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No. 869

# SUMMARY OF RESULTS OF TESTS MADE BY ALUMINUM RESEARCH LABORATORIES OF SPOT-WELDED JOINTS AND STRUCTURAL ELEMENTS

By E. C. Hartmann and G. W. Stickley
Aluminum Company of America



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## SUMMARY

Available information concerning spot welding as a means of joining aluminum-alloy parts has been summarized and comparisons have been made of the relative merits of spot-welded and riveted aluminum-alloy structural elements. The results indicated that spot welding was as satisfactory as riveting insofar as resistance to static loads is concerned. Spot welds showed slightly lower resistance to impact loads but definitely lower resistance to repeated loads than rivets.

## INTRODUCTION

Spot welding as a means of joining aluminum-alloy parts has been under investigation for a number of years by the Aluminum Research Laboratories, working in cooperation with the Jobbing Division of the Aluminum Company of America. Considerable data have been collected concerning the strengths of spot welds, and it is the purpose of this report to summarize the principal information available to date.

## TESTS

### Tests to Determine Minimum Static Shear Strengths of Representative Spot Welds in Various Aluminum Alloys

Tests of minimum static shear strengths were made to obtain comparative data on the spot-weld characteristics of a number of aluminum alloys. These data are intended to serve as a basis for establishing allowable stresses in spot welds for design purposes. The test samples were prepared in conformity with usual shop practice. The welds were made on No. JS-N1 alternating-current spot welder using a General Electric Ignitron timer. The welding tips were 5/8 inch in diameter with either 7° or 11° cone tips. All the sheet was washed in naphtha to remove grease and dirt, and all except the 2S sheet was given a 30-second etch with a solution of gum tragacanth and hydrofluoric acid.

For sheet thicknesses less than 0.04 inch, the test pieces were 1 inch wide and, for pieces thicker than 0.04 inch, the specimens were 1 1/2 inches wide. All specimens were simple lap joints containing two spot welds in tandem 1 inch apart for the thin specimens and 1 1/2 inch apart for the thick specimens. The edge distances were 1/2 and 3/4 inch and the total laps were 2 and 3 inches for the thin and thick specimens, respectively. All specimens were tested in New Kensington Plant Laboratory and, in the case of the heat-treated alloys, at least four days elapsed between the time of making the welds and the time of testing. A large number of specimens was made with the use of various machine settings within the normal range and, from these test data, minimum shear strengths in pounds per spot were selected. The resulting values have been plotted in figure 1.

### The Static Shear Strength of Wide Spot-Welded Joints in 0.051-inch Thick 52S-1/2H Sheet

In the study of spot-welded joints, the strengths of the spots and also the strength of joints in which various groups of spots are used must be known. Tests of the static shear strength were made for various lap joints in a 52S-1/2H sheet 0.051 inch thick; each joint was approximately 11 1/4 inches wide. These joints were made with one, two, or three lines of spot welds in the lap with the use of various spacings of spot welds, distances between rows, and edge distances. All the welded surfaces were given an etch of 30 seconds in a solution of gum tragacanth and hydrofluoric acid. All the welding was done on alternating-current machines. Single-, double-, and triple-riveted specimens made with the use of 3/16-inch 53S-W rivets were tested for comparison. These specimens were the same size as the spot-welded specimens. All specimens were tested with a special gripping device (fig. 2) which preliminary tests had shown to provide a reasonably uniform distribution of load. The results of these tests are plotted in figures 3 and 4. The conclusions from this investigation were as follows:

1. The strength per spot of the wide joints which failed in the spots varied with the spot spacing and number of rows. The highest value obtained was 810 pounds per spot and the average was about 720 pounds per spot. These values check fairly well with the results of tests of narrow strips cut from some of the wide joints, in which the highest value was found to be 900 pounds per spot and the average about 760 pounds per spot.

2. The strength per spot for wide specimens with a single row of spots was found to decrease very rapidly when the edge distance was less than 3/8 inch. The lowest value obtained was for an edge distance of 1/8 inch (total lap = 1/4 in.) in which case the load per spot was found to be as low as 293 pounds. The lowest test result for edge distances 3/8 inch or greater was 622 pounds per spot.

3. When the spots in the wide specimens were closer together than 1/2 inch for one row of spots, 3/4 inch for two rows of spots, and 1 1/4 inch for three rows of spots, failure of the specimens occurred by tearing the sheet rather than by spot failure. The maximum value of stress on the gross area corresponding to the ultimate load was 33,800 pounds per square inch, a value which is about 6 percent less than the corresponding tensile strength of the sheet as determined on tensile specimens 1/2 inch wide. The minimum value of stress on the gross area corresponding to the ultimate load was 27,000 pounds per square inch and the average was about 31,000 pounds per square inch.

4. The highest strengths in the wide spot-welded joints were obtained with the following spot spacings:

| Number of rows | Spacing (in.) | Maximum ultimate load per inch of width (lb) |
|---|---|---|
| 1 | [a]0 | 1557 |
| 2 | 3/4 | 1678 |
| 3 | 1 | 1686 |

[a]Continuous seam of overlapping spots.

5. The strongest wide spot-welded joints tested represent an efficiency of 94.3 percent based on the tensile strength of the unspliced sheet.

6. Joints with two rows of spot welds represent a distinct increase in strength over joints with one row of spot welds. Additional rows of spot welds, however, do not further increase the strength to any marked degree.

7. Although there is fair agreement between the results obtained for the wide specimens and for the narrow strips, particularly for specimens containing two or three rows of spots, it is evident that values obtained from tests of individual spots should be applied with caution in design calculations for spot-welded joints.

8. The wide-riveted joints tested for comparison with the spot-welded joints were not so strong as the spot-welded joints although the individual rivets used were of approximately the same strength as the individual spot welds.

9. The strongest wide-riveted joint had an efficiency of 86.6 percent in comparison with 94.3 percent for the strongest spot-welded joint.

## Shear Fatigue Tests of Spot Welds in Various Aluminum Alloys

In order to determine the strength of spot welds subjected to repeated shear loads, tests were made of welds in two thicknesses, 0.032 and 0.064 inch, of the following alloys of sheet: 3S-0, 3S-1/2H, 17S-T, Alclad 17S-T, 24S-T, Alclad 24S-T, Alclad 24S-RT, 52S-0, 52S-1/2H, and 53S-T. Metallographic examination of at least two welds from each group showed that, in general, the welds in 0.032 inch thick sheet were sound but those in 0.064-inch thick sheet contained some porosity. The individual specimens used, which are shown in figure 5, consisted of simple lap joints each with a single spot weld. These specimens were cut from panels welded with the use of alternating-current machines and the surfaces of the sheet were cleaned before welding. The 17S-T and 24S-T sheets were cleaned by etching in hydrofluoric acid; the other alloys were usually washed with benzine. Four specimens were tested simultaneously in rotating-beam fatigue machines, as illustrated in figure 6, except in those cases in which less than 15 cycles of stress were required to cause failure. During each revolution of the rotating-beam machine, each weld was subjected to a load that varied from a maximum in shear in one direction to a maximum in the opposite direction and back again. In the tests requiring less than 15 cycles, four specimens were tested simultaneously, using the same fixtures shown in figure 6; but the tensile and compressive loads were applied in an Amsler universal testing machine, the same as in ordinary tensile and compressive tests. In the present investigation, these tests that involved high loads and small numbers of cycles were made only on the welds in 0.032-inch thick sheet.

The test results and the static strengths are summarized in tables I and II. The results of the individual fatigue tests are plotted in figures 7 and 8. In these figures, the value plotted for the fatigue strength at 0.25 cycle is the static strength.

It will be noted that, for the 0.032-inch thick sheet, the endurance limits vary from 20 to 30 pounds per spot for the different alloys. The lowest endurance limits were those of joints in 24S-T and 52S-1/2H and the highest in Alclad 24S-T. These endurance limits range from 5 to 13 percent of the corresponding static strengths. In general, the high values were obtained with alloys in the annealed temper and with Alclad materials, and the low ones were obtained with alloys in cold-worked tempers and with nonclad heat-treated materials. The tests of joints in a sheet strip 0.064-inch thick, although quite incomplete, indicate endurance limits of 40 to 60 pounds per spot, with ratios of endurance limit to static strength about the same as for the 0.032-inch thick sheet.

In these tests the primary failures occurred in the sheet at or slightly within the weld and not through the main body of the weld. This condition is illustrated in figure 9. Inasmuch as the fatigue failures did not occur primarily by shearing of the welds, the test results indicate the strength of spot-welded joints in sheet strip of the widths used and not the fatigue strength of the welds themselves. They are, therefore, useful chiefly as an indication of the lower limits of resistance to fatigue and may be too conservative. It should also be remembered that the welds in the 0.064-inch thickness of the different alloys contained some porosity, which as indicated in a subsequent section of this report, has a harmful effect upon fatigue resistance.

Direct Tension-Compression Fatigue Tests of

Structural Members Built up from 1/8-inch

52S-1/2H Sheet

Direct tension-compression fatigue tests were conducted to obtain data on the relative merits of spot-welded and riveted aluminum-alloy structural elements subjected to completely reversed axial loads. Specimens were of the type shown in figure 10, which also shows the fixtures for the attachment of the specimens to the movable and fixed heads of the fatigue-testing machine. It will be noted that the specimen consisted essentially of three pairs of channels back to back spliced at intervals by means of cover plates spot welded or riveted to the flanges. All the spot welds were made on an alternating-current machine. The specimens were tested in a vertical position in a fatigue testing machine of 50,000-pound capacity. (See fig. 2 of reference 1.) The results of these tests are shown in table III and are plotted in figure 11. It is evident from figure 11 that the fatigue strength of the riveted specimens is considerably greater than that of the spot-welded specimens.

## Comparative Beam Tests of Spot-Welded and Riveted Girders of 17S-T and 61S-T under Static, Impact, and Fatigue Loads

Beam tests were conducted in order to make a general comparison of spot-welded girders and riveted girders under static, impact, and repeated loads. The specimens were designed primarily to represent a type of connection and thickness of material encountered in railway-car construction. Figure 12 shows the dimensions of the specimens and a list of the various combinations originally planned for this investigation. Items 8 to 14, however, were not completed and, therefore, were not tested.

All the spot welding on the specimens in this investigation was done on alternating-current machines. The flange welds were made using a 7/8-inch diameter 11° tip on the channel side of the weld and a flat tip on the cover-plate side. In the case of the 17S-T girders, the spot welds were formed by a special procedure that involved several applications of welding current spaced a short time apart, the welding pressure being maintained during the entire welding cycle. Spot welds representative of this practice on samples of 1/8-inch thick 17S-T gave static shear strengths of 2996 pounds per spot. Spot welds representative of the more normal procedure used on the 1/8-inch thick 61S-T gave static shear strengths of 1939 pounds per spot. Both of these static strength values are considered very satisfactory. Chisel tests on sample welds also indicated satisfactory welds. X-ray examination of some of the spot welds in one of the 17S-T girders indicated welds free from cracks with only a small amount of porosity.

In all tests a 60-inch span length was used with suitable bearing blocks at the center and at the ends of the span. In the static tests a 40,000-pound capacity Amsler testing machine was used and the arrangement for the test is shown in figure 13. The impact tests were made by dropping a 500-pound tup in a special impact-testing machine using the arrangement shown in figure 14. The fatigue tests were made using complete reversal of load in a fatigue testing machine of 50,000-pound capacity. (See fig. 2 of reference 1.) The arrangement for the fatigue tests is shown in figure 15. The results of these tests are shown in tables IV, V, and VI, and the fatigue test results are plotted in figure 16. These fatigue data have been summarized in another form in table VII. Two of the specimens after the completion of the impact test are shown in figure 17, and one of the fatigue specimens after the test is shown in figure 18. The conclusions drawn from this investigation are as follows:

1. All failures in the static-beam tests occurred by buckling of the cover plates. Some of the spot welds pulled apart after the plates had buckled but no rivet failures occurred.

2. The results of the static tests indicate that there is no marked difference between the loads and the load deflections for the riveted and the spot-welded construction, except that the girder with countersunk rivets carried less ultimate load than the others.

3. Failure of the girders in the impact tests occurred in substantially the same way as those in the static-load tests, namely by buckling of the cover plates. Failure of aluminum-alloy rivets usually did not occur until at least three drops had been made after the first buckle of the cover plates appeared. There were no failures of any steel rivets. Failure of spot welds by pulling apart usually occurred simultaneously with the first evidence of buckling of the cover plates in the impact tests.

4. The results indicate that there is no marked difference between the riveted and spot-welded constructions in regard to the total resistance to impact and the ability to withstand permanent set without fracture of the channel or cover plates.

5. In the fatigue tests failure in most of the specimens occurred by transverse fracture, sometimes in the channels and sometimes in the cover plates. In the riveted girders these fractures frequently passed through rivet holes and in the spot-welded girders they usually occurred at the edges of the spots. There were no rivet failures and failures occurred in only two tests by shearing spot welds.

6. In 17S-T the spot-welded girders had definitely lower fatigue strengths than any with rivets. The same was true for 61S-T girders welded in the T condition.

7. The fatigue strength of spot-welded 61S-T girders is appreciably higher when the artificial aging is done after instead of before welding and is higher than for any of the other spot-welded girders tested.

8. The fatigue strength of spot-welded 61S-T girders artificially aged after welding is about equal to that of either 17S-T or 61S-T girders made with hot-driven steel rivets but is definitely less than that of 17S-T and 61S-T girders made with cold-driven cone-point aluminum-alloy rivets.

## Comparative Tests of Spot-Welded and Riveted Box Beams of Alclad 24S-T Sheet

Static and fatigue strengths of spot-welded and riveted box beams fabricated from 14-gage Alclad 24S-T sheet are being compared in an investigation which is still in progress. Two designs of specimens, one of which is shown in figure 19, are being used, the differences being negligible as far as the object of the investigation is concerned. Both static and fatigue tests are being made in which specimens are tested as simple beams with either central or two-point loading as shown in figure 20. The arrangements used in the central loading tests are similar to those shown in figures 13 and 15.

The investigation includes tests of three lots of beams. In one, the beams were spot welded using alternating-current machines; in another, they were spot welded using energy-storage equipment; and, in the third, they were riveted. X-ray examination indicated that the alternating-current spot welds contained cracks, whereas the energy-storage welds were sound. Photomicrographs of sections through presumably typical welds from each of the two lots of beams are shown in figure 21. The corresponding static shear strengths of the two kinds of spot welds, as determined from auxiliary tests of lap-joint specimens, were about 590 and 970 pounds, respectively. The former value is considerably below the minimum (about 835 lb) shown in figure 1 for spot welds in 0.064-inch thick Alclad 24S-T sheet.

Static tests have been completed on the beams with alternating-current spot welds and on those which were riveted. Almost equal strengths were developed; the respective computed maximum bending stresses at failure were 25,000 and 25,100 pounds per square inch. Failures occurred by buckling of the compression flanges adjacent to the load point at the center of the span. No evidence of any spot weld or rivet failures was found. Because of the manner in which these beams failed, the beams with the energy-storage welds probably would have about the same static strength as the others.

Table VIII and figure 20 summarize the results of the fatigue tests under completely reversed bending. In the test of the beams with alternating-current spot welds, failure usually began as cracks through the welds. In the other two series of tests, many of the failures apparently began at locations other than those containing spot welds or rivets and, in some tests, the failures occurred entirely at such locations. When fatigue cracks did extend to a weld in the beams containing energy-storage welds, these cracks generally were tangent to the edge of the weld instead of passing through the weld. The results of the two series of tests in which failure began at locations other than those containing spot welds or rivets, therefore, are not necessarily indicative of the relative fatigue strengths of spot-welded and riveted beams. Comparing the results of the tests of the two lots of spot-welded beams, however, it is quite evident that the beams with the alternating-current welds were much inferior to those with the energy-storage welds. Much, if not all, of this difference can undoubtedly be attributed to differences in soundness of the welds, although the diameter of the energy-storage welds was greater than that of the alternating-current welds.

Figure 22 shows the fatigue failures which occurred in one of the beams containing alternating-current spot welds.

## General Discussion

The foregoing tests are not complete enough to permit final conclusions to be drawn. It is safe to say, however, even on the basis of the limited data presented herein, that spot-welded construction can be made to equal riveted construction in resistance to static and impact loadings. In resistance to fatigue it appears at present that spot-welded construction will not equal the best riveted construction unless the spot welds are more sound and free from cracks than the alternating-current welds used throughout most of these tests.

