interference used did not improve the fatigue strength of the joints. The interference used represents 0.003 inch per inch of hole diameter. This was about the maximum interference which would allow the bolt to be pulled through the hole without lubrication and without exceeding the recommended tightening torque.

As has been described earlier in this report, a plain-scarf joint and a double-shear joint, each of 75S-T6 aluminum alloy, were loaded in static tension to an average stress halfway between the yield and ultimate strengths previous to fatigue testing. The plain-scarf joint developed considerable visible plastic deformation under the static load imposed, as shown in figure 12. The deformations at the bolt holes, revealed by disassembly after the fatigue test, are shown in figure 13. The fracture is shown in figure 14. Measurements of the distance between the keyways of the plain-scarf joint indicated a permanent elongation of 0.110 inch. Bolt tightness of the joint was checked after completion of the fatigue test and the torque to tighten the nuts further was found to average about 60 percent of the torque used in the assembly of the joint. There was no visible permanent deformation in the double-shear joint which had been subjected to static preload; however, a permanent elongation of 0.009 inch was measured between the keyways of the specimen. After the fatigue test, the torque to tighten the nuts further was found to average only about 40 percent of the torque used in the assembly of this joint. The nuts in both preloaded joints had not been retightened after the preload was applied.

The direct-stress fatigue test results for the plain-scarf and double-shear aluminum-alloy joints, which had been preloaded with a static load, have been plotted in figures 8 and 11 and are included in the summary in table VI. It can be seen that the ratio of the fatigue life of the plain-scarf joint with preload to that of plain-scarf joint without preload is 5.9:1. The preloaded plain-scarf joint failed through the first row of bolt holes similar to the failure of the plain-scarf joint without preload shown in figure 15(b) (joint 2) of reference 1. The like ratio for the double-shear joints was found to be 1.4:1. As shown in figure 15, the preloaded double-shear joint failed in one of the outside members in a pattern quite unlike that of the corresponding joint without preload shown in figure 15(b) (joint 9B) of reference 1. Figure 16 shows the fractured surface of the preloaded specimen. Metallographic examination indicated that the fracture originated in a fretted area on the faying surface. No sign of additional fractures was evident in the tongue of this specimen. Unless the galling caused some reduction in life of this specimen, it would appear that the location of the critical section in the double-shear joint was changed by the preload imposed with little gain in fatigue life of the joint. It has been said that preloading to 67 percent of ultimate strength increases the fatigue life from two to tenfold. The result of the test on the preloaded plain-scarf joint is in agreement with such a statement. The National Bureau of Standards has reported results of fatigue tests on sheet with static preload (ref. 4) which show beneficial as well as detrimental effects of preloading on fatigue life. It would appear from the two tests made on bolted joints that preloading may or may not have significant beneficial effects on the fatigue life of a joint.

The locations of the failures in the joints used for the additional fatigue tests described herein are noted in table III. In general, the fractures were similar to those illustrated in figure 15(b) of reference 1 for like joint types. The fractures in the preloaded double-shear joint and plain-scarf joint and in the stepped double-shear joint, the new joint design tested, have already been discussed. As noted in table III, the nonuniform-step joint in 24S-T4 failed in the fillet; however, disassembly of the joint revealed additional cracks in the intact portion of the joint emanating from the holes in the first row as shown in figure 17. Micrographs of the additional cracks are shown in figure 18. The failures of the 75S-T6 and 14S-T6 joints described in reference 1 were through the first row of bolt holes although a crack developed in the fillet of the 75S-T6 specimen before any cracks were visible at the bolt holes.

In general, the nuts on the aircraft type of fasteners were found to be tight after completion of the fatigue tests. It has been discussed previously that the nuts on the preloaded joints were loosened as a result of the preload used. Based on the torque required to tighten the nuts further and neglecting all nuts on bolts in holes directly connected with fatigue failures, there were no significant differences between the initial and final tightness of the nuts with but one exception. One plain-scarf joint specimen (2R) was found to have torques on the nuts, after the fatigue test, averaging about 66 percent of the desired torque. The result of the test on this specimen is given in table III and is plotted in figure 9. It can be seen that this result is considerably lower in fatigue life than that of another similar specimen subjected to like test conditions. It is suspected that, inadvertently, the desired torque was not applied to the nuts of this particular specimen when it was assembled for test.

Fatigue Crack Detection

As stated previously, two joints which were intentionally not tested to complete fracture were checked to determine the effectiveness of penetrant inspection methods in indicating the existence of small fatigue cracks. The fatigue cracks, which were located in the tongue of the double-shear joints during preliminary disassembly, are shown in figures 19 and 20. The extent of these cracks as revealed by subsequent fracture of the specimens under static tensile loading is shown in the lower illustrations of these figures. Micrographs of cracks 1 and 2 are shown in figure 21. Indicated in this figure are the lengths of the cracks as measured on the surface by means of a micrometer microscope.

When the bolts were removed individually from the reassembled joints, it was found exceedingly difficult to obtain evidence of the existence of some of the cracks by means of the penetrant inspection methods used. In the case of the smallest crack no evidence of its existence was found. Further, no indication was obtained of the existence of the crack, about 0.009 inch long, shown in figures 17 and 18 when the methods were used with this joint in the disassembled condition.

Static Strength of Fatigued Joints

The static loads required to fail the 75S-T6 and 24S-T4 double-shear joints after the fatigue cracks shown in figures 19 and 20 had been developed are given in table VII. Included in the table are comparisons with the expected load based on the net area obtained by correcting for the cracks and the load-carrying capacity of a similar joint not having previous cyclic-stress history. Outlined on the fractured surfaces in figures 19 and 20 are the areas involved in reducing the net area for estimating the effective load-carrying section of the specimens. It can be seen that one section of the 75S-T6 joint between the bolt hole and the outside edge was completely fractured by the fatigue loading whereas the 24S-T4 joint did not completely fracture in this area. Before subjecting the 24S-T4 joint to the static loading, however, a saw cut was made into the bolt hole from the outside edge in order to produce more nearly identical conditions in the two specimens. The location of the cut is shown in figure 20. Thus for purposes of the comparison this section of the joint has been considered as though it had been completely fractured in fatigue. Further, the additional failure in the centrally located portion of the joint adjacent to the bolt hole in the 75S-T6 joint caused a substantially larger reduction in the section than was the case in the 24S-T4 joint. Thus the cracked 75S-T6 joint would be expected to be subjected to a larger eccentricity of loading than the cracked 24S-T4 joint.

When the static ultimate loads are compared with the expected loads, determined without considering differences in eccentricities of loading, it is seen in table VII that the 75S-T6 double-shear joint withstood about 45 percent of its ultimate expected load and the 24S-T4 double-shear joint withstood about 70 percent of its ultimate expected load. It is not known how much of the difference in the load-carrying capacities of the two specimens might be accounted for by the difference in the eccentricities of the loading resulting from differences in distribution of the remaining effective area.

SUMMARY OF RESULTS

From the foregoing data obtained from an extension of the work described in NACA Technical Note 2276 and discussion of static and fatigue tests on bolted joints in high-strength aluminum-alloy extruded bar, the following statements seem warranted:

1. Based on the results of static and direct-stress fatigue tests, the lots of 75S-T6 and 24S-T4 aluminum-alloy extruded bar used for some of the specimens tested in this extension of the investigation compare favorably with the earlier lots used for specimens tested in the original portion of the investigation so that the test results from both sets of tests should be directly comparable.

2. The static ultimate load withstood by the stepped double-shear joint, the new joint design tested in this investigation, (94,900 pounds) was lower than the ultimate loads of the double-shear (115,250 pounds), the uniform-step (107,800 pounds), the plain-scarf (107,250 pounds), and the nonuniform-step (100,000 pounds) joints, all joints having the same net-section area and being fabricated of 75S-T6 aluminum alloy.

3. The static failure in the stepped double-shear joint was by combined tension and bearing in the thin portions of both the tongue and outside members of the joint.

4. The static ultimate loads withstood by the 75S-T6 aluminum-alloy joints were consistently higher (17 to 29 percent) than the ultimate loads withstood by like joints of 24S-T4 and 14S-T6 alloy for the three designs compared.

5. When the fatigue lives of the 75S-T6 joints are compared at a mean load of 16,000 pounds ±10,670 pounds (stress ratio, 0.2), the stepped double-shear joint is found to have an intermediate fatigue life. Its fatigue life (111,400 cycles) at these loading conditions is less than the fatigue lives of the double-shear joint (187,400 cycles) and of the double-scarf joint (418,000 cycles).

6. The relations between the fatigue test results obtained from like joints of 75S-T6, 24S-T4, and 14S-T6 aluminum alloys were inconsistent when compared at like load ranges. The 24S-T4 plain-scarf joint was found to give consistently higher fatigue strengths than did the 75S-T6 or 14S-T6 joints, whereas there was no significant difference in the fatigue results of the nonuniform-step joints in the three alloys. The 75S-T6 double-shear joint excelled in fatigue lives over either the 24S-T4 or the 14S-T6 joints.

7. When the fatigue life of the 24S-T4 plain-scarf joint is compared with the fatigue life of the 75S-T6 plain-scarf joint at a 16,000-pound mean load and at 0 and 0.2 stress ratios, with the fatigue loading on the 24S-T4 joint adjusted to take account of the differences in static strengths of the two joints, the fatigue life of the 24S-T4 joint was found to exceed the fatigue life of the 75S-T6 joint by ratios of 4.6:1 at the 0 stress ratio and 12.4:1 at the 0.2 stress ratio. The effects of the design are reflected in the fact that, at the 0.2 stress ratio with a 16,000-pound mean load, the ratio of fatigue life of the poorest joint design to that of the best joint design, both of 75S-T6 aluminum alloy, was found to be greater than 18:1.

8. There was no significant difference in the fatigue lives of 75S-T6 plain-scarf joints fabricated with bolt clearance compared with like joints fabricated with bolt interference and tested either under direct-tension loading or partially reversed loading. It has not been established by these tests whether or not larger bolt interferences would be beneficial in improving the fatigue life of such joints.

9. When a plain-scarf joint of 75S-T6 alloy was preloaded in static tension to a computed stress on the net section halfway between the yield and ultimate strengths, the fatigue life of the joint was increased over that of a like joint without preload by a ratio of 5.9:1. Like static preload on a double-shear joint caused a change in the location of the fatigue failure with little beneficial effect on its fatigue life, the ratio of fatigue lives of the preloaded to the nonpreloaded double-shear joints being 1.4:1.

10. In general, no significant bolt looseness was found after completion of the fatigue tests.

11. Penetrant inspection methods, applied to partially disassembled joints, did not reveal the existence of some of the fatigue cracks. In fact, even when applied to a completely disassembled joint, the penetrant inspection methods failed to disclose a fatigue crack which was about 0.009 inch long.

12. The static ultimate loads of the 75S-T6 and 24S-T4 double-shear joints with fatigue cracks were about 45 and 70 percent, respectively,

of the values estimated on the basis of the net areas obtained by correcting for the cracks. It is not known to what extent these values may have been affected by the differences in distribution of the effective areas.

Aluminum Research Laboratories,
Aluminum Company of America,
New Kensington, Pa., April 13, 1953.

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TABLE I

MECHANICAL PROPERTIES OF MATERIALS USED IN FATIGUE TESTS OF HIGH-STRENGTH ALUMINUM-ALLOY BOLTED JOINTS

[Standard 0.5-in. round specimens,[a] cut longitudinally from $1\frac{1}{4}$- by 4-in. extruded bar]

Alloy and temper	Material lot number	Tensile strength, psi	Yield strength, psi (b)	Elongation in 2 in., percent
75S-T6	[c]119561	86,950	79,400	12.1
	146305-1	94,900	87,800	9.0
	146305-2	92,500	84,800	9.0
		Av.[d] 88,600	81,100	11.3
24S-T4	[c]119560	77,900	59,500	14.2
	146287-1	85,300	65,700	10.5
	146287-2	84,500	64,900	12.0
		Av.[d] 80,700	61,800	13.0
14S-T6	[c]119559	74,300	67,300	10.0

[a]See fig. 7 of ref. 5.

[b]Stress at offset of 0.2 percent. Templin Autographic Extensometer (500X).

[c]Average values for original lot of material; from table I, ref. 1.

[d]Average values for original and new lot of material.

TABLE II

SUMMARY OF RESULTS OF STATIC TESTS ON HIGH-STRENGTH

ALUMINUM-ALLOY BOLTED JOINTS

Specimen	Description	Alloy and temper	Wt. of joint, lb (a)	Ultimate load, lb	Load per lb of wt., lb	Average deformation, in. (b)	Location of fracture
11A	Stepped double-shear	75S-T6	3.25	94,900	29,200	0.0060	Second row of bolt holes in tongue and outside members, combined tension and bearing
[c]1B	Nonuniform-step	75S-T6	4.34	100,000	23,000	.0098	First row of bolt holes
1E	Nonuniform-step	14S-T6	4.38	85,700	19,500	.0115	
1F	Nonuniform-step	24S-T4	4.38	84,000	19,200	.0100	
[c]6A	Double-shear	75S-T6	4.25	115,250	27,200	.0050	First row of bolt holes, tongue
6F	Double-shear	14S-T6	4.00	89,500	22,400	.0078	
6G	Double-shear	24S-T4	4.12	94,400	22,900	.0078	

[a]Weight based on length of $10\frac{5}{8}$ in. for each joint, distance between fulcra.

