NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2452

FLEXURAL FATIGUE STRENGTHS OF RIVETED BOX BEAMS - ALCLAD 14S-T6, ALCLAD 75S-T6, AND VARIOUS TEMPERS OF ALCLAD 24S

By I. D. Eaton and Marshall Holt
Aluminum Company of America

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SUMMARY

In order to gain new knowledge of the fatigue strength of built-up structures, flexural fatigue tests were made on riveted box beams of 14S-T6, 75S-T6, and various tempers of 24S alclad aluminum-alloy sheet.

Of the five alloy-temper combinations studied in riveted box-beam sections the flexural fatigue strengths were found to lie in a rather narrow band and no one combination was found to have higher strength values than all others for the entire range of fatigue life covered in these tests. This is in contrast with the results of a previous investigation where the moduli of failure and impact strengths vary about as the tensile strengths of the material.

Most of the specimens had more than one failure at completion of the tests; the most common failure involved rivet holes in the channel. The fatigue strengths of the box beams were found to exceed the net-section fatigue strengths of riveted lap joints having single rivets of the same diameter and sheet of the same thickness.

INTRODUCTION

For several years the Aluminum Research Laboratories of the Aluminum Company of America has been investigating the fatigue characteristics of riveted and spot-welded joints and structural components of particular interest to aircraft manufacturers. The results of several of these investigations have been presented in references 1 to 5.

The investigation described in this report was initiated in order to gain new knowledge of the fatigue strengths of built-up structures. It includes the results of flexural fatigue tests on riveted box beams of alclad sheet in three high-strength aluminum alloys. A comparison of similar beams fabricated by spot-welding and riveting of alclad 24S-T3 is given in reference 5 and an investigation of the static and impact strengths of beams fabricated of the same lots of sheet used in this study is described in reference 6.

The object of this investigation was to determine and compare the flexural fatigue strengths of built-up riveted box beams in alclad aluminum-alloy sheet of 14S-T6, 75S-T6, and various tempers of 24S.

This work was done by the Aluminum Company of America and has been made available to the NACA for publication because of its general interest.

MATERIALS

Alclad flat sheet, nominally 0.064 inch thick, of the following alloys and tempers was used to fabricate the specimens for this investigation: 14S-T6, 75S-T6, 24S-T3, 24S-T36, and 24S-T81. The mechanical properties of the sheet materials given in table I compare favorably with the typical mechanical properties for such materials listed in table 20 of reference 7. The rivets were supplied by the Edgewater, New Jersey, Works as 24S-T4 rivets. Based on the average of eight tests of separately riveted test specimens of the type illustrated in figure 1, the static shear strength of the rivets was 44,650 psi which compares favorably with the average value given in table 2 of reference 8.

SPECIMENS

All specimens were fabricated by the Jobbing Development Section, New Kensington Works of the Aluminum Company of America. The details of the specimen are illustrated in figure 2. It is simply a box beam made of two formed channels and two flat sheets, all nominally 0.064 inch thick, riveted together to form the box section. The 24S-T31 (after driving, 24S-T4 rivets are referred to as 24S-T31 rivets) rivets were all 1/8 inch in diameter. The over-all length of the specimen was 30 inches and the span length was 28 inches. There were two load points each 4 inches from the center of the specimen producing a constant bending moment over the center 8 inches of the specimen. The load brackets and supports were attached by bolting to spacers fitted within the box section so that the flanges were free of contacts with the loading device. There was clearance between the attachment bolts and the webs of the beams but a snug fit on a shear pin which extended through the web and into the spacer. It was thought that this arrangement maintained the shape of the cross section and minimized concentrations of stress at these points.

At least six specimens were fabricated from each of the alloys and tempers studied. Two sets of specimens of alclad 24S sheet were tested in the -T81 temper. One of these sets was fabricated from alclad 24S-T81 sheet; the other was fabricated from 24S-T3 sheet and aged to the -T81 temper after fabrication.

PROCEDURE

The fatigue tests were made in Unit No. 3 of the Aluminum Research Laboratories' Structural Fatigue Testing Machines shown in the background of figure 3 and described in reference 9. The test setup is illustrated in figure 4. Evident in this photograph is the generous use of flexure plates and reduced-section loading posts which act as fulcra to reduce the restraint at the loading and support fixtures.

Particular care was taken in installing the beams in the loading fixtures to avoid the introduction of initial stresses. Four Type A-12 SR-4 strain gages were installed on the cover plates of each specimen, two gages on each cover plate at the center of the span and 3/4 inch from each edge of the plate. Strain readings[1] were determined for these locations at various stages of the installation and the fixtures were shimmed as required to keep the prestress at a minimum. It developed that the maximum stress as measured at any one gage location, tension or compression, due to installation of the specimen in the fixtures was less than 4 percent of the maximum stress in the loading cycle. The average prestress measured for all specimens was found to be 170 psi or an average of less than 1 percent of the individual stress ranges.

The desired test conditions were obtained by (1) Adjustment of the crank displacement to obtain the desired variable load and (2) adjustment of the turnbuckle at the end of the loading beam to obtain the desired mean load, zero in the case of these tests since the loading was to be completely reversed. When the desired test conditions were obtained an additional set of strain-gage readings was obtained to determine the magnitude of the stress range at the strain-gage locations. The specimen was then subjected to the desired test conditions for a few cycles, the loading was checked and readjusted to the desired test conditions, if necessary, and the test continued with periodic checks to assure that the desired load conditions were maintained throughout the test. Further, the automatic cut-off switch, an integral part of the machine, was set so that a change in load range of less than 600 pounds would stop the machine. The tests were considered complete at the end of about 25 million cycles or when a failure was visible.

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[1]Readings made on Type K Baldwin-Southwark portable strain indicator.

RESULTS

The results of the fatigue tests of box-beam specimens are given in table II. The table lists the actual load range including the inertia effects mentioned in reference 9, the nominal calculated extreme fiber stress, the number of cycles to failure, and the location of failure. The nominal calculated extreme fiber stress was determined by applying the flexure formula (Mc/I) where M is computed from the load range and I/c represents the section modulus based on the nominal dimensions of the section in figure 2. Calculated maximum stresses based on the extremes of the measured specimen dimensions deviated from the stresses listed by less than 3 percent, a variation which is considered satisfactorily small. Further, the measured stresses at the center of the span, determined by the strain-gage readings, were found to deviate from the nominal calculated stresses by less than 5 percent with an average deviation of 2.5 percent for stresses below ±20,000 psi. Above this stress the deviation was sometimes considerably larger because of buckling in the cover plates. In general, it can be said that the nominal calculated stress appears to be slightly lower than the measured stress although for several specimens the measured stress was lower than the calculated stress.

The results have been plotted as S-N curves in figures 5(a) to 5(d). The results for all the specimens tested are plotted in figure 5(a) and define a rather narrow band within which all the test results lie. In figures 5(b), 5(c), and 5(d) an effort has been made to draw curves representing the average flexural fatigue strengths of the box beams for each alloy-temper combination tested. In some cases, particularly of alclad 14S-T6 and alclad 75S-T6 box beams, the data points define a single curve very closely, whereas the data points from the 24S-T81 box beams show considerable scatter from any reasonably smooth curve. This is probably due to unintentional differences in the specimens. The scatter encountered in rotating-beam tests on the high-strength aluminum alloys is discussed in reference 10 and appears to be much greater than that shown in figure 5(a).

The test results for the alclad 24S-T81 specimens plotted in figure 5(d) indicate that there is very little difference, if any, in the fatigue strengths of such specimens fabricated from aged sheet or aged after fabrication. In fact, the average fatigue strengths for the two fabrication procedures have been represented by a single curve.

The average S-N curves for the various alloy-temper combinations tested have been replotted in figure 5(e) and summarized in table III. It is evident that no one of these combinations has an advantage in fatigue strength over all the other materials for the entire range of cycles to failure studied. This is in agreement with conclusion 5 of reference 10. From the data presented here it appears that the flexural fatigue strength of the alclad 24S-T81 specimens is generally lower than that of any of the other alloy-temper combinations tested. However, referring to figure 5(a), one finds that the fatigue lives of some alclad 24S-T81 specimens, both in aged-sheet and post-aged specimens, equal or exceed the fatigue life of at least one individual specimen of each of the other alloy-temper combinations.

The test results given in reference 6 indicate that both the modulus of failure in the static test and the resistance to impact vary about as the tensile strengths of the various alloys and tempers tested. This is in contrast with the results of these fatigue tests where it appears that fatigue strength and tensile strength are unrelated.

Fatigue-test results of single $\frac{1}{8}$-inch-diameter rivets in aluminum-alloy lap joints have been published in reference 2. When these test results are transposed to P/A stresses on the net section of the sheet, the curves are found to lie considerably below the band of Mc/I stresses for the box beams. For example, at 10^6 cycles the fatigue strength of the lap joint is about one-third that of the box beams.

