C.P. No. 227
(17,899)
A.R.C. Technical Report

C.P. No. 227
(17,899)
A.R.C. Technical Report

MINISTRY OF SUPPLY

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

Correlated Fatigue Data for Aircraft Structural Joints

By

R. B. Heywood, Ph.D., M.I.Mech.E.

LONDON: HER MAJESTY'S STATIONERY OFFICE

TWO SHILLINGS NET

C.P. No. 227

U.D.C. No. 539.431:629.13:519.24

Report No. Structures 184

June, 1955

ROYAL AIRCRAFT ESTABLISHMENT

Correlated Fatigue Data for Aircraft Structural Joints

by

R.B. Heywood, Ph.D., M.I.Mech.E.

SUMMARY

Results of fatigue tests carried out at R.A.E. on typical aircraft wing structural joints are correlated to give an indication of general fatigue behaviour. The results are plotted in the form of S - Log N curves, and these indicate that the mode of behaviour cannot be attributed to any single factor, such as the type of aluminium alloy, the ultimate tensile strength, or the mean stress of the fatigue cycle. The detailed method of design undoubtedly has a predominant influence on behaviour, but this quality is not revealed by a broad classification according to the proportion of load transmitted at holes.

LIST OF CONTENTS

APPENDIX

TABLE

LIST OF ILLUSTRATIONS

1 Introduction

In a previous report by Fisher[1] results of fatigue tests at R.A.E. on a number of aircraft structural joints were presented by means of a table and an S - Log N graph. Additional information accumulated since the publication of that report has enabled a more comprehensive comparison to be made, with special attention being paid to the following:-

General shape of S - Log N curve, with an indication of scatter.

Effect of method of design on fatigue behaviour, as represented by the proportion of load transferred at holes.

Effect of composition of aluminium alloy.

Effect of tensile strength of aluminium alloy.

The general influence of these factors is indicated in the present report by plotting the results of some 230 tests in graphical form (Figs.1 to 4).

2 Scope of Investigation

The structural joints and components considered are representative of those used in modern aircraft wings, and are of widely differing designs.

The results are confined to the following:-

(1) Fatigue test results on joints and spar booms in which a constant fatigue loading cycle in axial tension is used throughout the test, so that the conditions are representative of those on the tension side of a wing.

(2) The results relate to extruded, rolled or forged aluminium alloy members. Failures in sheet material such as in skins or webs are not included, as the additional parameter thereby introduced might increase scatter.

3 Results

3.1 S - Log N Curve

Individual fatigue results of the joint tests are shown in the graph of Fig.1, with the alternating stress plotted against the logarithm of the cycles to failure. The alternating stress is based on the minimum cross-sectional area, which is usually but not necessarily the section of fatigue failure. However for failure at an end of a specimen instead of in the test length, the minimum area at the end is used, even though the cross-section in the test length may be of smaller area.

The average curve with limits of $\pm 50\%$ shown in this and succeeding figures has been derived from formula (1) given in the Appendix. Most of the plotted points fall within the limits bounded by the upper and lower curves, those falling above comprising experimental joints in which special measures have been taken to increase fatigue strength, and those below or near the lower line by joints having unusually bad design features.

In Fig.1 the individual points are plotted according to the mean stress of the fatigue loading cycle, and these show that the beneficial effect usually associated with low mean stress is not substantiated. However, other investigations have indicated that for a given alternating stress, the endurance is approximately inversely proportional to the mean stress. As the range of mean stress used for joints is not wide, the comparatively small effect of this parameter is masked by others which have a greater influence on the endurance.

3.2 Design of Component

The results shown in the graph of Fig.1 are replotted in Fig.2, with the individual points arranged to distinguish between the four design features:-

(1) Single loaded hole, with the entire load transmitted by means of a pin or bolt.

(2) Two or more loaded holes, so that by simple loading assumptions, 50% or less of the load is transmitted through any given hole.

(3) Unloaded hole, which may however be filled with a plug.

(4) Failure not at a hole.

On a numerical basis, the percentage failures due to each of the above causes is respectively:-

	Design feature	Number of fatigue failures, per cent
(1)	Loaded hole - 100% load transmitted	11
(2)	Loaded hole - less than 50% load transmitted	70
(3)	Unloaded hole	11
(4)	Failure not at a hole	8

Thus 92% of the fatigue failures have started from a hole, and the case of the loaded hole in which load is shared is by far the most predominant cause of failure. The above percentages do not necessarily represent an absolute measure of fatigue strengths of the design features, for all features are not present in all specimens, but they probably indicate the pattern of failures most likely to be produced in the event of fatigue failures occurring in aircraft.

With joints having bolts in shear, about 75% of the failures start at an extreme bolt hole rather than at some intermediate hole. Hence to improve joint efficiency, special care must be taken to avoid high load concentrations at the extreme holes.

Failures away from holes are comparatively rare, showing that few severe stress concentrations other than holes are present in aircraft joints. Such failures are often due to relative movement between mating members, so causing failure by fretting fatigue.

It is surprising that the fatigue strength for unloaded holes is little if any better than that for loaded holes which carry 0 to 50% of the applied load. The explanation is that a bolt or rivet completely filling a hole reduces the distortion at the hole boundary, and this in turn reduces the stress concentration factor, possibly to a value less than that for an open hole[2]. In addition, the fatigue strength of some loaded hole specimens has been increased by the use of interference fit pins or by means of a high degree of bolt clamping. Many of the points lying above the upper curve in Fig.2 represent joints which have been treated by one of these methods. It is apparent that all open holes should be filled with a tight fitting pin if a better than average fatigue strength is required.

