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The Influence of Pre-Loading on the Fatigue Life of Aircraft Components and Structures

By

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The Influence of Pre-Loading on the Fatigue Life of Aircraft Components and Structures

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SUMMARY

Tests on aircraft components and structures are described which show that pre-loading can have a marked influence on fatigue behaviour. Tensile pre-loading may increase the life - in one instance a hundredfold improvement was obtained - and compressive pre-loading may reduce the life. The effect is attributed to residual stresses and to load redistributions induced by pre-loading.

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1 Introduction

In a paper published in the Journal of the Institute of Metals in 1946, Forrest[1] demonstrated that the fatigue strength of certain aluminium alloy parts could be markedly increased by pre-loading. The implication that a similar trend might be obtained generally for aircraft components and structures has been investigated at R.A.E., and the results of tests are described in the present report. Consideration is given to three types of specimen: unnotched specimen, notched specimen and a structure.

2 Experimental Results

2.1 Unnotched Specimens

In fatigue tests carried out by Aluminium Laboratories Ltd. and quoted by Teed[2], the stretching of a plain polished bar in the aluminium alloy B.S. L.1 produced a small but progressive reduction in fatigue strength with increase in stretch, see Table I.

Tests on plain specimens made in clad sheet material to Specification D.T.D.546 B have confirmed that the fatigue strength is not appreciably affected by pre-loading, see Appendix I.

2.2 Parts with Stress Raiser

Fatigue tests on the effect of pre-loading of simple notched specimens have been conducted on the following types of specimen:-

Sheet specimen with transverse hole (Appendix I).

Simple lug with load applied to hole (Appendix II).

Channel-sectioned part, containing bolts, rivets and open holes (Appendix III).

Circular and flat bars with transverse hole (Appendix IV).

Circumferential V notch in round specimen (Appendix VII).

Spot welded joint (Appendix VII).

The detailed results are given in the Appendices, and the general results show that pre-loads in tension exceeding a certain amount increase life, and in compression reduce life. Extruded parts are particularly sensitive to pre-load - in some cases the life was increased by ten or even one hundred times by a tensile pre-load, or reduced to one twentieth by a compressive pre-load.

Specimens made from sheet as distinct from extruded material were not so sensitive to pre-loads. This may have been because residual stresses due to pre-loading tended to fade during the fatigue test, since the nominal fatigue stresses used were comparatively high. Similar behaviour showing no effect due to pre-loading has been reported[4] for notched specimens made in a very low strength aluminium alloy of $11\frac{1}{2}$ tons per sq in. tensile strength.

2.3 Structural Elements

Tests on channel section specimens described in Appendix III show that a substantial increase in endurance is obtained by tensile pre-loading when redundancy is present due to the attachment of sheet material by rivets and bolts.

The fatigue testing of a number of aircraft joints of different designs has also shown the advantages of a tensile pre-load, see Appendix V. In all cases the joints consisted of an aluminium alloy boom to which was attached steel end fittings by means of bolts in shear.

Tests on Meteor tailplanes subjected to various degrees of pre-load have similarly shown an improvement in life, both for the skin and the spar boom, see Appendix VI. Very high pre-loads tended to produce buckling on the compression side of the tailplane and this represented a practical limit to the amount of load that could reasonably be applied.

An improvement in life due to pre-loading (ranging from 43% to 235% increase in life) has been obtained by Johnstone and Payne[5] for Mustang wings in which comparatively high alternating loads were used in the fatigue tests (±16 to ±27% of failing load). Results are expressed in terms of load and not in terms of stress, and so cannot be compared with other data.

3 Comparison of Results

A comparison of results for aluminium alloy sheet specimens in plain and transverse hole conditions is unnecessary, as the effect of pre-loading on endurance was comparatively small or non-existent.

For all other types of specimen, as given in Appendices II to VI, the results for tensile pre-loading are compared graphically in Fig. 7, with the degree of pre-load expressed as a percentage of the 0.1% proof stress of the material.* Fig. 7 shows that with one exception, a consistent and substantial increase in endurance is obtained by pre-loading. The exception refers to a test on a transverse hole specimen, in which flaws were found at the point of origin of the fatigue crack.

The comparison is simplified by using ratios of endurance for pre-loaded and non pre-loaded parts, as shown in Fig. 8. In spite of the scatter that is present due to the widely different conditions used in individual tests, the general trend in results shows that a pre-load equivalent to 80% or more of the 0.1% proof stress produces a substantial increase in endurance. The upper limit of the pre-load stress at which the increase is obtained has been established for the loaded lug case described in Appendix II, and from this it appears that the improvement is obtained up to the point where static failure intervenes. This is confirmed by the very high prior loads used by Templin, as described in para 2.2.

4 Discussion

The effect of pre-loading is twofold - it produces residual stresses due to differential plastic straining actions, and it alters the load distribution amongst the redundant members of a structure. Both can effect the subsequent fatigue behaviour, principally because there is a change in the mean stress distribution. At stress concentrations, the residual compressive stresses induced by tensile pre-loading should be beneficial in fatigue, and for compressive pre-loading, the residual tensile stresses should be harmful.

An extreme example of pre-loading arises in a structure or component which has been subjected to a static test to destruction and is then repaired and tested in fatigue. Results from the fatigue test are likely to be

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* The following values of the 0.1% proof stress have been assumed

D.T.D. 363A - 33 t.s.i.
D.T.D. 364B - 28 t.s.i.
D.T.D. 683 - 30 t.s.i.
RR 77 - 30 t.s.i. (Appendix IV)

dangerously misleading as they may show a much greater endurance - and hence a greater estimated safe life - than would be obtained from a structure not given the static test. Also the position of fatigue failure might be quite different for the two cases. The fatigue test is thus valueless, and the policy of attempting to economise by using a single specimen for both static and fatigue tests cannot be recommended.

One peculiar outcome of the effect of pre-load is that a component of smaller section but otherwise similar to another one may actually be the stronger in fatigue if the smaller component has received the benefits of a tensile pre-load. Such a result might even be obtained if both components were subjected to the same pre-load. This might arise when the pre-load produced a stress of less than 60% of the 0.1% proof stress in the larger component and of 80-100% of the proof stress in the smaller one. Thus, the general effect of a tensile pre-load is to increase the fatigue strength of the initially weaker components whilst leaving the stronger ones unaffected. This levelling out of fatigue strengths makes it essential to execute careful interpretations and assessments of results on components that have been pre-loaded.

The plastic distortion accompanying pre-loading also requires careful consideration. Pre-loads may correspond to a stress of less than the 0.1% proof stress, so that the general distortion is small, but there may be local highly stressed regions with relatively large distortions. Thus circular holes tend to become alongated, particularly when load is applied at the hole, and this may cause slackness in connected members. Also permanent buckling may occur in structures.

With the loaded lug tests described in Appendix II, the subsequent reaming of holes stretched by pre-loading did not have any deleterious effect on fatigue strength. It would appear that distortion can be overcome by machining, provided that the machining operation itself does not remove or introduce residual stresses.

Although residual stresses approaching the proof stress can be induced by pre-loading, the possibility of stresses being relieved in the subsequent fatigue test must be considered. Relief would occur when the sum of the residual and fatigue stresses at any point exceeds the dynamic yield criterion of the material used, and this may happen during the first loading cycle of the fatigue test[6]. Loss of residual stress, and therefore a reduction in effect on life, is most likely to be obtained if fatigue stresses are high, or if the material has a low yield strength.

