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Investigation of the Fatigue of Extruded Tubular Booms

By

W. A. P. Fisher and H. Yeomans

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W.A.P. Fisher
and
H. Yeomans

SUMMARY

Earlier tests on Viking tubular spar booms having shown considerable scatter and low fatigue strength, a special programme of tests was undertaken in order to ascertain the cause.

Three types of specimen made from Aluminium Alloy Extruded Tube to Material Specification D.T.D.364, were tested and the results compared. The types of specimen were:-

(a) Extruded tube specimens lightly machined on the outside - having transverse holes drilled through the tube. (These represented the critical section of the Viking replacement and Valetta spar boom).

(b) Plain extruded tube with the centre portion reduced to ensure failure in the test section.

(c) Solid polished bar specimens made from the walls of the extruded tubes.

The results showed that the fatigue strength of the plain tube, with the original extruded bore, was less than half that of the polished bar. Fatigue cracking started in every tube from an obvious flaw on the inner surface.

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1 Introduction

The original Viking spar, consisting of two tubular booms (material Specification D.T.D.364) mounted side by side, had a fatigue failure in service originating at one of the transverse holes. In consequence, all Viking lower spar booms were replaced by Valetta booms which have the same outside diameter but greater wall thickness.

Fatigue tests on Viking spar booms made from extruded tube (material Specification D.T.D.364) have indicated a fatigue strength greatly inferior to that of D.T.D.364 alloy in polished bar form, even when allowance is made for the presence of transverse holes.

Previous investigations into the fatigue strength of Z extrusions to the same material specification showed that the presence of the unmachined extruded surface had a marked weakening effect in fatigue, although the static properties were normal. Spar booms made from extruded tube, though machined externally, still have the extruded surface present on the inside. Although the fatigue crack in the boom which failed in service originated at the outer surface of the tube, the fatigue cracking of Viking spar booms under test almost invariably begins at the inner surface and spreads outwards. Thus the practical basic fatigue strength of the tube, in the absence of artificial stress raisers, is apparently governed by the inner surface of the tube. In order that the tubular form of spar may be assessed in comparison with solid machined spars, it is necessary to compare this basic fatigue strength with that for polished machined specimens.

The tests reported below were designed to this end as follows: three lengths of Valetta spar extruded tubing were selected at random from stock, and from each length the following test specimens were prepared:

1.1 Fatigue Specimens

(a) Representative Specimens Extruded tubes having one or four transverse holes to represent the critical portion of Valetta spar booms.

(b) Machined on Outer Surface Only Tubes with threaded ends and with the central portion machined externally to approximately 0.1" wall thickness so as to induce failure in the middle portion which was entirely free from holes or notches. These will be termed 'Necked Specimens'.

(c) Machined All Over Wöhler and Haigh specimens.

1.2 Static Control Test Specimens

Two tensile test pieces from each tube.

1.3 Thus comparison was afforded between the fatigue strength of -

the extruded tube representing the actual wing spars

the basic extruded tube

the parent material in polished bar form.

2 Tests on Spar Tubes with Transverse Holes

2.1 Test Specimens

Two types of specimen were used in this test and are shown in Fig.1 and Fig.2.

All the specimens were made by Vickers-Armstrong Ltd. from Aluminium Alloy Extruded Tube to Specification D.T.D.364. The inside diameter, as extruded, was 1.10" and the outside diameter was machined to 2.20".

Specimen Type 1 The eight specimens of this type, made from two lengths of tube, were numbered VXA1 to VXA4 from tube A and VXB1 to VXB4 from tube B. Each specimen had four 19/64" diameter holes spaced 1.50" apart and one ¼" diameter hole through the tube. The ends of the specimens were threaded to suit adaptors used for fitting the specimens into the testing machine.

Specimens VXA1 and VXA2 had the 19/64" diameter holes reamed to 5/16" diameter and shear brace gusset plates were fitted, using 5/16" diameter bolts, as in the aircraft, with a light drive fit.

Specimen Type 2 The three specimens of this type numbered 4, 5 and 6, were made from tube similar to that used for the above specimens. Each specimen had one 5/16" diameter hole drilled through the tube at the mid-length. The ends of the tubes were fitted with steel fork-end sleeved fittings similar to those used on the aircraft spar booms.

2.2 Method of Testing

The specimens were tested in a 60 ton Schenck Fatigue Testing Machine using the screwed end adaptors or fork-end fittings as used for the Viking specimens.

2.3 Loading Conditions

The applied test loads for the various specimens were as follows:-

Specimen VXA4	-	16.5 ± 4.98 tons
Specimens VXA3, B1 and B4	-	16.5 ± 4.28 tons
Specimens VXB2 and B3	-	15.4 ± 4.0 tons
Specimens VXA1 and A2	-	15.4 ± 4.65 tons
Specimens 4, 5 and 6	-	16.5 ± 4.98 tons

Specimens VXA1 and A2 were preloaded to 31.0 tons, i.e. twice the 1g load.

The nominal stresses of the specimens at a section through the tube at a 5/16" diameter hole are shown on Table I.

2.4 Test Results

The results of the tests are shown on Table I and are shown plotted on Fig.7.

All the fractures in the tubes were due to fatigue cracks which had started at the surface of the unmachined bore.