The location of failures in each specimen has been given in table II. The failures have been located with reference to the rivet numbers shown in figure 2. It should be noted that the majority of the specimens had more than one failure. Of the 79 failures observed in 34 specimens, 69 went through one or more rivet holes, 5 failures were in the sheet between rivet holes, 2 failures were confined to the fillet of the formed channel, 1 failure started at a loading hole, and 2 were rivet failures. Of the 34 specimens tested to failure, 20 specimens had failures in the cover plates and in the channels, and 14 specimens had failures in the channels only.

Typical failures are illustrated in figures 6(a) through 6(e). The general location of the failures can be seen in figure 6(a) through 6(c). Figures 6(d) and 6(e) are close-ups of the individual fractures in the beams illustrated in figures 6(a) and 6(b), respectively. Although the fixtures were designed to reduce the effects of stress concentration at the load points, it can be seen that some failures involved one or more of these holes. Of the 64 channel failures observed, 29 involved the loading holes; however, many of the 35 remaining channel failures had not reached a loading hole at the completion of the test.

Five specimens were sectioned in order to observe the origin of the fatigue fractures. Twelve separate failures were observed; nine failures progressed to include loading holes, eight went through rivet holes in the channels, three went between rivets in the channels, and two were cover-plate failures. Each of the nine failures which involved loading holes originated at a rivet hole or in the fillet of the channel. The three failures which went between rivets and one of the eight failures which went through a rivet hole originated in the fillet. Both cover-plate failures and five of the six channel failures which went through rivet holes started at the rivet hole. In view of the large number of failures, several in one specimen in many cases, it is difficult to determine which section of the specimen has the most critical stress condition. The evidence indicates, however, that the fillet and rivet holes in the channel are more vulnerable than other portions of the specimen.

As has been pointed out the fractures in the specimens were not confined to the region of maximum computed stress and none of the specimens had failures confined to the cover plates. Fourteen specimens apparently had no cover-plate failures. In general, the failures occurred slightly outside the region of maximum bending moment. This casts some doubt on the value of using the nominal computed maximum stress as the variable in the interpretation of the results; however, since all specimens were loaded in the same manner, comparisons based entirely on these data are unaffected by the use of stress rather than load. Comparisons with data from other types of specimens will be facilitated by this choice of variable.

SUMMARY OF RESULTS

From the foregoing data and discussion of flexural fatigue tests on riveted box beams of 14S-T6, 75S-T6, and various tempers of 24S aluminum-alloy alclad sheet, the following statements seem warranted:

1. The mechanical properties of the materials used in this investigation compare favorably with typical published values.

2. Of the five alloy-temper combinations studied in riveted box-beam sections, no one combination has higher flexural fatigue strength than all others for the entire range of fatigue life covered in these tests. This is in contrast with the results of a previous investigation where the moduli of failure and impact strengths vary about as the tensile strengths of the material.

3. The flexural fatigue results of riveted box beams of all the alloys studied lie in a rather narrow band. For example, the fatigue strengths at 10^6 cycles range between 6000 and 9000 psi while at 10^7 cycles they range between 4000 and 7000 psi.

4. Most of the specimens had more than one failure at completion of the tests; the most common failure involved rivet holes in the channel.

5. The fatigue strengths of the box beams exceed the net-section fatigue strengths of riveted lap joints having single rivets of the same diameter and sheet of the same thickness.

Aluminum Research Laboratories
Aluminum Company of America
New Kensington, Pa., November 24, 1950

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10. Templin, R. L., Howell, F. M., and Hartmann, E. C.: Effect of Grain Direction on Fatigue Properties of Aluminum Alloys. Product Engineering, vol. 21, no. 7, July 1950, pp. 126-130.

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TABLE I

MECHANICAL PROPERTIES[1] OF MATERIALS USED IN

FABRICATION OF BOX BEAMS

[All material, 0.064-in. sheet]

Alloy and temper	Tensile strength (psi)	Yield strength (psi) (2)	Elongation in 2 in. (percent)
Alclad 14S-T6	70,700	64,500	10.1
Alclad 24S-T3	69,700	54,900	19.8
Alclad 24S-T36	71,900	61,950	15.1
Alclad 24S-T81	68,700	61,100	7.0
Alclad 75S-T6	80,500	72,000	12.7

[1]Standard tension test specimens for sheet metals were used. (See fig. 2 of reference 11.)

[2]Stress at offset of 0.2 percent. Templin autographic extensometer (500X).

TABLE II

RESULTS OF FLEXURAL FATIGUE TESTS ON RIVETED BOX BEAMS OF ALCLAD 14S-T6,

ALCLAD 75S-T6, AND VARIOUS TEMPERS OF ALCLAD 24S

$\left[\text{Nominal stress ratio: } \frac{\text{Minimum stress}}{\text{Maximum stress}} = -1\right]$

Specimen designation	Actual load cycle (lb) Minimum	Actual load cycle (lb) Maximum	Load range (lb)	Calculated nominal maximum stress range (psi) (1)	Number of cycles to failure	Location of failure (2) Channel	Location of failure (2) Cover plate	Location of failure (2) Miscellaneous
Alclad 14S-T6								
80557-3	-10,190	9,950	20,140	±23,300	22,200	1,3		Rivets 4 and 5
-2	-6,450	6,450	12,900	±14,900	100,700	2		
-4	-4,400	4,360	8,760	±10,120	371,800	1,2		
-5	-3,200	3,100	6,300	±7,290	866,300	1,2	3	
-6	-2,240	2,360	4,600	±5,320	2,299,100	3,4,7	3	
-7	-2,050	1,940	3,990	±4,620	33,501,300	No failure, removed		
-1	-1,740	1,650	3,390	±3,920	39,604,400	No failure, removed		
Alclad 75S-T6								
75981-4	-10,390	10,260	20,650	±23,900	18,300	1		Rivets 2,3,4,5
-1	-7,700	7,700	15,400	±17,800	65,300	1, 0-1	1,2	
-5	-7,320	7,090	14,410	±16,690	81,300	1, 0-1	2	
-2	-5,650	5,620	11,270	±13,050	203,800	3, 0-1	0,4	
-3	-4,140	4,130	8,270	±9,570	388,000	2,4,2	3	
-7	-3,520	3,410	6,930	±8,020	1,473,900	1,5		
-6	-2,900	2,825	5,725	±6,630	59,568,200	No failure, removed		
Alclad 24S-T3								
75979-5	-9,590	9,590	19,180	±22,200	37,500	1		
-3	-8,420	8,490	16,910	±19,550	43,700	1		
-7	-6,180	6,240	12,420	±14,380	281,400	3 at 0-1 2 at 1, 2 at 0	2 at 1	
-1	-4,340	4,340	8,680	±10,050	503,000	3	4	
-2	-3,040	3,080	6,120	±7,080	3,871,800	5		
-4	-2,480	2,460	4,940	±5,710	13,381,900	2		
Alclad 24S-T36								
75980-2	-11,920	11,840	23,760	±27,450	23,000	1,0	1	
-3	-8,550	8,550	17,100	±19,800	94,800	0-1, 1		
-6	-6,030	6,210	12,240	±14,150	280,900	0-1, 2	3	
-7	-4,530	4,440	8,970	±10,400	327,600	1		
-4	-3,180	3,270	6,450	±7,460	1,995,000	3		
-1	-2,690	2,600	5,290	±6,120	2,433,200	2,3		
-5	-2,420	2,360	4,780	±5,530	27,807,100	No failure, removed		
Alclad 24S-T81 (aged sheet)								
75988-5	-12,900	12,800	25,700	±29,750	2,600	1		Bolt hole
-7	-8,550	8,400	16,950	±19,600	57,400	1	2	
-3	-6,200	6,180	12,380	±14,300	150,500	0,1	2	
-6	-3,930	3,930	7,860	±8,980	320,000	1	2	
-2	-2,210	2,180	4,390	±5,080	6,033,500	6,7	7	
-4	-1,510	1,490	3,000	±3,470	28,960,100	No failure, removed		
Alclad 24S-T81 (aged after fabrication)								
75979-13	-10,640	10,620	21,260	±24,600	18,700	1	2	
-12	-8,500	8,500	17,000	±19,660	19,900	1	2	
-8	-6,060	6,050	12,100	±14,000	149,100	1,2	3	
-11	-3,980	3,930	7,910	±9,150	427,200	1	2	
-10	-2,380	2,280	4,660	±5,390	1,743,600	1,2	2	
-14	-1,900	1,820	3,720	±4,300	7,465,500	3	3	

[1]Calculated nominal maximum stress range based on actual load range, nominal specimen dimensions of figure 2, and Mc/I at mid-section of specimen. $S_{max} = \pm 1.157 \times$ load range.

[2]Failures are located by reference to rivet numbers shown in figure 2. Dash indicates failure between two indicated rivet locations (0-1 failure in sheet between locations 0 and 1).