5 Conclusions

The results of fatigue tests on a variety of aluminium alloy specimens have shown that the effect of pre-loading on life depends on the type of specimen, the proof stress of the material, and the magnitude of pre-load and fatigue loads. With plain specimens, pre-loading has a comparatively small or non-existent influence on life. Simple sheet specimens containing a transverse hole give some increase in life for tensile pre-loading, but the increase diminishes with increase in the fatigue test loads. With more complicated designs embodying the use of sheet material, a greater improvement in life due to tensile pre-loading is obtained, and this has been demonstrated by tests on Meteor tailplanes.

Extruded aluminium alloy parts and structures are more sensitive to the effect of a pre-load than simple sheet specimens. A tensile pre-load increases life, the increase rapidly becoming greater with increase in pre-load. Thus a fivefold increase may be expected for a pre-load equivalent to 80% of the proof stress, but for a pre-load to 100% the life may be increased by as much as one hundred times. On the other hand, compressive pre-loading has the reverse effect, and the life may be reduced to only one-tenth the value if the pre-load is of sufficient intensity.

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APPENDIX 1

Fatigue Tests on D.T.D.546 B Aluminium Alloy Sheet Specimens

Specimens in 16 s.w.g. clad sheet to Specification D.T.D.546 B were made with their longitudinal axes in the direction of rolling. Both plain and transverse hole specimens to the general dimensions shown in Fig. 1 were tested in an R.A.E. fluctuating tension fatigue machine. The edges of the plain specimens were polished by hand, and the holes of the notched specimens were drilled to 0.116 in. diameter, reamed to $\frac{1}{8}$ in., chamfered and finally polished by hand with 000 grade crocus paper.

The tensile strength of the sheet was found to be 28.7 tons per sq in. The pre-load was applied in a tensile testing machine, with the maximum load held for 1 minute.

All fatigue tests were carried out at the same nominal stress of 10 ± 5 tons per sq. in. across the smallest section. The individual results are given in Table II.

Tests by Metallurgy Department

Specimens cut longitudinally from D.T.D.546 B sheet material were made with a reamed $\frac{1}{8}$ in. diameter hole in a test portion of 0.5 in. width, the general proportions being similar to those shown in Fig. 1. The corners of the hole were left square, with all burrs carefully removed. The results comparing tensile pre-loaded with non pre-loaded specimens for a repeated axial load type of test in a Haigh machine (2000 cycles per minute) are given in Table III.

APPENDIX II

Fatigue Tests on Lugs

R.A.E. Tests

Direct-stress endurance tests were carried out on a number of pin-loaded lugs, some of which had been pre-loaded in tension for one minute.

Fig. 2 gives the essential dimensions of the specimen and shows the results obtained. The specimens were fully machined from extruded, D.T.D. 364 B bar, 2 in × $\frac{3}{8}$ in. The holes were 0.752 in. diameter and gave a clearance of 0.002 in. between the high tensile steel pin and the hole. The holes, which had a reamed finish, were given a 1/32 in. chamfer.

The elongation of the holes caused by stretching the specimen was very marked in cases of high pre-loading (Table IV). As this would produce an undesirable slackness between mating members, the effect of removing cold-worked material by machining the hole circular after the pre-loading operation was investigated. Specimens 12 and 3 were treated in this manner, the procedure being as follows:-

1 The holes were drilled and reamed, 0.020 in. (approx.) undersize.

2 The specimens were pre-loaded, and the load removed after one minute.

3 The holes were reamed to the full diameter of 0.752 in.

The endurance tests were then carried out as for the other specimens. The mean and alternating stresses adopted for the endurance tests were 6 ± 2.2 ton/in.^{2}, based on the net section at the hole. In cases where failure did not occur after a minimum of 10 million cycles had been completed, the alternating stress and, in certain instances the mean stress, were increased.

Table IV gives the pre-load stress, fatigue stresses, and endurance for each specimen. Also included are the stretch (measured in terms of the elongation of the hole) and increase in thickness of the specimen due to bearing pressure.

Saunders-Roe Tests

Similar tests on lugs have been made by Saunders-Roe Ltd. for the Ministry of Supply[3], with the object of ascertaining the effect of alternating stress on endurance of pre-loaded and non pre-loaded specimens. The pre-load was applied for 5 minutes, and was of the same magnitude for all specimens, equivalent to a tensile stress of 19.65 tons per sq in. at the hole section, or 60% of the 0.1% proof stress. In the subsequent fatigue test a tensile mean stress of 7.15 tons per sq in. was used.

The lug specimens were machined from D.T.D.683 aluminium alloy extrusions to the dimensions shown in Fig. 3. The holes were jig bored and all burrs and sharp edges were removed, but no chamfering or radiusing was carried out. Loading pins were made from B.S. S.98 bar to a diameter of 0.7490 to 0.7495 in. Two static tests on lug specimens gave nominal stresses of 37.7 and 38.4 tons per sq in.

The individual results are given in Table V and are plotted in Fig. 3. The curves indicate that an improvement in life of 2 to 3 times is obtained for alternating stresses below 4.5 tons per sq in. due to pre-loading. The improvement rapidly diminishes for greater alternating stresses, due to the approach of peak stress in the fatigue test (mean plus alternating stress) to the pre-load stress.

APPENDIX III

Fatigue Tests on Channel-Sectioned Parts

Five channel-sectioned boom specimens machined from extruded material to Specification D.T.D.363 A were pre-loaded to different amounts for one minute and tested in fatigue at a loading equivalent to stresses of 7.09 ± 2.72 tons per sq in. at the minimum section. A photograph of a fractured specimen is shown in Fig. 4. Load was applied to the specimen ends through 7/8" diameter shear pins which had not been subjected to pre-load.

Three specimens fractured at a hole or holes in the middle portion of the channel. Failure of an attachment pin in the two other specimens caused premature failure of the lug ends. The results of the endurance tests together with the pre-load stresses applied to each specimen are given below.

Nominal Stress in Pre-Loading Operation tons per sq in.	Corresponding Percentage of Static Strength	Endurance Cycles	Remarks
0	0	82,200	Mean endurance of 8 specimens
16.74	37.2	68,500	
20.10	44.6	62,100	
24.25	53.9	343,100	
26.75	59.4	444,700	Failure of attachment pin
26.75	59.4	265,500	Failure of attachment pin

APPENDIX IV

Fatigue Tests on Transverse Hole Specimens

Round Bars with a Central Transverse Hole

Fatigue tests in direct stress were made on round bar specimens containing a transverse hole. Of 11 specimens, 5 were pre-loaded for one minute in tension, 4 pre-loaded in compression, and the remaining 2 specimens were fatigue tested without being pre-loaded.

Fig. 6 gives the essential dimensions of the specimen. Buckling due to the high compressive loads was satisfactorily avoided by making the specimen comparatively short and robust. A $2\frac{1}{2}$ in. diameter bar of aluminium alloy RR.77 (D.T.D.683) was used to make the specimens. The 3/16 in. diameter hole was drilled and reamed, the sharp edges of the latter being removed with the aid of 000 grade emery paper stretched over a conically shaped bar.

