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Some Fatigue Characteristics of a Two Spar Light Alloy Structure (Meteor 4 Tailplane)

By

K. R. Raithby, B.Sc., A.F.R.Ae.S. and Jennifer Longson

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SUMMARY

Results are given for fatigue tests on sixty-one Meteor tailplanes, treated as representative small-scale wing systems and tested under a variety of loading conditions. The object of the investigation was to study the fatigue characteristics of a typical aircraft structure, in particular the effects of mean load and alternating load on the endurance. The effects of preloading, periodic overloading and low temperatures were also investigated.

Endurance curves are given for different mean loads; the results indicate that, for a given alternating load, the endurance is roughly inversely proportional to mean load. Substantial improvements in endurance may be obtained by preloading and by periodic overloading. The endurance at low temperatures is higher than at room temperature.

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1 Introduction

Fatigue tests have been made on sixty-one Meteor 4 tailplanes under various loading conditions as part of a wider programme of research into the fatigue properties of aircraft structures. These Meteor tailplanes were chosen because they were available off a continuous production line and were a convenient size for repetition testing on an extensive scale. They were treated, however, as small scale specimens of wings having two spars without bolted joints. The tests have no direct connection with the normal functioning of the tailplanes as part of the Meteor aircraft.

Fatigue tests under reversed loading at room temperature and at low temperatures have already been reported[1,2] but for completeness the results are also included in this report.

2 Structural Features of the Meteor 4 Tailplane

The Meteor 4 tailplane is of two spar light alloy construction, with diaphragm type ribs and with top and bottom skins stiffened by stringers that are discontinuous across the ribs. The spar booms are L section extrusions of L40 material, continuous across the span, the rear spar being straight and the front spar cranked about 6 inches outboard of the root attachment points.

Over the inboard half of the tailplane the skins are of aluminium alloy (DTD 390) while outboard they are of high tensile steel (DTD 138). There are a number of unreinforced access holes in the top and bottom skins near the root attachments. In most of the fatigue tests skin cracks originated at these cut outs at a comparatively early stage, causing an appreciable increase in spar boom stresses. In an attempt to assess the effects of these cut outs, tests were made on six tailplanes with modified skinning in which the cut outs were eliminated.

A general arrangement of a test specimen is shown in Fig.1. The tailplanes used for the tests were selected in small batches from the production line over a period of about a year.

3 Range of Investigation

The primary purpose of the investigation was to determine the relative effects of mean and alternating load on endurance for a typical structure. Some tests were also made to investigate the effects on endurance of the following:-

(i) Low temperatures
(ii) Skin cut-outs
(iii) Preloading
(iv) Periodic overloading

4 Loading Conditions

Each tailplane was tested under a loading condition in which the mean and alternating loads were applied at a single point near each tip. The magnitude of the loading was based on the mean static failing load of three tailplanes and is given in Tables I to VI for the various tests. The loads are expressed as percentages of the load to produce a bending moment at 11.5 in. from the tailplane centreline* equal to the mean

* i.e. position of failure in static strength tests.

bending moment at failure in static strength tests on three tailplanes[1]. Shear and bending moment curves for both mean and alternating loads are given in Fig.2. Corresponding spar boom stresses at the beginning of the test, calculated from the applied bending moments, are given in Table VII. Except for one series of tests, in which the stress range in the rear spar top boom was kept constant, (Table IV) the loads were kept the same throughout a particular test, irrespective of any change in stiffness or stress distribution. Extensive skin cracking resulted in a considerable increase in the spar boom stresses over an appreciable proportion of the life.

5 Method of Test

For tests at low alternating loads the resonance method was used, load being applied by means of a rotating mass exciter as described in Ref.1. The mean load was applied at rib 8, near each tip, by dead load suspended through rubber shock absorber cord. The length of rubber cord was such that the natural frequency of the mean load system was about 1 c.p.s., compared with the tailplane frequency of about 12 c.p s. Strain gauges on the spar booms were used to measure the alternating load, the gauges having first been calibrated by applying dead load to the tailplane at rib 8. A general view of a tailplane under test, showing the method of applying the mean load is given in Fig.13.

For tests at alternating loads greater than 30% of the static failing load the tailplane was mounted inverted in a test frame and load was applied at rib 8. The minimum load (i.e. mean load minus alternating load) was first applied through a shot-bag loaded link and lever system. A repeated up load, varying from zero to the maximum (i.e. mean plus alternating), was then applied by means of a pneumatic jack connected through levers and wire cables to the tailplane. The jack was controlled by electrical relays operated by the pointer of a spring balance used to measure the load on the tailplane. A general view of a tailplane in the test rig is given in Fig.14 (taken after failure of the specimen).

6 Results of Tests

6.1 Endurance

The results of each series of tests are given in Tables I to VI and Figs.3 to 9, in which the endurance of the tailplane is given as the number of load cycles to produce failure of one spar boom. In most cases extensive skin cracking developed at an early stage, sometimes starting at only about 1/10 of the total life, with the result that for an appreciable proportion of the life the spar stresses at the point of failure were increased by as much as 40% above the stresses given in Table VII.

6.2 Skin cracks

The effect of skin cracking on spar stresses is illustrated in Figs.10 and 11. In Fig.10 the effective width of skin, expressed as a proportion of the distance between the spars, is plotted against number of cycles; corresponding changes in spar boom stress are given in Fig.11. The actual skin failures and their relation to the final spar boom failure are shown in Fig.15. The increase in stress applies to both mean and alternating stress in the booms. Most of the major skin failures originated from unreinforced cut outs, although some originated from rivet holes. Skin cracks in the compression surface originated from local buckling of the skin where stringers were discontinuous across ribs.

In an attempt to assess the effects of the skin cut-outs, tests were done on six modified tailplanes in which the cut-outs were eliminated. The results were still affected by major skin cracks, however, which developed either at the lap joint on the tailplane centreline or from the corner of the skin at the rear of rib 2, as shown in Fig.16.

The effect of the skin cut-outs on the endurance is discussed further in para. 7.4 below.

6.3 Rivet failures

Rivet failures often occurred at the chordwise lap joint between the steel and aluminium alloy skins at rib 5. At later stages some failure of skin to spar boom rivets occurred, usually after skin cracks had developed. Typical rivet failures may be seen in Fig.15.

6.4 Spar boom failures

In the majority of cases the final spar boom failure occurred through rivet holes in the top (tension) boom of the front or rear spar near the root. Typical failures are shown in Fig.17. There was some variation in the position of failure, as indicated in Tables I to VI. In most cases, spar failure occurred on the side which had the more extensive skin cracking, i.e. the side on which the spar boom stresses became higher, but in some cases failure occurred on the less highly stressed side. Some failures, particularly those in the front spar, occurred where the boom had been formed during manufacture and were probably influenced by residual stresses, since the nominal stress at the point of failure was as low as 70% of the maximum stress in the rear spar.

Two tailplanes failed near the skin lap joint at rib 5 instead of near the root, one of them being associated with extensive rivet failures along the skin joint, the other with a skin crack adjacent to the skin joint. One of the high alternating load tailplanes (No.43, Table I) failed by compression of the front spar boom after only 3 load cycles. The failure appeared to be due primarily to shear failure of rivets attaching the skin to the boom, thus allowing the boom to fail by instability. With one tailplane the boom failure originated from the inner corner of the flange at a point where there was no geometrical stress concentration. This failure is shown in Fig.18. A similar failure occurred in one of the tailplanes tested under reversed loading at low temperature[2].

7 Discussion of Test Results

7.1 Effect of Mean Load

In Fig.4 alternating load is plotted against mean load for failure in a given number of cycles, based on the endurance curves of Fig.3. Fig.4 agrees fairly well with the results of Australian tests on Mustang wings.[3] In Fig.12(a) the curves of constant endurance have been replotted in terms of the ratio of fatigue strength at a particular mean load to the fatigue strength at zero mean load, fatigue strength being defined as the alternating load that will cause failure in a given number of cycles at a particular mean load. It will be seen that the fatigue strength drops off very rapidly at small values of mean load.

In Fig.12(b) the effect of mean load on endurance under a particular alternating load is shown. Over most of the range the endurance is roughly inversely proportional to the mean load.

7.2 Scatter

Tests on six tailplanes under a loading of 10% ± 10% of the static failing load gave a standard deviation on $\log_e$ endurance of 0.166, that is a multiplying factor of 1.47. This is equivalent to a coefficient of variation of about 10% on fatigue strength. Of the six tailplanes, three failed in the rear spar and three in the front spar (where the nominal stress was only about 70% of that in the rear). There is thus some scatter in position of failure which may have reduced the scatter on endurance.

7.3 Effects of low temperatures

The effects of low temperatures have been dealt with in a previous report[2] but the results are given again in Fig.5. There appears to be a significant increase in endurance with reduction of temperature, the endurance at -60°C being about twice that at room temperature. It is interesting to note that at -60°C there appears to be a tendency for several independent cracks to develop in the spar booms before final failure.

7.4 Effects of skin cut-outs

The presence of skin cut-outs has an appreciable effect on the endurance because of the increase in spar boom stresses resulting from major skin failures originating from the cut-outs. Tests on tailplanes with modified skinning (Fig.6) were inconclusive, since major skin cracks still developed sufficiently close to the final spar boom failure to have an effect on the spar boom stresses. Tests on standard tailplanes in which the range of stress in the rear spar tension boom was kept constant were insufficient in number to be conclusive, but they indicated an increase in endurance of between three and four times for a mean load of 25% of the static failing load. (Fig.7).

7.5 Effect of preloading

A single overload applied in the same sense as the mean load gives an appreciable increase in endurance under a fatigue loading of 25% ± 7.5% of the static failing load as shown by Fig.8, the increase being about four times for a preload of 75% of the static failing load. This effect may be partly due to delay in the development of skin cracks.

The effect of ten overloads applied before the fatigue test appears to be to give a further slight increase in endurance, but this conclusion is based on only one test result and can therefore be only tentative.

7.6 Effect of Periodic Overloading

The effect of periodic overloading is to give a marked increase in endurance under a fatigue loading of 25% ± 7.5% of the static failing load as shown by Fig.9. An overload of 50% of the static failing load, applied periodically as indicated in Table VI, increases the endurance about five times, compared with about 1½ times for a single preload. Again, this increase may be partly due to delay in the initiation and slower propagation of the skin cracks.

8 Conclusions

Fatigue tests on a number of tailplanes under a variety of different arbitrary loading conditions give some indication of the fatigue behaviour of a simple structure. The effect of skin cracks developing from unreinforced cut-outs is to increase the spar boom stresses appreciably over a considerable proportion of each test. It might be argued, therefore, that the results given are pessimistic if applied to a structure where such cracks, if they developed at all, would be repaired in service. On the other hand, all test loads were based on the static failing load of the tailplane; static failure occurred by instability of the compression booms of the spars and at the point of failure in the fatigue tests the tension booms only developed about 85% of their specification ultimate tensile strength. From this point of view the fatigue test results might be considered optimistic. In Ref.1 an attempt was made to correct for these effects and it seems reasonable to assume that the two effects cancel each other out to a large extent. The test results may therefore be taken to be representative of the behaviour of a typical structure under fatigue loading.

The tests have confirmed that the fatigue life of a structure is appreciably affected by both mean and alternating load, by the application of overloads both before and during the fatigue test and, to a lesser extent, by temperature.

REFERENCES

No.	Author	Title, etc.
1	K. D. Raithby	Fatigue Tests on Typical Two Spar Light Alloy Structures (Meteor 4 Tailplanes) under Reversed Loading C.P. 88 May 1951.
2	K. D. Raithby	Effects of Low Temperature on the Fatigue Strength of a Two Spar Light Alloy Structure (Meteor 4 Tailplane). R.A.E. Report No. Structures 145, April 1953. A.R.C. 16,114 Strut.1643
3	J. L. Kepert and A. O. Payne	Interim Report on Fatigue Characteristics of a Typical Metal Wing. Commonwealth of Australia. A.R.L. Report No. S.M.207, January 1955.