TABLE III

SUMMARY OF FLEXURAL FATIGUE TEST RESULTS ON RIVETED BEAMS OF ALCLAD 14S-T6, ALCLAD 75S-T6, AND VARIOUS TEMPERS OF ALCLAD 24S

$$\left[\text{Nominal stress ratio: } \frac{\text{Minimum stress}}{\text{Maximum stress}} = -1\right]$$

Alloy and temper	Flexural fatigue strength (psi) at -			
	3×10^4 cycles	10^5 cycles	10^6 cycles	10^7 cycles
Alclad 14S-T6	±21,200	±15,500	±6,800	±4,700
Alclad 24S-T3	±22,300	±17,400	±8,800	±6,000
Alclad 24S-T36	±25,000	±18,500	±8,000	±5,750
Alclad 24S-T81	±20,000	±14,800	±6,800	±4,600
Alclad 75S-T6	±21,500	±16,400	±8,000	±7,000

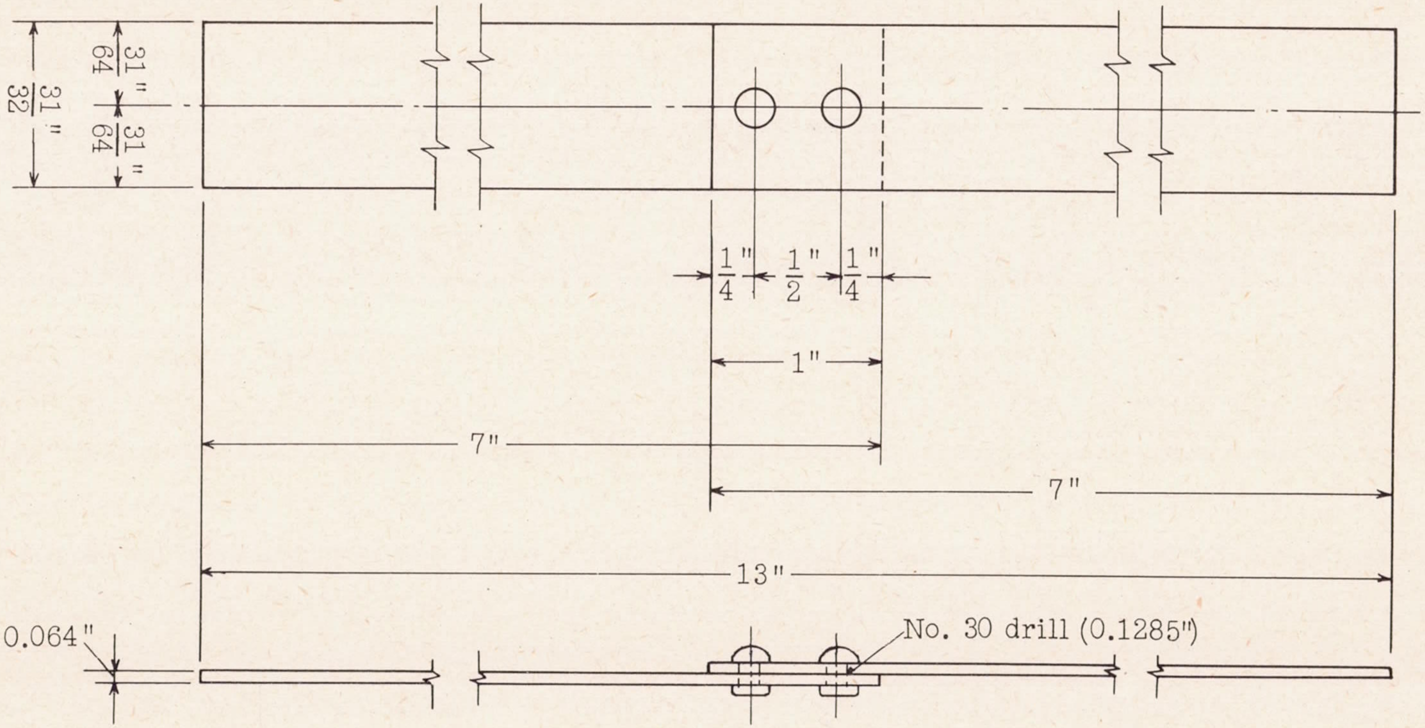


Figure 1.- Shear specimen for $\frac{1}{8}$ - inch rivets.

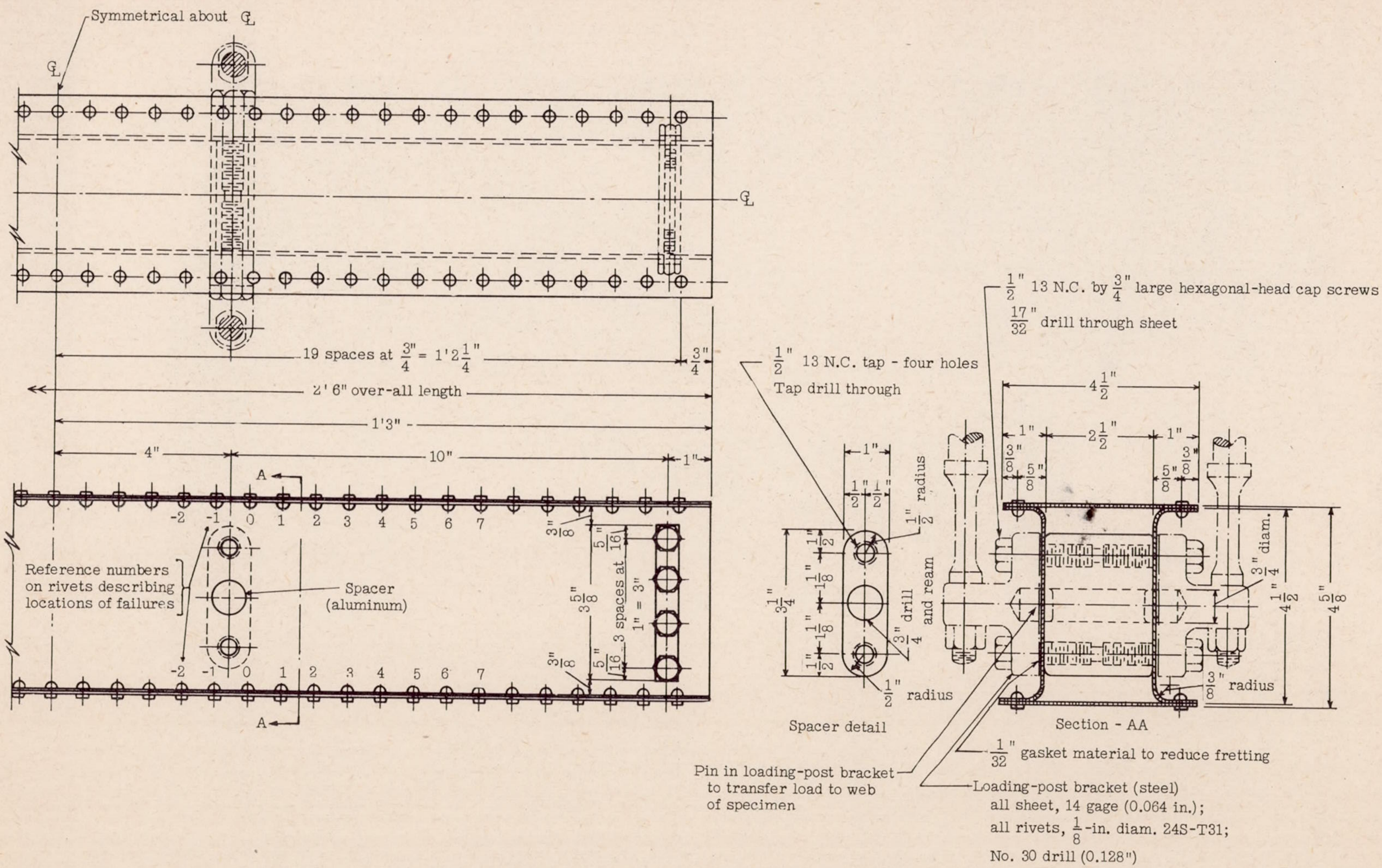


Figure 2.- Details of specimen.