All pre-loads were applied to the specimens in a 10 ±10 ton Avery-Schenck pulsator. The fatigue tests were made at nominal stresses of 9 ± 3.5 tons per sq in. at the net section through the transverse hole. The results of the tests are given in Table VI and shown plotted in Fig. 6.

Flat Bars with a Central Transverse Hole

Additional data on the effect of compressive pre-loading was obtained from tests on flat bars with a central transverse hole, made in material to Specification D.T.D.364 B. The dimensions at the hole section were 0.9 in. × 0.3 in., with the reamed hole of $\frac{1}{4}$ in. diameter. Burrs at edges of the hole were removed with fine emery paper. The results obtained for different degrees of compressive pre-load are given in Table VII.

APPENDIX V

Fatigue Tests on Wing Joints

All the joints described in this appendix relate to parts identical in design with those used in certain aircraft, but adapted for testing purposes by duplication of the joint at each end of the specimen. Load was applied through a single pin to each end fitting.

Type A The specimens consisted of a channel section boom in aluminium alloy D.T.D.683, to which was attached on inside and outside of channel, steel fittings by means of multiple bolts in shear. The nominal stresses at the point of failure of the channel in the fatigue test were 5.36 ± 1.97 tons per sq in.

Mean endurance of three specimens without pre-load = 145,000 cycles.

Endurance of one specimen after subjecting to a pre-load equivalent to 19.5 tons per sq in. = 2,370,000 cycles.

Type B The specimens consisted of a T section boom in aluminium alloy D.T.D.683, to which was attached a forked steel fitting by means of multiple bolts in double shear. The nominal stresses at the point of failure of the boom in the fatigue test were 7.82 ± 2.37 tons per sq in.

Endurance of specimen without pre-load = 87,000 cycles.

Endurance after pre-load equivalent to 19.0 tons per sq in. = 130,000 cycles.

Endurance after pre-load equivalent to 25.0 tons per sq in. = 375,000 cycles.

Type C The specimens consisted of booms in aluminium alloy D.T.D.364, rectangular in section with a web extension on one side. Steel straps were attached to the boom by multiple bolts in double shear. The nominal stresses near the point of failure of the boom in the fatigue test were 6.35 ± 1.85 tons per sq in. The specimens were tested at the College of Aeronautics, Cranfield.

Mean endurance of three specimens without pre-load = 580,000 cycles.

Endurance of specimen after pre-load equivalent to 13.5 tons per sq in. = 464,000 cycles.

Endurance of specimen after pre-load equivalent to 14.8 tons per sq in. = 1,790,000 cycles.

APPENDIX VI

Fatigue Tests on Meteor 4 Tailplanes

A series of fatigue tests has been carried out at the Royal Aircraft Establishment on Meteor 4 tailplanes under several different conditions of loading. The first report of this work describing the general method of test is given in Ref. 7. The tailplane is representative of a typical two spar structure, with the spars of angle section extrusions in B.S. 2 L 40 material and the skin over the central portion of clad aluminium alloy to D.T.D.390.

The tailplanes were supported at the attachment points near the centre, and were vibrated near resonant frequency in bending by means of an out of balance mass exciter, as shown in Fig. 5. The pre-loading was applied by bending the tailplane, and in the subsequent fatigue test the loads applied were 25% ± 7.5% of the static failing load of the tailplane. The results are shown in the following table:-

Effect of Pre-Load on the Fatigue Strength of Meteor Tailplanes

Pre-Load, Expressed as a Percentage of		Cycles to Failure, 10^6	
S.F.L.*	0.1% Proof Stress+	First Major Skin Failure (Crack of 1" Length)	Spar Failure
0	0	0.2	0.85
50	53	0.3	1.29
$66\frac{2}{3}$	70	1.0	1.825
50, 75	53, 79	2.5	3.50

Note:- Result for zero pre-load has been obtained from an endurance curve. The endurance for 50% pre-load has been corrected for a loading of 25 ± 7.5% S.F.L., instead of 25 ± 7.2% S.F.L. as actually used in the test.

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* Based on mean static failing load of three tailplanes. These failures were on compression side of tailplane. 100% S.F.L. is approximately equivalent to 22.8 tons per sq in. at points of fatigue failure.

\+ Minimum specification 0.1% proof stress for spar boom material = 21 tons per sq in. In all cases the nominal stress in the spar boom at 11.5 in. from the centre line of the tailplane is expressed as a percentage of this proof stress.

APPENDIX VII

Fatigue tests on (a) circumferentially notched specimens, and (b) spot welded joints

Circumferentially notched specimens

Forrest[1] has ascertained the effect of a tensile pre-load on specimens containing a circumferential notch and tested in rotating bending. The material used was B.S.6 L.1, and a circumferential notch of 45° included angle, 0.04 in. depth and 0.01 in. root radius was machined so as to give a minimum diameter of 0.32 in. The following fatigue strengths were obtained for failure in 50 million cycles:-

Fatigue strength of plain test pieces = ±10 tons per sq in.

Fatigue strength of notched test pieces = ±3.5 to ±4 tons per sq in.

Fatigue strength of notched test pieces given an axial pre-load of 25 tons per sq in. = ±8 tons per sq in.

Forrest's findings have been confirmed by Templin (discussion in Ref. 4) for specimens made in the aluminium alloy 75S-T6 (zinc addition), having a tensile strength of 37.5 tons per sq in. and a 0.2% proof stress of 32.4 tons per sq in. A 60° circumferential notch of 0.0002 in. root radius and 0.075 in. depth was machined in specimens of 0.48 in. full diameter. The specimens were tested in rotating bending and gave the following results:-

Nominal Stress at Notched Section Due to Axial Pre-Load, tons per sq in.	Fatigue Strength at 10^7 Cycles, tons per sq in.
0	±5.35
+37.5	±9.37
-37.5	±1.79

The fatigue strength of plain specimens not subjected to a pre-load was ±13.2 tons per sq in. The notched specimens had a greater tensile strength than the plain specimens, so making it possible to apply the very high pre-load used.

Spot welded joints

Forrest has also shown that spot welded joints can be given an increased fatigue strength by a tensile pre-load. Joints containing a single spot weld were made in 20 gauge clad sheet to D.T.D.546 A, and without pre-load gave a fatigue strength of 60 ± 30 lb per specimen for failure in 20 million cycles, whereas specimens given a pre-load equal to two-thirds of the static strength had a fatigue strength of 90 ± 45 lb per specimen.