The fatigue strength of joints in which the entire load is transmitted through a single pin or bolt is about the same as that for the average joint. The exceptional points shown in Fig.2 representing the low fatigue strength of ±1,500 p.s.i. at endurances in excess of $2\frac{1}{2}$ million cycles are not typical of average practice, because of the large size and relative proportions of the specimens - 2.5 in. pin diameter, 6 in. overall width, and 4 in. thickness. On the other hand, some of the other lugs show an appreciably greater fatigue strength than the average joint, and this is attributed to the use of an interference fit or to the application of a high pre-load.

3.3 Composition of Aluminium Alloy

The same points are replotted in Fig.3 to show the effect of composition of the aluminium alloy. The results indicate that aluminium alloys with zinc (D.T.D.363A and D.T.D.683) possess slightly lower fatigue strengths than those for alloys without zinc (D.T.D.364B, now B.S.S. L.65, D.T.D.464A, now B.S.S. L.63 and B.S.S. 2L.40). Thus approximately 45% of results for the alloys with zinc lie above the average curve shown, compared with approximately 70% for the alloys without zinc. The explanation for this difference might be attributed to the slightly greater mean stresses normally used with the higher strength alloys with zinc, but a correction for mean stress on the lines given in paragraph 3.1 does not cause these proportions to change by more than a few per cent.

3.4 Tensile Strength

The general influence of tensile strength of the aluminium alloy is shown in the graph of Fig.4. The alternating stress is plotted as a percentage of tensile strength, and points are distinguished according to whether the tensile strength is below 30 t.s.i., in the range from 30-35 t.s.i., or above 35 t.s.i.

In most cases the minimum specification tensile strength of the material is used to obtain the ratio of alternating stress to tensile strength, but in a very few cases where stresses could not be ascertained, the ratio of alternating load to static failing load of the joint is employed.

The full curve shown in Fig.4 with limits of ±50% has been derived from formula (1) given in the Appendix, assuming a tensile strength of 35 t.s.i.

The general trend in results shows that the fatigue strength does not increase with increase in tensile strength when the latter has values above 35 t.s.i. that is, for the alloys with zinc, D.T.D.363A and D.T.D.683. For tensile strengths below 35 t.s.i. it is not possible to discriminate between results for joints with tensile strengths in the range from 30 to 35 t.s.i., and those with strengths below 30 t.s.i. However in general, the advantage of a high static design stress of a joint achieved by use of a high strength material is not likewise imparted to fatigue strength.

4 Average Curve

An average curve based on the analysis given in the Appendix is shown in Fig.5. For design purposes, if Dr. Walker's assumption[3] is made that 2 million cycles of an alternating load equal to $\pm 7\frac{1}{2}\%$ of the factored load due to a 50 feet per sec gust is equivalent to 30,000 flying hours for a 5g aircraft, then the alternating stress for the average design of joint must not exceed $\pm$2,600 p.s.i. for this life to be achieved. This is equivalent to a design stress of only 35,000 p.s.i. for the 50 feet per sec gust case. For new civil aircraft this low stress makes it imperative that the detail design of members from a fatigue point of view should be carefully considered and the necessary development work undertaken, so that fatigue strengths can be raised above those for the average design and so permit the use of greater design stresses.

Representative test mean and alternating stresses that have been used for wing joints of civil aircraft are given in Table I, together with typical ranges of endurance. The average alternating stress is approximately 3,870 p.s.i., corresponding to $3,870 \times 100/7\frac{1}{2} = 51,700$ p.s.i. design stress for the 50 feet per sec gust case; this is appreciably greater than the stress of 35,000 p.s.i. given above for a safe life of 30,000 flying hours, and is the fundamental reason why active measures have been and are being taken to modify and improve existing designs of aircraft joints.

5 Fatigue Stress Concentration Factor

It is of interest to compare the fatigue strength as obtained from the average joint curve with that for plain aluminium alloy specimens, see Fig.6. The ratio of alternating stresses for plain and jointed specimens gives the value of the strength reduction factor, and the high values so found indicate the large reduction obtained by fabricating the material into the form of a joint. Although it appears that these values exceed those for the theoretical stress concentration factor, there is actually no intrinsic discrepancy present, since no allowance is made here for the effect of stress concentrations on mean stress, or for a size effect that may present with plain specimens.

6 Conclusions

(1) The fatigue strength of typical aluminium alloy structural joints depends principally on the detailed method of design, but not so much on the tensile strength of the material, the mean stress of the fatigue cycle, or the composition of the aluminium alloy. For failure in given cycles, the joints of best design are able to sustain an alternating stress of about four times the magnitude of that for joints of the worst design, but even for the best joints the alternating stress is only a small fraction (about one quarter) of that for polished laboratory specimens, demonstrating that considerable further improvement should still be possible.

(2) The single design feature causing most failures is that due to a hole, and it is relatively unimportant whether or not there is load transference. The use of interference fit bolts or rivets, of high clamping action by the bolt, and of pre-loading are devices that can improve fatigue strength.