TABLE I

Tests with various mean and alternating loads (Fig.3)

Tailplane Number	Mean Load % of S.F.L.+	Alternating Load % of S.F.L.+	No. of cycles to failure of spar boom	Position of Spar Boom Failure
1	Max. load 103		1	(Static strength tests. Compression
2	Max. load 99		1	(failure of rear spar top boom about
3	Max. load 98		1	(11.5 in. from centre line.
4	0.8	±10	6.440×10^6	Port rear top 6.7 in. from ℄
7	0.8	±10.5	3.330 "	Port rear bottom 6.7 in. " "
5	2.5	±20	0.315 "	Stbd. rear top 6.7 in. " "
8	2.5	±20	0.323 "	Port front top 11.5 in. " "
6	2.5	±30	0.054 "	Port rear top 6.7 in. " "
10	2.5	±30	0.065 "	Stbd. front top 8.5 in. " "
54	2.5	±60	1,150	Port rear top 6.7 in. " "
17	7.5	±11	1.100×10^6	Port front top 40.0 in. from ℄
26	7.5	±11.5	0.811 "	Stbd. rear top 6.7 in. " "
27	7.5	+21.5	0.065 "	Port front top 11.0 in. " "
20	10	±10	0.517 "	Stbd. rear top 6.7 in. " "
21	10	±10	1.150 "	Stbd. front top 9.5 in. " "
28	10	±10	0.577 "	Stbd. front top 9.7 in. " "
30	10	±10	0.880 "	Port rear top 3.3 in. " "
31	10	±10	1.382 "	Port front top 8.5 in. " "
32	10	±10	0.763 "	Stbd. rear top 6.7 in. " "
19	10	±12	0.543 "	Port front top 9.5 in. " "
22	10	±20	0.110 "	Port rear top 6.7 in. " "
16	15	±10	0.642 "	Stbd. rear top 6.7 in. " "
18	15	±18	0.075 "	Stbd. rear top 6.7 in. " "

/Table I Contd.

TABLE I (Contd.)

Tailplane number	Mean Load % of S.F.L.+	Alternating Load % of S.F.L.+	No. of cycles to failure of spar boom	Position of Spar Boom Failure
12	* 25	±6	1.036×10^6	Stbd. rear top 5.8 in. from ℄
11	* 25	±10	0.286 "	Stbd. rear top 5.8 in. " "
9	* 25	±19	0.030 "	Stbd. rear top 12.5 in. " "
33	25	±3.5	26.863 "	Stbd. rear top 9.5 in. " "
34	25	±4	4.100 "	Stbd. rear top 6.7 in. " "
15	25	±6	1.413 "	Stbd. rear top 6.7 in. " "
13	25	±10	0.384 "	Port front top 9.5 in. " "
14	25	±20	0.029 "	Stbd. rear top 6.7 in. " "
37	25	±30	3009	Port rear top 6.7 in. " "
39	25	±40	819	Port rear top 6.7 in. " "
41	25	±55	181	Stbd. rear top 6.7 in. " "
43	25	±65	3	Compression failure of Stbd. front bottom about 11.5 in. from ℄
55	25	±65	204	Stbd. top (front 10.9 in. from ℄ Stbd. top (rear 6.7 in. " "
57	50	±3.5	2.587×10^6	Port rear top 5.8 in. from ℄
29	50	±8.5	0.100 "	Stbd. rear top 6.7 in. " "
56	50	±25	0.0101 "	Port top (front 10.8 in. " " Port top (rear 6.7 in. " "

\+ S.F.L. = equivalent static load to give a bending moment at 11.5 in. from ℄ equal to mean bending moment at failure in static strength tests

* = with increased torsion, on mean load only

TABLE II

Tests at low temperatures (Fig.5)

Temperature during test	Tailplane Number	Mean Load % of S.F.L.+	Alternating Load % of S.F.L.+	No. of cycles to failure of spar boom	Position of spar boom failure
$-30^{\circ}C$	24	2.5	±16.5	1.116×10^6	(Stbd. front top 12.1 in. from ℄ (Stbd. rear top 1.1 in. " "
$-30^{\circ}C$	23	2.5	±23	0.374 "	Port rear top 12.2 in. " "
$-30^{\circ}C$	25	2.5	±28	0.140 "	Stbd. front top 10.8 in. " "
$-60^{\circ}C$	40	2.5	±19	1.056 "	Stbd. front and rear top (4 cracks)
$-60^{\circ}C$	36	2.5	±26.5	0.171 "	Port and Stbd. front and rear top (3 cracks)
$-60^{\circ}C$	38	2.5	±26.5	0.233 "	Port rear top 5.8 in. from ℄

TABLE III

Tests on modified tailplanes* (inverted for test) (Fig.5)

Tailplane Number	Mean Load % of S.F.L.+	Alternating load % of S.F.L.+	No. of cycles to failure of spar boom	Position of spar boom failure
50	2.5	±11.5	4.312×10^6	Port rear bottom, 44.0 in. from ℄
49	2.5	±20	0.276 "	Stbd.front bottom 9.5 in. " "
51	2.5	±20	0.434 "	Stbd. front bottom 13.0 in. " "
47	25	±6	2.157 "	Stbd. rear bottom 0.5 in. " "
46	25	±10	0.652 "	Stbd. front bottom 0.5 in. " "
48	25	±20	0.061 "	Port rear bottom 11.0 in. " "

* Skin cut-outs were omitted, so avoiding some of the stress concentrations in the skin.
\+ Based on mean static failing load (S.F.L.) of three standard tailplanes

/Table IV

TABLE IV

Tests with constant stress range in rear spar boom at rib 2* (Fig.7)

Tailplane Number	Mean Load % of S.F.L.+	Alternating Load % of S.F.L.+	No. of cycles to failure of spar boom	Position of spar boom failure
45	25	±10	0.725×10^6	Port rear top, 6.0 in. from ℄
53	25	±10	3.436 "	Port front top, 9.5 in. " "
52	25	±20	0.098 "	Stbd. rear top, 6.7 in. " "

* This necessitates reducing the load as skin cracks develop. Values of mean and alternating loads given are those at the beginning of the test.

TABLE V

Tests with preloads applied to the tailplanes (Fig.8)

Tailplane Number	Mean Load % of S.F.L.+	Alternating Load % of S.F.L.+	Preload % of S.F.L.+	No. of times Preload Applied	No. of cycles to failure of spar boom	Position of spar boom failure
35*	25	±7.2	50	1	1.288×10^6	Port rear top, 6.0 in. from ℄
44	25	±7.5	66.7	1	1.825 "	Stbd. rear top, 6.7 in. " "
42	25	±7.5	50 75	1 1	3.500 "	Stbd. rear top, 6.7 in. " "
60	25	±7.5	40	10	1.110 "	Stbd. rear top, 6.8 in. " "

* Estimated endurance for ±7.5% S.F.L. = 1.220×10^6 cycles.

\+ Based on mean static failing load (S.F.L.) of three tailplanes

TABLE VI

Tests with periodically applied overloads (Fig.9)

This table gives results of fatigue tests on tailplanes which were given overloads at the beginning of and during the fatigue test at the following intervals:-

	Every	20,000 cycles	to	500,000 cycles	
Then	"	50,000 "	"	1,000,000	"
"	"	100,000 "	"	2,000,000	"
"	"	650,000 "	"	failure	

Tailplane Number	Mean Load % of S.F.L.+	Alternating Load % of S.F.L.+	Periodic Overload % of S.F.L.+	No. of cycles to failure of spar boom	Position of spar boom failure
59	25	±7.5	40	1.138×10^6	Port rear top, 6.7 in. from ℄
61	25	±7.5	45	1.762 "	Port rear top, 6.0 in. " "
58	25	±7.5	50	4.166 "	Port front top, 9.8 in. " "

\+ Based on mean static failing load (S.F.L.) of three tailplanes.

TABLE VII

Estimated spar boom stresses at beginning of test

Stresses are expressed in terms of the mean load M and alternating load A, expressed as a percentage of the mean static failing load.

Distance from tailplane centre-line - in.	6.5	11.5	40.6
Stress in front spar tension boom (on net area) - lb/in^2	370(M±A)	350(M±A)	360(M±A)
Stress in rear spar tension boom (on net area) - lb/in^2	500(M+A)	510(M±A)	560(M±A)

Note For tailplanes 9, 11 and 12, in which the mean load was applied to the outer elevator hinges, the mean stress was increased by about 10% in the rear spar and decreased by about 20% in the front spar near the tailplane root attachments.

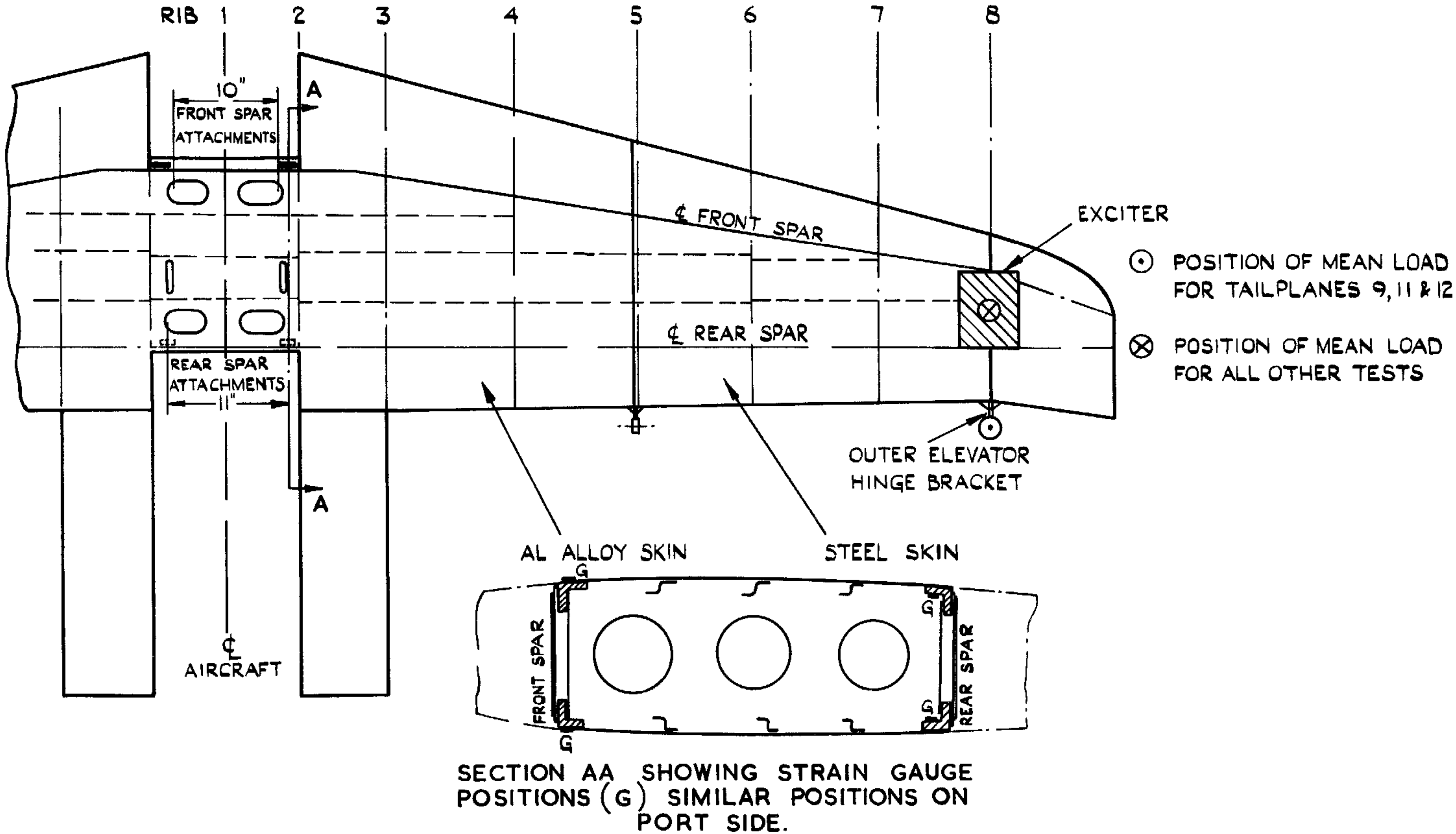


FIG. 1. GENERAL ARRANGEMENT OF TEST SPECIMEN.