Even though the spot-welded specimens used in the tests described herein were not consistently equal to riveted specimens in resistance to fatigue, this does not mean that spot welding should not be used structurally. There are many structural applications, even in locations subjected regularly to vibration and repeated loading, in which the highest order of resistance to fatigue is not essential. Experience has shown that spot-welded parts and structures are capable of withstanding quite severe service conditions. For example, many aircraft fuel tanks spot welded on the same alternating-current machines used in the preparation of the specimens described in this report have been tested on vibration machines approved for such tests by the Army and Navy and have shown satisfactory life. The results of these tests and the behavior of the tanks in service are adequate evidence that, in spite of the relatively poor fatigue strengths of the alternating-current spot welds in the laboratory tests, it is possible to design spot-welded structures which will satisfactorily withstand vibratory stresses.

Aluminum Research Laboratories
Aluminum Company of America,
New Kensington, Pa., May 13, 1942.

## REFERENCE

1. Templin, R. L.: Fatigue Machines for Testing Structural Units. A.S.T.M. Proc., vol. 39, 1939, pp. 711-721.

TABLE I

STATIC AND SHEAR FATIGUE TESTS OF ALTERNATING-CURRENT SPOT WELDS IN SHEET STRIP

| Sheet alloy and temper | 14-gage sheet, 1 in. wide | | | 20-gage sheet, 1/2 in. wide | | |
|---|---|---|---|---|---|---|
| | Static strength (lb) | Endurance limit (lb) (a) | Endurance ratio | Static strength (lb) | Endurance limit (lb) (a) | Endurance ratio |
| 3S-0 | 529 | [b]50 | 0.09 | 222 | 28 | 0.13 |
| 3S-1/2H | 542 | 60 | .11 | 222 | 22 | .10 |
| 17S-T | 894 | --- | --- | 342 | 22 | .06 |
| Alclad 17S-T | 866 | --- | --- | 428 | 27 | .06 |
| 24S-T | 1213 | --- | --- | 381 | [b]20 | .05 |
| Alclad 24S-T | 977 | 40 | .04 | 362 | 30 | .08 |
| Alclad 24S-RT | 1111 | --- | --- | 449 | 28 | .06 |
| 52S-0 | 818 | 35 | .04 | 255 | 26 | .10 |
| 52S-1/2H | 1036 | --- | --- | 238 | 21 | .09 |
| 53S-T | 712 | --- | --- | 353 | 27 | .08 |

[a]For 14-gage sheet, 40-million cycle basis; for 20-gage sheet, 200-million-cycle basis.

[b]Estimated from incomplete tests.

TABLE II

SHEAR FATIGUE STRENGTHS OF ALTERNATING-CURRENT SPOT WELDS IN SHEET STRIP

| Sheet alloy and temper \ Cycles | Fatigue strength, lb per spot | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 10 | 100 | 1000 | 10,000 | 100,000 | 1,000,000 | 10,000,000 | 100,000,000 | 500,000,000 |
| **Sheet, 0.032 in. thick** | | | | | | | | | |
| 3S-0 | 152 | 111 | 77 | 52 | 37 | 30 | 28 | 28 | 28 |
| 3S-1/2H | 147 | 109 | 76 | 52 | 38 | 30 | 24 | 22 | 22 |
| 17S-T | 250 | 192 | 140 | 92 | 56 | 34 | 23 | 22 | 22 |
| Alclad 17S-T | 246 | 196 | 152 | 110 | 72 | 39 | 27 | 27 | 27 |
| 24S-T | 222 | 208 | 147 | 94 | 54 | 33 | 22 | 20 | 20 |
| Alclad 24S-T | [a]270 | [a]216 | [a]163 | [a]113 | [a]71 | 41 | 31 | 30 | 30 |
| Alclad 24S-RT | 275 | 198 | 147 | 108 | 72 | 40 | 29 | 28 | 28 |
| 52S-0 | 180 | 142 | 110 | 82 | 56 | 37 | 28 | 26 | 26 |
| 52S-1/2H | 183 | 148 | 115 | 83 | 53 | 28 | 23 | 21 | 21 |
| 53S-T | 266 | 212 | 163 | 116 | 75 | 41 | 30 | 28 | 27 |
| **Sheet, 0.064 in. thick** | | | | | | | | | |
| 3S-0 | --- | --- | --- | --- | 94 | 68 | 55 | 50 | 50 |
| 3S-1/2H | --- | --- | --- | --- | 103 | 82 | 65 | 60 | 60 |
| Alclad 24S-T | --- | --- | --- | --- | 180 | 94 | 53 | 42 | 40 |
| 52S-0 | --- | --- | --- | --- | 154 | 77 | 43 | 38 | 35 |
| 52S-1/2H | --- | --- | --- | --- | 168 | 88 | --- | --- | --- |
| 53S-T | --- | --- | --- | --- | 147 | 80 | --- | --- | --- |

[a]Estimated values.

TABLE III

RESULTS OF DIRECT TENSION-COMPRESSION FATIGUE TESTS OF STRUCTURAL MEMBERS CONSTRUCTED FROM 1/8-INCH 52S-1/2H SHEET

[All tests made with complete reversal of load]

| Specimen | Tensile area of cover plate (sq in.) | | Number of spots or rivets transferring load | Area of one rivet in shear (sq in.) | Bearing area of one rivet (sq in.) | Total load on specimen (lb) | Tensile stress in cover plate (lb/sq in.) | | Total load per spot or rivet (lb) | Shear stress in rivets (lb/sq in.) | Bearing stress (lb/sq in.) | Number of cycles at failure (a) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Gross area | Net area | | | | | Gross area | Net area | | | | |
| Spot-welded specimens | | | | | | | | | | | | |
| 1 | 1.135 | ---- | 36 | ---- | ---- | ±6990 | ±6150 | ---- | 194 | ---- | ---- | 20,700 |
| 2 | 1.135 | ---- | 36 | ---- | ---- | ±5000 | ±4400 | ---- | 139 | ---- | ---- | 220,900 |
| 3 | 1.135 | ---- | 72 | ---- | ---- | ±4980 | ±4390 | ---- | 69 | ---- | ---- | 169,700 |
| 8 | 1.135 | ---- | 48 | ---- | ---- | ±4950 | ±4360 | ---- | 103 | ---- | ---- | 197,500 |
| Riveted specimens | | | | | | | | | | | | |
| 5 | 1.135 | 1.007 | 36 | 0.0519 | 0.0319 | ±7010 | ±6170 | ±6950 | 195 | 3750 | 6080 | 950,700 |
| 6 | 1.135 | 1.007 | 36 | 0.0519 | 0.0319 | ±5564 | ±4900 | ±5520 | 155 | 2970 | 4830 | 1,908,000 |
| 7 | 1.135 | 1.007 | 36 | 0.0519 | 0.0319 | ±4515 | ±3970 | ±4470 | 125 | 2410 | 3920 | 12,854,800 |

[a]All specimens except 1 and 7 failed by transverse fatigue fracture of the cover plates through the spot welds or rivet holes. Specimen 1 sheared 18 spot welds; Specimen 7 did not fail.

TABLE IV

ULTIMATE LOADS AND MODULI OF FAILURE FROM STATIC BEAM TESTS

| Specimen | Plates and channels | Connections | Ultimate load (lb) | Modulus of failure (lb/sq in.) (a) |
|---|---|---|---|---|
| 1-A | 17S-T | Button-head steel rivets | 13,300 | 39,500 |
| 1-B | 17S-T | Button-head steel rivets | 11,930 | 35,400 |
| 2-A | 17S-T | Cone-point A17S-T rivets | 11,560 | 34,300 |
| 2-B | 17S-T | Cone-point A17S-T rivets | 12,200 | 36,200 |
| 3-A | 17S-T | Countersunk A17S-T rivets | 10,300 | 30,600 |
| 3-B | 17S-T | Countersunk A17S-T rivets | 10,650 | 31,600 |
| 4-A | 17S-T | Spot welds | 11,650 | 34,600 |
| 4-B | 17S-T | Spot welds | 12,650 | 37,500 |
| 5-A | 61S-T | Button-head steel rivets | 12,410 | 36,800 |
| 5-B | 61S-T | Button-head steel rivets | 12,000 | 35,600 |
| 6-A | 61S-T | Cone-point 53S-W rivets | 12,275 | 36,400 |
| 6-B | 61S-T | Cone-point 53S-W rivets | 12,265 | 36,400 |
| 7-A | 61S-T | Spot welds | 11,920 | 35,400 |
| 7-B | 61S-T | Spot welds | 11,900 | 35,400 |

[a]Obtained by substituting ultimate load P in the ordinary beam formula. Stress = Mc/I. In this case the stress is calculated at the edge of the 2 1/2-in. center bearing block so that the complete expression for modulus of failure is

$$\text{Modulus of failure} = \frac{P}{4}(60 - 2.5) \times \frac{2.125}{10.30} = 2.97P$$

## TABLE V

### IMPACT TESTS OF GIRDERS

| Specimen | Plates and channels | Connections | Height of drop for first buckle (in.) | Height of drop for first rivet or spot failure (in.) | Height of drop at completion of test (in.) | Permanent set at completion of test (in.) |
|---|---|---|---|---|---|---|
| 1-C | 17S-T | Button-head steel rivets | 10 | No failure | 16 | 5.721 |
| 1-D | 17S-T | Button-head steel rivets | 9 | No failure | 17 | 6.894 |
| 2-C | 17S-T | Cone-point A17S-T rivets | 8 | 12 | 16 | 5.465 |
| 2-D | 17S-T | Cone-point A17S-T rivets | 9 | 17 | 17 | 7.008 |
| 3-C | 17S-T | Countersunk A17S-T rivets | 7 | 12 | 19 | 6.060 |
| 3-D | 17S-T | Countersunk A17S-T rivets | 7 | 11 | 17 | 5.231 |
| 4-C | 17S-T | Spot welds | 8 | 8 | 14 | 5.082 |
| 4-D | 17S-T | Spot welds | 9 | 10 | [illegible] | 5.607 |
| 5-C | 61S-T | Button-head steel rivets | 10 | No failure | 16 | 5.445 |
| 5-D | 61S-T | Button-head steel rivets | 9 | No failure | 15 | 5.214 |
| 6-C | 61S-T | Cone-point 53S-W rivets | 9 | 11 | 16 | 5.834 |
| 6-D | 61S-T | Cone-point 53S-W rivets | 12 | 15 | 17 | 5.802 |
| 7-C | 61S-T | Spot welds | 9 | 9 | 15 | 7.103 |
| 7-D | 61S-T | Spot welds | 8 | 8 | 14 | 5.350 |

## TABLE VI

### BEAM-FATIGUE TESTS OF GIRDERS

| Item | Channel and plate | Load, lb (b) / Connection | Cycles to failure (a) ±4000 | ±3000 | ±2500 | ±2000 | ±1500 | ±1000 |
|---|---|---|---|---|---|---|---|---|
| 1 | 17S-T | Button-head steel rivets | 89,800(A) | 192,100(F) | - | 1,050,300(A) | 2,058,800(A) | - |
| 2 | 17S-T | Cone-point A17S-T rivets | 211,700(A) | 701,000(G) | - | 1,192,000(A) | 3,517,600(G) | - |
| 3 | 17S-T | Countersunk A17S-T rivets | 141,300(A) | 424,300(D) | 672,600(A) | 5,111,300[c] | - | - |
| 4 | 17S-T | Spot welds | 79,200(F) | 89,300(F) | - | 338,600(F) | - | 2,713,300(F) |
| 5 | 61S-T | Button-head steel rivets | 40,600(A) | 191,600(A) | - | 1,046,800(A) | 3,368,100(G) | - |
| 6 | 61S-T | Cone-point 53S-W rivets | 302,400(A) | 586,500(C) | - | 1,142,100(C) | 1,234,300(C) | - |
| 7 | 61S-T | Spot welds | 24,400(E) | 104,700(F) | - | 402,700(B) | - | 4,409,700(B) |
| 15 | 61S-T | Spot welds (aged after welding) | 56,400(E) | 219,000(F) | - | 694,400(H) | - | - |

[a] A - Cracks at rivet hole (or spot weld) in main channel, usually at stiffener channel.
B - Cracks at rivet hole (or spot weld) in cover plate.
C - Cracks across cover plate and above spacer channel (under center clamp), but not through any rivet hole or spot weld.
D - Crack at rivet hole in main channel; also crack in corner of channel and not at any rivet hole.
E - Spot welds between cover plate and channels sheared.
F - Same as A and B.
G - Same as A and C.
H - Same as B and C.

[b] The loads applied were such that the bending stresses varied from a maximum in tension to the same numerical value in compression.

[c] No failure; test discontinued.

TABLE VII

SUMMARY OF FATIGUE STRENGTHS OF SPOT-WELDED
AND RIVETED 17S-T AND 61S-T GIRDERS

| Item | Channel and plate | Cycles / Connection | Maximum load supported, lb 10,000 | 100,000 | 1,000,000 | 10,000,000 |
|---|---|---|---|---|---|---|
| 1 | 17S-T | Button-head steel rivets | — | 3700 | 2000 | — |
| 2 | 17S-T | Cone-point A17S-T rivets | — | [a]4600 | 2600 | — |
| 3 | 17S-T | Countersunk A17S-T rivets | — | [a]4400 | 2300 | [a]2000 |
| 4 | 17S-T | Spot welds | — | 3200 | 1400 | [a]800 |
| 5 | 61S-T | Button-head steel rivets | — | 3400 | 1900 | — |
| 6 | 61S-T | Cone-point 53S-W rivets | — | — | 2200 | — |
| 7 | 61S-T | Spot welds | [a]4700 | 3000 | 1500 | [a]900 |
| 15 | 61S-T | Spot welds (aged after welding) | — | 3600 | [a]1800 | — |

[a]Estimated

TABLE VIII

FATIGUE TESTS OF ALCLAD 24S-T BOX BEAMS

[All tests made with complete reversal of stress]

| Construction | Loading arrangement in test | Maximum bending stress (lb/sq in.) | Cycles at failure | Location of failure |
|---|---|---|---|---|
| Spot welded (a-c) | Central | ±16,000 | 2,300 | Cover plate under center bearing block. |
| | | ± 7,560 | 31,400 | Cracks in spot welds near center of span. |
| | | ± 3,480 | 465,300 | Cracks through spot weld in channel. |
| | | ± 2,080 | 2,171,500 | Cracks in spot welds near center of span. |
| Spot welded (energy-storage) | Two-point | ±15,320 | 60,700 | Cover plates and channel sections, through only one spot weld. |
| | | ±10,050 | 239,500 | Cover plates and channel sections. No failure through spot weld. |
| | | ± 7,670 | 306,300 | Channel sections. One crack at edge of weld. |
| | | ± 5,020 | [a]8,600,000 | No failure. Test still running. (7-23-42) |
| Riveted | Central | ±15,700 | 26,200 | Cover plate under center bearing block. |
| | | ±12,600 | 80,100 | Cover plate under center bearing block. |
| | | ± 7,690 | 1,087,700 | Channel sections. |
| | | ± 4,860 | 4,804,600 | Channel sections. |

[a]See remarks in last column.

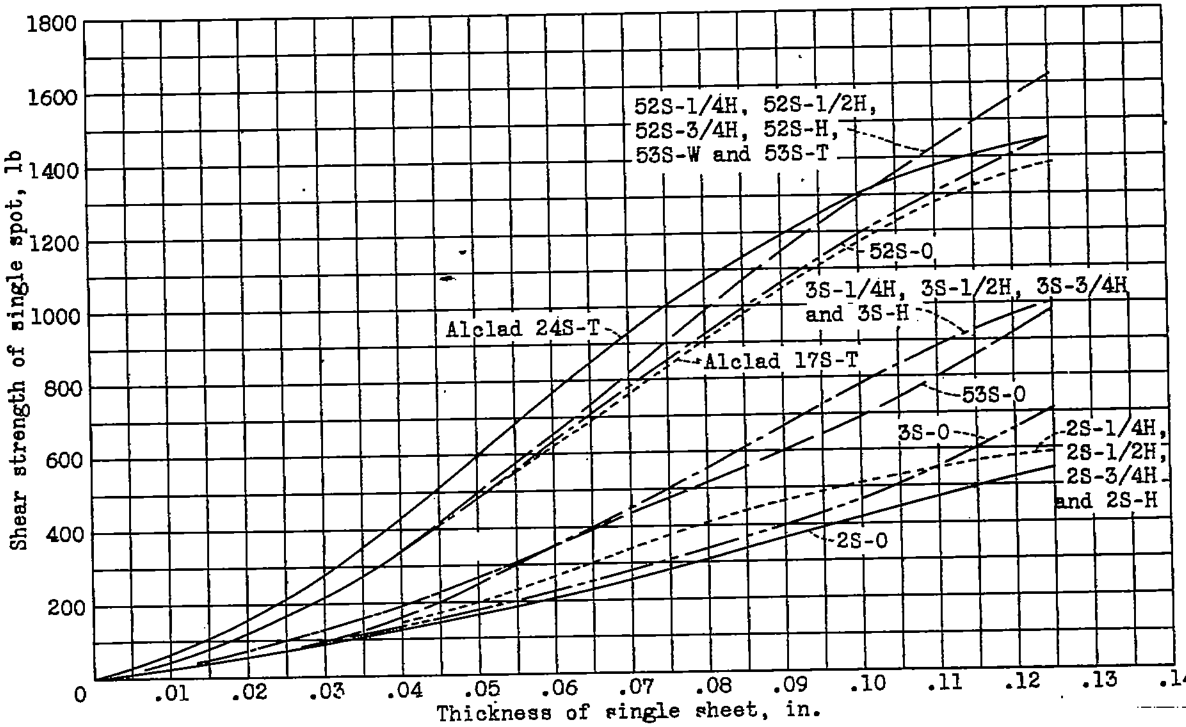



Figure 1.- Minimum shear strength of spot welds.