[b]Deformation measured under 16,000-lb load over length of 8 in. for each joint.

[c]Results taken from ref. 1.

TABLE III

RESULTS OF ADDITIONAL FATIGUE TESTS ON HIGH-STRENGTH

ALUMINUM-ALLOY BOLTED JOINTS

[Original tests described in ref. 1]

Specimen	Alloy and temper	Actual load cycle, lb				Number of cycles to failure	Location of failure
		Min.	Max.	Mean	Variable		
Stepped double-shear joint							
11	75S-T6	5,370	26,580	15,975	10,605	111,400	In thin portion of tongue
Nonuniform-step joints							
1C	24S-T4	5,410	26,670	16,040	10,630	22,500	Fillet
1D	14S-T6	5,480	26,560	16,020	10,540	22,900	Through first row of bolt holes
Plain-scarf joints							
[a]2R	24S-T4	4,020	19,930	11,975	7,955	204,700	Through first row of bolt holes
2V	24S-T4	20	24,010	12,015	11,995	194,100	
2W	24S-T4	4,060	20,040	12,050	7,990	1,872,800	
[b]2S	75S-T6	5,340	26,650	15,995	10,655	51,400	Through first row of bolt holes
[b]2T	75S-T6	-11,920	35,910	11,995	23,915	13,800	
[c]2U	75S-T6	5,370	26,690	16,030	10,660	325,600	
Double-shear joints							
6B	75S-T6	5,390	26,670	16,030	10,640	187,400	In tongue, through first row of bolt holes
6C	14S-T6	5,390	26,640	16,015	10,625	79,800	
6D	24S-T4	5,370	26,650	16,010	10,640	124,400	
[c]6E	75S-T6	4,840	27,180	16,010	11,170	263,200	In outside member, through first row of bolt holes

[a]Specimen found to have low torque on bolts.

[b]Bolt holes reamed to 0.0020 ±0.0005 in. clearance over measured bolt diameter; all others reamed to 0.0015±0.0005 in. interference.

[c]Joints loaded above yield strength previous to fatigue test.

TABLE IV

SUMMARY OF FATIGUE TEST RESULTS ON HIGH-STRENGTH ALUMINUM-ALLOY BOLTED JOINTS

[Fatigue life at 16,000-lb mean load, ±10,670-lb variable load (Stress ratio, 0.2)]

Specimen type	Alloy and temper	Number of cycles to failure	Fatigue life ratio (a)
Double-scarf	75S-T6	[b]418,000	18.5
Plain-scarf	24S-T4	[b]197,000	8.7
Double-shear	75S-T6	187,400	8.3
Double-shear	24S-T4	124,400	5.5
Stepped double-shear	75S-T6	111,400	4.9
Double-shear	14S-T6	79,800	3.5
Bolted-keyed[c]	75S-T6	[b]78,200	3.5
Plain-scarf	75S-T6	[b]55,000	2.4
Nonuniform-step	14S-T6	22,900	1.0
Nonuniform-step	75S-T6	[b]22,600	1.0
Nonuniform-step	24S-T4	22,500	1.0

[a]Fatigue life ratio equals cycles to failure (any joint) divided by cycles to failure for nonuniform-step joint of 75S-T6.

[b]Results taken from ref. 1.

[c]Keys driven in.

TABLE V

SUMMARY OF FATIGUE TEST RESULTS ON HIGH-STRENGTH

ALUMINUM-ALLOY BOLTED JOINTS OF 75S-T6, 24S-T4, and 14S-T6

Stress ratio (a)	Nominal mean load, lb	Nominal variable load, lb	Number of cycles to failure (b)		
			75S-T6	24S-T4	14S-T6
Double-shear joint					
0.2	16,000	±10,670	187,400	124,400(0.7)	79,800(0.4)
Nonuniform-step joint					
0.2	16,000	±10,670	[c]22,600	22,500(1.0)	22,900(1.0)
Plain-scarf joint					
-0.33	16,000	±32,000	[c]3,700	[c]5,100(1.4)	-------------
0	16,000	±16,000	[c]21,700	[c]45,300(2.1)	-------------
.2	16,000	±10,670	[c]55,000	[c]197,000(3.6)	-------------
.5	16,000	±5,330	[c]210,800	[c]3,897,100(18.5)	[c]364,000(1.7)
0	12,000	±12,000	[c]73,500	194,100(2.6)	-------------
.2	12,000	±8,000	[c]212,700	1,872,800(8.8)	-------------
0	16,000	±16,000	[c]21,700	---------------	
0	13,600	±13,600	--------	[d]100,000[4.6]	-------------
.2	16,000	±10,670	[c]55,000	---------------	
.2	13,600	±9,070	--------	[d]680,000[12.4]	-------------

[a]Stress ratio equals minimum load divided by maximum load.

[b]Number in parenthesis is ratio of fatigue life of 24S-T4 or 14S-T6 joint to that of 75S-T6 joint at like mean load and stress ratio. Number in brackets is ratio of fatigue life of 24S-T4 joint at 13,600-lb mean load to that of 75S-T6 joint at 16,000-lb mean-load at like stress ratios.

[c]Results taken from ref. 1.

[d]Value taken from curve, fig. 10; not test point.

TABLE VI

SUMMARY OF FATIGUE TEST RESULTS ON HIGH-STRENGTH

ALUMINUM-ALLOY 75S-T6 BOLTED JOINTS

Specimen type	Stress ratio (a)	Nominal mean load, lb	Nominal variable load, lb	Number of cycles to failure			Fatigue life ratio (c)	Fatigue life ratio (d)
				Interference fit, not preloaded (b)	Clearance fit, not preloaded (b)	Interference fit, preloaded (b)		
Plain-scarf	0.2	16,000	±10,670	[e]55,000	51,400	325,600	0.9	5.9
Plain-scarf	-.33	12,000	±24,000	[e]13,500	13,800	-------	1.0	---
Double-shear	.2	16,000	±10,670	187,400	------	263,200	---	1.4

[a]Stress ratio equals minimum load divided by maximum load.

[b]Interference fit, holes reamed 0.0015 in. under measured bolt diameter; clearance fit, holes reamed 0.0020 in. over measured bolt diameter; preload, static preload above yield strength prior to fatigue test.

[c]Fatigue life ratio equals cycles to failure for joint with clearance fit divided by cycles to failure for joint with interference fit.

[d]Fatigue life ratio equals cycles to failure for preloaded joint divided by cycles to failure for joint without preload.

[e]Results taken from ref. 1.

TABLE VII

SUMMARY OF STATIC-STRENGTH RESULTS FOR 75S-T6 AND 24S-T4

DOUBLE-SHEAR JOINTS WITH AND WITHOUT FATIGUE CRACKS

ORIGINATING FROM BOLT HOLES

Specimen	Alloy and temper	Joint without fatigue cracks		Joint with fatigue cracks (a)			
		Ultimate load, lb	Net area, sq in.	Net area, sq in. (b)	Expected ultimate load, lb (c)	Actual load, lb (d)	Percent of expected load (e)
6B	75S-T6	[f]115,250	1.20	0.81	77,900	35,500	45.5
6D	24S-T4	94,400	1.20	.85	70,900	48,500	68.5

[a]Extent of fatigue cracks shown in figs. 20 and 21.

[b]Net area calculated on basis of nonfatigued section shown in figs. 20 and 21.

[c]Calculated using ratios of areas (joint with fatigue crack divided by joint without fatigue crack) times ultimate load on joint without fatigue cracks.

[d]Static ultimate load.

[e]Ratio of actual load to expected load times 100.

[f]Result taken from ref. 1.

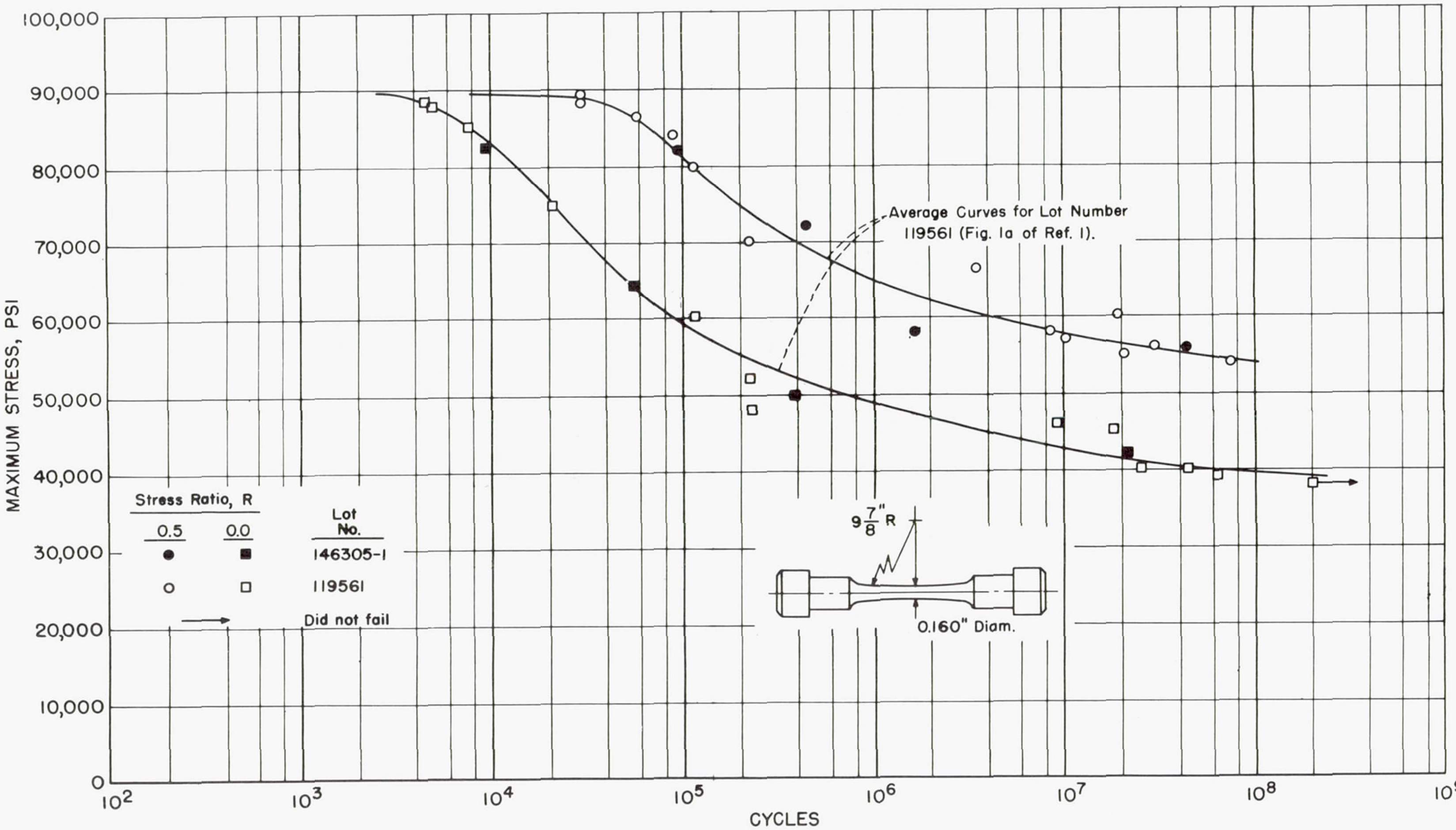

Figure 1.- Direct tension-compression fatigue data for 75S-T6 extruded bar $\left(1\frac{1}{4}\text{ by 4 inches}\right)$.