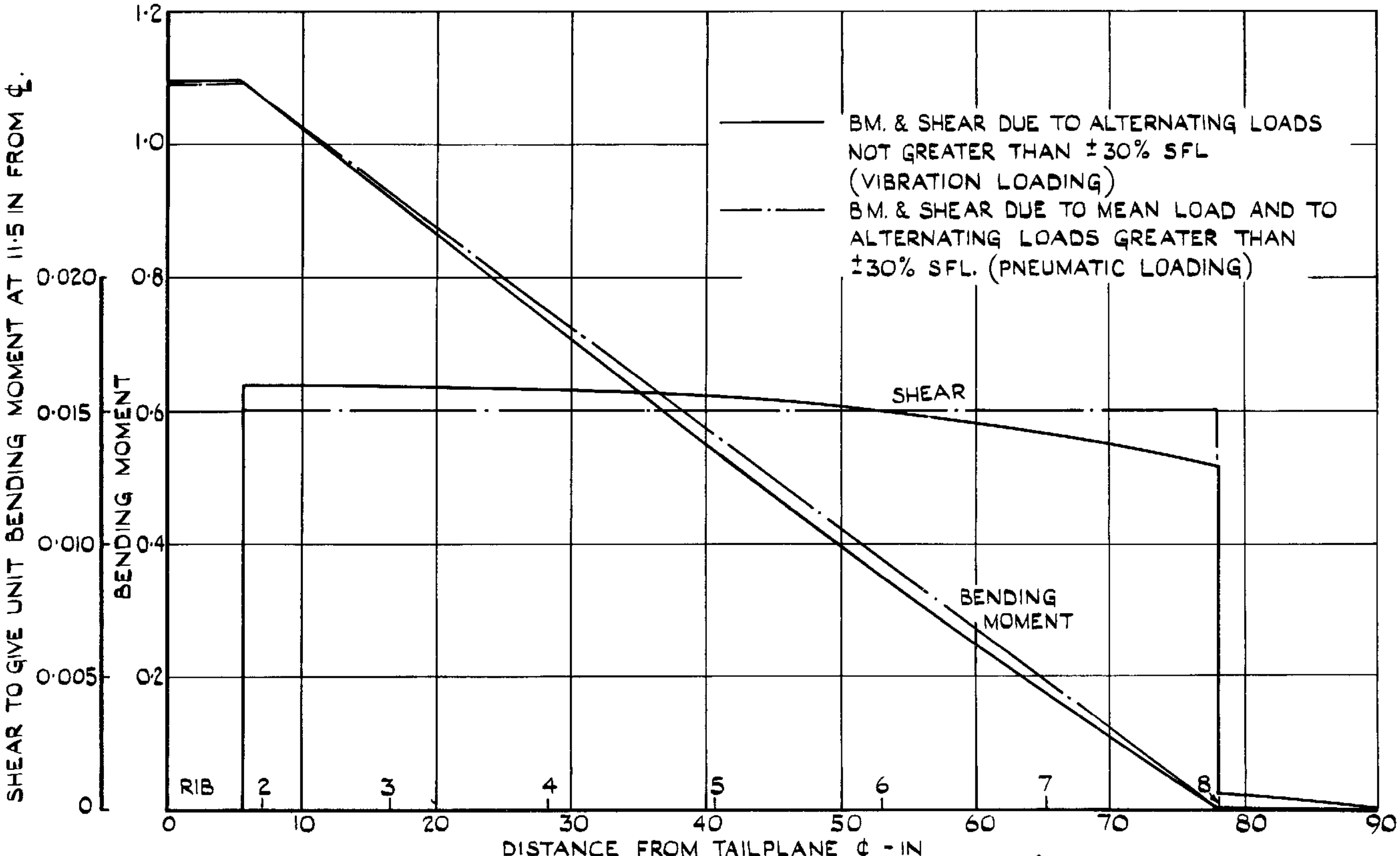


FIG. 2. SHEAR AND BENDING MOMENT CURVES (UNIT B.M. AT 11·5 IN. FROM ℄.)

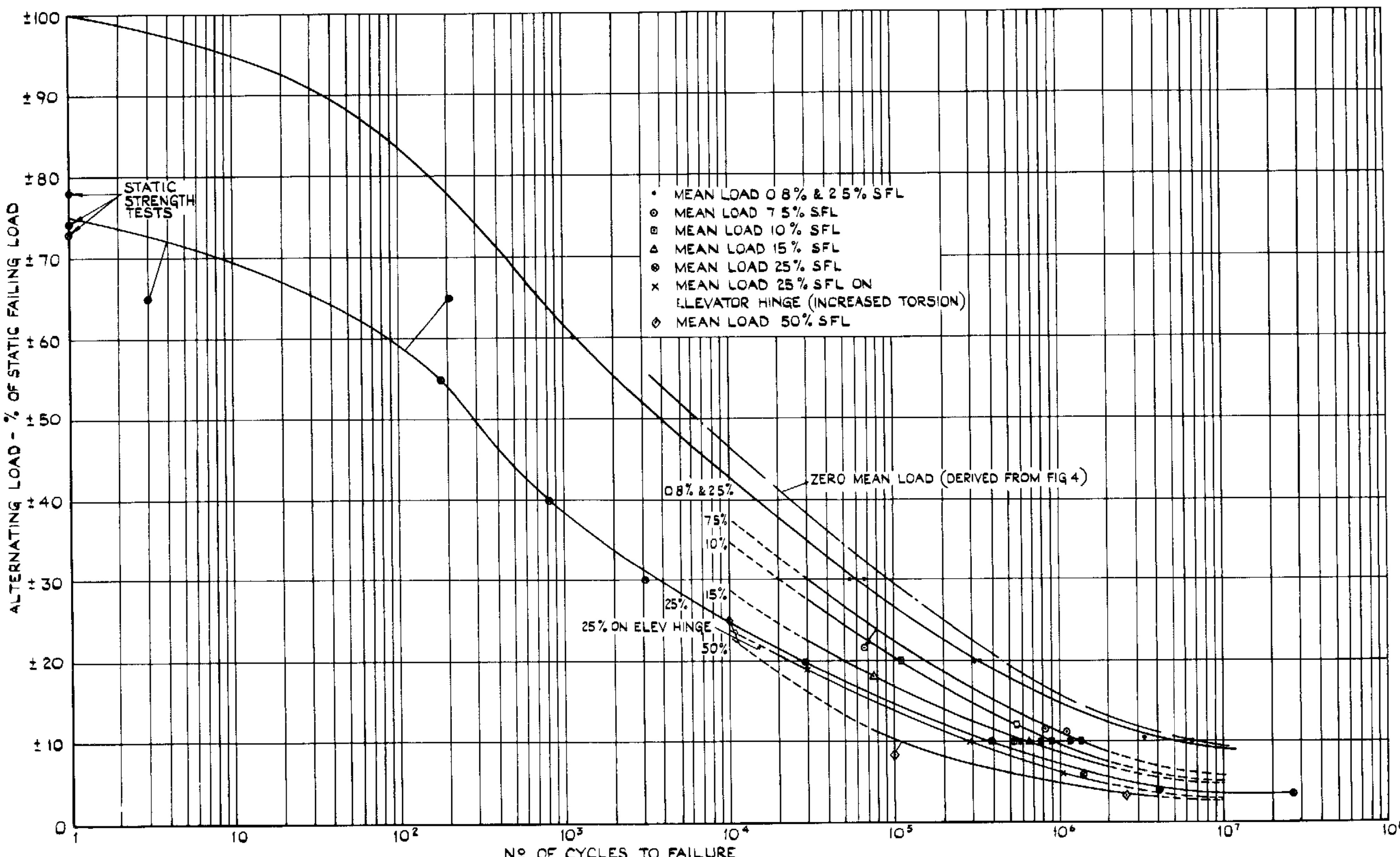


FIG. 3. ENDURANCE CURVES FOR VARIOUS MEAN LOADS (TABLE I.)

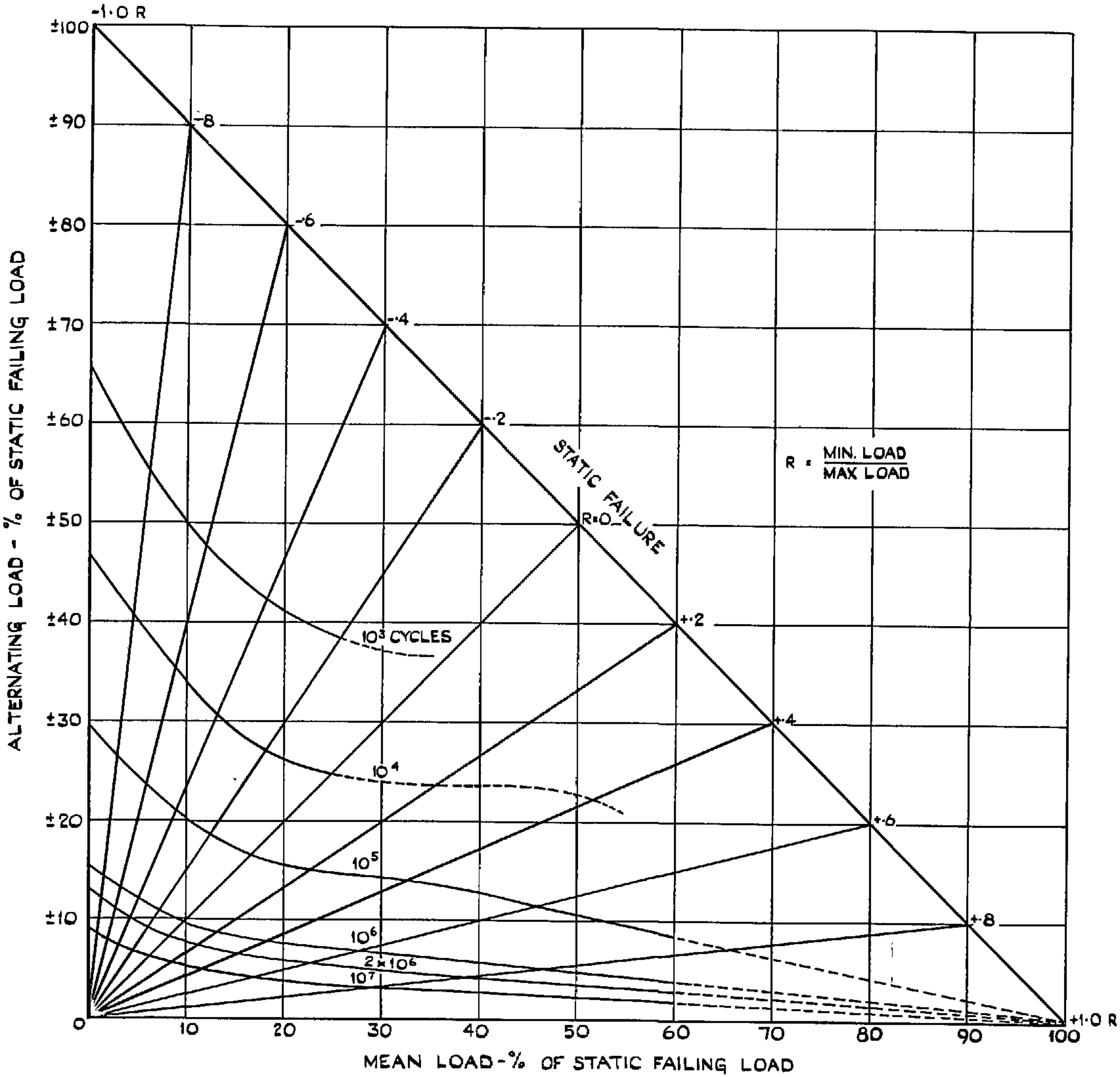


FIG. 4. CURVES OF CONSTANT ENDURANCE.