3 Tests on Valetta Spar Tube 'Necked' Specimens

Three lengths of Aluminium Alloy Extruded Tube to Specification D.T.D. 364 were selected from the stock held by Vickers-Armstrong Ltd. A part of each length of tube was used in the making of control specimens and the remainder was used in the making of the 'necked' specimens described below.

3.1 Test Specimens

A general view of the specimens is shown on Fig.3. The ends were screwed to suit the fatigue testing machine adaptors, the central portion was necked to a diameter of 1.33". The original extruded bore of the tube, 1.10" diameter, was left unmachined. The cross sectional area of the necked portion was 0.44 sq in.

Note: These specimens were left plain, i.e. the tubes were not drilled.

3.2 Method of Testing

The specimens were tested in a 20 ton Avery-Schenck Fatigue Testing Machine.

3.3 Loading Conditions

The mean loads applied to all the specimens produced nominal mean stresses of 20,000 lb/sq in. across the necked portion of the specimen. The alternating loads, for each specimen, were varied to give results suitable for an S-N curve.

3.4 Test Results

The results of the tests are shown on Table II and are shown plotted on Fig. 7.

Specimens No.3 and No.4 remained unbroken after withstanding 20 million cycles at alternating stresses of ± 6,000 and ± 8,000 lb/sq in. They were retested, later, at an alternating stress of ± 16,000 lb/sq in., the new specimen numbers being 7 and 8; the endurance was about the same as that of specimen No.1 which had not been tested previously.

Three of the specimens fractured in the middle of the necked parallel length, two failed at the end of the parallel length and one failed at both the end and the middle.

On close examination of the specimens it was found that the cracks had started at flaws in the bore of the tube, having the appearance of longitudinal cavities. The interior of the cavities had a very irregular surface. Enlarged photographs of one of these flaws can be seen in Figs. No. 4 and 5.

4 Control Tests on Small Specimens made from Spar Tube

Control test specimens were made from three lengths of tube as described previously.

4.1 Test Specimens

Each tube was cut into three lengths, the maximum number of test pieces being obtained from each. Location of the test pieces, Wöhler, Haigh and Static Tensile, is shown on Fig. No.6, this pattern being identical for each tube. Standard size Wöhler test pieces were used, 0.3125" diameter at the test section, sub-standard Haigh test pieces were used with a diameter of 0.15" along a gauge length of 0.5". Standard test pieces were used for the tensile tests.

4.2 Method of Testing

The reversed bending tests were made in Wöhler machines operating at 2000 cycles/minute and the fluctuating tension tests in Haigh electromagnetic machines operating at 6000 cycles/minute.

4.3 Loading Conditions

The nominal mean stress for the Haigh fluctuating tension tests was 25,000 lb/sq in.

4.4 Test Results

The results for the three tests are shown on Tables III, IV and V, and the Haigh test results are shown plotted on Fig. No.7.

From both the Wöhler and the Haigh test results it appears that Tube No.1 has a higher intrinsic fatigue strength than Tubes No.2 and 3.

The tensile test results indicate a variation in the ultimate tensile strengths along and round each tube.

The 0.1% proof stress was below 85% ultimate stress with one exception (86.3%).

5 Discussion of Results

From the results shown plotted on Fig.7, it can be seen that disregarding the effect of mean stress the fatigue strength of the polished bar specimens is 2.25 times greater than that of the undrilled tube specimens with the original extruded bore. It is also 4.5 times greater than that of the tube specimens with the transverse holes.

The theoretical stress concentration for a transverse hole in a tube is not known exactly, but it is reasonable to suppose that it does not exceed 3. On experience of tests with similar material, with smooth machined surfaces all over, the fatigue strength reduction factor would not be expected to exceed 2.7. Thus the actual fatigue strength reduction factor of 4.5 must be attributed to a great extent to the condition of the unmachined bore of the tube.

At the aircraft spar boom joint, the bore of the tube is skimmed out. The increased basic fatigue strength resulting from the local removal of flaws may account for the experimental fact that on the average the joints of the Viking booms have a longer life than the basic tube at the shear brace connection holes.

6 Conclusions

The presence of the unmachined extruded surface of the bore in the tubes, as used for the 'Viking' and 'Valetta' spar booms, has a marked adverse effect on the basic fatigue strength of the tube. The failures of the necked specimens show that the flaws occurring at the inner service are a source of fatigue. Scatter in the endurance of tubular spar booms is probably largely due to the chances of such flaws occurring at the side of a transverse hole, where the local stress is high due to the presence of the hole. The Valetta tubes are unlikely to be better in this respect than the original Viking ones, their sole merit as a replacement being a reduction in nominal stresses from the increased cross sectional area.

TABLE I

Fatigue Test Results of Tubular Specimens with Transverse Holes

Specimen No.	No. of 5/16" Dia. Transverse Holes in Specimen	Nominal Mean Stress lb/sq in.	Nominal Alternating Stress ± lb/sq in.	Endurance Cycles	Remarks
VXA1	4	13,730	4,150	879,000	Fractured through ¼" dia. hole.
VXA2	4	13,730	4,150	1,459,800	
VXA3	4	14,700	3,840	1,385,900	
VXA4	4	14,700	4,430	405,000	
VXB1	4	14,700	3,840	1,083,000	
VXB2	4	13,730	3,570	1,529,700	
VXB3	4	13,730	3,570	1,966,100 U/B	Fractured at screwed end.
VXB4	4	14,700	3,840	1,411,500	
4	1	15,000	4,510	1,218,200 U/B	Fractured at end fitting inner sleeve.
5	1	15,000	4,510	956,400	
6	1	15,000	4,510	3,188,400 U/B	Fractured at end fitting lug.