(3) The design stress for the 50 feet per sec gust case should be of the order of 35,000 p.s.i. if an aircraft life of 30,000 flying hours is required, and if a joint of average design is assumed.

REFERENCES

No.	Author	Title, etc.
1	W.A.P. Fisher	Empirical data on fatigue of aircraft structural joints RAE Report No. Structures 133, August, 1952 ARC.15,350
2	R.B. Heywood	Designing by photoelasticity *Chapman and Hall Ltd. London 1952 (page 289)*
3	P.B. Walker	Design criterion for fatigue of wings J. Roy. Aeron. Soc., Vol.57, January, 1953

APPENDIX

Derivation of Average Joint Curve

A glance at the fatigue curves given in this report shows that the majority of tests have been carried out at an alternating stress of the order of ±4,000 p.s.i., few at a stress of about half this value. It is believed that this limitation makes it difficult to deduce the average curve from the general data, and accordingly an analysis has been made on selected joints in which the alternating stress has been varied from one test to another. Results for these joints are plotted in Fig.7, using logarithmic scales. For the range of stresses covered, the curves are practically parallel straight lines, so enabling an average curve for all these joints to be estimated. For alternating stresses below 10,000 p.s.i., the formula for the average curve is

$$\text{Alternating stress (p.s.i.)} = 1500\left(1 + \frac{1000}{\sqrt{N}}\right) \qquad (1)$$

where N is the number of cycles to failure.

This formula may be extended to alternating stresses greater than 10,000 p.s.i. by the elaboration,

$$\text{Alternating stress (p.s.i.)} = 1500\left(1 + \frac{1000}{\sqrt{N+B}}\right) \qquad (2)$$

where B is a constant whose value is ascertained from behaviour under static loading. For example, if it is assumed that the static failing stress is 64,000 p.s.i. and that the mean stress of interest in the fatigue cycle is 15,000 p.s.i., then the equivalent alternating stress at static failure is 49,000 p.s.i. and this leads to a value of B of 1,000.

These formulae are particular cases of a general formula that has been proposed by Weibul in Sweden.

TABLE I

Typical mean and alternating stresses used
for tests on aircraft joints

Aircraft Reference	Material Spec. D.T.D.	1g Mean Stress p.s.i.	Alternating Stress p.s.i.*	Typical endurance cycles
A	363A	11,000	3,100	60,000 to 300,000
B	683	11,000	3,300	300,000 to 1,000,000
C	363A	9,000	3,400	200,000 to 1,000,000
D	364	14,000	3,400	500,000 to 700,000
E	364	13,500	3,800	400,000 to 500,000
F	364	14,000	4,000	300,000 to 2,000,000
G	683	12,000	4,000	70,000 to 200,000
H	683	12,500	4,000	100,000 to 1,000,000
I	363A	14,500	4,100	150,000 to 400,000
J	464	14,500	4,400	500,000 to 3,000,000
K	464	15,000	4,500	200,000 to 3,000,000
L	363A	12,500	4,500	400,000 to 3,000,000
Mean		12,800	3,870	260,000 to 1,340,000
Minimum		9,000	3,100	60,000
Maximum		15,000	4,500	3,000,000

*Corresponding to 7½% of factored 50 feet per sec gust case.

Wt.2078.CP227.K3 - Printed in Great Britain.