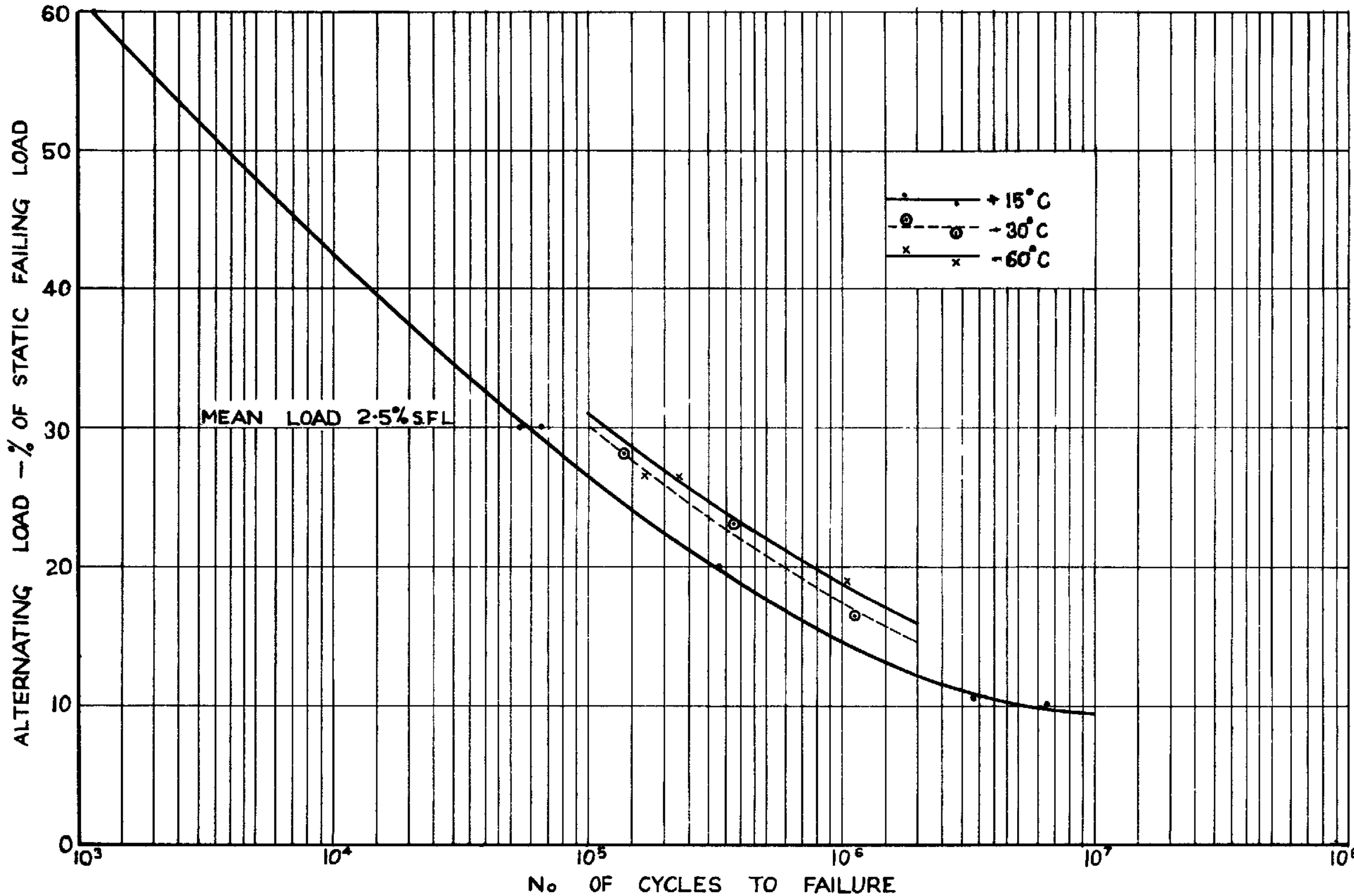


FIG.5. EFFECT OF LOW TEMPERATURES ON ENDURANCE (TABLE II.)

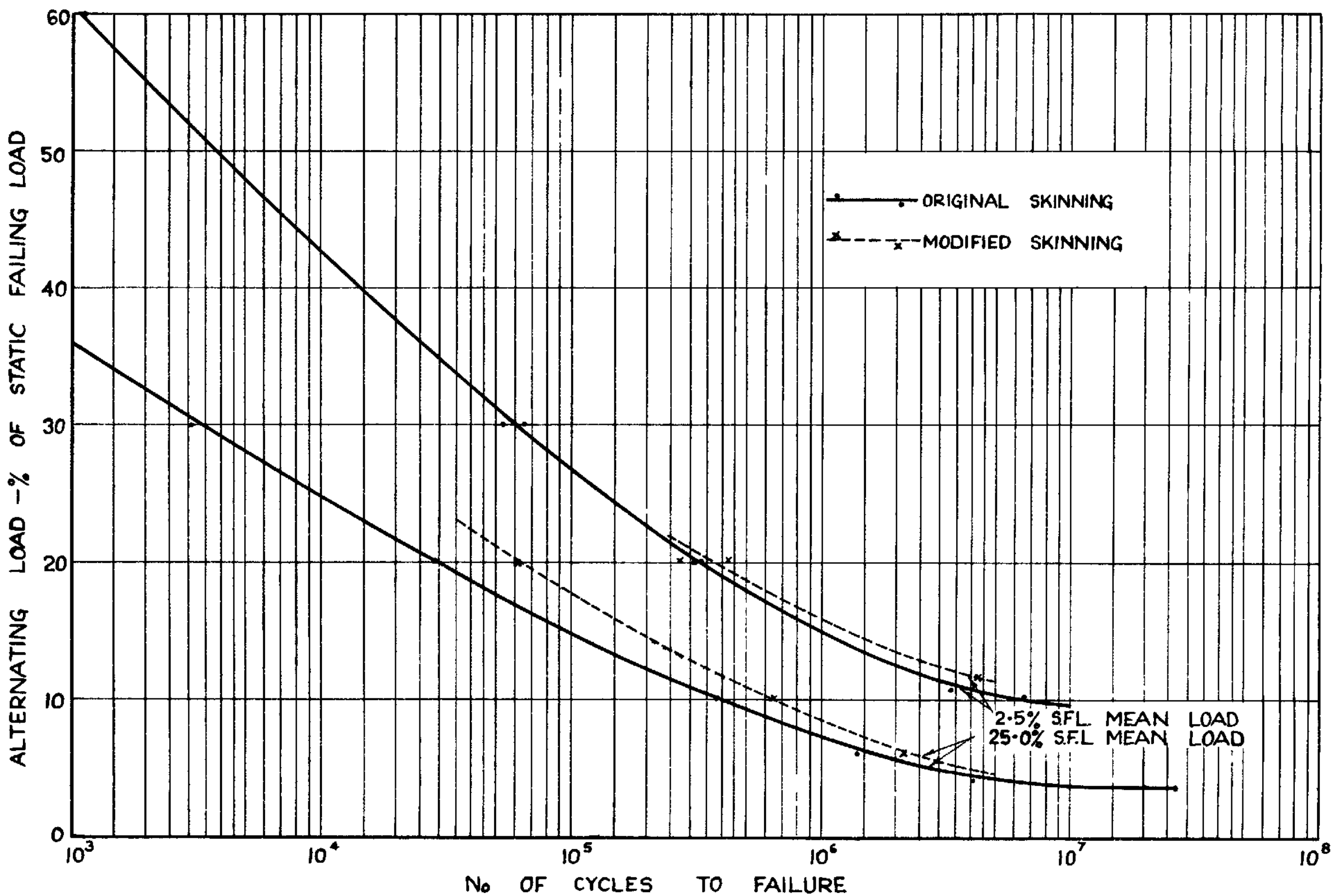


FIG. 6. ENDURANCE CURVES FOR ORIGINAL & MODIFIED TAILPLANES (TABLE III)

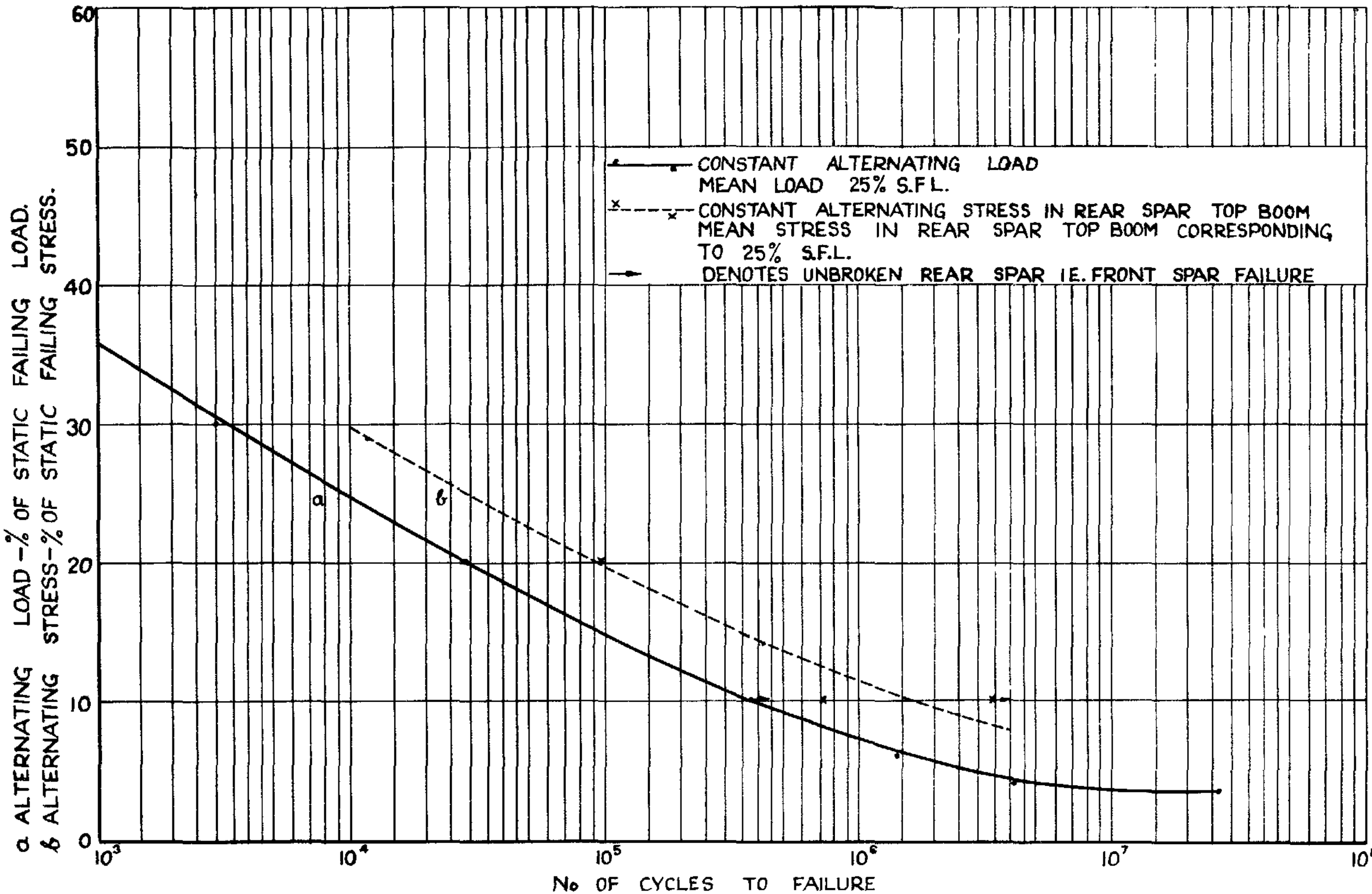


FIG. 7. ENDURANCE CURVES FOR 'CONSTANT LOAD' AND 'CONSTANT STRESS' TESTS. (TABLE IV)