4-hole specimens were of screwed end type. Single hole specimens were of forked end sleeved joint type.
U/B. Unbroken in test length

TABLE II

Fatigue Results for 'Necked' Tube Specimens

Specimen No.	Tube No.	Alternating Stress ± lb/sq in.	Endurance Cycles	Remarks
1	3	16,000	36,900	
2	2	10,000	318,600	
3	3	6,000	20,000,000	Unbroken
4	1	8,000	20,000,000	Unbroken
5	1	9,000	163,000	
6	2	9,000	142,000	
7	3	16,000	66,600	No.3 Specn. re-tested.
8	1	16,000	70,600	No.4 Specn. re-tested.

Mean stress for all specimens = 20,000 lb/sq in.

TABLE III

Wöhler Fatigue Test Results

Tube No.	Alternating Stress ± lb/sq in.	Endurance Cycles	Remarks
1	26,700	13,111,000	Unbroken
	29,000	6,029,000	
	24,600	24,991,000	
	22,500	51,921,000	
	33,700	1,810,000	
	23,500	39,889,000	
	38,100	100,000	
	40,200	114,000	
2	26,900	4,700,000	Unbroken
	24,600	20,923,000	
	23,200	29,767,000	
	22,500	66,998,000	
	47,100	49,000	
	40,200	89,000	
	31,400	879,000	
	35,900	162,000	
3	26,800	2,421,000	
	22,700	32,111,000	
	24,700	8,309,000	
	21,700	44,139,000	
	40,200	110,000	
	46,000	38,000	
	35,900	84,000	
	31,500	610,000	

TABLE V

Tensile Test Results

Tube	1						2						3					
Mark	T1	T2	T3	T4	T5	T6	T1	T2	T3	T4	T5	T6	T1	T2	T3	T4	T5	T6
Diameter ins.	0.337	0.337	0.3375	0.253	0.3375	0.3375	0.357	0.356	0.357	0.357	0.357	0.356	0.357	0.356	0.3565	0.3565	0.357	0.3565
P.L. tons/sq in.	17.0	18.0	14.0	16.9	17.0	14.0	17.0	17.1	17.9	17.0	15.2	17.9	17.0	18.0	17.0	16.1	17.0	17.0
0.1% P.S. tons/sq in.	30.2	26.6	28.5	29.2	28.1	28.1	29.9	28.0	29.7	28.8	28.7	27.7	31.0	31.0	28.5	30.1	29.1	29.6
0.2% P.S. tons/sq in.	31.0	27.7	29.8	30.1	29.1	29.2	31.0	29.3	30.5	30.1	29.8	29.2	32.0	32.1	29.7	31.0	30.2	30.8
0.5% P.S. tons/sq in.	31.8	28.6	30.6	31.0	30.1	30.2	32.1	30.5	31.4	31.0	30.5	30.2	33.0	32.9	30.9	31.8	31.1	31.7
Ultimate stress tons/sq in.	35.9	33.1	35.4	36.2	35.0	35.1	36.3	35.4	36.1	35.8	35.7	35.5	35.9	36.4	35.5	36.2	35.1	36.1
'E' x 10^6 lb/sq in.	10.5	10.4	10.4	10.7	10.5	10.4	10.2	10.3	10.4	10.1	10.1	10.1	10.2	10.5	10.6	10.4	10.6	10.4
Elong. on 4 √A %	12	11	12	16	12	12	12	12	12	11	12	12	12	11	10	11	11	11
0.1% P.S. % of Ult.	84	80.3	80.6	80.6	80.3	80.1	82.5	79.2	82.3	80.5	80.5	78.1	86.3	85.2	80.3	83.1	83	82

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TABLE IV

Haigh Fatigue Test Results

Tube No.	Alternating Stress ± lb/sq in.	Endurance Cycles	Remarks
1	18,000	115.610,500	Unbroken
	18,500	103,372,000	Unbroken
	18,750	71,833,000	
	20,000	216,000	
	19,000	248,000	
	22,000	2,879,000	
	20,000	286,000	
	21,000	2,117,000	
	23,000	265,000	
2	19,000	513,000	
	18,500	323,000	
	18,000	592,000	
	17,000	766,000	
	16,000	17,908,000	
	15,500	105,052,000	Unbroken
	21,000	285,000	
	23,000	330,000	
	26,000	130,000	
3	19,000	254,000	
	18,000	2,360,000	
	15,000	13,475,000	
	17,000	12,318,000	
	16,000	647,000	
	15,500	10,823,000	
	14,000	101,028,000	Unbroken
	17,000	2,515,000	

Mean stress for all specimens = 25,000 lb/sq in.