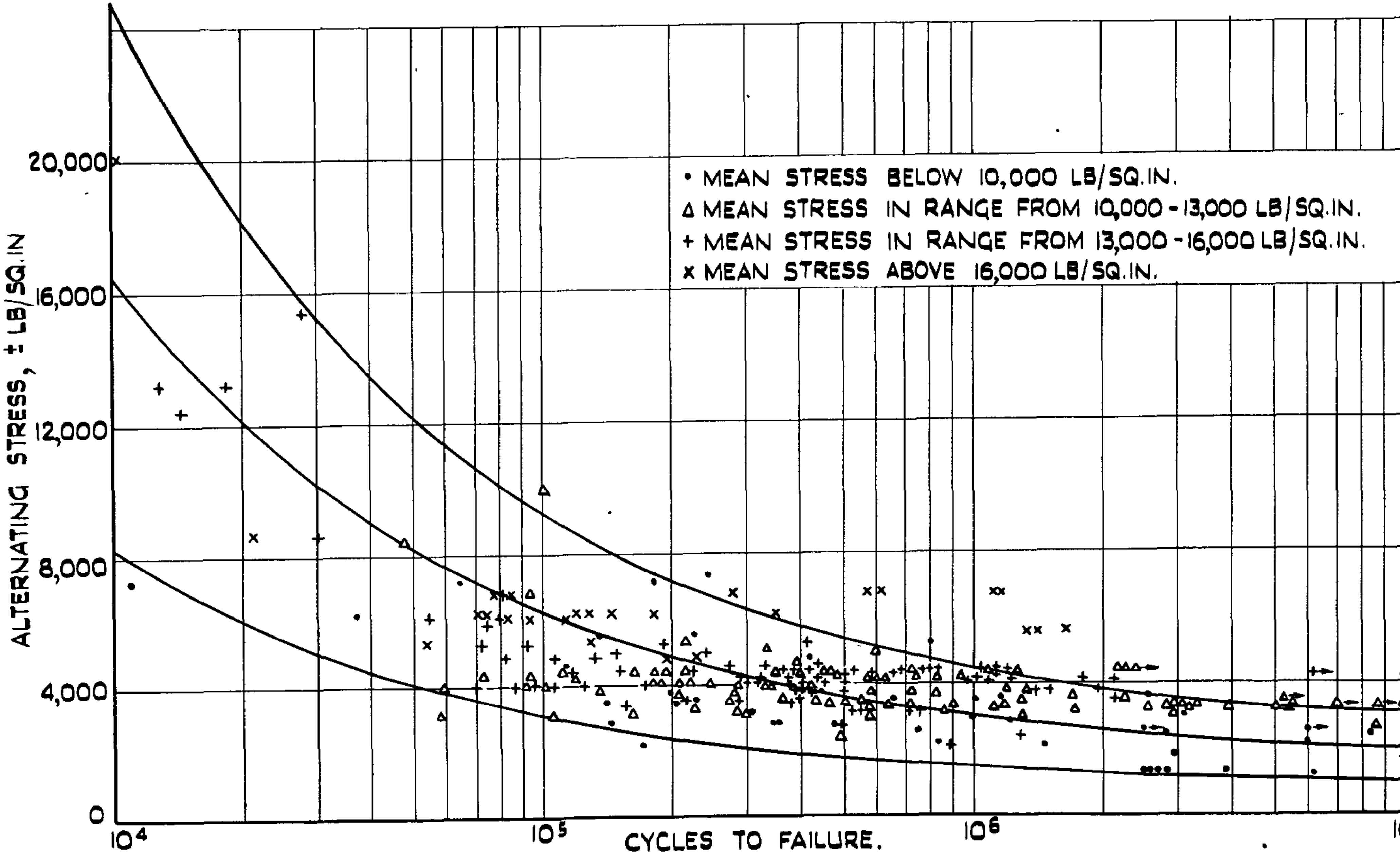

FIG. 1. FATIGUE RESULTS SHOWING INFLUENCE OF MEAN STRESS.

FIG. 1.

FIG. 2.

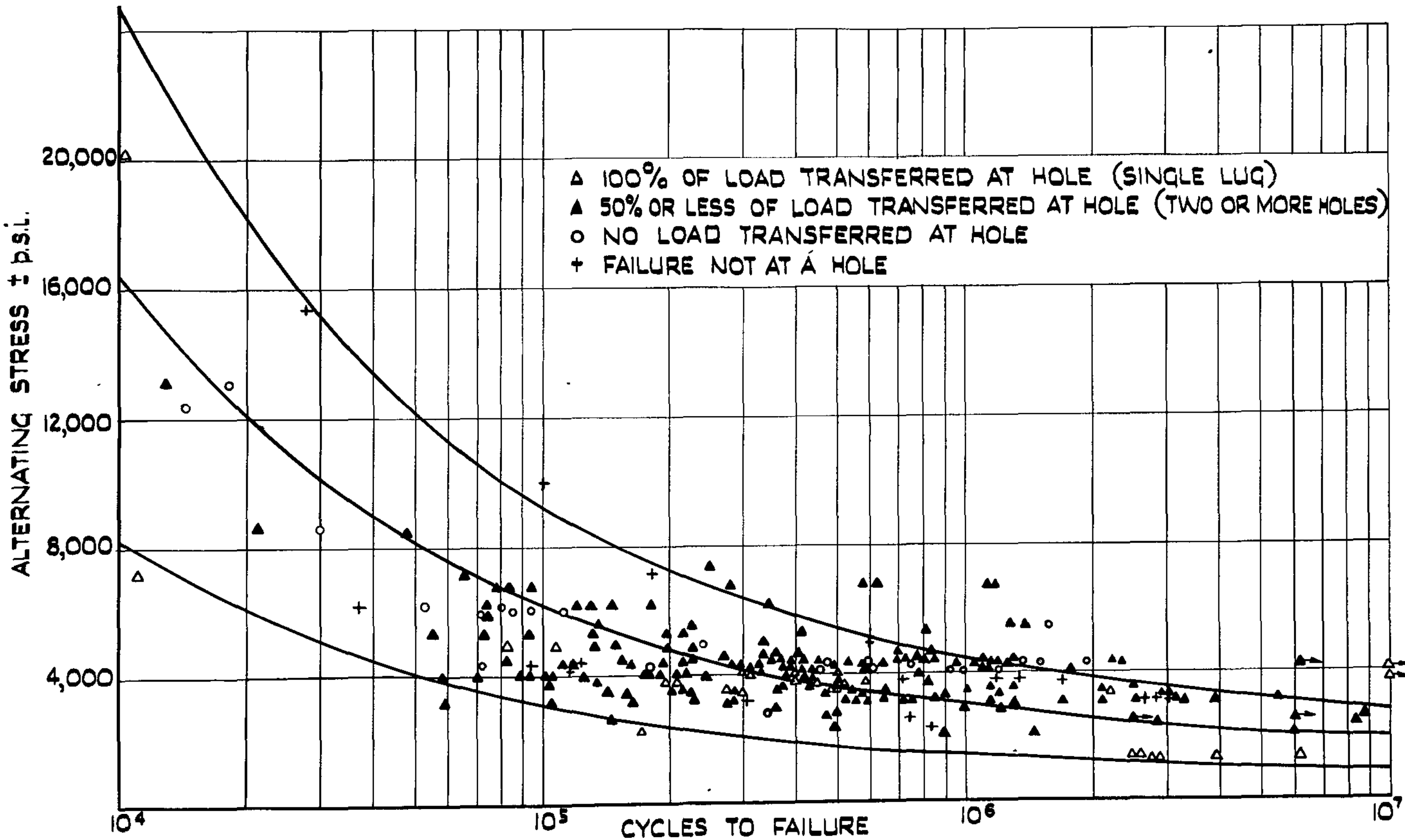

FIG. 2. FATIGUE RESULTS SHOWING INFLUENCE OF DESIGN FEATURES.