TABLE I

Effect of Pre-Loading on the Fatigue Strength of B.S. L.1 Plain Specimens Tested in Rotating Bending (Teed[2])

	Fatigue Strength for Failure in 50 × 10^6 Cycles, tons per sq in.			
Stretch Produced by Pre-Load, %	0	3	6	9
When overstrained				
(A) Immediately after quenching and then allowed to age before test	±12.0	±11.5	±11.0	±11.0
(B) 1 hour after quenching and then allowed to age before test	±12.0	±11.8	±11.3	±10.5
(C) After heat treatment and ageing	±12.0	±12.0	±11.5	±10.5

TABLE II

Results of Fatigue Tests on Sheet Specimens (Appendix I)

Type of Specimen	Nominal Stress Applied in Pre-Loading t.s.i.	Cycles to Failure in Individual Tests 10^6	Geometric Mean Cycles to Failure 10^6
Plain	0	0.237, 0.304, 0.305	0.280
	18	0.314	
	20	0.265	
	22	0.370	
	24	0.294	
	26	0.271	
	28	0.396	
With transverse hole	0	0.036;0.048;0.063;0.085;0.097 0.114	0.062
	18		
	20	0.035, 0.047, 0.105	0.056
	22	0.052, 0.077, 0.118	0.078
	24	0.048, 0.080, 0.117	0.077
	26	0.078, 0.092, 0.130	0.098
	28	0.034, 0.125	0.065

TABLE III

Results of Repeated Load Fatigue Tests on Sheet Specimens (Appendix I)

Nominal Stress Applied in Pre-Loading, t.s.i.	Fatigue Stresses t.s.i.	Cycles to Failure in Individual Tests	Geometric Mean Cycles to Failure
0	6.70 ± 6.70	31,850;33,117;35,050	33,320
26.8	6.70 ± 6.70	88,667; 114,000; 114,833	105,100
0	8.93 ± 8.93	9,567; 9,800;10,733	10,020
26.8	8.93 ± 8.93	15,230;17,600;17,800	16,840
0	11.16 ±11.16	3,500; 3,967; 4,033	3,817
26.8	11.16 11.16	4,600; 5,267; 5,750	5,185

TABLE IV

Results of Fatigue Tests on Loaded Lugs (Appendix II)

Static Strength of Lug = 31.8 tons per sq in.

Number of Specimen	Nominal Stress at Hole Section Due to Pre-Load tons per sq in.	Diametral Stretch at Hole Due to Pre-Load in.		Increase in Thickness at End of Hole Due to Bearing Pressure in.		Fatigue Stresses at Hole Section tons per sq in.	Cycles to Failure (millions)
		Hole 1	Hole 2	Hole 1	Hole 2		
1	0	-	-	-	-	6.0 ± 2.2	0.082
3	0	-	-	-	-	6.0 ± 2.2	0.108
2	0	-	-	-	-	6.0 ± 2.2	0.135
6	18.0	-	-	-	-	6.0 ± 2.2	0.164
4	22.14	0.004*	0.004	0.003*	0.001	6.0 ± 2.2	0.198
7	24.0	- *	0.007	0.006*	-	6.0 ± 2.2	0.991
8	25.0	0.020	0.023	0.019	0.024	(6.0 ± 2.2 (6.0 ± 3.0 (6.0 ± 4.0	14.07U 10.53U 0.168
5	25.9	0.016*	0.012	0.014*	0.008R	(6.0 ± 2.2 (6.0 ± 3.0	11.63U 0.113
9	27.25	0.009*	0.014	0.008*	0.005R	6.0 ± 2.2	0.816
10	28.15	0.020	0.028	0.013R	0.027*	6.0 ± 2.2	13.52
11	29.0	0.026	0.052	0.012R	0.010R	(6.0 ± 2.2 (6.0 ± 3.5 (8.0 ± 3.7	13.63U 1.12U 0.370
		Effect of reaming holes after pre-loading					
12	28.0	0.005+	0.033+	-	-	6.0 ± 2.2	7.79U
13	28.0	0	0	0.008	0.010	(6.0 ± 2.2 (6.0 ± 4.0 (7.5 ± 4.0	14.07U 1.05U 2.45

U Unbroken * Failure occurred at this hole + Subsequent reaming did not clean up holes

R Lateral restraint inadvertently applied to specimen during pre-loading

TABLE V

Results of Fatigue Tests on Loaded Lugs Carried Out by Saunders-Roe, Ltd. (Appendix II)

Nominal mean stress at hole section during fatigue test
= 7.15 tons per sq in.

Nominal Alternating Stress at Hole Section ± tons per sq in.	Cycles to Failure No Pre-Load millions	Cycles to Failure 19.65 tons per sq. in. Pre-Load Stress at Hole Section millions
6.92	0.0108	
6.40	0.0090	
6.25	0.0092	0.0142
6.25	0.0106	-
6.25	0.0126	-
5.36	0.0177	0.0257
4.47	0.0257	0.0562
3.57	0.0353	0.0822
3.57	-	0.136
3.12	0.0405	0.117
2.68	0.0563	-
2.23	0.100	0.202
2.23	-	0.236
1.785	0.120	0.462
1.785	0.126	0.491
1.785	0.127	0.513
1.785	0.165	-
1.34	0.188	0.547
1.34	-	0.643
1.115	0.522	0.740*
1.115	-	3.72
0.895	2.07	-
0.850	1.58	-
0.760	3.95	-

* Specimen retested to give failure at other hole, in 1.20 million cycles

TABLE VI

Results of Fatigue Tests on Round Bars with a Transverse Hole (Appendix IV)

Tensile strength of material (by test) = 35.8 tons per sq in.

Specification tensile strength of material = 35.0 tons per sq in.

0.1% proof stress (specification and by test) = 30.0 tons per sq in.

Net area of cross-section through hole = 0.389 tons per sq in.

Stresses at hole section applied in fatigue tests = 9 ± 3.5 tons per sq in.

Number of Specimen	Nominal Stress at Hole Section Due to Pre-Load tons per sq in.	Nominal Pre-Load Stress as a Percentage of the Specification 0.1% Proof Stress	Cycles to Failure (millions)
1	0	-	0.462
2	0	-	0.181
3	24.25 (tension)	80.9	0.472
4	27.05 (tension)	90.2	0.784
5	30.90 (tension)	103.0	3.33
6	33.20 (tension)	110.6	8.21
7	33.48 (tension)	111.6	0.186
8	7.72 (compression)	25.75	0.165
9	12.85 (compression)	42.9	0.066
10	21.00 (compression)	70.1	0.050
11	27.05 (compression)	90.2	0.054

Examination of the fracture in this specimen showed a number of flaws at the edge of the transverse hole, in the neighbourhood of the start of the fatigue crack.

TABLE VII

Results of Fatigue Tests on Flat Bars with a Transverse Hole (Appendix IV)

Nominal Compressive Stress in Pre-Loading, t.s.i.	Fatigue Stresses t.s.i.	Cycles to Failure in Individual Tests 10^6	Geometric Mean Cycles to Failure 10^6
0	9 ± 3.5	6.05; 6.16u; 12.1u	7.7 (u)
10	9 ± 3.5	1.96; 11.6u	4.8 (u)
20	9 ± 3.5	0.143;0.192*;0.201; 0.712;0.917u	0.32
0	10.5 ± 3.75	0.093;0.095;0.108	0.98
20	10.5 ± 3.75	0.078;0.102;0.120	0.99