TABLE V

Tensile Test Results

Tube	1						2						3					
Mark	T1	T2	T3	T4	T5	T6	T1	T2	T3	T4	T5	T6	T1	T2	T3	T4	T5	T6
Diameter ins.	0.337	0.337	0.3375	0.253	0.3375	0.3375	0.357	0.356	0.357	0.357	0.357	0.356	0.357	0.356	0.3565	0.3565	0.357	0.3565
P.L. tons/sq in.	17.0	18.0	14.0	16.9	17.0	14.0	17.0	17.1	17.9	17.0	15.2	17.9	17.0	18.0	17.0	16.1	17.0	17.0
0.1% P.S. tons/sq in.	30.2	26.6	28.5	29.2	28.1	28.1	29.9	28.0	29.7	28.8	28.7	27.7	31.0	31.0	28.5	30.1	29.1	29.6
0.2% P.S. tons/sq in.	31.0	27.7	29.8	30.1	29.1	29.2	31.0	29.3	30.5	30.1	29.8	29.2	32.0	32.1	29.7	31.0	30.2	30.8
0.5% P.S. tons/sq in.	31.8	28.6	30.6	31.0	30.1	30.2	32.1	30.5	31.4	31.0	30.5	30.2	33.0	32.9	30.9	31.8	31.1	31.7
Ultimate stress tons/sq in.	35.9	33.1	35.4	36.2	35.0	35.1	36.3	35.4	36.1	35.8	35.7	35.5	35.9	36.4	35.5	36.2	35.1	36.1
'E' × 10^6 lb/sq in.	10.5	10.4	10.4	10.7	10.5	10.4	10.2	10.3	10.4	10.1	10.1	10.1	10.2	10.5	10.6	10.4	10.6	10.4
Elong. on 4 √A %	12	11	12	16	12	12	12	12	12	11	12	12	12	11	10	11	11	11
0.1% P.S. % of Ult.	84	80.3	80.6	80.6	80.3	80.1	82.5	79.2	82.3	80.5	80.5	78.1	86.3	85.2	80.3	83.1	83	82

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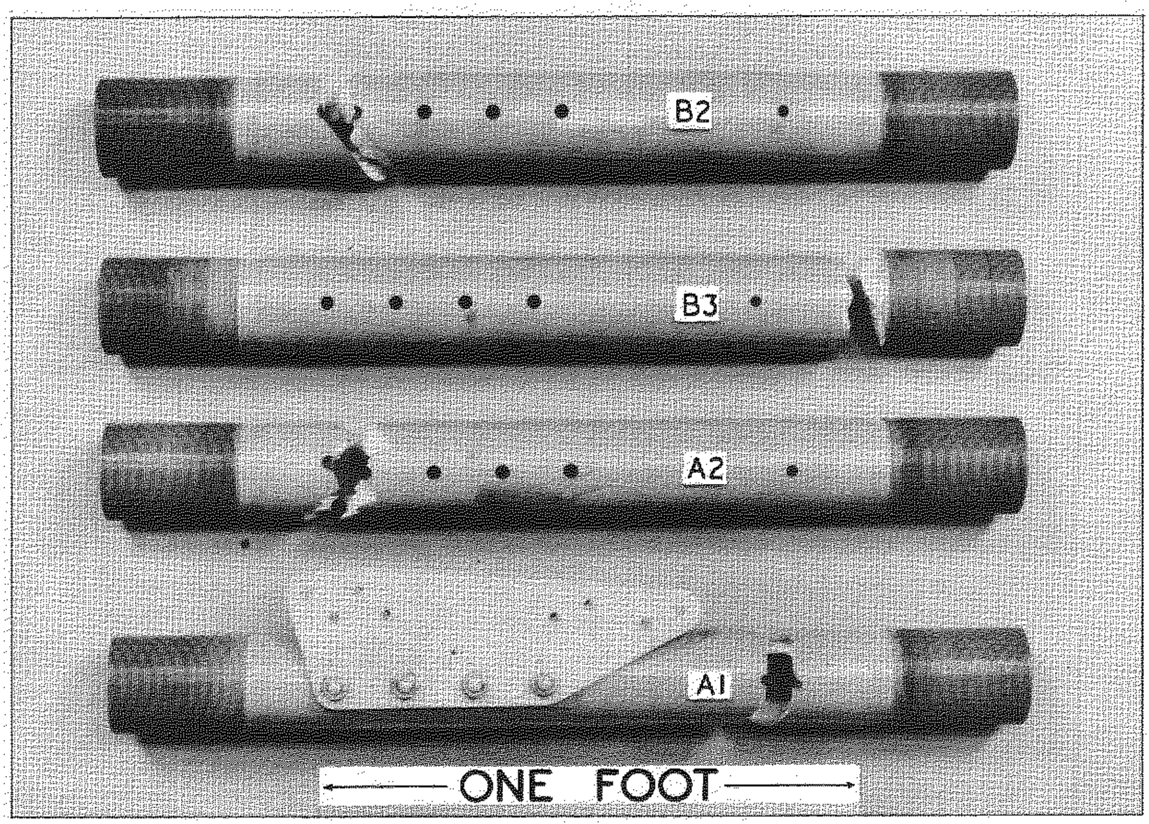


