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BOLTED JOINT FATIGUE PROGRAMME. VOLUME 3. STAGE 2. SUPPLEMENTAR--ETC(U)
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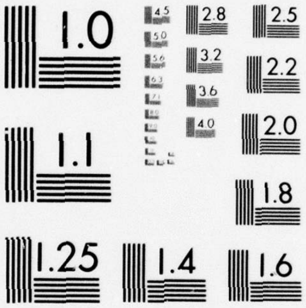

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PROCUREMENT EXECUTIVE MINISTRY OF DEFENCE

BOLTED JOINT FATIGUE PROGRAMME

VOLUME III

STAGE 2 SUPPLEMENTARY INVESTIGATIONS 1 to 6

R H SANDIFER

REPORT OF WORK CONDUCTED UNDER THE
DIRECTION OF THE FATIGUE COMMITTEE OF
THE ENGINEERING SCIENCES DATA UNIT
(PREVIOUSLY THE FATIGUE COMMITTEE OF
THE ROYAL AERONAUTICAL SOCIETY)
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S/T-MEMO-1-77-VOL-3

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BOLTED JOINT FATIGUE PROGRAMME,

VOLUME 3,

STAGE 2, SUPPLEMENTARY INVESTIGATIONS 1 TO 6

By

⑩

R.H. Sandifer

⑪ May 78

⑫ 173p.

(Report of work conducted under the direction of the Fatigue Committee of the Engineering Sciences Data Unit (previously the Fatigue Committee of the Royal Aeronautical Society), 251-259 Regent Street, London W1R 7AD).

SUMMARY

The programme consisted of two major parts - a photoelastic investigation into the stress distribution and resulting stress concentration factors in a family of simple bolted joints, and a correlated series of fatigue tests on bolted metal joints having the same geometrical form as the photoelastic ones using a commonly employed aluminium alloy for the plates and a steel in current use for the pins.

Issued May 1978

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BOLTED JOINT FATIGUE PROGRAMME STAGE 2

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SUPPLEMENTARY INVESTIGATION No.6

BOLTED JOINT FATIGUE PROGRAMME
OF THE ROYAL AERONAUTICAL SOCIETY
FATIGUE COMMITTEE

STAGE 2

VOLUME III SUMMARY

An extensive programme of research into the fatigue endurance, and general behaviour of single pin bolted joints has recently been completed, and is reported in VOLUMES I and II of this S and T Memo.

The programme was first suggested by the Royal Aeronautical Society and the work has been financed by the Ministry of Defence and its predecessors, while the progress has been monitored periodically by the Royal Aeronautical Society's Fatigue Committee.

The main part of this work (referred to above) has, for convenience, become known as 'Stage 1', but during the development of the research it became obvious that information on a number of associated aspects would be most helpful, and since there were sufficient reserve test specimens to permit an extension of the test programme, a number of Supplementary Investigations were planned and agreed, and have now become known collectively, as Stage 2.

VOLUME III

S.I. No.1 - The effect on endurance of pre-stressing the holes by pressing an oversize hard steel ball through them i.e. "Ballising".

S.I. No.2 - The effect of using flat-sided pins (The flats being parallel to the direction of load).

S.I. No.3 - The effect of pre-loading the test specimens.

S.I. No.4 - The effect of transmission of load by clamping.

S.I. No.5 - Some evidence of the influence on endurance of surface finish and hole edge chamfering of loaded push fit pin joint.

S.I. No.6 - The influence of small variations in pin fit.

VOLUME IV

S.I. No.7 - The effect on endurance of radiusing the edges of the bolt holes, by press forming.

S.I. No.8 - Stress corrosion tests on standard and non-standard specimens.

S.I. No.9 - An extension to lower stress levels of some of the tests described in Stage 1.

SUPPLEMENTARY INVESTIGATION No.1

THE EFFECT ON ENDURANCE OF PRE-STRESSING THE HOLES BY PRESSING AN OVERSIZE HARD STEEL BALL THROUGH THEM i.e. "BALLISING"

1. INTRODUCTION

The majority of fatigue failures in the bolted joints of this research have their origins in cracks that start at the edges of bolt holes and thus it is natural to give consideration to the possibility of improving the fatigue resistance of this region. An obvious method of effecting such an improvement is to create a small region of compression around the hole by locally cold-working the surface of the hole, and a convenient way of doing this is to force an over-size steel ball through the hole.

A small programme of tests on specimens so treated was therefore arranged, the specimens being prepared at Short Bros. and Harland and the fatigue test being carried out by Department of Metallurgy at Cambridge University. The loaded push fit pin was chosen as the most useful configuration for this research.

2. THE TESTS

The form and general characteristics of the specimens were the same as for the main programme of the Stage 1 tests except that only medium size specimens were used.

Figure (0) of this report shows the main features of the specimens and is extracted from Figure 2.2 of the main report on Stage 1. Only mean stresses of 0.25 f_t and 0.15 f_t were employed because in the Stage 1 tests on interference fit pins these levels of mean stress showed the greatest improvement in endurances, relative to those of push-fit.

The same three ratios of d/D (pin diameter to width of specimen) were used as in Stage 1, namely 1/4, 3/8 and 1/2 for which the nominal geometric stress concentration factors (i.e. ignoring prestressing of holes) are 3.73, 2.72 and 2.22 respectively.

A range of three degrees of interference between the ball and the pin hole was investigated, namely $1^{o}/o$, $2^{o}/o$ and $4^{o}/o$.

Endurance curves for each configuration, loading and degree of pre-stressing were obtained, together with a control endurance curve, i.e. no pre-stressing, for each value of S_m/f_t and d/D. To minimise errors of machine settings the control tests were carried out immediately after the corresponding tests with the pre-stressed holes.

In all cases three nominally identical specimens were tested for each stress level, except for the controls, when only one specimen per stress level was tested.

Three specimens of each type for at least two degrees of pre-stressing were manufactured for inclusion in the stress corrosion tests covered by S.I. No.8. During the pre-stressing process no lubrication of the ball or of the hole was employed.

It should be noted that in the preliminary tests for this investigation Cambridge University Staff had difficulties in achieving satisfactory pin fits, due to distortion of the holes and to burrs left at the edges of the holes, after the ballising process. A jig-borer was therefore used to improve the shape of the holes and the edges of the holes were lightly filed and polished with fine emery paper to remove the burrs. It was arranged that for later tests Short Brothers and Harland should ensure that the holes were corrected for taper and "barrelling" and that the edges of the holes were de-burred after the pre-stressing process. The recommended procedure was to remove the minimum amount of material by reaming and honing, the final hole surface finish to be comparable with that of the original specimens. Also any metal raised at the edges of the holes was to be removed by file and the filed area hand polished flat to the original finish.

3. NOTATION

For convenience, the relevant Notation of the Stage 1 Report is repeated below -

d = Nominal diameter of hole and pin

D = Width of parallel section of test specimen

f_t = Average Tensile strength of plate material (from tests)

f_p = Average 0.2^{o}/o Proof Stress of plate material (from tests)

K'_t = Geometric Stress Concentration factor based on net area of cross section of test specimen

N = Endurance

S_m = Mean Stress on net area

S_a = Alternating Stress on net area associated with S_m

t = Thickness of plate specimen

4. RESULTS

These are presented in Tables 1 to 9 and are plotted on Figures 1 to 9; all curves are for logarithm mean values at each stress level. Each figure deals with a particular value of d/D (1/4, 3/8 or 1/2) combined with a particular amount of oversize of the ball, (1^{o}/o, 2^{o}/o or 4^{o}/o), and shows the results for both $S_m/f_t = 0.25$ and 0.15.

The control endurance curves are identifiable with a given value of S_m/f_t and d/D.

As a matter of interest on Figures 1, 2 and 3 there are also shown where available - the corresponding "control" curves for the particular configuration and mean stress, taken from the Stage 1 tests. These are the curves shown thus ---------, and in theory they should be identical with the curves of the control tests which were made at the same time as the pre-stressed hole tests. The actual agreement is quite good for d/D = 1/4 and 3/8, but the Stage 1 curves are slightly optimistic at both levels of mean stress for d/D = 1/2. This is not surprising since there is generally more scatter of all results at d/D = 1/2.

Having established reasonable agreement between the results of these two sets of control tests, the results of those tested currently with the pre-stressed hole tests will be used in the following analysis.

Figures 1 to 9 also show that there is significantly more scatter of results for a given stress level at low values of alternating stress, and in fact there were a number of unbroken specimens at 10^7 cycles for the $S_m/f_t = 0.15$ group. Some of the extreme scatter could have been due to excessive "barrelling" with the $4^o/o$ oversize ball. For these reasons some judgement was required in order to obtain reasonable curves when the endurances were high and/or the scatter large.

5. ANALYSIS

Although it is clear from Figures 1 to 9 that the pre-stressed holes are generally beneficial, it was thought that the picture would become clearer if the curves were re-plotted to show on one graph all three degrees of pre-stressing for given values of d/D and S_m/f_t. This form of presentation is shown on Figures 10 to 15 inclusive.

It is clear from these figures that for almost all combinations of d/D and S_m/f_t the optimum amount of pre-stressing corresponds to a $2^o/o$ or just over $2^o/o$ oversize ball, and that in general a $4^o/o$ oversize ball is too large. It is possible that the reason for this is the excessive barrelling which occurs if the ball is greater than say, $2\frac{1}{2}^o/o$ to $3^o/o$.

In order to present a numerical assessment of the improvement in endurance that results from this process the actual values of the Endurance Increase Ratio, i.e.

$$\frac{\text{Endurance of Specimen with Pre-stressed Hole}}{\text{Endurance of Control Specimen}}$$

have been tabulated for two convenient levels of alternating stress, one high and one low - see Table 10.

Furthermore, in order to give a more graphical presentation, these ratios (or rather Logarithms of these ratios, for obvious convenience) have been plotted on Figures 16, 17 and 18 for $d/D = 1/4$, $3/8$ and $1/2$ respectively.

6. CONCLUSIONS

(i) The use of an oversize ball pressed through the pin hole will give an increase in the endurance of a joint having a loaded push fit pin, for a range of $1^{o}/o$ to $4^{o}/o$ oversize. However, for almost all the combinations of d/D, S_m/f_t and S_a/f_t tested, the maximum endurance increase ratio is obtained by the use of a $2^{o}/o$ to $2\frac{1}{2}^{o}/o$ oversize ball.

The results that show exceptions to this are as follows, but in view of the comparatively small number of specimens tested, these exceptions should be viewed with caution.

(a) **At $S_m/f_t = 0.25$**

For high d/D (1/2) and low S_a/f_t (0.08) the maximum endurance increase ratio occurs for a $1^{o}/o$ oversize ball, rather than for $2^{o}/o$ or $2\frac{1}{2}^{o}/o$ (see Figure 18).

(b) **At $S_m/f_t = 0.15$**

For $d/D = 1/4$ and $3/8$ and at high S_a/f_t (0.15) the improvement in endurance continues up to a $4^{o}/o$ oversize ball (see Figures 16 and 17).

It should be noted that there were a number of unbroken specimens associated with the exception at $S_m/f_t = 0.25$ and low S_a/f_t and therefore it is difficult to be precise when estimating endurance increase ratios (see Figure 9).

For the two exceptions at $S_m/f_t = 0.15$ it would appear that some of the $2^{o}/o$ oversize ball results are unusually low, particularly at $S_a/f_t = 0.10$ for $d/D = 1/4$ (see Figure 4) and at $S_a/f_t = 0.125$ for $d/D = 3/8$ (see Figure 5). These $2^{o}/o$, $S_m/f_t = 0.15$ curves would have been significantly steeper and further to the right at their upper ends if the particular results had been more in keeping with the remainder of the results, and in consequence the maximum improvement would again occur nearer to a $2^{o}/o$ oversize ball.

(ii) Choosing the maximum increase in endurance as noted above, from Figures 16 to 18 and converting the log-ratios back to normal ratios leads to Table II "Maximum Endurance Increase Ratios". All these maxima occur at $2^{o}/o$ to $2\frac{1}{2}^{o}/o$ oversize ball except as stated in conclusion (i) above, and for these exceptions the maximum value occurring has been quoted regardless of ball size, on the assumption that if a much larger population of results were available the "exceptions" would not arise.

(iii) Finally, notwithstanding the detail figures give in Table II a simplified but conservative range of endurance increase ratios would be as follows:

	Endurance Increase Ratio		
d/D	1/4	3/8	1/2
High S_a/f_t	1.5 to 2.0	1.5 to 3.5	2.5 to 25
Low S_a/f_t	5	35 to 70	35 to 70

In each range the lower figure corresponds approximately to $S_m/f_t = 0.25$ and the higher figure approximately to $S_m/f_t = 0.15$.

SUPPLEMENTARY INVESTIGATION No.1

TABLE 1 PRE-STRESSED HOLE LOADED PUSH FIT PIN Reference Figure 1

1°/o OVERSIZE BALL

Specimen Type 2B 5/16 d/D = 1/4 Nominal $K'_t = 3.73^{+}$

Tested at Cambridge University

Testing Machine, 6 Ton Losenhausen, Speed 1500 c.p.m.

Specimen Identification Number	Stress Levels (°/o Ultimate)		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
23.16.A	25	22½	11 810	4.073	10 550 control
23.16.D			10 650	4.027	
23.17.B			9 210	3.964	
26.10.A			7 710	3.886	
23.18.C	25	15	28 700	4.456	25 460 control
23.18.A			27 730	4.442	
23.17.C			19 960	4.300	
26.10.C			32 220	4.507	
24.3.B	25	10	137 180	5.137	105 660 control
23.18.E			114 650	5.060	
23.18.D			65 160	4.815	
26.11.A			54 350	4.735	
24.13.B	25	7½	502 200	5.702	386 440 control
24.8.6			419 540	5.622	
24.7.B			237 590	5.375	
26.11.B			121 620	5.083	
24.15.A	15	12½	211 600	5.325	144 870 control
24.14.A			148 330	5.171	
24.14.B			74 690	4.872	
26.11.E			59 510	4.775	
24.16.A	15	10	270 950	5.433	156 100 control
24.17.A			111 710	5.046	
24.16.B			85 650	4.932	
26.12.C			182 320	5.260	
24.18.A	15	7½	6 849 000	6.835	2 505 360 control
24.17.B			386 560	5.587	
24.17.C			280 520	5.449	
26.12.D			108 830	5.035	
24.19.B	15	5	10 531 000U	7.021U	>18 425 670 control
24.1.D			9 295 000	6.967	
24.2.E			5 451 000	6.736	
26.12.E			656 680	5.815	

U Unbroken

\+ i.e. before ballising

SUPPLEMENTARY INVESTIGATION No.1

TABLE 2 PRE-STRESSED HOLE LOADED PUSH FIT PIN **Reference Figure 2**

1^{o}/o OVERSIZE BALL

Specimen Type 2D 15/32 d/D = 3/8 Nominal $K_t' = 2.72^{+}$

Tested at Cambridge University

Testing Machine, 6 Ton Losenhausen, Speed 1500 c.p.m.

Specimen Identification Number	Stress Levels (^{o}/o Ultimate)		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
7.17.C	25	22½	18 200	4.260	15 730
7.17.D			15 560	4.191	
7.17.E			13 440	4.130	
9.19.E			26 470	4.420	control
7.18.B	25	15	27 930	4.445	25 280
7.18.C			25 940	4.412	
7.18.A			21 970	4.340	
9.20.A			41 230	4.615	control
7.18.D	25	10	89 890	4.954	82 610
7.18.E			84 020	4.924	
7.19.A			73 920	4.868	
9.20.B			117 520	5.070	control
7.19.D	25	7½	2 266 410	6.355	931 430
7.19.C			417 300	5.620	
7.19.B			110 580	5.041	
9.20.C			190 340	5.280	control
7.20.A	17½$^{\times}$	12½$^{\times}$	101 600$^{\times}$	5.004	83 000$^{\times}$
7.20.B			76 900$^{\times}$	4.885	
7.19.E			72 130$^{\times}$	4.860	
9.20.D			97 810$^{\times}$	4.990	control$^{\times}$
7.20.C	17½$^{\times}$	10	98 220$^{\times}$	4.993	84 800$^{\times}$
9.11.A			85 860$^{\times}$	4.933	
7.20.D			81 320$^{\times}$	4.910	
9.17.E			103 070$^{\times}$	5.012	control$^{\times}$
9.11.C	15	7½	11 984 640U	7.078U	>7 605 400
9.11.D			10 586 270U	7.024U	
9.11.B			254 240	5.405	
13.2.E			239 640	5.112	control
9.12.B	15	5	12 755 000U	7.105U	>7 895 670
9.12.A			10 346 000	7.014	
9.11.E			586 000	5.767	
13.3.B			721 860	5.860	control

U Unbroken

× **Mean stress inadvertently set at 17½^{o}/o ultimate instead of 15^{o}/o, but as first approximation endurances marked × have been corrected by multiplying by 17.5/15.0 = 1.17 when plotting on Figure 2.**

\+ **i.e. before ballising**

SUPPLEMENTARY INVESTIGATION No.1

TABLE 3 **PRE-STRESSED HOLE LOADED PUSH FIT PIN** **Reference Figure 3**

1^{o}/o OVERSIZE BALL

Specimen Type 2D 5/8 d/D = 1/2 Nominal $K_t' = 2.22^+$

Tested at Cambridge University

Testing Machine, 6 Ton Losenhausen, Speed 1500 c.p.m.

Specimen Identification Number	Stress Levels (°/o Ultimate)		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
6.5.D	25	22½	29 830	4.474	27 590
6.5.B			29 500	4.469	
6.5.C			23 440	4.369	
6.1.A			19 200	4.282	control
6.6.C	25	15	78 250	4.894	65 160
6.6.A			67 700	4.830	
6.6.B			49 540	4.695	
6.1.B			44 790	4.650	control
6.6.D	25	10	3 189 000	6.503	1722 500
6.7.A			1 064 300	6.027	
6.6.E			914 190	5.960	
6.1.C			100 450	5.002	control
6.7.D	25	7½	10 568 000U	7.023U	>8 629 100
6.7.C			10 553 550U	7.021U	
6.7.B			4 765 000	6.677	
6.1.D			243 120	5.385	control
6.7.E	15	12½	12 586 000	7.100	4 383 650
6.8.A			355 150	5.550	
6.8.B			209 790	5.321	
6.2.B			197 900	5.296	control
6.8.C	15	10	9 921 890	6.996	4 564 000
6.9.B			3 474 690	6.541	
6.9.A			295 440	5.470	
6.2.C			183 190	5.262	control
6.9.E	15	7½	14 832 000U	7.170U	>12 233 670
6.9.D			11 273 000U	7.053U	
6.9.C			10 596 000U	7.025U	
6.2.D			407 290	5.610	control

U **Unbroken**

\+ i.e. before ballising

SUPPLEMENTARY INVESTIGATION No.1

TABLE 4 PRE-STRESSED HOLE LOADED PUSH FIT PIN **Reference Figure 4**

2^{o}/o OVERSIZE BALL

Specimen Type 2B 5/16 d/D = 1/4 Nominal $K'_t = 3.73^+$

Tested at Cambridge University

Testing Machine, 6 Ton Losenhausen, Speed 1500 c.p.m.

Specimen Identification Number	Stress Levels (^{o}/o Ultimate)		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
19.1.F 19.10.F 19.4.F	25	22½	14 810 13 650 11 900	4.170 4.135 4.125	13 450
27.16.F 19.18.F 20.16.F	25	15	34 190 28 980 26 960	4.533 4.460 4.430	30 040
20.18.F 22.5.F 22.4.F	25	10	130 110 92 540 77 610	5.115 4.965 4.890	100 090
22.9.F 23.18.F 22.6.F	25	7½	2 158 790 306 750 213 950	6.335 5.485 5.329	893 160
24.16.F 24.15.F 24.4.F	15	12	219 100 145 040 84 210	5.340 5.160 4.925	149 450
24.17.F 25.17.F 26.10.F	15	10	280 210 173 920 141 710	5.448 5.240 5.150	198 620
26.14.F 26.15.F 27.14.F	15	7½	10 550 000U 10 522 000U 409 120	7.022U 7.020U 5.611	>7 160 370
27.16.F 27.15.F	15	5	11 178 000U 10 588 000U	7.049U 7.023U	>10 883 000

U Unbroken

\+ i.e. before ballising

TABLE 5 PRE-STRESSED HOLE LOADED PUSH FIT PIN Reference Figure 5

2^{o}/o OVERSIZE BALL

Specimen Type 2D 15/32 d/D = 3/8 Nominal $K'_t = 2.72^+$

Tested at Cambridge University

Testing Machine, 6 Ton Losenhausen, Speed 1500 c.p.m.

Specimen Identification Number	Stress Levels (^{o}/o Ultimate)		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
14.20.G 14.16.G 14.19.F	25	22½	47 000 36 680 33 630	4.672 4.564 4.526	39 100
15.2.E 15.1.G 15.2.D	25	15	73 750 70 630 58 190	4.866 4.848 4.765	67 520
14.2.E 13.6.G	25	10	12 670 000U 297 690	7.135U 5.472	>6 483 840
14.8.G 14.3.D 12.19.C	25	7½	10 585 000U 7 190 730 454 130	7.022U 6.855 5.656	>6 076 620
14.12.G 14.11.G	15	12½	681 500 190 440	5.834 5.278	435 970
14.14.G 14.14.D 14.13.B	15	10	10 825 000U 10 601 000U 10 546 000U	7.035U 7.025U 7.022U	>10 657 330

U **Unbroken**

\+ **i.e. before ballising**

TABLE 6 PRE-STRESSED HOLE LOADED PUSH FIT PIN Reference Figure 6
2°/o OVERSIZE BALL
Specimen Type 2D 5/8 d/D = 1/2 Nominal $K_t' = 2.22^+$
Tested at Cambridge University
Testing Machine, 6 Ton Losenhausen, Speed 1500 c.p.m.

Specimen Identification Number	Stress Levels (°/o Ultimate)		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
5.9.A	25	22½	58 550	4.767	44 420
5.9.B			41 700	4.620	
5.9.D			33 000	4.518	
5.10.B	25	15	125 970	5.097	113 240
5.10.C			114 930	5.056	
5.10.D			98 820	4.994	
5.11.A	25	10	10 342 000U	7.015U	>3 617 990
5.11.C			336 450	5.526	
5.11.B			175 520	5.243	
5.13.C	25	7½	12 452 000U	7.095U	>8 365 610
5.11.D			12 036 000U	7.080U	
5.13.A			608 820	5.784	
5.14.B	15	12½	10 727 840U	7.030U	>8 162 710
5.13.D			10 611 880U	7.026U	
5.13.E			3 148 410	6.497	
5.15.A	15	10	10 581 000U	7.023U	>10 570 000
5.14.D			10 568 000U	7.022U	
5.14.E			10 561 000U	7.021U	

TABLE 7 PRE-STRESSED HOLE LOADED PUSH FIT PIN Reference Figure 7
4°/o OVERSIZE BALL
Specimen Type 2B 5/16 d/D = 1/4 Nominal $K_t' = 3.73^+$
Tested at Cambridge University
Testing Machine, 6 Ton Losenhausen, Speed 1500 c.p.m.

Specimen Identification Number	Stress Levels (°/o Ultimate)		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
25.5.C	25	22½	10 480	4.020	10 060
25.4.C			10 280	4.012	
25.4.B			9 420	3.973	
25.6.C	25	15	27 460	4.437	21 800
25.8.B			19 130	4.281	
25.9.B			18 800	4.274	
25.9.D	25	10	83 390	4.920	66 380
25.10.E			59 740	4.775	
25.11.C			56 000	4.748	
25.11.D	25	7½	177 210	5.248	159 790
25.12.A			160 290	5.205	
25.12.C			141 880	5.151	
25.12.E	15	12½	145 660	5.162	137 110
25.13.B			135 220	5.130	
25.12.D			130 440	5.115	
25.13.E	15	10	788 970	5.897	354 790
25.13.C			158 900	5.201	
25.13.D			116 490	5.066	
26.12.D	15	7½	4 001 170	6.601	1 718 260
25.14.E			655 550	5.816	
26.3.C			498 070	5.697	
26.5.E	15	5	4 921 800	6.691	4 324 680
26.4.B			4 460 000	6.650	
26.3.D			3 592 250	6.555	

\+ i.e. before ballising

U unbroken

SUPPLEMENTARY INVESTIGATION No.1

TABLE 8 PRE-STRESSED HOLE LOADED PUSH FIT PIN **Reference Figure 8**

4^o/o OVERSIZE BALL

Specimen Type 2D 15/32 d/D = 3/8 Nominal $K_t' = 2.72^+$

Tested at Cambridge University

Testing Machine, 6 Ton Losenhausen, Speed 1500 c.p.m.

Specimen Identification Number	Stress Levels (^{o}/o Ultimate)		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
9.14.D 9.14.E 9.14.B	25	22½	39 250 38 470 26 030	4.594 4.584 4.416	34 580
9.15.B 9.15.A 9.15.C	25	15	71 830 61 190 40 490	4.855 4.787 4.605	57 840
9.15.D 9.16.A 9.15.E	25	10	1 133 080 255 480 122 470	6.054 5.408 5.088	503 680
9.16.D 9.16.B 9.16.C	25	7½	3 003 360 1 203 740 301 820	6.477 6.080 5.480	1 502 970
9.17.B 9.17.A 9.16.E	15	12½	1 129 590 499 920 377 600	6.051 5.697 5.575	669 040
9.17.D 9.17.C 9.18.A	15	10	10 611 000U 662 500 502 230	7.025U 5.820 5.701	>3 925 240
9.18.B 9.18.D 9.18.C	15	7½	12 690 000U 10 643 000U 10 544 000U	7.104U 7.027U 7.022U	>11 292 330

U unbroken

\+ i.e. before ballising

TABLE 9 PRE-STRESSED HOLE LOADED PUSH FIT PIN **Reference Figure 9**

$4^{o}/o$ OVERSIZE BALL

Specimen Type 2D 5/8 d/D = 1/2 Nominal $K'_t = 2.22^+$

Tested at Cambridge University

Testing Machine, 6 Ton Losenhausen, Speed 1500 c.p.m.

Specimen Identification Number	Stress Levels (°/o Ultimate)		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
3.4.B	25	22½	28 180	4.450	22 950
3.3.E			22 810	4.357	
3.3.D			17 850	4.252	
3.6.C	25	15	57 040	4.756	53 930
3.5.A			56 850	4.753	
3.7.A			47 890	4.680	
3.8.D	25	10	207 220	5.316	149 070
3.9.A			125 430	5.096	
3.7.D			114 550	5.060	
3.10.A	25	7½	7 587 000	6.880	4 301 270
3.9.D			4 399 000	6.642	
3.9.B			917 810	5.962	
3.10.B	15	12½	739 440	5.868	371 840
3.11.D			216 370	5.335	
3.12.A			159 710	5.202	
3.12.B	15	10	1 326 290	6.121	620 450
3.13.A			314 620	5.496	
3.12.D			220 430	5.343	
3.15.E	15	7½	12 699 000U	7.104U	>9 247 500
3.14.C			10 563 490U	7.024U	
3.15.B			4 480 000	6.650	
3.20.A	15	5	14 845 000U	7.171U	>13 182 230
3.19.E			14 508 000U	7.161U	
3.17.B			10 193 690U	7.007U	

U unbroken

\+ i.e. before ballising

TABLE 10 ENDURANCE INCREASE RATIOS FOR FULL RANGE OF TESTS

$$\text{ENDURANCE INCREASE RATIO} = \frac{\text{ENDURANCE OF SPECIMEN WITH PRE-STRESSED HOLE}}{\text{ENDURANCE OF CONTROL SPECIMEN}}$$

(a) d/D = 1/4 (Nominal $K'_t = 3.73$)

S_m/f_t	0.25		0.15	
S_a/f_t	0.20	0.08	0.15	0.08
Increase Ratios:-				
1°/o Control	1.35	2.66	1.18	3.66
2°/o Control	1.75	4.95	1.08	4.88
4°/o Control	1.25	1.38	1.94	4.45

TABLE 10 (Cont.)

SUPPLEMENTARY INVESTIGATION No.1

(b) d/D = 3/8 (Nominal $K_t' = 2.72$)

S_m/f_t	0.25		0.15	
S_a/f_t	0.20	0.08	0.15	0.08
Increase Ratios:-				
1°/o Control	0.60	1.26	0.70	1.77
2°/o Control	1.58	59.0	1.11	>500
4°/o Control	1.34	8.80	3.70	94.0

(c) d/D = 1/2 (Nominal $K_t' = 2.22$)

S_m/f_t	0.25		0.15	
S_a/f_t	0.20	0.08	0.15	0.08
Increase Ratios:-				
1°/o Control	1.50	37.2	12.4	31.6
2°/o Control	2.37	18.6	59.0	70.0
4°/o Control	1.25	4.20	1.94	7.9

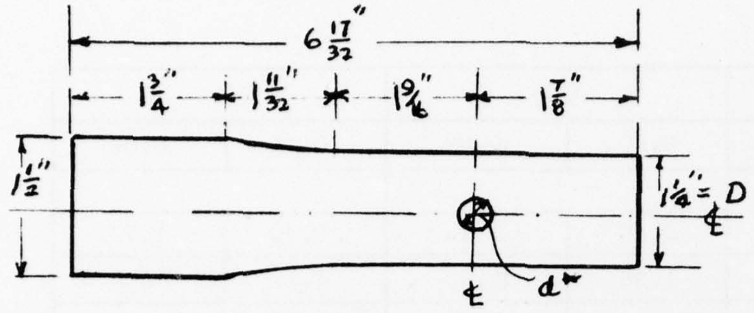
TABLE 11 MAXIMUM ENDURANCE INCREASE RATIOS
(Generally for 2°/o to 2.5°/o OVERSIZE BALL)

d/D	1/4		3/8		1/2	
S_m/f_t / S_a/f_t	0.25	0.15	0.25	0.15	0.25	0.15
0.20	1.80		1.60		2.40	
0.15		1.95		3.70		59.0
0.08	4.90	5.25	60.0	500	37.0	71.0

FIG (O) DETAILS OF SPECIMENS (MEDIUM SIZE)

SCALE - HALF SIZE

PLATES - MATERIAL B.S. L71

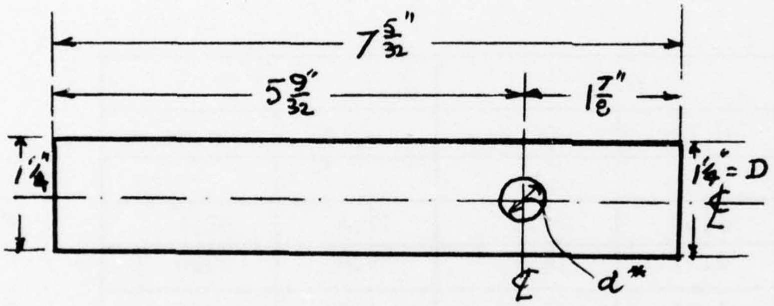


SPECIMEN TYPE 2B 5/16

* $d = 5/16''$

$d/D = 1/4$

Thickness = $5/32''$



SPECIMEN TYPES -

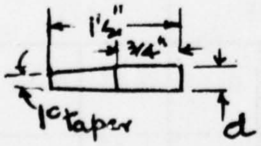
2D 15/32 & 2D 5/8

* $d = \frac{15}{32}''$ and $5/8''$

$d/D = 3/8$ and $1/2$

Thickness = $5/32''$

PINS - MATERIAL B.S. S94



NOTES

1. Type D specimen is the same as Type B Except for lack of wide end which is not necessary when d/D is greater than 1/4.

2. Hole diameter drilled to tolerance of ± 0.003" and pin dia made to even closer tolerances. By means of selective assembly a final push fit to a 'clearance' of ± 0.003" was achieved.

3. Load applied to pin in double shear by separate side plates, and specimens tested in 6ton Losenhausen Fatigue Testing Machine operating at 1500 c.p.m.