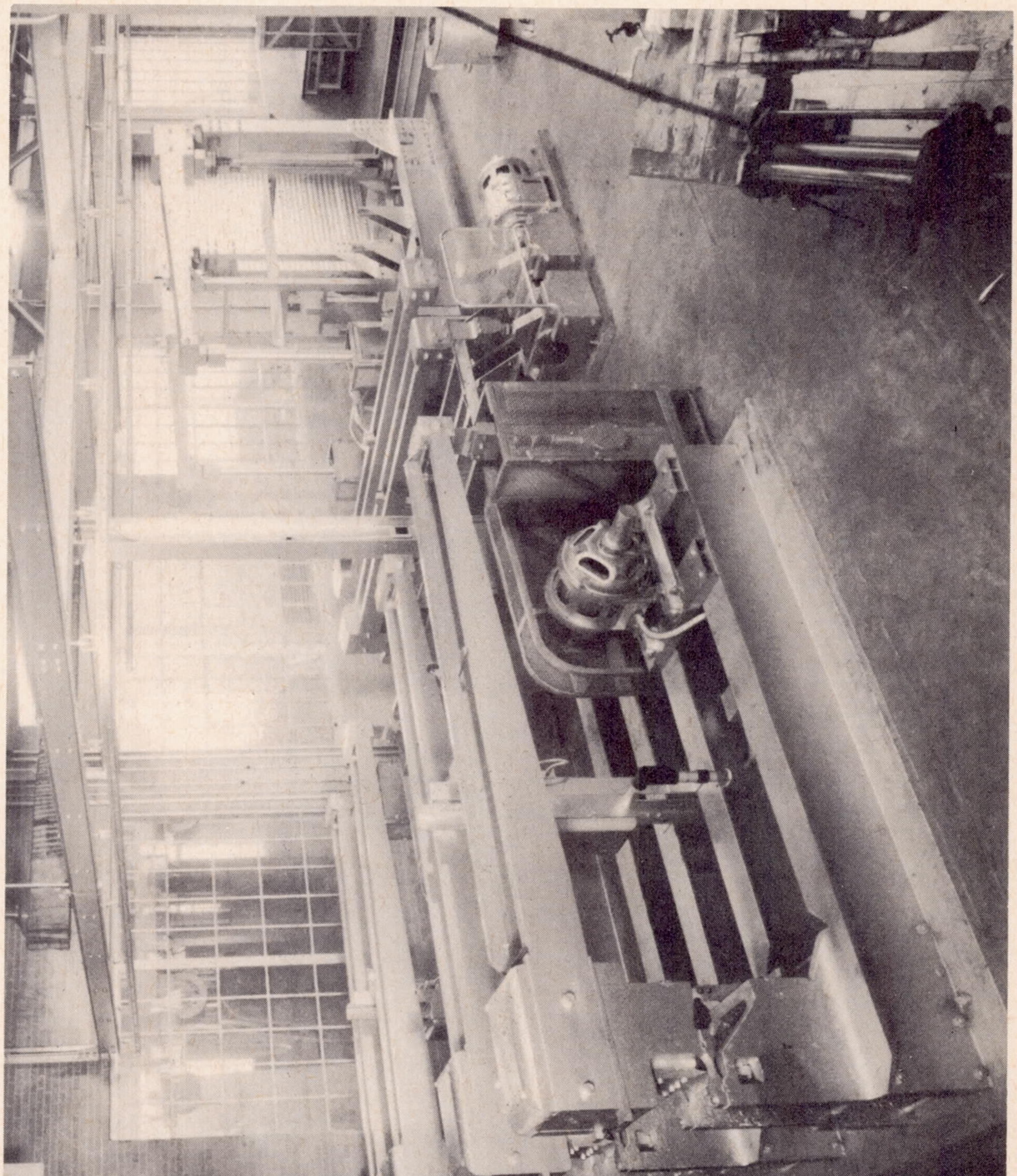


Figure 3.- Fatigue machines for testing structural units.

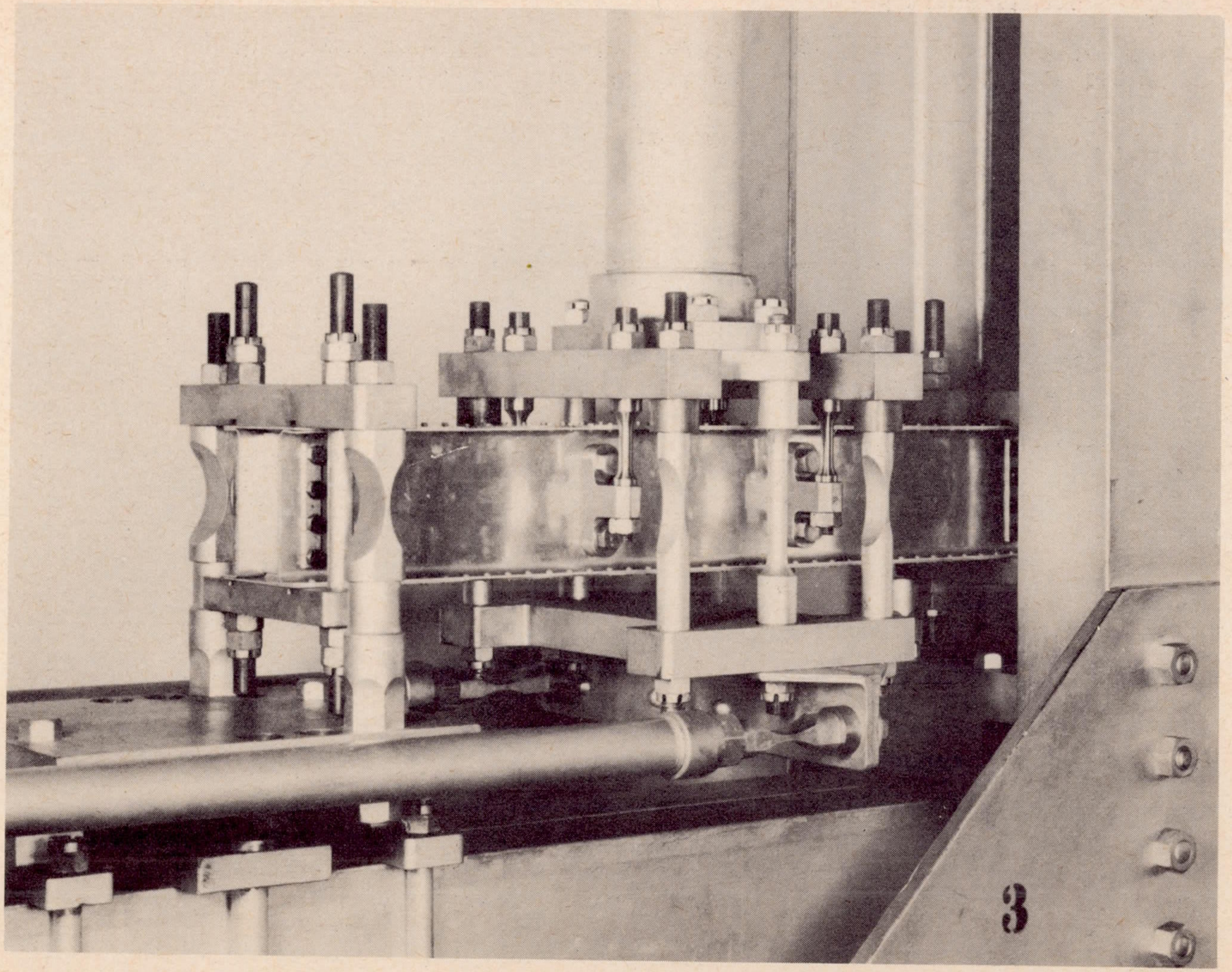
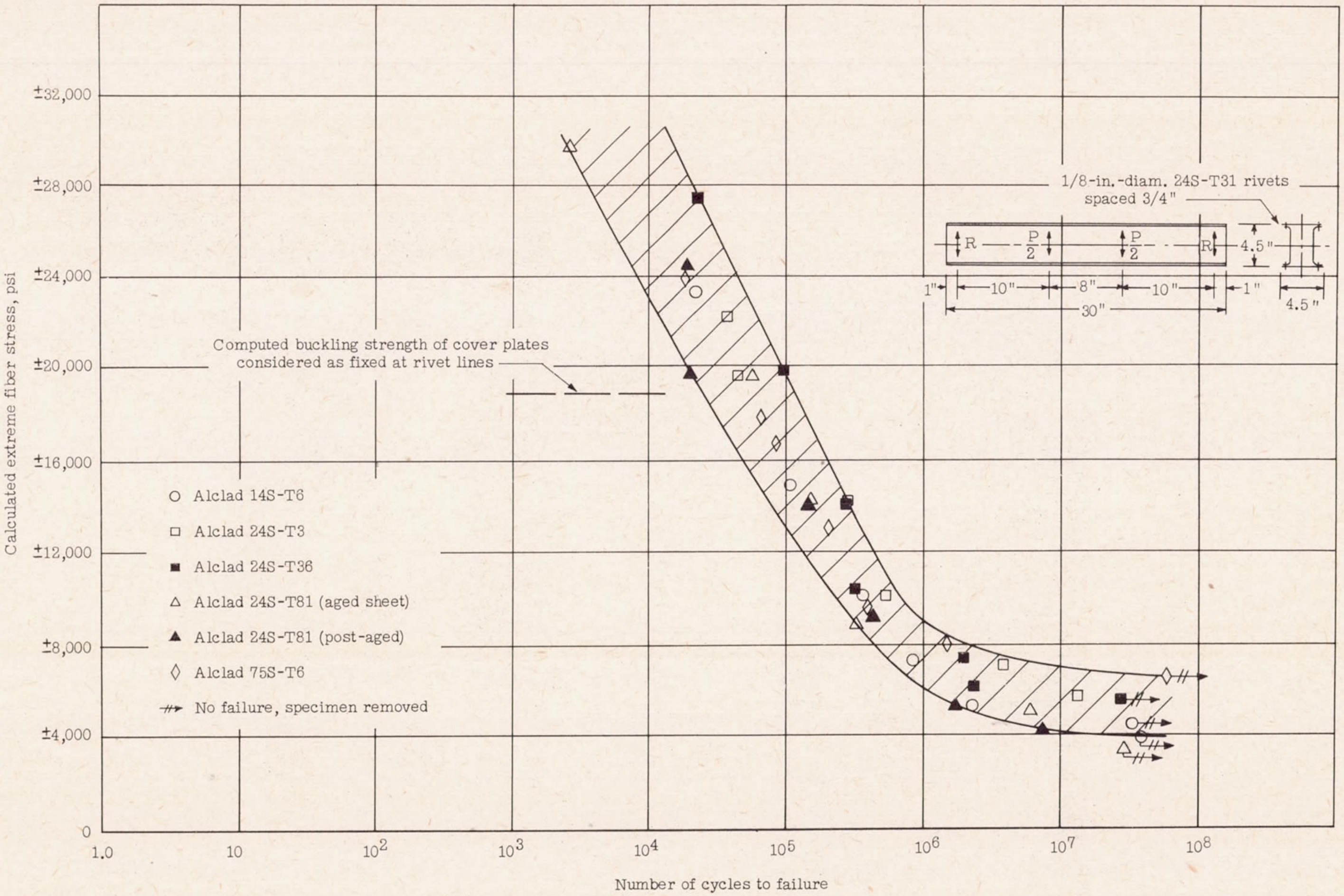
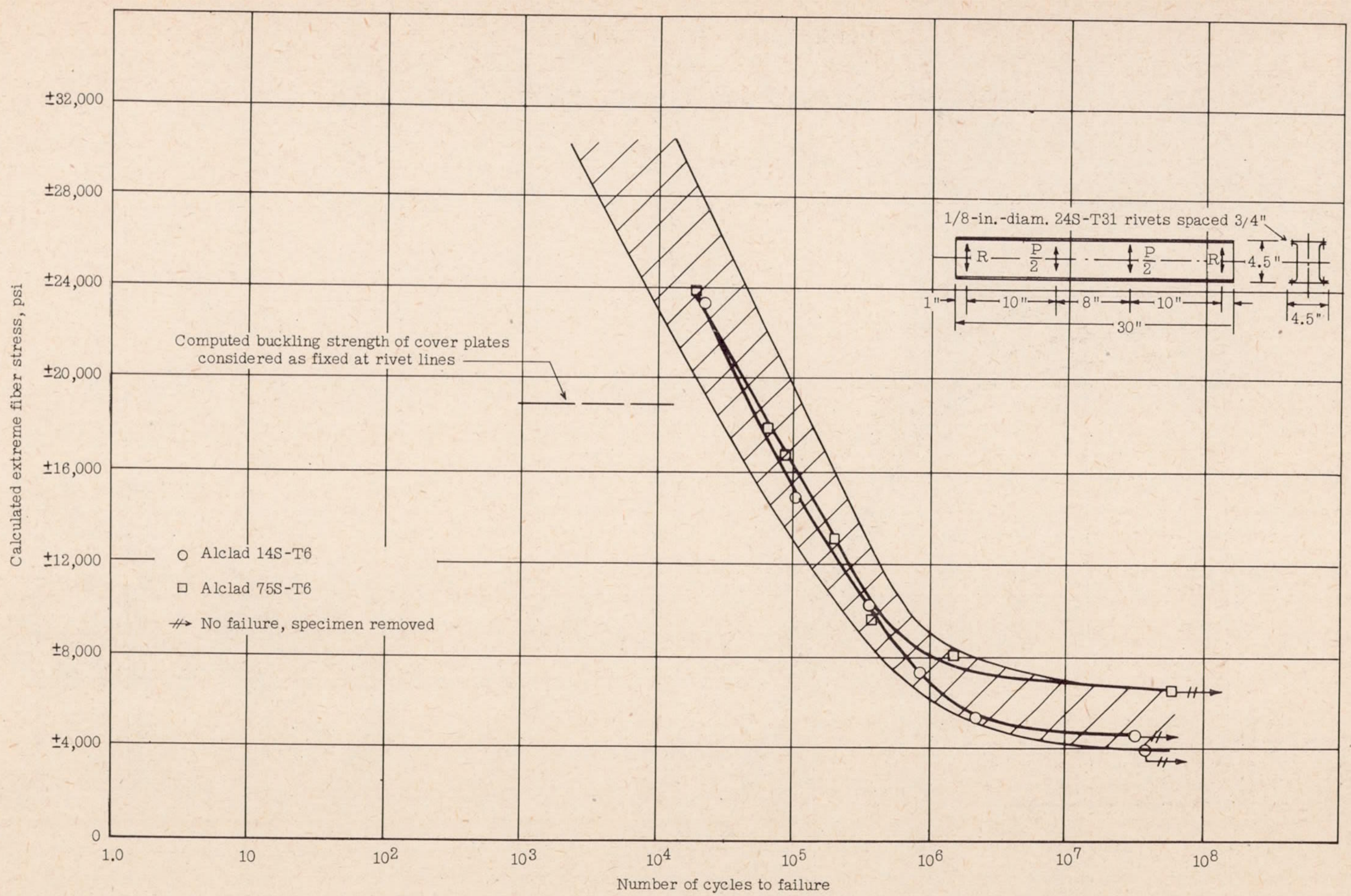