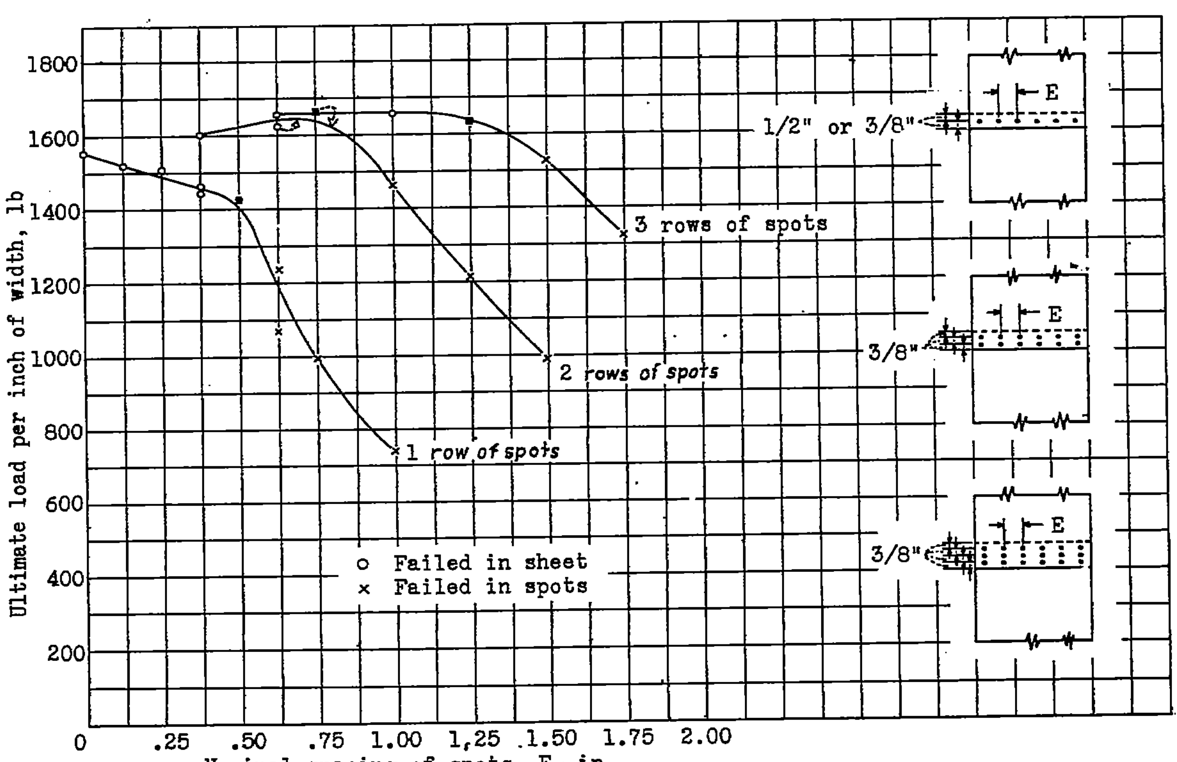



Figure 3.- Effect of spacing on strength of spot-welded joints in 0.051-inch thick 52S-$\frac{1}{2}$H sheet.

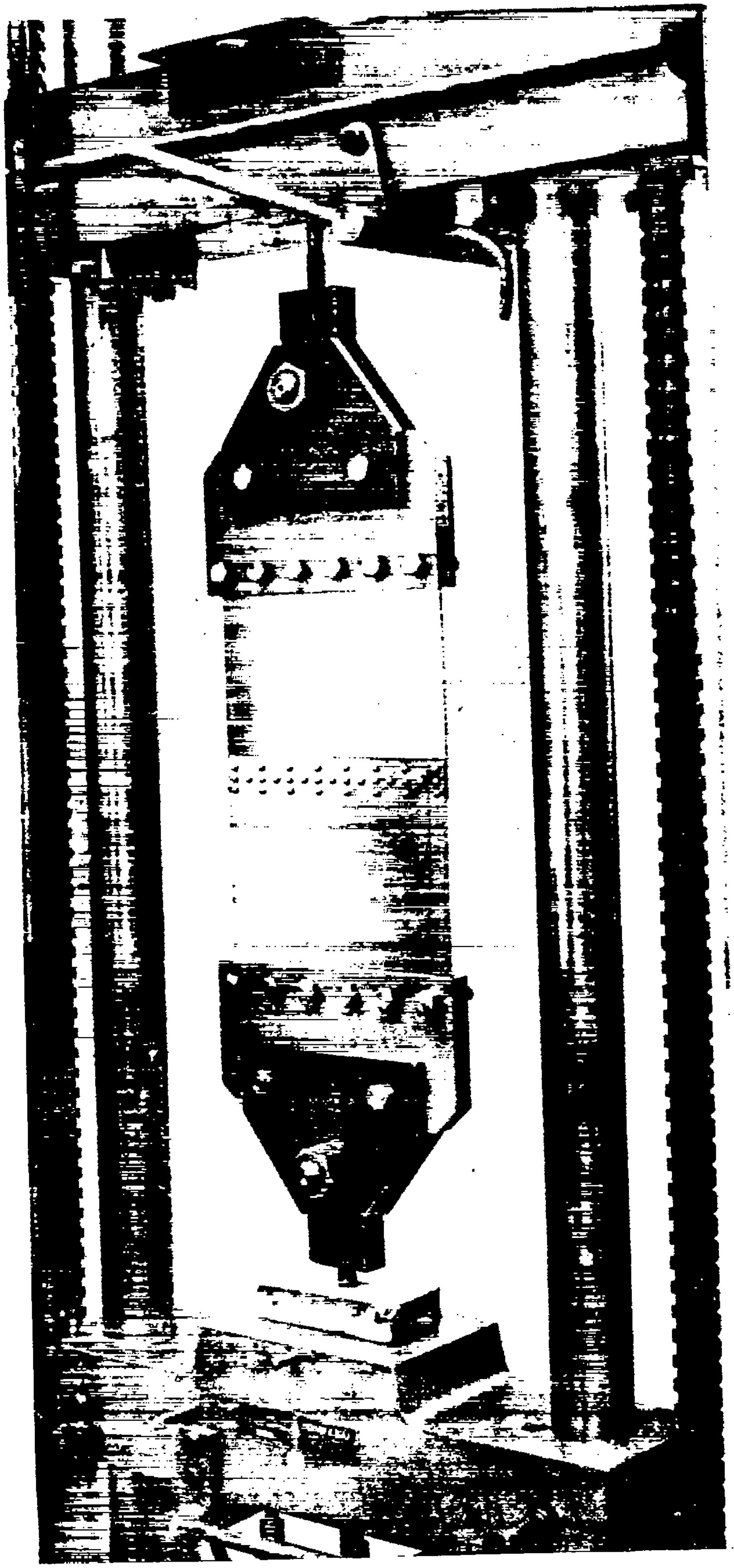


Figure 2. Test of wide riveted joint in 52S-1/2H sheet 0.051 inch thick.

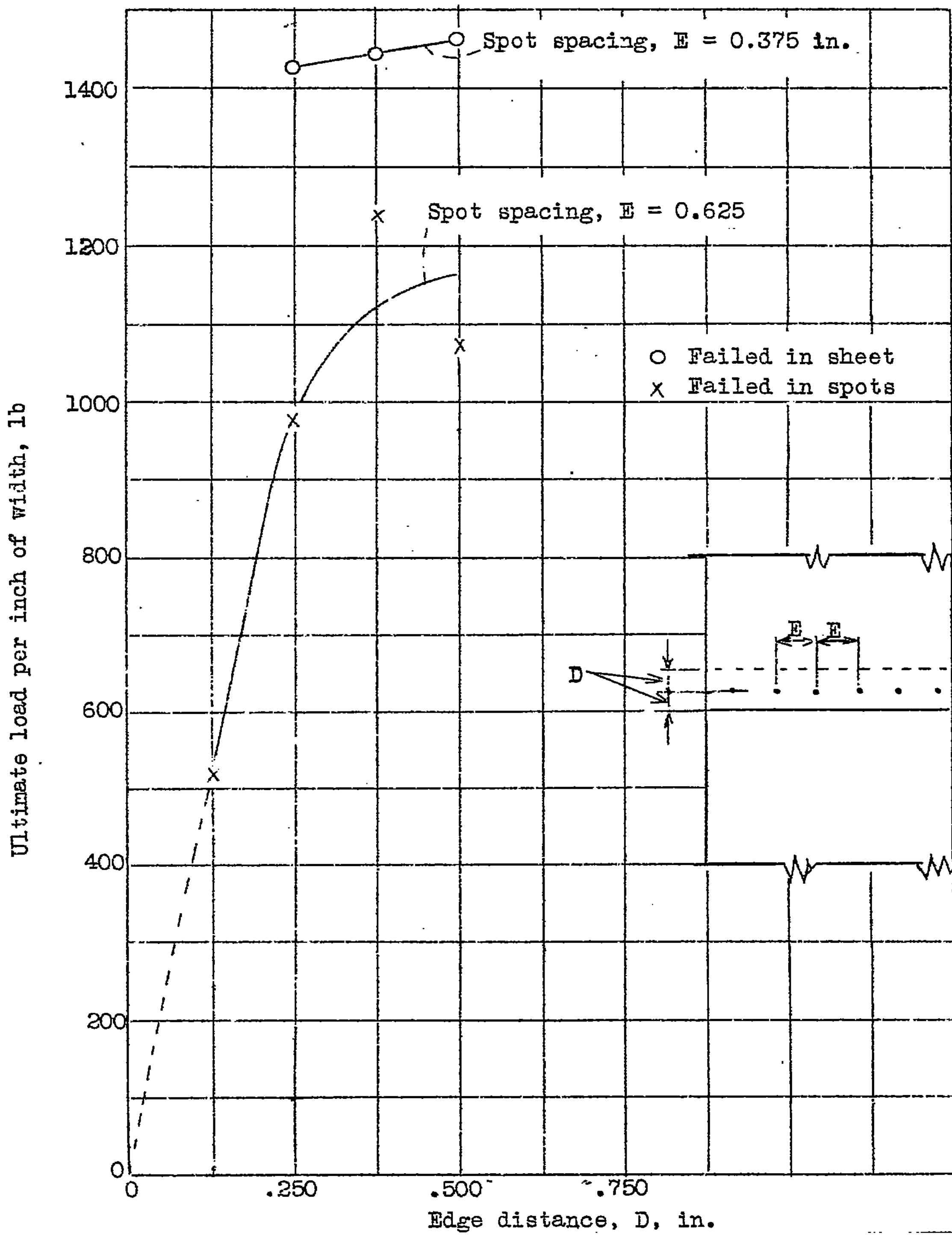
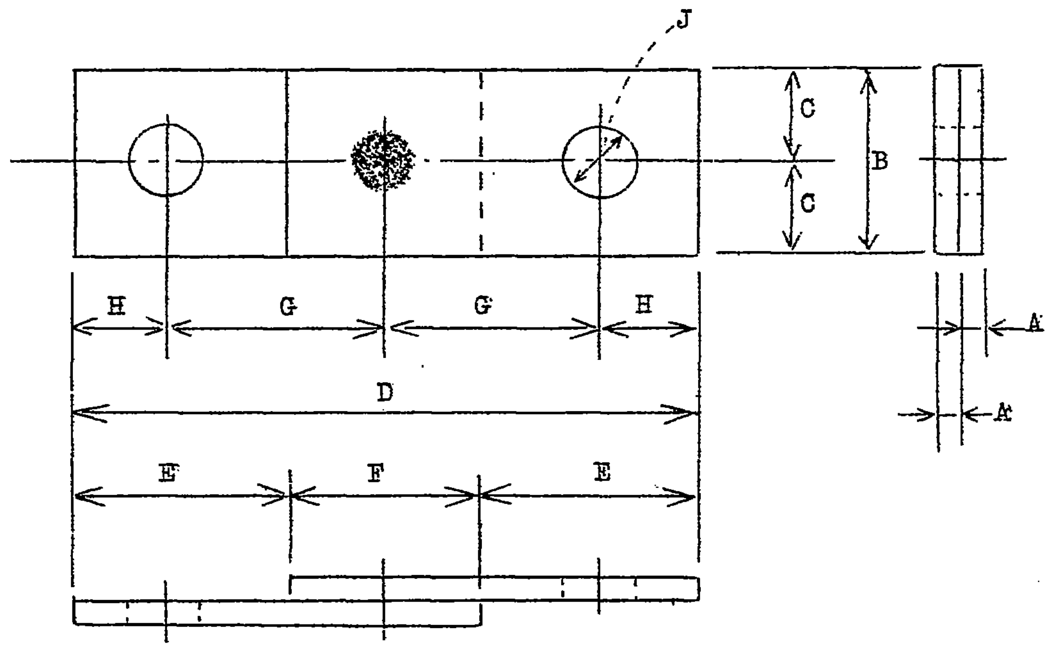



Figure 4.- Effect of edge distance on strength of spot-welded joints in .051-inch thick 52S-$\frac{1}{2}$H sheet.




Specimens for shear fatigue tests.

| Gage No. | A | B | C | D | E | F | G | H | J |
|---|---|---|---|---|---|---|---|---|---|
| 14 | .064 | 1 | 1/2 | 4-3/16 | 1-15/32 | 1-1/4 | 1-15/32 | 5/8 | 25/64 |
| 20 | .032 | 1/2 | 1/4 | 1-5/8 | 9/16 | 1/2 | 9/16 | 1/4 | .191 |

Figure 5.- Specimens for shear-fatigue tests.

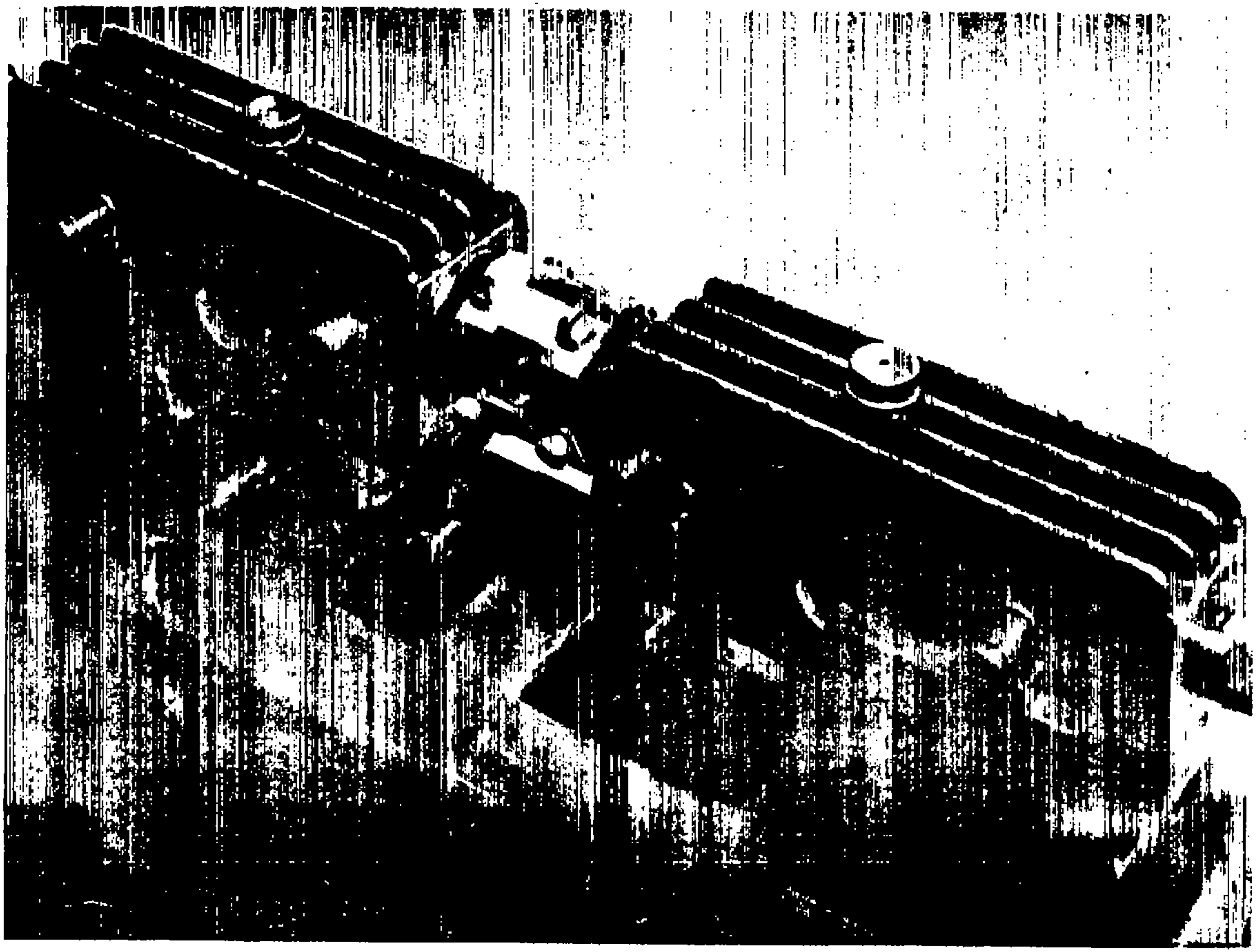


Figure 6. - Fatigue tests of spot-welded joints in a sheet 0.032 inch thick.