FIG. 1 SUPPLEMENTARY INVESTIGATION N°.1 Ref. Table 1

PRE-STRESSED HOLE 1% OVERSIZE BALL

LOADED PUSH FIT PINS

MEDIUM SIZE SPECIMEN – TYPE 28 5/16 $d/D = 1/4$ $S_m/f_t = 0.25 \& 0.15$

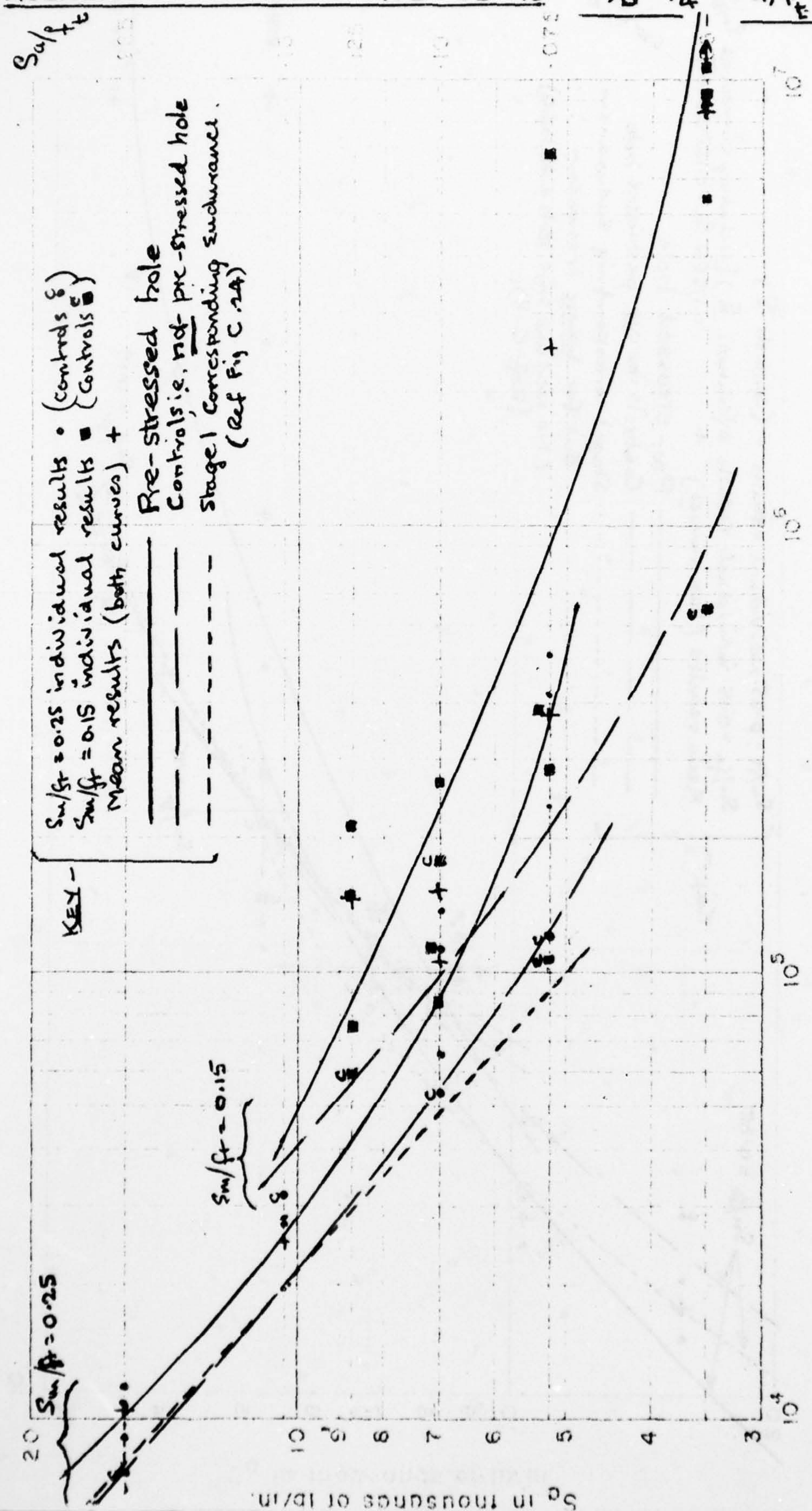


FIG. 2 SUPPLEMENTARY INVESTIGATION Nº 1

Ref. Table 2

PRE-STRESSED HOLE

1% OVERSIZE BALL

LOADED PUSH FIT PIN MEDIUM SIZE SPECIMEN TYPE 2. D 15/32 d/D = 3/8

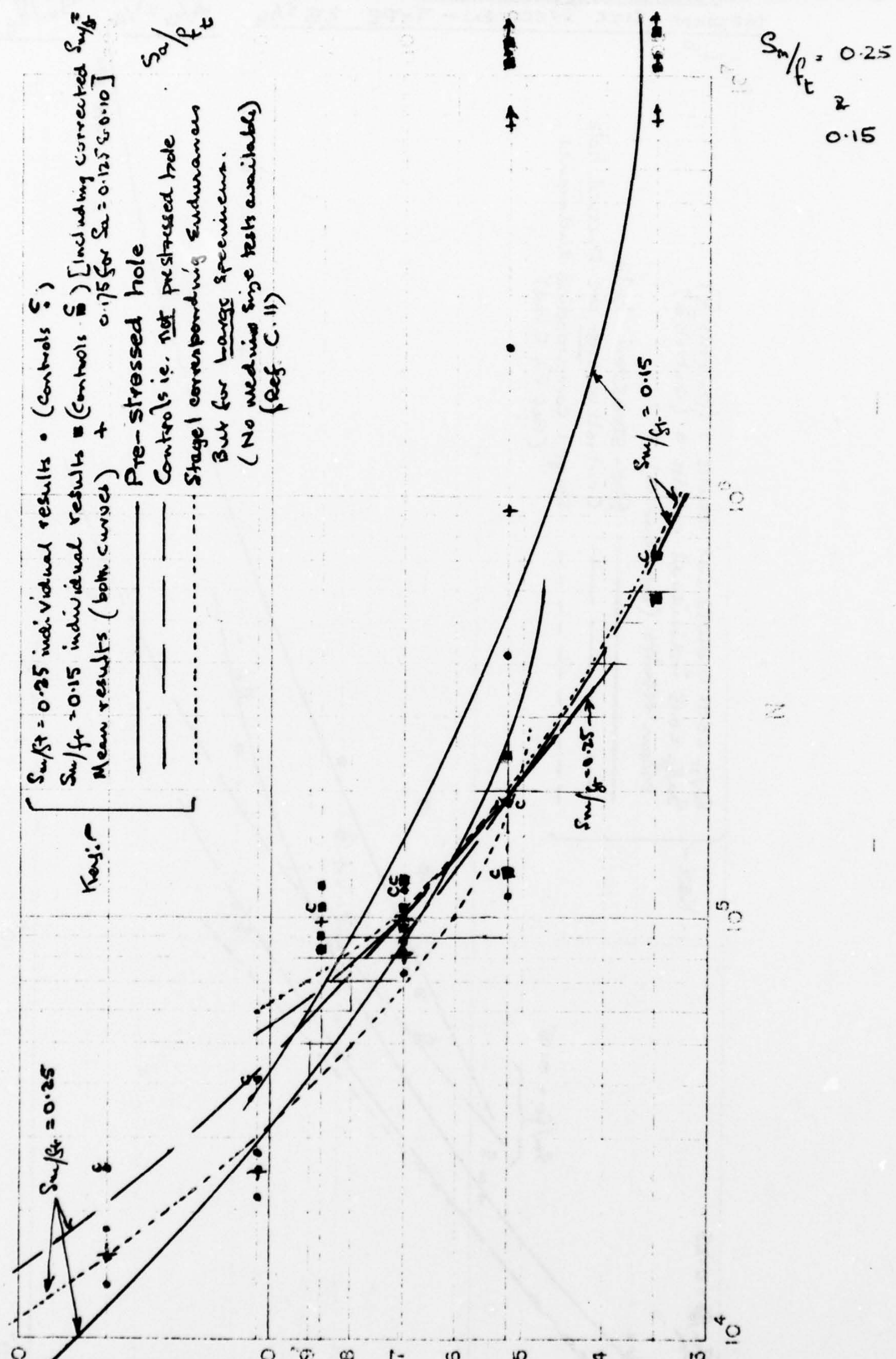


FIG.3 SUPPLEMENTARY INVESTIGATION No1 Ref. Table 3

PRE-STRESSED HOLE 1% OVERSIZE BALL

LOADED PUSH FIT PIN MEDIUMSIZE SPECIMEN TYPE 2D 5/8 $d/D = 1/2$

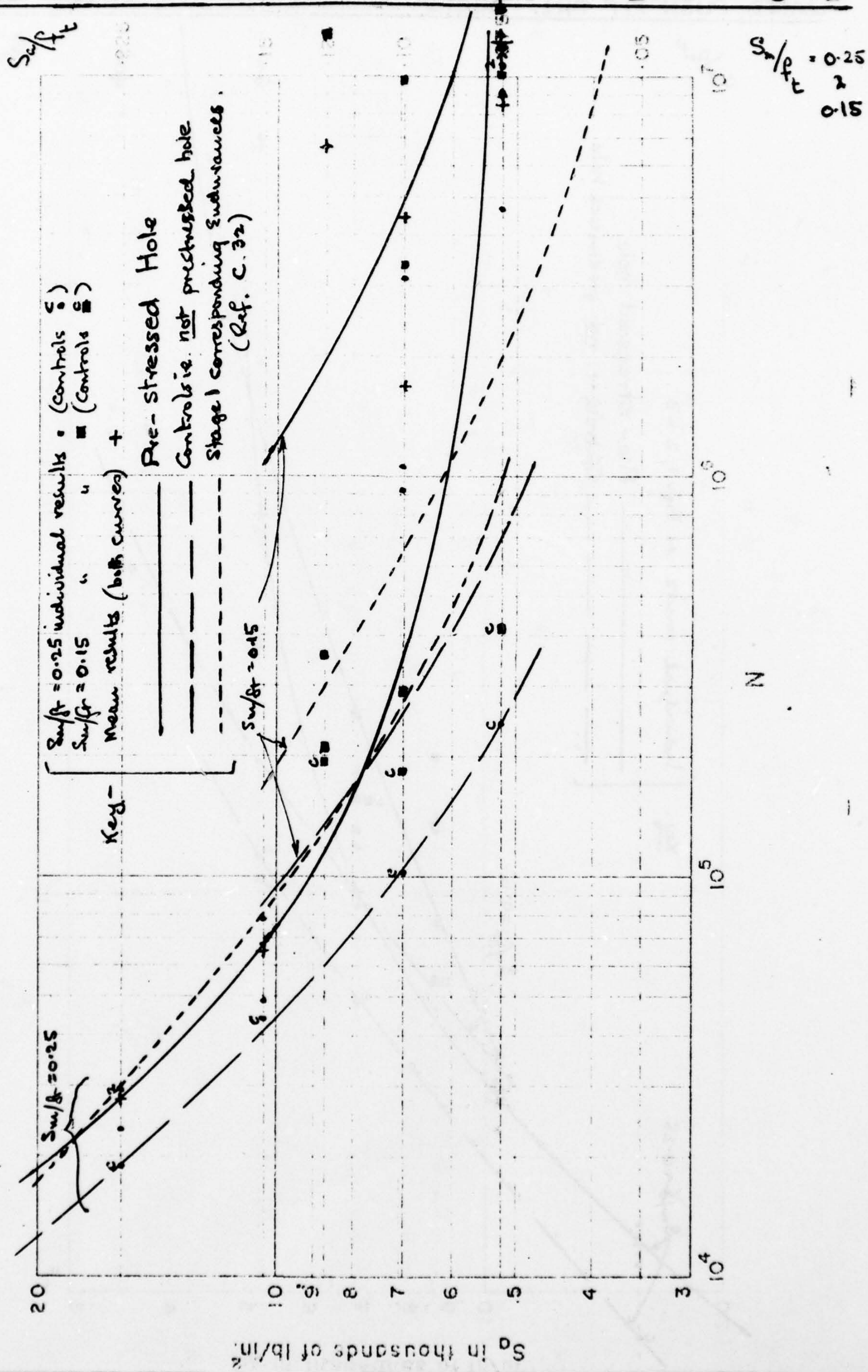


FIG. 4 SUPPLEMENTARY INVESTIGATION N°1 Ref. Table 4

PRE-STRESSED HOLE 2% OVERSIZE BALL

LOADED PUSH FIT PIN MEDIUM SIZE SPECIMEN TYPE 2B 5/16 d/D = 1/4

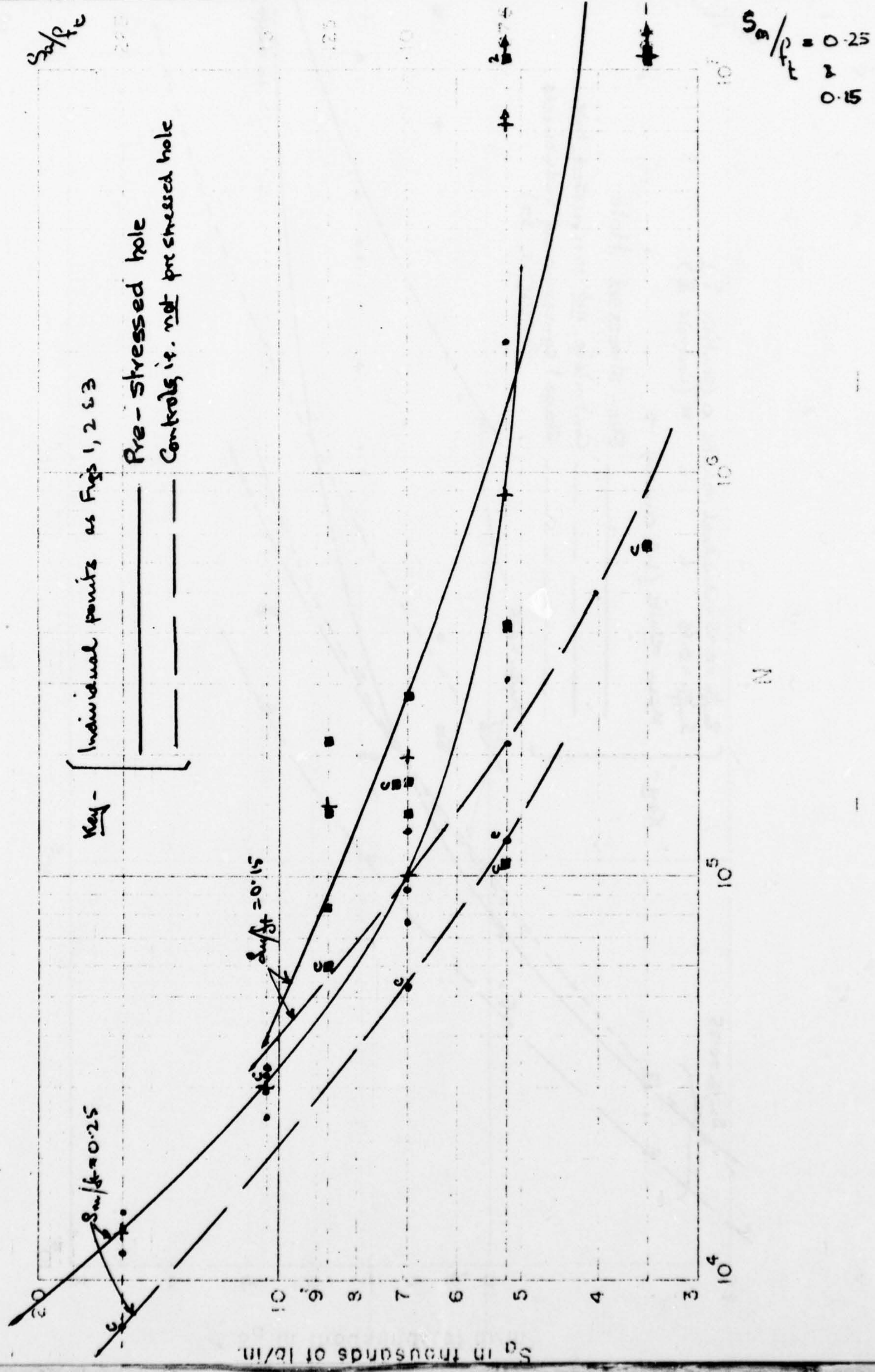


FIG. 5 SUPPLEMENTARY INVESTIGATION N°1 Ref. Table 5

PRE-STRESSED HOLE 2% OVERSIZE BALL

LOADED PUSH FIT PIN MEDIUM SIZE SPECIMEN - TYPE 2D 15/32 $d/D = 3/8$

$S_n/f_t = 0{\cdot}25$ & $0{\cdot}15$

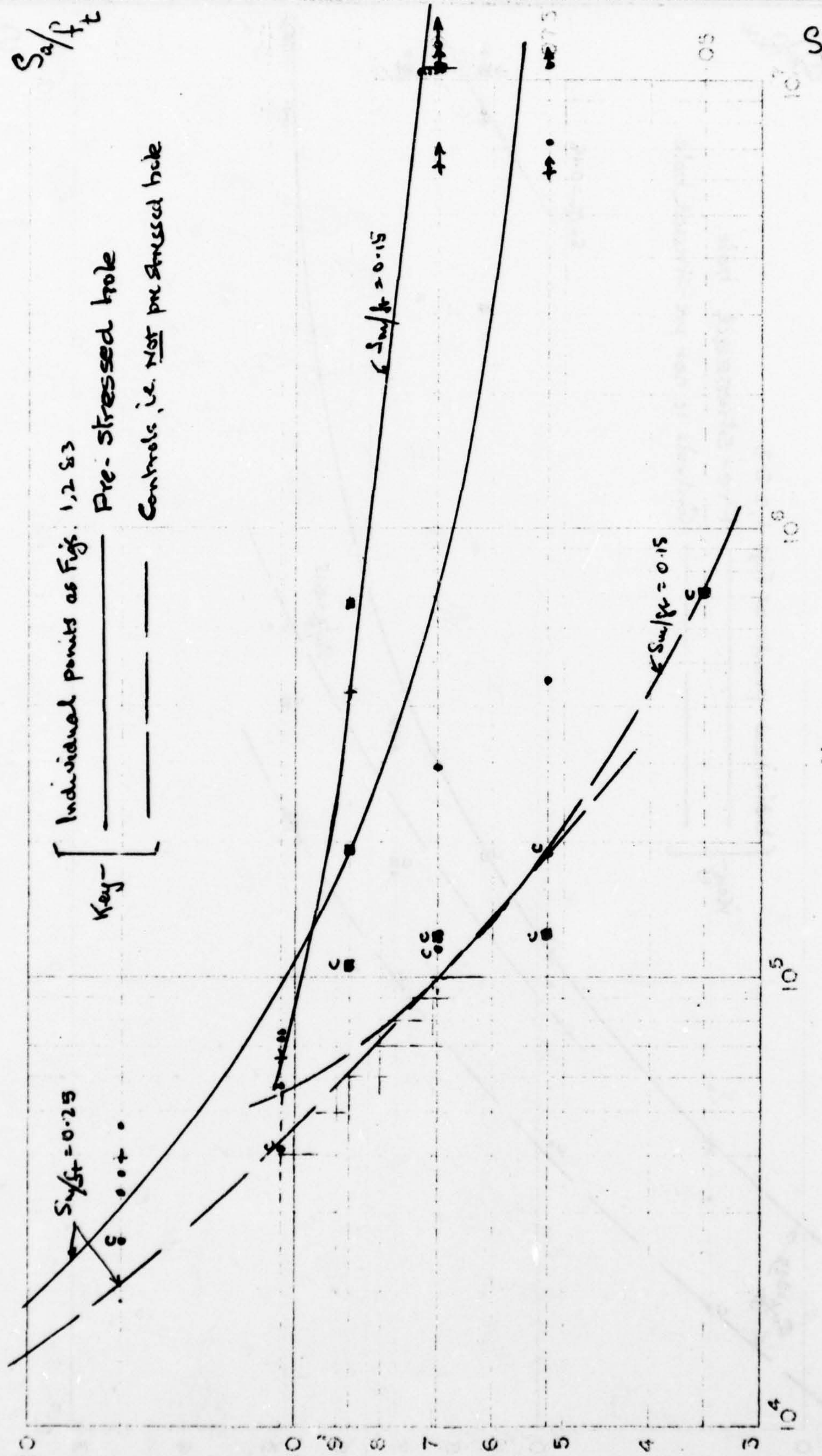
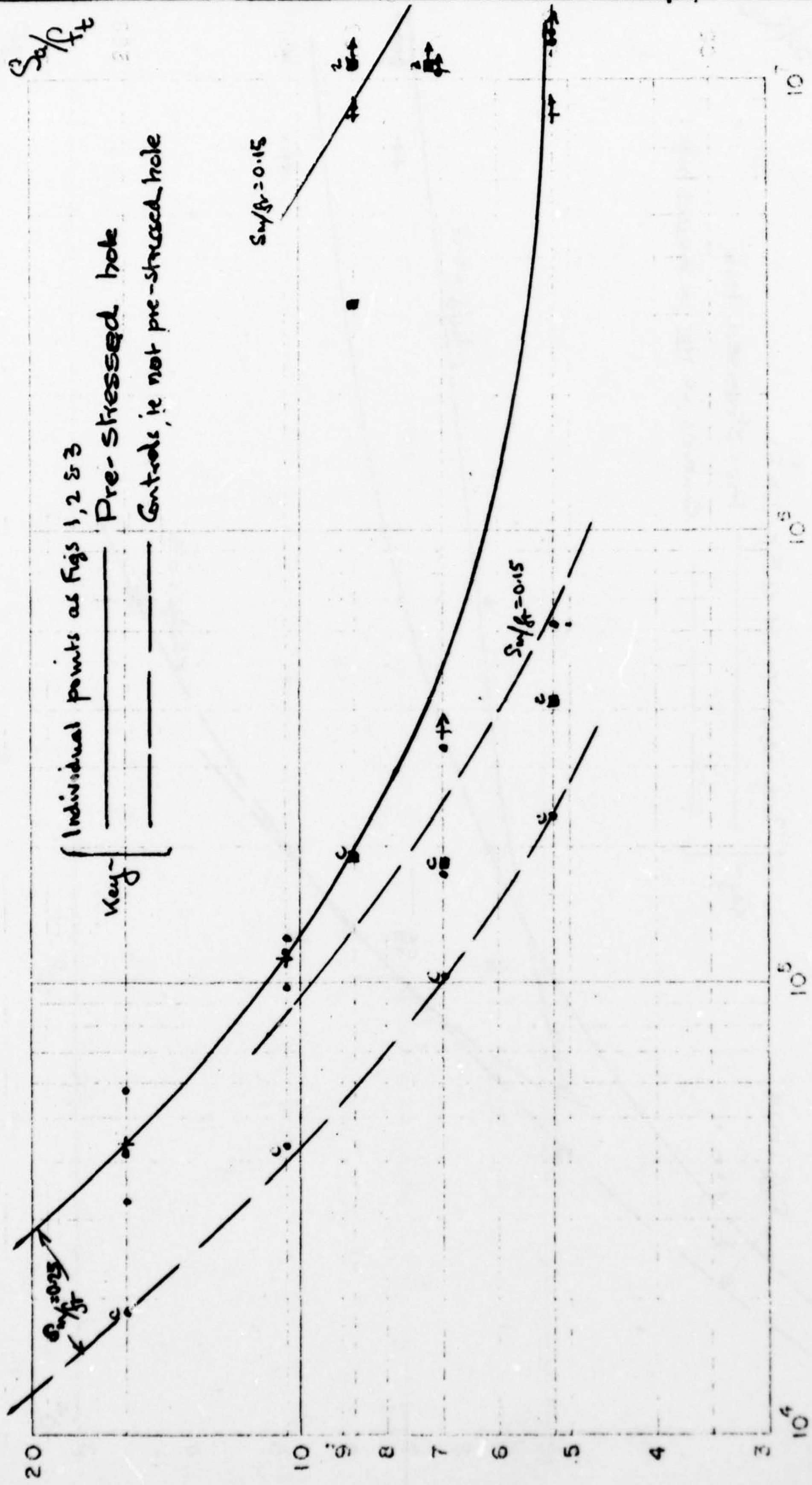