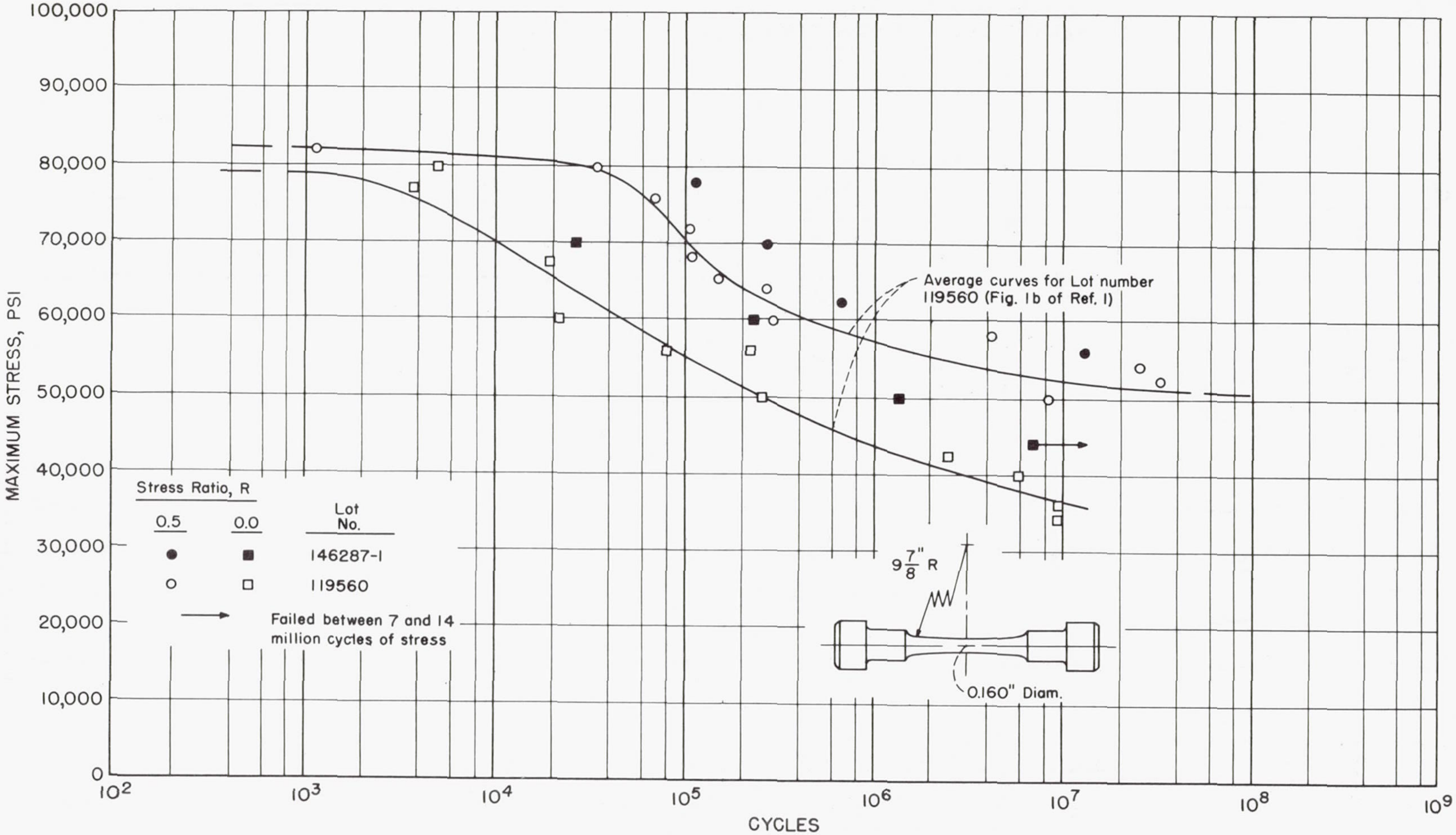

Figure 2.- Direct tension-compression fatigue data for 24S-T4 extruded bar $\left(1\frac{1}{4}\text{ by 4 inches}\right)$.

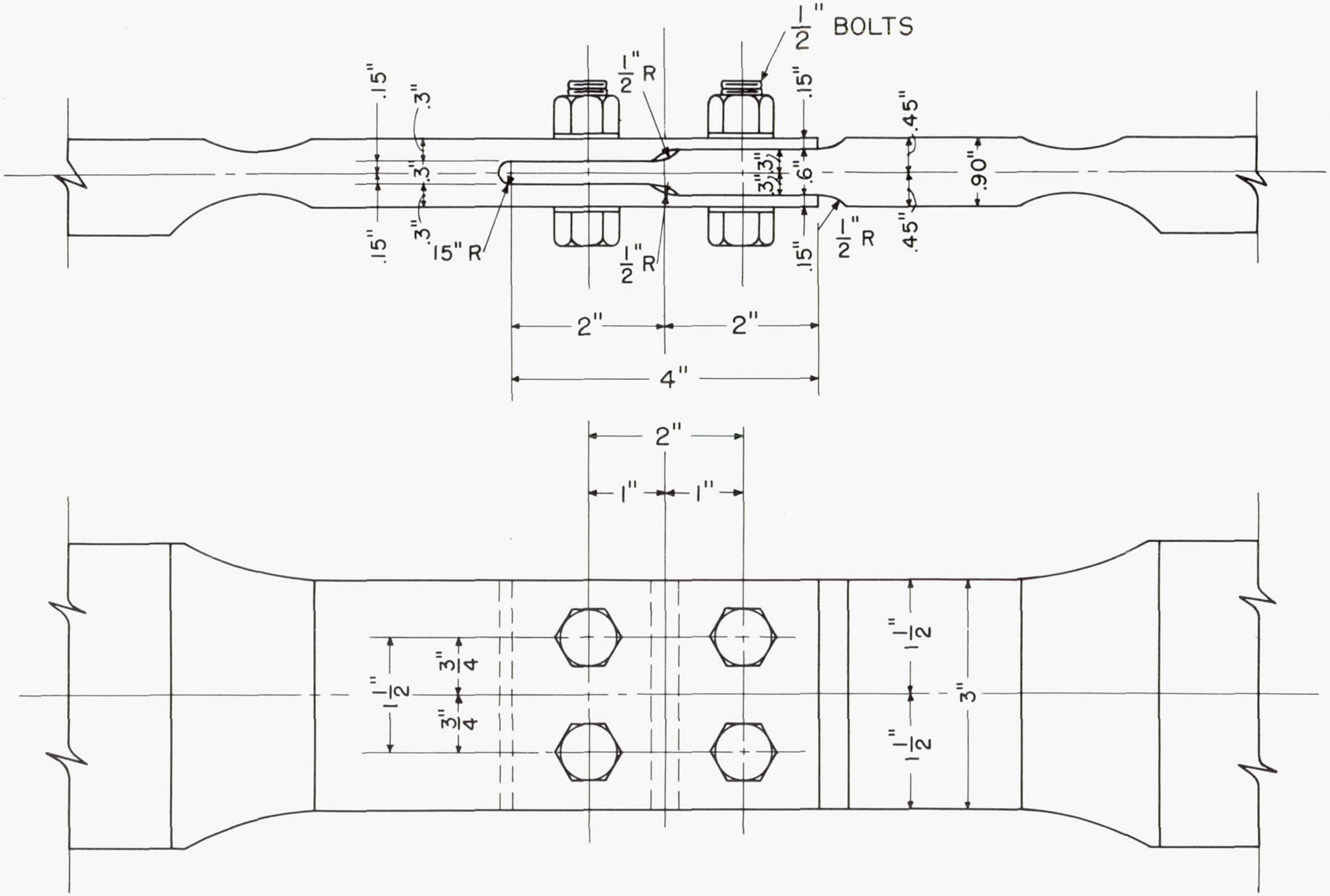

Figure 3.- Stepped double-shear joint specimen.

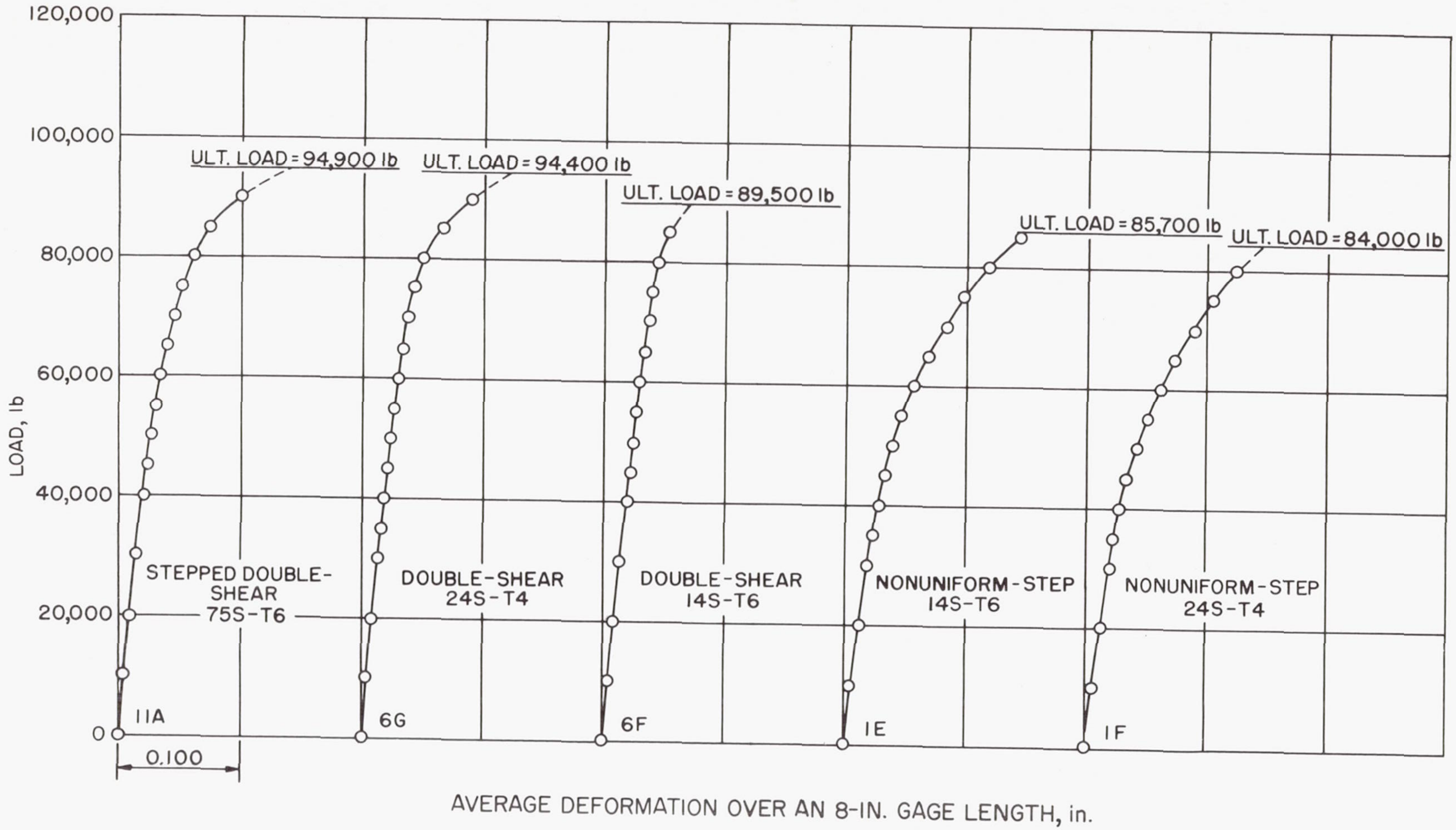

Figure 4.- Curves of static tensile load against deformation for high-strength aluminum-alloy bolted joints.

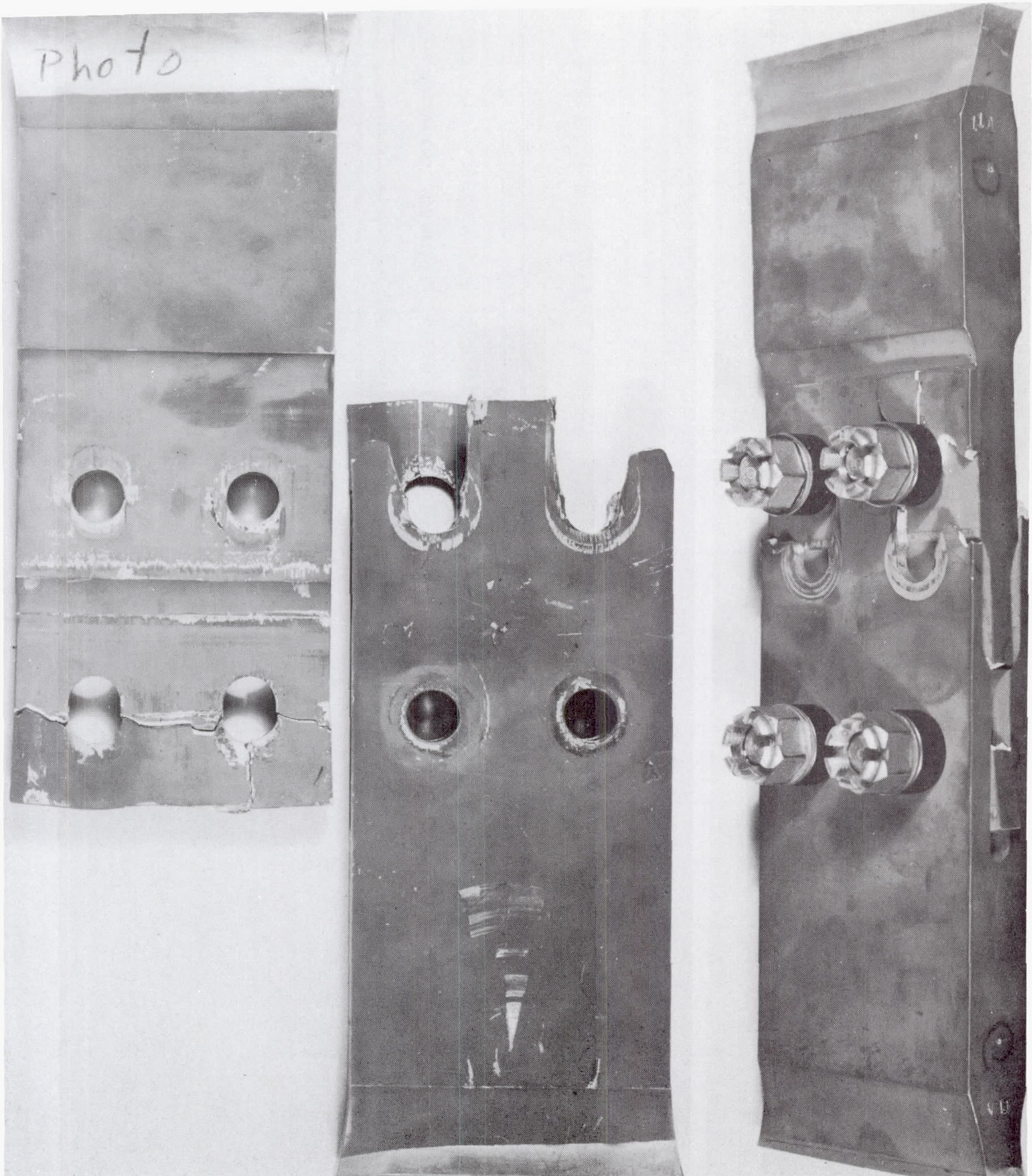

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Figure 5.- Static fracture of 75S-T6 stepped double-shear joint.