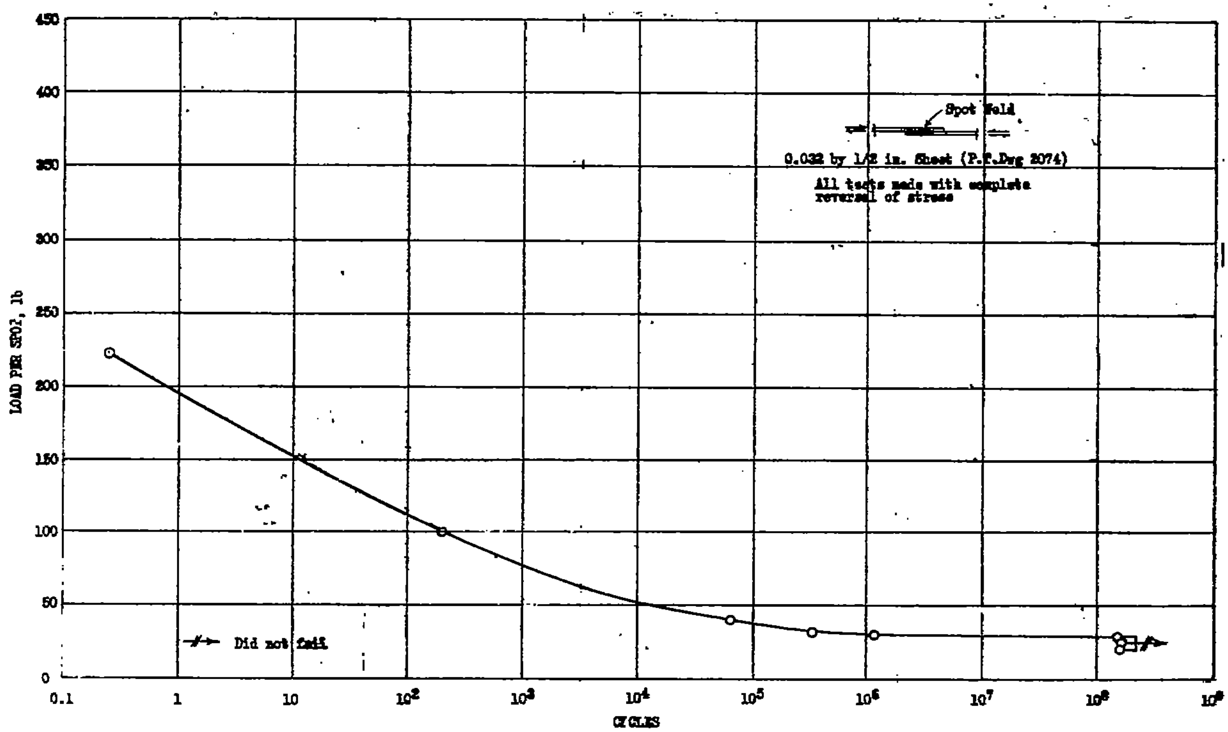
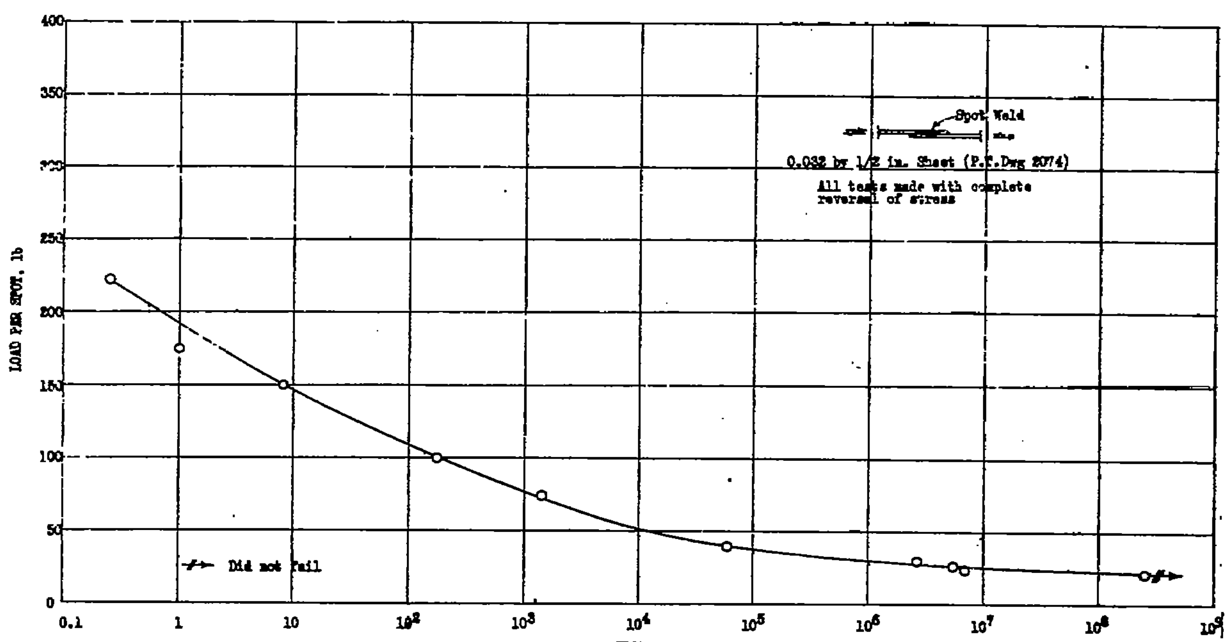


