C.P. No. 371
(18,726)
A.R.C. Technical Report

C.P. No. 371
(18,726)
A.R.C. Technical Report

MINISTRY OF SUPPLY

AERONAUTICAL RESEARCH COUNCIL
CURRENT PAPERS

Experimental Correlation between the Endurance of a Wing Spar Joint and the Ratio between 0.1 per cent Proof and Ultimate Tensile Strengths of the Material

By

W. A. P. Fisher, B.A., A.M.I.Mech.E.

LONDON: HER MAJESTY'S STATIONERY OFFICE

1958

PRICE 2s. 6d. NET

UNCLASSIFIED

C.P. No. 371

U.D.C. No. 629.13.014.34: 624.078: 620.172

Report No. Structures 205
May, 1956

ROYAL AIRCRAFT ESTABLISHMENT

Experimental Correlation between the Endurance of a Wing Spar Joint and the Ratio between 0.1% Proof and Ultimate Tensile Strengths of the Material

by

W.A.P. Fisher, B.A., A.M.I.Mech.E.

SUMMARY

Axial fatigue tests were made on a series of specimens representing the Viking outer wing spar joint. Significant correlation was found between low Proof/U.T.S. ratios of the material and high endurance of the joint.

Tests on Dove boom research specimens indicate that this correlation is not peculiar to the Viking joint and the results are in agreement with theoretical and experimental work published by K. Gunn.

LIST OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

1 Introduction

Seventeen specimens representing an early design of outer wing joint of the Viking aircraft were tested in fatigue under the same loading conditions. The endurances varied from 278,000 to more than 6,000,000 cycles. This scatter is unexpectedly large, the more so since only the weaker of the two joints in each specimen was broken.

Further investigation indicates that there is a correlation between the fatigue endurance and the ratio of 0.1% proof stress to ultimate tensile stress of the material. When due regard is given to the fatigue loading actions of a transport aircraft, it seems possible that substantial gains in aircraft life might be obtained either by a more rigid selection of material under existing specifications or by the manufacture of a material to a new specification. The purpose of this note is to set down this evidence, to discuss it, and to suggest that further work is needed. A simple theory is given in an Appendix that demonstrates why the plastic range is important.

2 Test Specimens

The specimens were as shown in Fig.1. The basic extrusions were taken from stock used for the manufacture of aircraft outer wing spars. Away from the joint, the spar is machined to a Tee section, but the joint itself is correctly reproduced.

The 4" × 2.2" end of the machined extrusion, Spec. D.T.D.364B, is machined to a 2-prong parallel fork, which fits into a 3-prong steel fork end connection. The members are joined by two transverse steel bolts. The same form of joint is repeated at the other end of the specimen.

The specimens were anodised all over, including the bore of the holes. The steel bolts, which were cadmium plated, were a light tap fit in the holes, and were assembled without jointing compound.

3 Fatigue Test Conditions

Each specimen was pre-loaded in tension by one application of 53 tons, corresponding to the load in the joint when the aircraft is flying under 2g normal acceleration. This pre-loading to '2g' is standard procedure at R.A.E. in tests of joints of transport aircraft.

The fatigue test was made with a loading of 26.5 ± 7.95 tons, representing 1g ± 0.075 times the design ultimate load for the 50 ft/sec gust case.

The nett area of cross section at the inner bolt hole was 4.16 in^2, so that the average stresses at this section were 28,600 lb/in^2 when pre-loaded, and 14,300 ± 4,280 lb/in^2 in the fatigue test.

4 Test Results

4.1 Fatigue Test Results

Sixteen specimens failed through the innermost bolt hole. Specimen No.9 was still intact after 6,000,000 cycles and the test was stopped.

The endurances are given in Table 1.

4.1.1 Description of Fractured Surfaces

Photographs of the fractured surfaces of specimens Nos.1 to 6 are shown in Figs.6, 7 and 8

The fatigue cracks started in the bore of the inner bolt hole, sometimes at the outer or inner face, but in at least 3 cases from inside the bore.

There are indications of fretting, notably in specimens 3, 4 and 6, between the parallel faces of the alloy lugs and the steel fork ends; but this fretting was apparently unrelated to the fatigue failures.

Evidence of fretting in the bore of the holes is shown in specimen No.5, but the remainder are relatively clean. All specimens showed cracking on both sides of the bore. In Nos.2, 5 and 6 the second lug was ruptured with no sign of fatigue, and in Nos.1, 3 and 4 the second lug was intact. The bolts showed only slight indications of fretting in the bore. No photographs were made of these.

4.2 Static Control Tests

Static tensile control tests were made on specimens 8, 9, 10, 13, 14, 15, 16, 17, and 18. These nine specimens were all that were available, the remainder having been scrapped. The specimens were made and tested by Vickers-Armstrong Ltd., Weybridge, who noted in their test report the correlation between low proof/ultimate ratio and long endurance for the joint.

Four test pieces were cut from each fatigue specimen at standard positions as shown in Fig.2 and were identified as follows:-

A	Longitudinal core
B	Longitudinal edge
C	Transverse edge
D	Transverse core

e.g. control test piece No.B/17 was cut longitudinally from an edge of specimen No.17 and so on.

The tensile test results are given in Tables 2A, 2B, 2C and 2D. To facilitate analysis, the nine specimens have been arranged in ascending order of endurance, and a broken line has been drawn between the six specimens having endurances below 0.5 million cycles and the three specimens which lasted for over 2 million cycles.

5 Correlation of Results

In Tables 2A, 2B and 2D the proof/ultimate ratios of the three long-life specimens are well below those of the short-lived specimens; with one exception (No.8) this is also the case in Table 2C. Thus the significance of the low proof/ultimate ratio is beyond doubt.

In Tables 2A and 2B there is also a significant increase of % elongation in the specimens with high endurance, but the transverse test pieces (see Tables 2C and 2D) show little variation in this respect. Values of maximum stress show no significant trend. The tensile results, therefore, show up differences in plastic range rather than differences in ultimate strength. The consistency of the results is best shown graphically, as in Fig.3, where the proof/ultimate ratios for all four test pieces from each specimen are plotted against the logarithm of the endurance. The faired curves all show the same trend

5.1 Statistical Significance of the Combined Results

As both the endurances and the proof/ultimate ratios fall into two distinct groups, elaborate tests of significance are unnecessary.

The three specimens having the lowest proof/ultimate ratio gave much longer endurance than the remaining six. The number of different combinations of nine specimens in three is 84. Thus the odds against fortuitous agreement between the grouping in the fatigue tests and that in the static tests are 84 to 1.

6 Discussion

For this particular joint and under the test conditions used, it is clear that the variation in endurance is bound up with variations in the longitudinal tensile plastic range. The material for the specimens was used 'as received', i.e. heat treated in accordance with specification. Unfortunately, full details of the heat treatment are not available; but the properties of specimens 8, 9, and 10 appear to differ significantly from those of the remainder.

It is shown in the Appendix that a high pre-load induces a local residual compressive stress at the critical section provided the material has a good capacity for yielding. In the subsequent fatigue loading, the mean stress in this critical region is thereby reduced, as compared with what it would have been had there been no pre-load, while the alternating stress is unchanged. With this smaller local mean stress, the endurance of the joint is substantially increased.

Gunn's work[1] on notched specimens establishes that a low proof/ultimate ratio is desirable from the fatigue aspect even if there is no pre-load. A fortiori it is to be expected that, with a 2g pre-load, joints made from material with a low proof/ultimate ratio should show to greater advantage in fatigue than others made from material to the same specification but with a higher proof/ultimate ratio. This expectation is fully confirmed by the tests reported in this note.