FIG. 6 SUPPLEMENTARY INVESTIGATION Nº1 Ref. Table 6

PRE-STRESSED HOLE

2% OVERSIZE BALL

LOADED PUSH FIT PIN MEDIUM SIZE SPECIMEN TYPE $2D^{5/8}$ $d/D = 1/2$



$S_m/f_t = 0.25$
&
0.15

FIG. 7 SUPPLEMENTARY INVESTIGATION No 1 Ref. TABLE 7

PRE-STRESSED HOLE 4% OVERSIZE BALL

LOADED PUSH-FIT PIN MEDIUM SIZE SPECIMEN TYPE 2B 5/16. d/D = 1/4

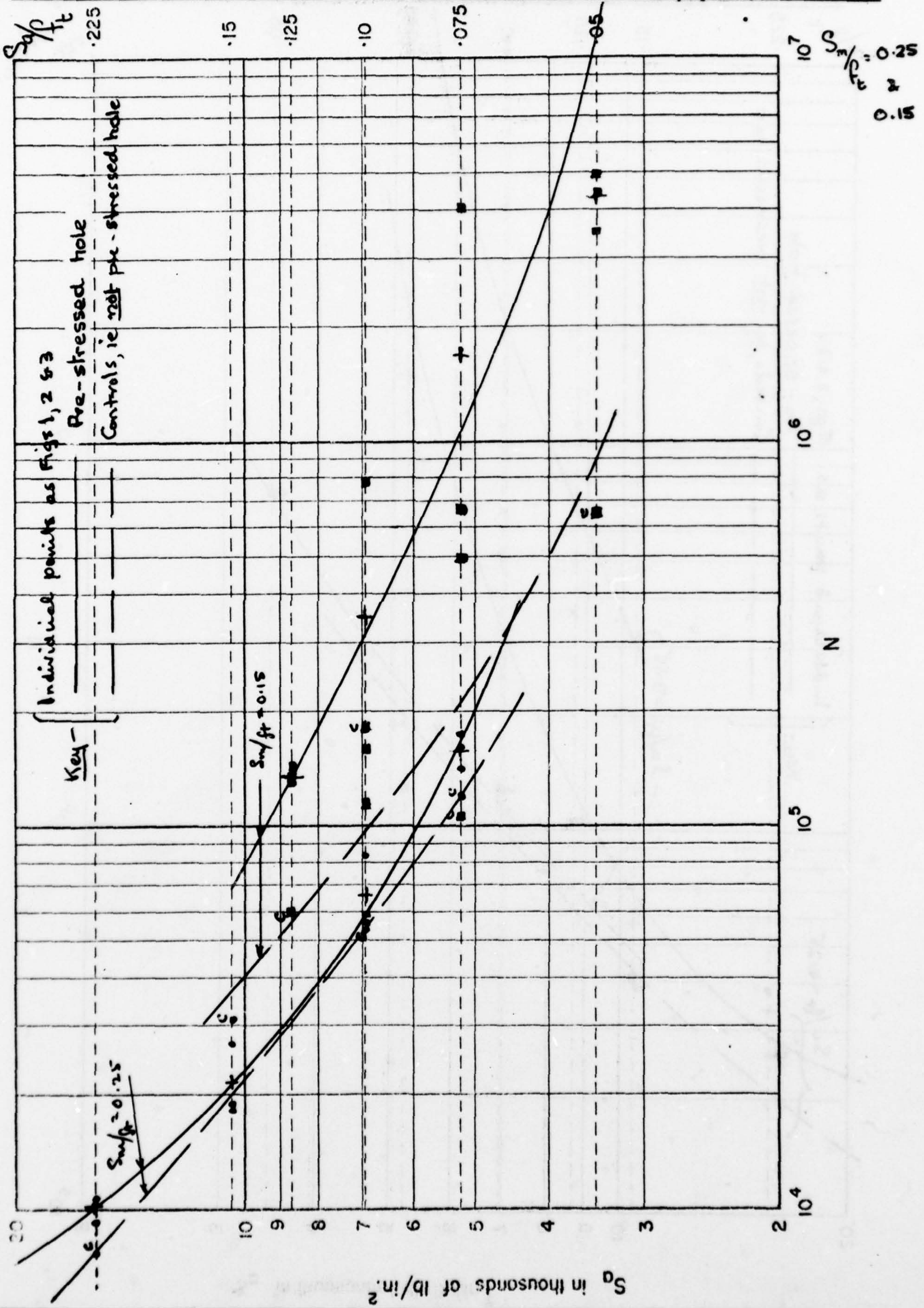


FIG 8. SUPPLEMENTARY INVESTIGATION N° 1 Ref. Table 8

PRE-STRESSED HOLE 4% OVERSIZE BALL

LOADED PUSH FIT PIN MEDIUM SIZE SPECIMEN - TYPE 2B 15/32 d/D = 3/8

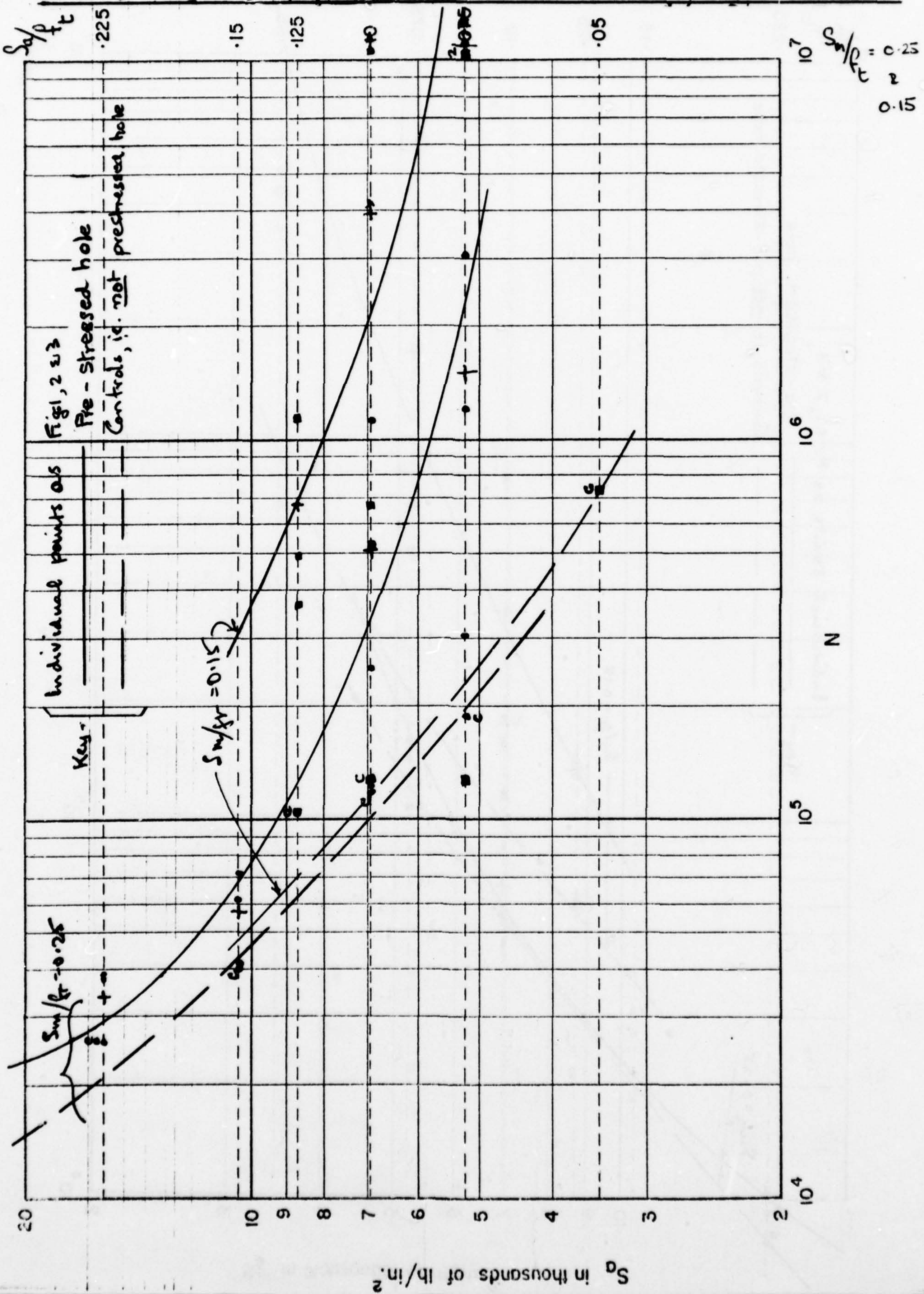


FIG. 9 SUPPLEMENTARY INVESTIGATION Nº1 Ref. Table 9

PRE-STRESSED HOLE 4% OVERSIZE BALL

LOADED PUSH FIT PIN MEDIUM SIZE SPECIMEN TYPE 2D 5/8 d/D = 1/2

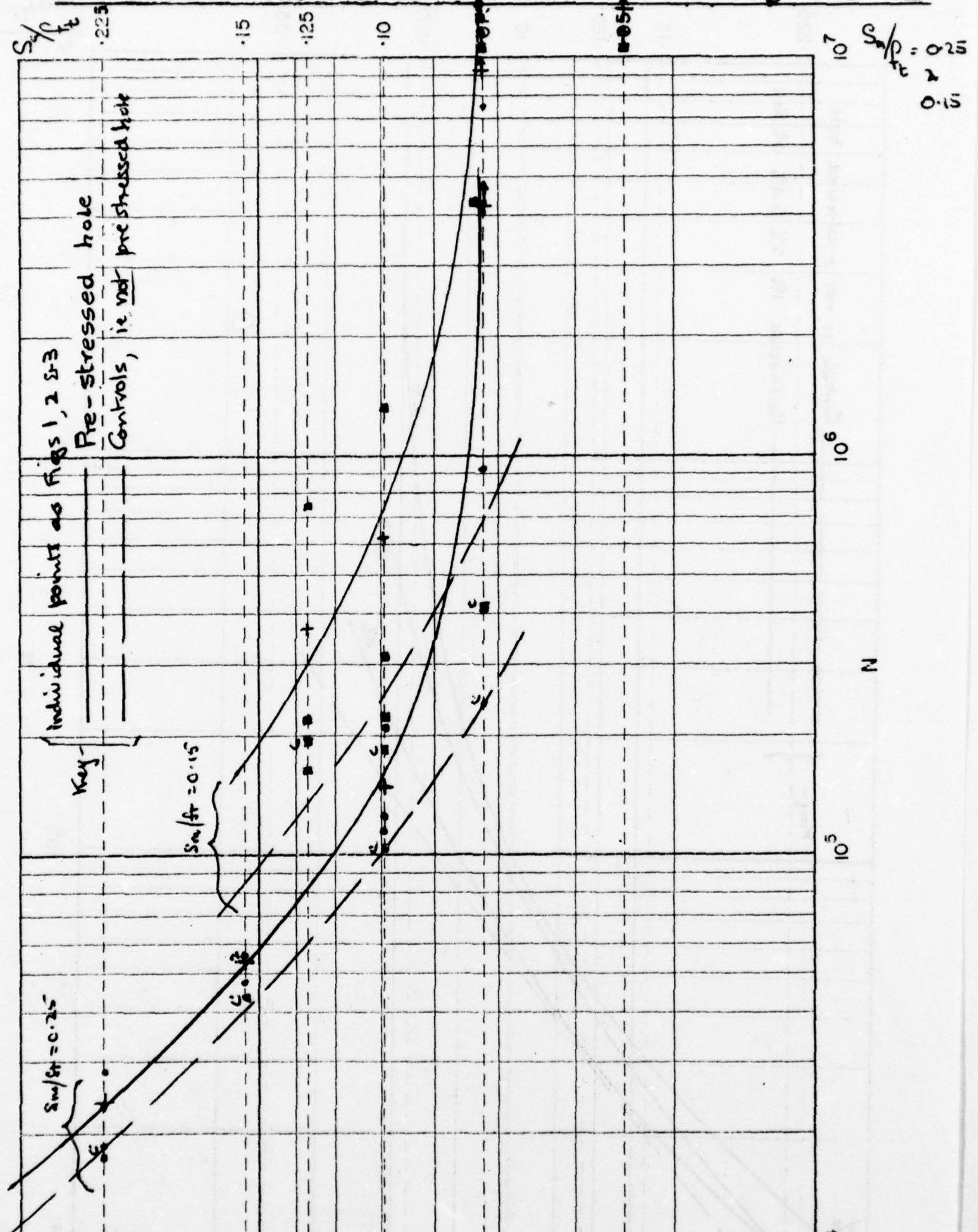


FIG. 10   S.I. No 1   PRESTRESSED HOLE

24

LOADED PUSH FIT PIN · EFFECT OF BALL SIZE $S_m/f_t = 0.25$

$d/D = 1/4$

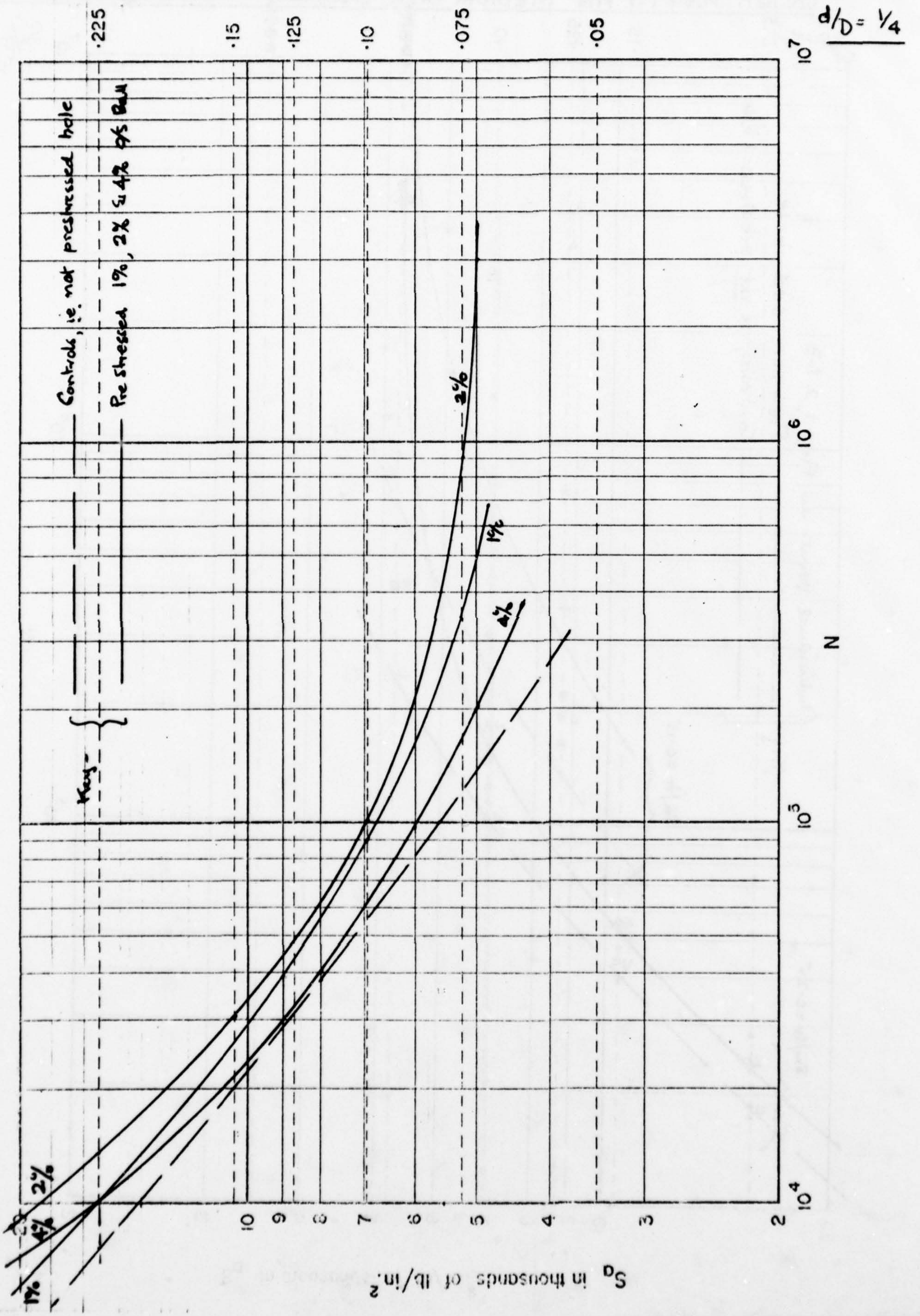


FIG. 11 **S.I. Nº 1** **PRESTRESSED HOLE**

LOADED PUSH FIT PIN

EFFECT OF BALL SIZE

$S_u/f_t = 0{\cdot}25$, $d/D = 3/8$

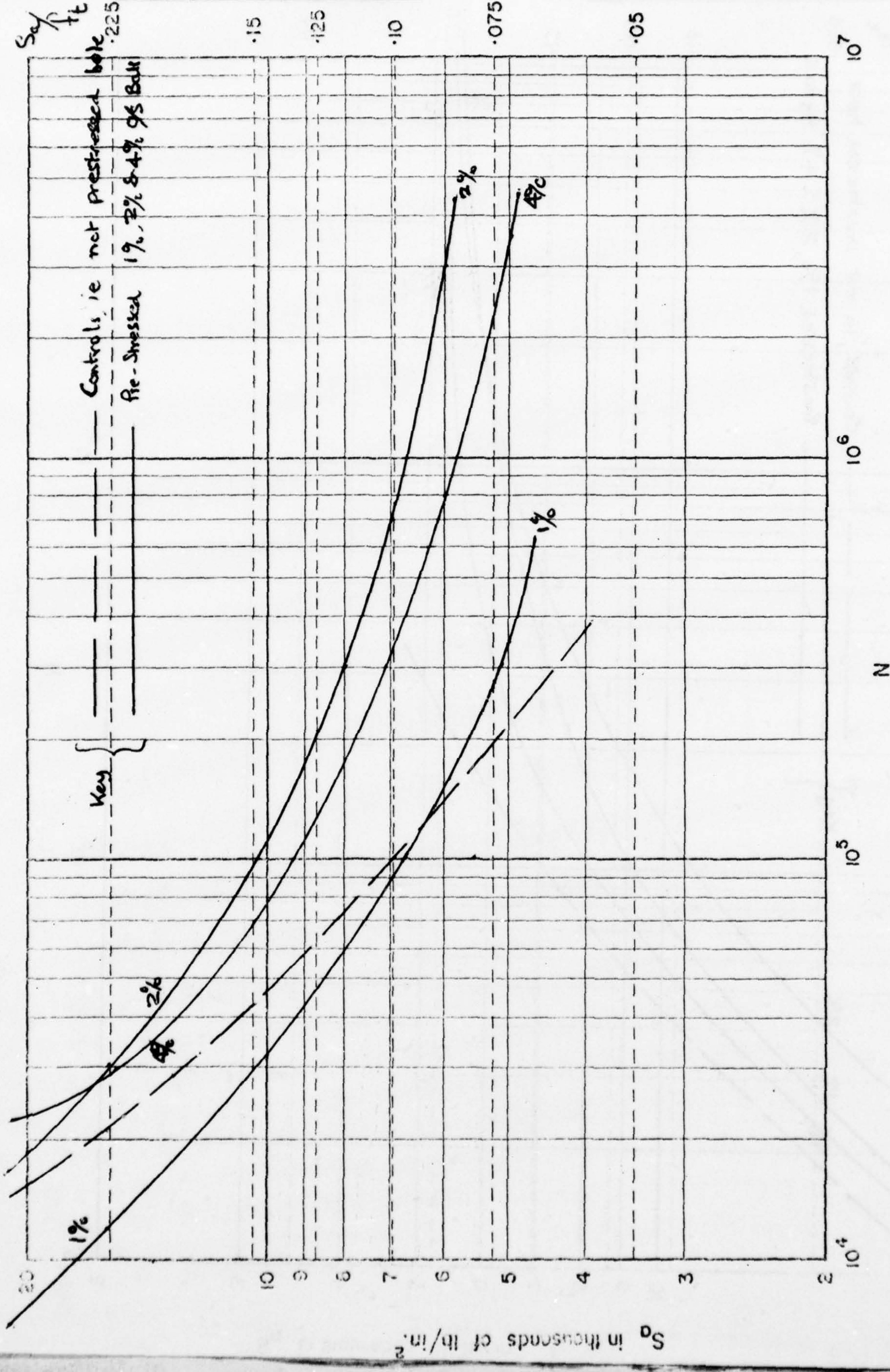
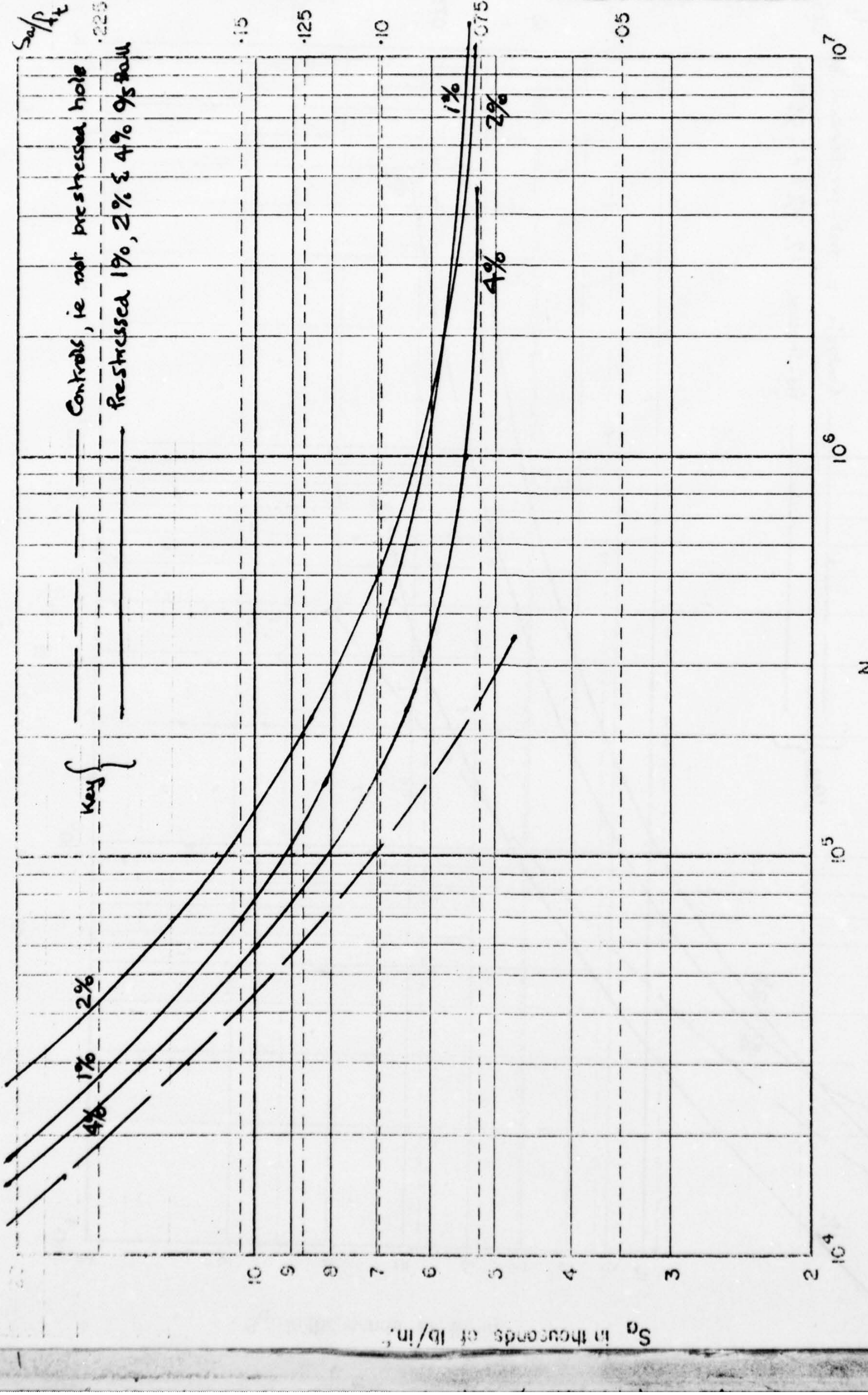


FIG 12 **Sl. No 1** **PRESTRESSED HOLE**

26

LOADED PUSH FIT PIN

EFFECT OF BALL SIZE $S_m/f_t = 0\cdot25$, $d/D = 1/2$



LOADED PUSH FIT PIN EFFECT OF BALL SIZE $d/D = 1/4$

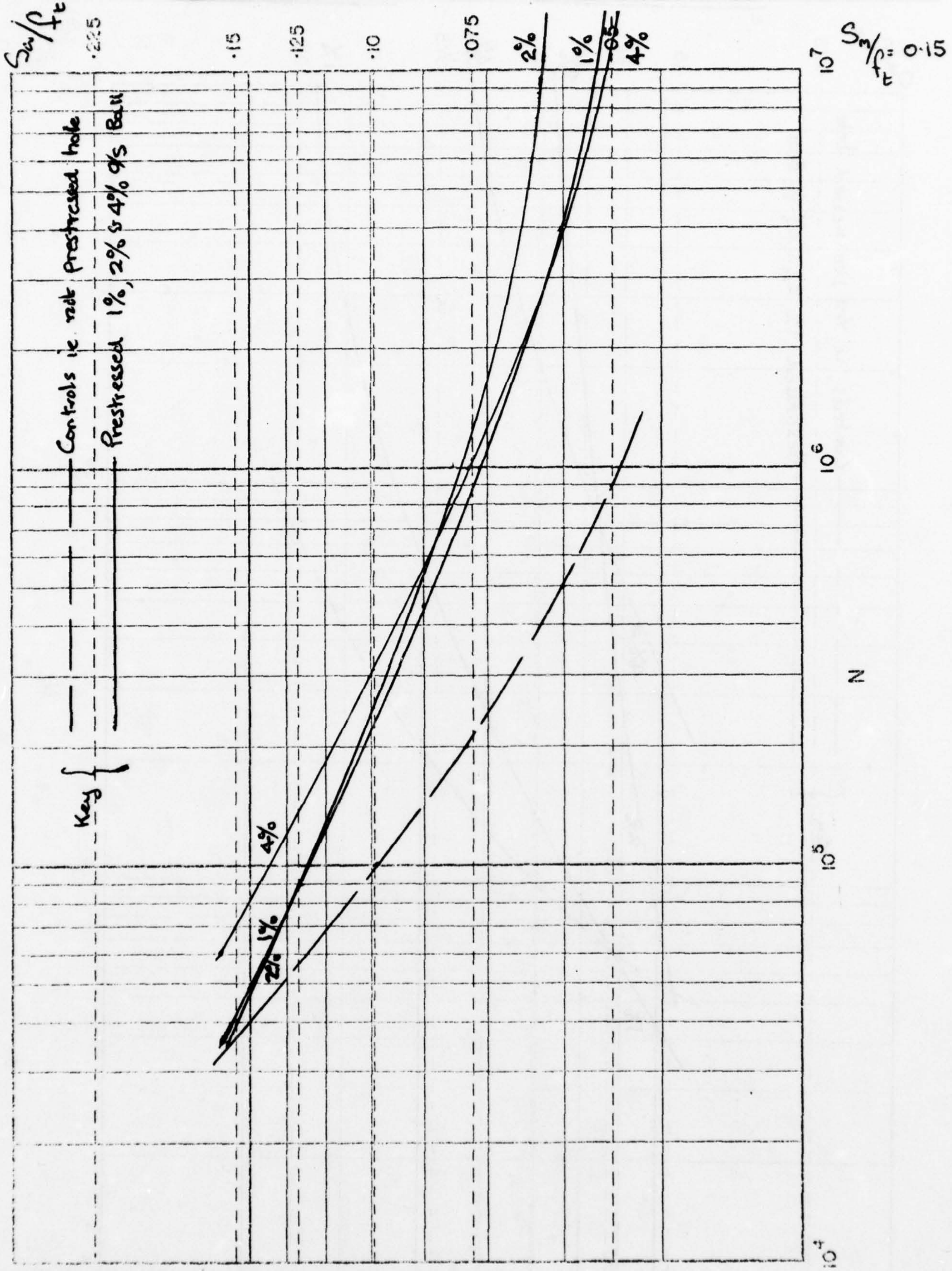


FIG. 14   S.I. No 1   PRESTRESSED HOLE

LOADED PUSH FIT PIN   EFFECT OF BALL SIZE $d/D = 3/8$

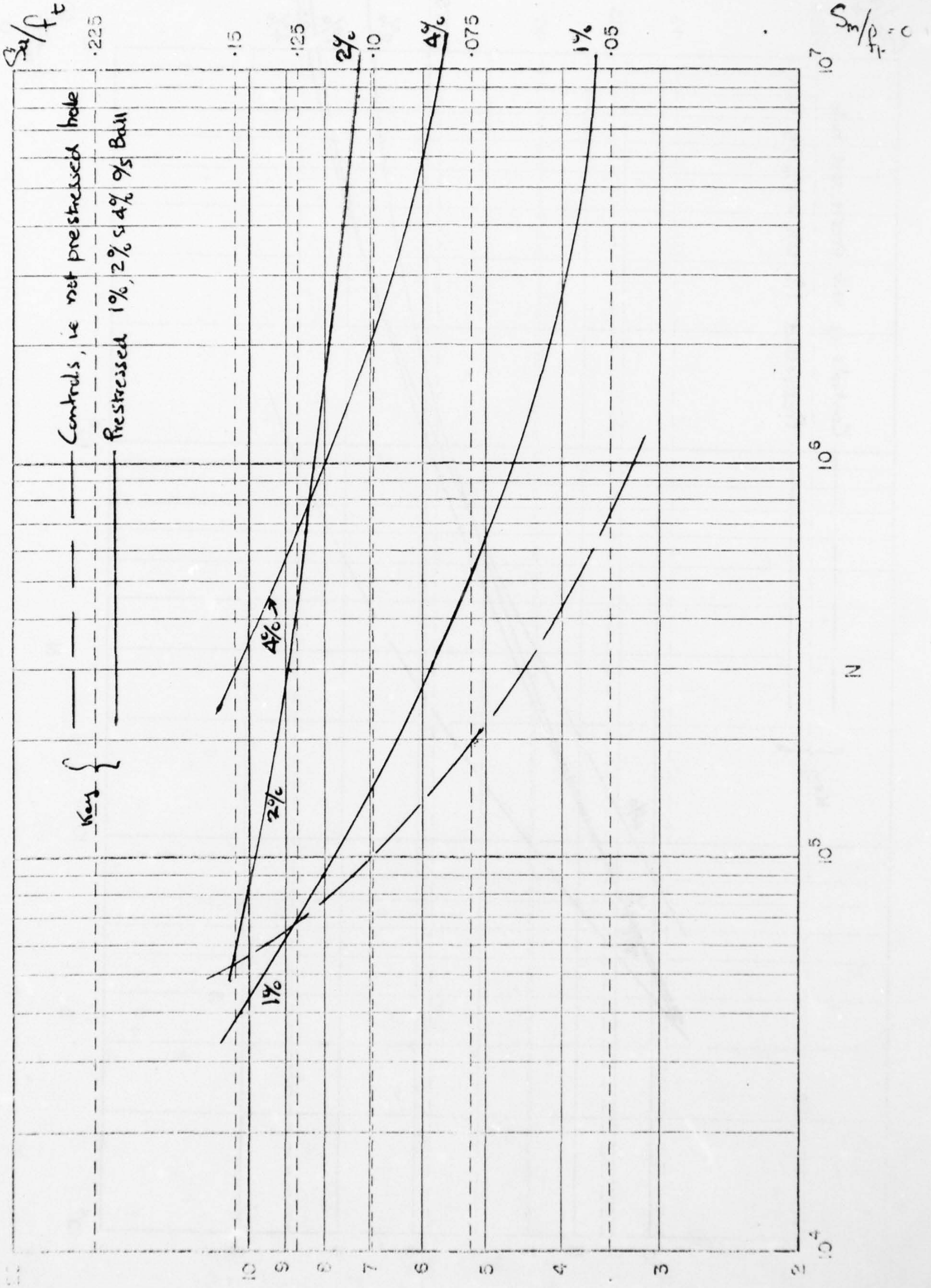


FIG. 15 S.1. No 1 PRESTRESSED HOLE

LOADED PUSH FIT PIN EFFECT OF BALL SIZE

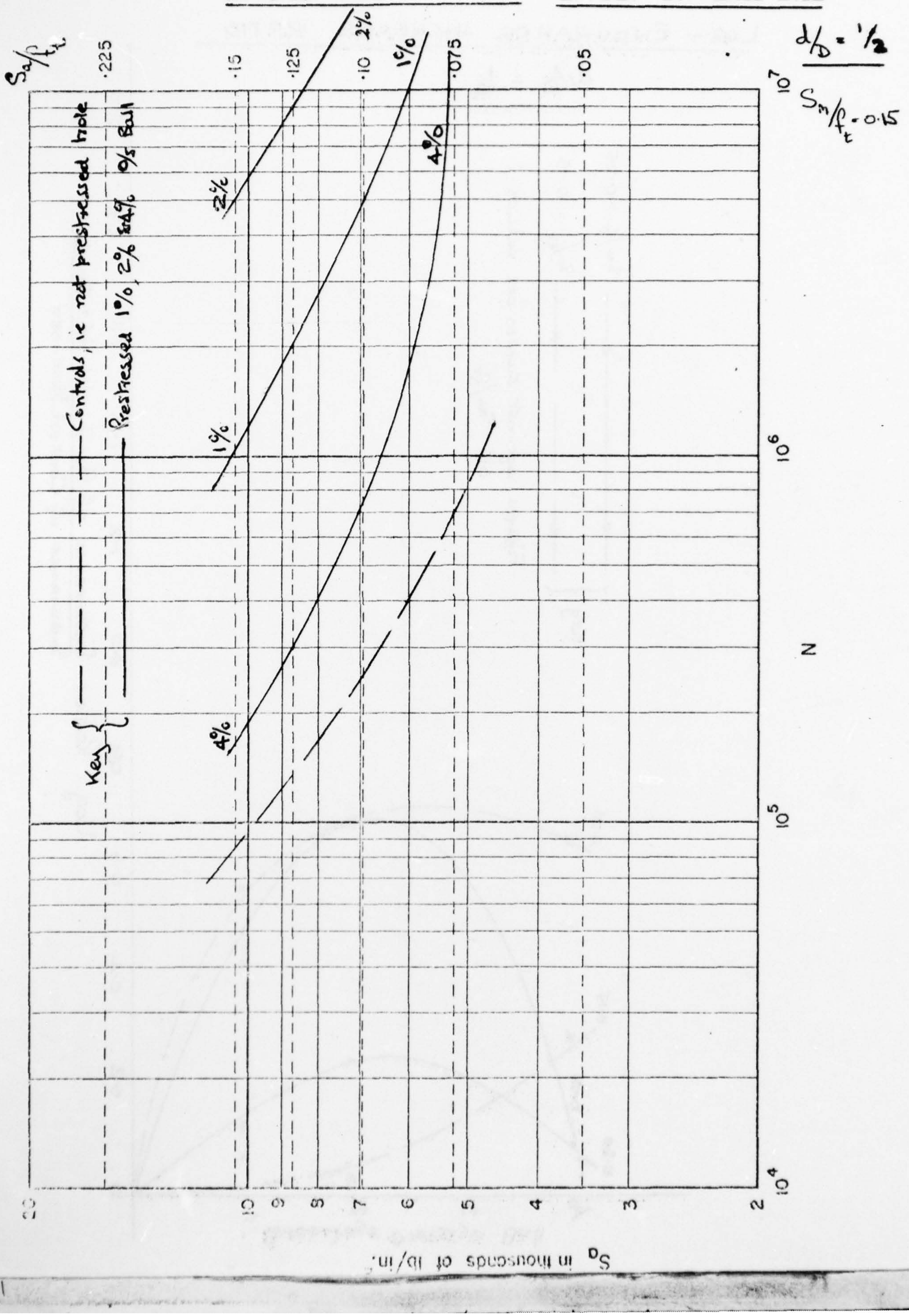


FIG. 16 **S.I. No 1** **PRE-STRESSED HOLE**

LOADED PUSH FIT PIN

LOG - ENDURANCE INCREASE RATIO

$d/D = 1/4$

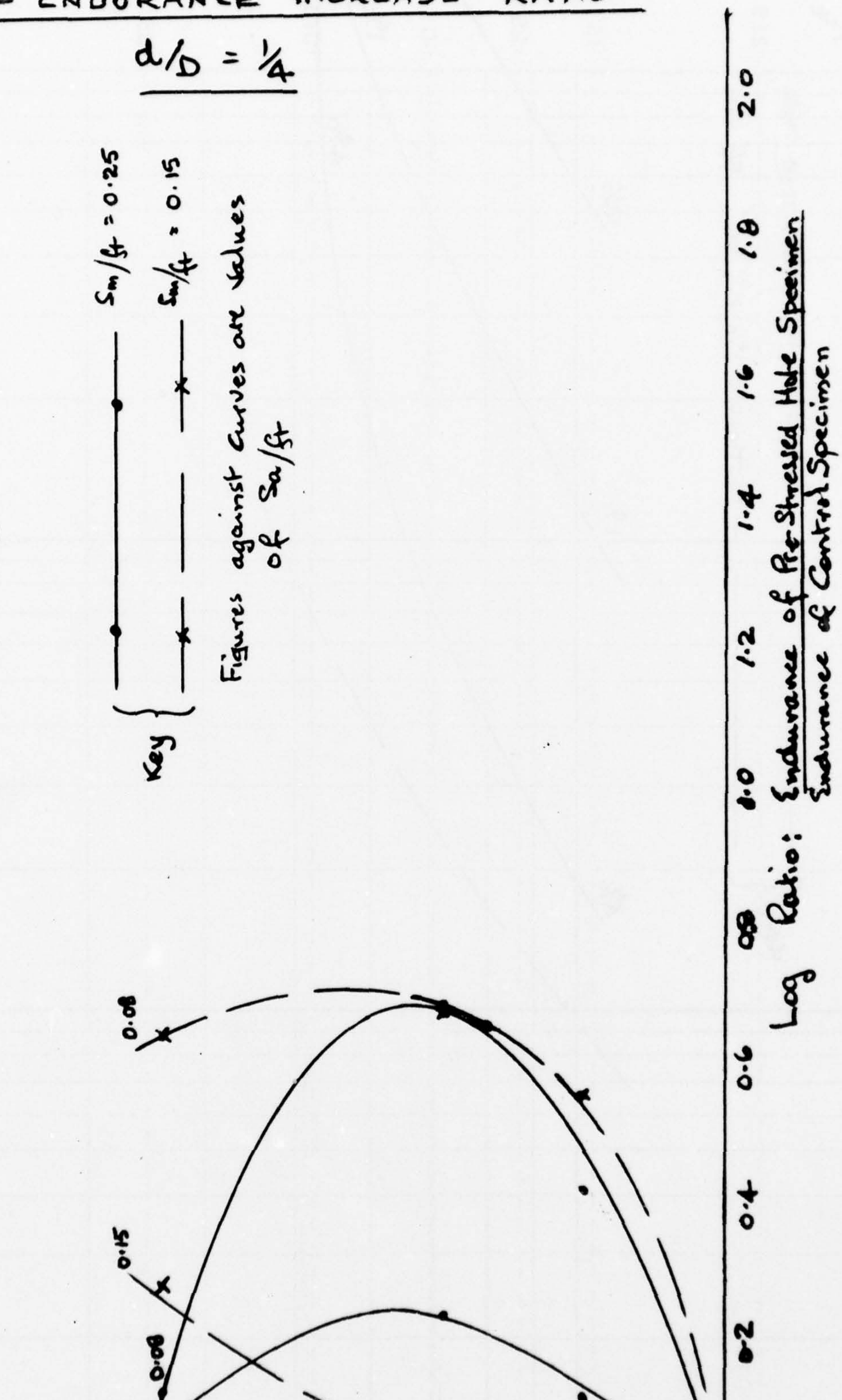


FIG 17 S.I. No 1

LOADED PUSH FIT PIN

LOG- ENDURANCE INCREASE RATIO

PRE-STRESSED HOLE

$d/D = 3/8$

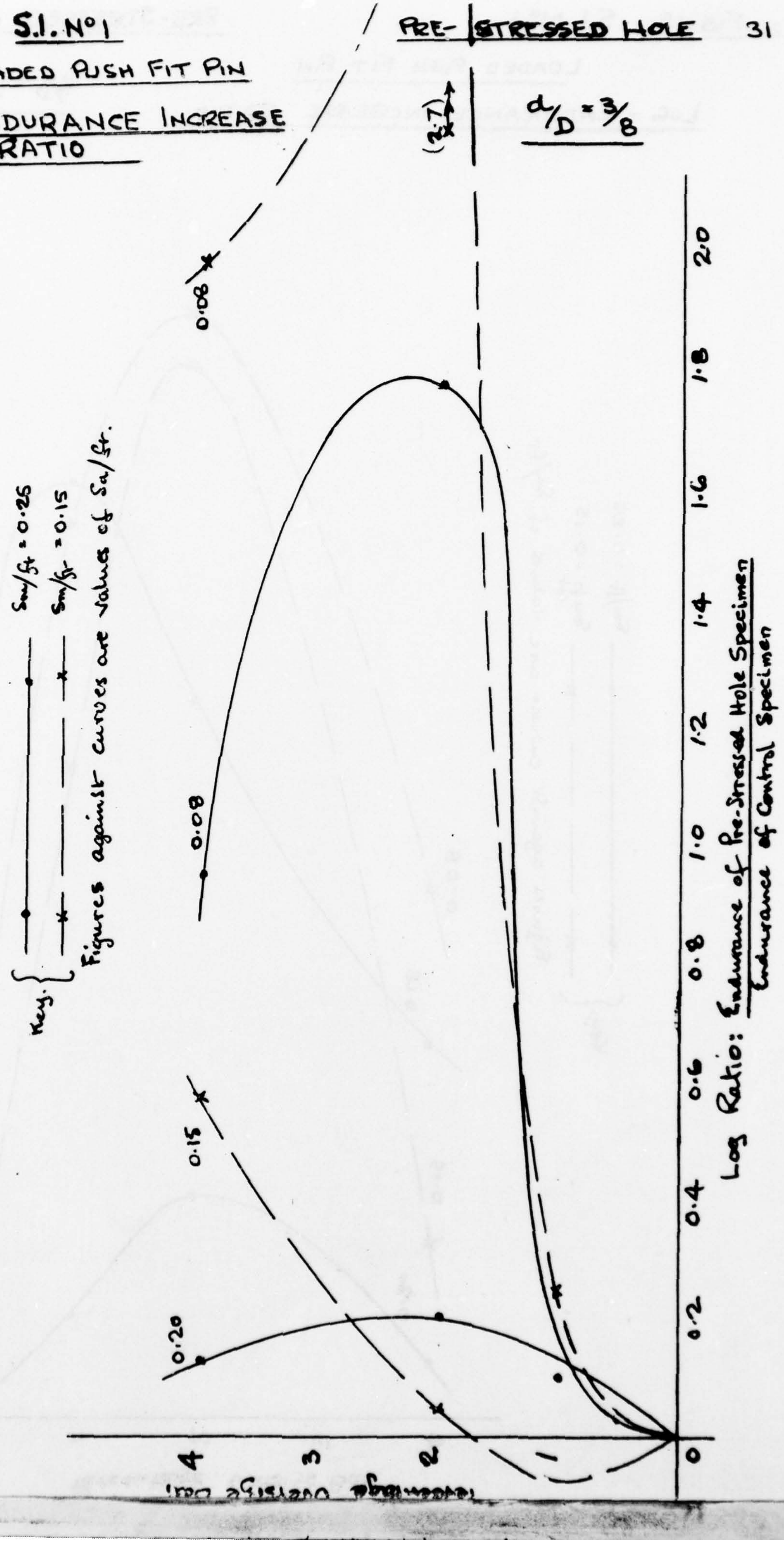
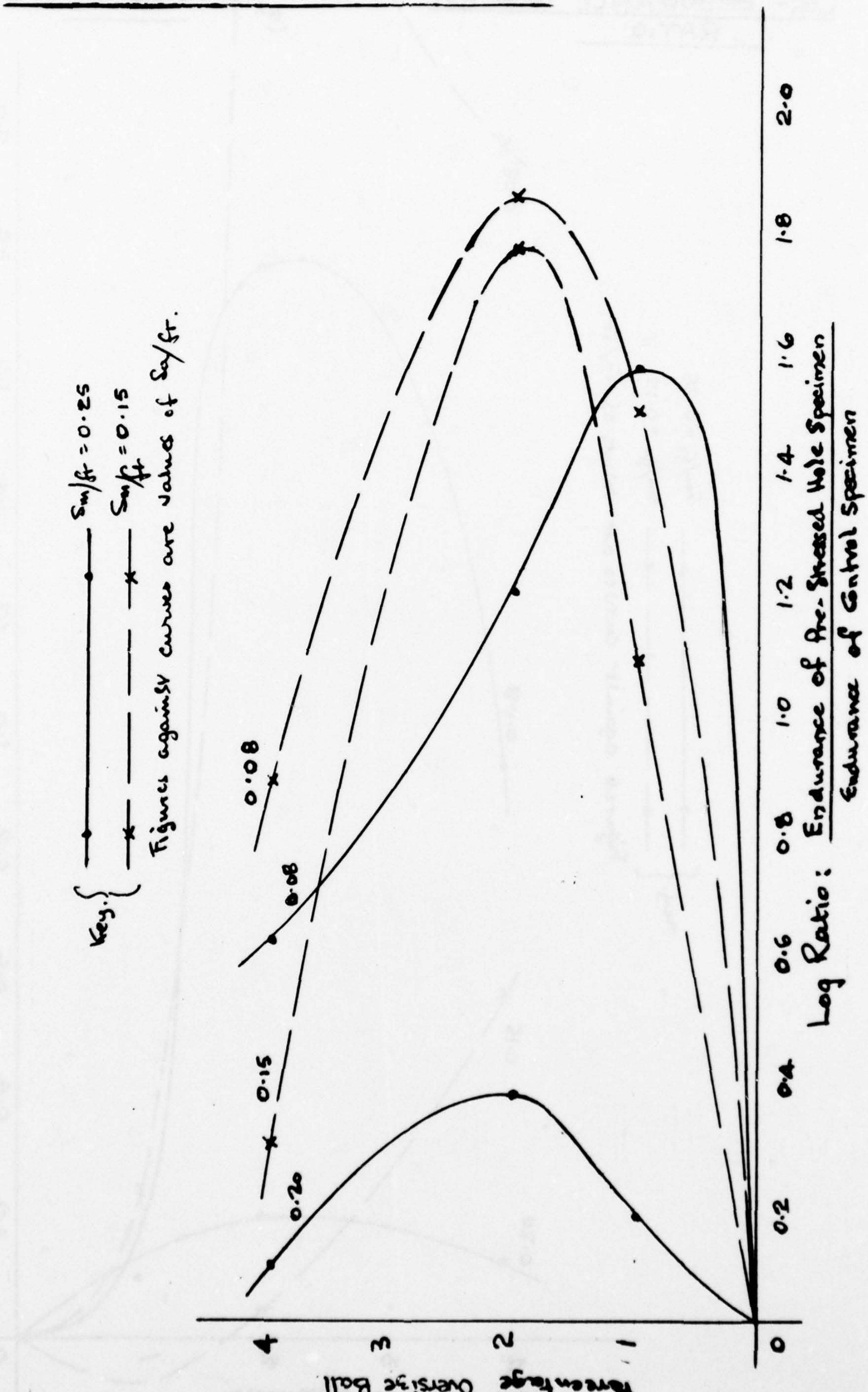


FIG. 18 **S.I. N° 1** **PRE-STRESSED HOLE**

LOADED PUSH FIT PIN

LOG - ENDURANCE INCREASE RATIO **d/D = 1/2**



SUPPLEMENTARY INVESTIGATION No.2

THE EFFECT OF USING FLAT-SIDED PINS (THE FLATS BEING PARALLEL TO THE DIRECTION OF LOAD)

1. INTRODUCTION

A number of investigators have experimented with the use of bolts or pins manufactured with flats on both sides of the bolt, and positioned so that the flats were assembled parallel to the direction of the applied load. The objective of such a device is to remove the possibility of fretting occurring at the region of maximum stress concentration, namely at or near the extremities of the transverse diameter of the bolt hole. Fretting may still occur near the edges of the flats, but the associated stress in these regions will be lower than the maximum stress. Thus the formation of cracks in the specimen should be delayed.