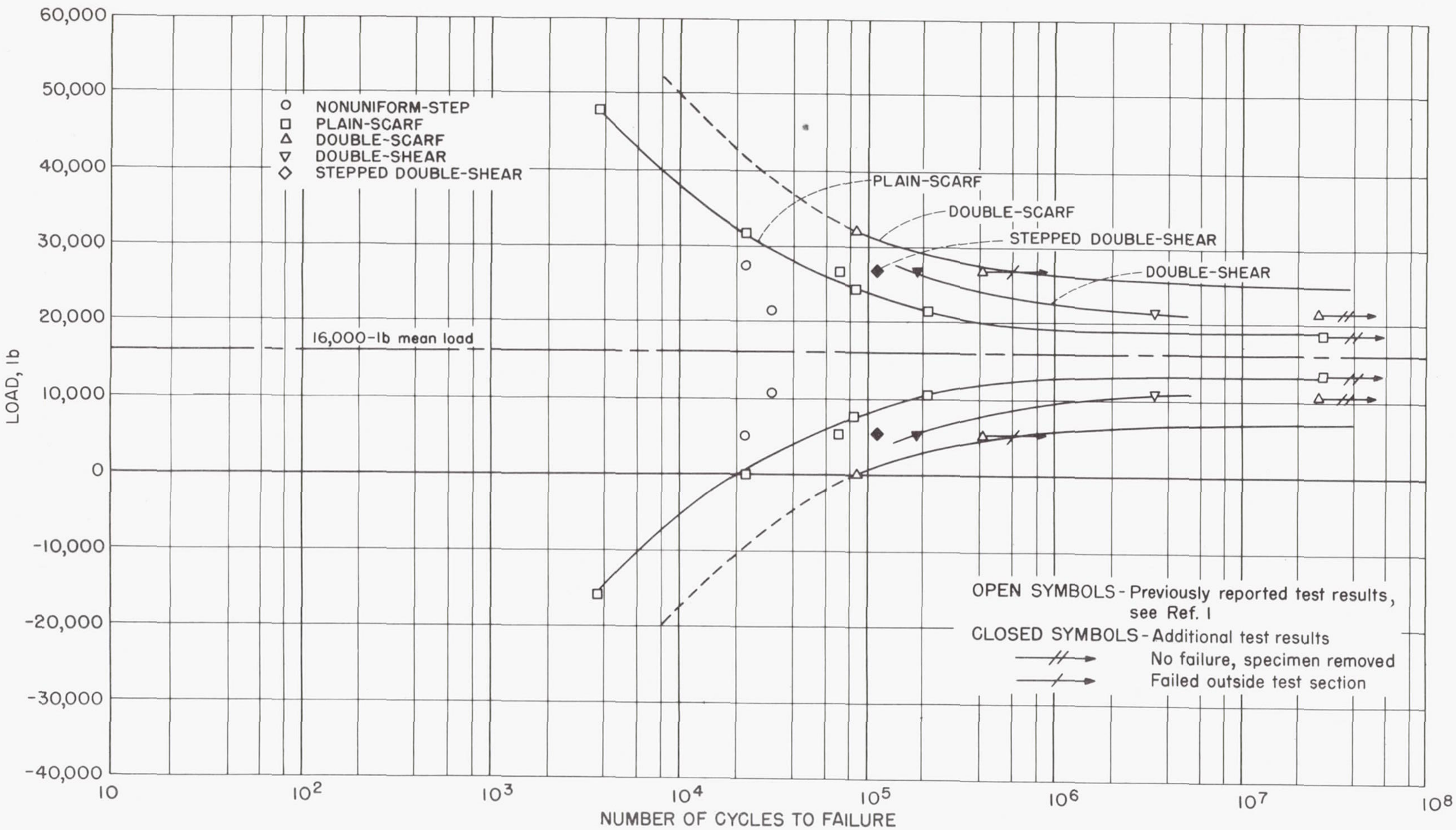

Figure 6.- Direct-stress fatigue curves for 75S-T6 aluminum-alloy bolted joints. Mean load, 16,000 pounds.

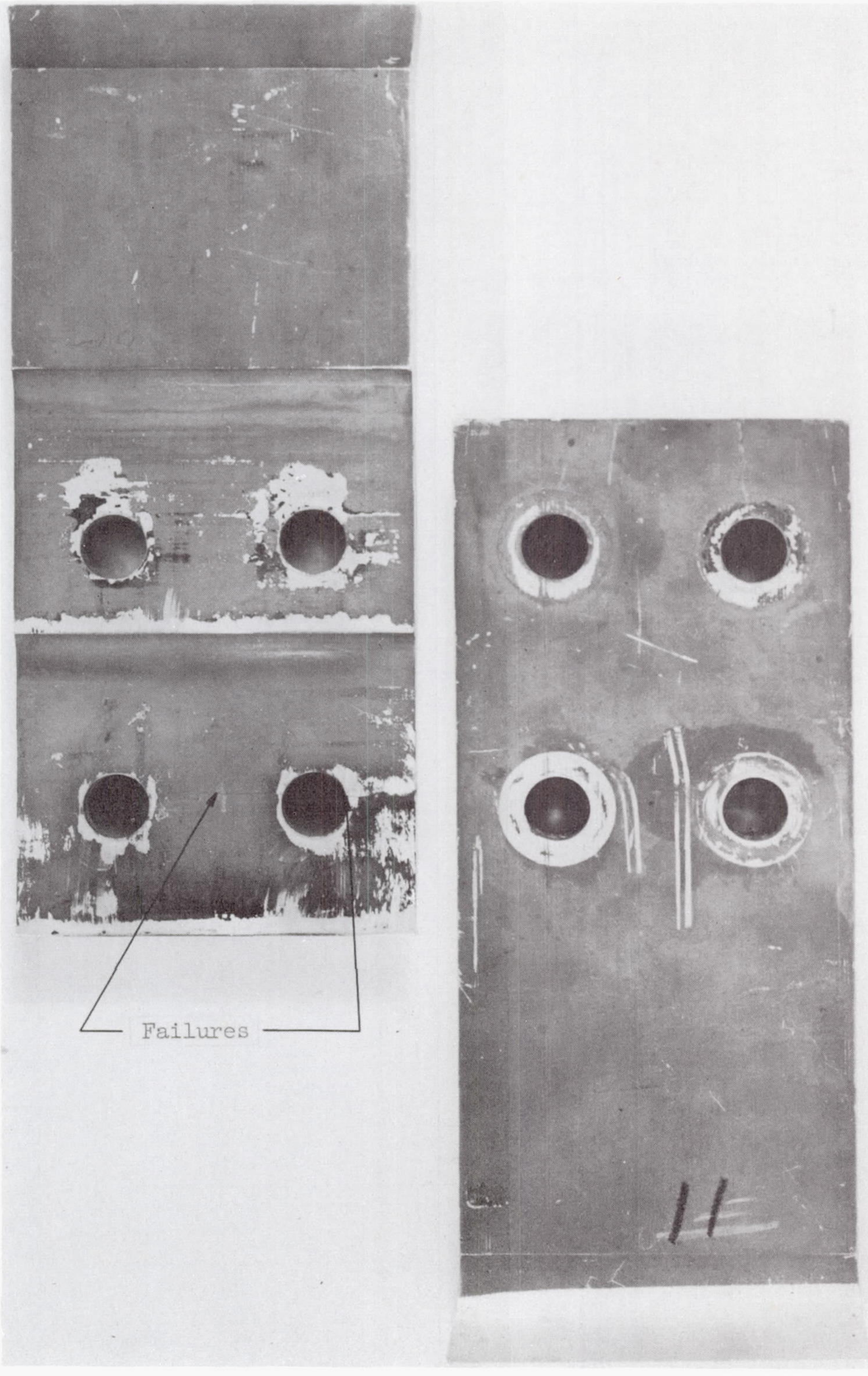

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Figure 7.- Fatigue failures in stepped double-shear joint.

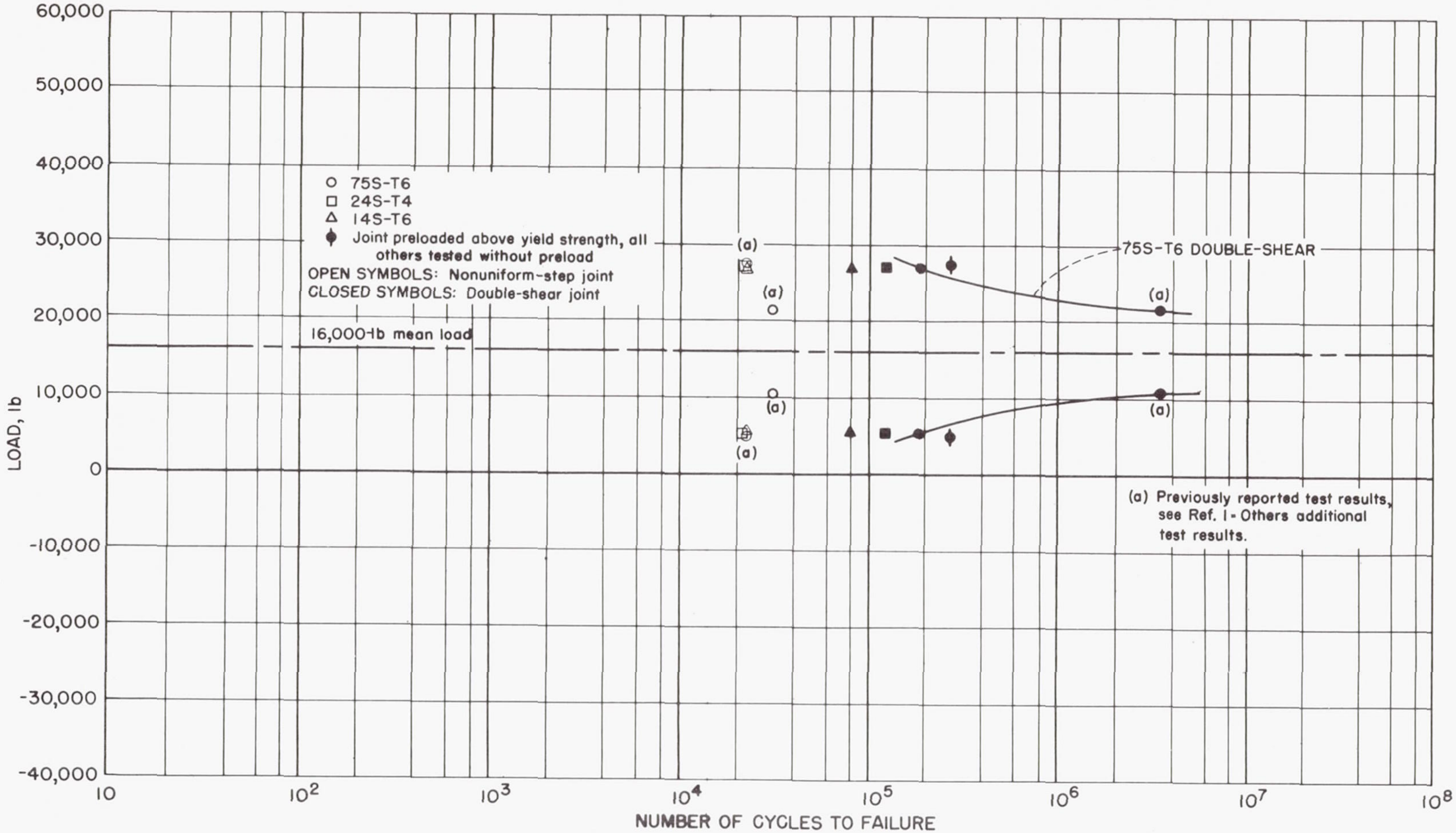

Figure 8.- Direct-stress fatigue curves for double-shear and nonuniform-step joints of 75S-T6, 24S-T4, and 14S-T6 aluminum alloys. Mean load, 16,000 pounds.