FIG.1. SHOWING TYPE 1 SPECIMENS OF SPAR TUBES WITH TRANSVERSE HOLES

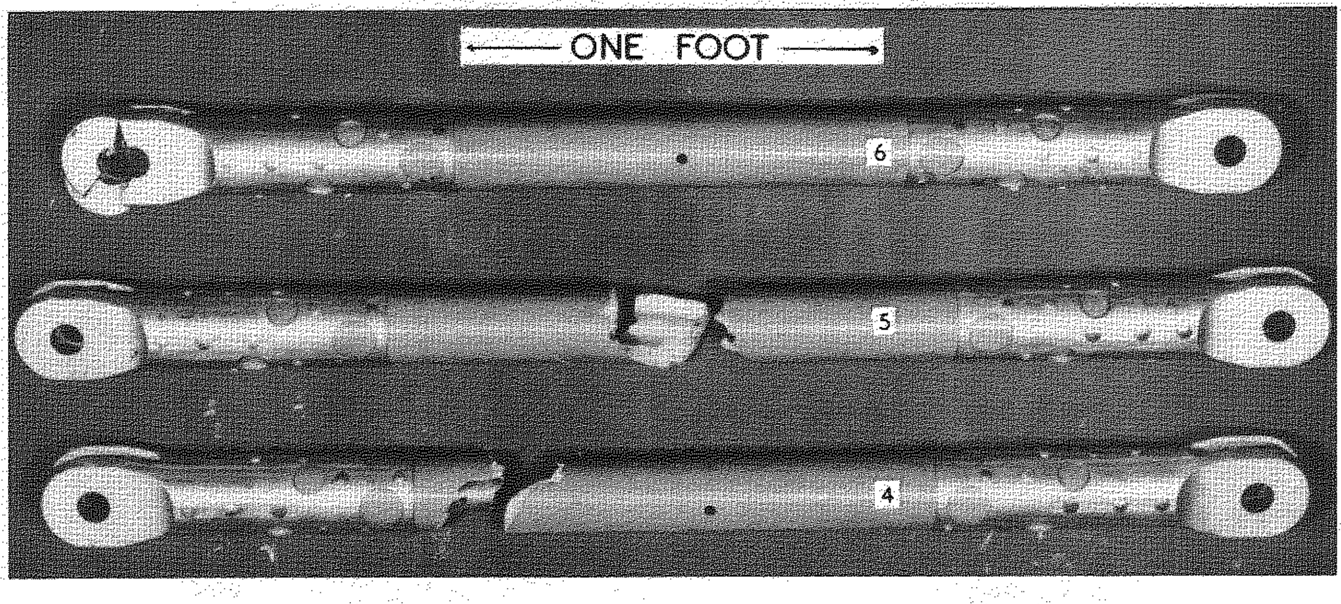


FIG.2. SHOWING TYPE 2 SPECIMENS OF SPAR