The test conditions are derived from the measurement of loads on aircraft in operations; the cyclic loading is of the same order as that estimated to give the greatest fatigue damage and a load equivalent to the 2g pre-load has been found to occur early in the life of each aircraft so that any beneficial effect from such a pre-load[2] can be relied upon. It is therefore reasonable to expect that the improvement in endurance shown in these tests is a real indication of a corresponding longer life in the wing joint of an aircraft. It also follows that an improvement is to be expected when there are stress concentrations at places other than wing joints.

Thus there appears to be a prima facie case for the selection of material with a low proof/ultimate ratio for use in the tension surface of a wing. At this stage the upper limits that should be quoted for the proof/ultimate ratio are a matter of opinion. Furthermore, the limits need to be related to the position of the test piece in the bar. In accord with Tables 2A and 2B it is suggested that a ratio should not exceed 83% at the core and 87.5% near to the edge of the bar.

7 Concluding Remarks

These tests show a correlation between high endurance and low proof/ultimate ratio for a particular design of wing spar joint made from extruded alloy to D.T.D.364B, when tested at fixed mean and alternating stress after a 2g pre-load. More systematic investigations on other types of joints etc. are needed before any general conclusions can be drawn. But, taken in conjunction with similar effects found by other workers for notched specimens these results indicate that from the fatigue aspect a high proof/ultimate ratio is undesirable.

REFERENCES

No.	Author	Title, etc.
1	K. Gunn	Effect of yielding on the fatigue properties of test pieces containing stress concentrations Aeronautical Quarterly Vol. VI No. 4 p. 277 November, 1955
2	R.B. Heywood	The influence of pre-loading on the fatigue life of aircraft components and structures C.P. 232 June, 1955

Attached:-

Appendix
Tables 1 - 3
Figs. 1 - 8

APPENDIX

The improvement in endurance for a notched bar or a joint from the effect of local yielding may be explained theoretically as follows:-

First, consider a test bar containing a "stress raiser" (e.g. a hole or a notch) under axial tension. By photo-elastic or other means, it can be shown that the local tensile stress rises to a peak at the boundary of the notch.

If the strain is perfectly elastic, the local peak stress (Fig.4a) is equal to $K_e \times f$

where K_e = elastic (or theoretical) stress concentration factor

f = nominal stress on the cross section through the notch.

But if $K_e \times f$ exceeds the 0.1% Proof Stress, when the load is progressively increased from zero, local plastic deformation occurs as soon as the Proof Stress f_p is locally exceeded. Thus, at the full nominal stress f, the critical stress at the notch is less than $K_e \times f$, as shown in Fig.4b.

If the load is completely removed, a compressive residual stress will occur at this critical region owing to elastic behaviour on relaxation of stress. When a cyclic load is applied over a mean tensile load, the effect of this residual compressive stress is to reduce the local mean stress, resulting in enhanced fatigue life.

Next, consider a 2-bolt parallel-sided joint such as the Viking wing spar joint. As indicated in Fig.5, assuming that the end load is shared equally by the two bolts, the nominal stress on the cross section through bolt hole A will be twice that on the section through bolt hole B (the two cross sections being equal). The stress distributions will be somewhat as shown by the curves 1 and 2. A K_e value of about 3.5 exists at the boundary of hole A. If the 0.1% Proof Stress be denoted by f_p, yielding will begin at the boundary of hole A when the nominal stress reaches $\frac{1}{3.5} f_p$. Taking f_p as 28 tons/in^2, yielding will commence when the nominal stress is $\frac{28}{3.5}$ tons/in^2, i.e. about 8 tons/in^2 which is about 1.25g for this joint. The broken curve shows how the stress would vary across the section if completely elastic behaviour were assumed, and the full curve indicates the effect of plastic deformation. The chain-dotted curve shows the distribution of residual stress, indicating compressive stress near the boundary of the hole. On application of a fresh tensile load, the mean stress locally is greatly reduced because of the compressive residual stress. The shaded area indicates the small volume of material subjected to plastic strain during the initial loading.

The lower the Proof Stress, the greater is the plastic strain and also the residual compressive stress. A rough estimate based on an appropriate stress strain curve indicates that a nominal pre-stress of 12.8 tons/in^2 corresponding to a 2g load could produce a residual local compression stress of about the same amount. Whether or not the fatigue cycle alone, without the 2g pre-load, can give endurances responsive to plastic yielding depends on the stress range and on the value of K_e.

TABLE 1

Fatigue Test Results

Specimen	Cycles to Failure 10^6
1	0.6446
2	0.5851
3	1.1156
4	0.4234
5	0.6719
6	3.3608
7	0.2944
* 8	2.5497
* 9	6.1399 unbroken
* 10	2.9028
11	0.4825
12	not tested
* 13	0.3061
* 14	0.2979
* 15	0.3372
* 16	0.4508
* 17	0.2782
* 18	0.3382

* Static control tests made

TABLE 2A

Longitudinal Core Test Pieces

Specimen No.	Cycles to failure 10^6	0.1% P.S. T/in^2	Max. Stress T/in^2	Elongation %	0.1% Proof/Max. Stress Ratio %
A/17	0.2782	28.03	31.89	10.7	87.9
14	0.2979	28.36	31.85	10.7	89.0
13	0.3061	28.08	31.56	10.3	89.1
15	0.3372	27.06	31.64	10.3	85.4
18	0.3382	27.77	31.35	10.3	88.5
16	0.4508	27.46	31.47	11.1	87.3
8	2.5497	25.89	31.59	12.8	82.0
10	2.9028	26.50	31.84	12.8	83.2
9	6.1399 (unbroken)	25.64	31.78	13.1	80.8

TABLE 2B

Longitudinal Edge Test Pieces

Specimen No.	0.1% P.S. T/in^2	Max. Stress T/in^2	Elongation %	Proof/Max. Stress Ratio %
B/17	30.04	33.06	10.3	91.0
14	Scrapped in manufacture			
13	29.41	32.54	9.4	90.5
15	30.05	32.84	9.8	91.5
18	30.65	33.29	8.1	92.1
16	29.60	32.26	9.4	91.8
8	29.43	33.78	11.1	87.3
10	29.16	33.53	10.7	87.0
9	29.44	34.02	10.7	86.7

TABLE 2C

Transverse Edge Test Piece

Specimen No.	0.1% P.S. T/in^2	Max. Stress T/in^2	Elongation %	Proof/Max. Stress Ratio %
C/17	24.84	28.75	6.8	86.4
14*	27.53	29.36	5.0	93.0*
13	25.20	28.89	7.7	87.3
15	25.11	29.02	6.0	86.4
18	25.23	29.56	6.4	85.4
16	25.16	29.76	6.8	84.5
8	24.67	28.80	6.8	85.7
10	23.75	29.10	6.0	81.7
9	22.32	28.34	6.4	78.8

* Inaccurate proof determination gave false proof/maximum value

TABLE 2D

Transverse Core Test Pieces

Specimen No.	0.1% P.S. T/in^2	Max. Stress T/in^2	Elongation %	Proof/Max. Stress Ratio %
D/17	25.31	28.99	4.3	87.3
14	24.72	29.05	5.0	85.0
13*	25.16	27.73	3.9	90.7*
15	24.46	28.58	6.0	85.7
18	24.51	28.37	6.8	86.4
16	24.37	29.05	6.0	83.9
8	22.61	28.63	6.0	79.0
10	22.74	28.42	6.0	80.0
9	22.51	28.74	7.3	78.3