u = Specimen did not fail in test section

* = Specimen previously run for 12,100,000 cycles without pre-load

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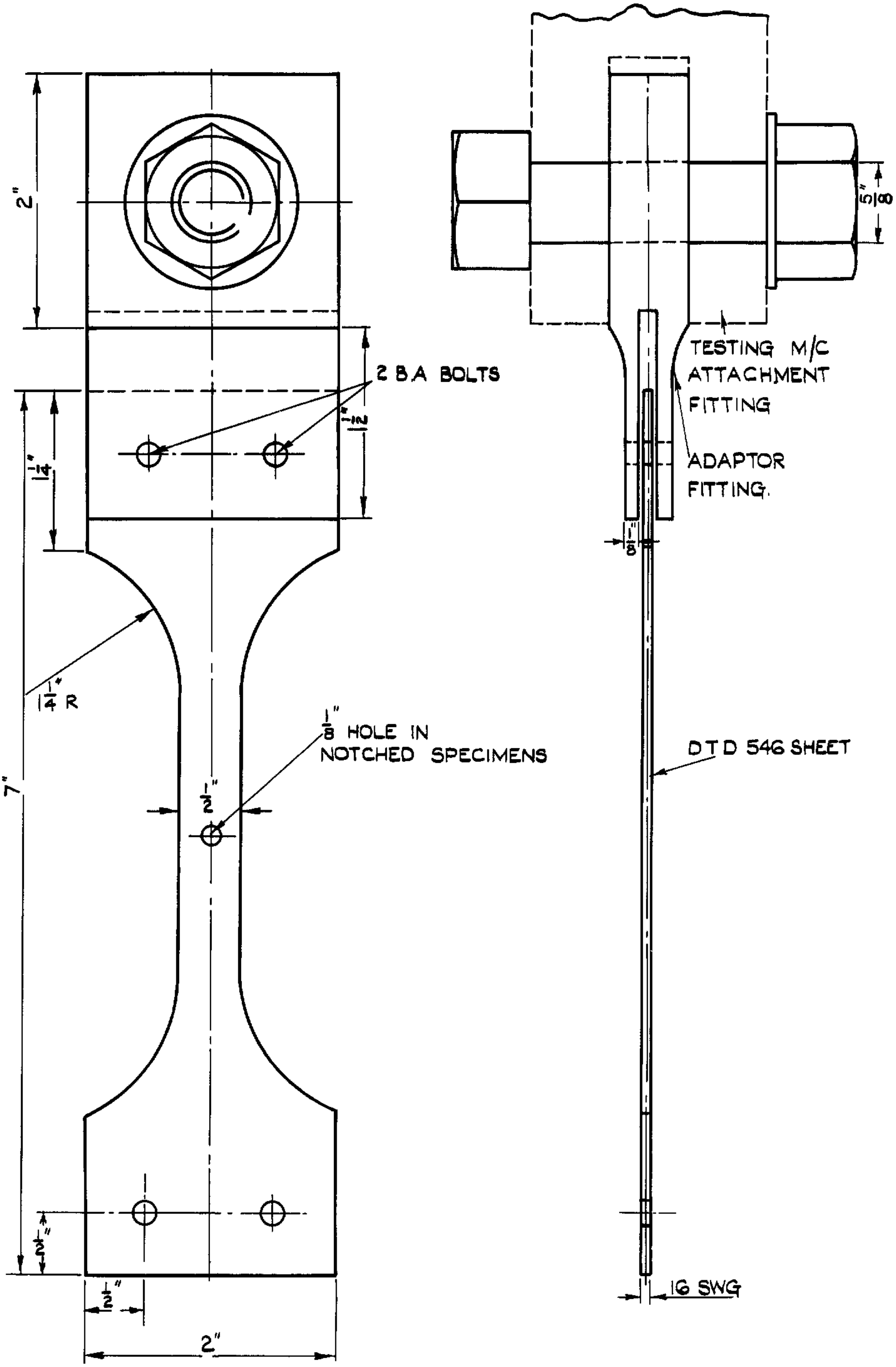

FIG. 1. DETAILS OF SHEET SPECIMENS (APPENDIX I)

FIG. 2.

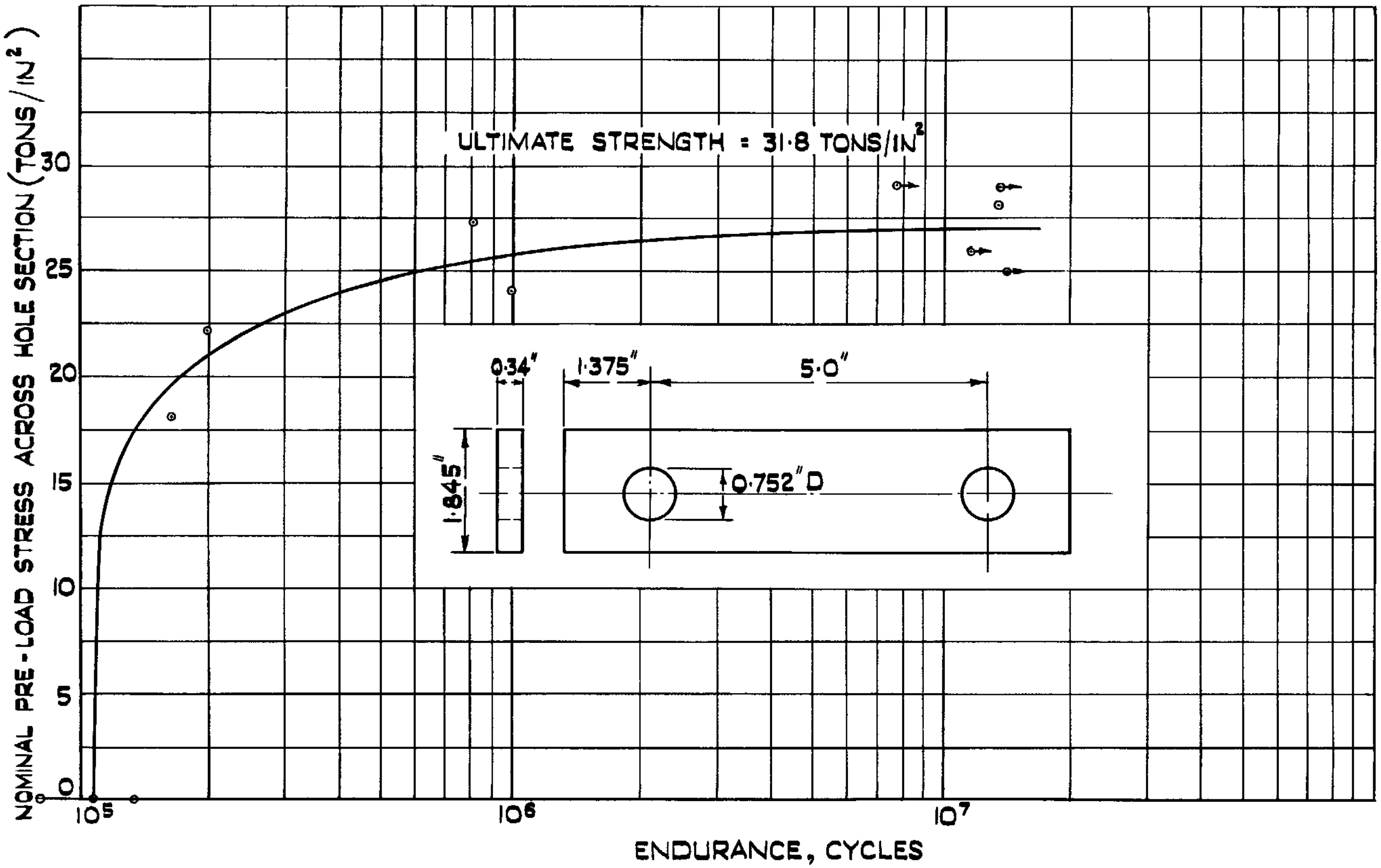

FIG. 2. EFFECT OF PRE-LOAD ON THE ENDURANCE OF LUGS. (APPENDIX 2)

FIG. 3.