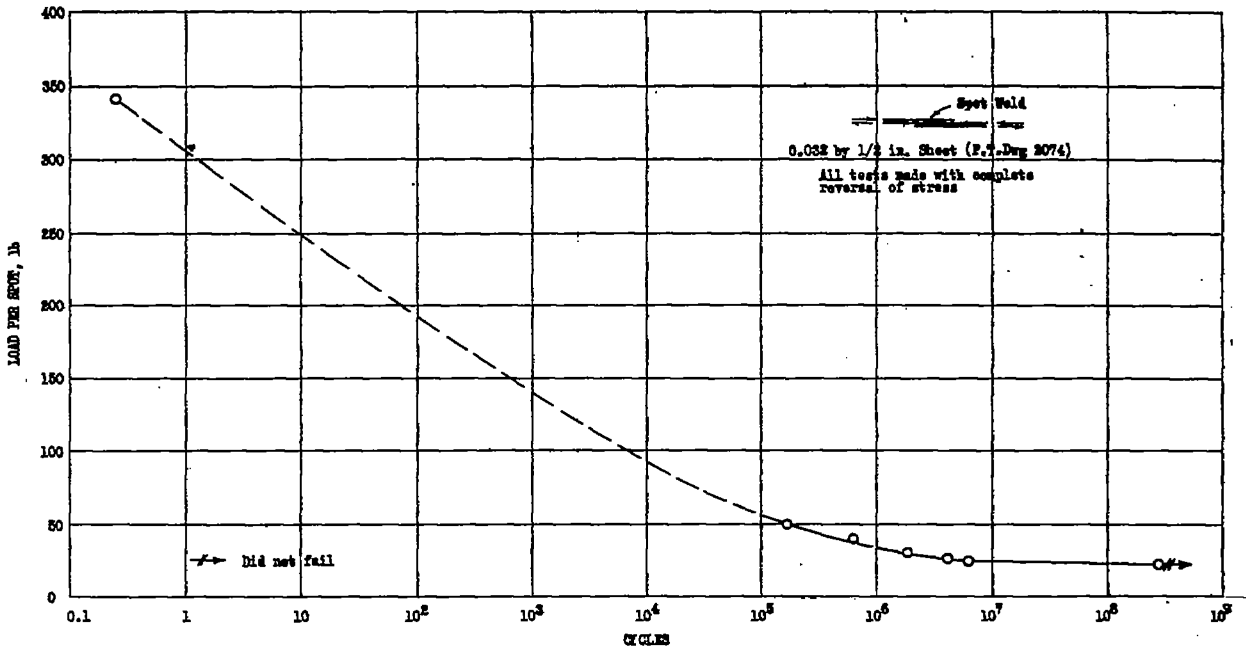

Figure 7a to j.- FATIGUE CURVE FOR SPOT-WELDED JOINTS IN SHEAR

7(a) A-c Welds; 3S-0 Sheet; 20 gage



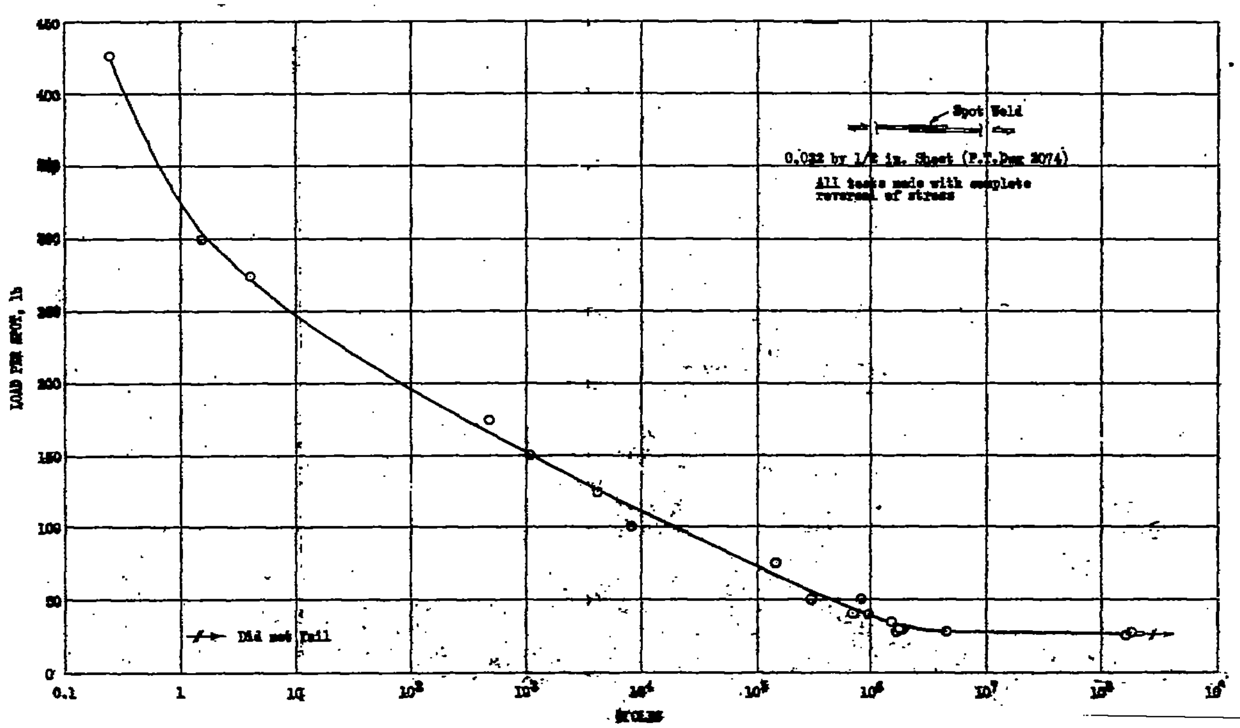

FATIGUE CURVE FOR SPOT-WELDED JOINTS IN SHEAR

7(b) A-c Welds; 3S-1/2H Sheet; 20 gage



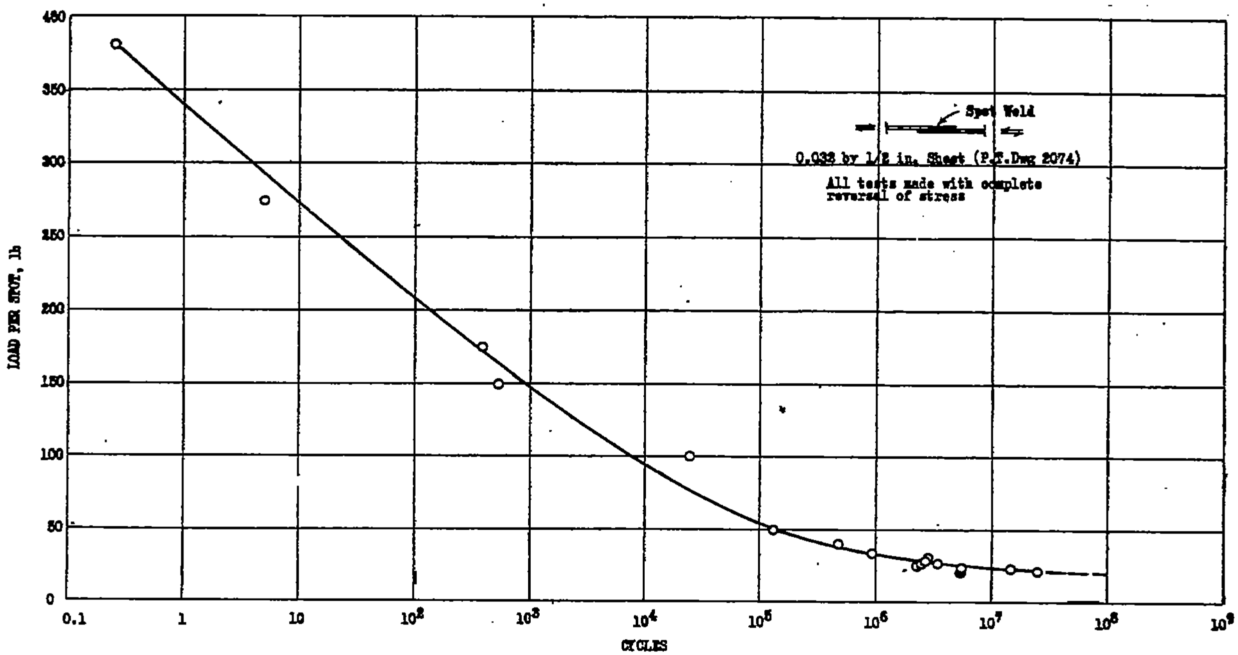

FATIGUE CURVE FOR SPOT-WELDED JOINTS IN SHEAR

7(c) A-c Welds; 17S-T Sheet; 20 gage



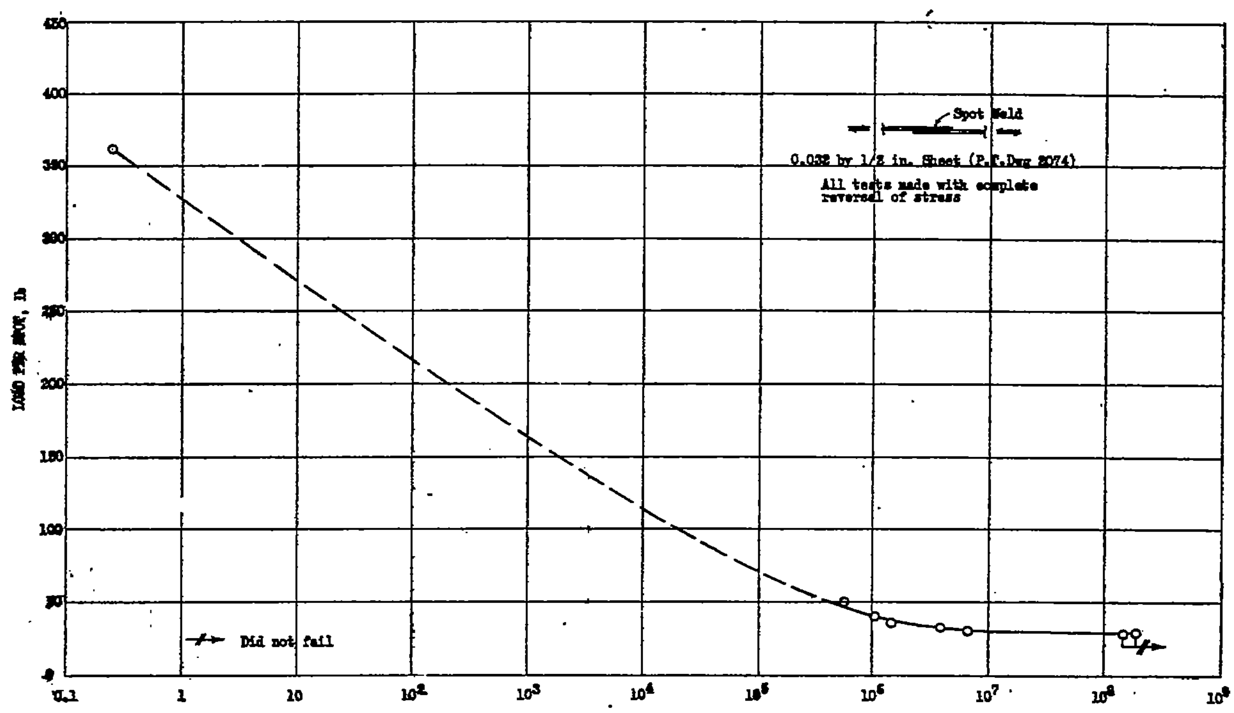

FATIGUE CURVE FOR SPOT-WELDED JOINTS IN SHEAR

7(d) A-c Welds; Alclad 17S T Sheet; 20 gage



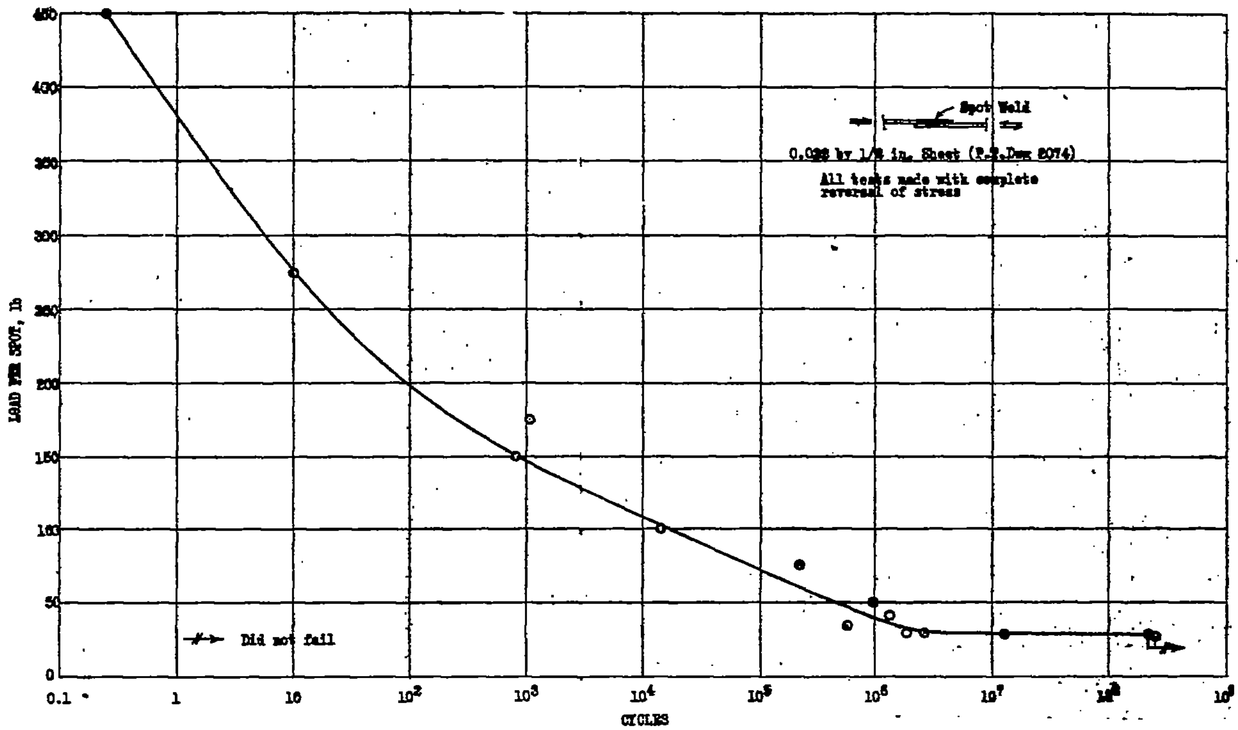

FATIGUE CURVE FOR SPOT-WELDED JOINTS IN SHEAR

7(e) A-c Welds; 24S-T Sheet; 20 gage



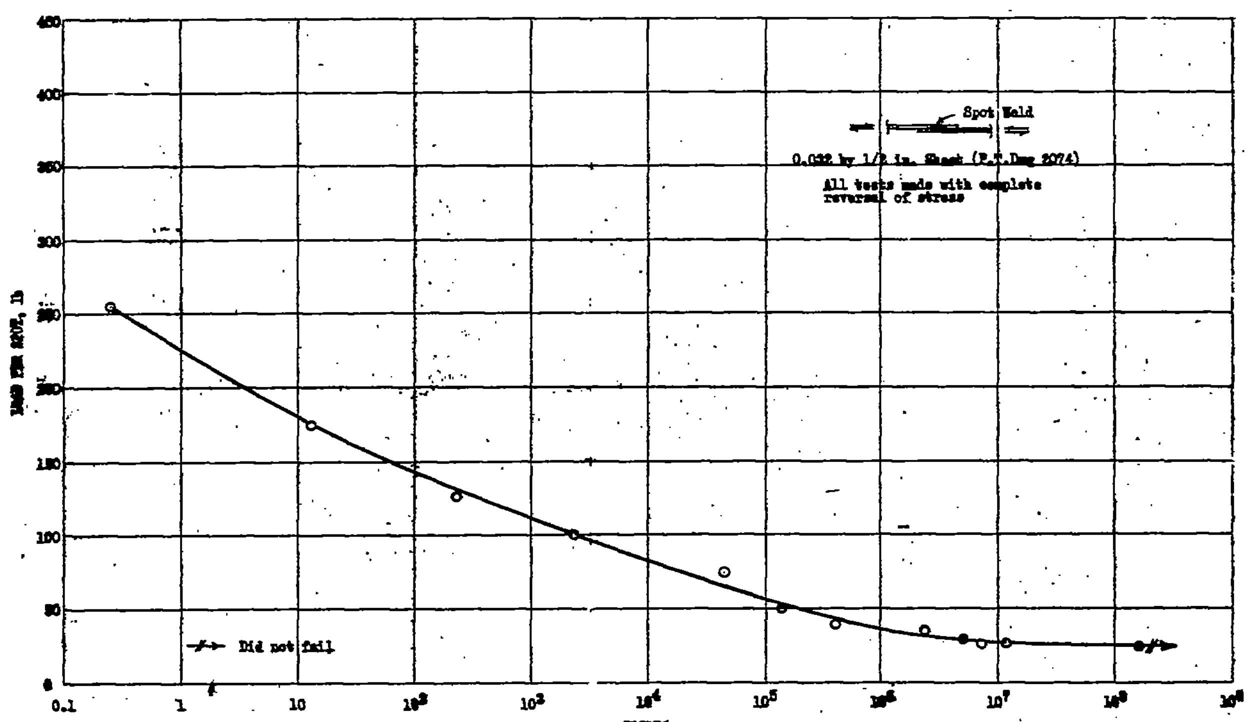

FATIGUE CURVE FOR SPOT-WELDED JOINTS IN SHEAR

7(f) A-c Welds; Alclad 24S-T Sheet; 20 gage



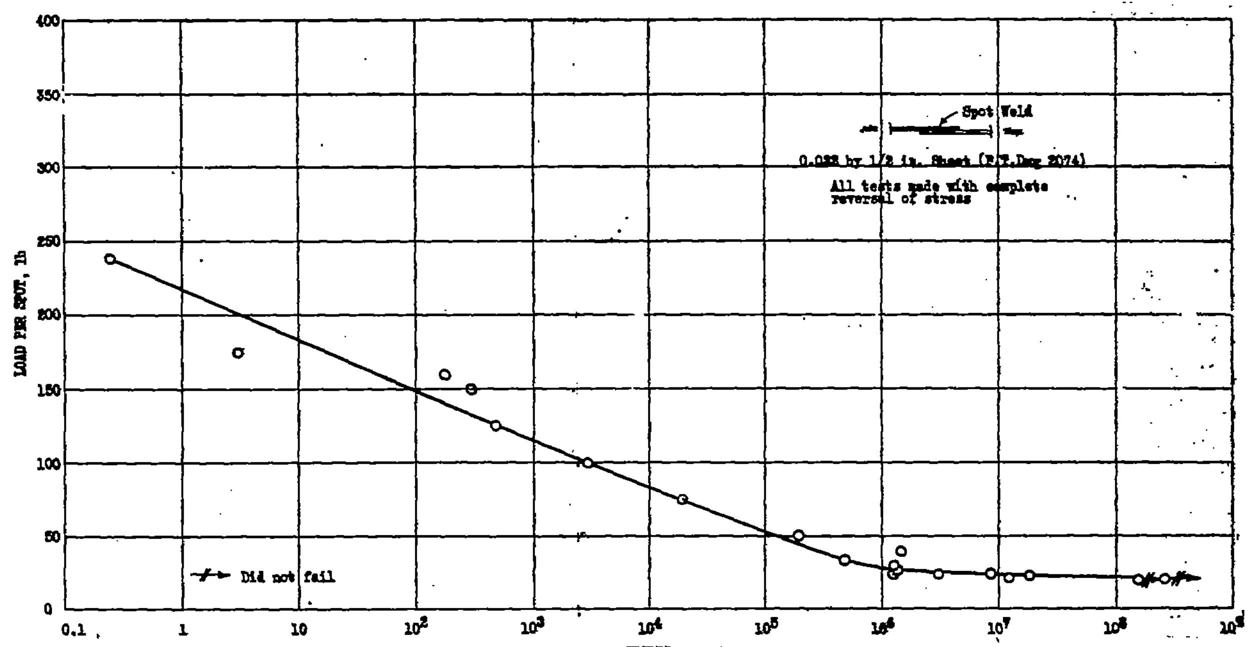

FATIGUE CURVE FOR SPOT-WELDED JOINTS IN SHEAR

7(g) A-c Welds; Alclad 24S-RT Sheet; 20 gage



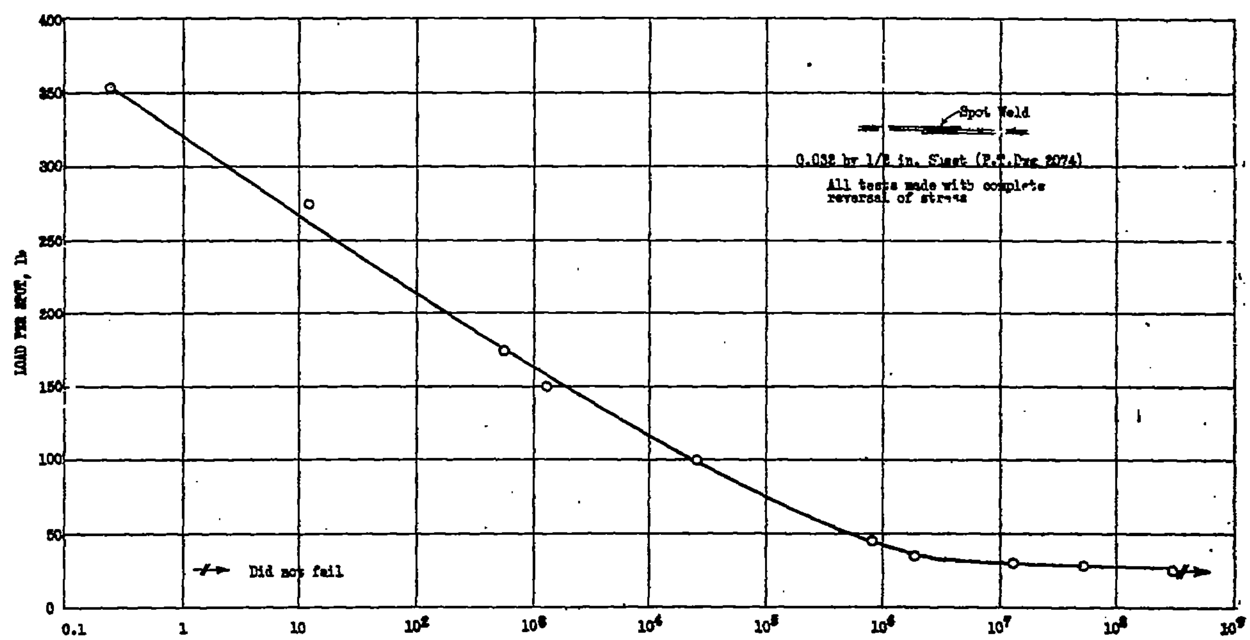

FATIGUE CURVE FOR SPOT-WELDED JOINTS IN SHEAR

7(h) A-c Welds; 52S-0 Sheet; 20 gage



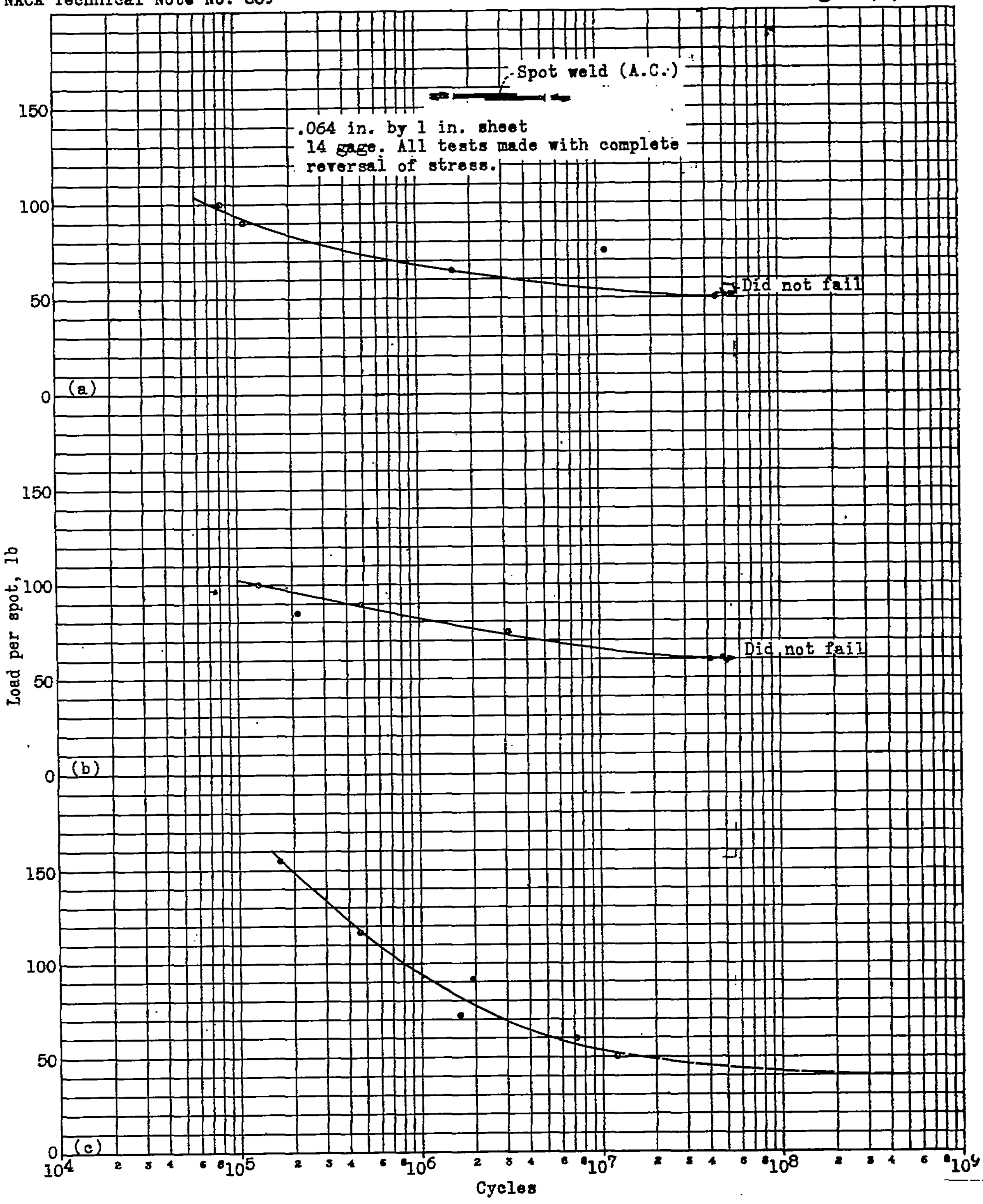

FATIGUE CURVE FOR SPOT-WELDED JOINTS IN SHEAR

7(i) A-e Welds; 52S-1/2H Sheet; 20 gage



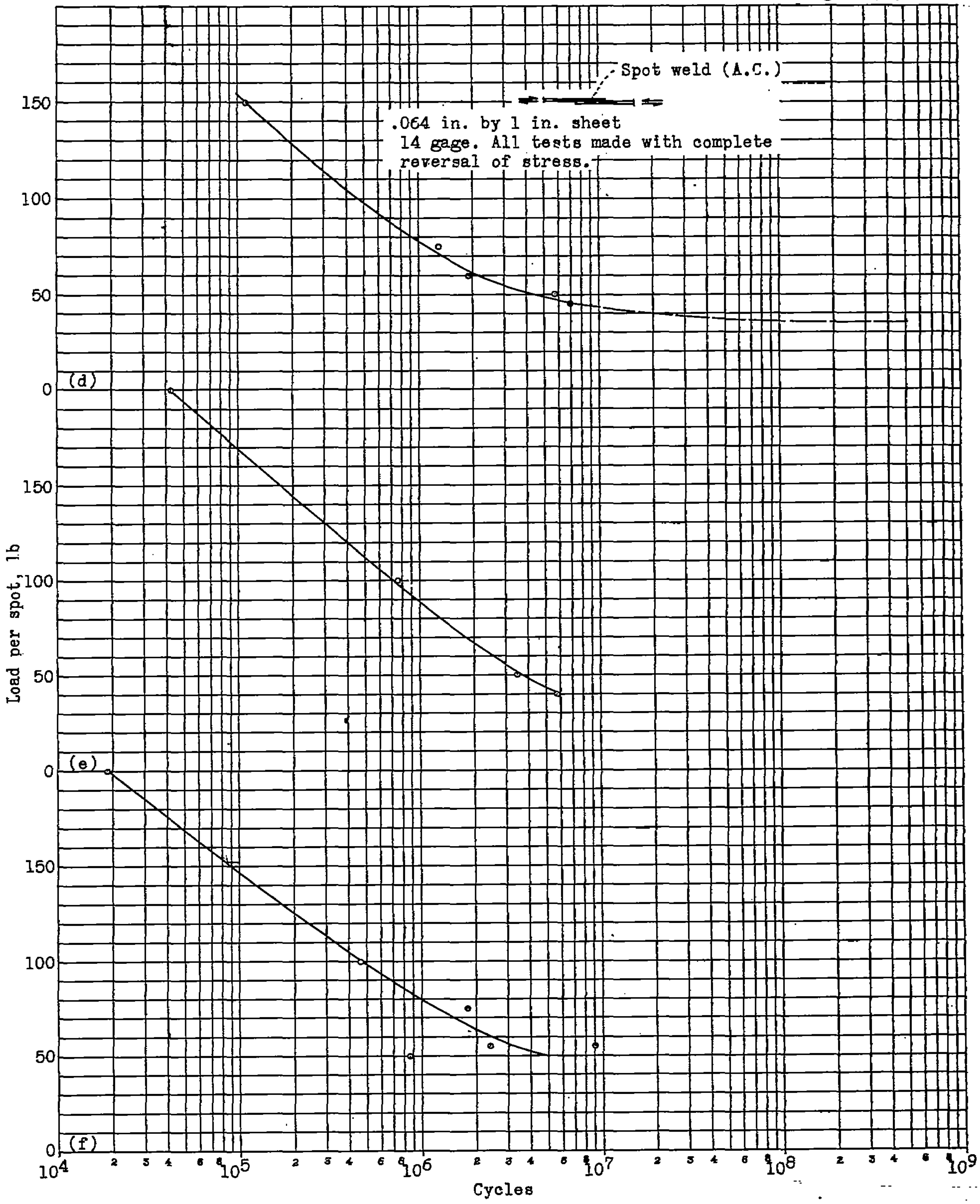

FATIGUE CURVE FOR SPOT-WELDED JOINTS IN SHEAR

7(j) A-e Welds; 53S-T Sheet; 20 gage




(a) Sheet, 3S-0 (b) Sheet, 3S-1/2H (c) Sheet, Alclad 24S-T

Figure 8a to f.- Fatigue curves for spot-welded joints in shear.




(d) Sheet, 52S-0 (e) Sheet, 52S-1/2H (f) Sheet, 53S-T

Figure 8.- Concluded.

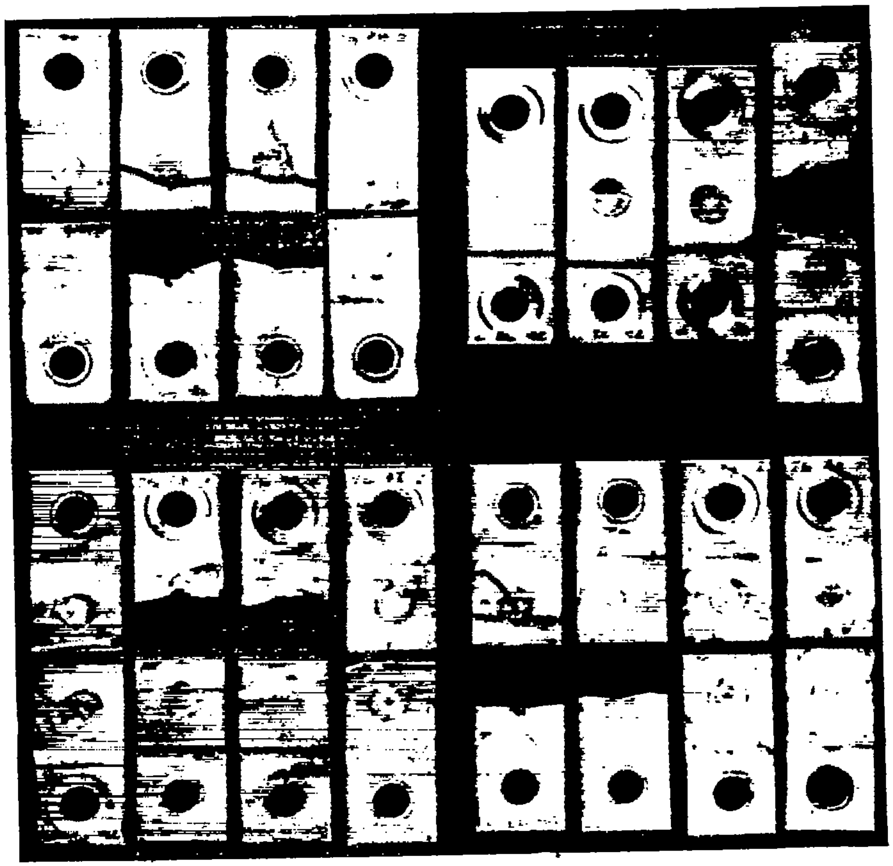


Figure 9. - Typical fatigue failures of spot-welded joints in Alclad 24S-T sheet 0.032 inch thick.

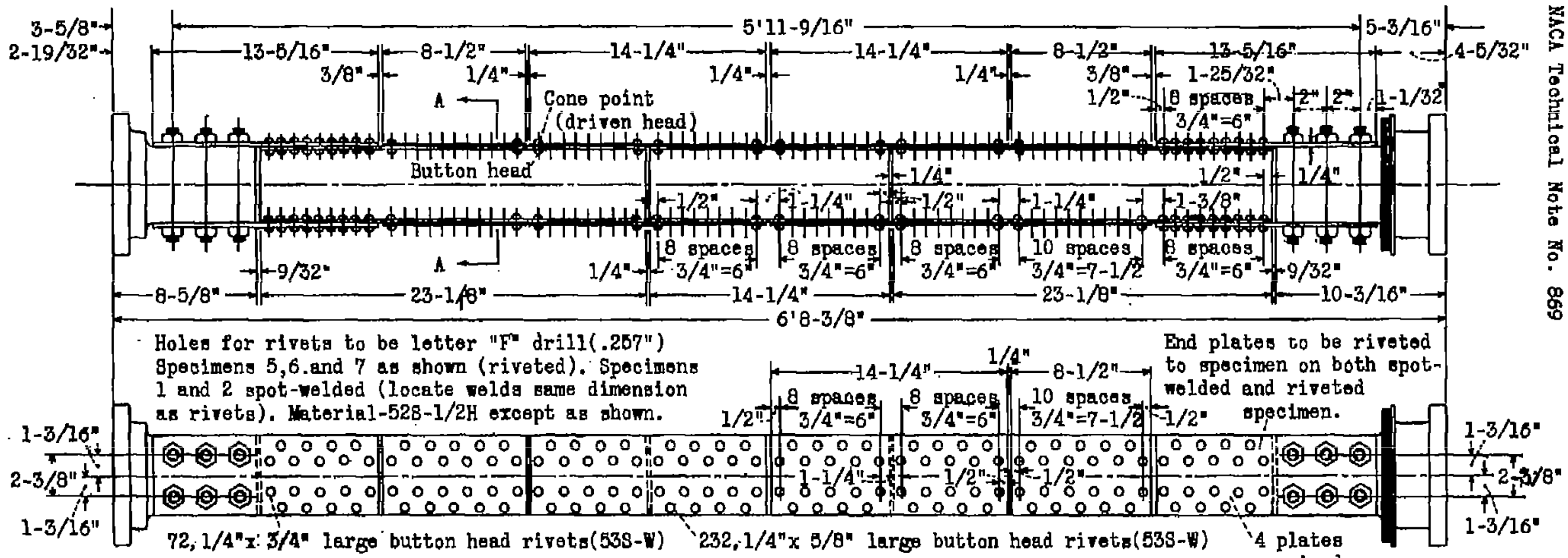
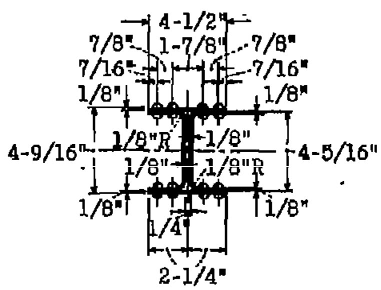



Figure 10.- Built-up structural members for direct tension-compression fatigue tests.




Section A-A

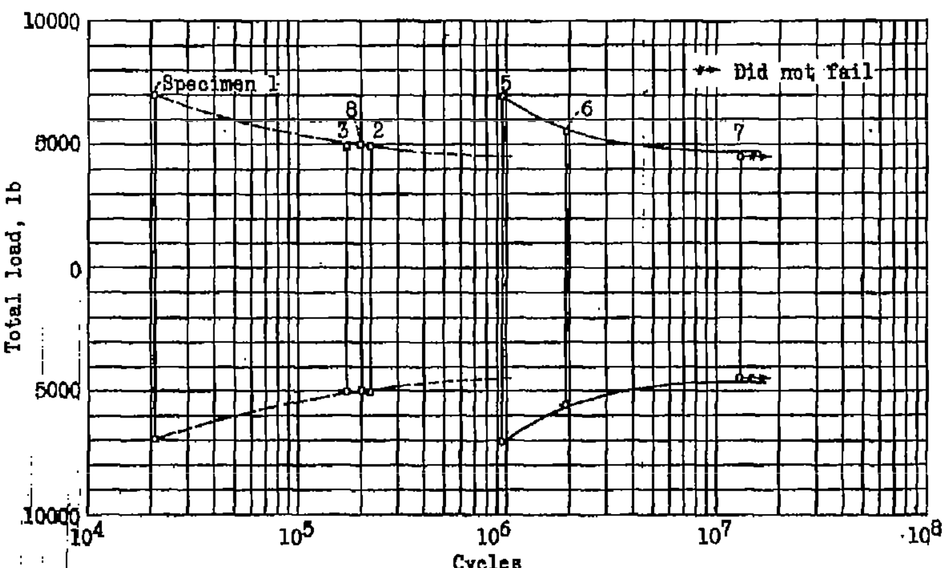
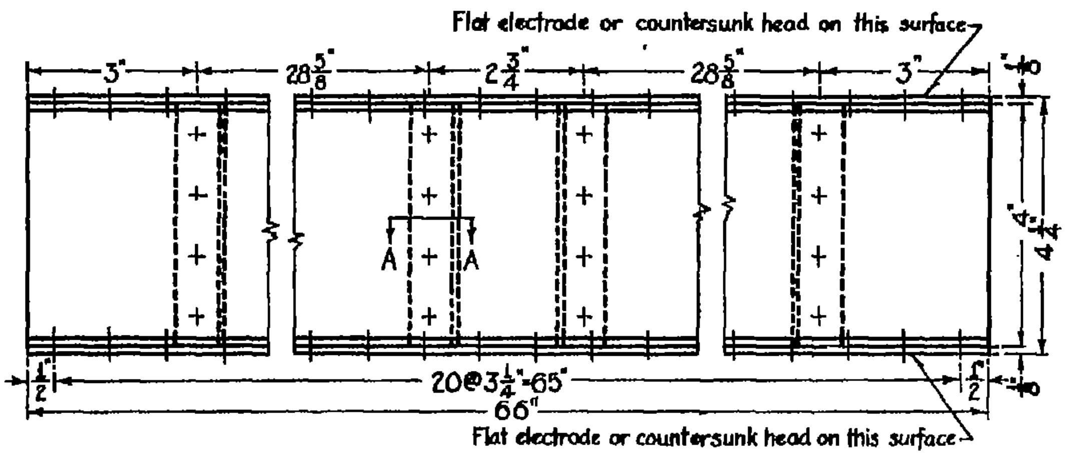
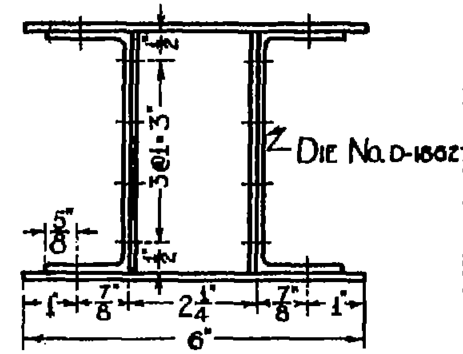


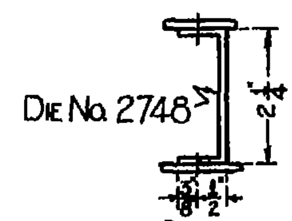