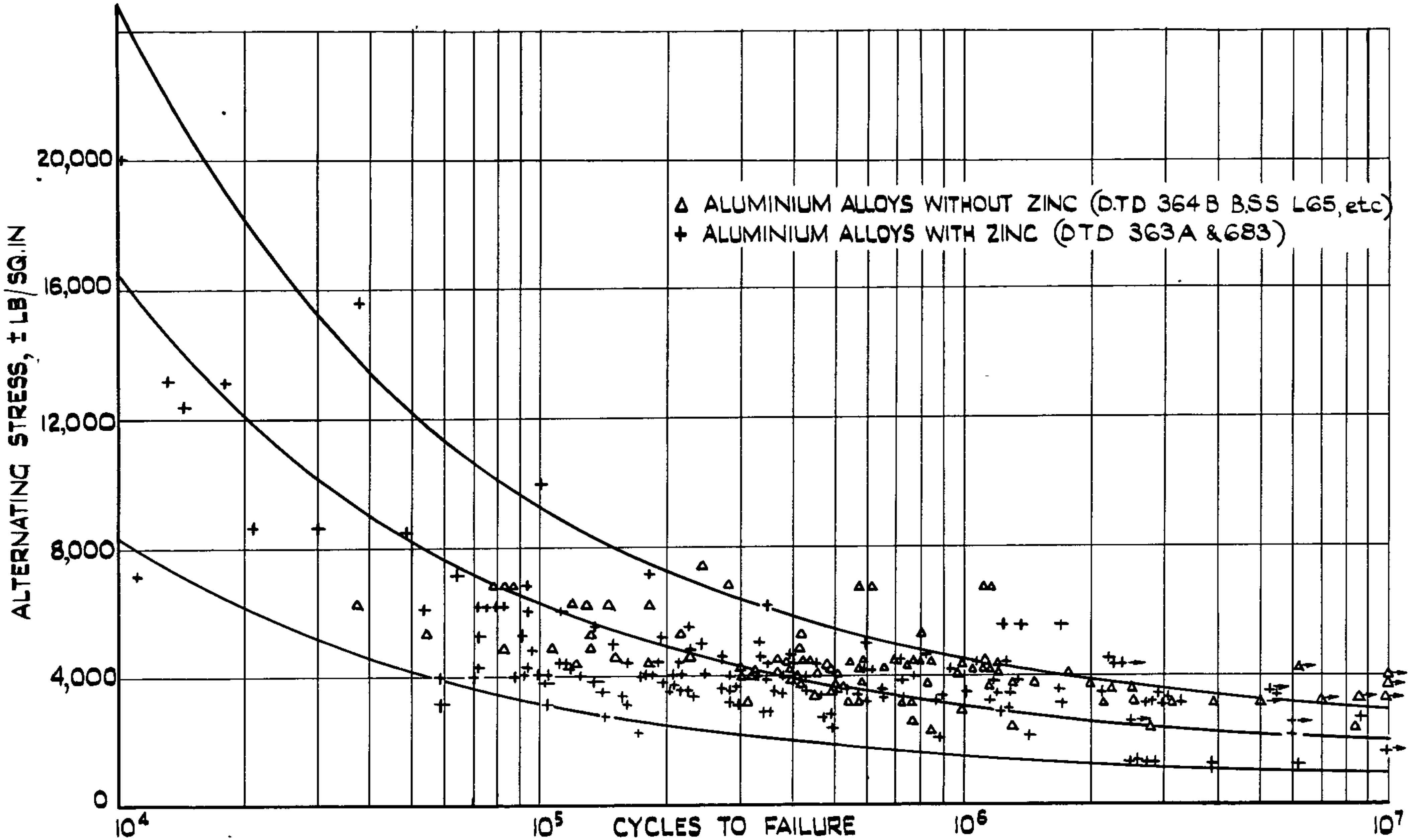

FIG. 3. FATIGUE RESULTS SHOWING INFLUENCE OF ZINC IN ALUMINIUM ALLOY.

FIG. 3.

FIG. 4.