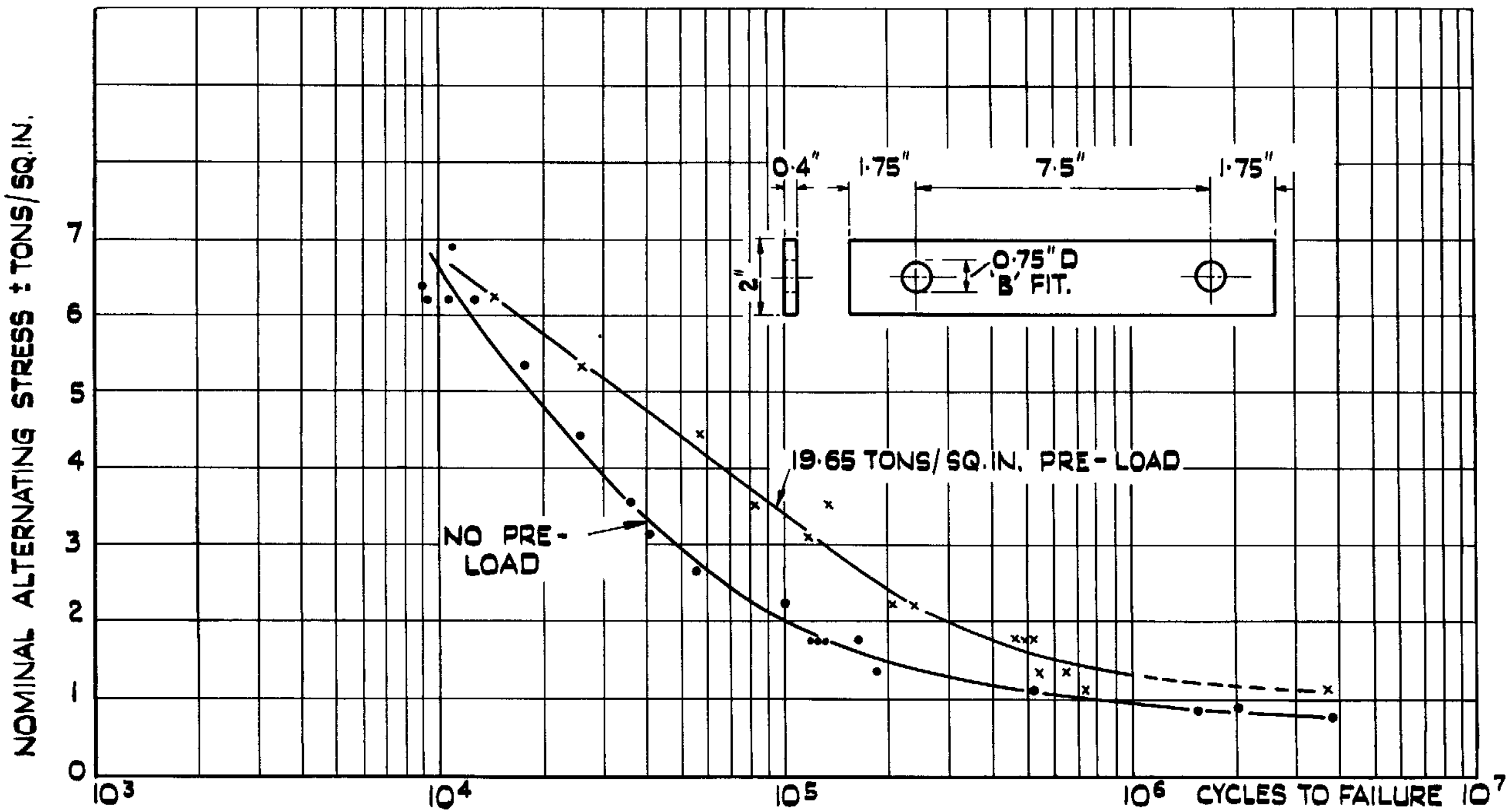

FIG. 3. FATIGUE STRENGTH OF LUGS WITH AND WITHOUT PRE-LOADING.

NOMINAL MEAN STRESS DURING FATIGUE TEST = 7·15 TONS/SQ.IN.
(APPENDIX 2. SAUNDERS-ROE TESTS)

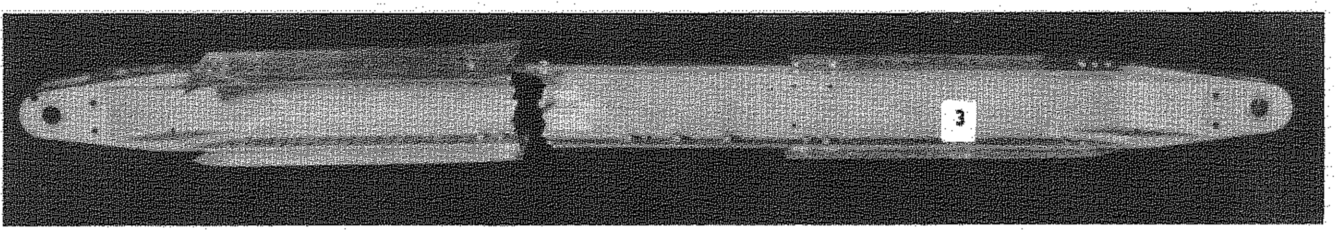

FIG.4. FRACTURED CHANNEL SPECIMEN (APPENDIX 3)