* Inaccurate proof stress determination gave false proof/maximum value

WT.2078.C.P.371.K3 - Printed in Great Britain

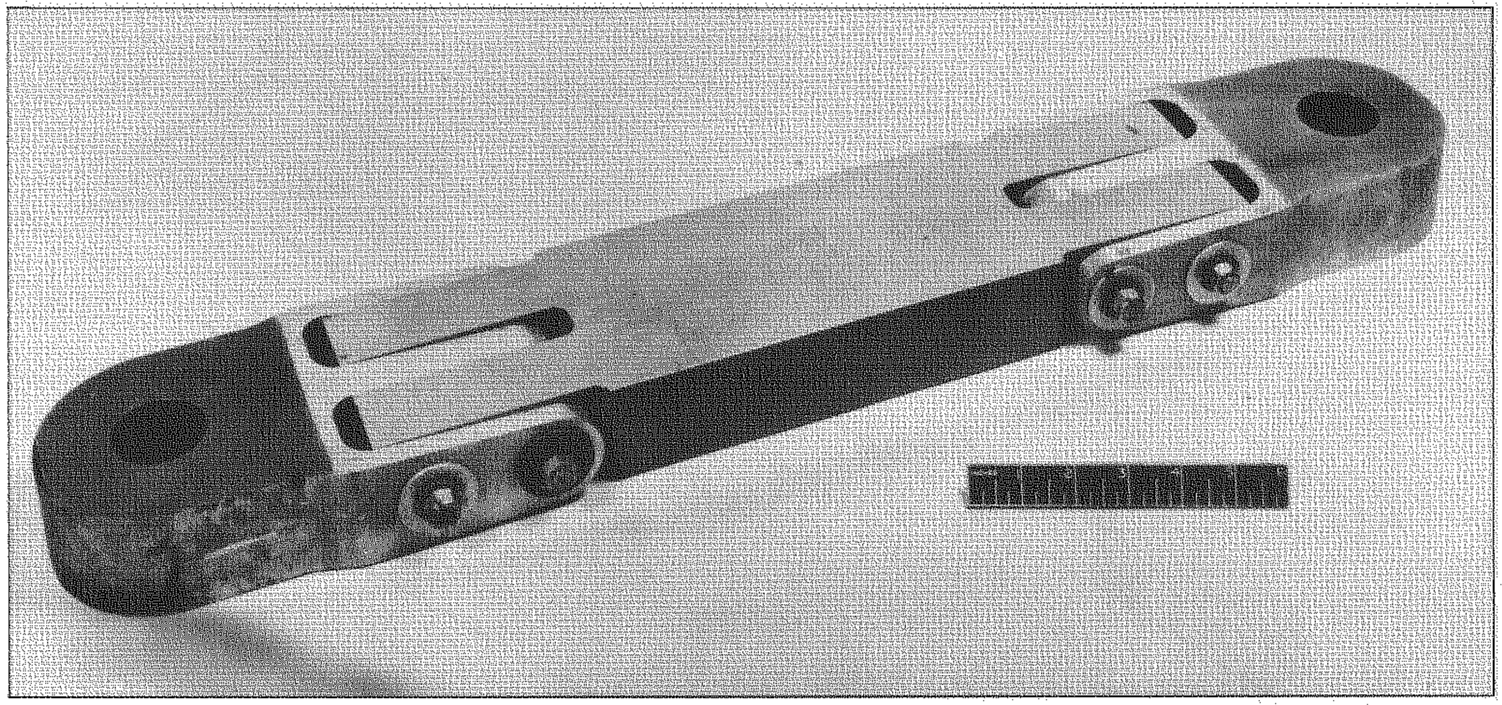


FIG.1. VIKING WING JOINT TEST SPECIMEN

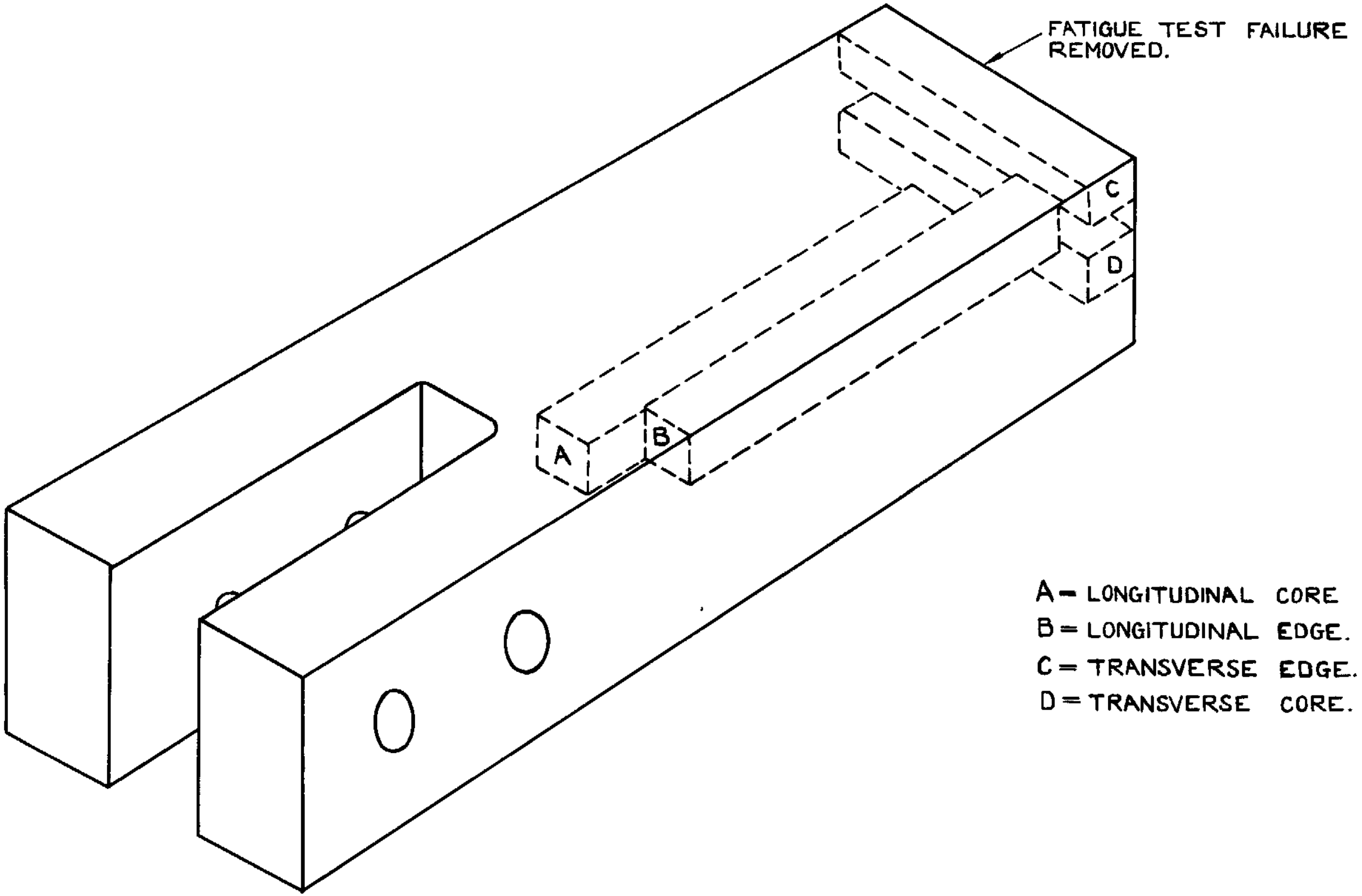


FIG. 2. POSITION OF TENSILE TEST PIECES.