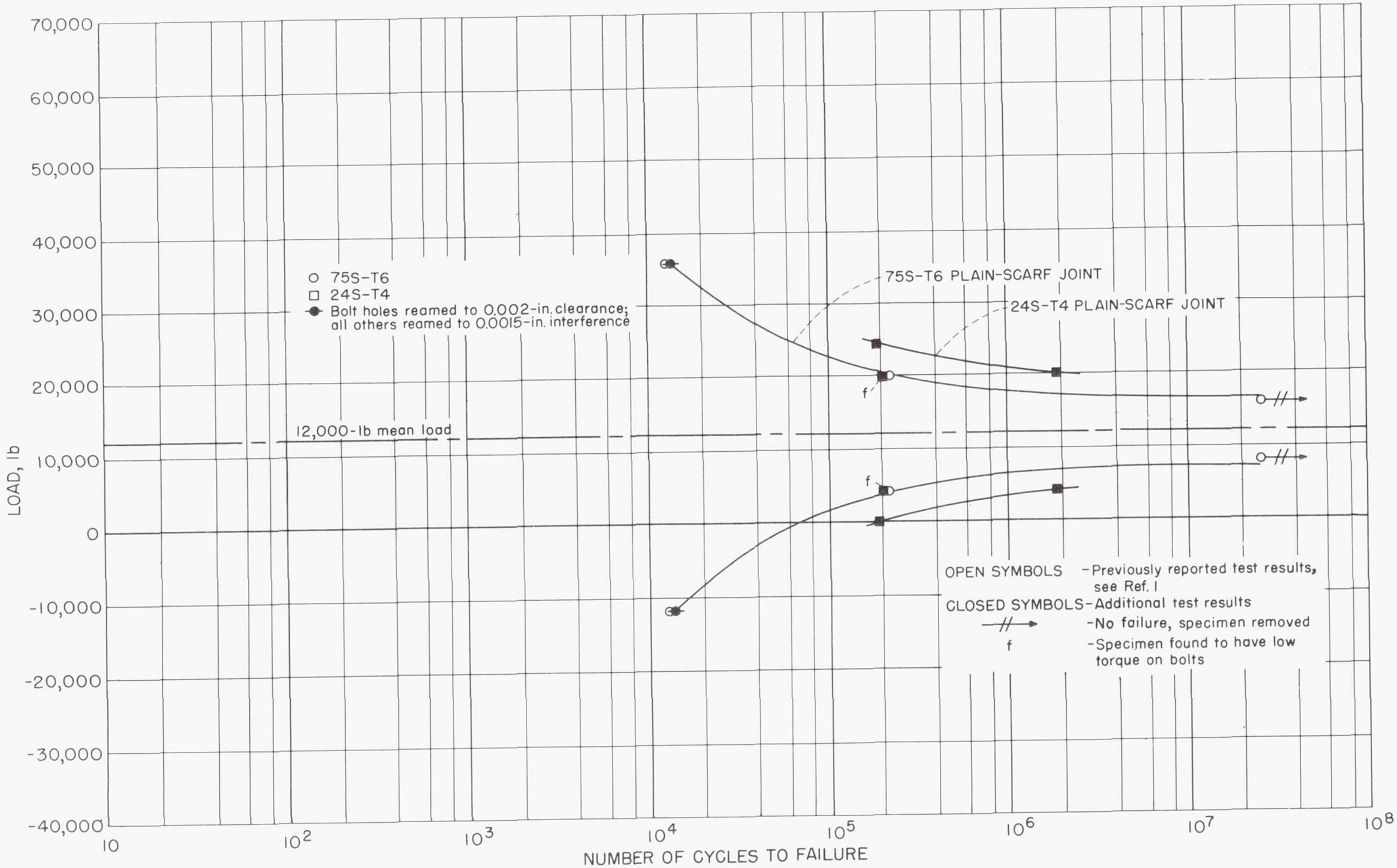

Figure 9.- Direct-stress fatigue curves for plain-scarf joints of 75S-T6 and 24S-T4 aluminum alloy. Mean load, 12,000 pounds.

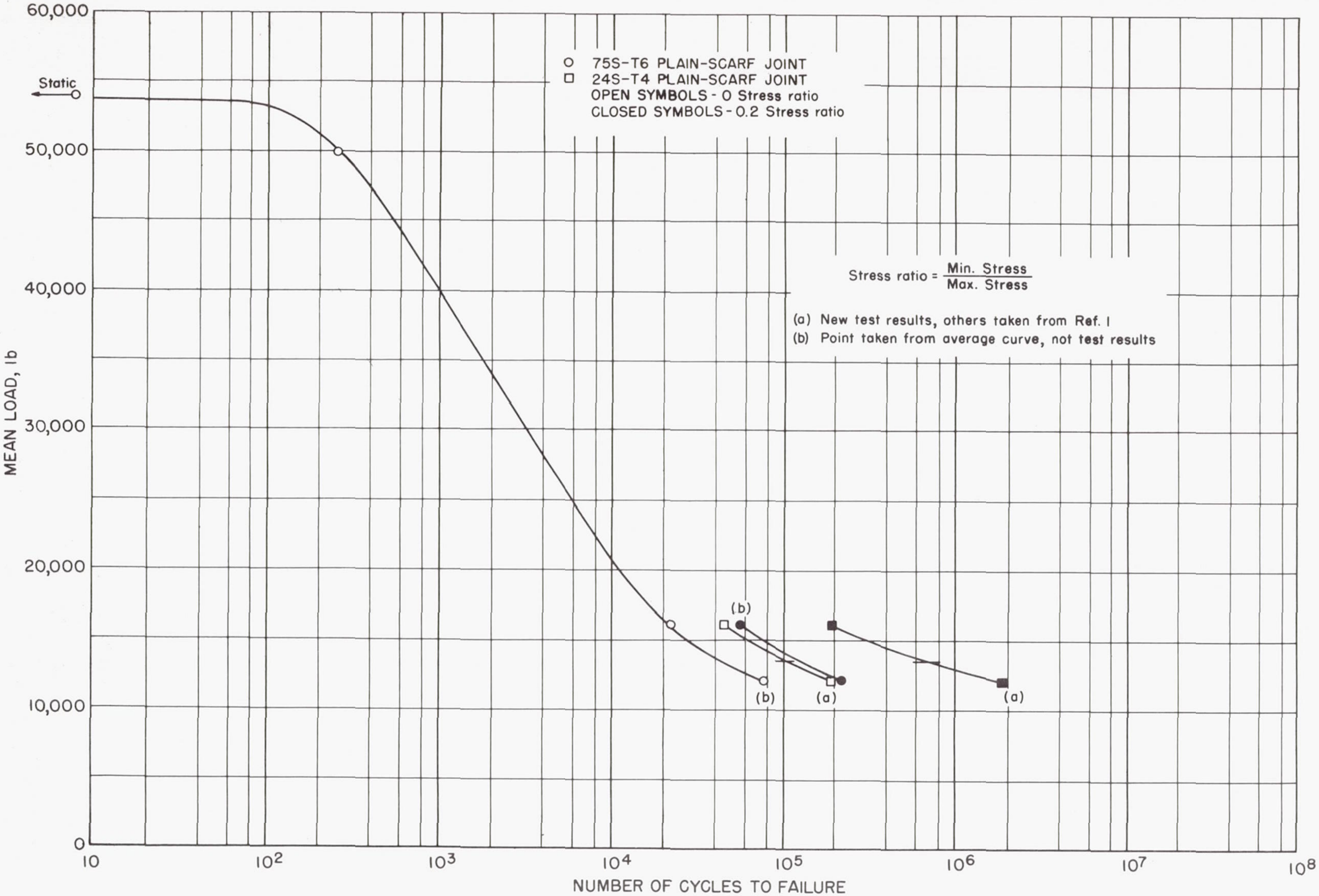

Figure 10.- Direct-stress fatigue curves for plain-scarf joints of 75S-T6 and 24S-T4 aluminum alloy. Mean load versus number of cycles to failure.

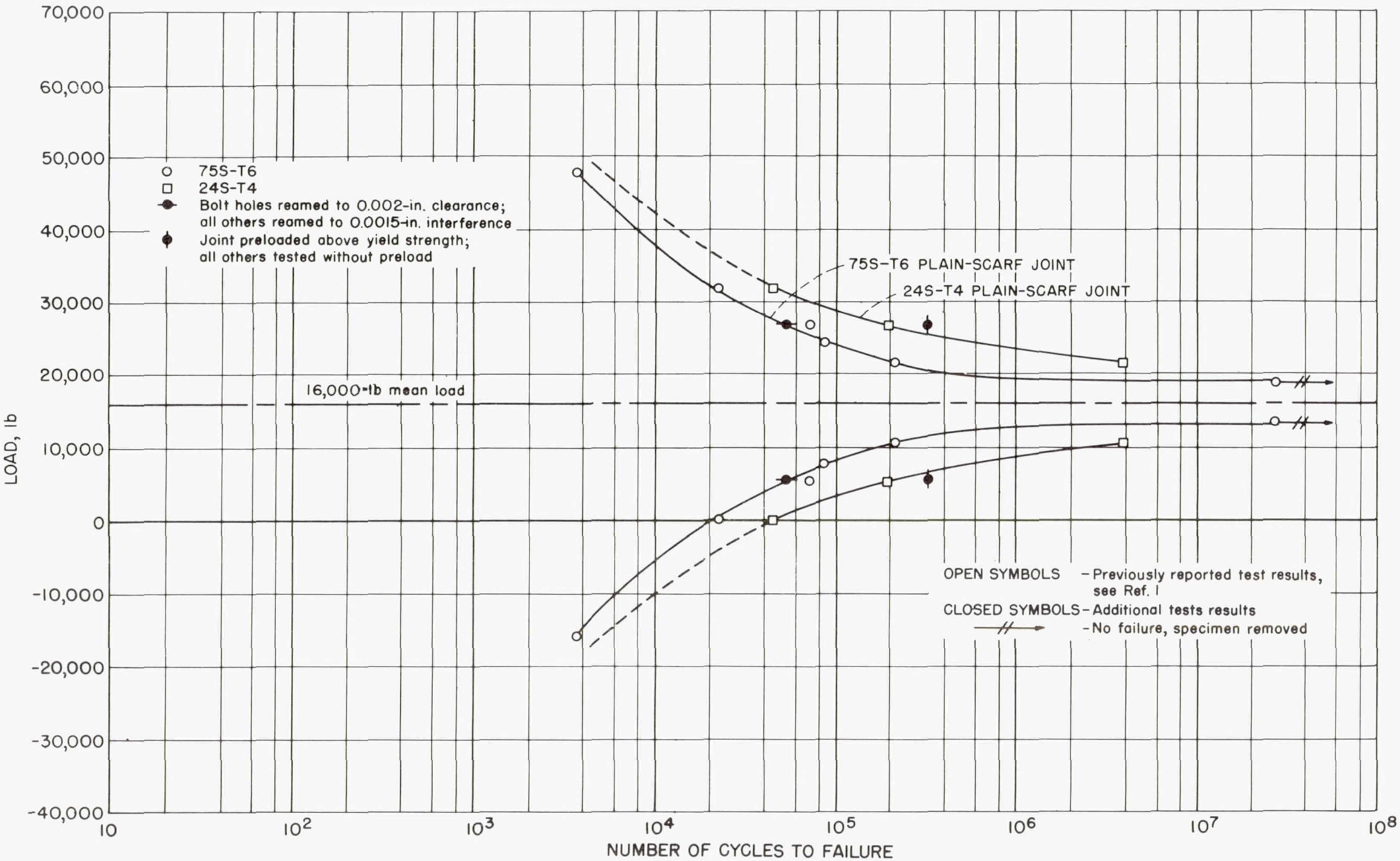

Figure 11.- Direct-stress fatigue curves for plain-scarf joints of 75S-T6 and 24S-T4 aluminum alloy. Mean load, 16,000 pounds.