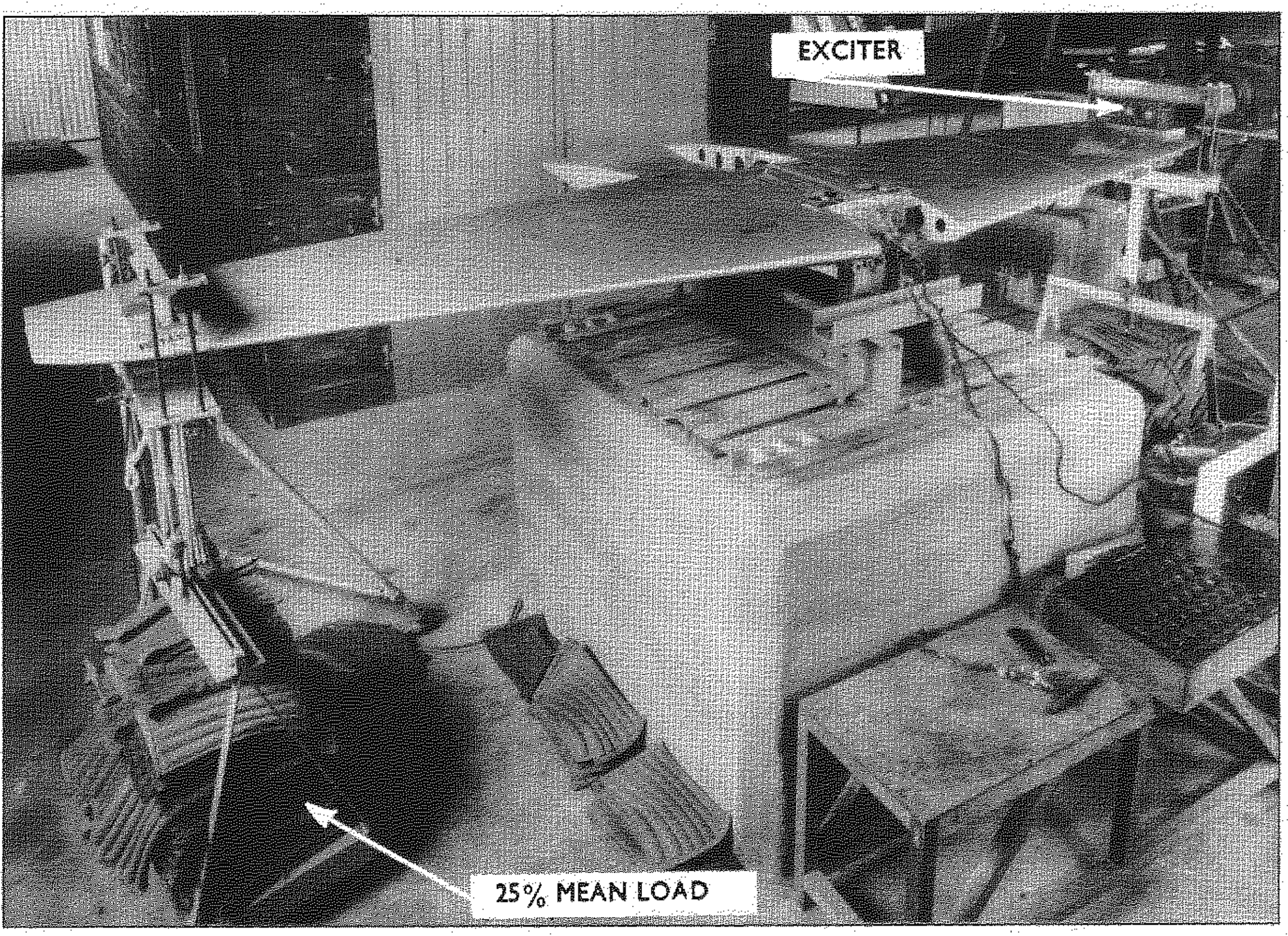

FIG.5. FATIGUE TEST ON METEOR 4 TAILPLANE (APPENDIX 6)

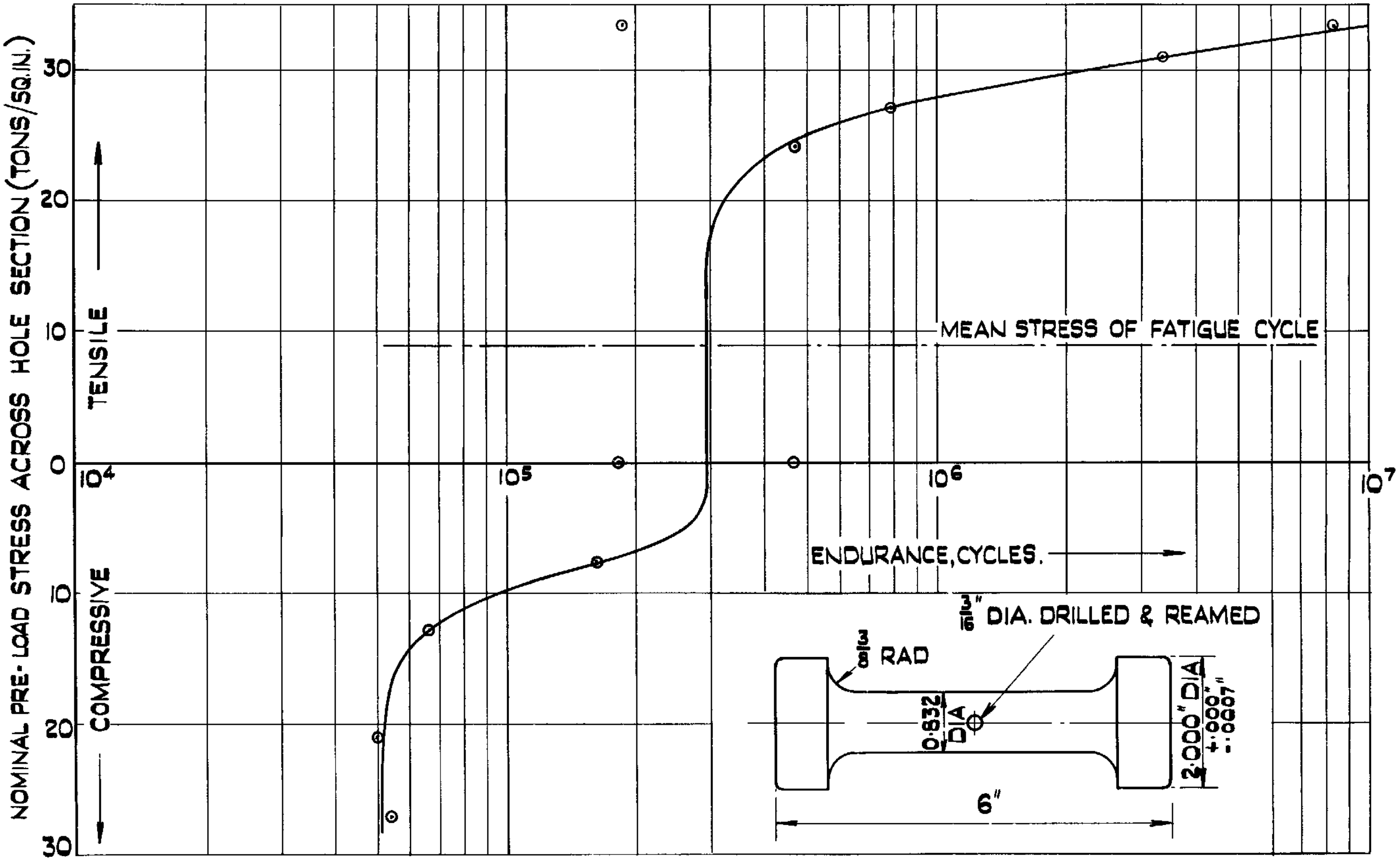

FIG. 6. EFFECT OF PRE-LOAD ON THE ENDURANCE OF ROUND BARS WITH A TRANSVERSE HOLE. (APPENDIX 4)

FIG. 7.