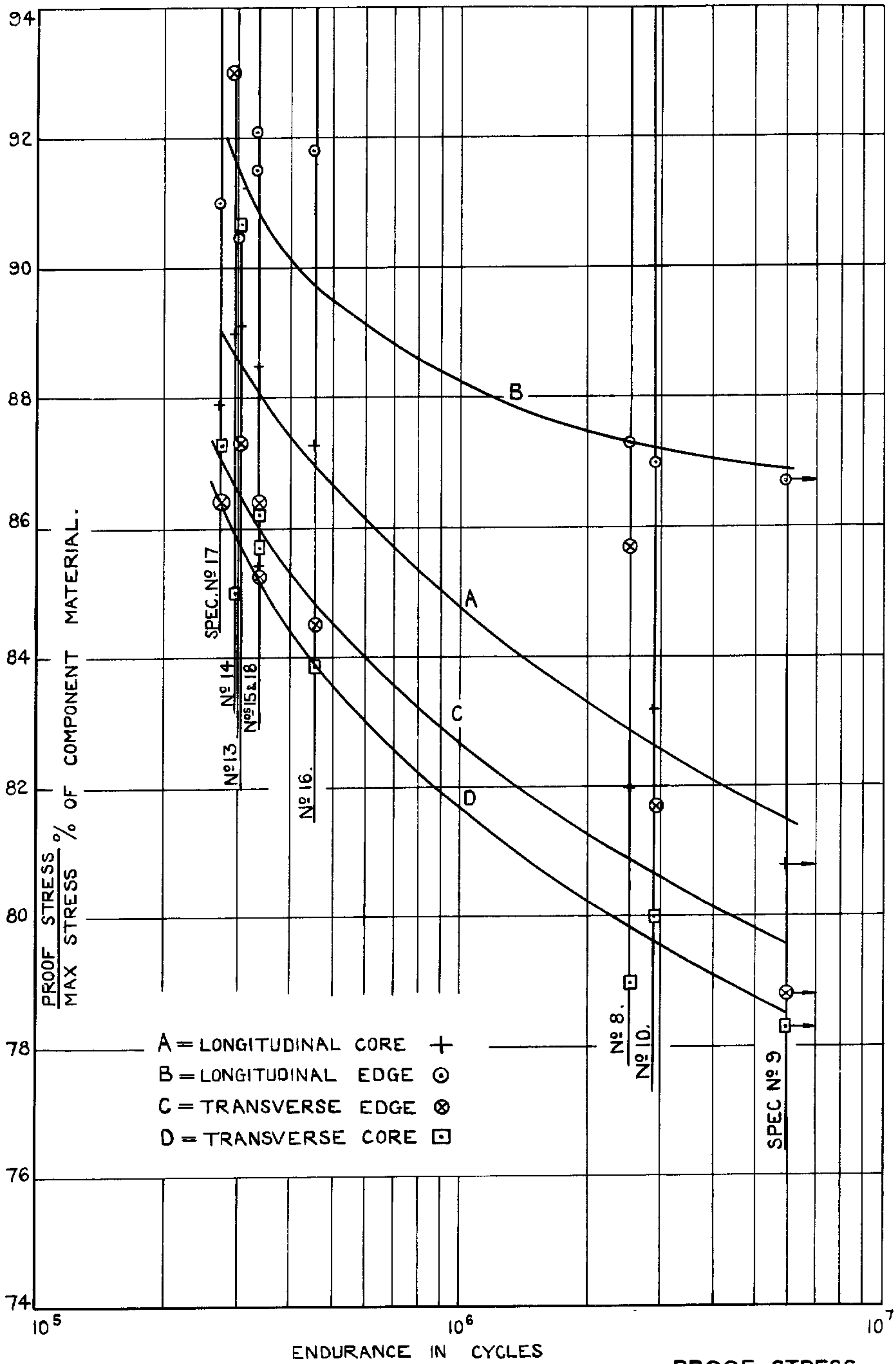
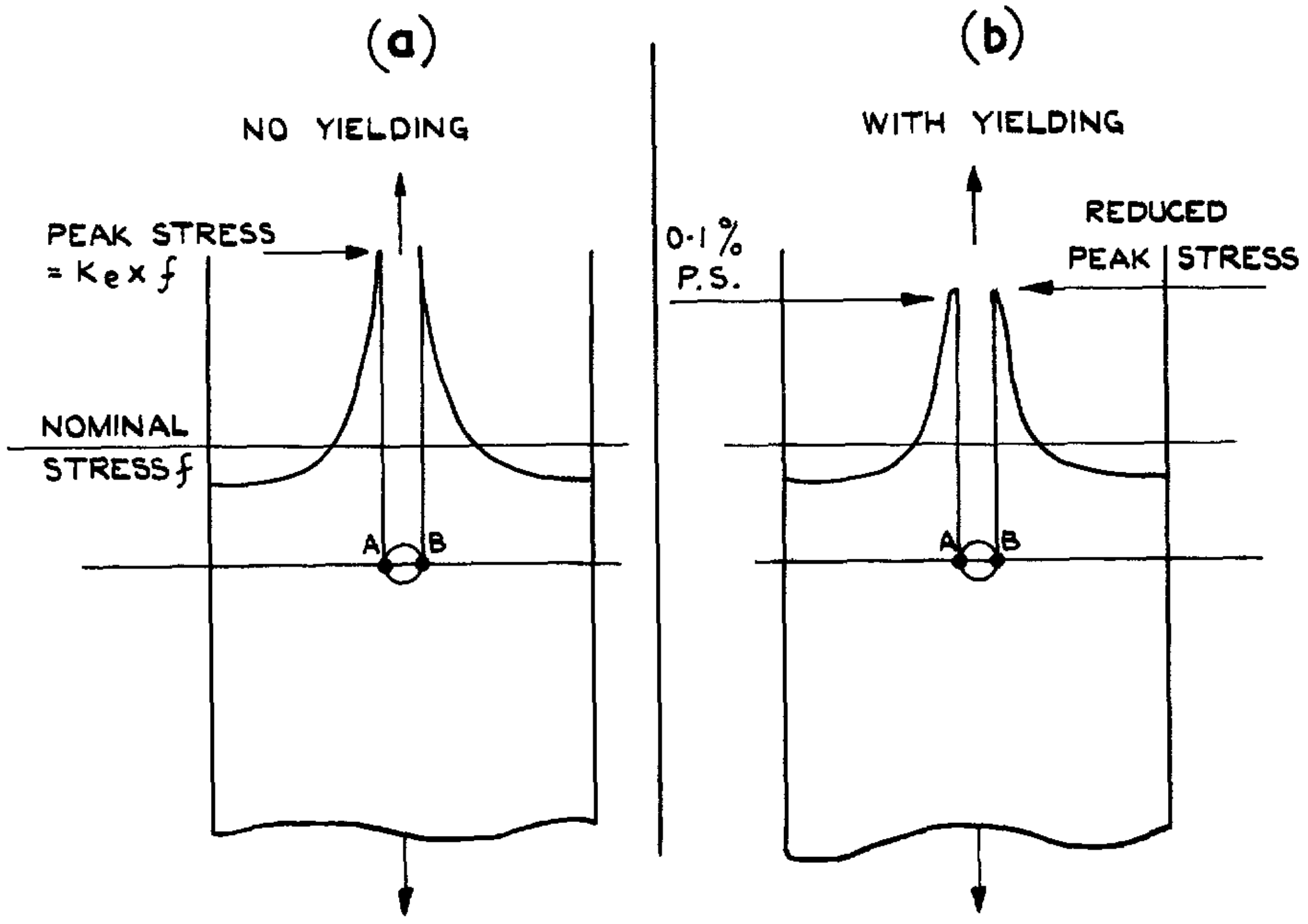


FIG. 3. THE RELATIONSHIP BETWEEN $\frac{\text{PROOF STRESS}}{\text{MAX. STRESS}}\%$ AND THE FATIGUE LIFE OF VIKING OUTER FATIGUE SPECIMENS.



STRESS DISTRIBUTION UNDER SINGLE APPLIED LOAD.