A small programme of tests was therefore arranged.

2. NOTATION (Units are in lb and inches throughout)

For convenience the relevant Notation from the Stage 1 report is repeated below -

d = Nominal diameter of hole and pin

D = Width of parallel section of test specimen

f_t = Average Tensile Strength of plate material (from tests)

f_p = Average 0.2°/o Proof Stress of plate material (from tests)

K'_t = Geometric Stress Concentration factor based on net area of cross section of test specimen

N = Endurance

S_m = Mean Stress on net area

S_a = Alternating Stress on net area associated with S_m

t = Thickness of plate specimen

3. TEST PROGRAMME AND STRESS LEVELS

All the tests were carried out by Short Brothers and Harland Ltd using a 20 Ton Avery-Schenck fatigue testing machine operating at 2000 c.p.m. All the plate specimens and pins were taken from stock remaining from Stage 1 of this research.

Only the large size specimens were tested because these were considered to be more likely to demonstrate any advantages than either the small or medium size. Both push fit and interference fit pins were included. Stage 1 had shown that for d/D = 1/4 there was but a small difference between endurances for a push fit and an interference fit pin, possibly because of the high stress concentration factor associated with d/D = 1/4. Therefore only specimens with d/D = 3/8 and 1/4 were tested.

All specimens were to the type "D", i.e. of parallel width with a single pin at one end and with all the load transmitted by the pin.

In regard to the extent of the flats on the pins, one other investigator (Reference 2) had found that a subtended angle of at least $\pm 40^{o}$ from the transverse diameter was necessary in order to achieve a significant effect. For this supplementary investigation $\pm 45^{o}$ was chosen, and retaining clips were used to prevent rotation of the bolts from their chosen position.

It was clear that the maximum benefit (if any) from the use of flat-sided bolts would be obtained at low values of mean and alternating stresses since such conditions of loading were more likely to produce fretting. Consequently the stress levels chosen for these tests were

$$S_m = 0.25\ f_t \text{ and } 0.15\ f_t$$

$$S_a = 0.225\ f_t \text{ down to } 0.05\ f_t \quad \text{for} \quad S_m = 0.25\ f_t$$

$$\text{and } 0.14\ f_t \text{ down to } 0.05\ f_t \quad \text{for} \quad S_m = 0.15\ f_t$$

Table 1 gives particulars of the range of tests.

Figure 1 gives details of the geometry of the specimens and the materials used.

4. RESULTS

Tables 2 and 3 give the endurances for push fit pins (with flat sides) for d/D = 3/8 and 1/2 respectively. Tables 4 and 5 give similar results for $0.4^{o}/o$ interference fit pins (with flat sides). Table 6 gives endurances for some round pins with a push fit, tested as controls at the time of testing the flat sided pins. Although these were a little lower than the corresponding Stage 1 endurances, they were not seriously so, and therefore the relevant

Stage 1 endurance curves for round pins have been used for all comparisons when assessing the merits of the flat sided pins, rather than repeating the full range of Stage 1 tests. The appropriate references to the Stage 1 endurance curves are given on each of the figures presenting the endurances of the current test specimens.

Thus Figure 2 presents endurance curves for specimens to type 1D3/4 (d/D = 3/8) with flat sided pins to push fit standard for mean stresses of 0.25 ft and 0.15 f_t. In addition Figure 2 shows the Stage 1 endurance curves for the same configuration but with round pins, and for the same two values of mean stress, together with the few control test results obtained concurrently with the present tests.

Figure 3 shows similar data for push fit pins with flat sides, but for specimens to type 1.D.1 (d/D = 1/2). In this instance there was no comparative endurance curve for the large size of specimen in Stage 1 and so the medium size endurances have been plotted and "corrected" by a factor of 1/1.7 on endurances, assessed from Stage 1, Figure 4.46 to give an approximate estimate for endurances of large size specimens.

Figures 4 and 5 give corresponding data, but for pins with 0.4°/o interference fit instead of push fit, but no comparisons were possible for $S_m/f_t = 0.15$ because of the limited amount of data from Stage 1.

Finally in order to supplement the information in the tables and figures noted above, a selected number of specimens was examined in detail for nature of failure, with special reference to fretting and the origins of cracks. The information is presented on Table 7 for push fit pins and on Table 8 for interference fit pins. Moreover Tables 2 to 5 are annotated with respect to the degree of fretting in accordance with the data on Tables 7 and 8.

5. DISCUSSION OF RESULTS

5.1 Push Fit Pins (Tables and Figures 2 and 3 and Table 7)

For both values of d/D (3/8 and 1/2) there was more scatter of results at the lower values of S_a/f_t than at the higher values. Also the scatter at low values of S_a/f_t was a little more than that for round pins. The endurances for pins with flat sides were generally greater than those for the corresponding tests with conventional round pins, at the lower values of S_a/f_t approximately below $S_a/f_t = 0.075$ for d/D = 3/8 and below $S_a/f_t = 0.125$ for d/D = 1/2. The extent of the gain ranged from the order of 5 to 20 times, the factor increasing with decrease of S_a/f_t. At values of S_a/f_t above these levels there was little significant improvement for the use of flat sided pins. The influence of d/D on the results was not large, but in favour of the higher value. In regard to the nature of the failures (see Table 7), appreciable fretting occurred only on two of the twelve specimens examined and this was for specimens tested at almost the lowest stress levels, and with the higher value of d/D (lower S.C.F.). The fretting was entirely between the pin and the hole on the loaded region, and the crack origins generally near the corners of the flats, again on the loaded region of the hole.

5.2 0.4^{o}/o Interference Fit Pins (Tables and Figures 4 and 5 and Table 8)

For this configuration the evidence shows that the flat sided pin has no advantage over the round pin, in fact in almost every comparison available the flat sided pin leads to endurances which are lower than those for the corresponding round pin. It would appear that the usual advantages accruing from the presence of an interference fit pin become nullified or reversed due to the presence of the flats on the pin, and a review of Table 8 shows that severe, or at least appreciable fretting occurred at or near the corners of the flats on the majority of the specimens examined, and almost invariably on the unloaded region of the hole. Crack origins were largely near the ends of a transverse diameter but some did occur near the corners of the flats.

5.3 Comparison with Other Research Investigators

5.3.1 J. Schijve, D. Brock and F.A. Jacobs (Reference 1)

Here the Authors were investigating several forms of lug type specimens, including those incorporating pins with flats. These particular specimens were approximately the same size as the medium specimens of the Bolted Joint Fatigue Research, but in the American Aluminium Alloy Material 7075 T6. The plates were 5 mm (0.20 in) thick and the pins were 10 mm (0.40 in) diameter; d/D was 0.33, and the pins were a push fit, slightly closer than those for the Bolted Joint Fatigue Research.

S_m/f_t was 0.27 and the resulting endurance curves (with and without flats - Figure 12 of Reference 1) were reasonably similar to those given on Figure 2 of this report for $S_m/f_t = 0.25$ but included a "cross over" from beneficial to otherwise at $S_a/f_t = 0.15$ instead of equal endurances at $S_m/f_t = 0.085$ on Figure 2. The agreement can be said to be good, remembering scatter, and the slightly different material.

5.3.2 D.J. White (Reference 2)

In this investigation the tests were made in a different material namely Specification F.V.520B (14^{o}/o Cr, 5^{o}/o Ni; ferritic stainless steel) average f_t = 150 000 lbs/in^2. The plates were 0.5 in thick 4.25 in wide and the pins made of En 25 steel and 2 in diameter. Thus d/D = 0.48. Clearance between the pin and the hole was 0.0004 in thus giving a push fit of a similar order to those of the Bolted Joint Fatigue Research. Varying degrees of flat were tested and showed that the best form was with a subtended angle of $\pm 40^o$ (cf. $\pm 45^o$ of Bolted Joint Fatigue Research). The mean stress for these tests was 15 tons/in^2 giving $S_m/f_t = 0.225$.

The tests can therefore be compared with those represented on Figure 3 (push fit, d/D = 1/2) of the present report. Insufficient data are given in Reference 3 to draw an accurate endurance curve for the joints containing pins with flats but at the fatigue endurance of 30 x 10^6 cycles the fatigue strength ratio, i.e. $\frac{\text{fatigue strength with flats}}{\text{fatigue strength with round pin}}$ was 2.9 (Reference Table 1, Figure 6 and Figure 2 of Reference 2). From Figure 3 of the present tests, at $S_m/f_t = 0.25$ and an endurance of 30 x 10^6 the fatigue strength ratio is 5.5/2.5 = 2.2 which gives a fair comparison.

N.B. No comparative data for interference fit pins are available.

6. CONCLUSIONS

6.1 Push Fit Pins

The use of pins with flat sides arranged so that they are parallel to the direction of applied load can be beneficial in terms of endurance, for push fit pins with the pin loaded, when the stress levels are comparatively low; i.e. alternating stresses not greater than the order of 0.075 f_t and 0.125 f_t. The improvement in endurance increases as the alternating stress decreases, ranging from the order of 5 to 20 times the endurance for joints with round pins. For higher values of alternating stress there was little or no improvement in endurance for the use of flat sided pins, in fact in some cases there was a reduction in endurance.

The present series of tests covered only mean stresses of 0.15 f_t and 0.25 f_t. It is not certain that the improvement would be fully maintained under the application of higher mean stresses.

From the results of a detailed examination of the nature of the failures of a representative number of these specimens it is clear that the presence of the flats restricts the fretting to regions where the stress is lower than the maximum and thus delays the onset of cracking.

It should be noted that it is of paramount importance that the flats are assembled and maintained in a direction parallel to the direction of the applied load, and that the edges of the flats should be radiused.

6.2 $0.4^{o}/o$ Interference Fit Pins

For this configuration the flat sided pin produces no advantage over the round pin, and in most of the comparisons the flat sided pin endurances were lower. It would appear that the flats on the pin have an adverse effect upon the stress pattern normally associated with an interference fit pin.

Appreciable or severe fretting occurred on the majority of specimens examined, and always at the unloaded region of the pin.

6.3 Comparisons with Other Investigators

Comparisons with the work described in References 1 and 2 support the conclusions of paragraph 6.1.

REFERENCES

1. SCHIJVE, J., BROCK, D., JACOBS, F.A. — Fatigue tests on Aluminium Alloy Lugs with special reference to Fretting N.L.R. - T.N.M. (paragraph 6.9, Table 7 and Figure 12). March 1962.

2. WHITE, D.J. — Effect of Pins with Flats and Resin-Bonded Polytetrafluorethylene coatings on the fatigue strength of large pinned connections made from alloy steel F.V.520B, Proc.Instn.Mech.Engrs., Vol.185, 49/71.

SUPPLEMENTARY INVESTIGATION No.2

TABLE 1 - PARTICULARS OF RANGE OF TESTS

ALL TESTS - PIN LOADED

SPECIMEN TYPES	1 D 3/4 and 1 D 1 i.e. Large size, d/D = 3/8 and 1/2 respectively.
PIN FITS	Push Fit (clearance ±0.0003 in) 0.4°/o Interference Fit (to within 0.0003 in of nominal) Applicable to both specimen types.
STRESS LEVELS	$S_m = 0.25\ f_t$, $S_a = 0.225\ f_t$ down to $0.05\ f_t$ $S_m = 0.15\ f_t$, $S_a = 0.14\ f_t$ down to $0.05\ f_t$ Stress levels applicable to both specimen types and to both degrees of pin fit.
NUMBER OF SPECIMENS	Minimum of 3 off for each combination of specimen type, pin fit and stress level.

SUPPLEMENTARY INVESTIGATION No.2

TABLE 2 SPECIMEN TYPE 1 D 3/4 - PUST FIT - d/D = 3/8 Reference Figure 2

Specimen Identity	Stress Levels (Percentage f_t)		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
12.12.A	25	10	100 100	5.000	75 060
14.2.C			67 600	4.827	
14.2.A			62 500	4.795	
14.2.D	25	7.5	138 600	5.141	128 700
14.2.E			125 800	5.097	
14.3.A			122 500	5.088	
14.3.C	25	5	2 307 200	6.362	1 116 000
14.10.D			1 625 700	6.210	
14.13.A			371 000	5.570	
15.4.A	25	4.25	>3 593 200	>6.555	>2 558 000
15.1.B			>2 709 400	>6.433	
15.4.D			1 717 700	6.234	
19.14.G	15	10	220 100	5.342	155 000
19.9.E			190 000	5.278	
15.7.A			89 100	4.950	
19.9.A	15	7.5	264 200	5.420	252 200
15.7.B			247 400	5.392	
17.11.D			245 400	5.388	
19.13.F	15	6	3 370 400+	6.527+	1 971 000
19.13.G			1 580 000	6.198	
19.14.A			1 436 600	6.156	
14.12.B	15	5.4	10 000 000U	7.000U	>2 427 700
14.11.C			10 000 000U	7.000U	
14.11.D			6 751 900	6.830	
14.12.C			1 118 800	6.049	
14.12.F			612 500	5.786	
14.12.D			442 600	5.645	
19.9.D	15	5	10 000 000U	7.000U	>10 000 000

U Unbroken

\+ light fretting (see Table 7)

Loads to insert pins ranged from 40 lb to 100 lb but some were not recorded.

SUPPLEMENTARY INVESTIGATION No.2

TABLE 3 SPECIMEN TYPE 1 D 1 - PUSH FIT - d/D = 1/2 Reference Figure 3

Specimen Identity	Stress Levels (Percentage f_t)		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
16.8.C	25	22.5	30 000	4.477	30 000
16.9.A	25	15	81 300$^+$	4.910$^+$	73 140
16.9.G			72 400	4.860	
16.5.G			66 500	4.823	
17.4.B	25	10	1 785 100	6.252	476 000
16.8.B			325 500	5.511	
16.11.F			185 600	5.261	
18.14.G	25	7.5	832 500	5.920	579 300
18.14.D			580 400	5.762	
18.2.E			440 090	5.645	
19.2.G	25	6.75	10 000 000U	7.000U	>10 000 000
19.2.B	25	5	10 000 000U	7.000U	>10 000 000
18.6.B	15	14	200 800	5.303	130 200
18.8.D			112 000	5.050	
18.7.G			98 100	4.990	
18.11.E	15	12.5	508 000	5.700	259 500
19.1.D			223 000$_+$	5.346$_+$	
19.4.A			153 800	5.185	
18.10.F	15	10	800 000	5.903	410 800
18.11.D			353 000	5.547	
18.10.E			245 000ϕ	5.389ϕ	
16.9.D	15	7.5	10 000 000U	7.000U	>5 715 000
16.9.B			6 708 500ϕ	6.825ϕ	
16.10.D			2 783 000	6.442	
18.14.A	15	6.5	11 000 000U	7.000U	>10 000 000
18.8.C			10 000 000U	7.000U	
18.8.E			10 000 000U	7.000U	
18.9.A			10 000 000U	7.000U	
18.13.C			10 000 000U	7.000U	
18.8.B			10 000 000U	7.000U	

U	Unbroken	
+	light fretting	See Table 7
ϕ	appreciable fretting	

Loads to insert pins very small where recorded

TABLE 4 SPECIMEN TYPE 1 D 3/4 - 0.4°/o INTERFERENCE FIT PIN - d/D = 3/8

Reference Figure 4

Specimen Identity	Stress Levels (Percentage f_t)		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
19.14.B 19.13.D 19.13.E	25	12.5	174 300 151 000 124 900×	5.242 5.178 5.006×	148 700
19.12.A 19.11.F 19.11.G	25	10	257 000 233 000+ 193 000	5.410 5.368+ 5.285	226 200
19.14.F 19.14.E	25	8.25	811 900 358 800	5.909 5.555	539 800
19.11.C 19.11.B 19.11.A	25	7.5	10 000 000U > 2 463 800 486 000+	7.000U >6.391 5.687+	>2 288 000
19.12.F 19.12.D 19.12.C	15	12.5	2 297 100 1 024 300 276 500×	6.360 6.010 5.440×	866 400
19.12.B 19.12.G 19.13.A	15	10	>3 975 500 768 300ϕ 410 000	>6.600 5.885ϕ 5.613	>1 077 000
19.14.C 19.14.D	15	8.25	4 084 500 937 200	6.610 5.972	1 956 000
19.13.C 19.13.B	15	7.5	10 000 000U 6 093 800ϕ	7.00U 6.783ϕ	>7 805 000

U Unbroken
× severe fretting
ϕ appreciable fretting
\+ light fretting
See Table 8

Loads to insert pins ranged from 1120 lb to 2020 lb

TABLE 5 SPECIMEN TYPE 1 D 1 - 0.4°/o INTERFERENCE FIT - d/D = 1/2 Reference Figure 5

Specimen Identity	Stress Levels (Percentage f_t)		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
16.2.E 16.2.D 16.5.F	25	22.5	207 200 198 200 155 000×	5.315 5.297 5.190×	185 300
16.10.A 16.11.E 16.11.D	25	15	274 400× 259 600 202 400	5.438× 5.414 5.305	243 400
16.2.B 16.5.A 16.2.A	25	12.5	2 323 000× 1 952 400 1 705 600	6.365× 6.290 6.232	1 977 000
18.8.G	25	11.75	10 000 000U	7.000U	>10 000 000
16.5.E	25	11.25	10 000 000U	7.000U	>10 000 000
18.2.B	25	10	10 000 000U	7.000U	>10 000 000
16.14.F 16.9.F	15	14	10 000 000U× 6 007 600×	7.000U× 6.750×	>7 750 000
16.9.C	15	12.5	10 000 000U×	7.000U×	>10 000 000

U Unbroken
× severe fretting, see Table 8

Loads to insert pins ranged from 1120 lb to 1790 lb

SUPPLEMENTARY INVESTIGATION No.2

TABLE 6 CONTROLS i.e. PLAIN PINS

Specimen Identity	Stress Levels (Percentage f_t)		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
(a) Specimen Type 1 D 3/4, Push Fit, d/D = 3/8 Ref.Figure 2					
14.11.A	15	5.4	548 200	5.737	383 390
14.9.F			447 600	5.651	
14.10.B			402 200	5.603	
14.10.A			342 300	5.533	
14.10.G			308 000	5.487	
14.10.C			307 800	5.486	
Loads to insert pins ranged from 40 lb to 298 lb					
(b) Specimen Type 1 D 1, Push Fit, d/D = 1/2, Ref.Figure 3					
16.1.B	15	6.5	568 500	5.753	365 800
18.1.C			419 300	5.622	
16.1.D			358 100	5.555	
18.5.F			339 300	5.530	
18.5.A			313 000	5.495	
18.6.A			264 500	5.420	
Loads to insert pins not greater than 20 lb					

Note These endurances were a little below the corresponding endurances of Stage 1, and S.I. Number 9.

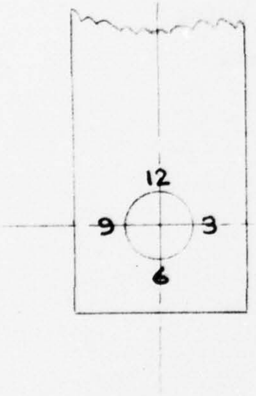
No further controls were therefore tested, it being considered that the Stage 1 endurances for plain (round) pins would suffice.

SUPPLEMENTARY INVESTIGATION No.2

TABLE 7 PUSH FIT PIN QUALITATIVE SUMMARY OF FAILURES

Specimen Identity	Stress Levels (Percentage f_t) $S_m \pm S_a$	Position of crack origins*		Fretting Positions*		Degree of Fretting
Specimen Type 1 D 3/4						
14.2.A	25 ± 10	8.30	-	-	-	-
14.2.E	25 ± 7.5	3	-	-	-	-
14.3.C	25 ± 5	7.30	-	-	-	-
15.7.A	15 ± 10	8.30	3.30	-	-	-
17.11.D	15 ± 7.5	8	3.30	-	-	-
19.13.F	15 ± 6	4.30	-	4.30 to 7.30		Light
Specimen Type 1 D 1						
16.9.A	25 ± 15	3	9	4	-	Light
16.11.F	25 ± 10	3.30	-	-	-	-
18.14.G	25 ± 7.5	3	-	-	-	-
19.4.A	15 ± 12.5	3	-	4.30 to 7.30		Light
18.10.E	15 ± 10	9	-	4.30 to 7.30		Appreciable
16.9.B	15 ± 7.5	7.30		4.30 to 7.30		Appreciable

*Clock face notation

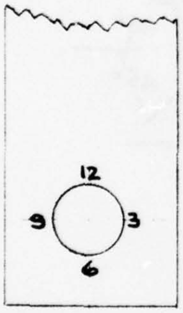


SUPPLEMENTARY INVESTIGATION No.2

TABLE 8 0.4°/o INTERFERENCE FIT PIN QUALITATIVE SUMMARY OF FAILURES

Specimen Identity	Stress Levels (Percentage f_t)	Position of crack origins*		Fretting Positions*		Degree of Fretting
	$S_m \pm S_a$					
Specimen Type 1 D 3/4						
19.13.E	25 ± 12.5	3	-	10.30	1.30	Severe
19.11.F	25 ± 10	3	-	10.30	1.30	Light
19.11.A	25 ± 7.5	8.30	-	10.30	1.30	Light
19.12.C	15 ± 12.5	3.30	-	10.30	1.30	Severe
19.12.G	15 ± 10	9	4.30	10.30	1.30	Appreciable
19.13.B	15 ± 7.5	7.30	-	11 to 1		Appreciable
Specimen Type 1 D 1						
16.5.F	25 ± 22.5	9	-	10.30	1.30	Severe
16.10.A	25 ± 15	3	-	10.30	1.30	Severe
16.2.B	25 ± 12.5	1.30	-	10.30	1.30	Severe
16.9.C	15 ± 12.5	-	-	10	1	Severe
16.9.F	15 ± 14	3	-	4.30	10	Severe
16.14.F	15 ± 14	-	-	10	1	Severe

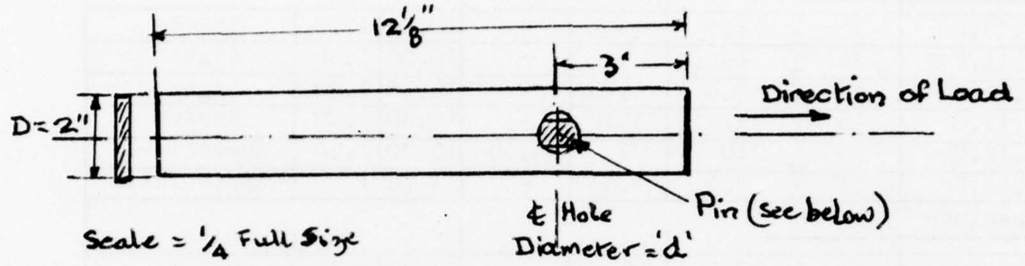
*Clock face notation



S.I. N° 2 - FLAT SIDED PINS

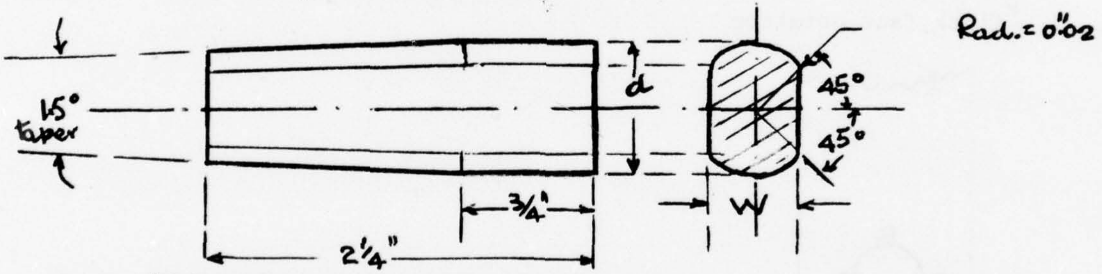
FIG. 1 DETAILS OF SPECIMENS AND PINS

PLATE Aluminium Alloy to Specification B.S. L71 - ¼" thick



Scale = ¼ Full Size

PIN Steel to Specification B.S. S 94.



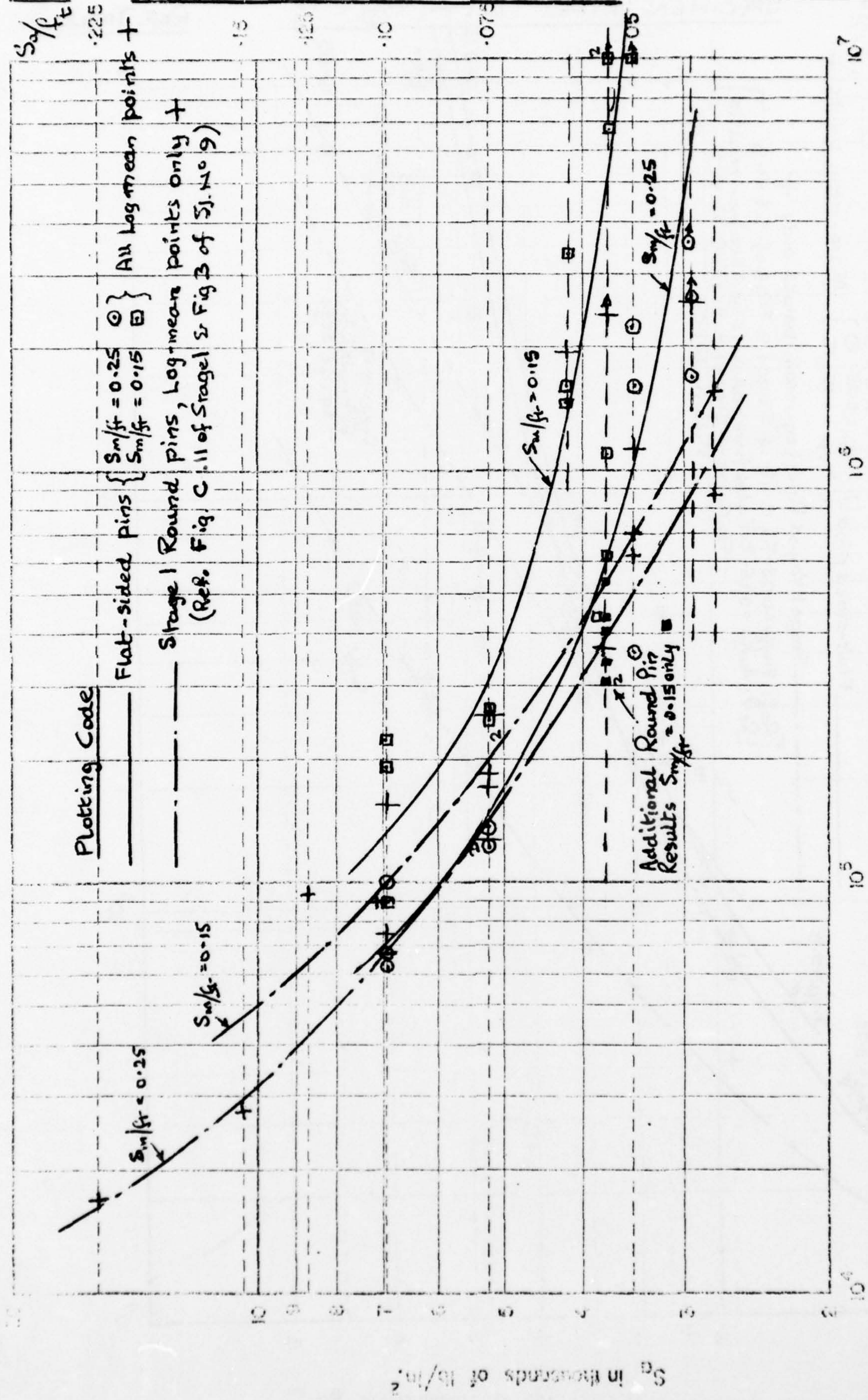
Scale - Full size

Specimen Type		1 D 3/4	1 D 1
d/D		3/8	1/2
Plate	Hole Diameter 'd'	0.75"+0.0003"	1.0"±0.0003"
	Length Limits	±0.01"	±0.01"
	Width Limits	±0.002"	±0.002"
Pin	Push Fit 'd'	$0.75''^{-0.0001''}_{-0.0002''}$	$1.0''^{-0.0001''}_{-0.0002''}$
	0.4°/o Interference Fit 'd'	$0.75''^{+0.0028''}_{+0.0029''}$	$1.0''^{+0.0038}_{+0.0039}$
	Width across flats 'w'	$0.53''^{+0}_{+0.002''}$	$0.707''^{+0}_{+0.002''}$

Sl. N° 2 - FLAT-SIDED PINS

PUSH FIT PIN - PIN LOADED

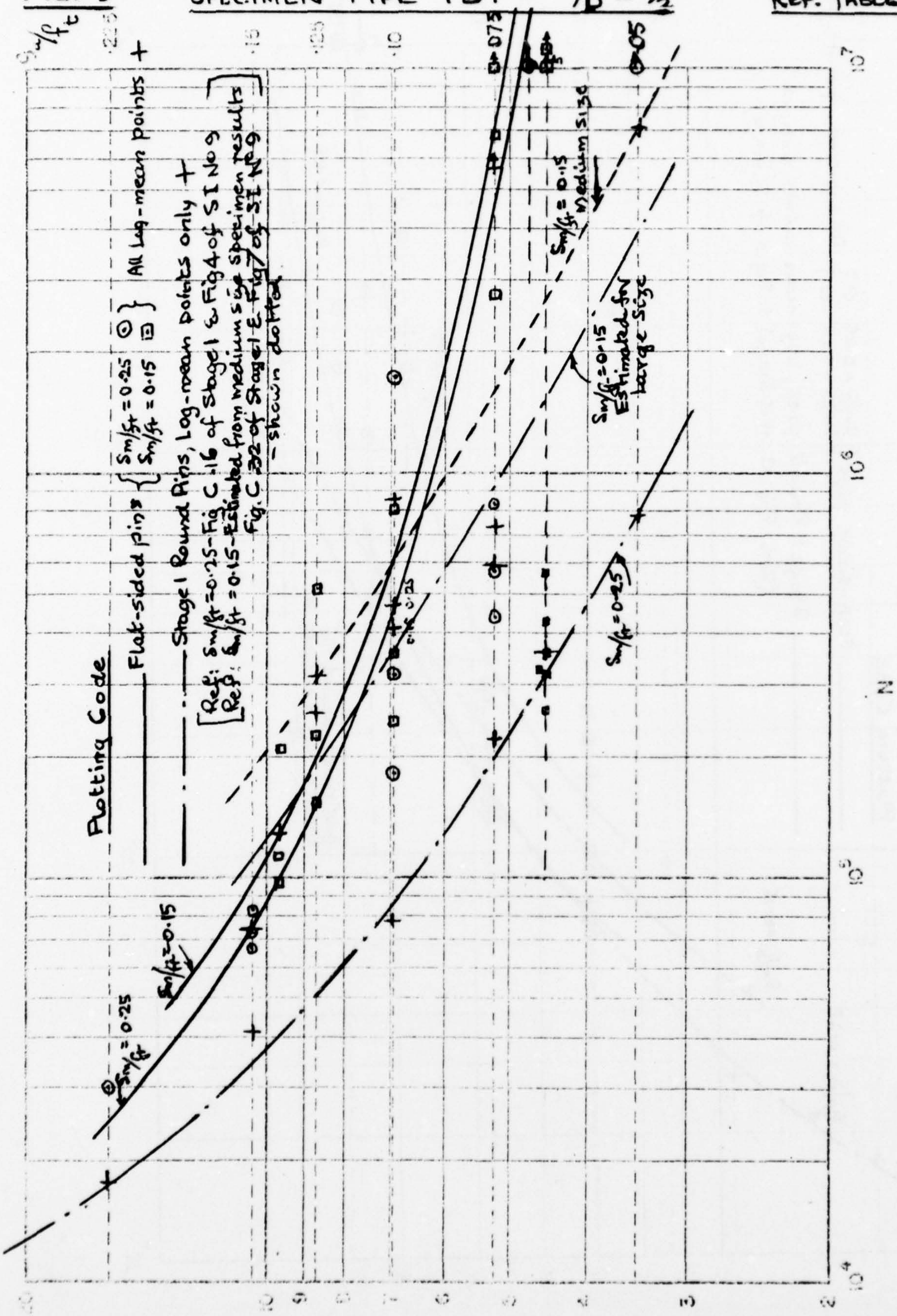
FIG. 2 SPECIMEN TYPE 1D 3/4 - d/D = 3/8 Ref. TABLE 2