Figure 4.- Fatigue test setup for flexural fatigue tests of riveted box beams.



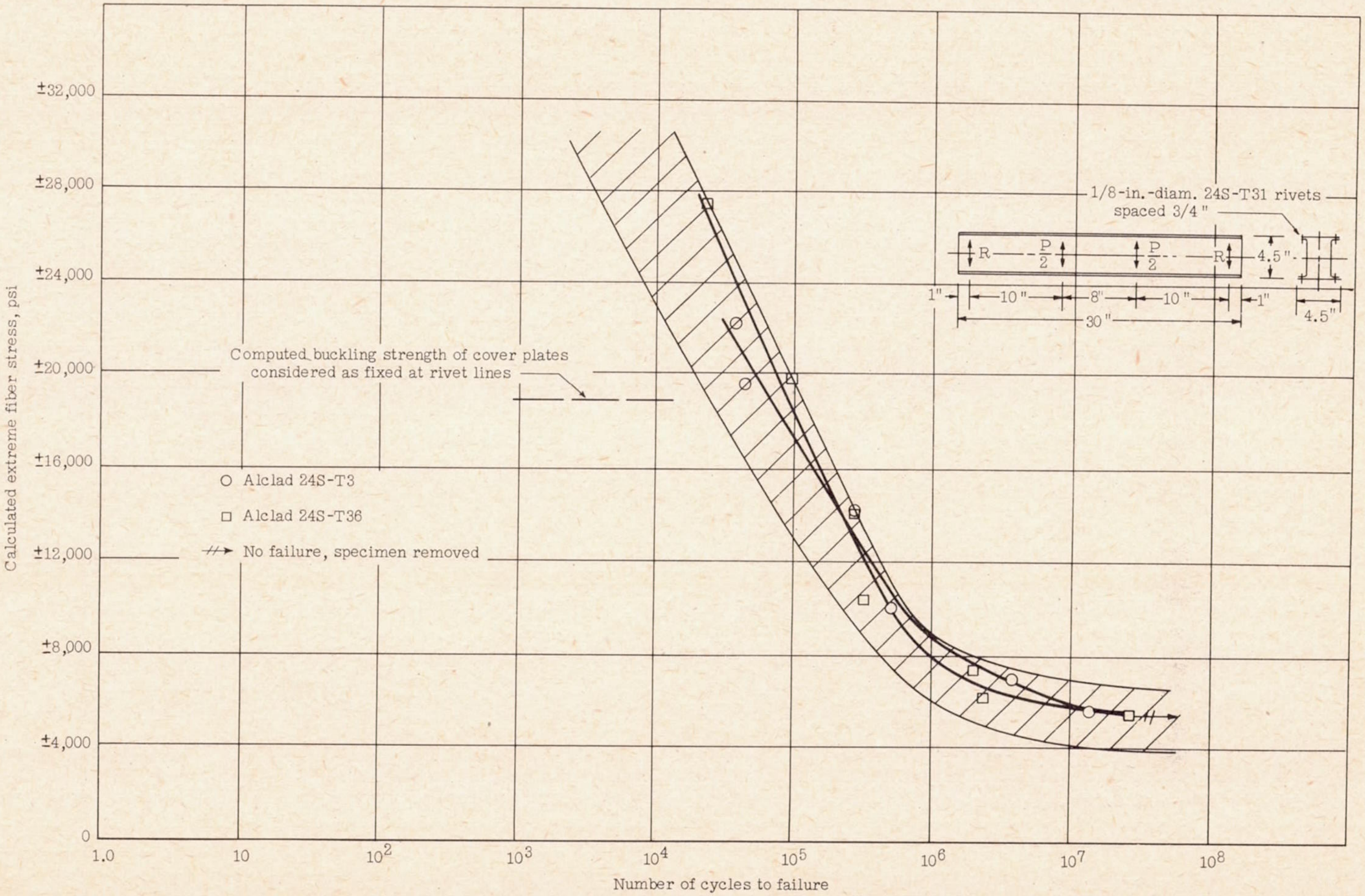
(a) All specimens tested.