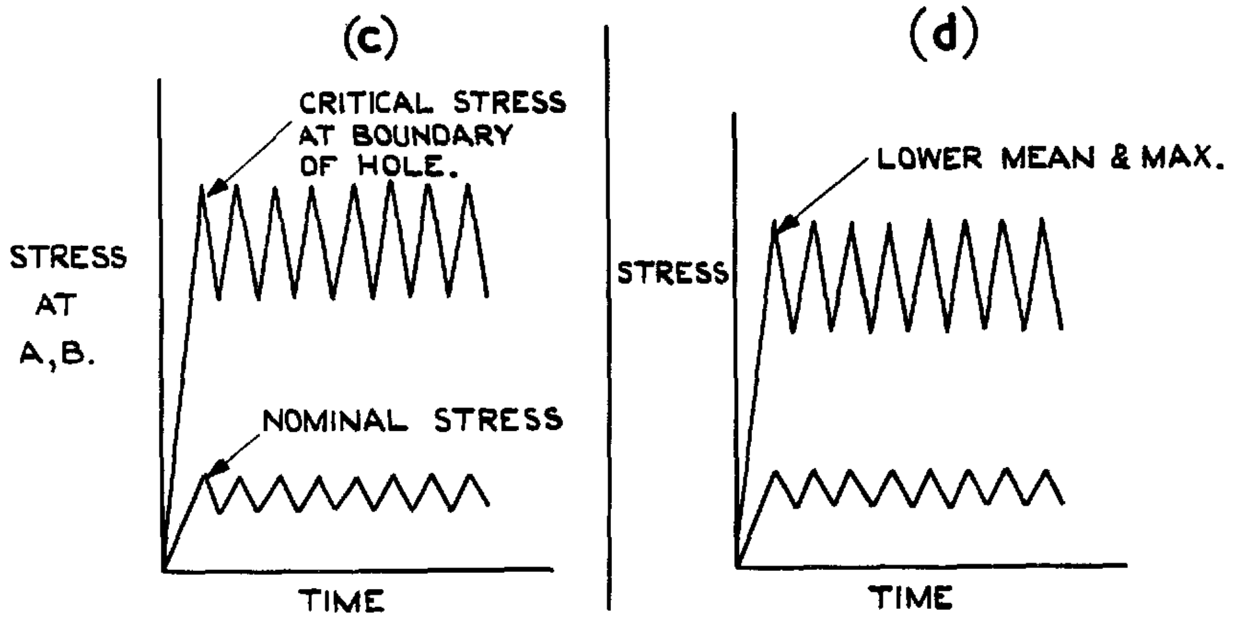


FIG. 4. (a-d.) EFFECT OF YIELDING ON CRITICAL STRESS UNDER CYCLIC LOADING.