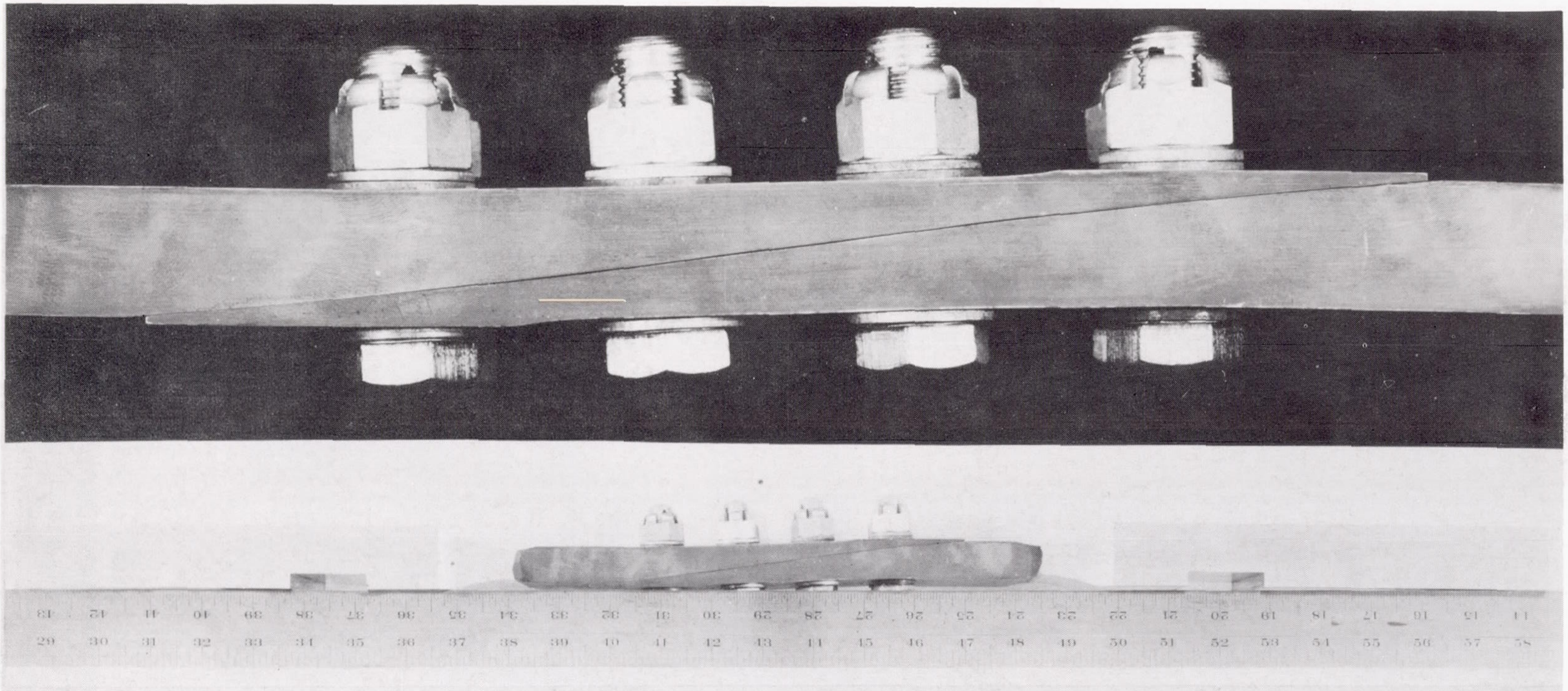

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Figure 12.- Permanent deformation in plain-scarf joint after static preloading to above the yield strength.

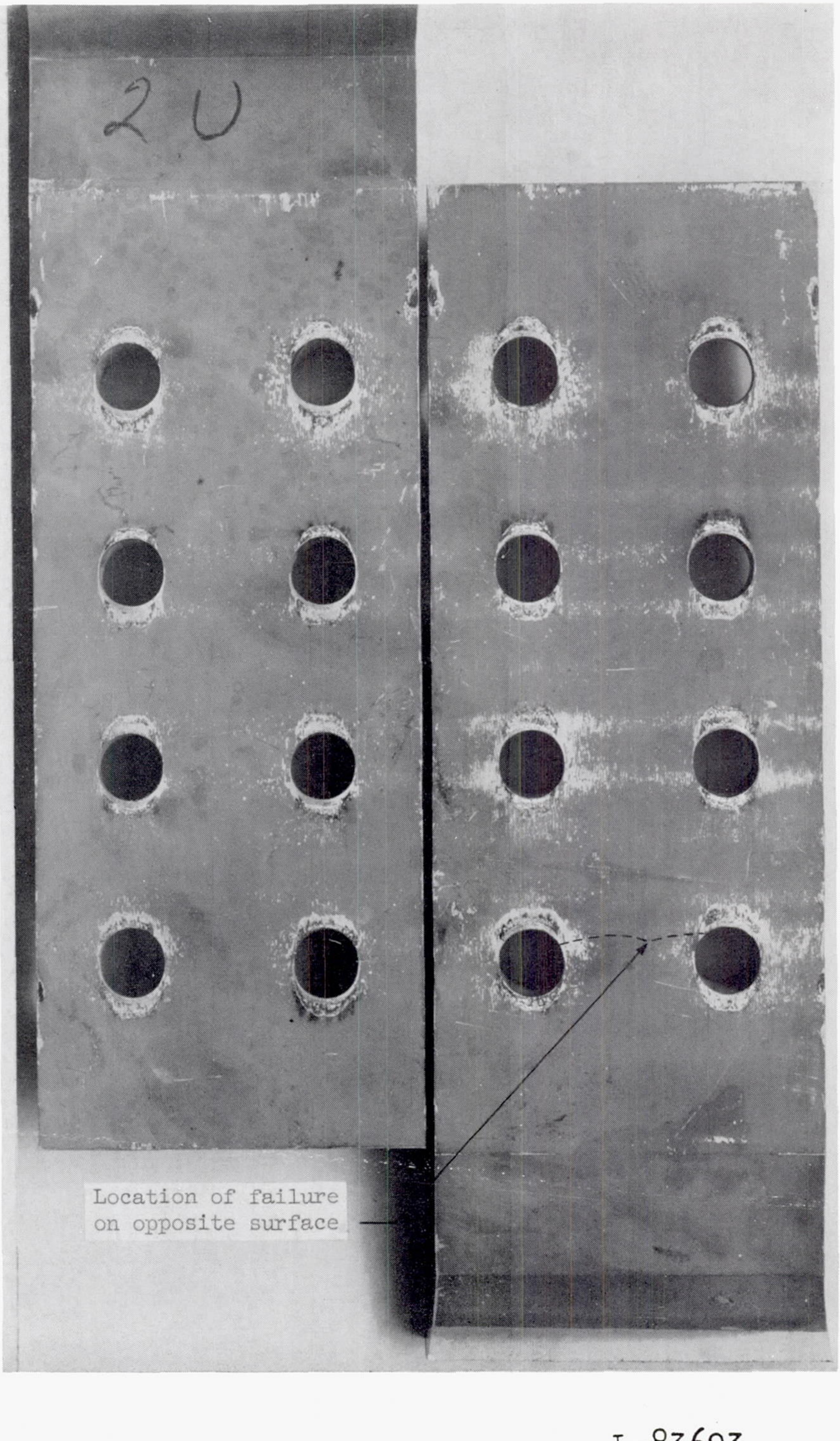

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Figure 13.- Plastic deformation at bolt holes of faying surfaces of plain-scarf joint which had been loaded to high static loading previous to fatigue test. Photographed after fatigue test. (For views of failure on opposite surface see fig. 14.)

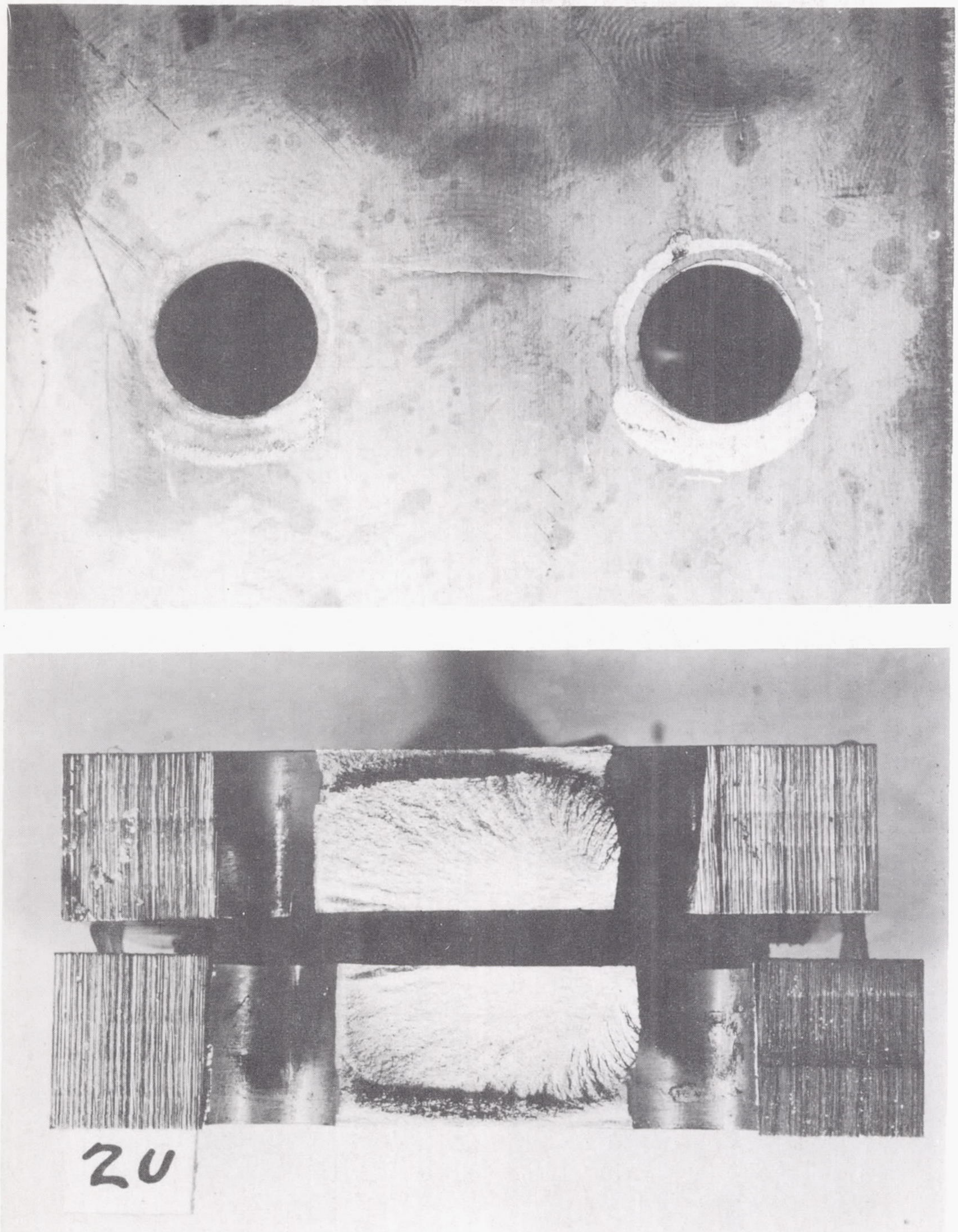

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Figure 14.- Fatigue failure of plain-scarf joint which has been loaded to high static loading previous to fatigue test. (For location of bolt holes see fig. 13.)

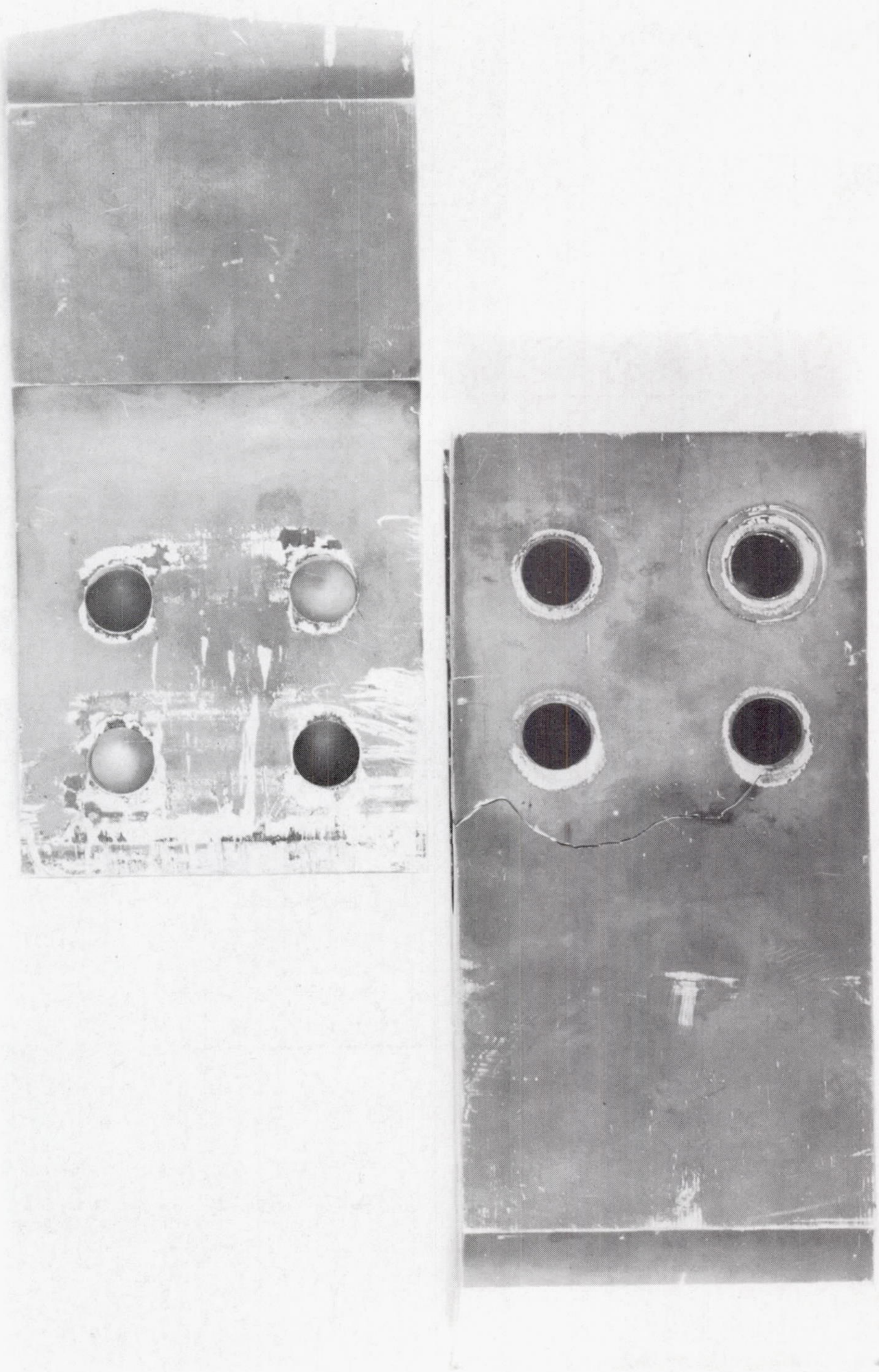

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Figure 15.- Fatigue failure in double-shear joint which had been loaded to high static loading previous to fatigue test.