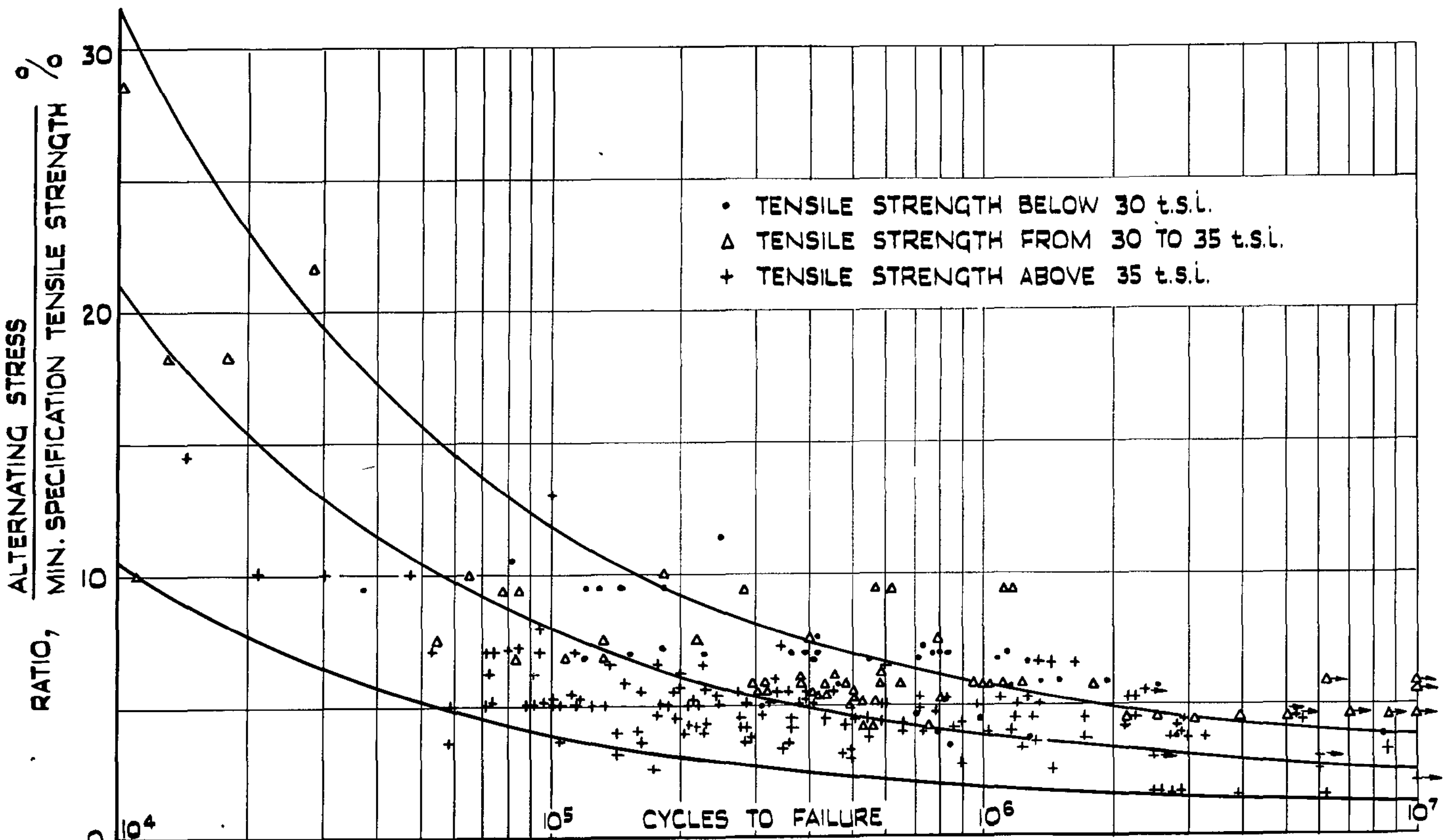

FIG. 4. FATIGUE RESULTS SHOWING INFLUENCE OF TENSILE STRENGTH OF THE ALUMINIUM ALLOY

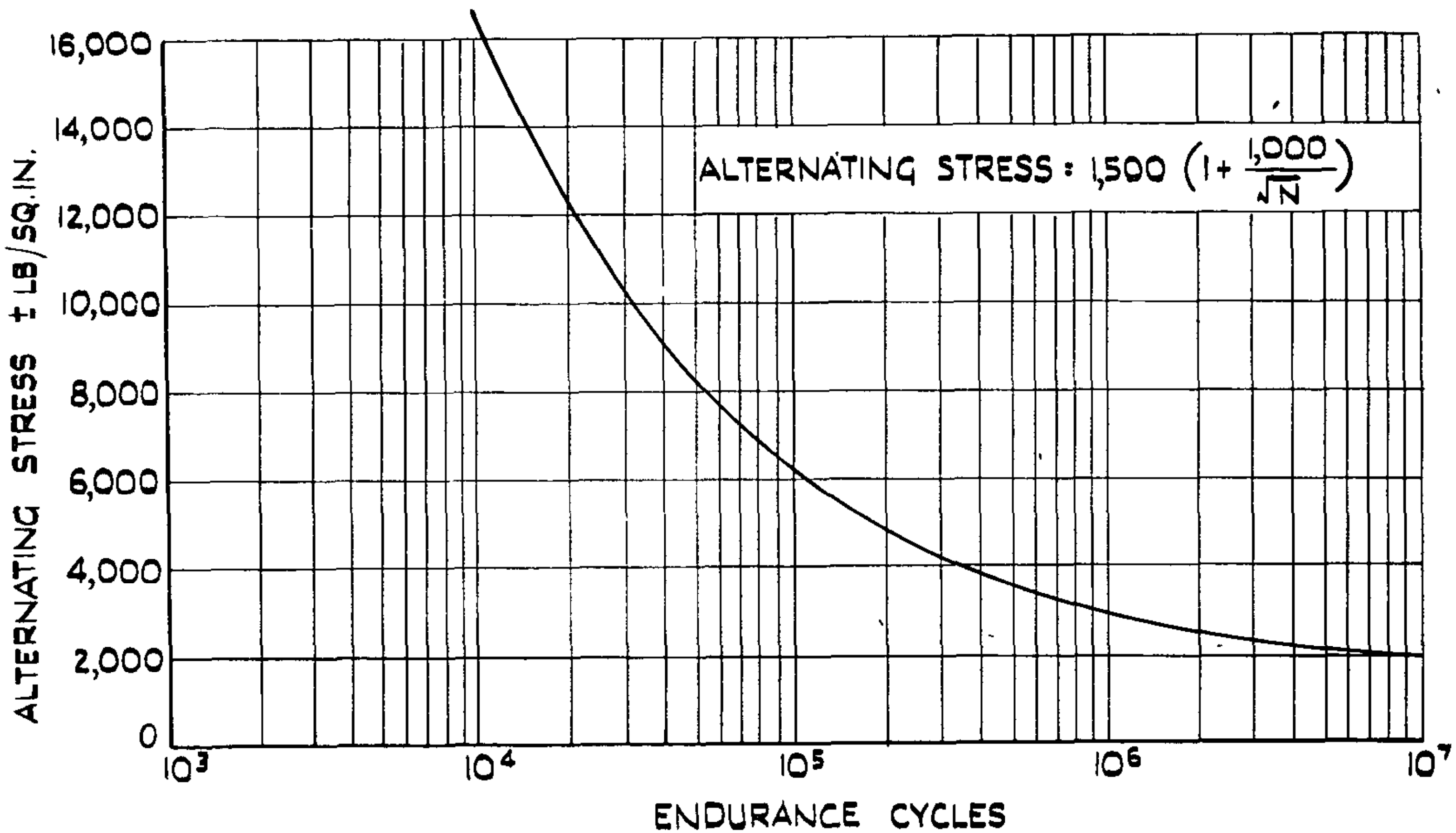

FIG. 5. AVERAGE FATIGUE CURVE FOR ALUMINIUM ALLOY AIRCRAFT PARTS OF DIFFERENT DESIGNS.

FIG. 6.