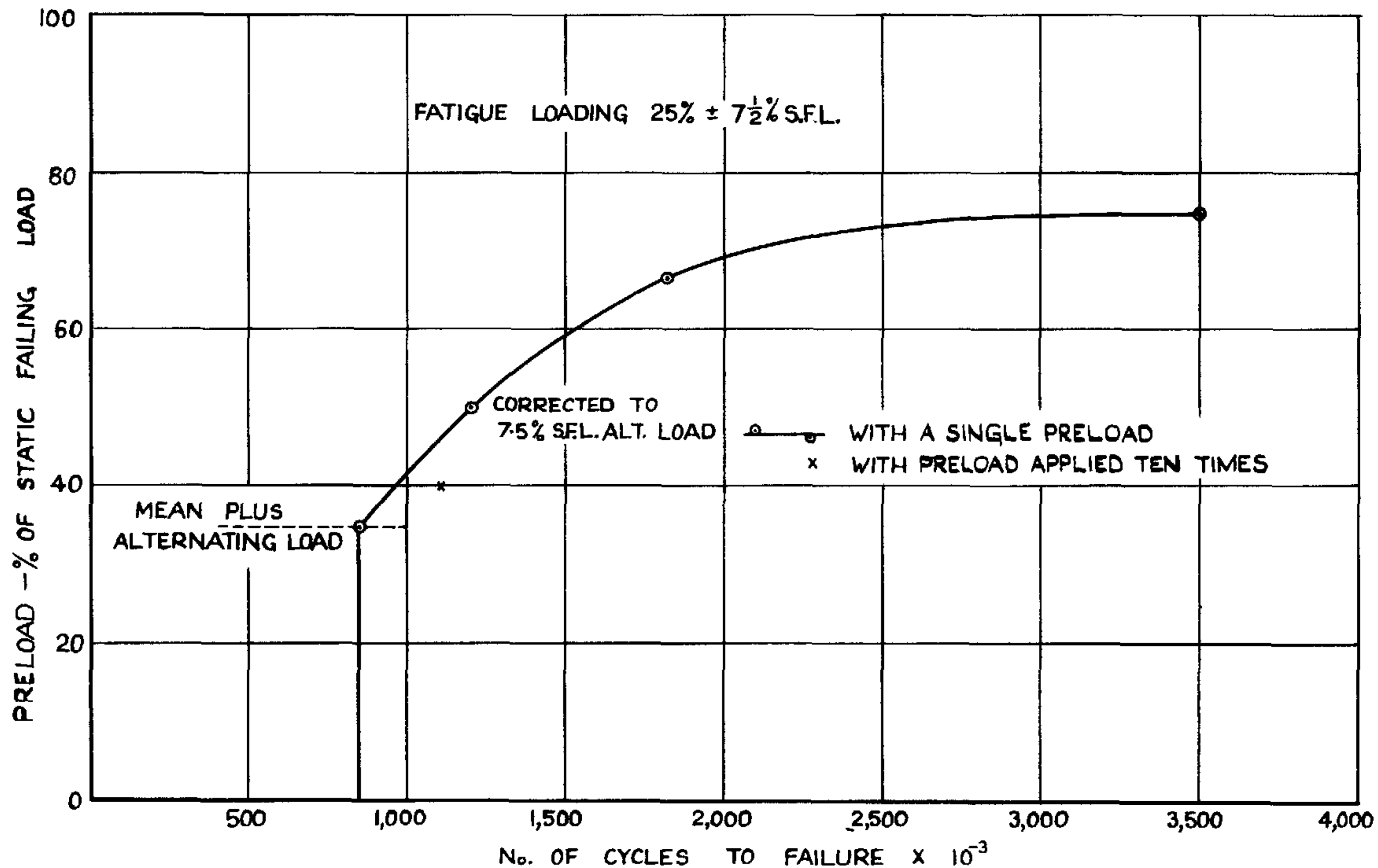


FIG. 8. EFFECT OF PRELOADING ON ENDURANCE (TABLE V.)

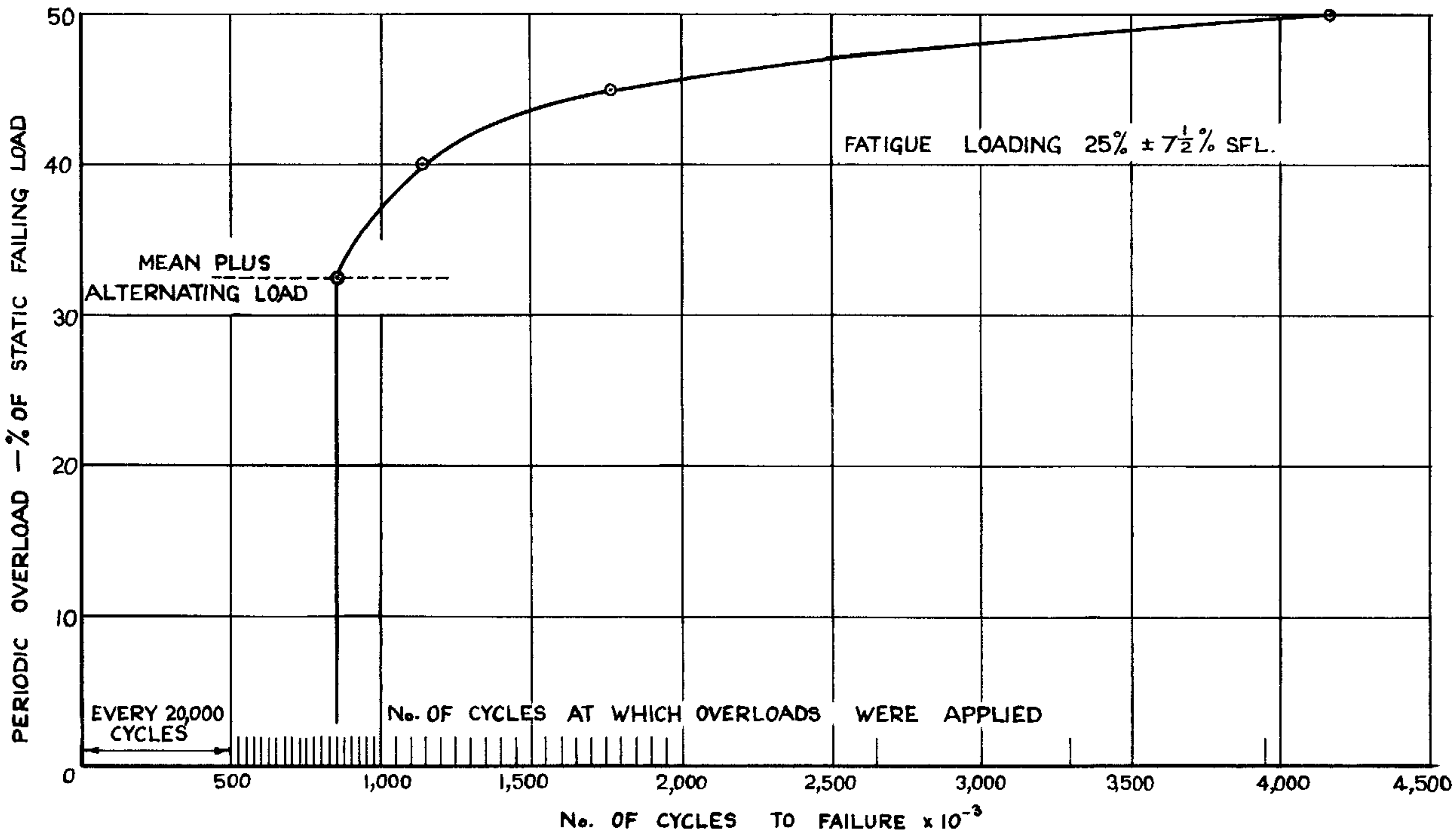
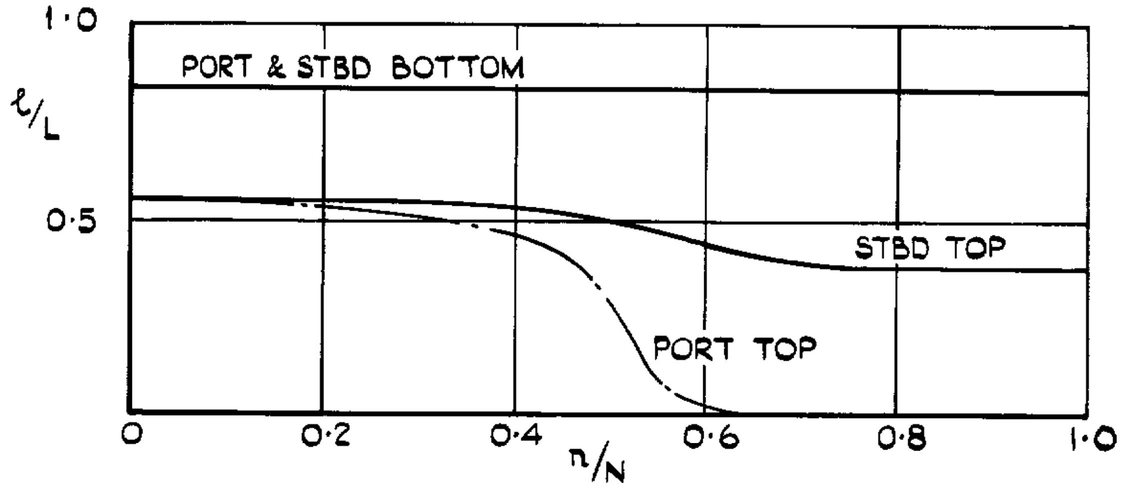
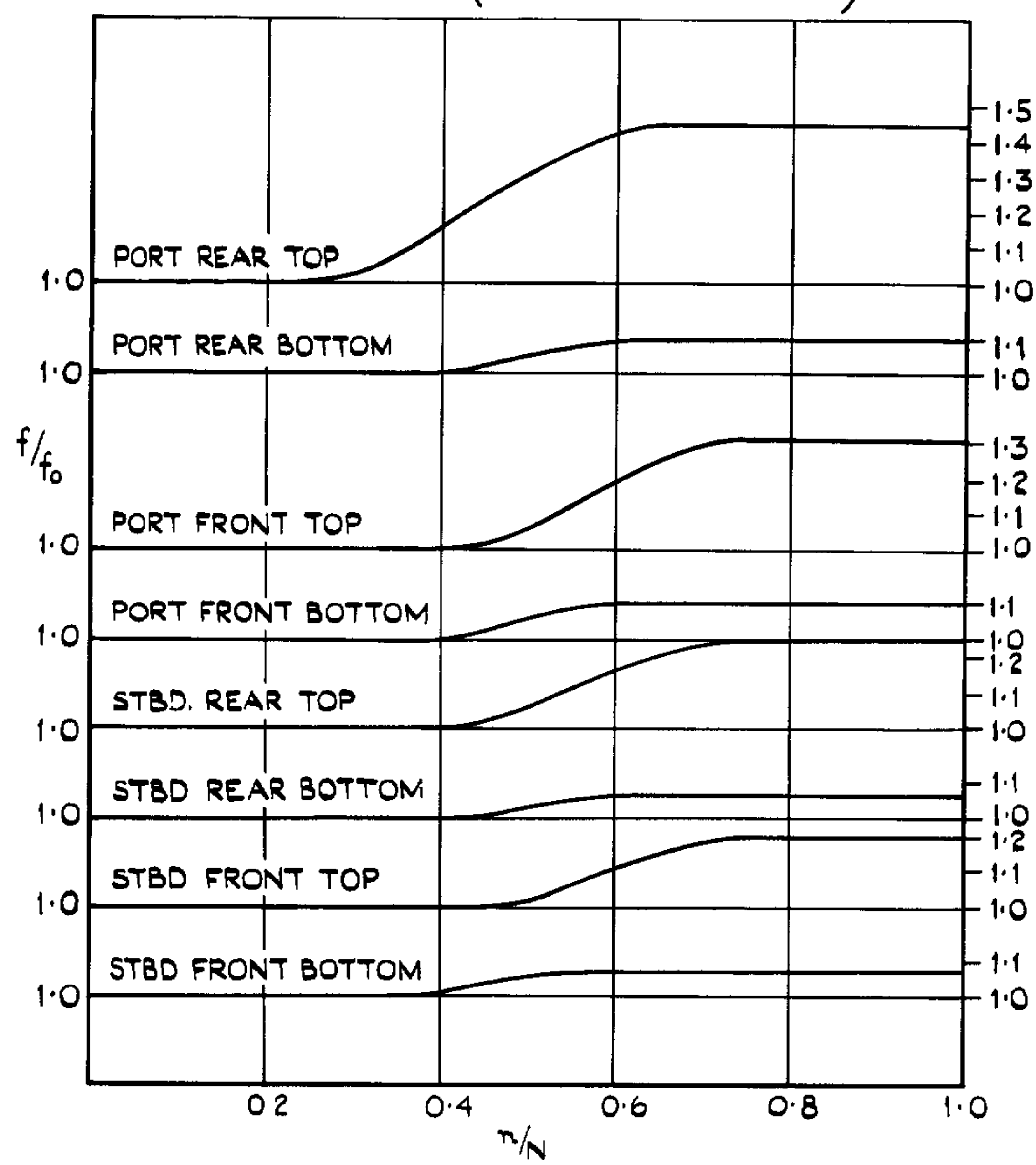


FIG. 9. EFFECT OF PERIODIC OVERLOADING ON ENDURANCE (TABLE VI.)