Figure 5.- Results of flexural fatigue tests on riveted box beams. Specimens made of 0.064-inch alclad sheet. All tests made with complete reversal of stress $\left(\text{stress ratio: } \frac{\text{Minimum stress}}{\text{Maximum stress}} = -1\right)$.



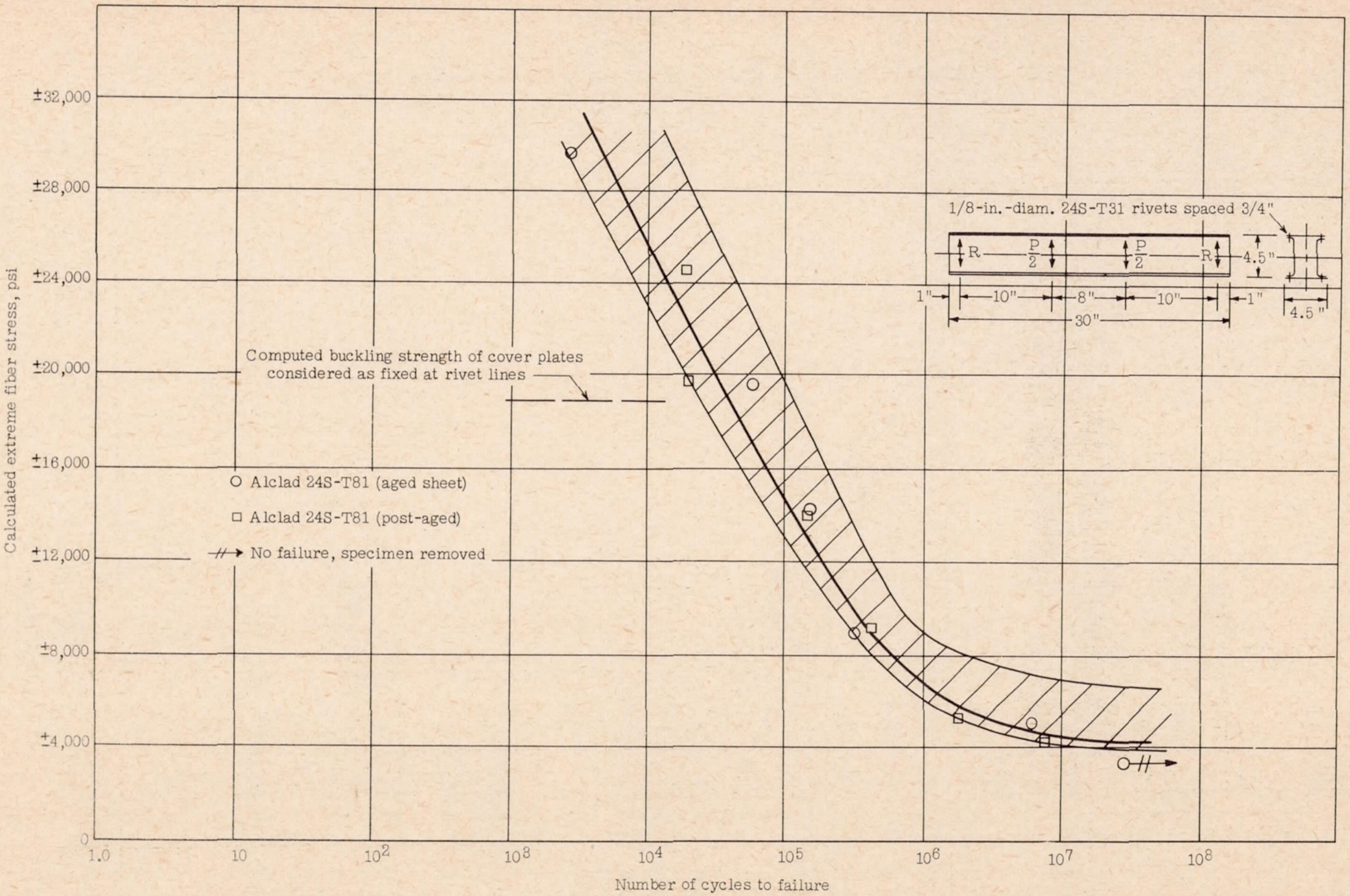
(b) Alclad 14S-T6 and 75S-T6 specimens.

Figure 5.- Continued.



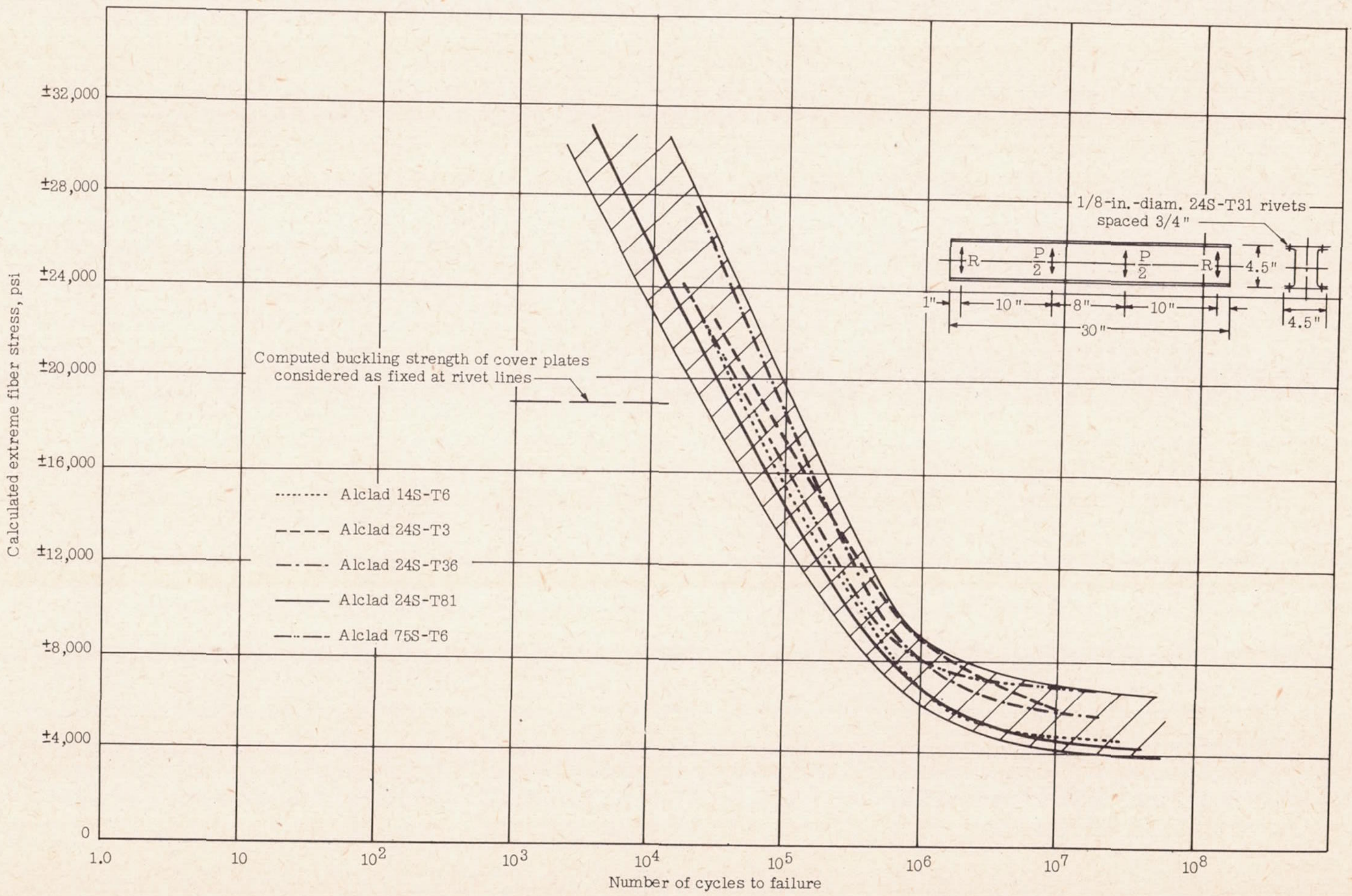
(c) Alclad 24S-T3 and 24S-T36 specimens.

Figure 5.- Continued.