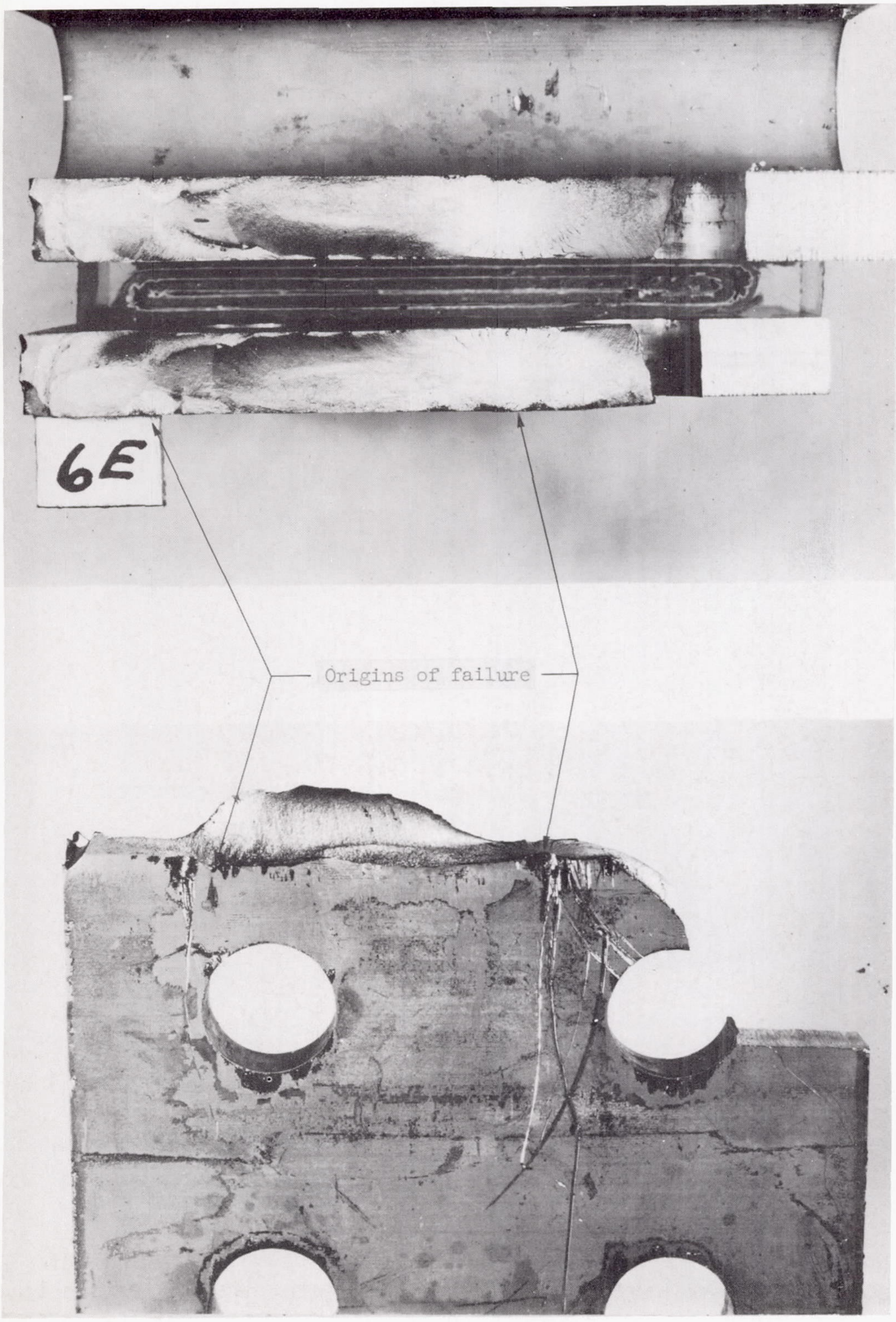

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Figure 16.- Failure of double-shear joint which had been loaded to high static loading previous to fatigue test.

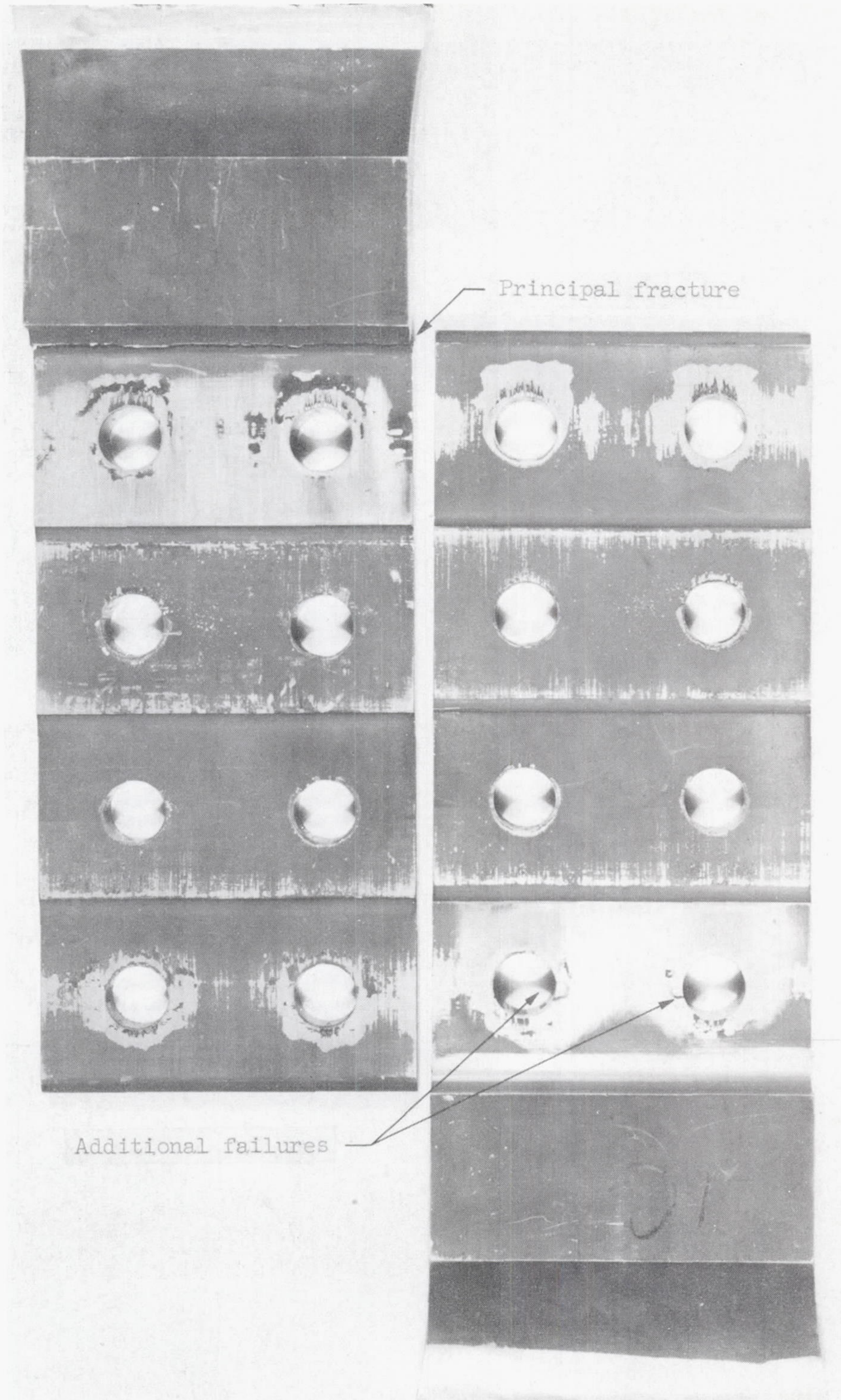

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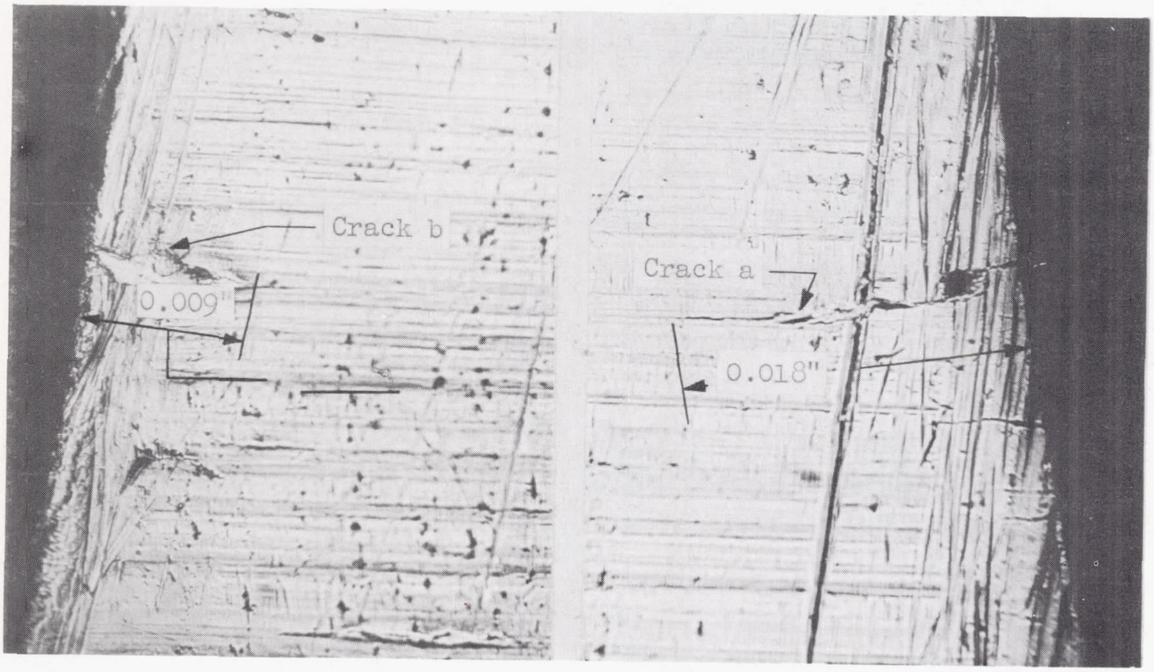
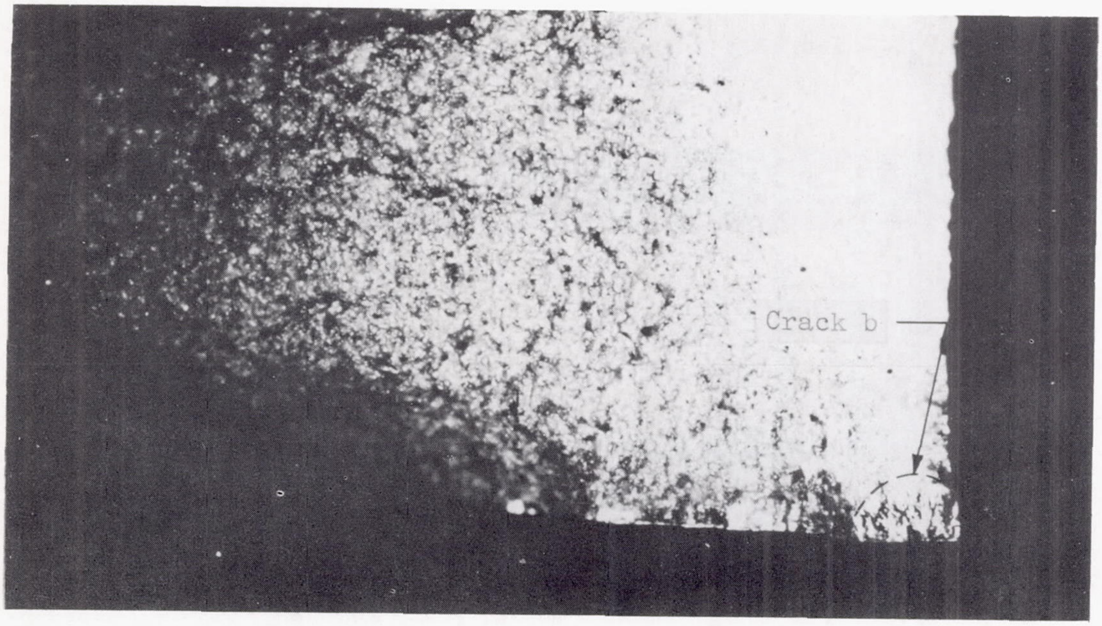
Figure 17.- Failures in 24S-T4 nonuniform-step joint.