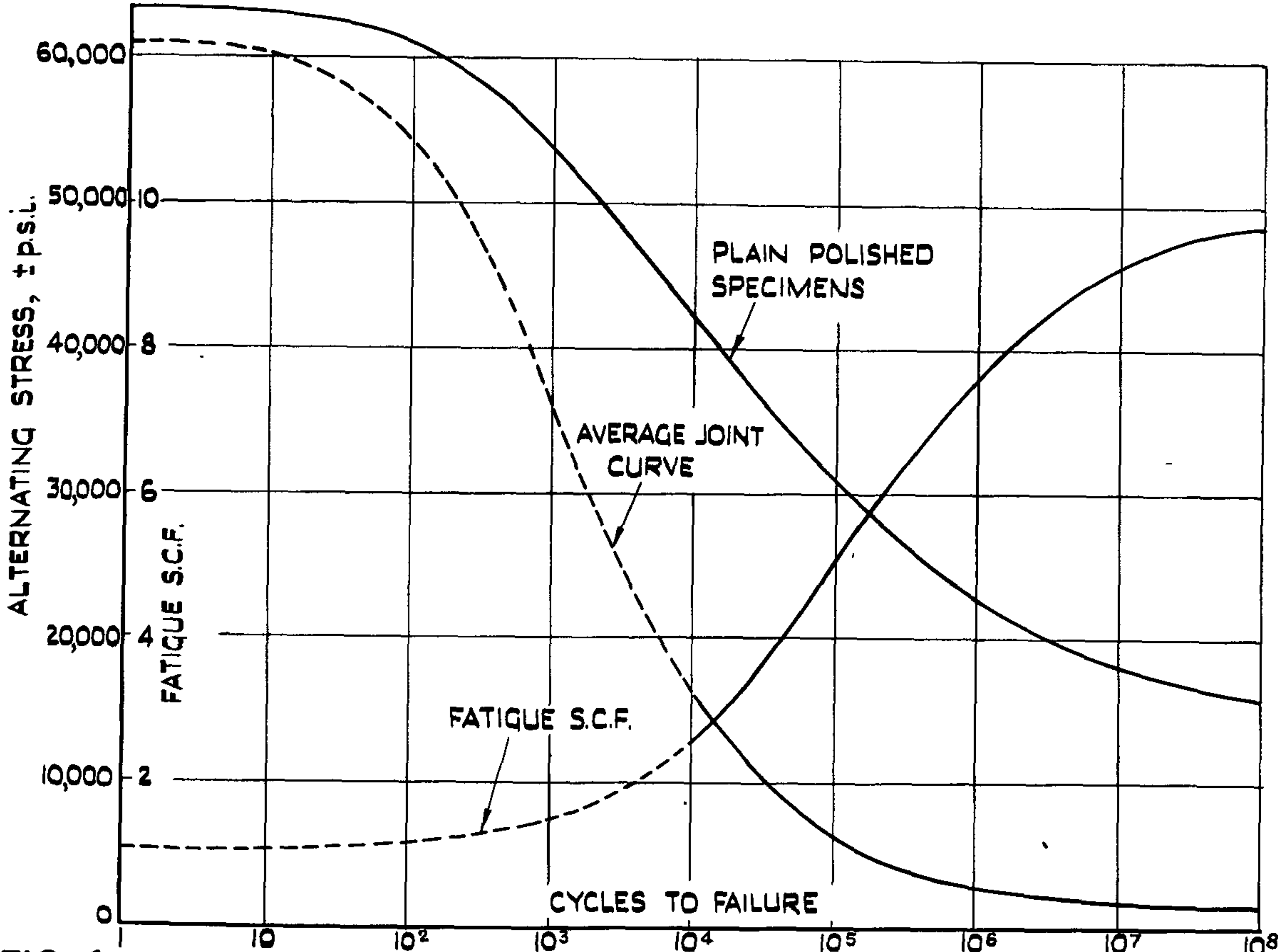

FIG. 6. COMPARISON OF FATIGUE STRENGTH OF AVERAGE JOINT WITH PLAIN SPECIMEN. 35 t.s.i. (78,400 p.s.i.) ALUM. ALLOY ASSUMED, WITH MEAN STRESS OF 15,000 p.s.i.

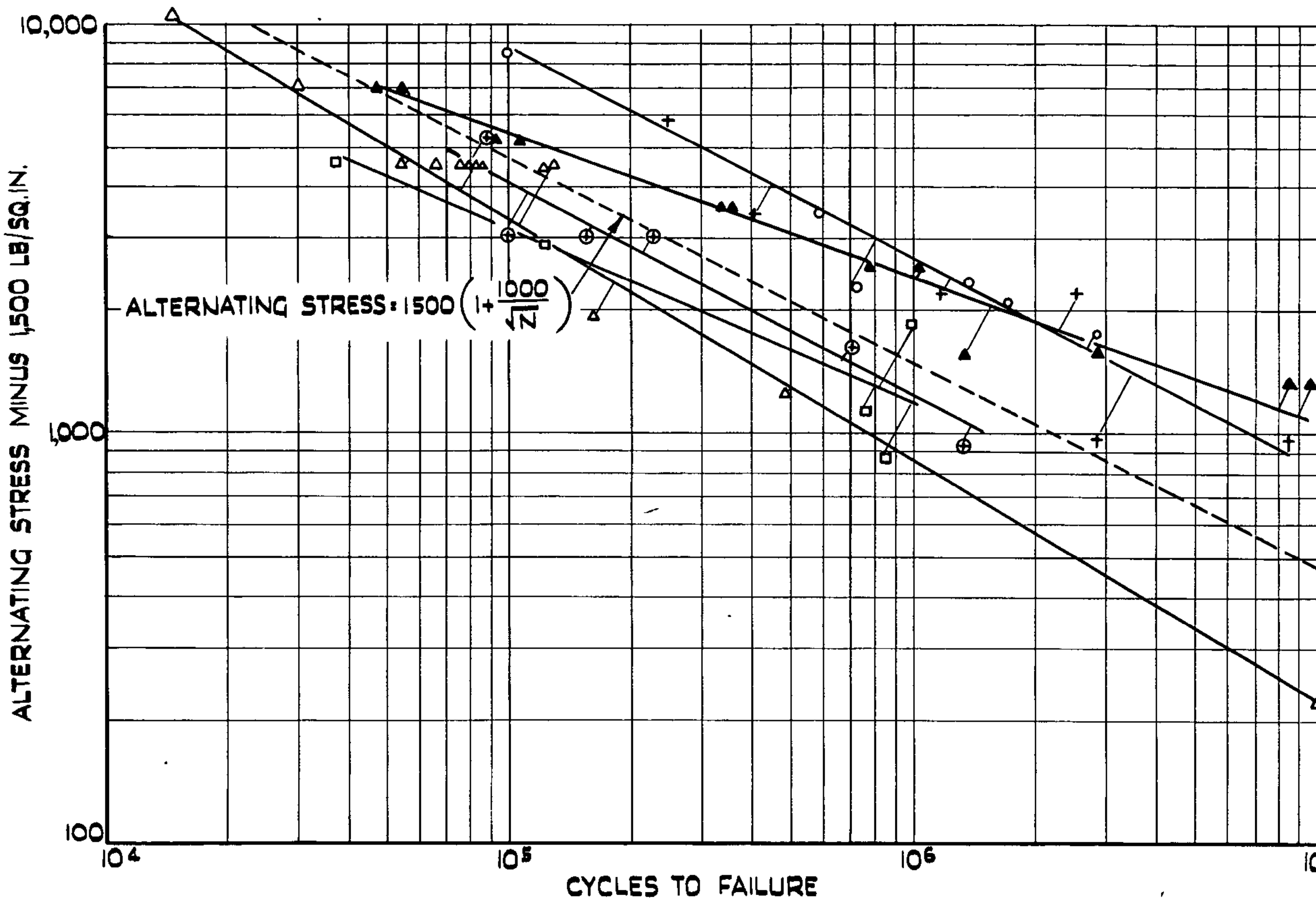

FIG.7. FATIGUE CURVES FOR PARTICULAR JOINTS.

FIG. 7.

Published by
HER MAJESTY'S STATIONERY OFFICE
To be purchased from
York House, Kingsway, London W C 2
423 Oxford Street, London W 1
P O Box 569, London S.E 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

S.O. Code No. 23-9009-27

C.P. No. 227