S1. Nº 2 - FLAT-SIDED PINS

PUSH FIT PIN - PIN LOADED

FIG. 3 SPECIMEN TYPE 1D1 - $d/D = 1/2$ Ref. TABLE 3



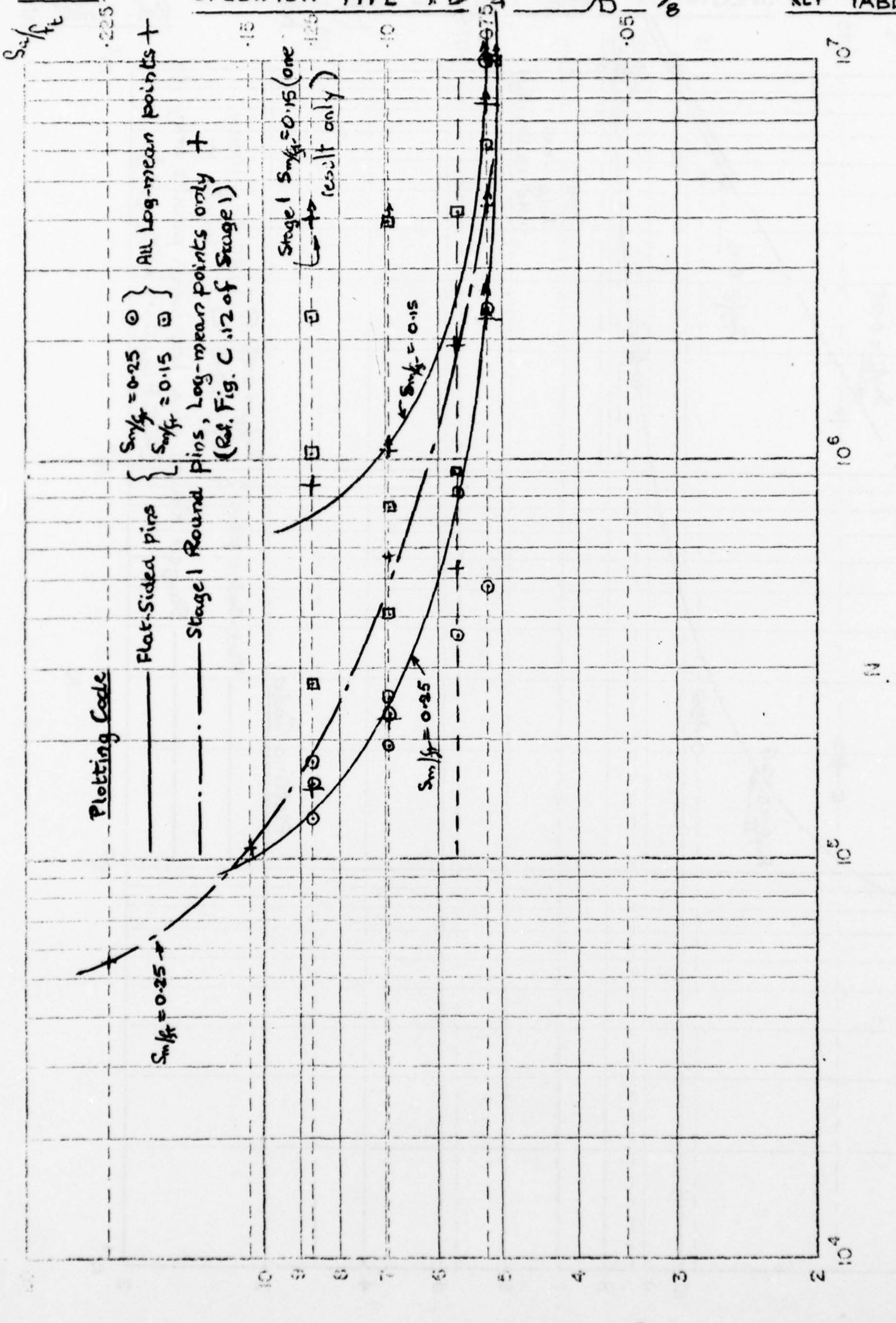
S.I. No 2 - FLAT-SIDED PINS

0.4% INTERFERENCE FIT PIN—PIN LOADED

FIG. 4

SPECIMEN TYPE 1.D $\frac{3}{4}$ - $d/D = 3/8$

REF TABLE 4

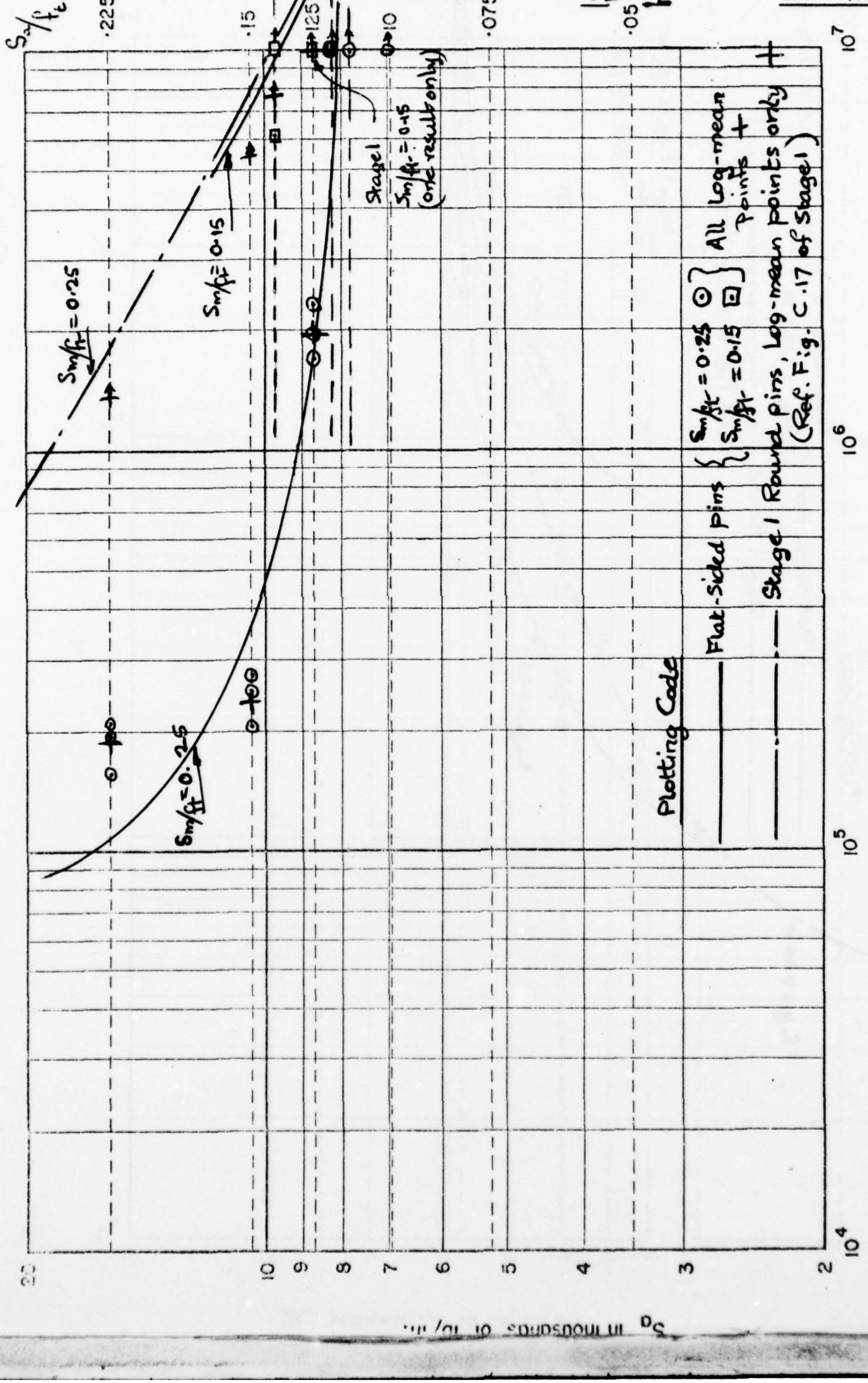


Sl. No 2 - FLAT-SIDED PINS

0.4% INTERFERENCE FIT PINS - PIN LOADED

FIG. 5 SPECIMEN TYPE 1D1 - $d/D = \frac{1}{2}$

Ref: TABLE 5



SUPPLEMENTARY INVESTIGATION No.3

THE EFFECT OF PRE-LOADING THE TEST SPECIMENS

1. INTRODUCTION

Accelerometer records from research aircraft and from aircraft operating in regular service have shown that occasional high loads can occur at any time in the life of the structure. Such loads may cause plastic deformation at regions of high stress concentration, which in turn may affect the subsequent fatigue life of that part of the structure. Supplementary Investigation No.3 was arranged to investigate one aspect of this particular feature, namely the application of a single high tensile load prior to the fatigue loading.

2. NOTATION (Units are in lb and inches throughout)

For convenience the relevant Notation from the Stage 1 report is repeated below -

d = Nominal Diameter of hole and pin

D = Width of parallel section of test specimen

f_t = Average Tensile Strength of plate material (from tests)

f_p = Average 0.2°/o Proof Stress of plate material (from tests)

K'_t = Geometric Stress Concentration factor based on net area of cross section of test specimen

N = Endurance

S_m = Mean Stress on net area

S_a = Alternating Stress on net area associated with S_m

t = Thickness of plate specimen

3. TEST PROGRAMME AND STRESS LEVELS

These tests were carried out in the Department of Metallurgy of the University of Cambridge, using a 2 Ton Amsler fatigue testing machine operating at 7500 c.p.m.

All the specimens were taken from stock remaining from Stage 1 of the research, and details are given on Figure 1 of this report.

Only specimens of the smallest size of those employed in Stage 1 were used for this investigation, largely due to availability of specimens and all were either of types '4B' or '4D', i.e. of the 'pin loaded' form. Type '4B' with the enlarged end was preferred for specimens with d/D = 1/4 because of the greater stress concentration factor associated with this particular value of d/D.

Three standards of pin fit were included, namely push fit, $0.4^{o}/o$ interference fit and $0.8^{o}/o$ interference fit. For each of these standards the previous three configurations of geometry were tested, i.e. d/D = 1/4, 3/8 and 1/2.

For the push fit specimens the corresponding nominal values of K_t' were 3.73, 2.72 and 2.22 respectively.

For the interference fit pin specimens it is not possible to quote single values of K_t' for group of specimens because the value changes with the magnitude of the loading.

A full range of specimens was subjected to an initial single pre-load giving a stress on the net area of 0.75 f_t and another full range subjected to an initial single pre-stress of 0.60 f_t.

Fatigue testing was then carried out at mean stress levels of 0.25 f_t and 0.15 f_t for each of the two levels of pre-stress, with alternating stress levels ranging from just below the mean stress level down to 0.075 f_t. In combinations where d/D and degree of interference were high some tests were omitted because the resulting endurances would have been well beyond 10^7 cycles. At each stress level three nominally identical specimens were tested.

Finally, a limited number of control tests were included for each specimen type (generally one specimen per stress level). These of course were not pre-loaded, but were fatigue tested currently with the main tests. Where available, the corresponding endurance curves from the Stage 1 tests have been used to help in the assessment of the effect of pre-loading. The full range of tests is summarised in Table 1.

4. RESULTS

4.1 Push Fit Pins

Tables 2a, 2b and 2c give the test results for specimens Type 4B 3/16, d/D = 1/4; 'a', 'b' and 'c' referring respectively to 0.75 f_t pre-stress, 0.60 f_t pre-stress and controls tested currently with them (hereafter described as 'current controls').

Figure 2 presents all the results contained in these three tables together with the corresponding Stage 1 endurance curves (where available) for specimens without pre-load.

Tables 3a, 3b and 3c give the test results for specimens Type 4D 9/32, d/D = 3/8; 'a', 'b' and 'c' having the same significance as given above.

Figure 3 presents all the results contained in Tables 3a, 3b and 3c together with the relevant Stage 1 and S.I. No.9 results.

Tables 4a, 4b and 4c give the test results for specimens Type 4D 3/8, d/D = 1/2 ('a', 'b' and 'c), again referring to 0.75 f_t pre-stress, 0.60 f_t pre-stress and current controls respectively).

Figure 4 presents all these results graphically together with the relevant Stage 1 and S.I. No.9 results.

4.2 0.4°/o Interference Fit Pins

Tables 5a, 5b and 5c contain test results for specimens Type 4B 3/16, d/D = 1/4, but with 0.4°/o interference fit pin instead of a push fit pin.

Figure 5 presents all these results together with the relevant Stage 1 data.

Tables 6a, 6b and 6c and Figure 6 cover similarly the test results for specimens Type 4D 9/32, d/D = 3/8 with a 0.4°/o interference fit pin.

Tables 7a, 7b and 7c and Figure 7 cover specimens Type 4D 3/8, d/D = 1/2 with a 0.4°/o interference fit pin.

4.3 0.8°/o Interference Fit Pins

Tables 8a to 10b together with Figures 8 to 10 present all the test results for similar specimen types but with 0.8°/o interference fit pins.

NOTE

Reference to all these tables and figures are given in the last two columns of Table 1 of this report.

4.4 Examination of Failures

From a close examination of the failed specimens a few were selected from among the push fit pin specimens as being illustrative of the types of failures, and degrees of fretting. Fretting was more evident on the push fit pin specimens than on those with interference fit pins. The particulars of these failures are given in Tables 11 and 12, covering push fit pins with d/D = 3/8 and 1/2 respectively.

5. DISCUSSION OF RESULTS

5.1 Push Fit Pins (Figures 2, 3 and 4 and Tables 13a and 13b)

From a study of these Figures and Tables it is clear that although in general the application of a pre-load does lead to an increase in the endurance of a joint with push fit pins, for a given applied stress (an increase in the stress level sustained for a given endurance), there are limitations and reservations which must be noted, because of the influence of geometry and mean stress. In fact it is convenient to discuss the effect of pre-load in terms of the influence of these two variables.

Taking first, the higher mean stress of $S_m/f_t = 0.25$, it was possible to draw reasonable endurance curves over most of the range covered (10^4 to 10^7 cycles), and it was noted that at least for $d/D = 1/4$ and $3/8$, there was an increase of endurance at a given stress level for pre-stresses of both 0.75 f_t and 0.60 f_t and the higher pre-stress level led to the greater increase of endurance. At $d/D = 1/2$ however, although the pre-stress level of 0.75 f_t was marginally more effective than that of 0.60 f_t, in both cases the resulting endurances were lower than those for the Stage 1 tests without pre-loading. This change of effect of the pre-load is thought to be due to the fact that the stress concentration factor for $d/D = 1/2$ is significantly lower than those for the other two values included in the tests.

For $S_m/f_t = 0.15$ the results show the same trend but apparently with less consistency, and not always so clearly marked as for $S_m/f_t = 0.25$.

It is suggested that this is partly due to the fact that the reduction of stress concentration at the critical locations, due to the application of the pre-load, cannot be so effective when a lower mean stress is operative.

Moreover, for the tests at $S_m/f_t = 0.15$ and at $d/D = 1/4$ there was insufficient data provided, both for the pre-loaded specimens and for the controls.

At $d/D = 3/8$ the increase in endurance for a pre-stress of 0.75 f_t appeared to be large, but most of the specimens were unbroken at 10^7 cycles and therefore ratios of increase of endurance could only be assessed approximately. More reliable comparisons were possible at a pre-stress of 0.60 f_t, where the gain was less for $S_m/f_t = 0.15$ compared with $S_m/f_t = 0.25$.

At $d/D = 1/2$ the increase of endurance for both levels of pre-stress was somewhat greater than for the mean stress of 0.25 f_t but it should be noted that the Stage 1 control curve for $S_m = 0.15$ f_t and the current control curve both lie mainly below the similar curves for $S_m/f_t = 0.25$, which is against normal expectations.

From the preceding discussion it is evident that to attempt to give numerical values to the magnitude of increased endurances due to pre-loading would be difficult, and the alternative of stating ratios of increase of alternating stress for a given endurance provides a more consistent means of assessment.

Tables 13a and 13b have therefore been prepared, giving values of the ratio

$$\frac{S_a \text{ with pre-load}}{S_a \text{ without pre-load}}$$

for a stated endurance, noting that these comparisons for both levels of pre-stress are made relative to Stage 1 and S.I.No.9 results where available, but relative to current controls only where no Stage 1 or S.I. No.9 results exist.

For convenience, the summaries from Tables 13a and 13b quoting ranges of these ratios for a range of endurances are given below.

At $S_m/f_t = 0.25$ (see Tables 13a for details)

d/D	1/4		3/8		1/2	
Pre-stress	0.75 f_t	0.60 f_t	0.75f_t	0.60 f_t	0.75 f_t	0.60 f_t
N 3×10^4 to 10^7	1.5 to 2.7	1.2 to 2.1	1.2 to 2.7	0.95 to 2.1	0.95 to 0.65	0.90 to 0.65

At $S_m/f_t = 0.15$ (See Table 13b for details)

d/D	1/4		3/8		1/2	
Pre-stress	0.75 f_t	0.60 f_t	0.75 f_t	0.60 f_t	0.75 f_t	0.60 f_t
N cycles 10^5 to 10^7	*	*	3.65 at 3×10^6 2.4 at 10^7	0.85 to 1.5	2.0 to 1.05	1.05 to 1.25

*Insufficient data available

In these tables the first figure of the range is associated with the lower endurance quoted whereas the second figure of the range is associated with the higher endurance quoted.

With regard to the influence of geometry, despite the limitations of available data at $S_m/f_t = 0.15$ both the tables and the associated figures 2 to 4 show this influence which is mainly that the lowest d/D ratio (highest stress concentration factor) leads to the greatest increase of S_a for a given endurance, and vice versa, thus supporting the statement made at the beginning of this paragraph.

5.2 $0.4^{o}/o$ Interference Fit Pins (Figures 5, 6 and 7 and Tables 14a and 14b)

In this group of test specimens, but only for $d/D = 1/4$, the results show the same trend as for specimens with push fit pins. Also, where data are available, the current controls and Stage 1 results are in fairly good agreement. Endurances for 0.75 f_t pre-stress are significantly greater than those for 0.60 f_t pre-stress for a mean stress of 0.25 f_t, but the order is slightly reversed for the lower mean stress of 0.15 f_t.

For $d/D = 3/8$ and $d/D = 1/2$, even allowing for the limitations of the data provided, there is generally a reduction in endurance for a given stress level when a pre-stress is applied. Moreover at $d/D = 1/2$ the higher pre-stress leads to a greater reduction in endurance. It appears therefore that for $0.4^{o}/o$ interference fit pin specimens a pre-load only increases the endurance when the stress concentration factor at the critical region is high (i.e. $d/D = 1/4$). For higher values of d/D the reverse is true, with a clear trend for less consistency and a greater scatter of results.

It would appear that the effects of the pre-load on a joint with a $0.4^{o}/o$ interference fit pin is generally to reduce the advantages of the interference fit pin.

Numerically it is only possible to quote reliable values for the ratio:

$\frac{S_a \text{ with pre-load}}{S_a \text{ without pre-load}}$ for the group of specimens with $d/D = 1/4$. These are given in Tables 14a and 14b but summarised below for convenience.

At $S_m/f_t = 0.25$ (See Table 14a for details)

$d/D = 1/4$ only

Pre-stress	0.75 f_t	0.60 f_t
N cycles		
3×10^4	1.45	1.25
to	to	to
3×10^6	1.8	1.5

At $S_m/f_t = 0.15$ (See Table 14b)

$d/D = 1/4$ only

Pre-stress	0.75 f_t	0.60 f_t
N cycles		
10^6	2.5	-
3×10^6	2.8	3.3

5.3 0.8^{o}/o Interference Fit Pin (Figures 8, 9 and 10 and Tables 15a and 15b)

As in the previous group tested, the application of a pre-load leads to an increase of endurance for a given stress level only when d/D = 1/4 (high stress concentration factor). Nevertheless, the increase is less marked than for the 0.4^{o}/o interference fit pins.

For values of d/D = 3/8 and 1/2 the application of the pre-load generally reduces the endurance for a given stress level, i.e. it impairs the benefits of the interference fit pin. This statement applies to both levels of mean stress included in these tests, in so far as data are available.

Tables 15a and 15b give values of the ratio;

$$\frac{S_a \text{ with pre-load}}{S_a \text{ without pre-load}}$$

for d/D = 1/4 only, and these ratios were summarised here for convenience.

At $S_m = 0.25$ ft (See Table 15a for details)

d/D = 1/4 only

Pre-stress	0.75 f_t	0.60 f_t
N cycles 3 x 10^4 to 10^6	1.15 to 2.1	1.1 to 1.8

At $S_m = 0.15$ ft (See Table 15b)

d/D = 1/4 only

Pre-stress	0.75 f_t	0.60 f_t
N cycles 10^7	1.03	0.97

5.4 Examination of Failures (Tables 11 and 12)

The specimens reported upon in Tables 11 and 12 were not the only ones exhibiting fretting but were considered to be typical of the majority of samples in the push fit pin range. Fretting was less evident on specimens with the highest stress concentration factor (d/D = 1/4) and so only specimens with d/D = 3/8 and 1/2 are listed. Furthermore, there was less fretting on the specimens with interference fit pins.

The degree of fretting varied, from "light" to "moderate" and sometimes "severe", within a given group of specimens. In general the least fretting was associated with the lowest endurances, but not always so. The most consistent evidence was the fact that almost all the fretting on specimens with d/D = 1/2 and on those tested at low stress levels with d/D = 3/8 occurred uniquely at 3.0 o'clock and 9.0 o'clock, i.e. at the ends of the transverse diameter. Moreover where cracks occurred, they were approximately in the same locations. All of the six specimens with d/D = 1/2 cracked on one side only.

6. CONCLUSIONS

6.1 Push Fit Pins (Figures 2, 3 and 4 and Tables 13a and 13b)

(a) Pre-load

The application of a pre-load to a push fit pin joint generally increased the endurance for a given alternating stress level (or the applied alternating stress for a given endurance). Nevertheless this improvement was influenced by the degree of stress concentration present and by the level of applied mean stress. The greater the magnitude of stress in the critical region, due to these two parameters, the greater the volume of material subjected to plastic deformation, and consequently the greater the improvement in fatigue performance.

In this test programme the pre-stress of 0.75 f_t led to somewhat greater gains in endurance than did the pre-stress of 0.60 f_t, but see remarks in paragraph (b) below. Since no tests were carried out at pre-stresses greater than 0.75 f_t it is not possible to claim that 0.75 f_t is an optimum, but it may be that a pre-stress much higher than 0.75 f_t could produce some adverse effects, e.g. the introduction of permanent set, or of back-lash in the joints.

(b) Geometry

For d/D = 1/4 and 3/8 (nominal $K_t' = 3.73$ and 2.72 respectively) the gain in endurance increased with increasing degree of stress concentration factor and vice versa. For d/D = 1/2 (nominal $K_t' = 2.22$ and the lowest K_t' employed in these tests) the improvement in endurance for a given stress level, due to pre-loading, was either reduced or nullified, particularly at the lower of the two mean stresses employed in these tests.

(c) Mean Stress

There was more scatter of results at the lower mean stress of 0.15 f_t, but many of the endurances achieved at this stress were well beyond 10^7 cycles and the specimens still unbroken. Thus the evidence at this lower level of mean stress was indecisive at times. Nevertheless the tests at the higher mean stress generally produced greater endurance gain ratios for a given alternating stress level (or greater alternating stress gain ratios for a given endurance.) Conversely, where the geometry was such that the K_t' was significantly low ($K_t' = 2.22$, $d/D = 1/2$) tests at the higher mean stress showed a reduction in endurance at a given alternating stress level for the application of a pre-load. (See paragraph (b) above)

(d) General

As commented in the discussion, the effect of the pre-load and the influence of geometry and mean stress are best expressed numerically by quoting ratios of $\frac{S_a \text{ with pre-load}}{S_a \text{ without pre-load}}$ for a given endurance and these are set out for push fit pin specimens in Tables 13a and 13b, but summarised here for convenience.

At $S_m = 0.25\ f_t$ (See Table 13a)

d/D	1/4		3/8		1/2	
Pre-stress	0.75 f_t	0.60 f_t	0.75 f_t	0.60 f_t	0.75 f_t	0.60 f_t
N 3×10^4 to 10^7	1.5 to 2.7	1.2 to 2.1	1.2 to 2.7	0.95 to 2.1	0.95 to 0.65	0.90 to 0.65

At $S_m/f_t = 0.15$ (See Table 13b for details)

d/D	1/4		3/8		1/2	
Pre-stress	0.75 f_t	0.60 f_t	0.75 f_t	0.60 f_t	0.75 f_t	0.60 f_t
N cycles 10^5 to 10^7	*	*	3.65 at 3×10^6 cycles 2.4 at 10^7 cycles	0.85 to 1.5	2.0 to 1.05	1.05 to 1.25

*Insufficient data available

6.2 0.4^{o}/o Interference Fit Pins (Figures 5, 6 and 7 and Tables 14a and 14b)

(a) For d/D = 1/4

The 0.4^{o}/o interference fit pin specimens showed the same trend as for the push fit pin specimens, namely that at both levels of pre-stress the resulting endurances were greater than for the corresponding specimens without pre-load. At the higher mean stress of $0.25\ f_t$ the endurances for $0.75\ f_t$ pre-stress were slightly greater than for $0.60\ f_t$ pre-stress, but the reverse was true for a mean stress of $0.15\ f_t$. Nevertheless the gain in all cases was significant.

(b) For d/D = 3/8 and 1/2

There was a reduction of endurance for almost all specimens, and as far as data were available this applied to both values of mean stress. It would appear that the application of the pre-stress in the presence of moderate and low degrees of stress concentration has an adverse effect upon the an interference fit pin.

(c) Numerical Values for the ratio of improvement of alternating stress *sustained at a given endurance* have therefore been quoted for d/D = 1/4 only and these are to be found in Tables 14a and 14b, but are summarised below.

At $S_m = 0.25\ f_t$ (See Table 14a for details)

d/D = 1/4 only

Pre-stress	$0.75\ f_t$	$0.60\ f_t$
N cycles 3×10^4 to 3×10^6	1.45 to 1.8	1.25 to 1.5

At $S_m = 0.15\ f_t$ (See Table 14b)

d/D = 1/4 only

Pre-stress	$0.75\ f_t$	$0.60\ f_t$
N cycles		
10^6	2.5	-
3×10^6	2.8	3.3

6.3 $0.8^{o}/o$ Interference Fit Pins (Figures 8, 9 and 10 and Tables 15a and 15b)

(a) For d/D = 1/4

There is still an increase in endurance for the application of a pre-load, at least for $S_m = 0.25\ f_t$ but as far as can be judged from the limited amount of data available this gain is marginal at $S_m = 0.15\ f_t$. In any case the gain at all stress levels is less than the similar gains for $0.4^{o}/o$ interference fit.

(b) For d/D = 3/8 and 1/2

As in the case of the lesser interference fit the application of a pre-load reduces the endurance, and presumably for the same reasons already stated.

(c) Numerical values for the ratio of increase of alternating stress sustained at a given endurance have been evaluated for d/D = 1/4 only and these are given in Tables 15a and 15b, but are summarised below.

At $S_m = 0.25\ f_t$ (See Table 15a for details)

d/D = 1/4 only

Pre-stress	$0.75\ f_t$	$0.60\ f_t$
N cycles 3×10^4 to 10^6	1.15 to 2.1	1.1 to 1.8

At $S_m = 0.15\ f_t$ (See Table 15b)

d/D = 1/4 only

Pre-stress	$0.75\ f_t$	$0.60\ f_t$
N cycles 10^7	1.03	0.97

6.4 Nature of Failures

A representative selection of failed specimens from the push fit pin group were examined in detail (see Tables 11 and 12). These were chosen because they showed a greater degree of fretting than specimens in the interference fit pin groups.

The failures were generally as would be expected except that nearly all those specimens examined from the group with $d/D = 1/2$ and those from the group with $d/D = 3/8$ and with low applied stress levels, had fretting uniquely at the ends of the transverse diameter. Moreover for all the specimens at $d/D = 1/2$ cracks occurred only on one side of the pin at the fretting location.

SUPPLEMENTARY INVESTIGATION No.3

TABLE 1 RANGE OF TESTS

Pin Fit	Specimen Type	d/D	Pre-stress	S_m/f_t x	References for Results		
					Table Nos.		Figure Nos.
Push Fit	4B 3/16	1/4	0.75 f_t	0.25 0.15	2a	$2c^+$	2
			0.60 f_t	0.25 0.15	2b		
	4D 9/32	3/8	0.75 f_t	0.25 0.15	3a	$3c^+$	3
			0.60 f_t	0.25 0.15	3b		
	4D 3/8	1/2	0.75 f_t	0.25 0.15	4a	4c	4
			0.60 f_t	0.25 0.15	4b		
0.4°/o Interference Fit	4B 3/16	1/4	0.75 f_t	0.25 0.15	5a	5c	5
			0.60 f_t	0.25 0.15	5b		
	4D 9/32	3/8	0.75 f_t	0.25 0.15	6a	6c	6
			0.60 f_t	0.25 0.15	6b		
	4D 3/8	1/2	0.75 f_t	0.25 0.15	7a	7c	7
			0.60 f_t	0.25 0.15	7b		
0.8°/o Interference Fit	4B 3/16	1/4	0.75 f_t	0.25 0.15	8a	8c	8
			0.60 f_t	0.25 0.15	8b		
	4D 9/32	3/8	0.75 f_t	0.25 0.15	9a	9c	9
			0.60 f_t	0.25 0.15	9b		
	4D 3/8	1/2	0.75 f_t	0.25 0.15	10a	+	10
			0.60 f_t	0.25 0.15	10b		

[x] Each value of mean stress coupled with an appropriate range of alternating stresses to produce on endurance curve.
Three specimens tested at each stress level, for all pre-loaded specimens.
Current control tests (generally one specimen tested at each stress level) for each specimen type and value of S_m/f_t.

[+] Tables 2c, 3c etc. give current control results, but note that there were no such controls for 0.8°/o interference fit with d/D = 1/2, and so there is no Table 10c.

SUPPLEMENTARY INVESTIGATION No.3

PUSH FIT PIN - PIN LOADED

TABLE 2a 0.75 f_t PRE-STRESS

Reference Figure 2

SPECIMEN TYPE 4B 3/16 d/D = 1/4 Nominal $K_t' = 3.73$

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Loads to insert pins, small.

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
10.15.E	25	22.5	64 500	4.809	56 800
10.15.B			63 500	4.802	
10.14.C			44 500	4.648	
10.18.F	25	15	778 800	5.890	710 000
9.14.J			747 000	5.872	
9.17.E			620 000	5.792	
9.18.A	25	10	11 308 000U	7.054U	>6 440 000
9.18.E			11 037 000U	7.043U	
9.18.B			2 150 000	6.332	
9.19.B	25	7.5	31 190 000U	7.495U	>17 100 000
9.19.C			15 800 000U	7.199U	
9.19.A			10 214 000U	7.010U	
9.21.B	15	12.5	12 440 000U	7.095U	>11 430 000
9.21.C			11 232 000U	7.050U	
8.15.D			10 671 000U	7.029U	

U denotes unbroken specimen

TABLE 2b 0.60 f_t PRE-STRESS

Reference Figure 2

SPECIMEN TYPE 4B 3/16 d/D = 1/2 Nominal $K_t' = 3.73$

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Loads to insert pins, small.

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
8.15.C	25	22.5	37 000	4.568	20 750
9.15.J			22 000	4.342	
8.15.B			11 000	4.404	
9.3.A	25	15	247 000	5.393	156 000
10.21.H			154 000	5.186	
9.4.C			101 000	5.005	
9.9.E	25	10	3 342 000	6.525	836 000
9.9.C			445 000	5.649	
9.9.A			390 000	5.591	
10.4.G	25	7.5	11 469 000U	7.060U	>8 080 000
10.3.G			10 001 000U	7.000U	
10.3.F			4 620 000	6.665	
10.16.G	15	12.5	10 540 000U	7.022U	>10 300 000
10.16.D			10 378 000U	7.014U	
10.15.H			10 000 000U	7.000U	

U denotes unbroken specimen

SUPPLEMENTARY INVESTIGATION No.3

PUSH FIT PIN - PIN LOADED

TABLE 2c CURRENT CONTROL TESTS i.e. no Pre-load **Reference Figure 2**

SPECIMEN TYPE 4 B 3/16 d/D = 1/4 $K'_t = 3.73$

Tested at Cambridge University

Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.

Loads to insert pins, small.

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
10.20.C	25	22.5	16 000	4.204	16 000
9.8.B	25	15	44 000	4.643	44 000
10.1.A	25	10	116 000	5.065	116 000
10.6.G	25	7.5	778 000	5.890	778 000
10.16.J	15	12.5	104 000	5.016	98 000
10.17.G			93 000	4.966	

TABLE 3a $0.75\ f_t$ PRE-STRESS **Reference Figure 3**

SPECIMEN TYPE 4 D 9/32 d/D = 3/8 Nominal $K'_t = 2.72$

Tested at Cambridge University

Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.

Loads to insert pins, small.