TUBES WITH TRANSVERSE HOLES

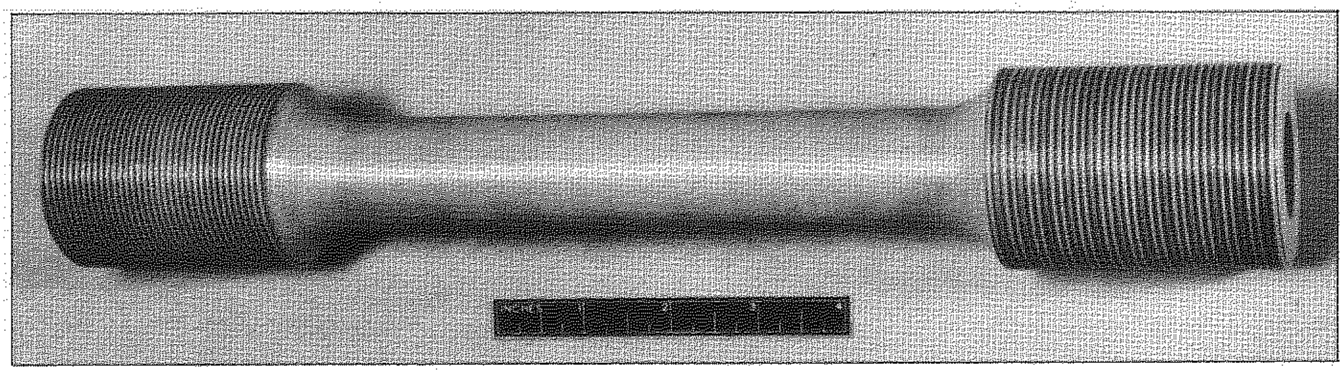
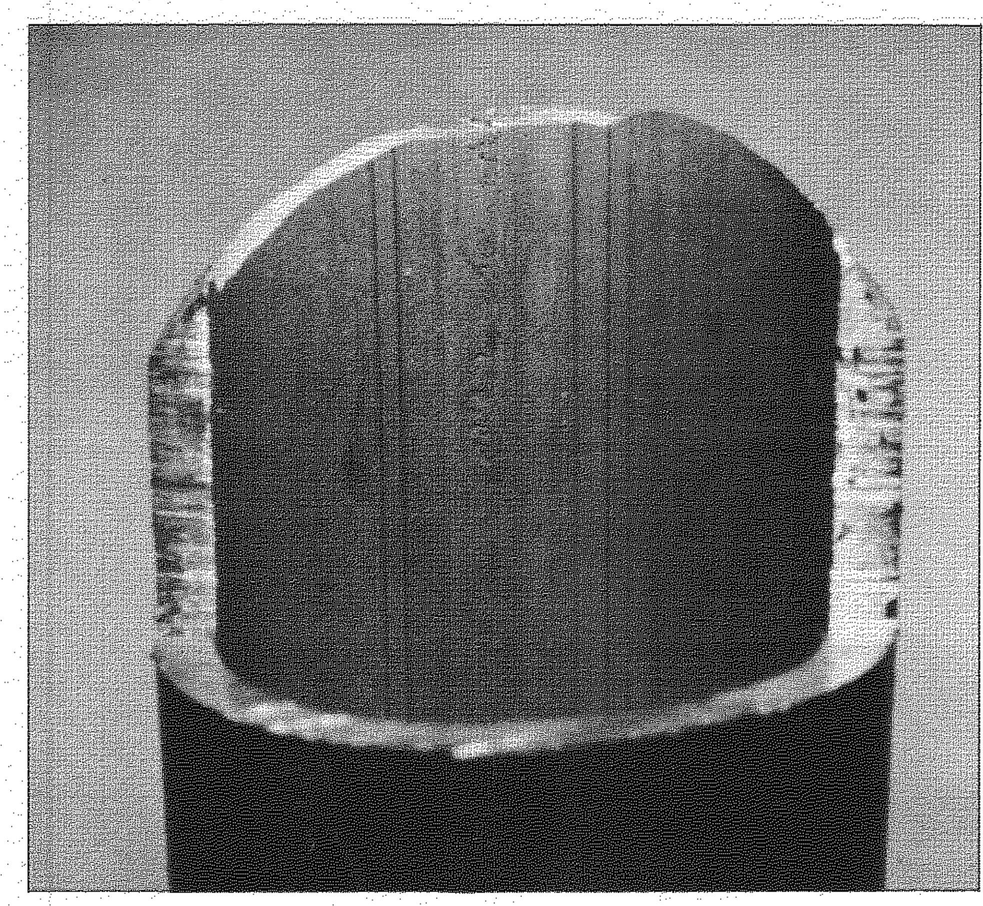
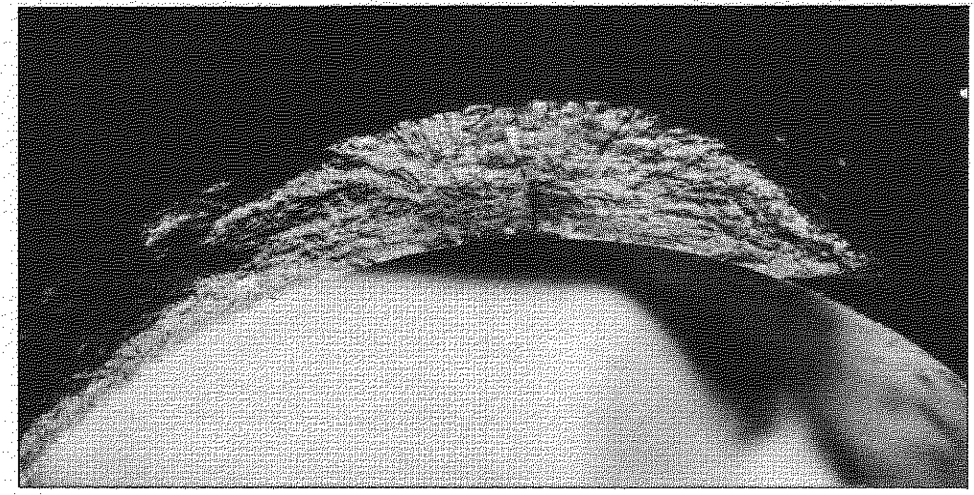