ℓ = EFFECTIVE WIDTH OF SKIN AFTER n CYCLES
L = DISTANCE BETWEEN SPARS.
N = Nº OF CYCLES TO FAILURE OF SPAR BOOM

FIG. 10. DEVELOPMENT OF SKIN CRACKS AT RIB 2. (TAILPLANE Nº. 22.)



f : SPAR BOOM STRESS AFTER n CYCLES.
f_0 : SPAR BOOM STRESS AT BEGINNING OF TEST.

FIG. 11. VARIATION OF SPAR BOOM STRESSES WITH Nº. OF CYCLES AT RIB 2. (TAILPLANE Nº. 22)

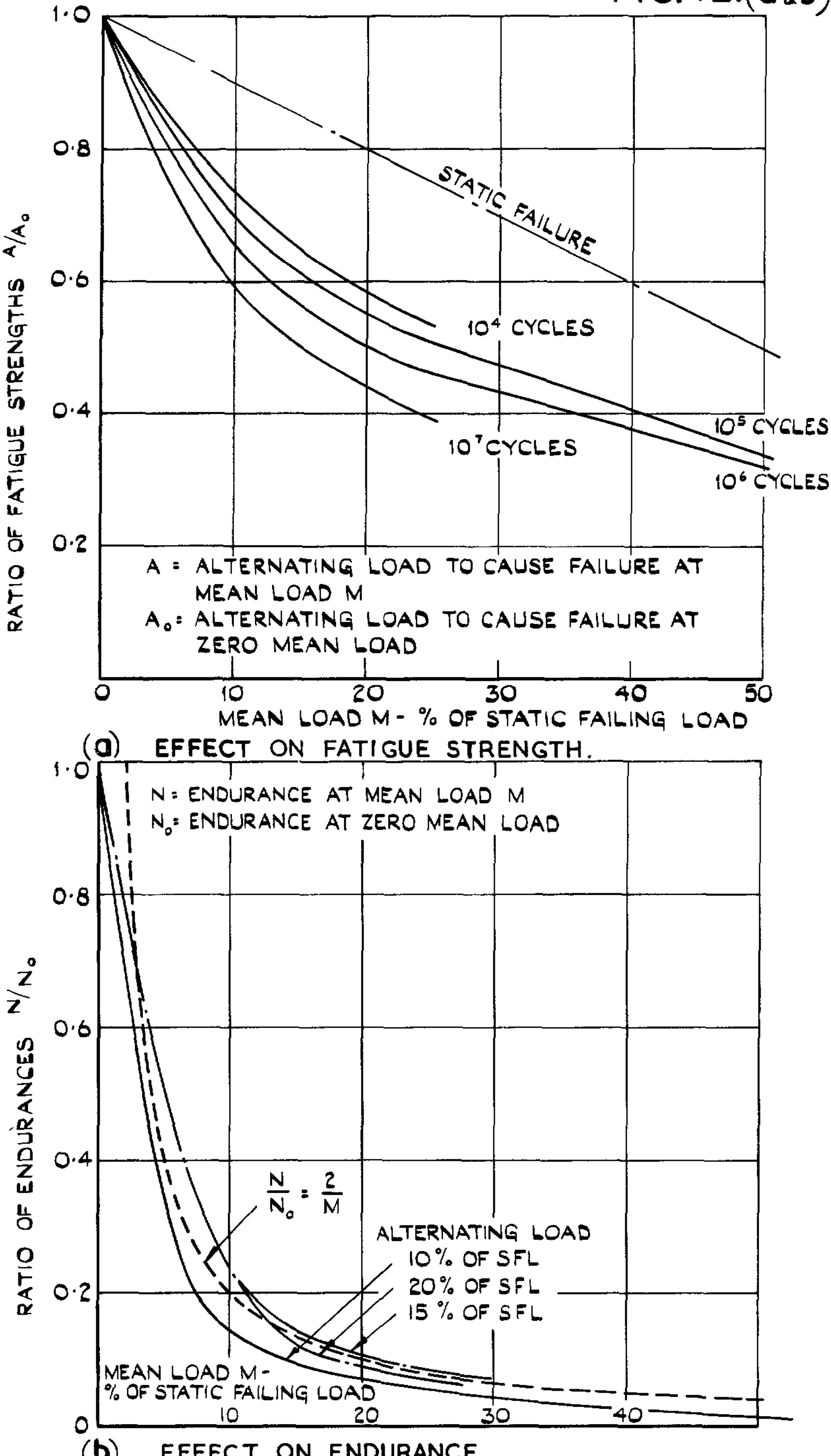


FIG.12 (a&b) EFFECTS OF MEAN LOAD ON FATIGUE STRENGTH AND ENDURANCE.