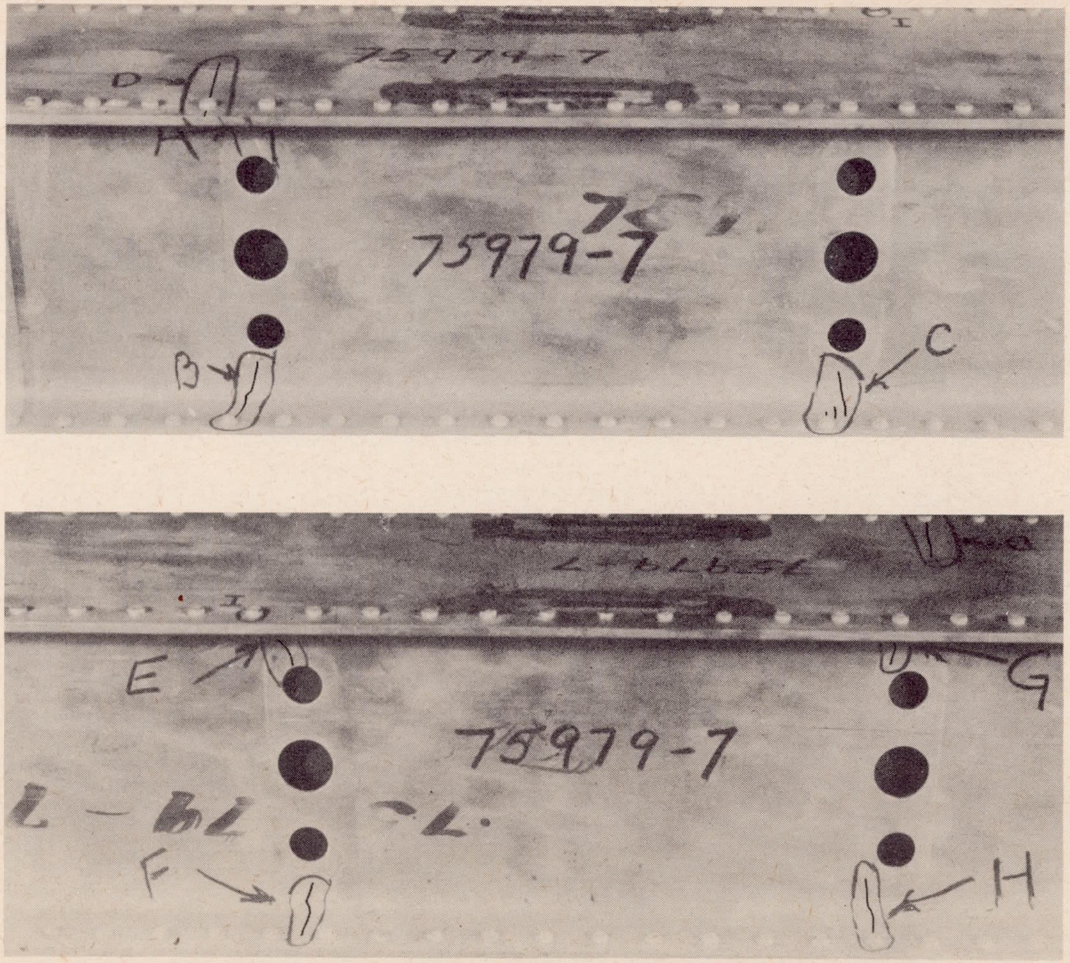
(d) Alclad 24S-T81 specimens.

Figure 5.- Continued.



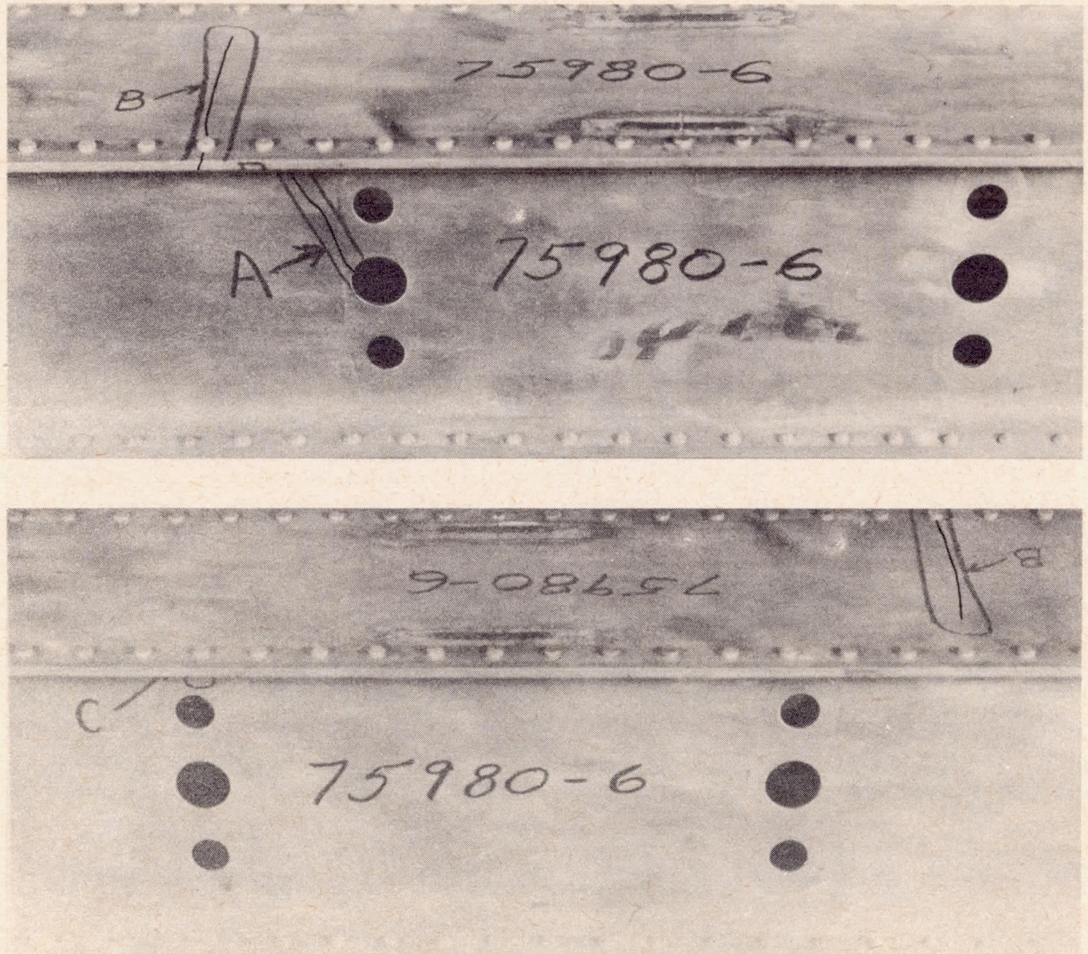
(e) Average curves for various combinations tested.

Figure 5.- Concluded.



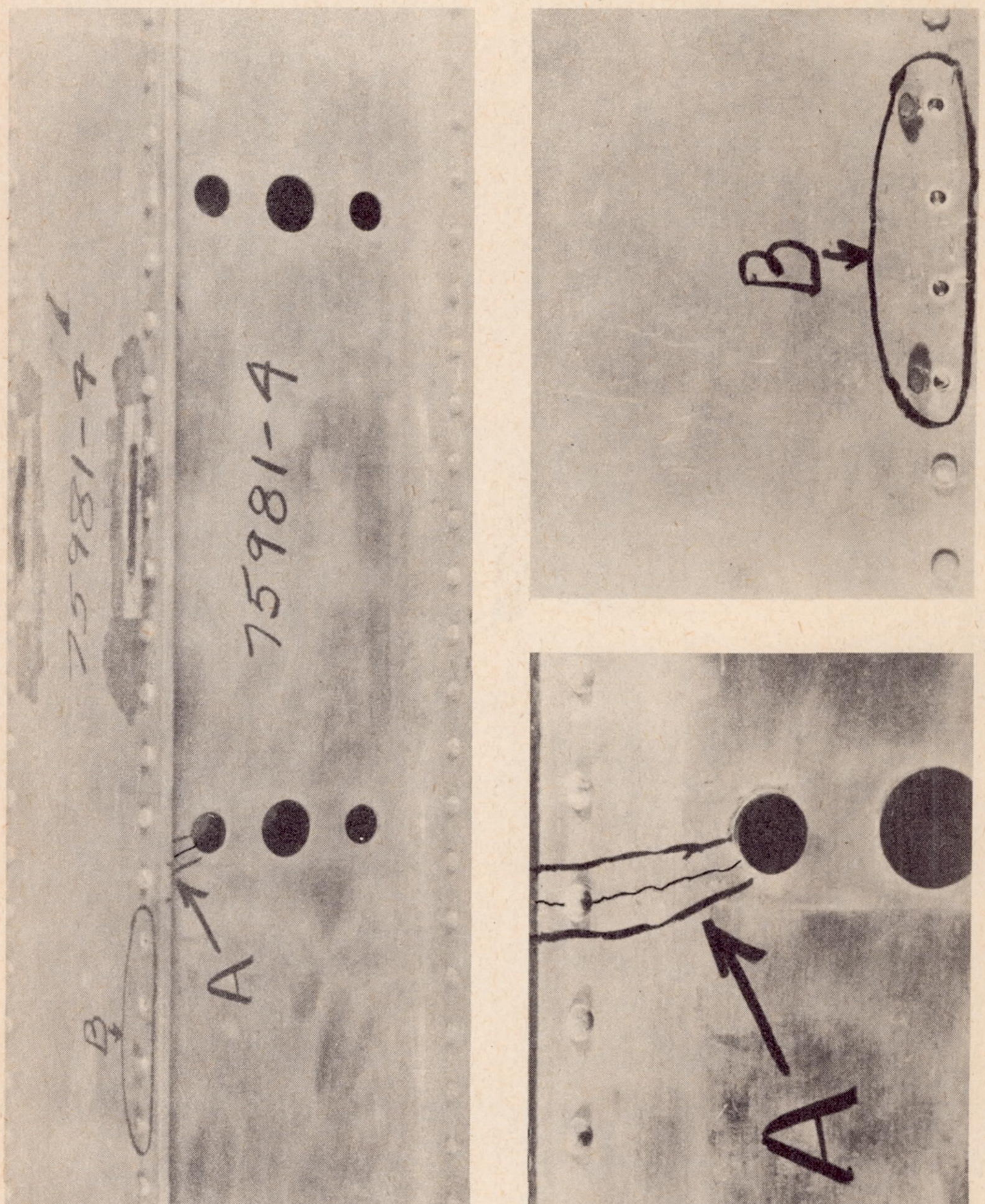
(a) Specimen 75979-7. For close-ups of individual failures see figure 6(d).