100X



25X

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Figure 18.- Enlargements of additional failures in 24S-T4 nonuniform-step joint. (For locations, see fig. 17.) Two photographs at top are of Faxfilm replicas.

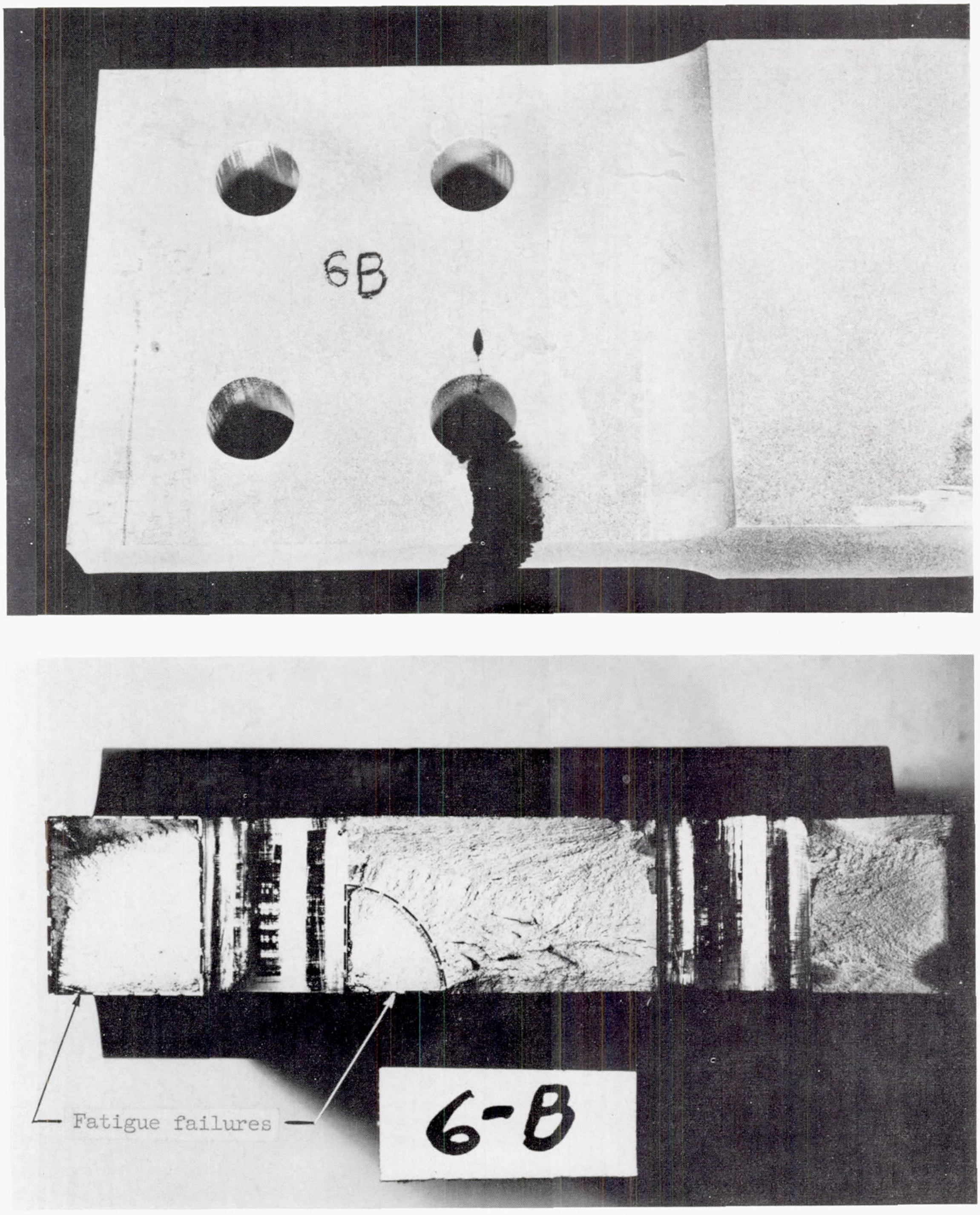

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Figure 19.- Failures in 75S-T6 double-shear joint.

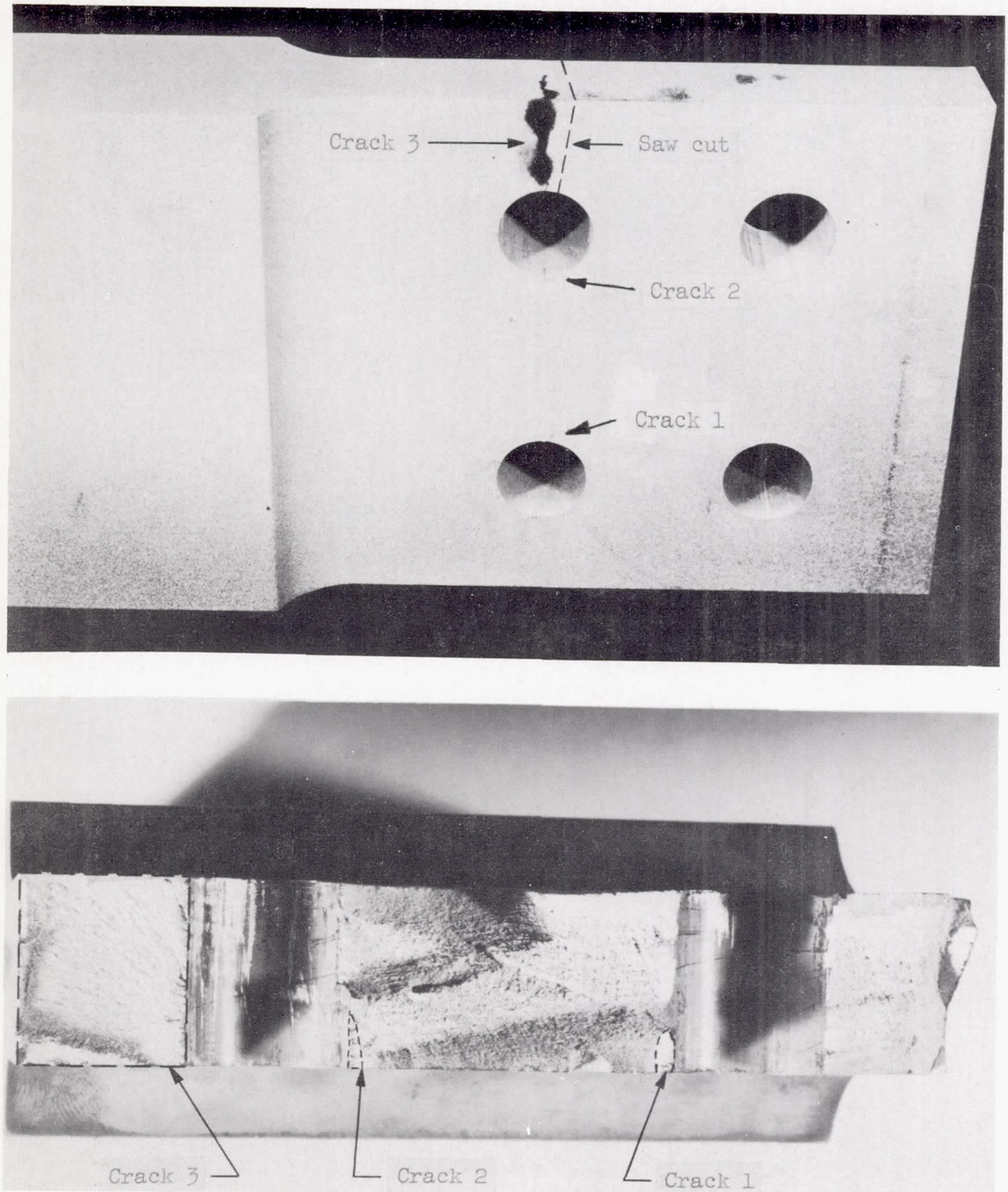

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Figure 20.- Failures in 24S-T4 double-shear joint. Specimen 6D. (For enlargement of small cracks see fig. 21.)

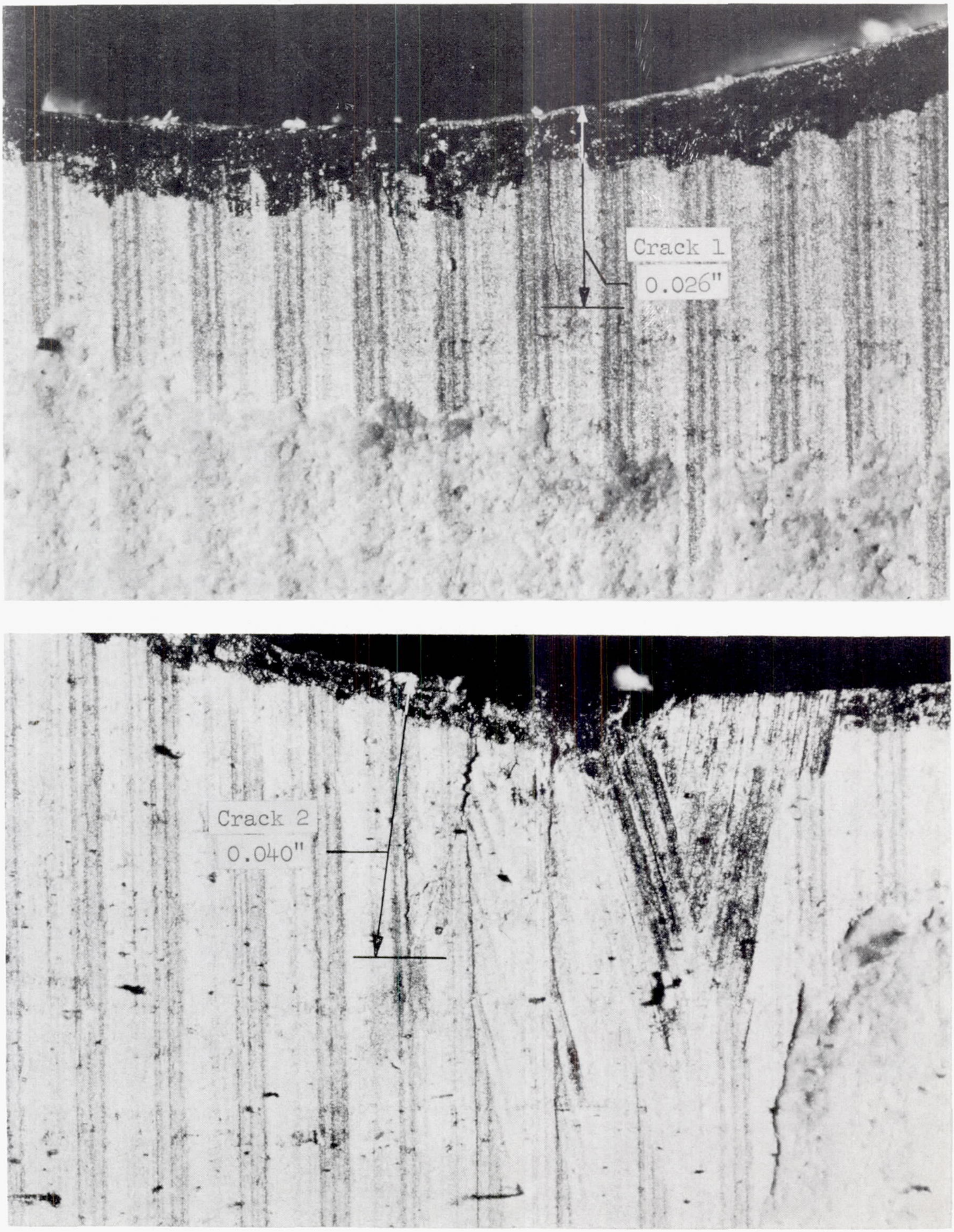

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Figure 21.- Enlargement of failures in double-shear joint. 50X. (For location see fig. 20.)

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