FIG.3. NECKED SPECIMEN WITH THREADED ENDS



x3

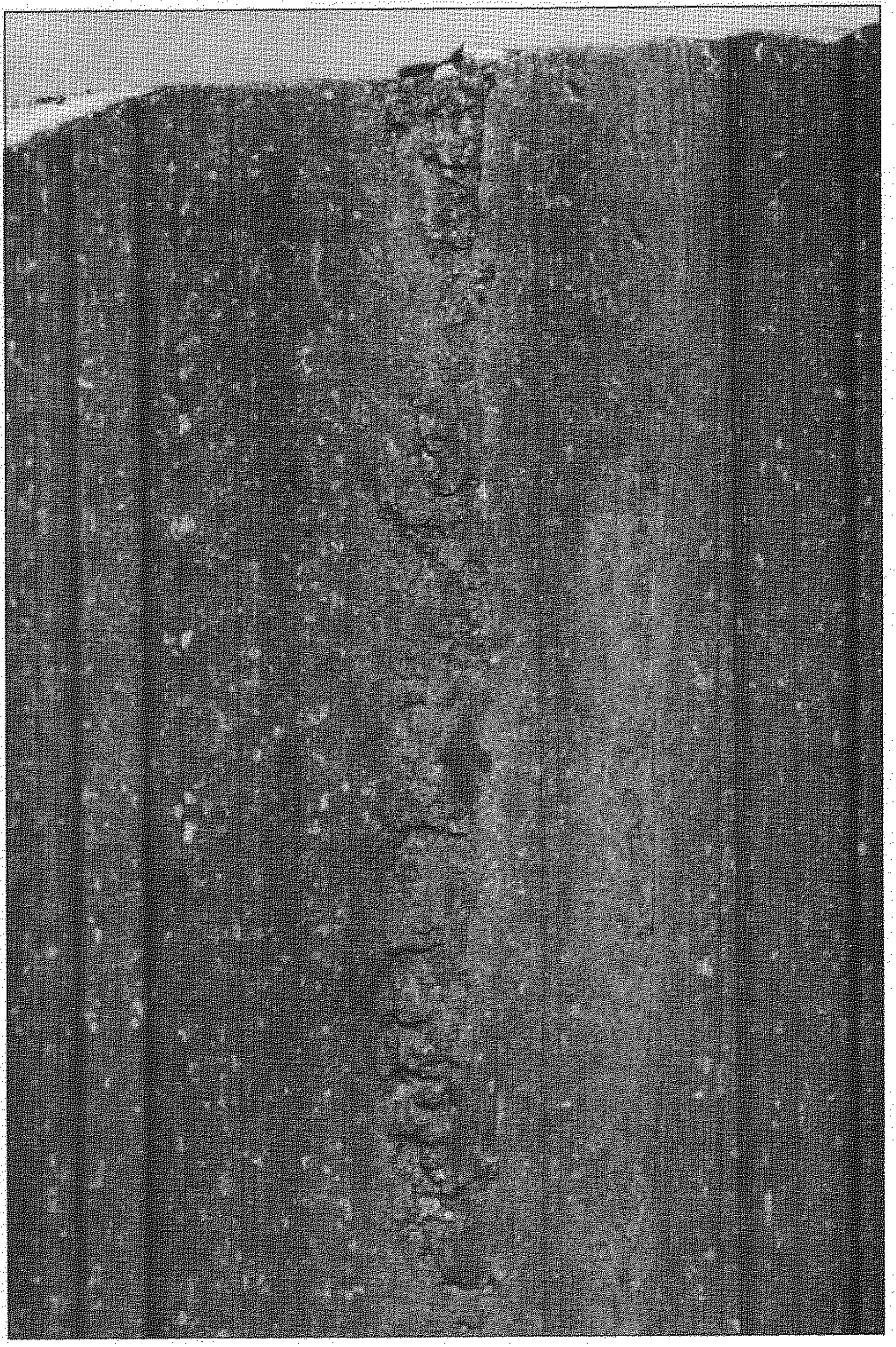
a. ENLARGED VIEW OF FLAW. THE WALL OF THE TUBE HAS BEEN CUT AWAY FOR CLARITY



x5

b. ENLARGED VIEW OF FATIGUE AREA SHOWING ORIGIN OF CRACK AT EXTRUDED INNER SURFACE

FIG.4. FLAW AND FATIGUE AREA.
SPAR TUBE NECKED SPECIMENS



x10

FIG.5. ENLARGED VIEW SHOWING FLAW ON INNER SURFACE OF TUBE SPAR TUBE NECKED SPECIMENS

FIG. 6.