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
20.23.L	25	22.5	50 000	4.699	42 900
20.24.B			45 000	4.653	
20.23.K			35 000	4.545	
20.24.F	25	15	749 000	5.873	380 000
20.24.C			312 000	5.493	
20.24.D			236 000	5.372	
20.24.J	25	10	11 530 000U	7.061U	>2 080 000
20.24.K			1 103 000	6.043	
20.24.H			718 000	5.855	
20.25.B	25	7.5	17 623 000UF	7.246UF	>4 200 000
20.25.A			1 002 000F	6.000F	
20.25.E	15	12.5	12 987 000	7.111	>8 700 000
20.25.C			10 932 000U	7.038U	
20.25.D			4 635 000F	6.664F	
20.25.J	15	10	10 851 000U	7.035U	>9 350 000
20.25.I			10 500 000U	7.020U	
20.25.H			7 096 000	6.850	
20.25.K	15	7.5	15 327 000U	7.135U	>11 850 000
20.25.L			11 419 000U	7.059U	
20.25.M			10 607 000U	7.026U	

U denotes unbroken specimen

F denotes specimen examined and reported upon for nature of failure

SUPPLEMENTARY INVESTIGATION No.3

PUSH FIT PIN - PIN LOADED

TABLE 3b 0.60 f_t PRE-STRESS Reference Figure 3

SPECIMEN TYPE 4 D 9/32 d/D = 3/8 Nominal $K'_t = 2.72$

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore - Speed 7500 c.p.m.
Loads to insert pins, small.

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
20.26.E	25	22.5	23 000	4.360	17 000
20.25.O			18 000F	4.255F	
20.26.C			12 000	4.079	
20.26.G	25	15	198 000	5.296	127 000
20.26.J			124 000	5.092	
20.26.H			84 000	4.925	
20.26.L	25	10	2 103 000	6.323	700 000
20.26.N			515 000	5.711	
20.27.C			326 000	5.512	
20.28.C	25	7.5	15 810 000U	7.200U	>1 870 000
20.27.E			776 000	5.890	
20.28.E			534 000	5.726	
20.28.F	15	12.5	308 000	5.488	231 000
20.28.D			233 000F	5.366F	
20.28.G			171 000	5.233	
20.28.H	15	10	1 425 000	6.154	1 150 000
20.29.J			1 220 000	6.085	
20.29.I			885 000	5.946	
20.29.M	15	7.5	11 430 000U	7.059U	>6 250 000
20.29.L			11 313 000U	7.053U	
20.29.K			1 808 000	6.275	
21.1.N	15	5	16 903 000UF	7.228UF	>15 000 000
20.29.N			14 629 000U	7.165U	
21.1.M			13 582 000U	7.132U	

U denotes unbroken specimen

F denotes specimen examined and reported upon for nature of failure

TABLE 3c CURRENT CONTROL TESTS i.e. no Pre-load Reference Figure 3

SPECIMEN TYPE 4 D 9/32 d/D = 3/8 $K'_t = 2.72$

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Loads to insert pins, small.

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
21.4.F	25	22.5	29 000	4.462	29 000
21.4.I	25	15	60 000	4.778	60 000
21.4.J	25	10	350 000	5.544	350 000
21.4.M	25	7.5	360 000	5.556	360 000
21.4.N	15	12.5	148 000	5.170	148 000
21.5.B	15	10	203 000	5.308	203 000
21.14.G	15	7.5	598 000	5.776	598 000
21.14.H	15	5	13 500 000U	7.130U	>13 500 000

U denotes unbroken specimen

SUPPLEMENTARY INVESTIGATION No.3

PUSH FIT PIN - PIN LOADED

TABLE 4b 0.60 f_t PRE-STRESS **Reference Figure 4**

SPECIMEN TYPE 4 D 3/8 d/D = 1/2 Nominal $K'_t = 2.22$

Tested at Cambridge University

Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.

Loads to insert pins, small

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
23.2.H 23.2.B 23.2.I	25	22.5	34 000 31 000 24 000F	4.531 4.491 4.380F	29 000
23.3.G 23.3.A 23.3.B	25	15	182 000 101 000 69 000	5.260 5.004 4.838	108 000
23.3.J 23.3.H 23.3.K	25	10	386 000 173 000 94 000	5.586 5.237 4.973	184 000
23.3.L 23.3.O 23.4.A	25	7.5	669 000 581 000 536 000	5.825 5.765 5.728	593 000
23.4.D 23.4.C 23.4.B	15	12.5	443 000 194 000 169 000F	5.646 5.288 5.227F	234 000
23.4.E 23.4.J 23.4.G	15	10	916 000 514 000 423 000	5.961 5.710 5.626	585 000
23.4.K 23.4.O 23.4.M	15	7.5	11 111 000U 3 559 000F 1 376 000F	7.045U 6.408F 6.138F	>3 390 000
23.5.H 23.5.B 23.5.E	15	5	11 520 000U 11 000 000U 10 066 000U	7.060U 7.040U 7.003U	>10 800 000

U denotes unbroken specimen

F denotes specimen examined and reported upon for nature of failure

TABLE 4c CURRENT CONTROL TESTS i.e. no Pre-load Reference Figure 4

SPECIMEN TYPE 4 D 3/8 d/D = 1/2 $K'_t = 2.22$

Tested at Cambridge University

Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.

Loads to insert pins, small.

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
23.6.H 23.6.I 23.6.J	25	22.5	288 000 114 000 29 000	5.460 5.058 4.462	98 300
23.6.K	25	15	61 000	4.784	61 000
23.6.M	25	10	539 000	5.730	539 000
23.6.N	25	7.5	327 000	5.513	327 000
23.6.O	15	12.5	76 000	4.880	76 000
23.7.C	15	10	170 000	5.230	170 000
23.7.D	15	7.5	775 000	5.888	775 000

SUPPLEMENTARY INVESTIGATION No.3
PUSH FIT PIN - PIN LOADED
TABLE 4a 0.75 f_t PRE-STRESS Reference Figure 4

SPECIMEN TYPE 4 D 3/8 d/D = 1/2 Nominal $K_t' = 2.22$

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Loads to insert pins, small.

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
22.7.K	25	22.5	44 000	4.642	32 500
22.8.I			29 000	4.462	
22.8.G			27 000	4.431	
22.9.L	25	15	134 000	5.126	95 000
22.9.A			81 000	4.908	
22.9.E			79 000	4.897	
22.11.H	25	10	246 000F	5.390F	212 000
22.12.C			214 000	5.330	
22.9.M			181 000	5.257	
22.13.J	25	7.5	760 000	5.880	612 000
22.12.H			570 000F	5.755F	
22.12.D			533 000	5.726	
22.14.E	15	12.5	1 149 000	6.060	606 000
22.17.D			445 000	5.648	
22.19.O			435 000	5.638	
22.29.C	15	10	1 263 000	6.101	880 000
22.20.C			1 028 000	6.011	
23.1.A			524 000	5.720	
23.1.J	15	7.5	1 915 000	6.155	1 650 000
23.1.H			1 430 000	6.281	
23.1.K	15	5	29 658 000U	7.473U	>16 300 000
23.1.N			14 184 000U	7.151U	
23.1.L			10 320 000U	7.012U	

U denotes unbroken specimen
F denotes specimen examined and reported upon for nature of failure

SUPPLEMENTARY INVESTIGATION No.3

TABLE 5a 0.4^{o}/o INTERFERENCE FIT PIN - PIN LOADED Reference Figure 5

0.75 f_t PRE-STRESS SPECIMEN TYPE 4 B 3/16 d/D = 1/4

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Range of loads to insert pins 165 to 305 lb

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
12.2.E	25	22.5	83 000	4.920	57 700
12.2.F			49 000	4.690	
12.1.O			47 000	4.671	
12.2.J	25	15	936 000	5.970	329 000
12.2.I			204 000	5.309	
12.2.H			187 000	5.271	
12.2.L	25	10	11 580 000U	7.061U	>10 900 000
12.2.M			11 076 000U	7.045U	
12.3.E			10 017 000U	7.006U	
12.4.M	15	12.5	11 717 000U	7.069U	>2 230 000
12.4.J			977 000	5.989	
12.4.A			955 000	5.980	
12.5.C	15	10	30 103 000U	7.479U	>16 100 000
12.5.A			12 270 000U	7.089U	
12.5.B			11 520 000U	7.051U	

U denotes unbroken specimen

TABLE 5b 0.60 f_t PRE-STRESS Reference Figure 5

SPECIMEN TYPE 4 B 3/16 d/D = 1/4

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore Speed 7500 c.p.m.
Range of loads to insert pins 120 to 225 lb

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
12.5.M	25	22.5	37 000	4.568	33 200
12.5.J			34 000	4.531	
12.5.F			29 000	4.462	
12.6.A	25	15	194 000	5.288	125 000
12.6.G			112 000	5.049	
12.5.O			91 000	4.958	
12.7.H	25	10	11 189 000U	7.048U	>3 500 000
12.7.A			2 778 000	6.444	
12.7.G			1 375 000	6.137	
12.7.J	25	7.5	15 771 000U	7.198U	>13 600 000
12.8.B			14 230 000U	7.153U	
12.8.C			11 102 000U	7.045U	
12.8.J	15	12.5	11 022 000U	7.042U	>4 830 000
12.8.L			4 906 000	6.691	
12.8.H			2 098 000	6.321	
12.8.O	15	10	14 040 000U	7.147U	>7 750 000
12.8.M			10 160 000U	7.005U	
12.9.D			3 253 000	6.513	
12.10.F	15	7.5	21 060 000U	7.324U	>13 450 000
12.10.G			11 250 000U	7.050U	
12.10.E			10 164 000U	7.006U	

U denotes unbroken specimen

SUPPLEMENTARY INVESTIGATION No.3

TABLE 5c 0.4^{o}/o INTERFERENCE FIT PIN - PIN LOADED

Reference Figure 5

CURRENT CONTROL TESTS i.e. no Pre-load

SPECIMEN TYPE 4 B 3/16 d/D = 1/4

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Range of loads to insert pins - 110 to 200 lb

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
12.2.G	25	22.5	16 000	4.204	16 000
12.2.K		15	44 000	4.643	44 000
12.3.I		10	131 000	5.117	131 000
12.4.O		7.5	1 002 000	6.001	1 002 000
12.9.M	15	12.5	149 000	5.172	149 000
12.9.K		10	165 000	5.217	120 500
12.9.J		10	89 000	4.949	
12.10.M		7.5	534 000	5.726	534 000
12.11.B		5	1 488 000	6.172	1 488 000

TABLE 6a 0.75 f_t PRE-STRESS

Reference Figure 6

SPECIMEN TYPE 4 D 9/32 d/D = 3/8

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Range of loads to insert pins 285 to 440 lb.

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
21.5.N	25	22.5	78 000	4.891	51 000
21.5.E			55 000	4.740	
21.5.K			31 000	4.490	
21.6.D	25	15	236 000	5.373	148 000
21.6.E			181 000	5.257	
21.6.C			76 000	4.880	
21.6.H	25	10	11 159 000U	7.046U	>8 800 000
21.6.G			10 178 000U	7.006U	
21.6.I			6 024 000	6.780	
21.14.J	25	7.5	10 278 000U	7.012U	>10 200 000
21.14.K			10 185 000U	7.007U	
21.6.O			10 140 000U	7.006U	
21.7.D	15	12.5	15 269 000U	7.183U	>11 650 000
21.7.B			10 229 000U	7.010U	
21.7.C			10 171 000U	7.006U	

U denotes unbroken specimen

SUPPLEMENTARY INVESTIGATION No.3

0.4°/o INTERFERENCE FIT PIN - PIN LOADED

TABLE 6b 0.60 f_t PRE-STRESS Reference Figure 6

SPECIMEN TYPE 4 D 9/32 d/D = 3/8

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Range of loads to insert pins 265 to 440 lb

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
21.7.H 21.7.F 21.7.G	25	22.5	72 000 43 000 43 000	4.856 4.633 4.633	51 000
21.7.K 21.7.L 21.7.J	25	15	143 000 143 000 120 000	5,164 5.164 5,078	136 500
21.7.N 21.14.L 21.14.M	25	10	1 118 000 804 000 224 000	6.045 5.905 5.349	585 000
21.8.B 21.8.D 21.8.A	25	7.5	2 487 000 2 171 000 1 318 000	6,394 6.336 6.118	1 925 000
21.8.I 21.8.G 21.8.H	15	12.5	1 001 000 816 000 517 000	6.001 5.912 5.712	750 000
21.8.K 21.8.L 21.8.M	15	10	10 448 000U 10 343 000U 10 166 000U	7.019U 7.012U 7.006U	>10 300 000

U denotes unbroken specimen

TABLE 6c CURRENT CONTROL TESTS i.e. no Pre-load Reference Figure 6

SPECIMEN TYPE 4 D 9/32 d/D = 3/8

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore Speed 7500 c.p.m.
Range of loads to insert pins 330 to 440 lb

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
21.7.I 21.5.O	25	22.5	81 000 61 000	4.907 4.785	70 300
21.6.F 21.7.M	25	15	326 000 274 000	5.513 5.436	298 000
21.6.L 21.7.O	25	10	3 526 000 468 000	6.546 5.670	1 280 000
21.7.A 21.8.F	25	7.5	10 168 000U 1 339 000X	7.002U 6.125X	>3 660 000
21.8.J 21.7.E	15	12.5	10 473 000U 10 210 000U	7.021U 7.009U	>10 350 000
21.8.N	15	10	20 387 000U	7.307U	>20 387 000

U denotes unbroken specimen
X specimen failed away from hole

SUPPLEMENTARY INVESTIGATION No.3

0.4^{o}/o INTERFERENCE FIT PIN - PIN LOADED

TABLE 7a 0.75 f_t PRE-STRESS — Reference Figure 7

SPECIMEN TYPE 4 D 3/8 d/D = 1/2

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Range of loads to insert pins 195 to 460 lb

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
22.18.D	25	22.5	633 000	5.801	430 000
22.17.0			583 000	5.765	
22.18.C			215 000	5.332	
22.18.G	25	15	1 627 000	6.210	728 000
22.18.L			522 000	5.718	
22.18.H			454 000	5.656	
22.19.B	25	10	16 831 000U	7.226U	>3 500 000
22.18.0			1 611 000	6.206	
22.19.A			1 595 000	6.202	
22.19.L	25	7.5	18 780 000U	7.273U	>8 660 000
22.19.E			10 044 000U	7.002U	
22.19.F			3 456 000	6.537	
22.25.0	15	12.5	21 170 000U	7.326U	>8 230 000
22.25.L			10 000 000U	7.000U	
22.20.F			2 644 000	6.420	
22.20.J	15	10	14 888 000U	7.172U	>11 610 000
22.20.H			10 445 000U	7.020U	
22.20.I			10 177 000U	7.003U	

U denotes unbroken specimen

TABLE 7b 0.60 f_t PRE-STRESS — Reference Figure 7

SPECIMEN TYPE 4 D 3/8 d/D = 1/2

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Range of loads to insert pins 290 to 485 lb

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
22.21.F	25	22.5	1 545 000	6.190	790 000
22.21.G			1 420 000	6.151	
22.21.J			224 000	5.347	
22.21.M	25	15	11 413 000U	7.056U	>11 160 000
22.21.L			11 331 000U	7.053U	
22.21.N			10 800 000U	7.033U	

U denotes unbroken specimen

TABLE 7c CURRENT CONTROLS i.e. no Pre-load — Reference Figure 7

SPECIMEN TYPE 4 D 3/8 d/D = 1/2

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Range of loads to insert pins 320 to 440 lb

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
22.18.F	25	22.5	10 145 000U	7.004U	>2 940 000
22.21.K			849 000	5.928	
22.18.N	25	15	21 890 000	7.340	>15 600 000
22.21.0			10 870 000U	7.036U	
22.19.C	25	10	12 640 000U	7.100U	>12 640 000
22.20.B		7.5	11 093 000U	7.045U	>11 093 000
22.20.G	15	12.5	10 350 000U	7.012U	>10 350 000
22.21.A		10	15 197 000U	7.180U	>15 197 000

U denotes unbroken specimen

SUPPLEMENTARY INVESTIGATION No.3

TABLE 8a 0.8°/o INTERFERENCE FIT PIN - PIN LOADED Reference Figure 8

0.75 f_t PRE-STRESS SPECIMEN TYPE 4 B 3/16 d/D = 1/4

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Range of loads to insert pins, 330 to 500 lb

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
12.11.A	25	22.5	53 000	4.724	32 000
12.7.O			31 000	4.491	
12.7.N			20 000	4.301	
12.12.M	25	15	1 012 000	6.001	207 000
12.12.B			143 000	5.155	
12.12.C			62 000	4.792	
12.1.J	25	10	11 284 000U	7.052U	>8 100 000
12.1.H			11 061 000U	7.043U	
12.1.I			4 272 000	6.630	
12.3.C	25	7.5	11 860 000U	7.074U	>11 300 000
12.3.A			11 578 000U	7.063U	
12.1.L			11 373 000U	7.054U	
12.3.N	15	12.5	12 028 000U	7.081U	>10 930 000
12.4.I			11 710 000U	7.068U	
12.2.C			9 241 000	6.965	
12.6.E	15	10	19 342 000U	7.285U	>14 800 000
12.6.F			14 158 000U	7.160U	
12.6.D			11 560 000U	7.063U	

U denotes unbroken specimen

TABLE 8b 0.60 f_t PRE-STRESS Reference Figure 8

SPECIMEN TYPE 4 B 3/16 d/D = 1/4

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Range of loads to insert pins, 330 to 485 lb

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
12.9.B	25	22.5	44 000	4.643	26 800
12.9.A			40 000	4.602	
12.7.F			11 000	4.041	
12.9.H	25	15	294 000	5.467	192 000
12.9.I			194 000	5.288	
12.9.C			124 000	5.093	
12.12.K	25	10	1 949 000	6.289	1 160 000
12.12.L			1 281 000	6.106	
12. 2.A			630 000	5.800	
12.2.B	25	7.5	10 507 000U	7.021U	>5 500 000
12.3.K			10 488 000U	7.020U	
12.3.J			1 516 000	6.180	
12.3.L	15	12.5	11 750 000U	7.069U	>6 820 000
12.3.O			11 083 000U	7.045U	
12.3.M			2 463 000	6.390	
9.11.A	15	10	15 198 000U	7.180U	>12 250 000
9.11.E			11 113 000U	7.045U	
12.5.G			11 061 000U	7.043U	

U denotes unbroken specimen

SUPPLEMENTARY INVESTIGATION No.3

0.8°/o INTERFERENCE FIT PIN - PIN LOADED

TABLE 8c CURRENT CONTROLS i.e. no Pre-load

Reference Figure 8

SPECIMEN TYPE 4 B 3/16 d/D = 1/4

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Range of loads to insert pins, 330 to 425 lb

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
12.12.A	25	22.5	13 000	4.113	13 000
12.1.G		15	92 000	4.964	92 000
12.1.K		10	250 000	5.398	250 000
12.3.B		7.5	872 000	5.840	872 000
12.5.H	15	12.5	12 982 000U	7.112U	>12 982 000
12.7.E		10	11 541 000U	7.060U	>11 541 000

U denotes unbroken specimen

TABLE 9a $0.75\ f_t$ PRE-STRESS

Reference Figure 9

SPECIMEN TYPE 4 D 9/32 d/D = 3/8

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Range of loads to insert pins, 500 to 800 lb

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
21.9.B 21.9.A 21.9.C	25	22.5	94 000 76 000 59 000	4.972 4.880 4.770	75 000
21.9.I 21.9.J 21.9.H	25	15	277 000 243 000 227 000	5.442 5.385 5.356	248 000
21.9.O 21.9.N 21.9.L	25	10	14 603 000U 2 143 000 1 559 000	7.165U 6.328 6.191	>3 650 000
21.10.C 21.10.B 21.10.F	25	7.5	19 628 000U 11 275 000U 10 287 000U	7.294U 7.052U 7.012U	>13 150 000
21.10.H 21.10.I 21.10.J	15	12.5	6 008 000 3 222 000 579 000	6.783 6.507 5.762	2 240 000
21.10.L 21.10.M 21.10.N	15	10	10 270 000U 10 159 000U 10 084 000U	7.012U 7.006U 7.002U	>10 200 000

U denotes unbroken specimen

SUPPLEMENTARY INVESTIGATION No.3
0.8^{o}/o INTERFERENCE FIT PIN - PIN LOADED

TABLE 9b 0.60 f_t PRE-STRESS

Reference Figure 9

SPECIMEN TYPE 4 D 9/32 d/D = 3/8

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Range of loads to insert pins, 580 to 715 lb

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
21.11.C	25	22.5	748 000	5.873	282 000
21.11.G			176 000	5.245	
21.11.A			170 000	5.230	
21.11.I	25	15	10 343 000U	7.013U	>6 850 000
21.11.J			10 181 000U	7.007U	
21.11.L			3 063 000J	6.485J	
21.11.N	25	10	32 876 000U	7.516U	>15 100 000
21.12.A			10 283 000U	7.012U	
21.11.O			10 179 000U	7.007U	
21.12.E	15	12.5	10 634 000U	7.028U	>10 350 000
21.12.D			10 275 000U	7.012U	
21.12.C			10 092 000U	7.004U	

U denotes unbroken specimen
J denotes failed at Jaws

TABLE 9c CURRENT CONTROLS i.e. no Pre-load

Reference Figure 9

SPECIMEN TYPE 4 D 9/32 d/D = 3/8

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Range of loads to insert pins, 560 to 800 lb

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
21.11.H	25	22.5	3 644 000	6.560	2 940 000
21.9.F			2 371 000	6.375	
21.9.K	25	15	5 591 000J	6.746J	4 050 000
21.11.M			2 938 000	6.466	
21.10.A	25	10	10 437 000U	7.020U	>10 250 000
21.12.B			10 008 000U	7.001U	
21.10.G	25	7.5	10 425 000U	7.018U	>10 425 000
21.10.K	15	12.5	19 737 000U	7.295U	>15 000 000
21.12.F			11 369 000U	7.054U	
21.10.O	15	10	6 758 000I	6.829I	>6 758 000

U denotes unbroken specimen
J denotes failed at Jaws
I denotes specimen fractured at a line of an inclusion and not at the pin hole.

SUPPLEMENTATY INVESTIGATION No.3

0.8°/o INTERFERENCE FIT PIN - PIN LOADED

TABLE 10a 0.75 f_t PRE-STRESS **Reference Figure 10**

SPECIMEN TYPE 4 D 3/8 d/D = 1/2

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Range of loads to insert pins, 640 to 825 lb

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
22.13.N 22.26.H 22.13.L 22.13.I	25	22.5	13 658 000U 11 142 000U 10 173 000U 2 517 000J	7.135U 7.046U 7.005U 6.400J	>7 900 000
22.23.J 22.13.O 22.23.K	25	15	15 504 000U 11 490 000U 11 293 000U	7.190U 7.060U 7.052U	>12 600 000
22.23.N 22.23.L 22.23.M	15	12.5	31 970 000U 12 551 000U 10 110 000U	7.505U 7.096U 7.005U	>16 000 000

U denotes unbroken specimen
J denotes specimen failed at jaws

TABLE 10b 0.60 f_t PRE-STRESS **Reference Figure 10**

SPECIMEN TYPE 4 D 3/8 d/D = 1/2

Tested at Cambridge University
Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.
Range of loads to insert pins, 690 to 815 lb

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
22.24.B 22.23.D 22.24.C	25	22.5	12 158 000U 12 010 000U 10 802 000U	7.084U 7.080U 7.033U	>11 650 000

U denotes unbroken specimen

NOTE

There were no current controls tested for this configuration

SUPPLEMENTARY INVESTIGATION No.3 PRE-LOADED SPECIMEN

TABLE 11

PUSH FIT PIN - PIN LOADED QUALITATIVE SUMMARY OF FAILURES

SPECIMEN TYPE 4 D 9/32 d/D = 3/8

Specimen Identity	Pre-stress	Stress Levels Percentage f_t		Position of Crack Origins*		Fretting Positions*	Degree of Fretting	Endurance Cycles
		S_m	$\pm S_a$					
20.25.B	0.75 f_t	25	7.5	-	-	2 to 11	severe	17 623 000U
20.25.A		25	7.5	8.30	3	3 to 9	light	1 002 000
20.25.D		15	12.5	8.30	3	4 to 8	severe	4 635 000
20.26.C	0.60 f_t	25	22.5	8.30	3	3 to 9	moderate	12 000
20.28.D		15	12.5	8.30	3.30	uniquely at 3 and 9	light	233 000
21.1.N		15	5	-	-		light	16 903 000U

U denotes unbroken

*CLOCK FACE NOTATION

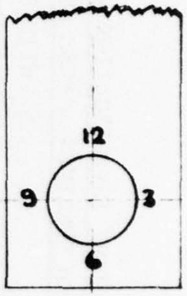


TABLE 12 SPECIMEN TYPE 4 D 3/8 d/D = 1/2

Specimen Identity	Pre-stress	Stress Levels Percentage f_t		Position of Crack Origins*		Fretting Positions*	Degree of Fretting	Endurance Cycles
		S_m	$\pm S_a$					
22.12.H	0.75 f_t	25	10	9	-	On all specimens fretting occurred uniquely at 3 o'clock and 9 o'clock-almost entire absence of fretting elsewhere.	light	570 000
22.11.H		25	10	9	-		moderate	246 000
23.2.I	0.60 f_t	25	22.5	9.30	-		moderate	24 000
23.4.B		15	12.5	9	-		moderate	169 000
23.4.O		15	7.5	9	-		moderate	2 559 000
23.4.M		15	7.5	9	-		light	1 376 000

SUPPLEMENTARY INVESTIGATION No.3

TABLE 13a PRE-LOADED SPECIMEN PUSH FIT PIN - PIN LOADED

VALUES OF RATIO: $\frac{S_a \text{ WITH PRE-LOAD}}{S_a \text{ WITHOUT PRE-LOAD}}$ FOR GIVEN ENDURANCE

MEAN STRESS = $0.25 f_t$

d/D	1/4		3/8		1/2	
Pre-stress	$0.75\ f_t$	$0.60\ f_t$	$0.75\ f_t$	$0.60\ f_t$	$0.75\ f_t$	$0.60\ f_t$
N Cycles						
3×10^4	1.50	1.20	1.18	0.95	0.95	0.90
10^5	2.03	1.46	1.49	1.17	0.80	0.76
3×10^5	2.35	1.65	1.83	1.45	0.70	0.65
10^6	2.55	1.76	2.00	1.56	0.65	0.63
3×10^6	2.60	1.84	2.23	1.75	0.78	0.73
10^7	2.70	2.10	2.68	2.10	-	-
SUMMARY 3×10^4	1.5	1.2	1.2	0.95	0.95	0.90
to	to	to	to	to	to	to
10^7	2.7	2.1	2.7	2.1	0.65	0.65

TABLE 13b MEAN STRESS = $0.15\ f_t$

d/D	1/4		3/8		1/2	
Pre-stress	$0.75\ f_t$	$0.60\ f_t$	$0.75\ f_t$	$0.60\ f_t$	$0.75\ f_t$	$0.60\ f_t$
N Cycles						
3×10^4	Insufficient Data	Insufficient Data	-	-	-	-
10^5			-	0.86	-	1.07
3×10^5			-	1.34	2.00	1.15
10^6			-	1.47	1.30	1.24
3×10^6			3.65	1.47	1.10	1.24
10^7			2.4	1.35	1.04	1.18
SUMMARY 10^5			3.65	0.85	2.0	1.05
	-	-	at 3×10^6			
to			2.4	to	to	to
10^7			at 10^7	1.5	1.05	1.25

TABLE 14a

SUPPLEMENTARY INVESTIGATION No.3

0.4°/o INTERFERENCE FIT PIN - PIN LOADED

VALUES OF RATIO: $\dfrac{S_a \text{ WITH PRE-LOAD}}{S_a \text{ WITHOUT PRE-LOAD}}$ FOR GIVEN ENDURANCE

MEAN STRESS = 0.25 f_t d/D = 1/4 only

Pre-stress	0.75 f_t	0.60 f_t
N Cycles		
3×10^4	1.46	1.24
10^5	1.71	1.40
3×10^5	1.77	1.50
10^6	1.68	1.50
3×10^6	1.61	1.52
10^7	-	-
SUMMARY 3×10^4	1.4	1.25
to	to	to
3×10^6	1.80	1.50

TABLE 14b

MEAN STRESS = 0.15 f_t d/D = 1/4 only

Pre-stress	0.75 f_t	0.60 f_t
N Cycles		
SUMMARY 10^6	2.5	-
3×10^6	2.8	3.3

TABLE 15a

SUPPLEMENTARY INVESTIGATION No.3

0.8°/o INTERFERENCE FIT PIN - PIN LOADED

VALUES OF RATIO: $\dfrac{S_a \text{ WITH PRE-LOAD}}{S_a \text{ WITHOUT PRE-LOAD}}$ FOR GIVEN ENDURANCE

MEAN STRESS = 0.25 f_t d/D = 1/4 only

Pre-stress	0.75 f_t	0.60 f_t
N Cycles		
3×10^4	1.16	1.11
10^5	1.54	1.46
3×10^5	1.85	1.68
10^6	2.12	1.78
SUMMARY 3×10^4	1.15	1.1
to	to	to
10^6	2.1	1.8

TABLE 15b

MEAN STRESS = 0.15 f_t d/D = 1/4 only

Pre-stress	0.75 f_t	0.60 f_t
N Cycles		
10^7	1.03	0.97

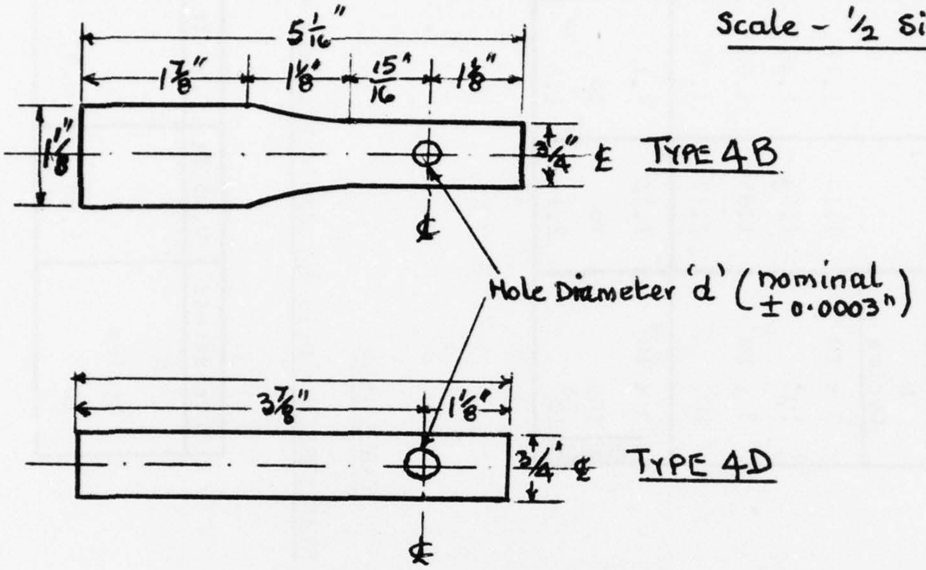
S.I. N°3 — PRE-LOADED SPECIMEN
PIN LOADED

FIGURE 1 DETAILS OF SPECIMENS

Unclad Sheet

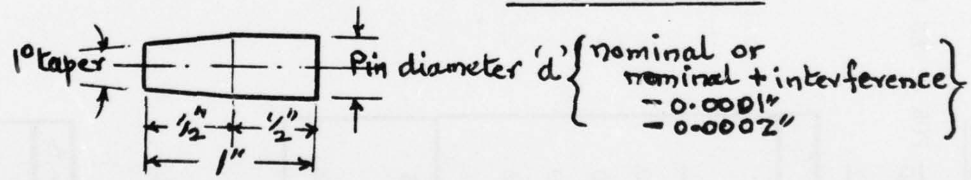
Aluminium Alloy to Specification B.S. L 71 - 3/32" thick

Scale - ½ Size



PIN - Steel to Specification B.S. S94

Scale - Full size



Pin Diameters (nominal)