Figure 11.- Direct tension-compression fatigue tests of spot-welded and riveted structural members. Sheet, 52S-1/2H; ratio of minimum stress to maximum stress, -1.0.

o Riveted specimens
ロ Spot-welded specimens




Hole diameter for riveted beams, $\frac{17}{64}$ inches




Section A-A

| ITEM NO. | NO. REQ'D | CHANNEL ALLOY | PLATE ALLOY | CONNECTIONS | CHANNEL SPACER CONNECTIONS (SECTION A-A) |
|---|---|---|---|---|---|
| 1 | 8 | 17S-T | 17S-T | 1/4 in. hot-driven button-head steel rivets | 1/4 in. hot-driven button-head steel rivets |
| 2 | 8 | 17S-T | 17S-T | 1/4 in. cold-driven cone-point head A17S-T rivets | 1/4 in cold-driven cone-point head A17S-T rivets |
| 3 | 8 | 17S-T | 17S-T | 1/4 in. cold-driven countersunk head A17S-T rivets | 1/4 in. cold-driven cone-point head A17S-T rivets |
| 4 | 8 | 17S-T | 17S-T | spot-welded | spot-welded |
| 5 | 8 | 61S-T | 61S-T | 1/4 in. hot-driven button-head steel rivets | 1/4 in. hot-driven button-head steel rivets |
| 6 | 8 | 61S-T | 61S-T | 1/4 in. cold-driven cone-point head 53S-W rivets | 1/4 in. cold-driven cone-point head 53S-W rivets |
| 7 | 8 | 61S-T | 61S-T | spot-welded | spot-welded |
| 8 | 8 | 53S-T | 53S-T | 1/4 in. cold-driven cone-point head 53S-W rivets | 1/4 in. cold-driven cone-point head 53S-W rivets |
| 9 | 8 | 53S-T | 53S-T | 1/4 in. cold-driven countersunk head 53S-W rivets | 1/4 in. cold-driven cone-point head 53S-W rivets |
| 10 | 8 | 53S-T | 53S-T | spot-welded | spot-welded |
| 11 | 8 | 61S-T | 4S-½H | 1/4 in. cold-driven cone-point head 53S-W rivets | 1/4 in. cold-driven cone-point head 53S-W rivets |
| 12 | 8 | 61S-T | 4S-½H | spot-welded | spot-welded |
| 13 | 8 | 53S-T | 4S-½H | 1/4 in. cold-driven cone-point head 53S-W rivets | 1/4 in. cold-driven cone-point head 53S-W rivets |
| 14 | 8 | 53S-T | 4S-½H | spot-welded | spot-welded |
| 15 | 3 | 61S-T | 61S-T | spot-welded in W condition | spot-welded in W condition |

NOTE:
Channel spacers (Section A-A) should be cut accurately square and 4 inches long.