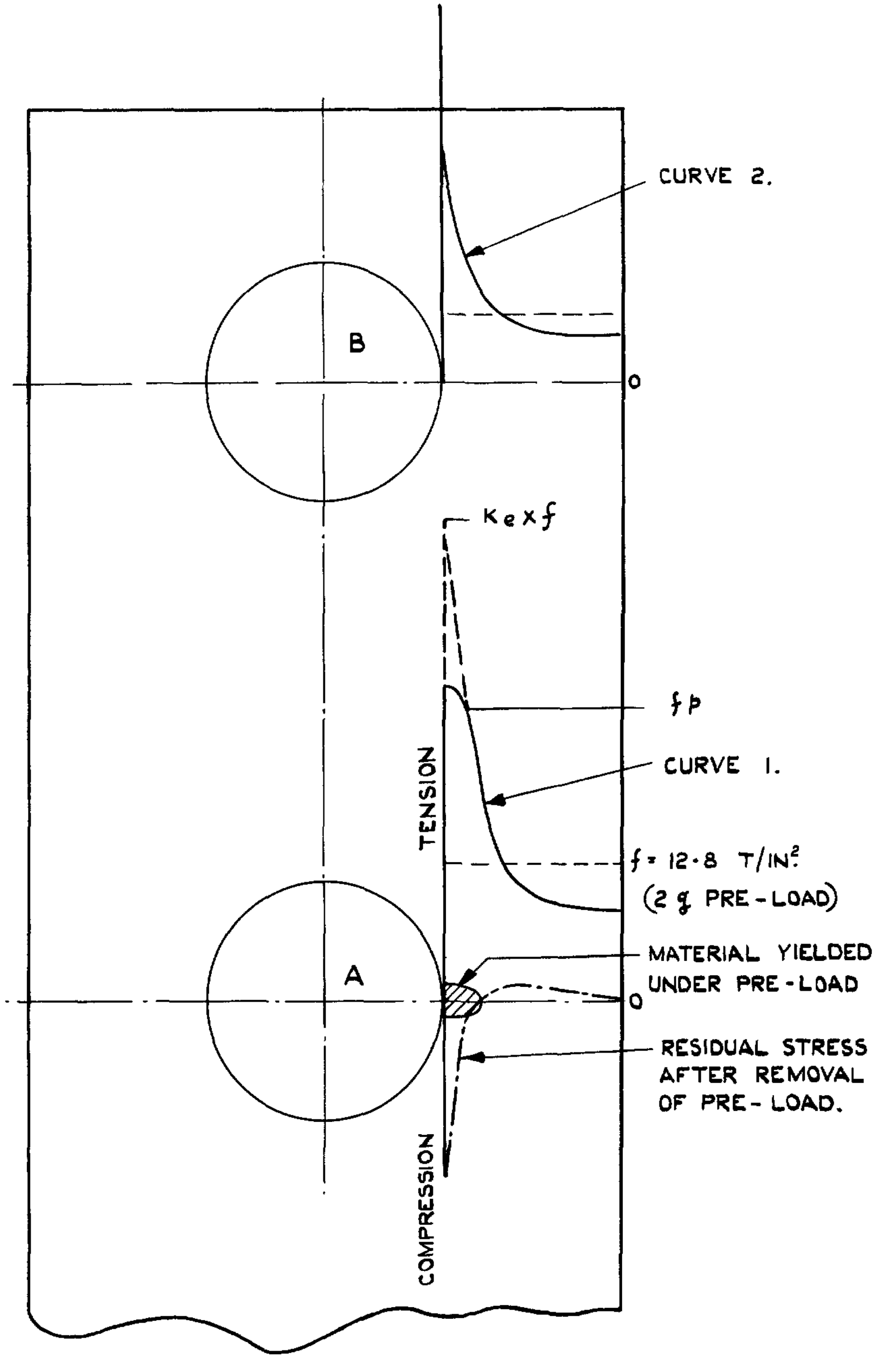
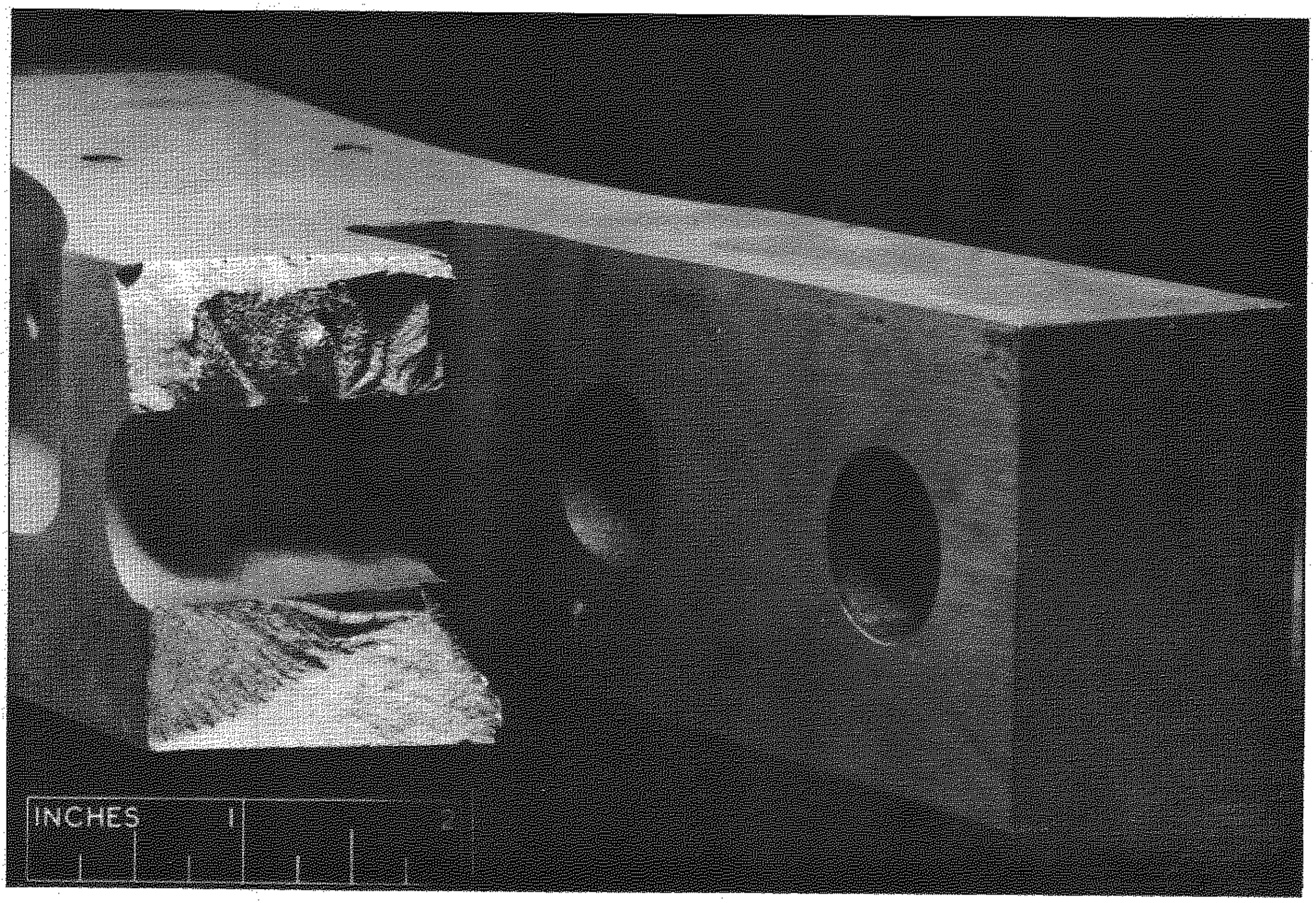
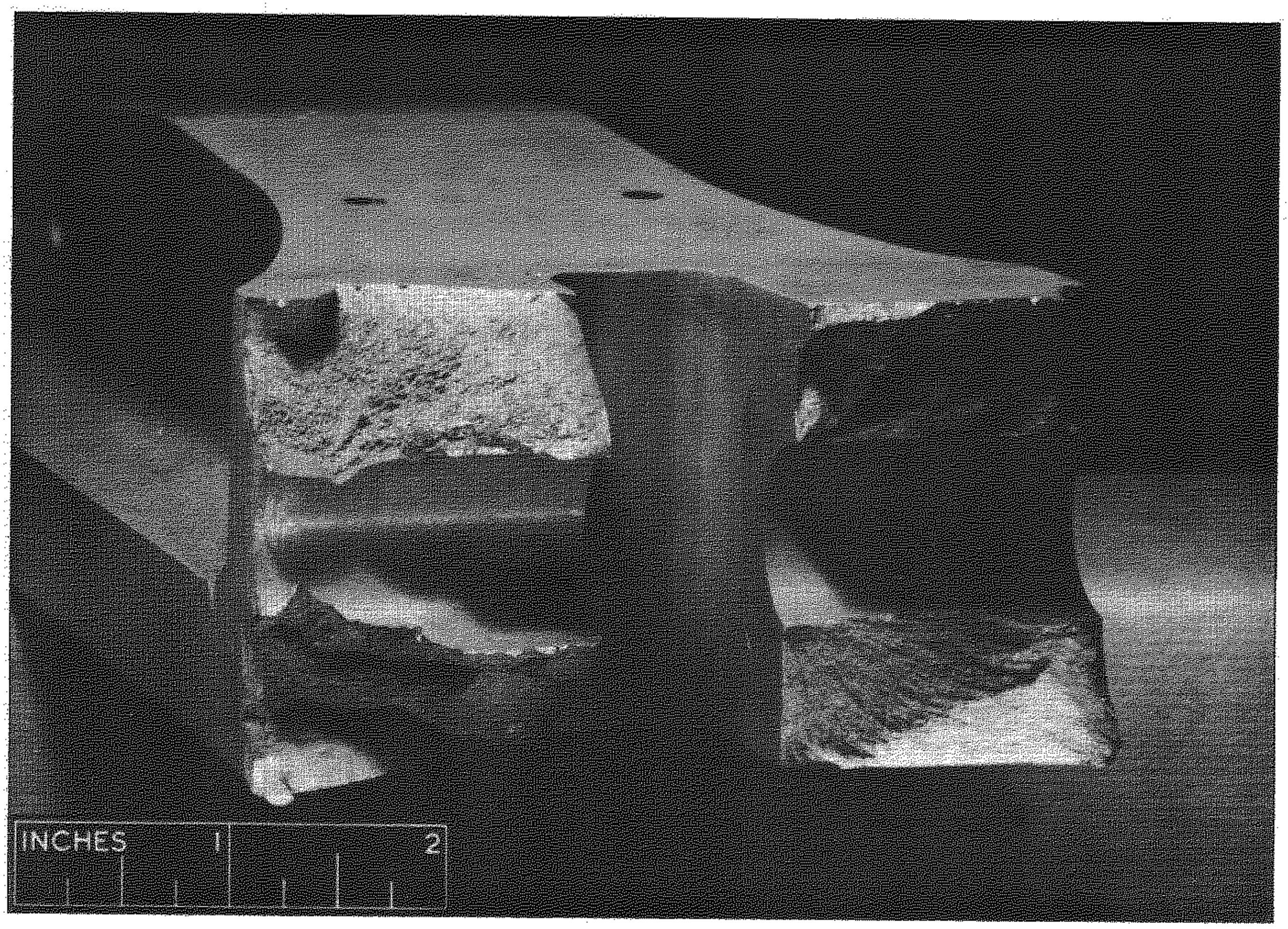


FIG. 5. EFFECT OF YIELDING ON A 2-BOLTED JOINT.