Type 4B $d/D = 1/4$ $d = 3/16"$

Type 4D { $d/D = 3/8$ $d = 9/32"$
$d/D = 1/2$ $d = 3/8"$

S.I. Nº 3 – PRE-LOADED SPECIMEN

PUSH FIT PIN – PIN LOADED

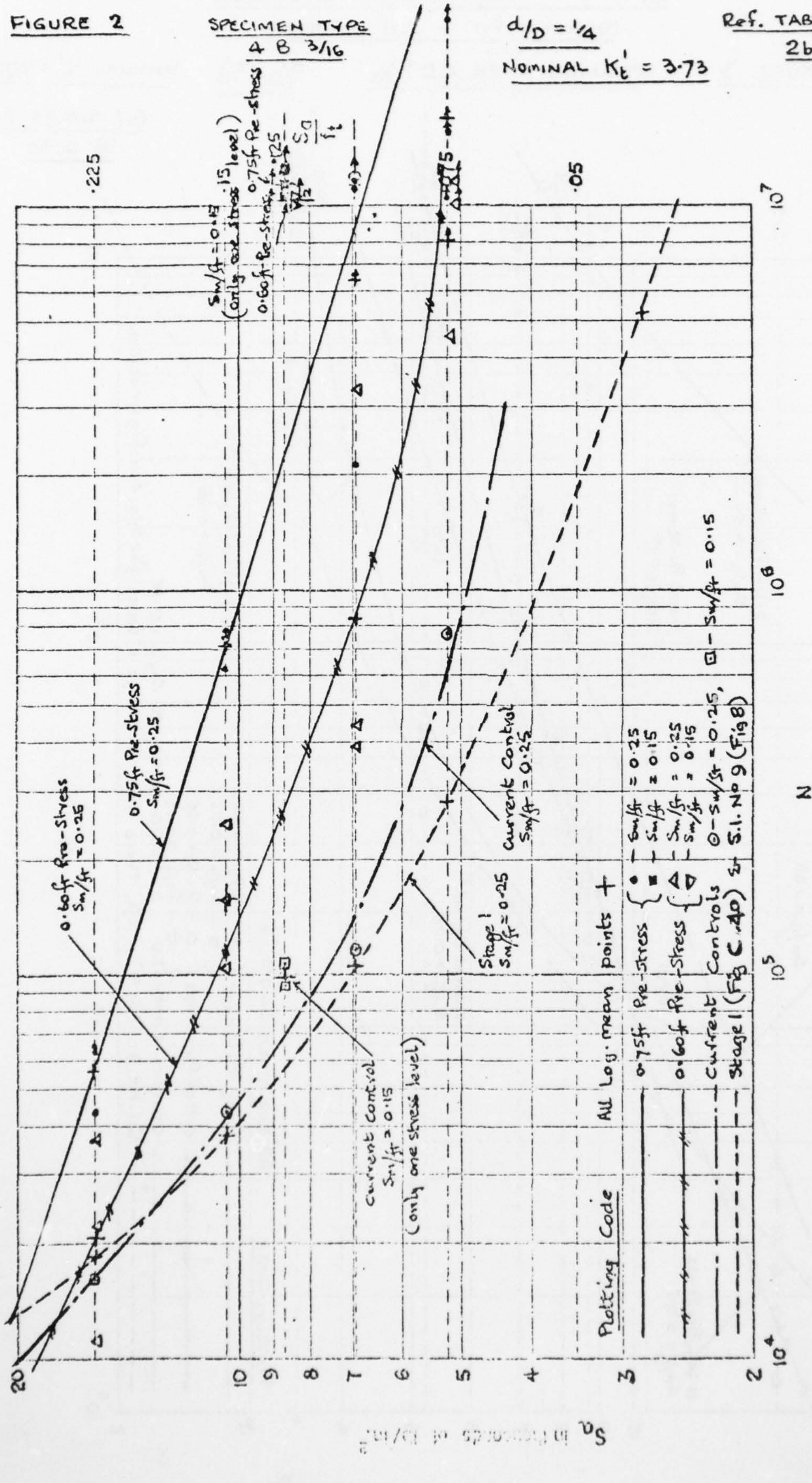
FIGURE 2

SPECIMEN TYPE
4 B 3/16

$d/D = 1/4$

NOMINAL $K_t' = 3\cdot73$

Ref. TABLES 2a, 2b & 2c

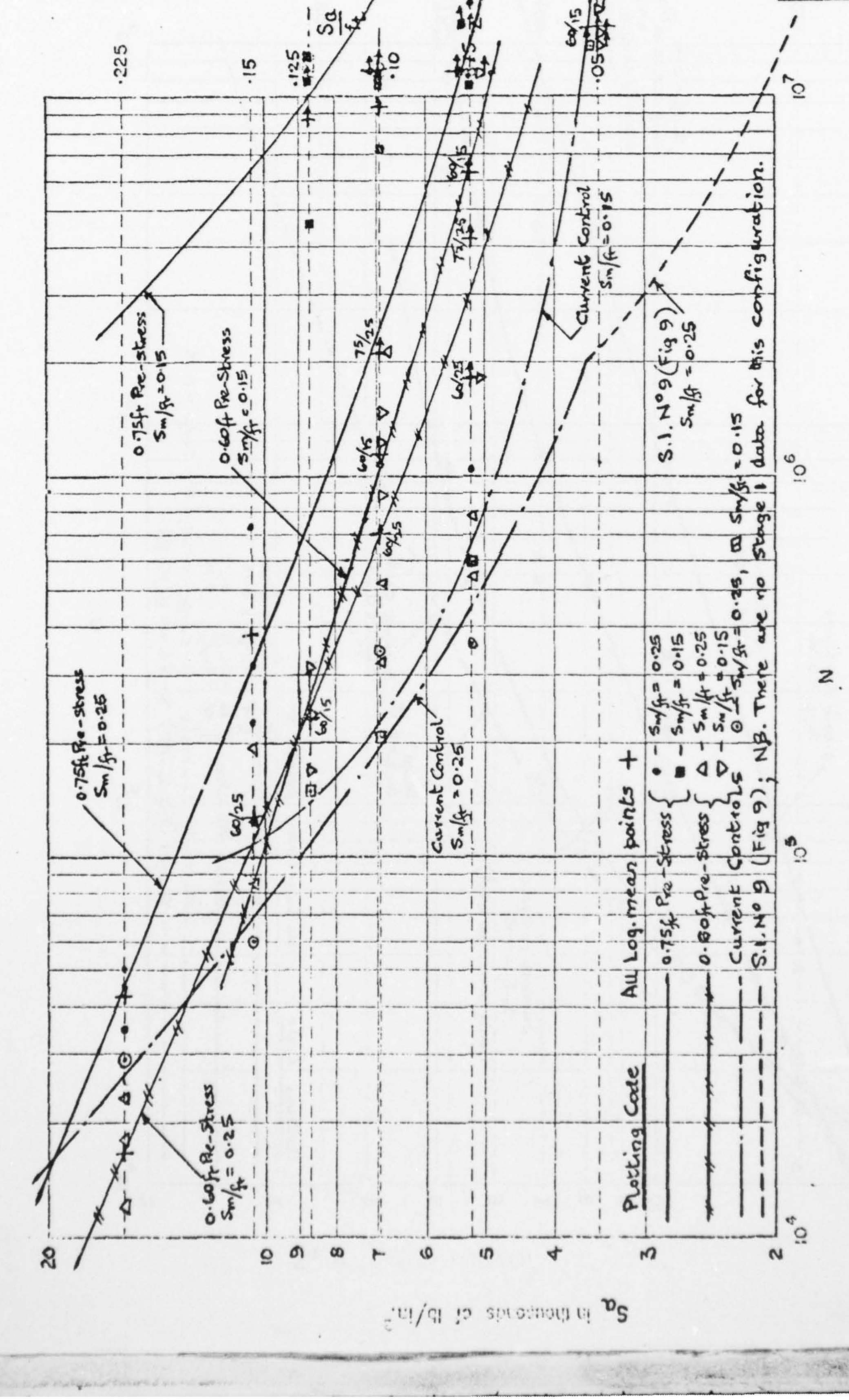


S.I. No 3 – PRE-LOADED SPECIMEN

PUSH FIT PIN – PIN LOADED

FIGURE 3 SPECIMEN TYPE 4D 9/32 $d/D = 3/8$ NOMINAL $K_t' = 2.72$

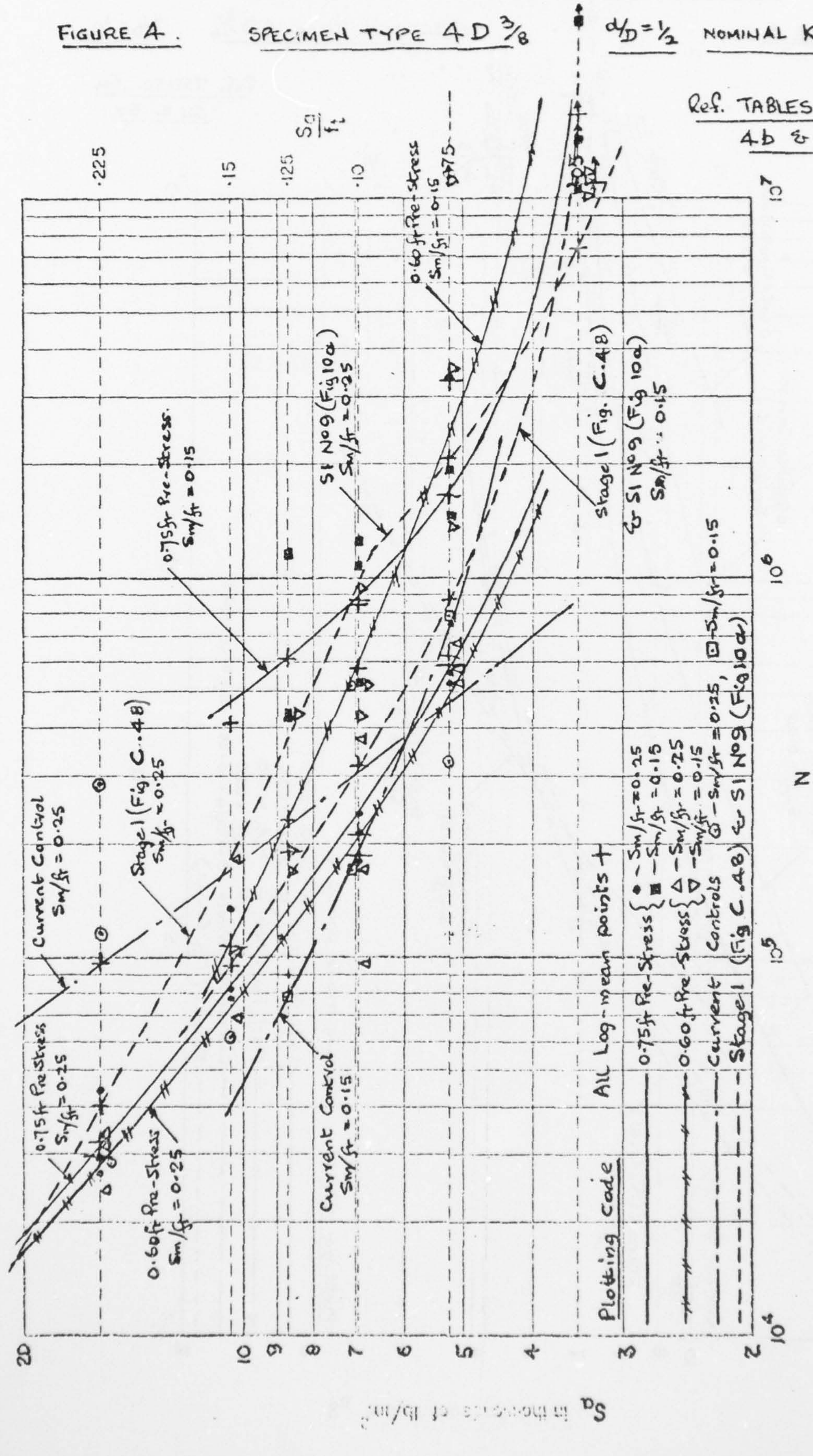
Ref. TABLES 3a, 3b & 3c



S.I. Nº 3 – PRE-LOADED SPECIMEN

PUSH FIT PIN – PIN LOADED

FIGURE 4. SPECIMEN TYPE 4D 3/8 $d/D = 1/2$ NOMINAL $K_t' = 2.22$



Ref. TABLES 4a, 4b & 4c

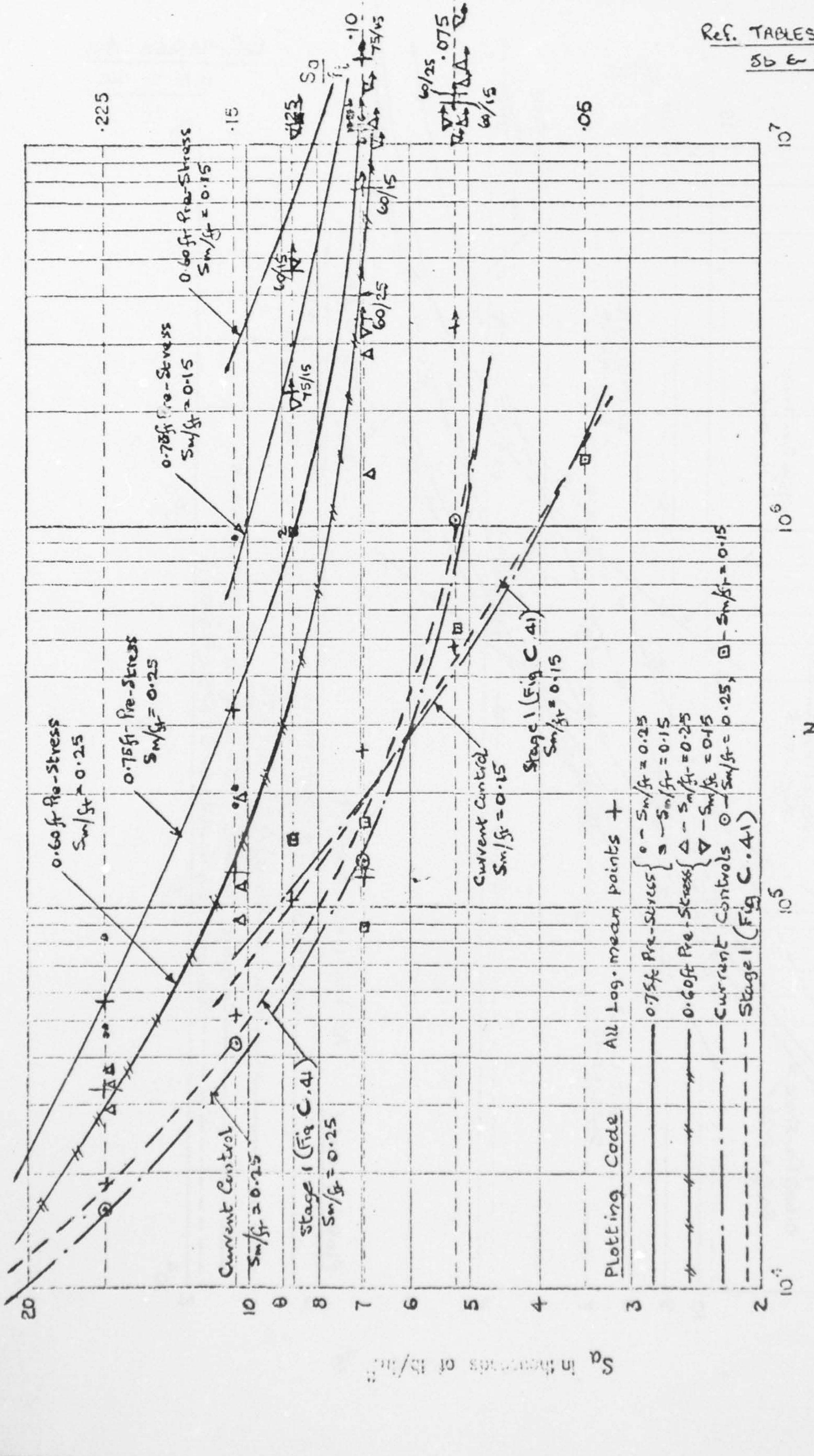
S.I. No 3 - PRE-LOADED SPECIMEN

0.4% INTERFERENCE FIT PIN - PIN LOADED

FIGURE 5

SPECIMEN TYPE 4B$\frac{3}{16}$ $d/D = 1/4$

Ref. TABLES 5a
5b & 5c



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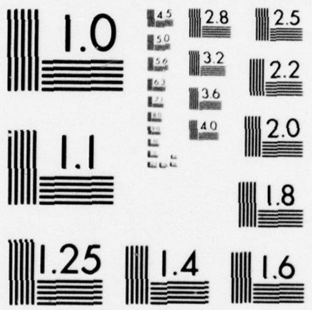


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

S.I. N° 3 - PRE-LOADED SPECIMEN

0.4% INTERFERENCE FIT PIN - PIN LOADED

FIGURE 6

SPECIMEN TYPE 4D 9/32 $d/D = 3/8$

Ref; TABLES 6a, 6b & 6c

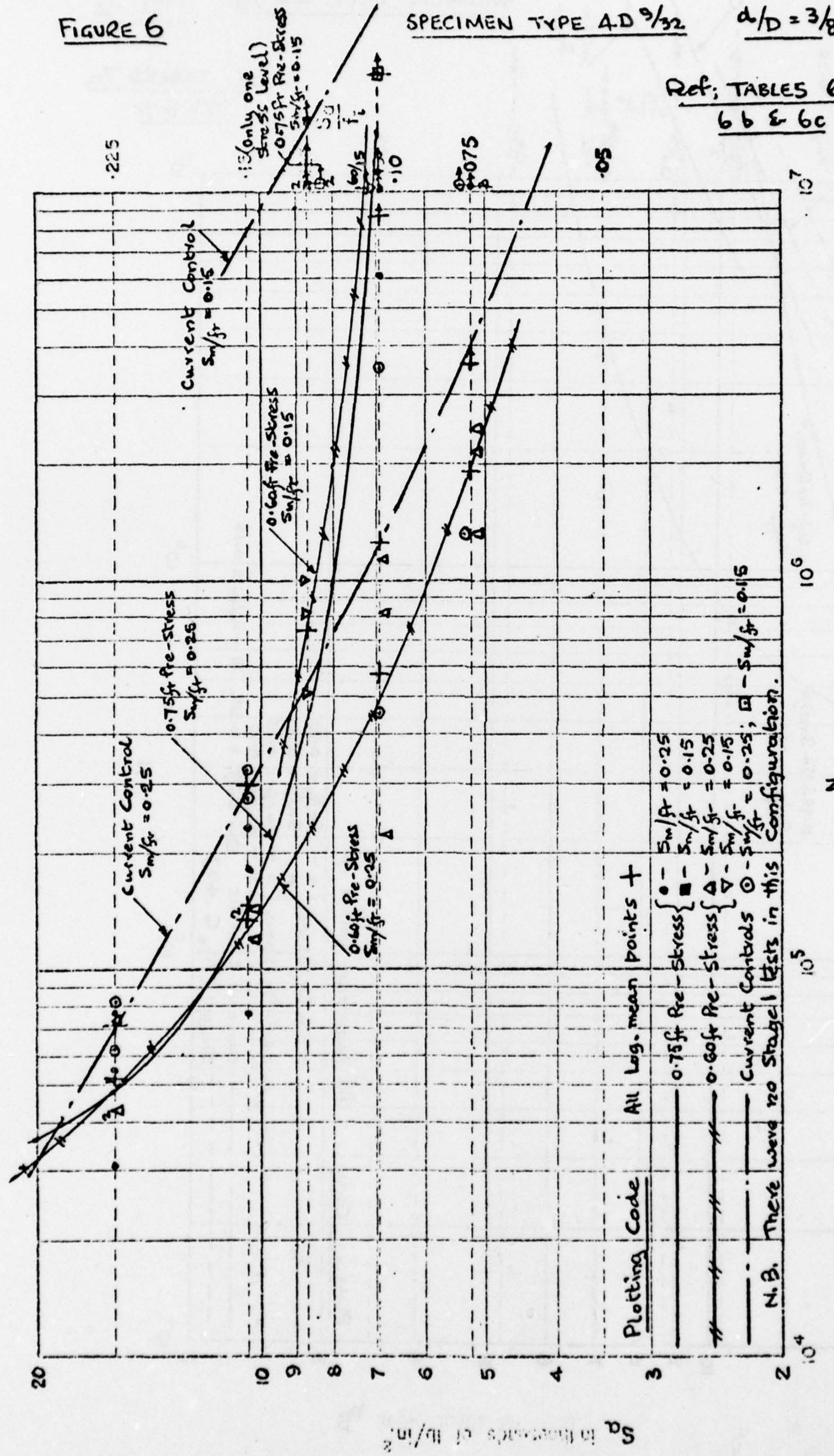


FIGURE 7

S.I. Nº 3 – PRE-LOADED SPECIMEN

0.4% INTERFERENCE FIT AN – PIN LOADED

SPECIMEN TYPE 4D 3/8   d/D = 1/2

Ref. TABLES 7a 7b & 7c

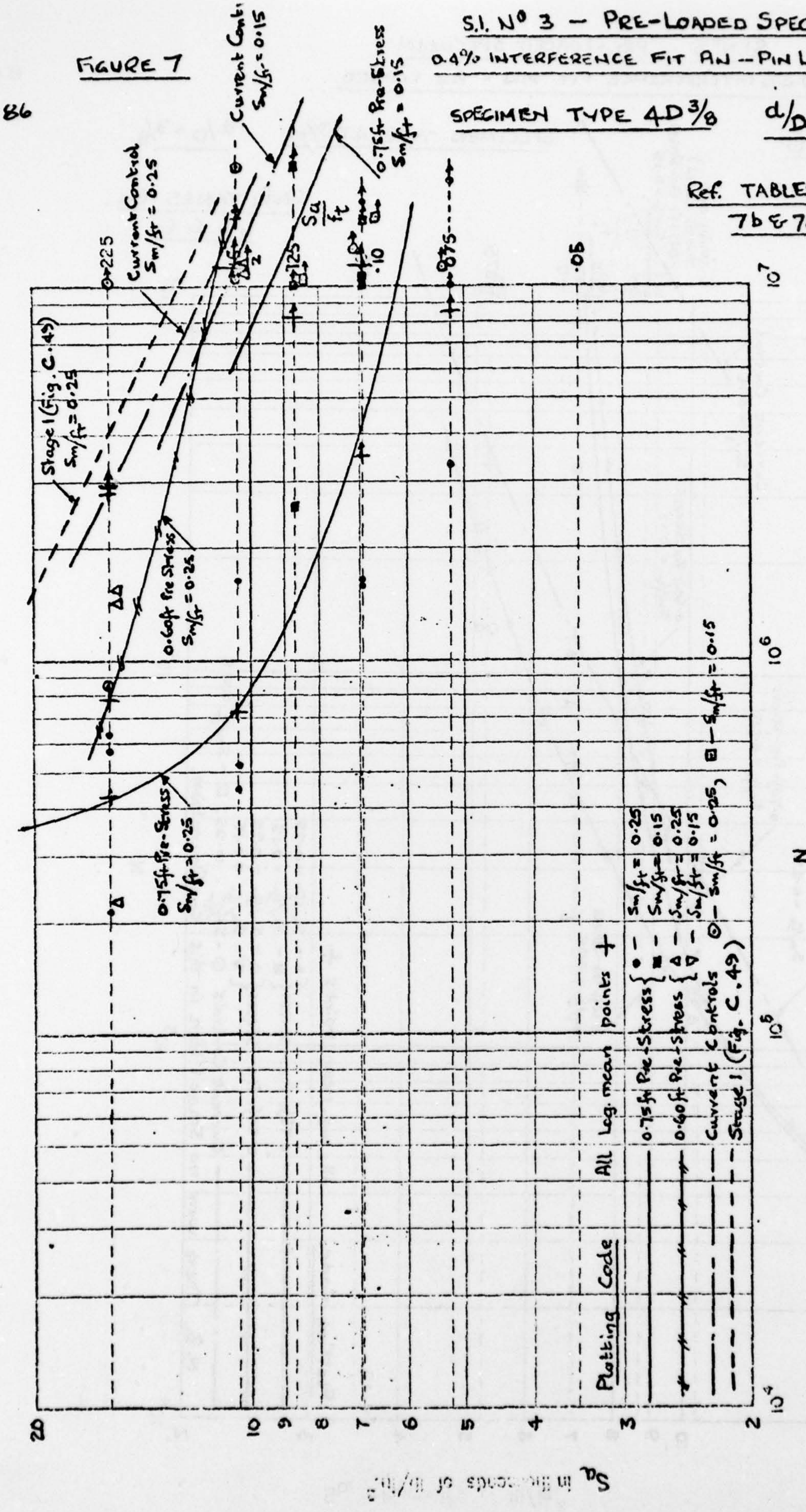


FIGURE 8

S1. Nº 3 – PRE-LOADED SPECIMEN

0.8% INTERFERENCE FIT PIN – PIN LOADED

SPECIMEN TYPE 4 B 3/16 d/D = 1/4

Ref. TABLES 8a
8b & 8c

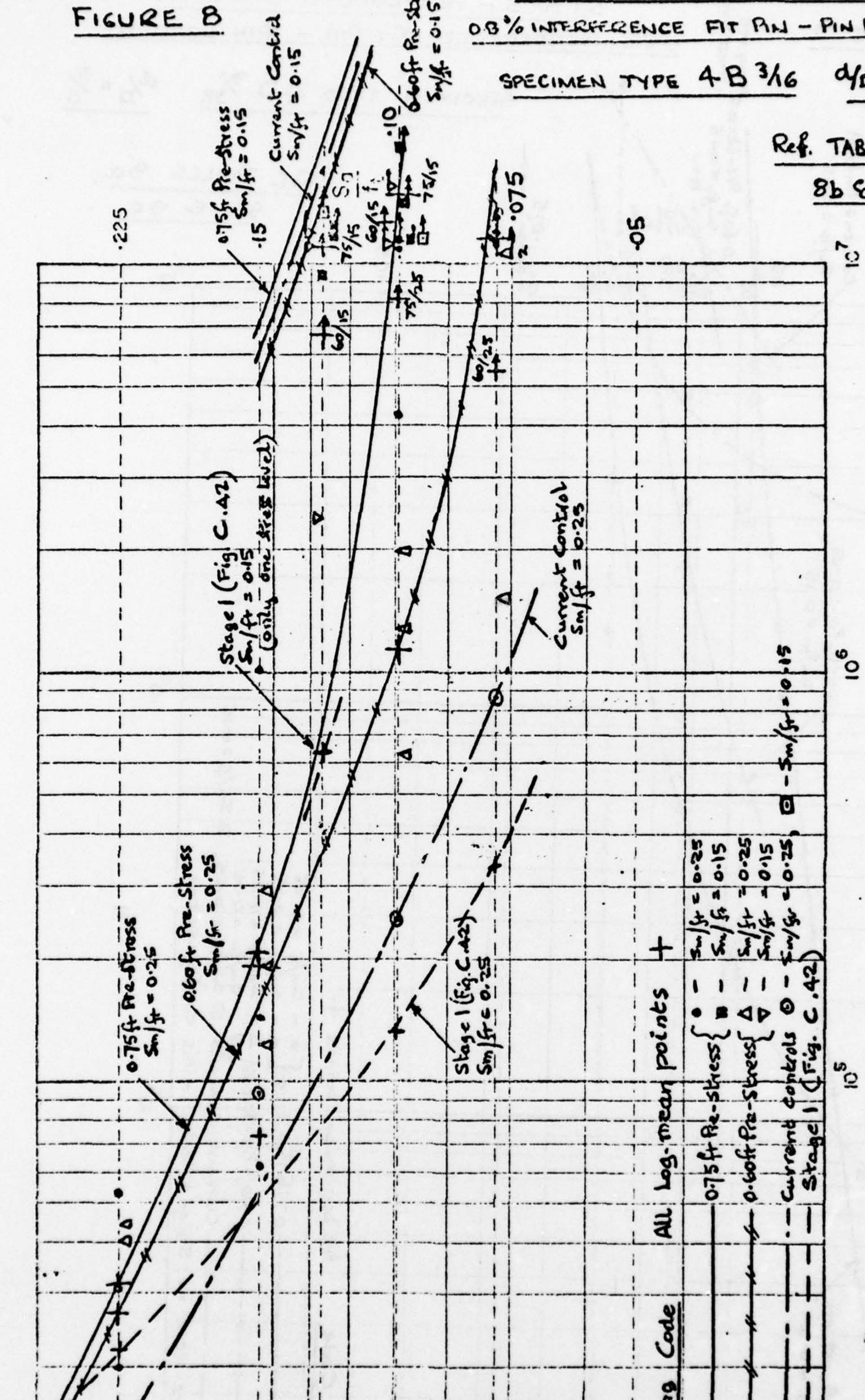


FIGURE 9

S.I. No 3 – PRE-LOADED SPECIMEN

0.8% INTERFERENCE FIT PIN – PIN LOADED

88

SPECIMEN TYPE 4D 9/32 $d/D = 3/8$

Ref. TABLES 9a, 9b & 9c

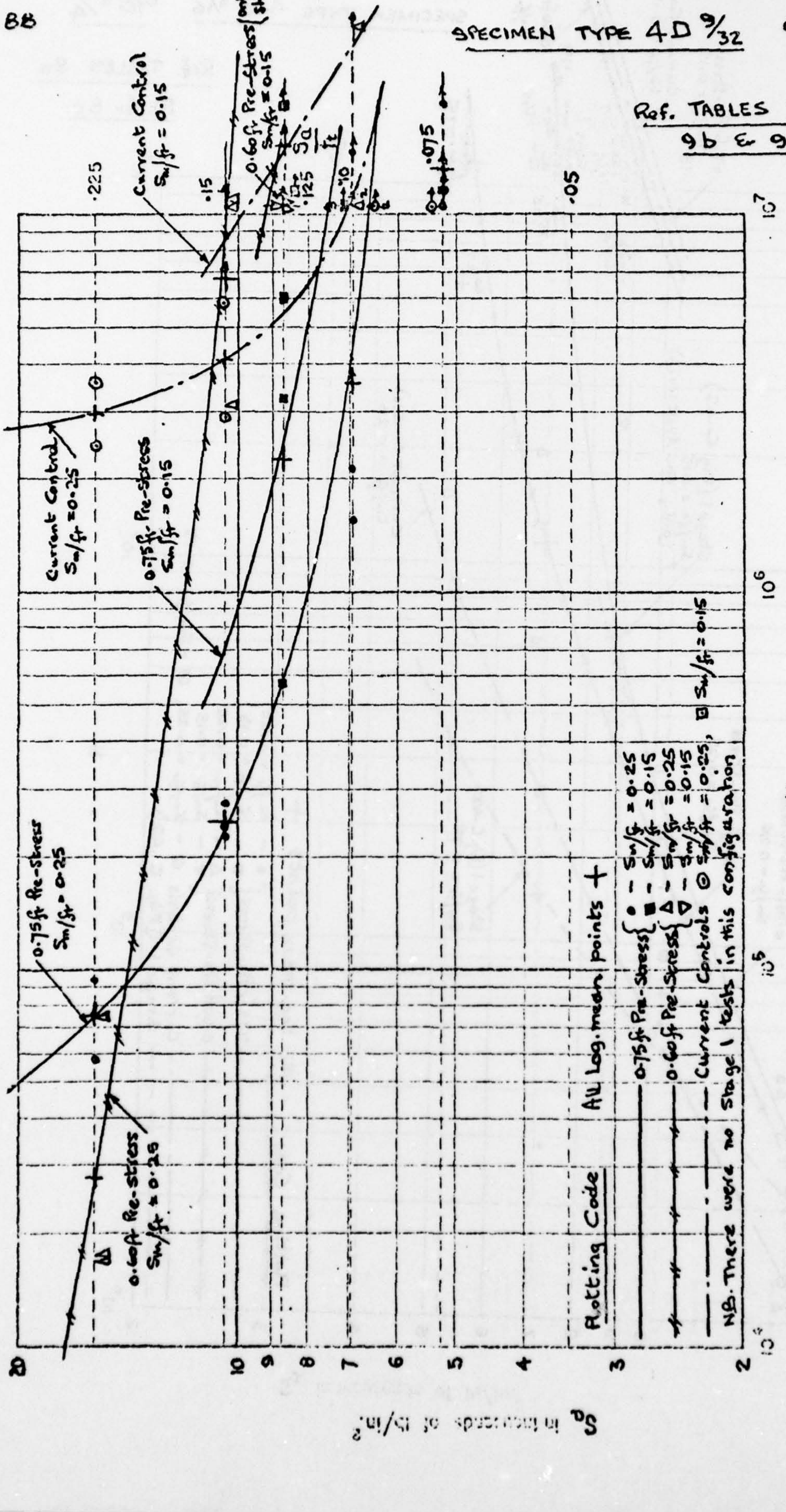


FIGURE 10

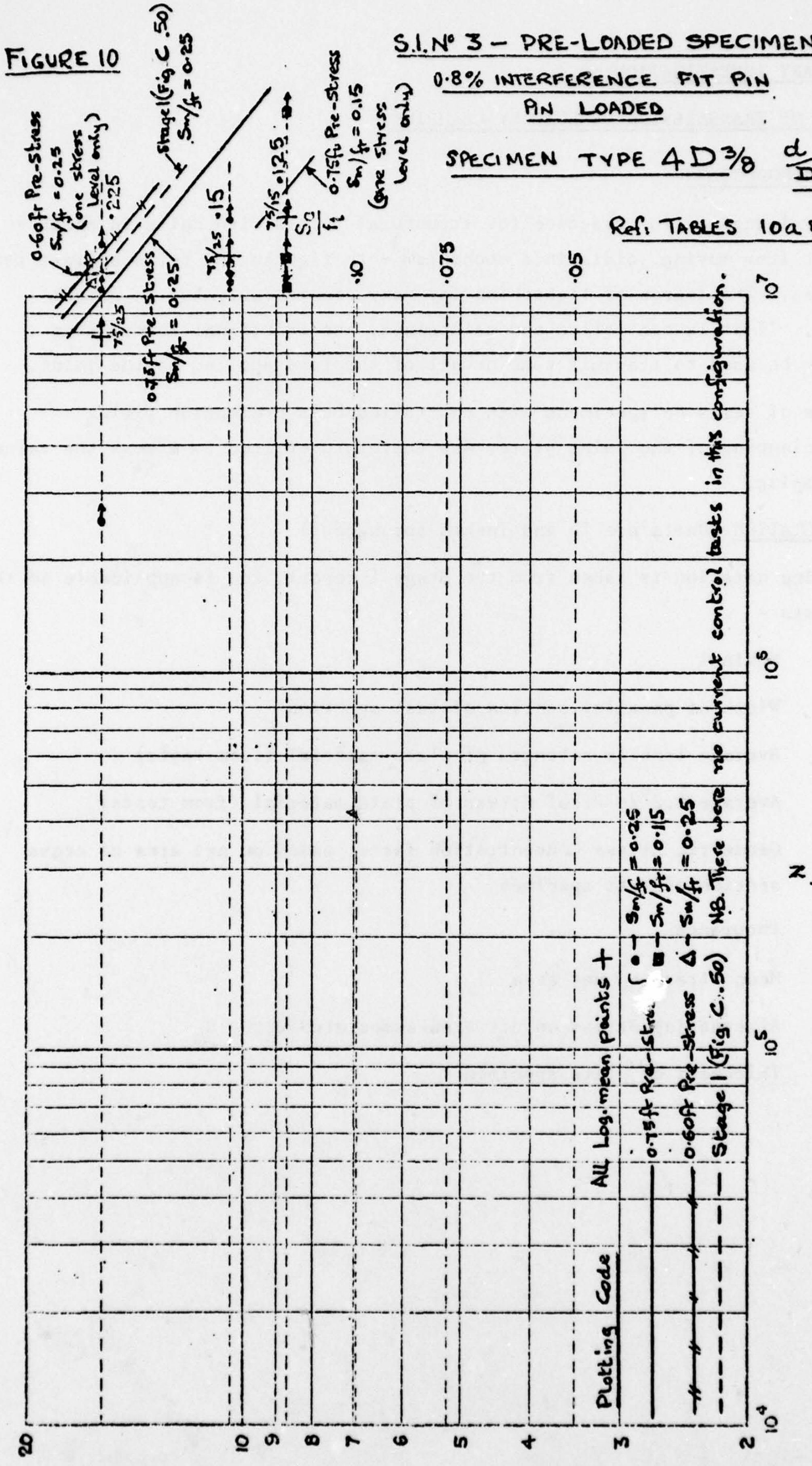
S.I. Nº 3 – PRE-LOADED SPECIMEN

0.8% INTERFERENCE FIT PIN

PIN LOADED

SPECIMEN TYPE 4D3/8 $\frac{d}{D} = \frac{1}{2}$

Ref: TABLES 10a & 10b



SUPPLEMENTARY INVESTIGATION No.4

THE EFFECT OF TRANSMISSION OF LOAD BY CLAMPING

1. INTRODUCTION

It is general engineering practice for structural joints with bolts in shear - as distinct from moving joints in a mechanism - to tighten the bolts against the joint plates. The degree of tightening may vary considerably but is seldom negligible. If it is controlled and maintained, the frictional forces thus created may be used to transmit some or all of the load applied to the joint.