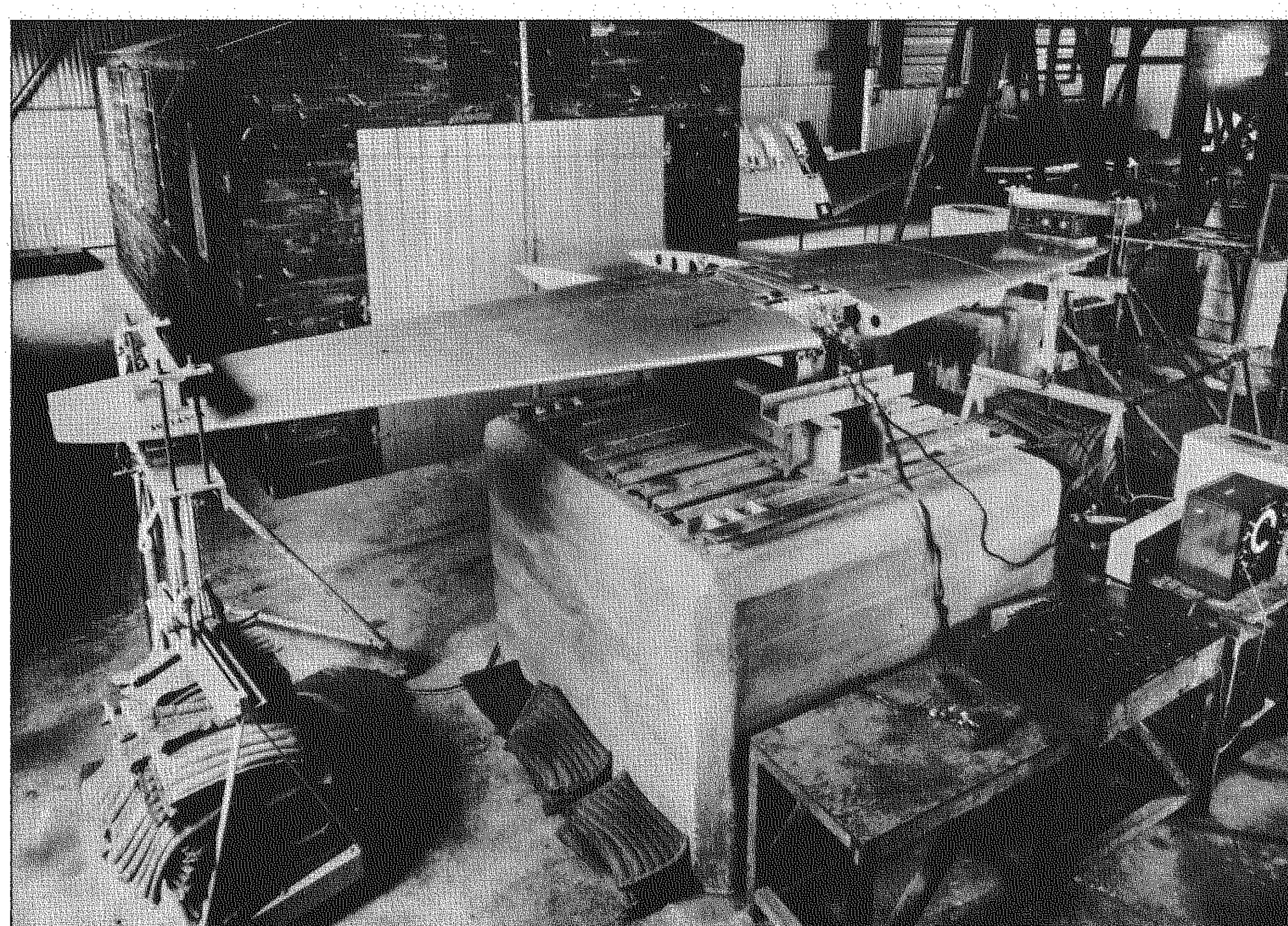


FIG.13. GENERAL VIEW OF TAILPLANE IN VIBRATION TEST RIG

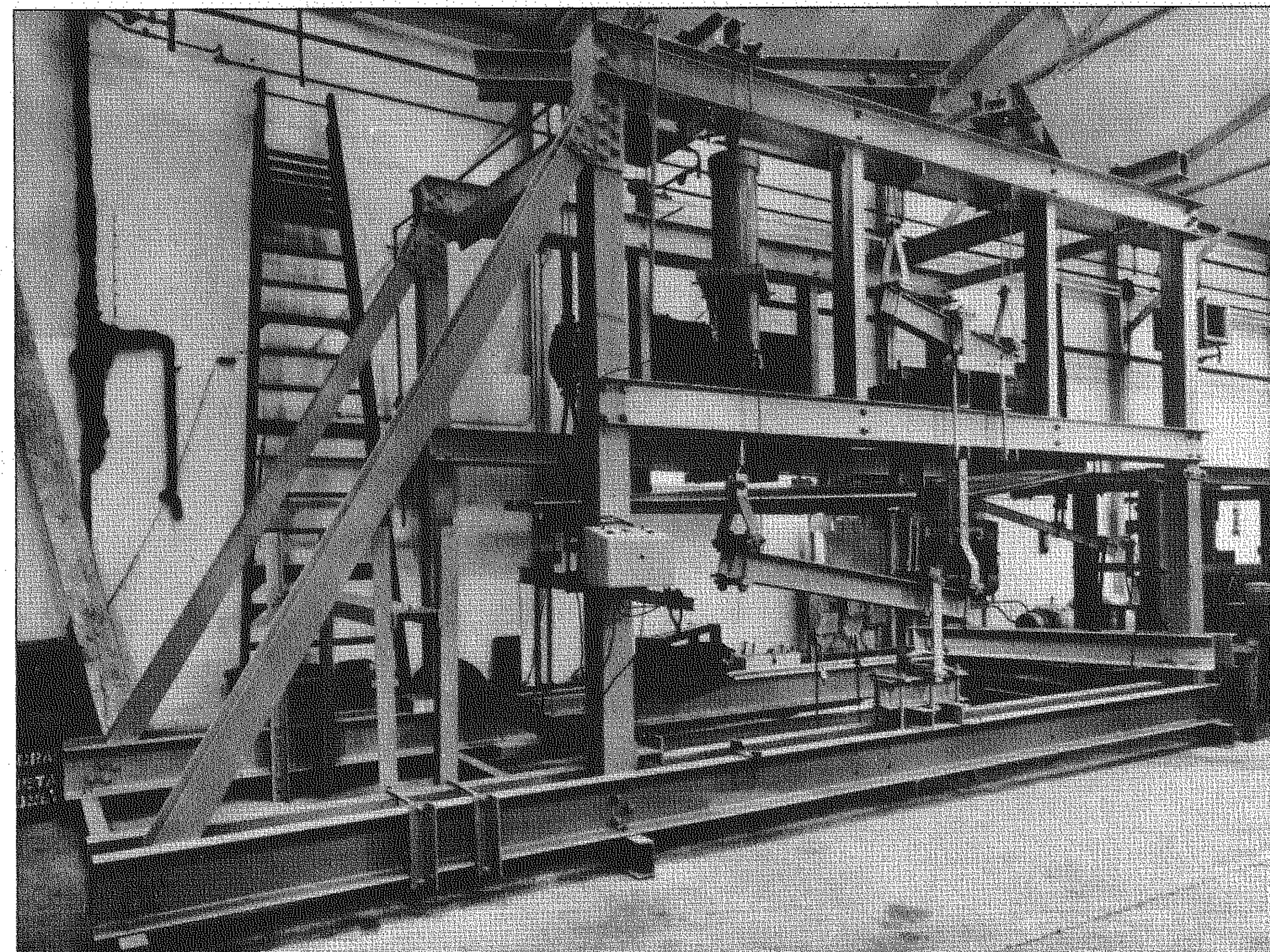


FIG.14. TAILPLANE IN PNEUMATIC TEST RIG

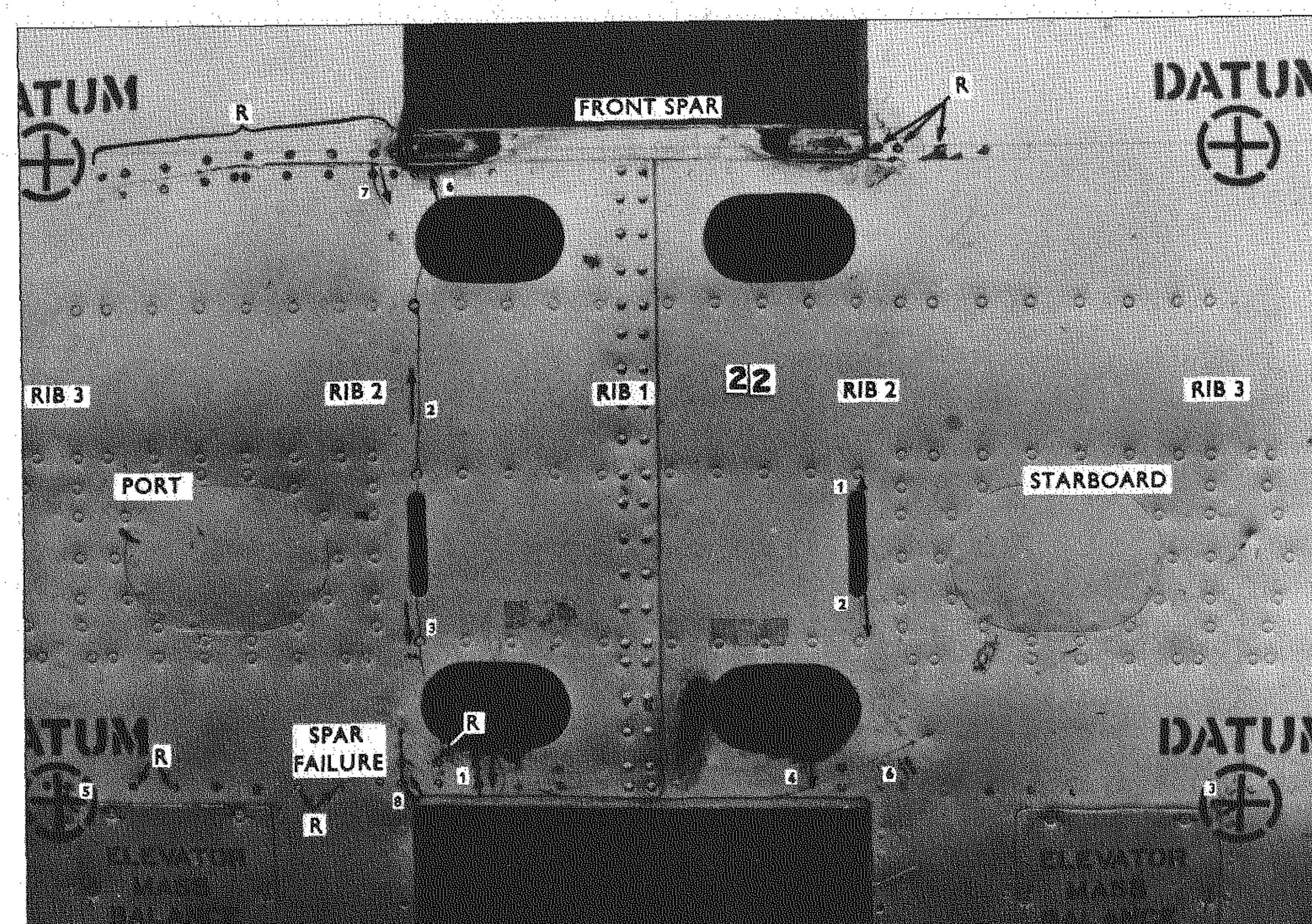


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FIG.15. TYPICAL SKIN CRACKS (TAILPLANE No.22)

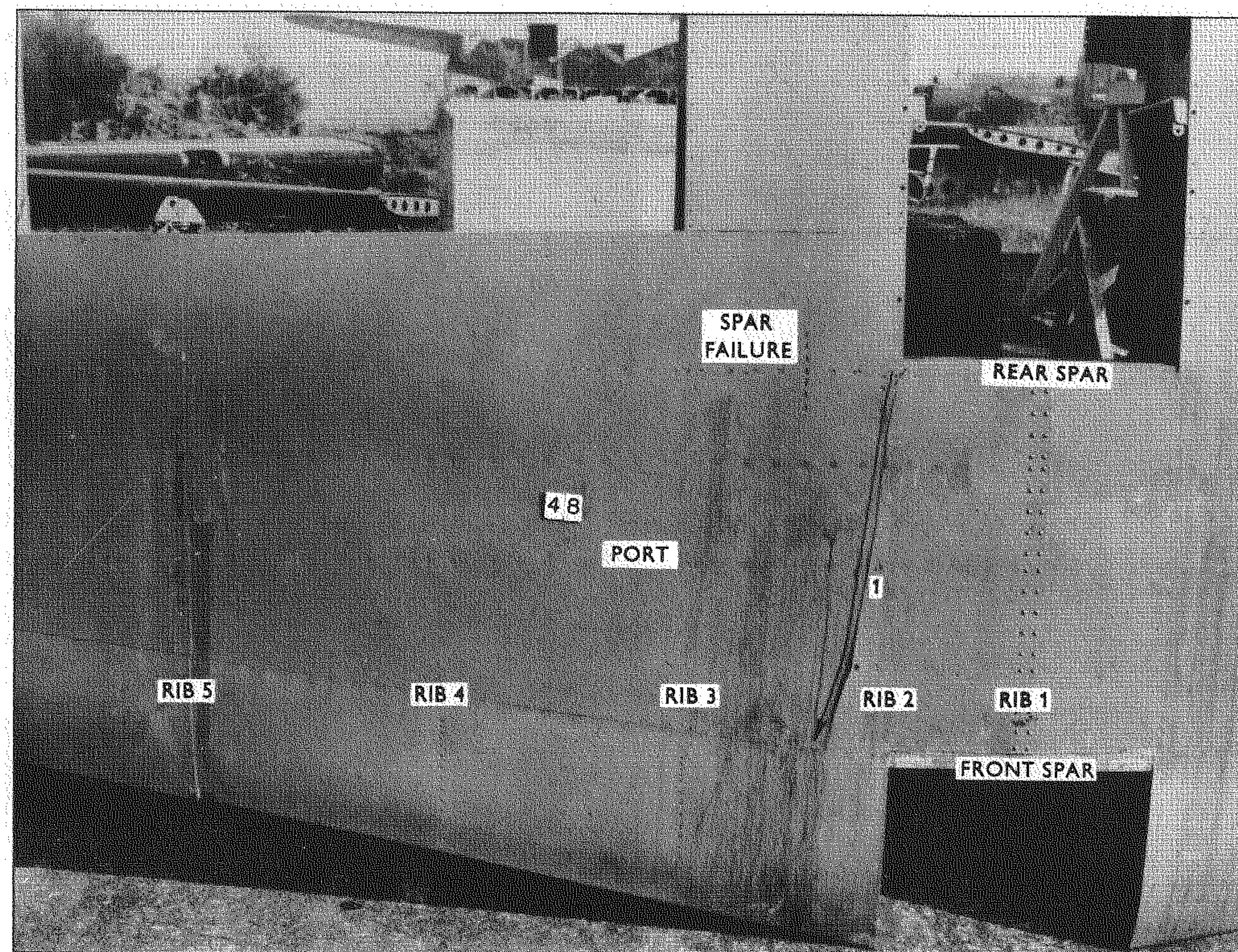
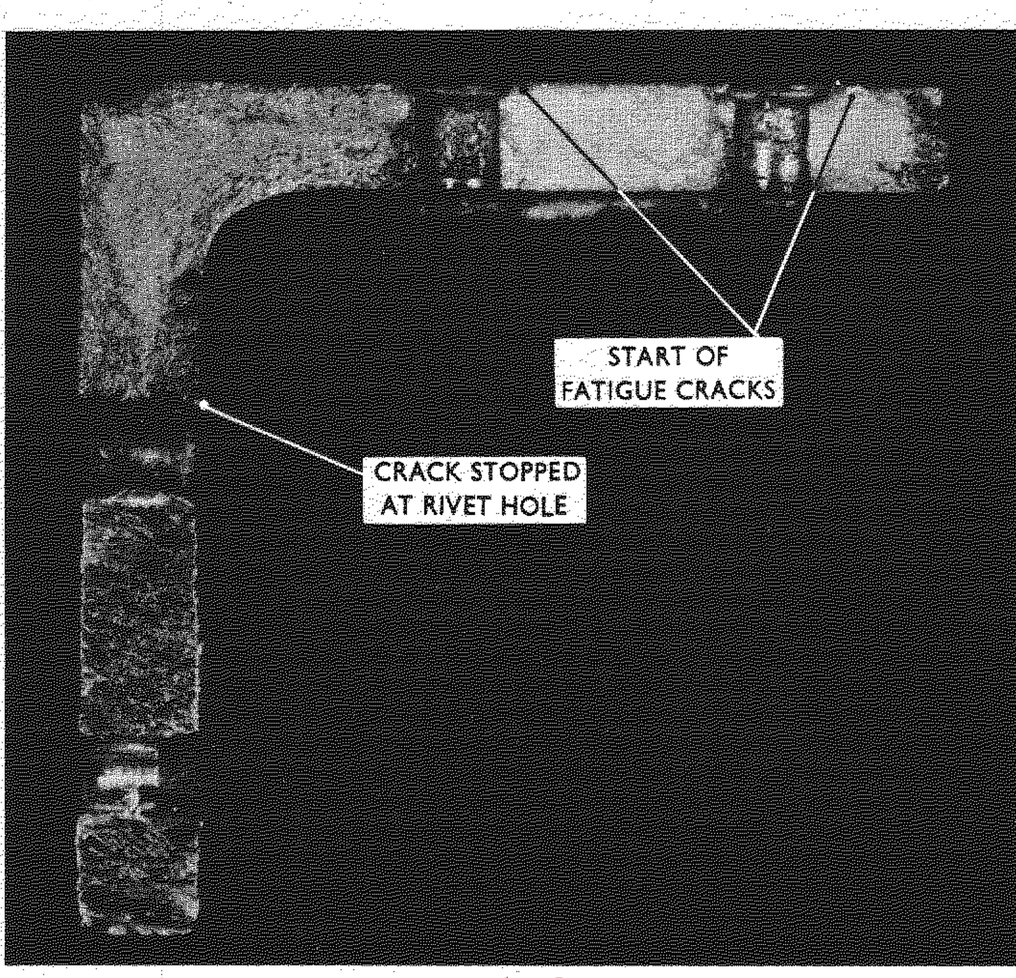
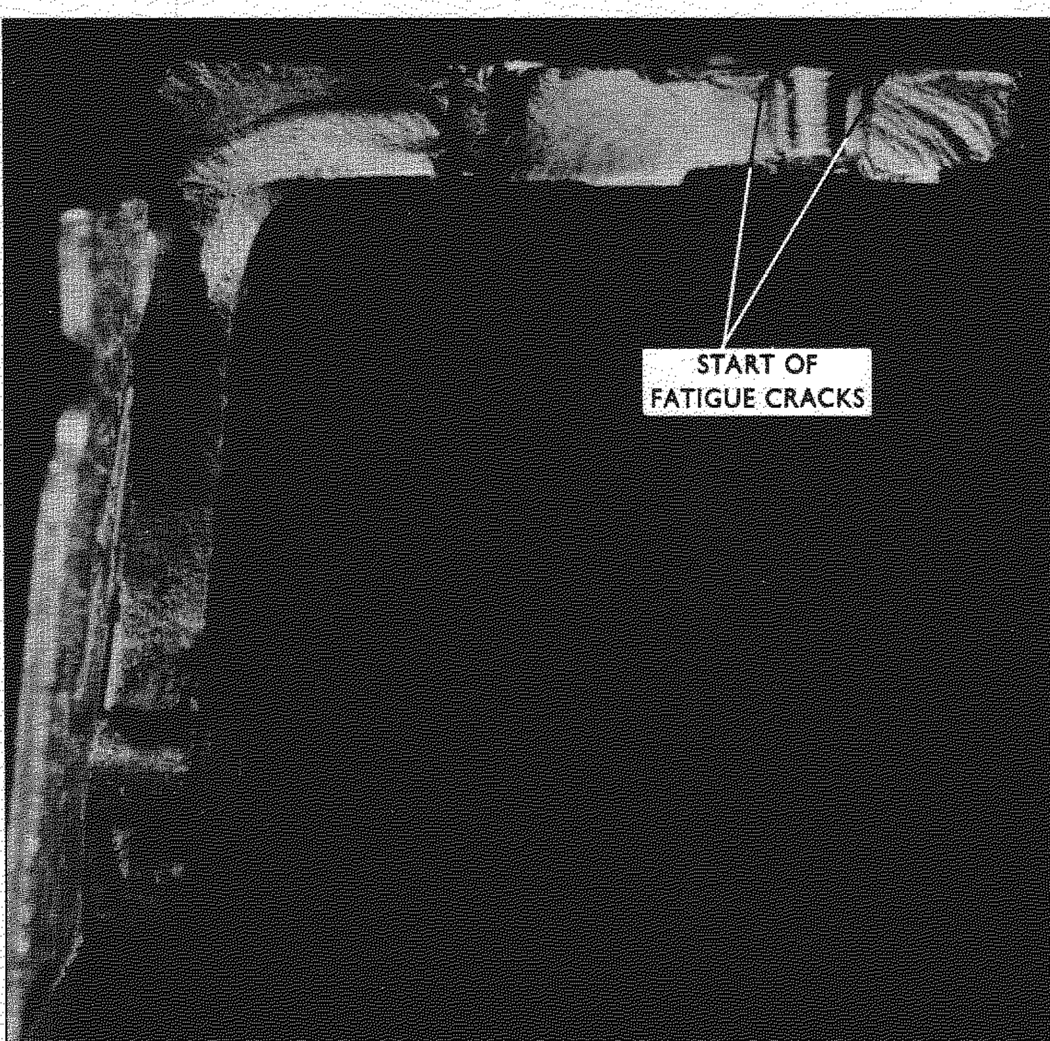