Figure 6.- Typical fatigue failures.



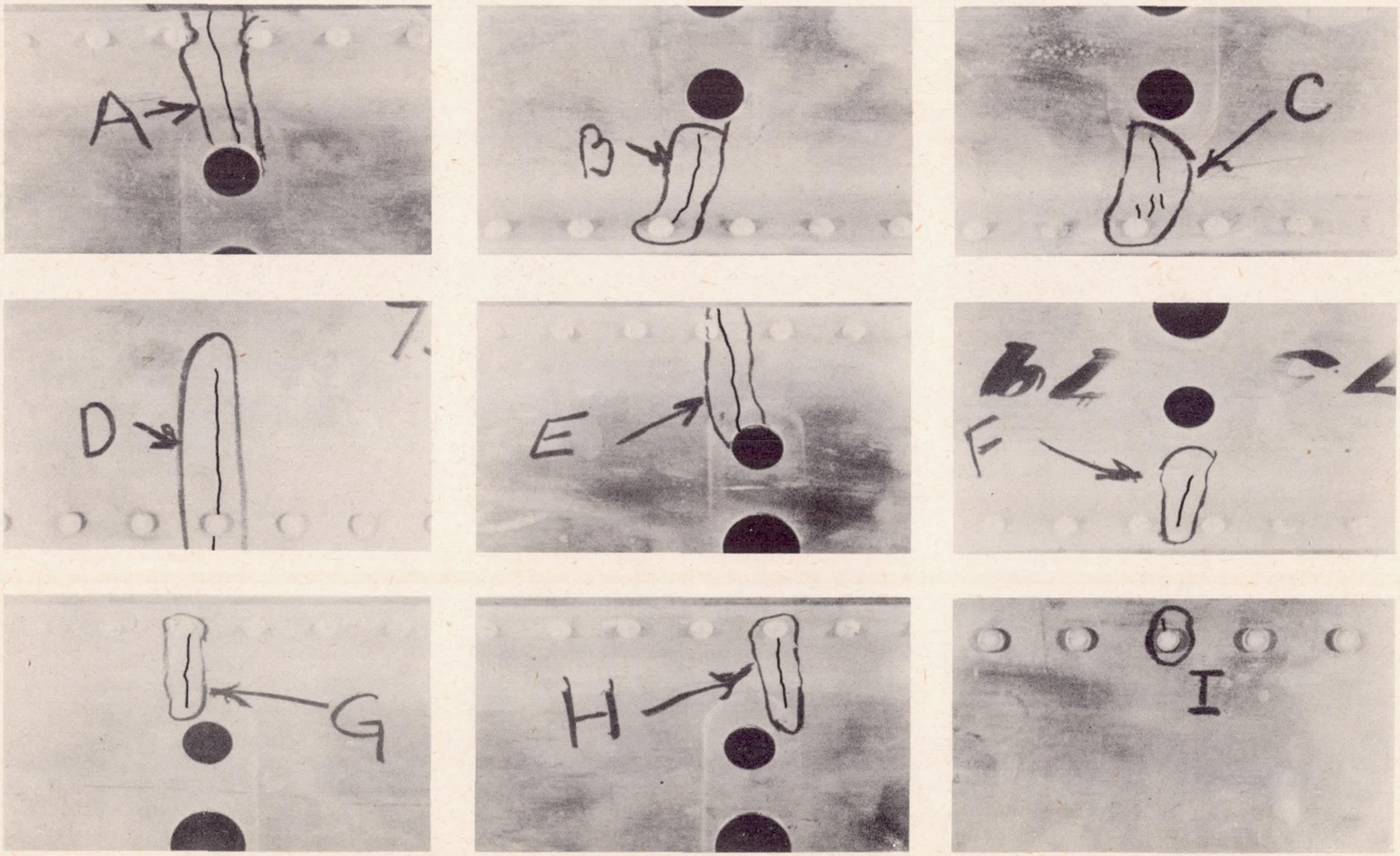
(b) Specimen 75980-6. For close-ups of individual fractures see figure 6(e).

Figure 6.- Continued.



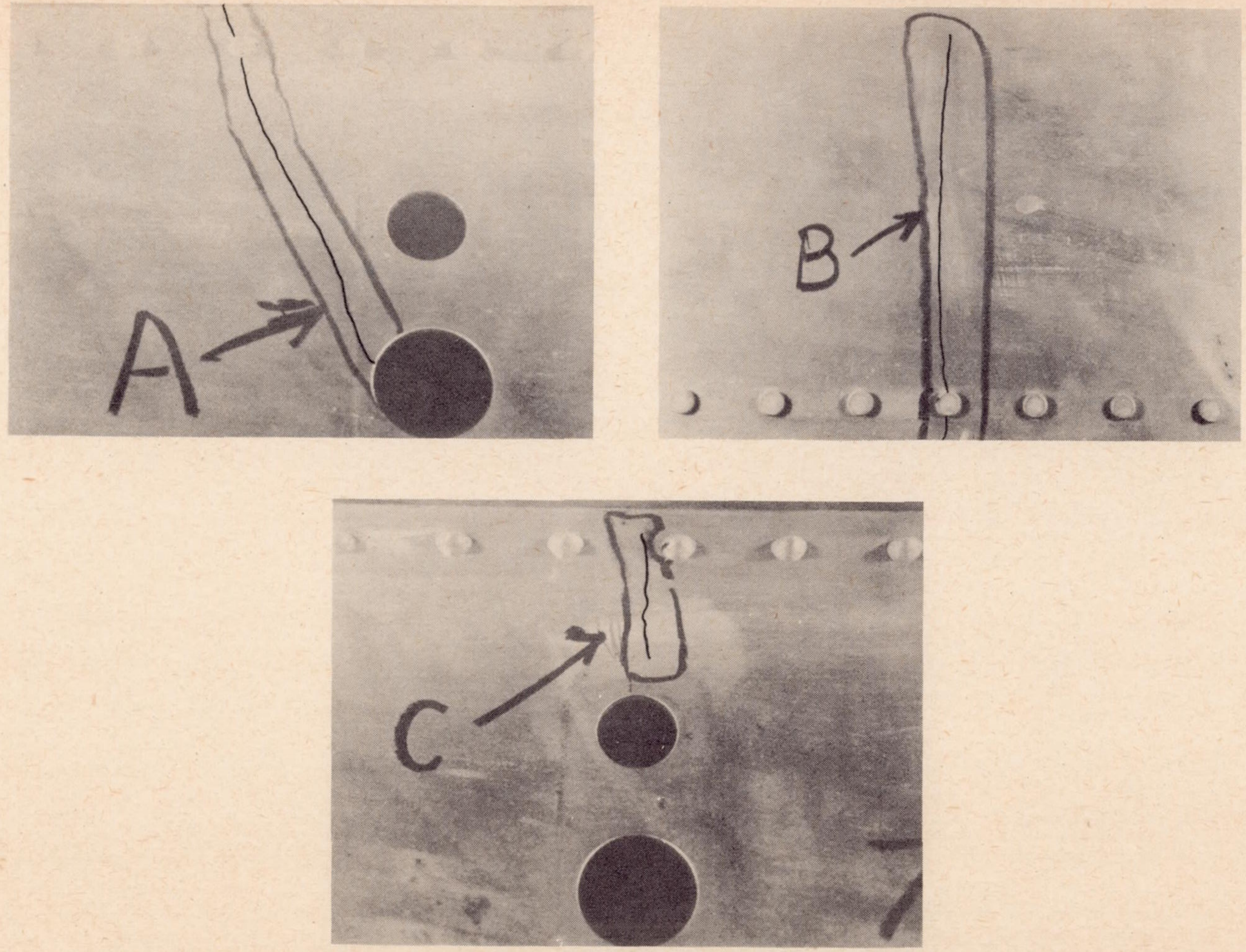
(c) Specimen 75981-4.

Figure 6.- Continued.



(d) Close-ups of fractures in specimen 75979-7.
For general location see figure 6(a).

Figure 6.- Continued.



(e) Close-ups of fractures in specimen 75980-6.
For general location see figure 6(b).

Figure 6.- Concluded.

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