FIGURE 12.- DETAIL DRAWING OF BEAM SPECIMENS.

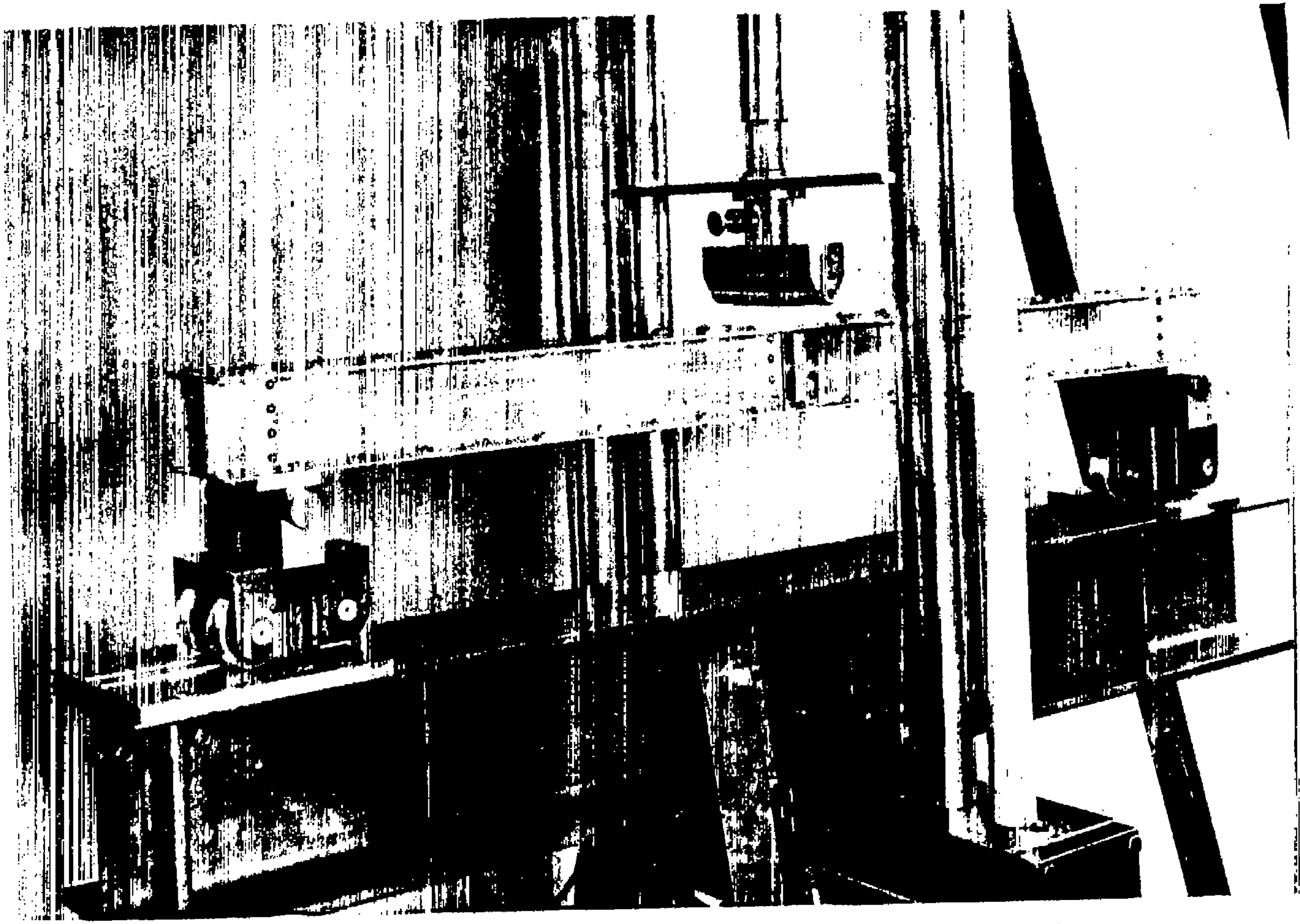


Figure 13. - Static test of riveted girder built up of 61S-T sheet 1/8 inch thick.

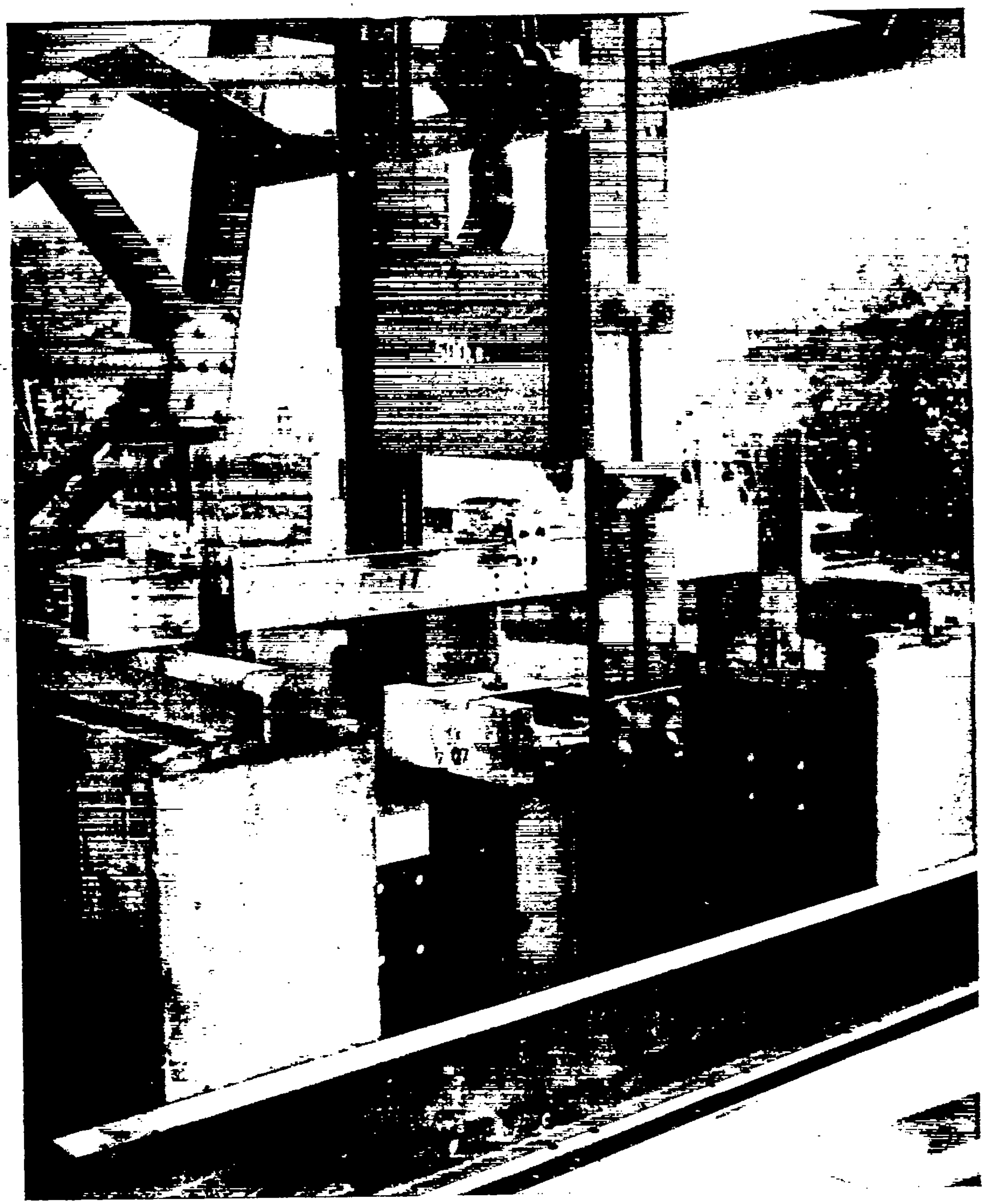


Figure 14.- Impact test of riveted girder built up of 61S-T sheet 1/8 inch thick.

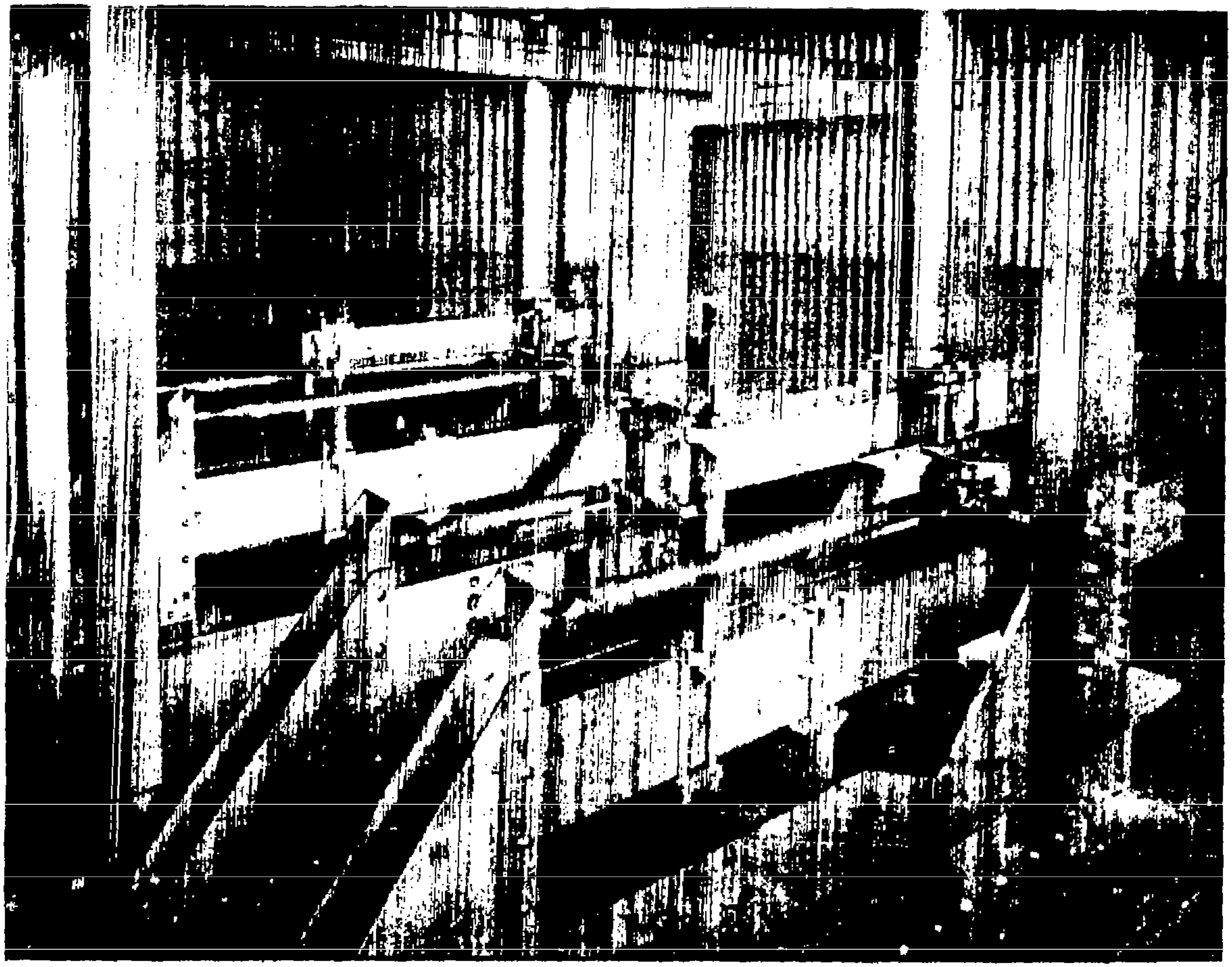
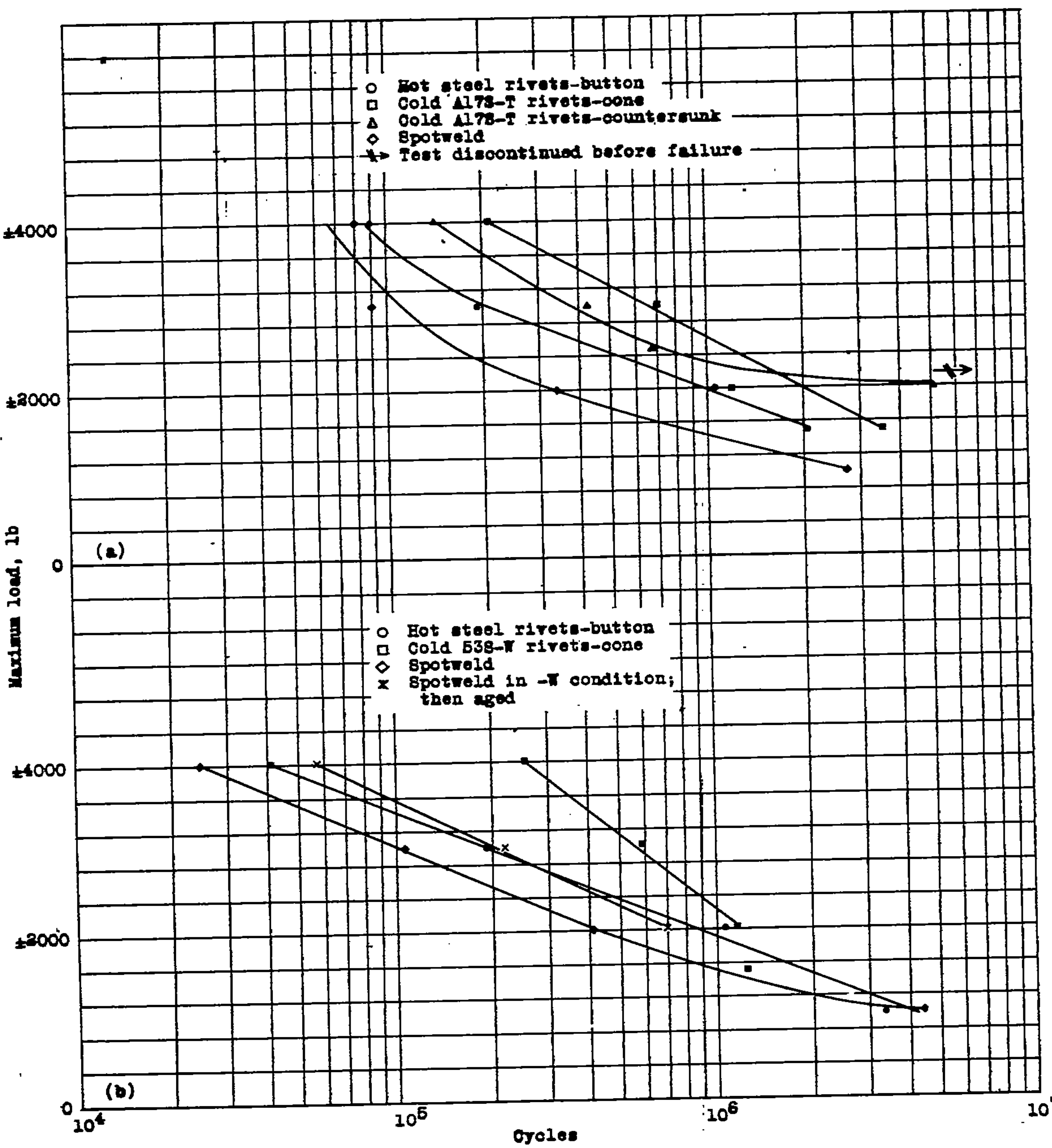


Figure 15. - Beam fatigue tests of spot welded girders made of 61S-T sheet 1/8 inch thick.