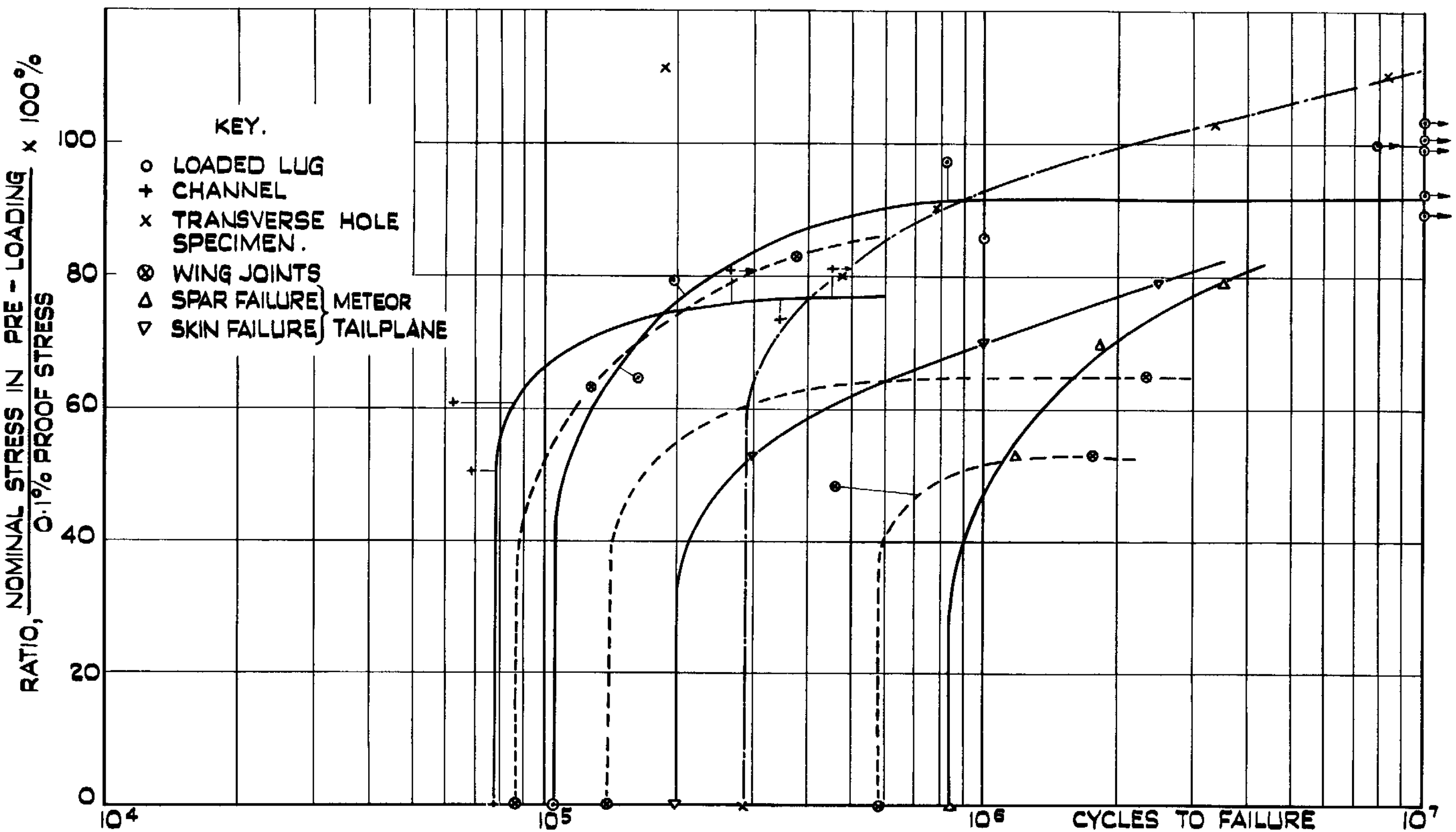

FIG. 7. EFFECT OF TENSILE PRE-LOAD ON ENDURANCE OF VARIOUS STRUCTURAL PARTS.

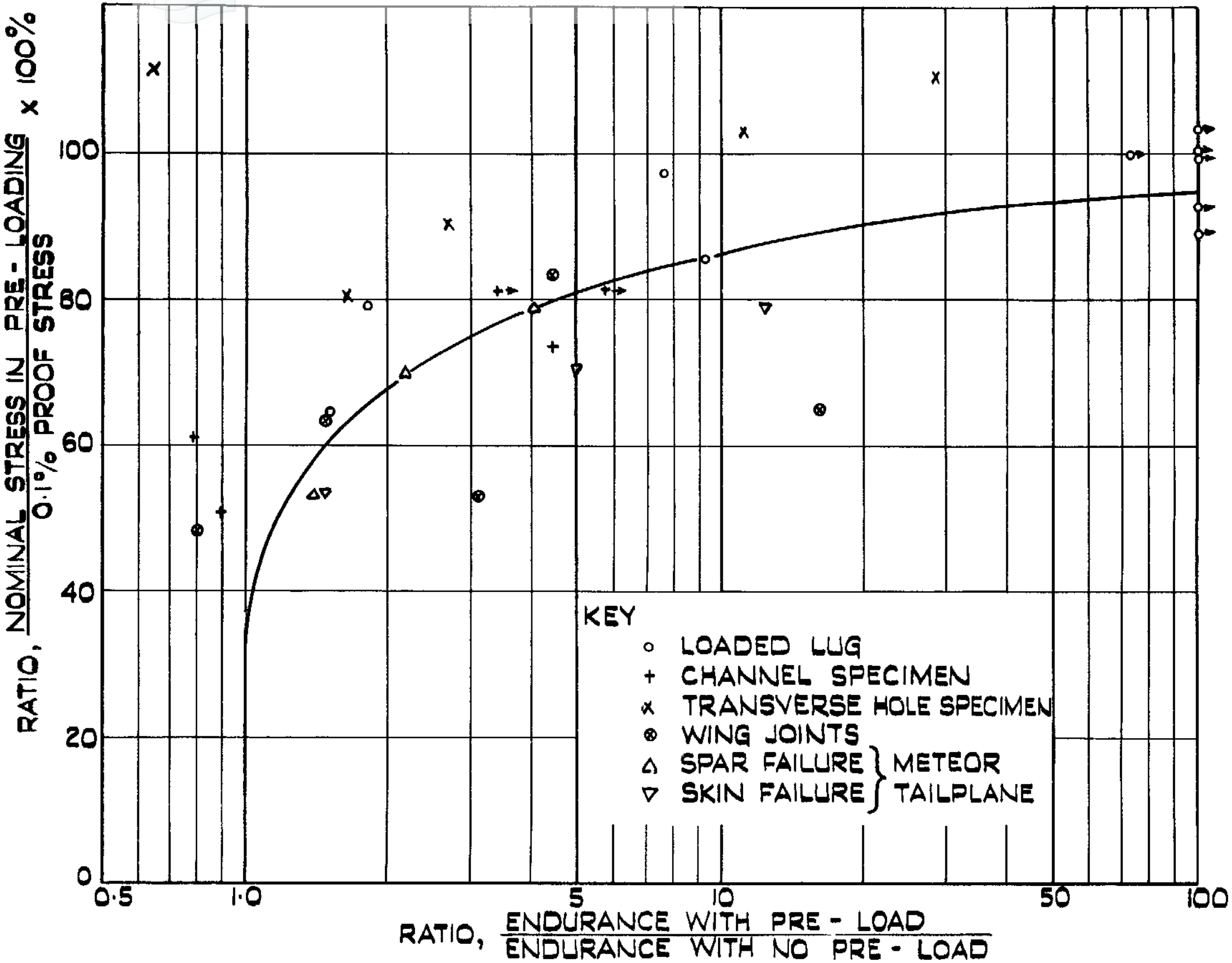

FIG.8. EFFECT OF TENSILE PRE-LOAD IN INCREASING THE ENDURANCE.

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