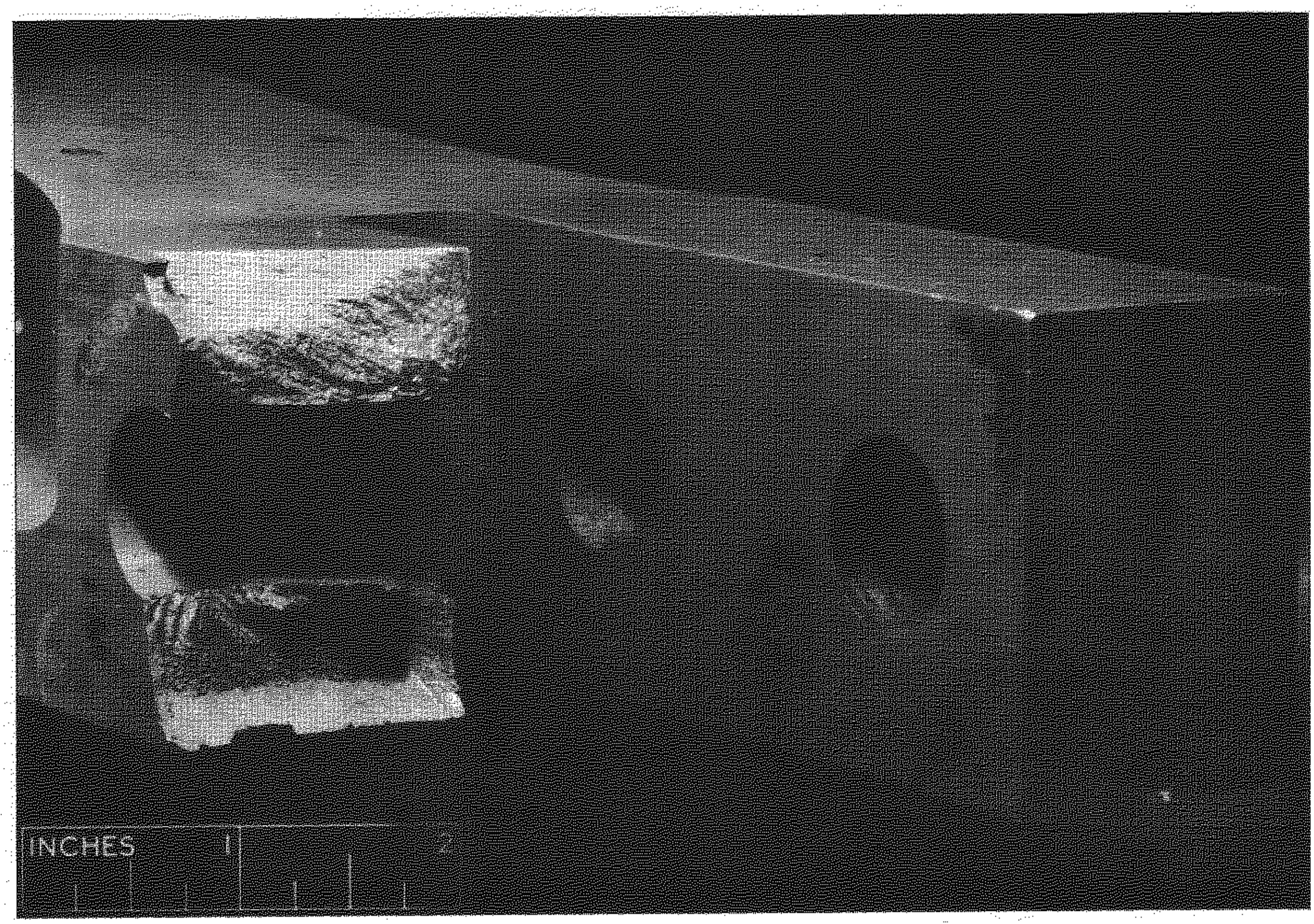
SPECIMEN 1



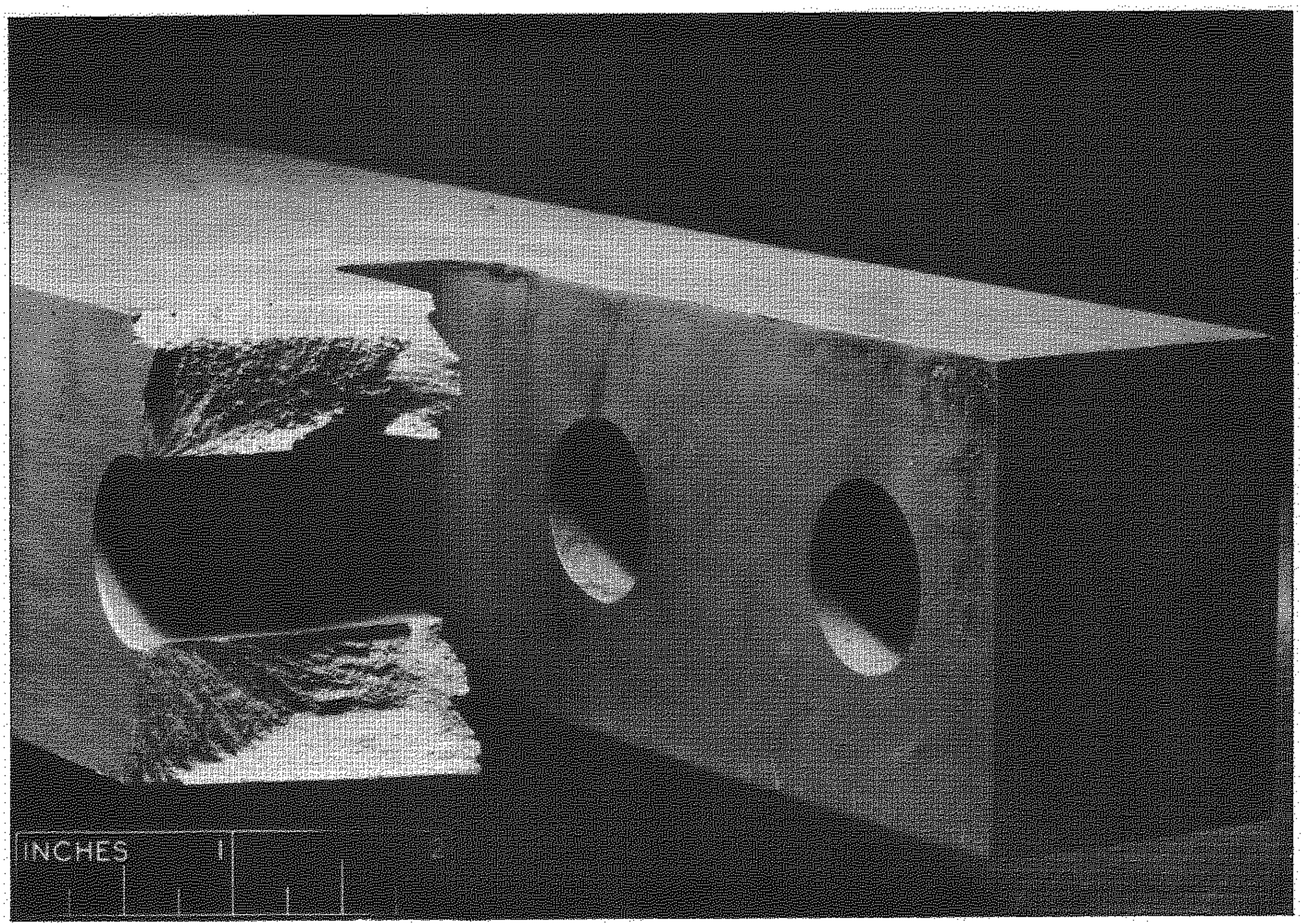
SPECIMEN 2

FIG.6. FRACTURES OF SPECIMENS

VIKING OUTER WING JOINTS



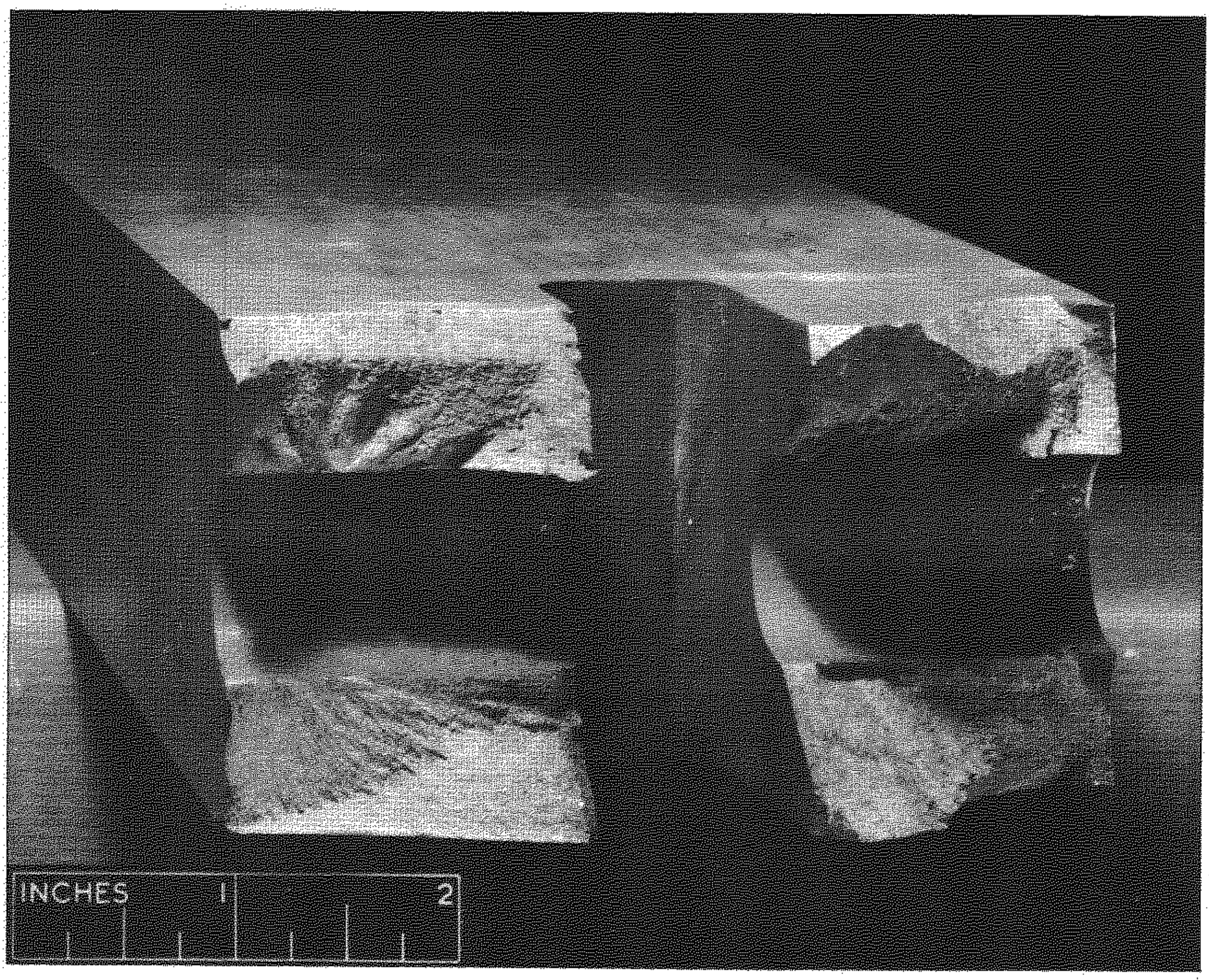
SPECIMEN 3



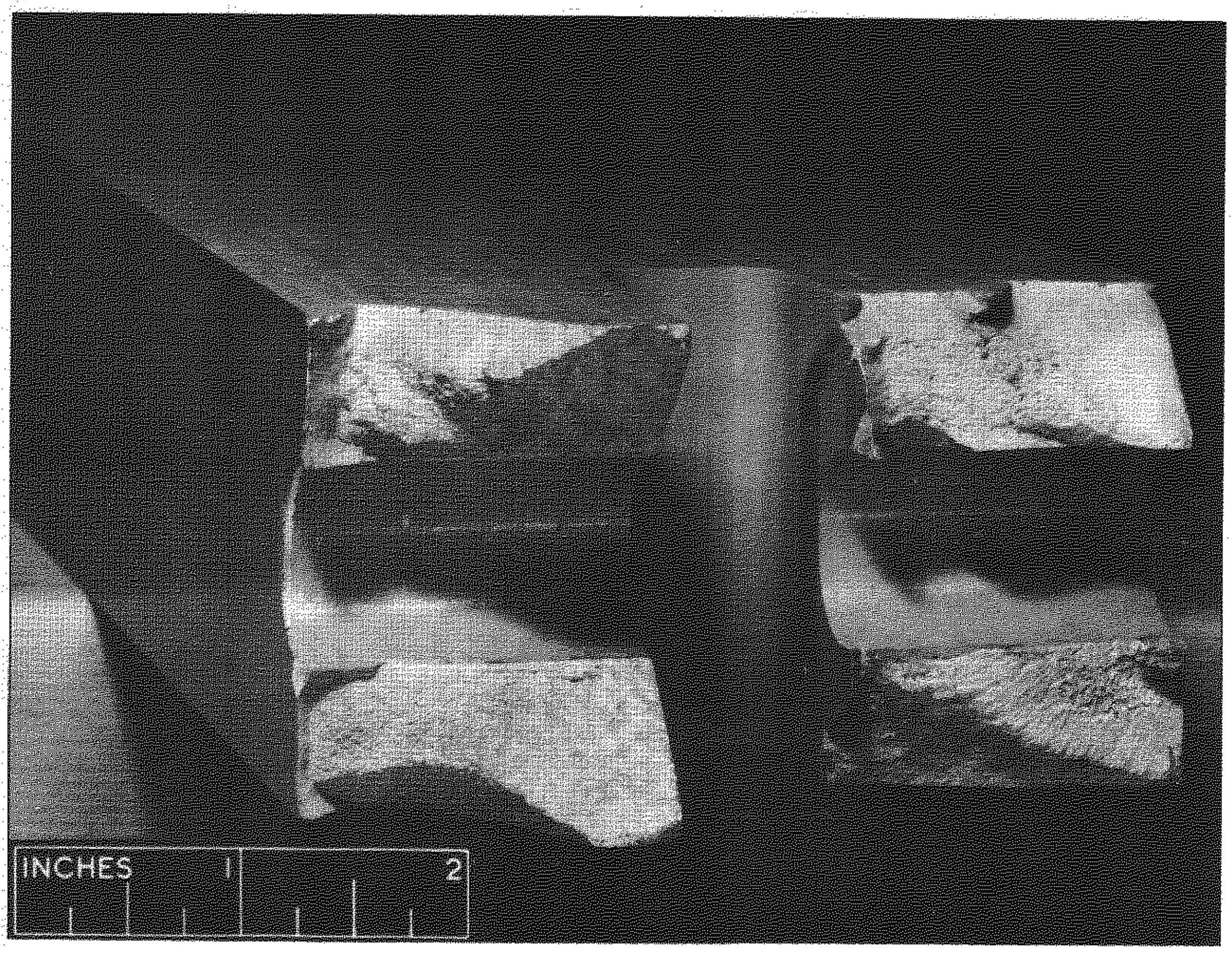
SPECIMEN 4

FIG.7. FRACTURES OF SPECIMENS

VIKING OUTER WING JOINTS



SPECIMEN 5



SPECIMEN 6

FIG.8. FRACTURES OF SPECIMENS
VIKING OUTER WING JOINTS

C.P. No. 371
(18,726)
A.R.C. Technical Report

Published by
HER MAJESTY'S STATIONERY OFFICE

To be purchased from
York House, Kingsway, London W C 2
423 Oxford Street, London W 1
13A Castle Street, Edinburgh 2
109 St Mary Street, Cardiff
39 King Street, Manchester 2
Tower Lane, Bristol 1
2 Edmund Street, Birmingham 3
80 Chichester Street, Belfast
or through any bookseller

PRINTED IN GREAT BRITAIN

S.O. Code No. 23-9010-71

C.P. No. 371