FIG.16. SKIN CRACK ON MODIFIED TAILPLANE

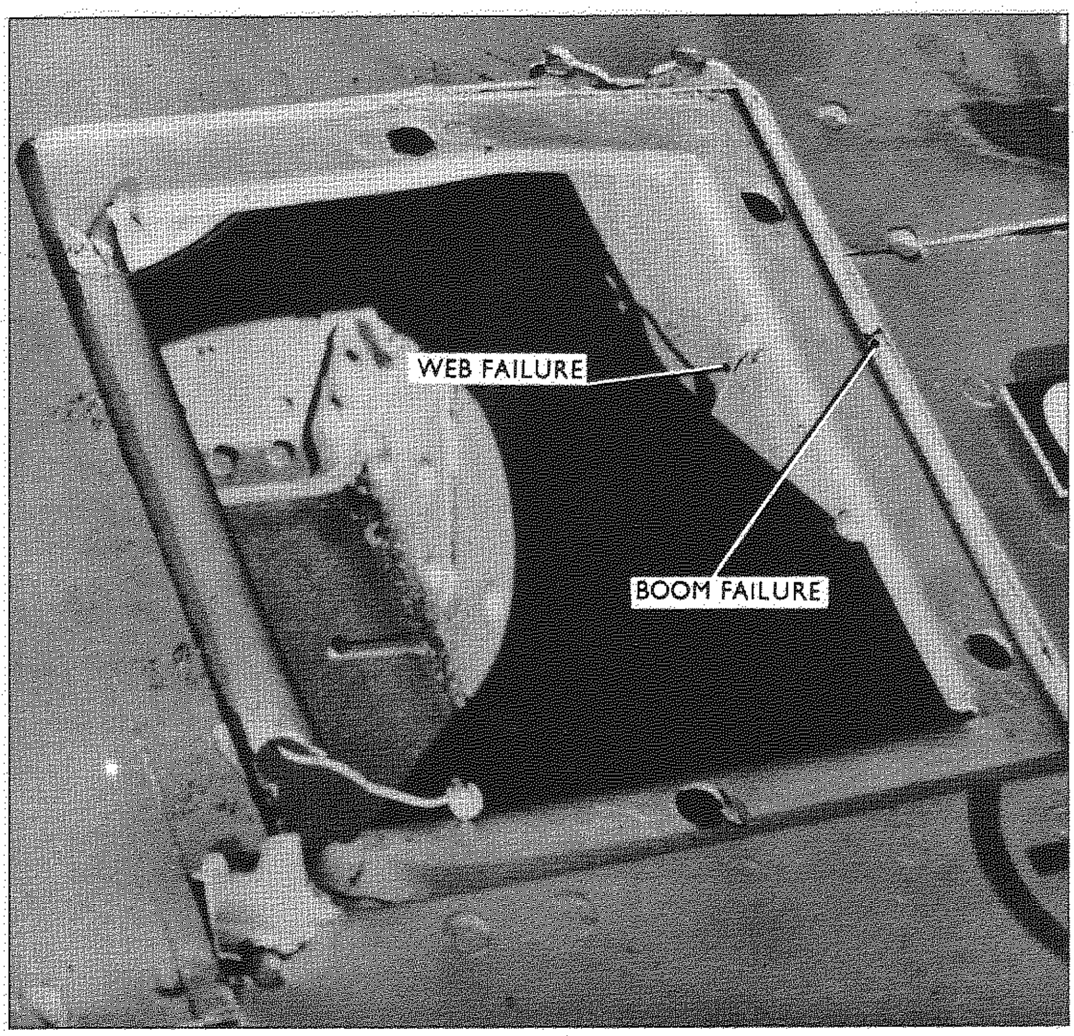


REAR SPAR, 5.5 in. FROM ℄ (TAILPLANE No.11)



FRONT SPAR, 9.5 in. FROM ℄ (TAILPLANE No.13)

FIG.17. TYPICAL SPAR BOOM FRACTURES



EXTERNAL APPEARANCE OF FAILURE

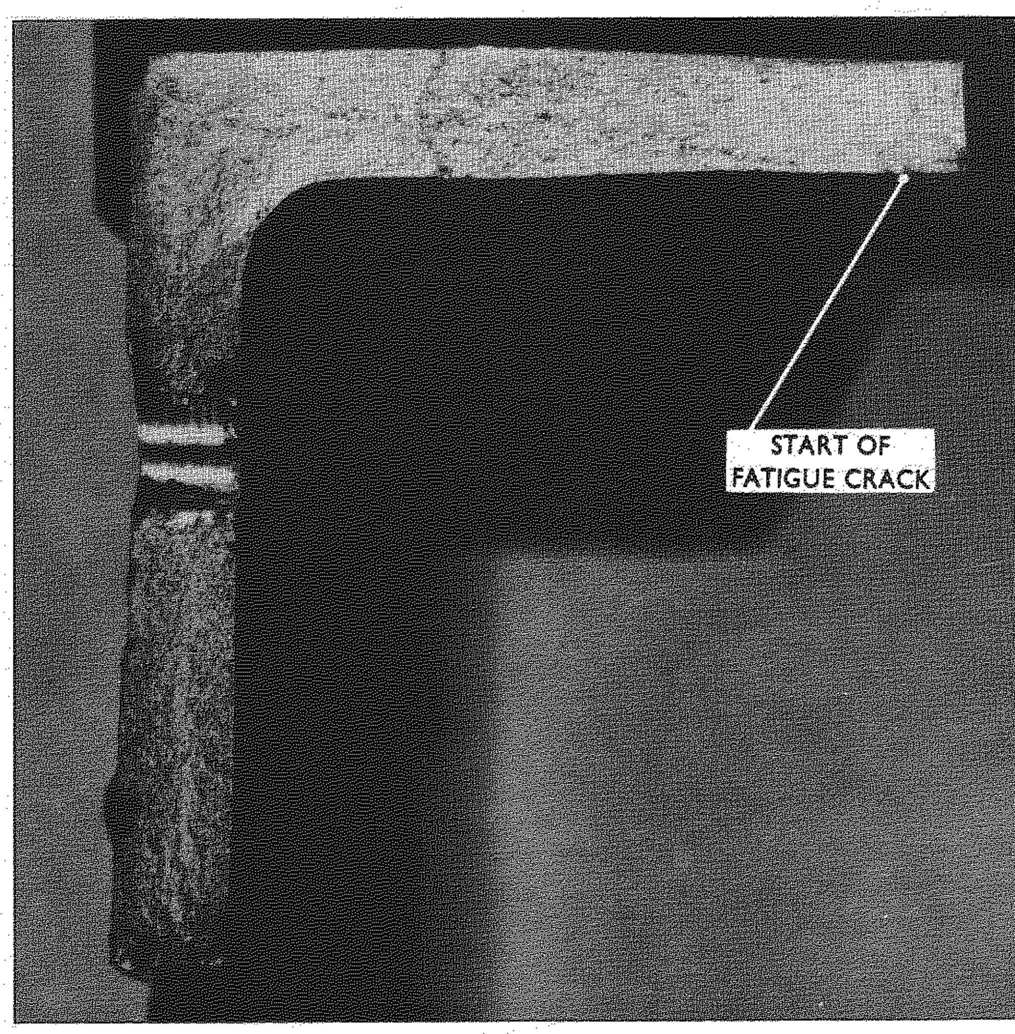


FIG.18. FRACTURE OF REAR SPAR TOP BOOM (TAILPLANE No.9)

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