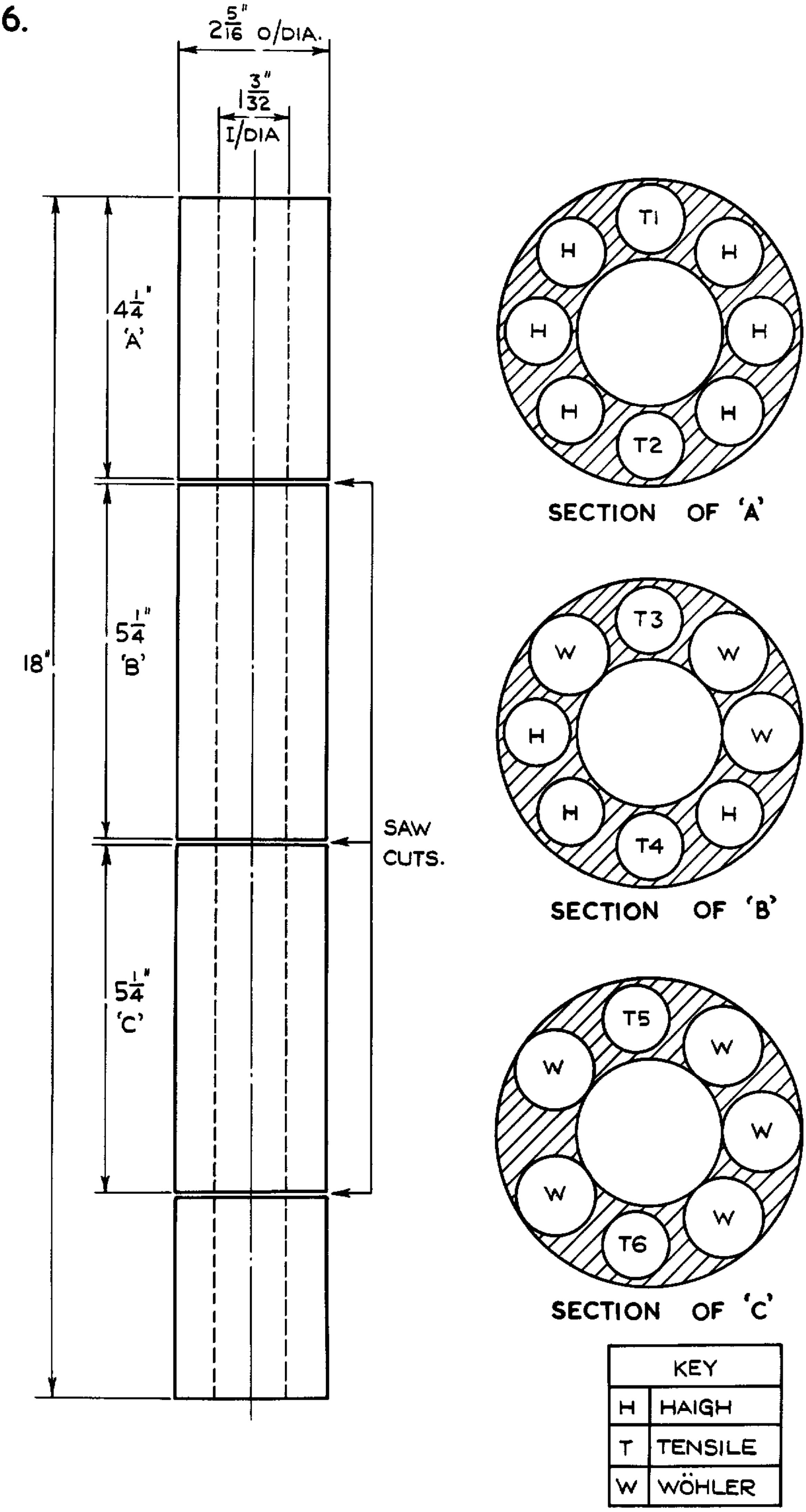


FIG. 6. LOCATION OF TEST PIECES IN EACH TUBE.

FIG. 7.

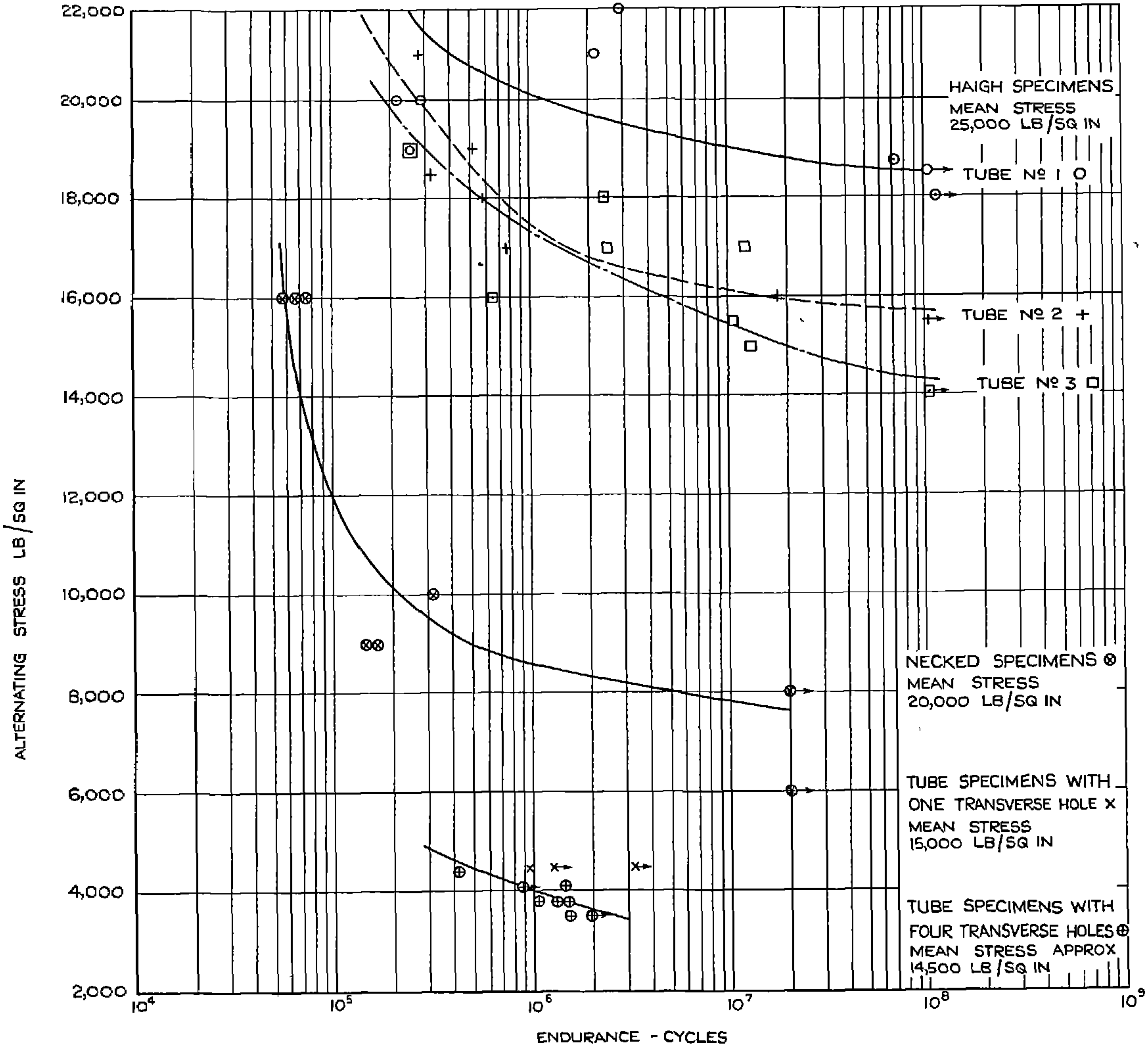


FIG. 7. INVESTIGATION OF THE FATIGUE OF EXTRUDED TUBULAR BOOMS.

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