(a) 17S-T girders (b) 61S-T girders

Figure 16a,b.- Beam fatigue tests of spot-welded and riveted girders.

(a) Riveted; height of drop, 16 inches.
(b) Spot welded; height of drop, 14 inches.

Figure 17.- Girders after completion of impact test.

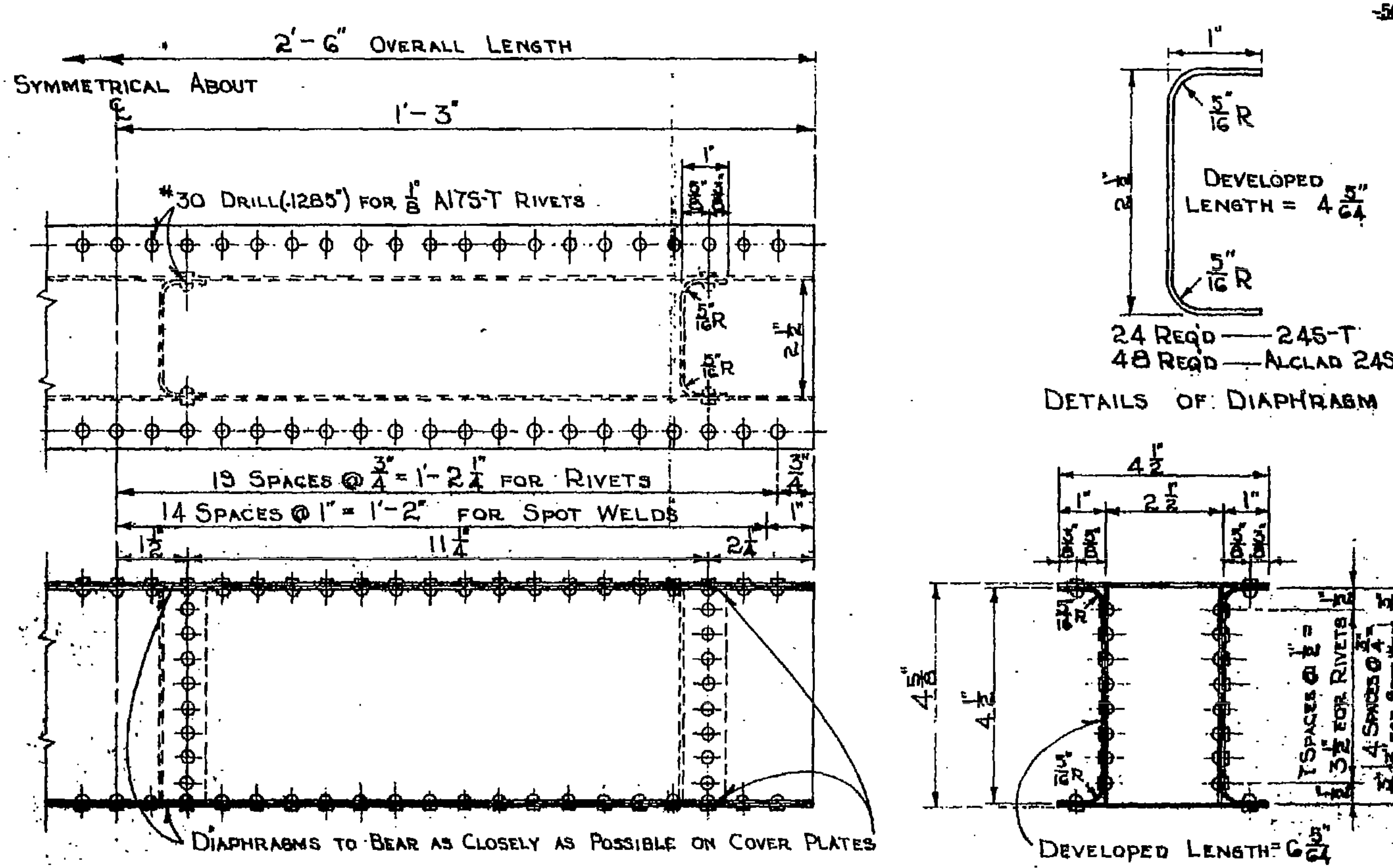



FIG. 19.- BUILT-UP BOX BEAM FOR COMPARATIVE STATIC AND FATIGUE TESTS OF PLAIN AND ALCLAD 24 S-T SHEET (FOR TEST UNDER CENTRAL LOADING)

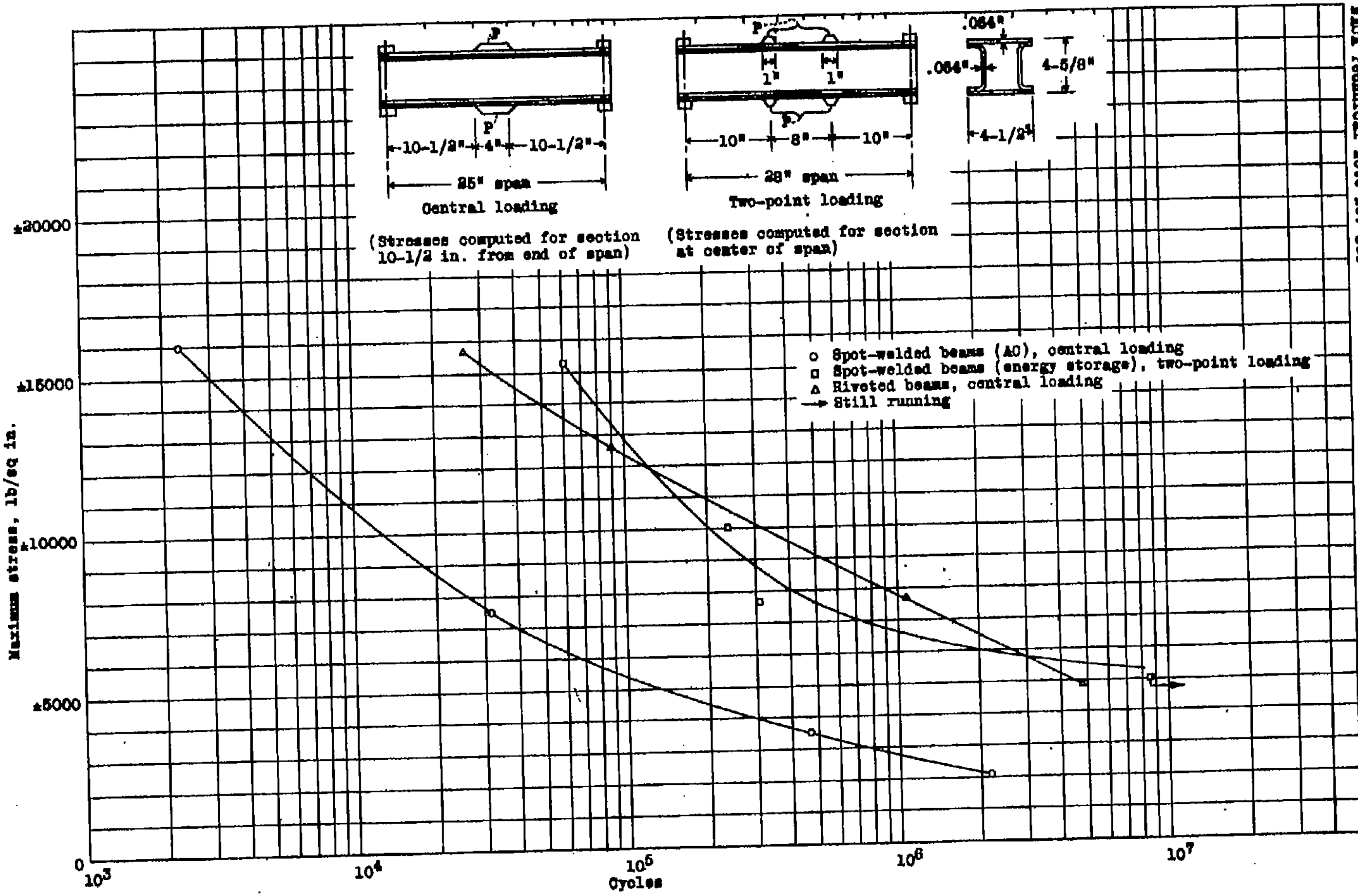
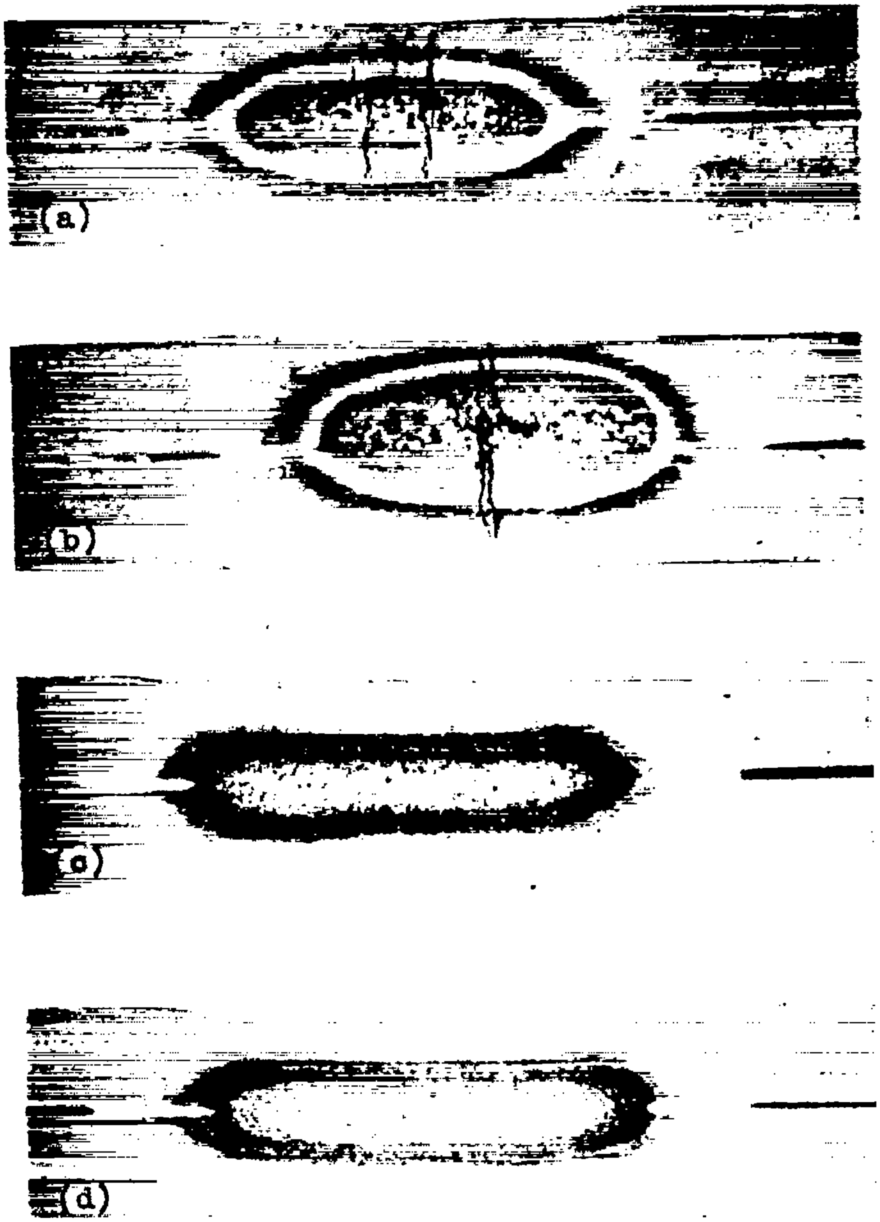



Figure 20.- Fatigue curves for Alclad 24S-T box beams. All tests made with complete reversal of stress.




(a) Alternating-current weld before test.
(b) Alternating-current weld after test.
(c) Energy-storage weld before test.
(d) Energy-storage weld after test.

Figure 21.- Sections through spot welds before and after fatigue tests. Magnification, 10 times.

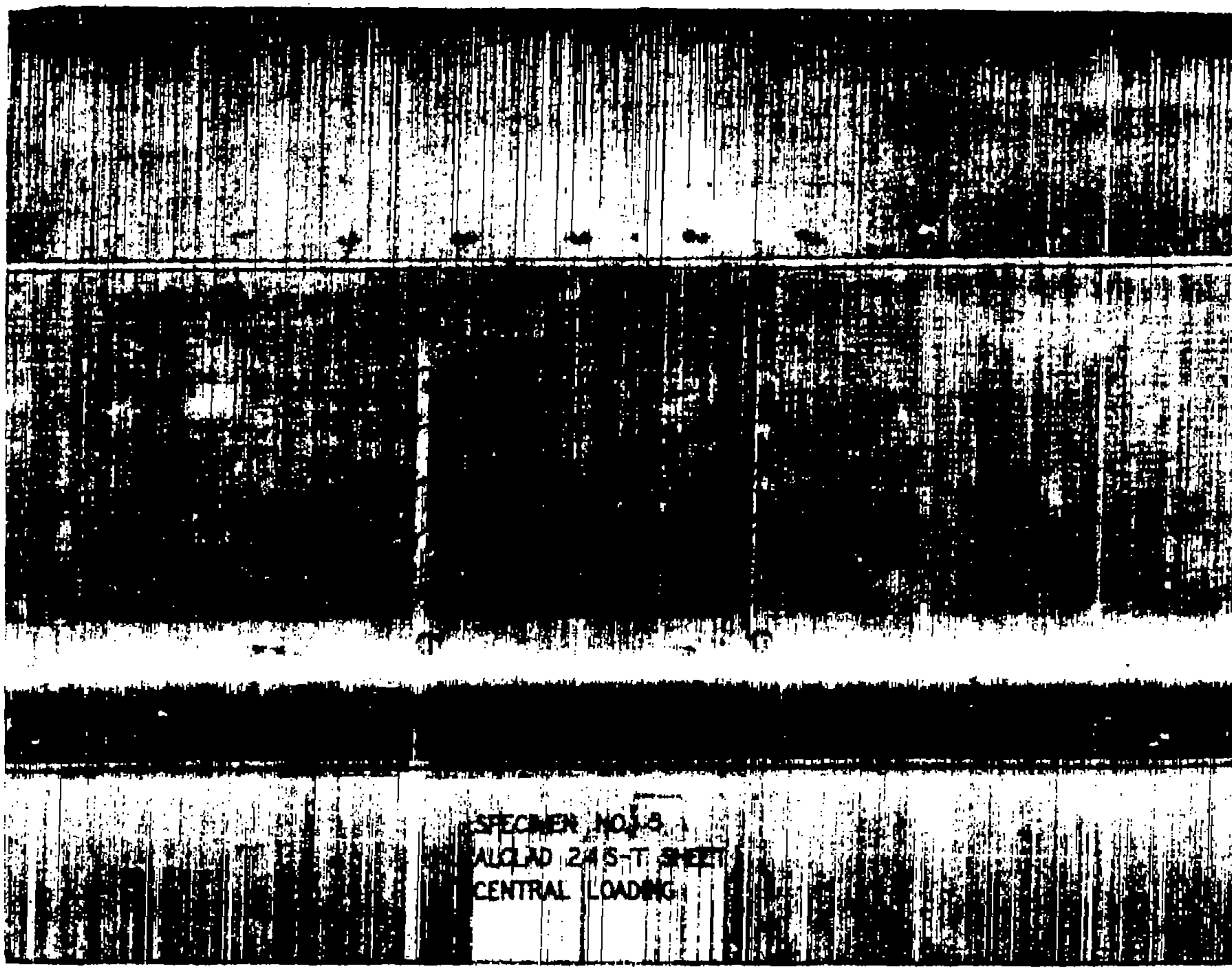



Figure 22. - Spot-weld fracture after failure in fatigue. Bending stress, ± 3460 pounds per square inch.

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OVER

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ABSTRACT:

Comparison is made of relative merits of spot-welded and riveted aluminum-alloy structural elements. Spot welds were tested for static shear strength, shear fatigue, and direct tension-compression fatigue. Spot-welded construction can be made to equal riveted construction in resistance to static and impact loadings. In resistance to fatigue, spot welds are inferior unless welds can be produced which are more sound and free from cracks than those examined.


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