A programme of tests on specimens with controlled bolt pretension giving resultant clamping of the joint plates was therefore evolved to assess the value of the clamping.

2. NOTATION (Units are lb and inches throughout)

The following notation is taken from the Stage 1 report, and is applicable to the present tests -

d = Nominal

D = Width of parallel section of test specimen

f_t = Average Tensile strength of plate material (from tests)

f_p = Average $0.2^{o}/o$ Proof Stress of plate material (from tests)

K'_t = Geometric Stress Concentration factor based on net area of cross section of test specimen

N = Endurance

S_m = Mean Stress on net area

S_a = Alternating Stress on net area associated with S_m

t = Thickness of plate specimen

3. THE TEST PROGRAMME

3.1 Test Specimens

The loaded pin form of joint was chosen, using the shapes of the large type "B" test specimen of Stage 1, but with rounded ends. For details of the test specimens see Figure 1 of this report. Only one nominal size of pin hole was chosen, namely 3/4 in diameter, leading to $d/D = 3/8$ for all tests. The material of the plates was aluminium alloy to British Standard Specification L71, as before, but not from the same batch of material as that used for all the Stage 1 tests. A 3/4 in diameter B.S. S96 steel bolt was used instead of a plain pin as in Stage 1, and with a standard mild steel washer in most cases, but in a few tests a specially designed washer was used, with a $1\frac{1}{4}$ in diameter counterbore on the faying surface (See Figure 1). The choice of a relatively large bolt was made to ensure an adequate clamping pressure, and the special washer to increase further the clamping area.

3.2 Bolt Pre-tension

Three groups of similar specimens were made, each group having a different degree of bolt pre-tension. The values chosen were $70^{o}/o$, $85^{o}/o$ and $100^{o}/o$ of the $0.2^{o}/o$ proof strength of the bolt giving clamping loads of 29 600 lb, 36 000 lb and 42 300 lb respectively. For convenience in this report reference is generally made to the percentage bolt pre-tensions rather than to the actual clamping loads. Some initial tests were made with a bolt pre-tension to only $40^{o}/o$ of the bolt proof strength, but joint slip occurred at a very early stage and so the minimum bolt pre-tension was raised to $70^{o}/o$ for the main programme. (For further comment see paragraph 5.2).

The prescribed amounts of bolt pre-tension were controlled by micrometer measurements of bolt extension, to pre-determined values obtained from appropriate stress-strain curves, derived from actual tests on nominally identical bolt assemblies - see Appendix to this report. This procedure was considered to be more accurate than that of inferring bolt tensions from applied bolt torque readings. However, the latter method can be used if preferred and Data Item 72022 gives relevant information.

3.3 Bolt Fit

The bolts were made to a tolerance of $\begin{matrix}-0.0002 \text{ in} \\ -0.0007 \text{ in}\end{matrix}$

The majority of specimens were manufactured with a push fit, the hole diameter being 0.75 in $\begin{matrix}+0.0007 \text{ in} \\ -0.0005 \text{ in}\end{matrix}$ but a few specimens were made with a large clearance fit, the hole diameter being 0.8125 in, i.e. 0.0625 in nominal clearance on diameter. Care was taken during assembly by means of a jig to ensure that the bolt was concentric with the hole in the plate.

For comparison, it may be noted that in Stage 1 of this research the push fit tolerances were achieved by selective assembly to a standard of ±0.0003 in, and the clearance fit specimens were to a standard of $^{+0.004 \text{ in}}_{+0.006 \text{ in}}$.

3.4 Assembly Treatment

All specimens in Stage 1 were protected from corrosion during pre-assembly storage by a strippable lacquer and then wrapped in brown paper, but on assembly these were removed and replaced, prior to testing, by a thin coat of lanolin grease.

The specimens used in the present investigation were manufactured, assembled and tested under laboratory conditions without a time interval for storage. As far as can be ascertained they were all degreased before assembly and then subjected to one of the following treatments -

(a) left dry,

(b) assembled with lanolin grease,

(c) assembled with "Thiokol" tank sealant between mating surfaces, and then painted overall with "Thiokol" after assembly, or

(d) assembled with "Duralac" primer between mating surfaces, and then painted overall to standard aircraft requirements after assembly.

3.5 Test Programme and Stress Levels

The tests were carried out by Messrs Short Brothers and Harland, Belfast, using a 20 ton Avery Schenck Fatigue testing machine, and testing at 2000 c.p.m.

Only one level of mean stress was employed, namely 14 000 lb/in^2, (earlier tests at S_m = 12 000 lb/in^2 had indicated that endurances would be beyond 10^7 cycles in far too many cases). Alternating stresses ranged from 11 000 lb/in^2 down to 4 000 lb/in^2.

In general only two specimens per combination of stress level, treatment and configuration were tested, as it was hoped that the variation in assembly treatment would have a much smaller effect on endurance than would the main feature of the tests, namely clamping by means of bolt pre-tension. The results proved this to be so. All the important variants of the programme are summarised in Table 1.

It may be noted that in the absence of a control test result on the particular batch of L71 plate used for these tests, it is not unreasonable for purposes of comparison with Stage 1 to assume that the value of f_t for the plate is the same as the average value used for the Stage 1 material, namely 69 400 lb/in^2. This leads to the following values of S_m/f_t and S_a/f_t (to the nearest 0.005).

S_m = 14 000 lb/in^2 (for all tests)

S_m/f_t = 14 000/69 400 = 0.20 approximately

S_a = 11 000 lb/in^2 S_a/f_t = 0.160

S_a = 10 000 lb/in^2 S_a/f_t = 0.145

S_a = 9 000 lb/in^2 S_a/f_t = 0.130

S_a = 8 000 lb/in^2 S_a/f_t = 0.115

S_a = 7 000 lb/in^2 S_a/f_t = 0.100

S_a = 6 000 lb/in^2 S_a/f_t = 0.085

S_a = 5 000 lb/in^2 S_a/f_t = 0.070

S_a = 4 000 lb/in^2 S_a/f_t = 0.060

4. RESULTS

4.1 The Tables

Tables 2, 3 and 4 present all the resulting endurances for tests on specimens with bolt pre-tensions of 70^{o}/o, 85^{o}/o and 100^{o}/o bolt proof strength respectively. Within each table they are arranged in the same order of configuration as listed in Table 1. It should be noted that it is only in the group at 70^{o}/o bolt pre-tension that specimens were tested in the two configurations, numbers 5 and 8, i.e. Type 65004, push fit pin, and Type 65006, clearance fit pin, both assembled with Duralac, and the special washers. The tests in these two configurations were added at a late stage in the programme to augment the data already received.

In the majority of tests, the specimens failed through the section at the bolt hole. Where this was not so, appropriate footnotes have been added to the tables.

4.2 The Figures

Graphical presentations of the results are given on the following figures.

Figure 2a shows the results of all the tests on specimens with push fit pins and 70^{o}/o bolt pre-tension, while Figure 2b shows the results for all the specimens with clearance fit pin and 70^{o}/o bolt pre-tension (Reference Table 2).

Figure 3a and 3b present similarly the results of all the tests on specimens with 85^{o}/o bolt pre-tension (Reference Table 3).

Figures 4a and 4b present the results of all the tests on specimens with 100^{o}/o bolt pre-tension (Reference Table 4).

In addition, each figure shows the relevant endurance curves from Stage 1 for $S_m/f_t = 0.15$ for both push fit pin, pin loaded and for $0.4^o/o$ interference fit pin, pin loaded, in order that comparisons may be made with the present tests at $S_m/f_t = 0.20$ (see Stage 1, Appendix C, Figures C.11 and C.12).

Figures 5a, 5b and 5c give re-arranged presentations of all endurance curves for this supplementary investigation, in order to facilitate a better appreciation of the relative merits of the three degrees of bolt pre-tension and also of the other variants included in the investigation. The choice of grouping of the curves in these last three figures has been governed entirely by considerations of clarity of presentation. Curves are identified by the number of the configuration coupled with the percentage bolt pre-tension, e.g. 4/100 represents configuration No.4 with $100^o/o$ bolt pre-tension, and configuration No.4 is for specimen type 65004 assembled with Duralac with a push fit pin and standard washer.

4.3 Examination of Specimens

A selected number of specimens were dismantled and examined in detail in order to determine the extent and location of fretting, the condition of the Duralac where applied, and to consider the influence of these features on the endurances achieved.

Tables 6a, 6b and 6c record the evidence so found from specimens with $70^o/o$, $85^o/o$ and $100^o/o$ bolt pre-tension respectively.

Table 7 summarises the mean endurances for the various groups of these specimens which were examined, and quotes ratios of mean endurance for comparisons between different treatments, pin fits and degrees of clamping.

5. DISCUSSION OF RESULTS

5.1 General Observations

A broad study of Figures 2a to 4b inclusive shows that there are quite a number of test specimens which were unbroken at 10^7 cycles. This has led to a little difficulty in drawing accurate endurance curves in some instances. It may be that the optimum choice of mean stress for this limited investigation should have been 0.25 f_t i.e. 17 400 lb/in^2. On the other hand, the modern requirement for long fatigue lives leads to lower design stresses than hitherto and 0.20 f_t or 14 000 lb/in^2 mean stress is not uncommon, for L71 material. However, experience and a uniform standard of judgement has produced a reasonable set of endurance curves for the test loadings.

The most important observation is that, whatever the degree of bolt pre-tension (within the range considered) and whatever the assembly treatment, all the results of these tests yield endurances very much greater than those for specimens with unclamped push fit pins under the same loading, and still significantly greater than the corresponding 0.4°/o interference fit pin configuration. It would appear therefore that a comparative cost effectiveness exercise, including the checking and maintaining of the bolt pre-tensions, is justified before resorting to interference fit pins in multi-bolted joints, with a high degree of load transmission. It is realised of course that the majority of all structural joints automatically incorporate some bolt tightening, but the resulting clamping effect cannot be relied upon unless the degree of bolt tightening is adequate and is controlled and recorded, and then subjected to subsequent periodic checks.

Notwithstanding the above remarks, there are noticeable differences between the endurances resulting from the three degrees of clamping and also from the other variants, and all of these will be considered first, after which a more detailed comparison will be made between the endurances for the clamped specimens with the bolts at 70°/o bolt pre-tension and the Stage 1 push fit and interference fit joints.

5.2 Degree of Clamping (As indicated by bolt pre-tension, Reference Figures 5a, 5b and 5c)

Each curve presents the mean endurances over a range of alternating stresses for a particular configuration at a stated degree of clamping and the effect of the variation of this clamping is best described by the relative positions and slopes of the endurance curves. To this end the following tabular statement is given. The two columns of comments describe the changes due to increasing the bolt pre-tension from 70°/o to 85°/o and from 85°/o to 100°/o.

Increase of slope is clearly not favourable and probably indicates excessive fretting.

Bolt Pre-tension ⟶ Configuration Number ↓	70°/o		85°/o		100°/o
1		No significant change		No significant change	
2		Small reduction of slope		Significant increase of endurance	
3		Small reduction of slope		Significant increase of slope	
4		Small reduction of endurance		Significant increase of endurance as S_a decreases	
6		Significant increase of slope		Return to order of endurance for 70°/o bolt pre-tension	
7		No significant change		No significant change	

NB

There are insufficient data for configurations Nos. 5 and 8 to enable similar comments to be made.

Reviewing the foregoing observations, it would appear that for this limited range of tests, specimens with a clamping load equivalent to a 70°/o bolt pre-tension generally gave better results than those with either 85°/o or 100°/o. Nevertheless, it is logical to assume that the clamping effect depends upon other factors besides bolt pre-tension, e.g. coefficient of friction, surface finish or treatment, bolt head and/or washer size, and upon plate and washer stiffnesses. Moreover only a few preliminary tests were made with bolt pre-tensions less than 70°/o bolt proof strength and although 40°/o proved to be too low it could be that (say) 60°/o would have proved in these tests to have been optimum. It should be noted that the application of 100°/o bolt pre-tension proved in practice to be extremely difficult to achieve.

Therefore the present test programme should not be regarded as a general indication of the behaviour of all types of bolted joints, and in a particular application one would be advised to explore a range of clamping loads, and variations of other physical characteristics such as those noted above, before finalising on the solution of the problem.

5.3 Assembly Treatment (Reference Figures 2a, 3a and 4a)

The relative merits of the four assembly treatments are shown in these three figures for each of the three bolt pre-tensions

Curves 1 - Dry
Curves 2 - Grease to DTD 825
Curves 3 - Thiokol fuel tank sealant to DTD 900/4610
Curves 4 - Duralac to DTD 369 and painted to DTD 5555 overall

For these four configurations all other variables have been kept constant, (e.g. all are push fit with standard washers).

It is clear that Configuration No.4 - Duralac assembly and painted overall - is superior to all the others tested, and consistently so for all three degrees of bolt tension. There is a slight element of uncertainty in regard to specimens assembled with Thiokol, partly because none were tested at alternating stresses above 8 000 lb/in^2 and partly because practically all unbroken specimens were not tested beyond 10^7 cycles. Nevertheless, there does seem to be sufficient evidence to support the apparent greater slope of the endurance curves for this treatment, and therefore it must be regarded as slightly inferior at low alternating stresses.

The greased specimens are generally slightly better, in terms of endurance, than the dry ones, possibly because of reduced fretting in the former. On the other hand the greased specimens in general have endurances somewhat less than those assembled with Duralac. Clearly, the greased specimens would in practice require constant maintenance attention or they would soon degenerate to the standard of the dry specimens and become increasingly susceptible to corrosion. In any case it is far more satisfactory to assemble with Duralac or an equivalent primer which meets the requirements of DTD 369, and contributes considerably to the prevention of corrosion.

5.4 Choice of Washer

5.4.1 With Push Fit Pin (Reference Figure 2a)

There is one stress level at which this comparison was made, namely 14 000 $\pm$10 000 lb/in^2 for configurations 4 and 5, but only at 70^o/o bolt pre-tension. Both groups of specimens were assembled with Duralac. The improvement in endurance for fitment of the special washer at this stress level was in the ratio of about 2:1.

Alternatively for a constant endurance the alternating stress can be increased by about 15^o/o.

5.4.2 With Clearance Fit Pin (Reference Figures 2b, 3b and 4b)

There is more evidence of the effect of fitting the special washer in this case, via configurations 6 and 7 which were for dry specimens but tested at all three degrees of bolt tension. The improvement achieved for fitment of the special washer was consistently good at all three degrees of bolt pre-tension.

Evaluating average endurances over the range of $S_a = 10\ 000\ lb/in^2$ to $8\ 000\ lb/in^2$ it can be said that the fitment of the special washer, with a clearance fit pin, leads to an improvement of from 4.1 to 8.1 on endurance at a given stress, the ratios tending to increase with decrease of alternating stress.

Alternatively, expressed as a improvement of permissible S_a for a given endurance, the improvement for fitment of the special washer ranges from 1.2 to 1.5 at S_a of the order of $10\ 000\ lb/in^2$, to from 1.3 to 1.75 at S_a of the order of $8\ 000\ lb/in^2$.

Thus in special cases the extra cost of a specifically designed counterbored washer is justified, particularly in conjunction with clearance fit pins.

5.5 Comparison of Pin Fits (Figures 2a and 4b inclusive)

5.5.1 With Dry Assembly and Standard Washer

Configurations 6 and 1 at all three levels of bolt pre-tension provide a reasonable amount of data for a comparison to be made.

From Figures 2a and 2b (70^o/o bolt pre-tension) the clearance fit produces marginally greater endurances than the push fit over the whole range of alternating stresses tested.

From Figures 3a and 3b (85^o/o bolt pre-tension) the clearance fit is somewhat superior in endurance above $S_a = 8\ 000\ lb/in^2$ but inferior below $8\ 000\ lb/in^2$ due to the steepness of curve 6.

From Figures 4a and 4b (100^o/o bolt pre-tension) the clearance fit is approximately equal or marginally inferior in endurance compared with the push fit pin.

Bearing in mind the scatter of results it cannot be claimed that the standard of pin fit makes a significant difference to the resulting endurances, when used with a standard washer and dry assembly.

5.5.2 With Duralac Assembly and Special Washers

The special counterbored washers were introduced into the test programme in order to ensure maximum load transmission due to clamping when a clearance fit pin was employed. Unfortunately there are only two sets of results in this configuration which enable a comparison of pin fits to be made i.e. Configurations 5 and 8 at 70^o/o bolt pre-tension. (Figures 2a and 2b).

The clearance fit mean endurance (at 10 000 lb/in^2 alternating stress) is 40^o/o greater than that for the push fit pin. Bearing in mind the inherent scatter present, this is not a large increase but could be worth while in special cases. In general therefore, the fit of the bolt does not have a significant influence upon the endurance, but when combined with a special counterboard washer the clearance fit does give some advantage, presumably due to the greater load that is transmitted by clamping.

5.6 Evidence from Examination of Selected Specimens

Firstly, it was observed that for all the specimens which had been assembled with Duralac, the Duralac was still liquid when the specimens were dismantled. Nevertheless, when the inspection was carried out 7 -8 days later, it was dry and set. The liquid state was reassuring and no doubt due to the efficient overall painting of the joint.

Reviewing the evidence given in Tables 6a, 6b, 6c and 7 leads to the following observations.

(i) There was hardly any fretting in the bore of the bolt holes but some degree of fretting occurred on the faces of almost every specimen examined. The fretting on the specimens treated with Duralac was generally (with one exception) only light to moderate, whereas about one half of the specimens assembled dry showed some heavy fretting. For the Duralac treated specimens the endurances tended to be inversely proportional to the degree and/or extent of the fretting. (Specimens, order numbers 2, 3 and 4, also 8 and 9).

(ii) Several of the specimens did not fail in the test area, but in the region of the grips, or sometimes the primary failure was in one of the side plates, followed by failure of the specimen. In these cases it was observed that the degree of fretting at, or to the rear of the bolt hole, was often light or moderate.

(iii) From the comparisons associated with Table 7 the indications are that in terms of endurance -

(a) Duralac treatment is superior to dry assembly.

(b) When the special washer is used, there is generally not a great deal of difference between the use of a push fit pin and a clearance fit pin, although specimen order number 8 with a clearance fit pin is particularly good.

(c) Other variants being constant, 85°/o bolt pre-tension is inferior to 70°/o bolt pre-tension.

(d) Other variants being constant 100°/o bolt pre-tension is superior to 70°/o bolt pre-tension (but see paragraph 5.2).

In general these latter observations support those already deduced from the tables and graphs of the full results.

5.7 General Comparisons between Clamped and Unclamped Joints (Figures 2a and 2b)

Having discussed the comparatively moderate differences between one configuration and another (all the clamped joints) it is appropriate to return to the earlier observation of paragraph 5.1, namely that all the clamped joints are significantly superior in endurance to those which are not clamped, such as are tested in Stage 1 of this research, for it will be remembered, all Stage 1 specimens were assembled with plain pins so that there could be no clamping.

There is more evidence available in this investigation for specimens with a clamping load equivalent to a pre-tension of 70°/o of the 0.2°/o bolt proof strength, and therefore this group alone will be analysed.

Table 5 presents comparative endurances for the present clamped specimens, and for those of the corresponding specimens of Stage 1 for loaded push fit pin and for 0.4°/o interference fit pin joint configurations. The Stage 1 endurances are interpolated from the curves given on Figures 2a to 4b inclusive for $S_m = 0.25\ f_t$ and $0.15\ f_t$, since the tests of Supplementary Investigation No.4 were all carried out for $S_m = 14\ 000\ \text{lb/in}^2 = 0.20\ f_t$. The comparisons are made for alternating stresses of 10 000, 8 000 and 6 000 lb/in^2.

The relative magnitude of the improvement in endurance for the clamped joint over the unclamped joint is also given in Table 5 in relation to both the push fit pin and to the 0.4°/o interference fit pin specimens of Stage 1. The improvement is expressed as an "Endurance Increase Ratio" which may be defined as the ratio of:-

$$\frac{\text{Endurance of clamped joint}}{\text{Endurance of Unclamped Joint}}$$

When compared with Stage 1 push fit pin specimens (greased), the endurance increase ratio for dry clamped joints ranges from about 9 at 10 000 lb/in^2 alternating stress to about 150 at 6 000 lb/in^2, but if the clamped joint is given special assembly treatment, such as Duralac, and painted overall, the endurance increase ratio ranges from the order of 40 at $S_a = 10\ 000\ \text{lb/in}^2$ to at least 250 at $S_a = 6\ 000\ \text{lb/in}^2$. Further improvements are obtainable if a clearance fit pin combined with a special counterbored washer is used.

Corresponding comparisons, but with a greased 0.4^{o}/o interference fit pin (unclamped) lead to more modest endurance increase ratios of the order of 2.5 at S_a = 10 000 lb/in^2 to about 11.5 at S_a = 6 000 lb/in^2 (dry) but if assembled with Duralac and painted overall, these ratios reach the order of at least 10 at S_a = 10 000 lb/in^2 and approximately 20 at S_a = 6 000 lb/in^2. Again, if a clearance fit pin combined with a special counterbored washer is used still further improvement in endurance is achieved.

6. CONCLUSION

The scope of the test programme reported herein is somewhat limited, but it would appear that large increases of endurance are obtainable if controlled joint clamping by means of bolt pre-tensioning is employed. The actual endurance increase ratios obtained vary considerably with the magnitude of the applied alternating stress, being greatest for low alternating stresses (order of 6 000 lb/in^2 and under) and least for high alternating stresses (order of 10 000 lb/in^2 or more). Some additional endurance may be achieved by the use of a special counterbored washer, combined with a clearance fit bolt. (See paragraph 5.7 and Table 5).

The use of Duralac to DTD 369 followed by painting overall gave the greatest endurance of all the assembly treatments tested in this investigation. Thiokol fuel tank sealant came next in order, with grease somewhat below this and the dry joint lowest of all, other variants being kept constant (see Tables 2 to 4 and Figures 2 to 5).

Where applicable, the detailed examination of selected specimens, following failure, supports the foregoing conclusions (see Tables 6 and 7).

In regard to the degree of clamping, the evidence of this test programme suggests that clamping to the equivalent of a bolt pre-tension of 70^{o}/o of the 0.2^{o}/o proof strength of the bolt was preferable to either 85^{o}/o or 100^{o}/o. A few tests with clamping to the equivalent of only 40^{o}/o bolt pre-tension led to excessive slip, but it could be that some value between 40^{o}/o and 70^{o}/o would have proved more advantageous in these particular tests.

The effectiveness of this method of increasing the endurance of a joint is also likely to be dependent upon a number of other features, such as plate and washer stiffness, bolt head and washer size, coefficient of friction and surface treatment. Therefore the present test programme should not be regarded as a general indication of the behaviour of all types of bolted joints, and in a particular application one would be advised to explore a range of clamping loads, and other physical characteristics such as those noted above, before finalising on the solution of the problem. Consideration must also be given to ensuring that the clamping forces are maintained throughout the life of the joint.

SUPPLEMENTARY INVESTIGATION No.4

TABLE 1 DETAILS OF SPECIMEN CONFIGURATIONS AND ASSEMBLY TREATMENTS

Configuration	1	2	3	4	5	6	7	8
Specimen Type	65004	65004	65004	65004	65004	65005	65006	65006
Assembly Treatment	Dry	Grease to D.T.D.825	"Thiokol" Fuel Tank Sealant To D.T.D. 900/4610	Duralac to D.T.D.369 and painted to D.T.D.5555 overall	Duralac to D.T.D.369 and painted to D.T.D.5555 overall	Dry	Dry	Duralac to D.T.D.369 and painted to D.T.D.5555 overall
Pin Fit	Push Fit	Push Fit	Push Fit	Push Fit	Push Fit	Clearance Fit	Clearance Fit	Clearance Fit
Washer	standard	standard	standard	standard	special	standard	special	special

NB

For details of specimen types and geometry, see Figure 1

SUPPLEMENTARY INVESTIGATION No.4

TABLE 2 ENDURANCES AT 70°/o BOLT PRE-TENSION FOR ALL TYPES OF SPECIMEN

Reference Figure 2a

All at Mean Stress, $S_m = 14\ 000\ \text{lb/in}^2$ (= 0.20 f_t)

Specimen Identity	Alternating Stress $\pm S_a$ lb/in^2	Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
1. Type 65004 - Dry, Push Fit Pin, Standard Washer				
×28.5.C	8 000	1 671 600	6.222	1 568 000
28.5.A	8 000	1 471 500	6.167	
28.7.A	7 000	4 234 100	6.624	4 234 100
28.5.E	6 000	10 000 000U	7.000U	>10 000 000
28.3.B	4 000	10 000 000U	7.000U	>10 000 000
28.5.D	4 000	10 000 000U	7.000U	
2. Type 65004 - Grease, Push Fit Pin, Standard Washer				
45.6.B	8 000	3 615 400	6.558	2 570 000
45.6.C	8 000	1 829 400	6.261	
45.5.D	7 000	8 600 000	6.935	5 866 100
45.6.A	7 000	4 000 700	6.603	
45.5.B	6 000	10 000 000U	7.000U	>10 000 000
45.5.C	6 000	10 000 000U	7.000U	
3. Type 65004 - Thiokol, Push Fit Pin, Standard Washer				
26.4.B	8 000	3 394 300	6.530	3 298 000
26.5.E	8 000	3 173 200	6.500	
26.6.B	6 000	9 285 000	6.966	7 224 000
26.8.E	6 000	5 621 900	6.750	
26.6.C	4 000	10 000 000U	7.000U	>10 000 000
24.7.C	4 000	10 000 000U	7.000U	
4. Type 65004 - Duralac, Push Fit pin, Standard Washer				
43.3.D	10 000	2 412 000	6.381	2 062 000
43.2.D	10 000	1 763 400	6.246	
43.4.B	8 000	7 970 000	6.902	5 883 000
43.4.C	8 000	4 343 000	6.637	
43.4.A	6 000	10 000 000U	7.000U	>10 000 000
43.3.A	6 000	10 000 000U	7.000U	
5. Type 65004 - Duralac, Push Fit Pin, Special Washer				
×45.8.D	10 000	6 440 800$^+$	6.809$^+$	4 367 200
×28.9.B	10 000	3 948 600SJ	6.597SJ	
×28.8.D	10 000	3 274 900SJ	6.515SJ	

(Table 2 continued on next page)

U -	denotes unbroken
+	specimen failed from fretted area
S	one side plate failed from fretted area
×	specimen dismantled and examined after failure
J	specimen failed in grip area

SUPPLEMENTARY INVESTIGATION No.4

TABLE 2 (cont.) ENDURANCES AT 70°/o BOLT PRE-TENSION FOR ALL TYPES OF SPECIMEN

Reference Figure 2

All at Mean Stress, $S_m = 14\ 000\ \mathrm{lb/in}^2 = 0.20\ f_t$

Specimen Identity	Alternating Stress $\pm S_a$ lb/in^2	Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
6. Type 65005 - Dry, Clearance Fit Pin, Standard Washer				
46.1.C	8 000	2 657 000	6.426	2 418 000
46.2.B	8 000	2 185 000	6.339	
46.2.A	6 000	10 000 000U	7.000U	>10 000 000
46.1.D	4 000	10 000 000U	7.000U	>10 000 000
46.1.B	4 000	10 000 000U	7.000U	
7. Type 65006 - Dry, Clearance Fit Pin, Special Washer				
×46.6.B	11 000	2 513 300ϕ_1	6.400ϕ_1	2 513 300
×46.5.C	10 000	5 370 000	6.730	2 950 000
×46.6.A	10 000	3 175 000SU	6.500SU	
×46.7.A	10 000	1 511 200J	6.178J	
46.5.D	8 000	10 000 000U	7.000U	>10 000 000
46.6.C	8 000	10 000 000U	7.000U	
8. Type 65006 - Duralac, Clearance Fit Pin, Special Washer				
44.6.B	10 000	12 257 900Uϕ_2	7.088Uϕ_2	>6 120 000
×44.6.C	10 000	7 792 900Sϕ_3^2J	6.890Sϕ_3^2J	
×44.6.D	10 000	2 397 900Fϕ_4	6.379Fϕ_4	

U	denotes unbroken
S	denotes specimen failure in the sideplates
ϕ_1	denotes slipping occurred at 811 300 cycles
ϕ_2	slipped after 2 242 300 cycles
ϕ_3	slipped after 3 160 000 cycles
ϕ_4	slipping occurred during first few minutes
F	Fretting occurred at point of failure
×	Specimen dismantled and examined after failure
J	Specimen failed in grip area

SUPPLEMENTARY INVESTIGATION No.4

TABLE 3 ENDURANCES AT 85^{o}/o BOLT PRE-TENSION FOR ALL TYPES OF SPECIMEN

Reference Figure 3a

All at Mean Stress $S_m = 14\ 000$ lb/in^2

Specimen Identity	Alternating Stress $\pm S_a$ lb/in^2	Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
1. Type 65004 - Dry, Push Fit Pin, Standard Washer				
28.2.E	8 000	4 139 000	6.616	3 155 000
28.1.D	8 000	2 411 000	6.382	
28.1.E	7 000	2 693 400	6.430	2 693 400
28.1.C	6 000	10 000 000U	7.000U	>10 000 000
2. Type 65004 - Grease, Push Fit Pin, Standard Washer				
45.3.B	8 000	1 851 000	6.267	1 609 100
45.4.D	8 000	1 732 000	6.239	
45.2.C	8 000	1 299 200	6.114	
45.5.A	7 000	10 000 000U	7.000U	>10 000 000
45.4.B	7 000	10 000 000U	7.000U	
45.4.C	6 000	10 000 000U	7.000U	>10 000 000
3. Type 65004 - Thiokol, Push Fit Pin, Standard Washer				
24.3.C	8 000	3 099 700	6.490	2 861 000
24.3.D	8 000	2 647 100	6.422	
24.1.D	6 000	9 499 800	6.977	5 184 500
26.2.E	6 000	2 828 800	6.452	
24.3.A	4 000	10 000 000U	7.000U	>10 000 000
26.7.C	4 000	10 000 000U	7.000U	
4. Type 65004 - Duralac, Push Fit Pin, Standard Washer				
43.2.A	10 000	1 508 600	6.179	1 381 000
43.1.D	10 000	1 281 800	6.107	
43.2.C	8 000	4 981 400	6.697	4 948 800
43.2.B	8 000	4 916 800	6.692	
43.1.B	6 000	10 000 000U	7.000U	>10 000 000
43.1.C	6 000	10 000 000U	7.000U	

(Table 3 continued on next page)

U denotes unbroken

NB

There is no specimen No.5 in this group

SUPPLEMENTARY INVESTIGATION No.4

TABLE 3 (Contd.) ENDURANCES AT 85^{o}/o BOLT-TENSION Reference Figure 3b

FOR ALL TYPES OF SPECIMEN

All at Mean Stress $S_m = 14\ 000\ \text{lb/in}^2 = 0.20\ f_t$

Specimen Identity	Alternating Stress $\pm S_a$ lb/in^2	Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
6. Type 65007 - Dry, Clearance Fit Pin, Standard Washer				
27.1.E	8 000	3 165 000	6.500	2 969 000
27.2.B	8 000	2 786 400	6.443	
27.1.C	6 000	7 983 400	6.901	6 216 000
27.1.B	6 000	4 841 700	6.685	
27.2.C	4 000	10 000 000U	7.000U	>10 000 000
7. Type 65006 - Dry, Clearance Fit Pin, Special Washer				
×46.4.B	10 000	10 000 000U	7.000U	>4 650 000
×46.4.C	10 000	2 170 800S	6.335S	
×46.5.A	9 000	4 466 600B	6.650B	3 474 700
×46.5.B	9 000	2 703 000A	6.430A	
46.4.D	8 000	10 000 000U	7.000U	>8 570 000
46.4.A	8 000	7 308 300	6.864	

U	denotes unbroken
S	denotes primary failure through one side plate and secondary failure through three joint plates
A	denotes specimen cracked through three joint plates
B	denotes failure in specimen one inch from centre of hole
×	Specimen dismantled and examined after failure

NB

There is no specimen No.8 in this group

SUPPLEMENTARY INVESTIGATION No.4

TABLE 4 ENDURANCES AT 100^{o}/o BOLT PRE-TENSION FOR ALL TYPES OF SPECIMEN

Reference Figure 4a

All at Mean Stress S_m = 14 000 lb/in^2 = 0.20 f_t

Specimen Identity	Alternating Stress $\pm S_a$ lb/in^2	Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
1. Type 65004 - Dry, Push Fit Pin, Standard Washer				
28.8.B	8 000	2 206 500	6.344	2 015 000
28.8.C	8 000	1 839 100	6.264	
×28.7.C	7 000	8 345 400A	6.921A	6 324 000
×28.7.D	7 000	4 792 800A	6.675A	
28.8.A	6 000	10 000 000U	7.000U	>11 550 000
28.7.E	6 000	13 248 800AB	7.122AB	
2. Type 65004 - Grease, Push Fit Pin, Standard Washer				
45.7.D	10 000	1 388 200	6.143	1 104 500
45.6.D	10 000	878 600	5.944	
45.7.A	9 000	1 753 900	6.243	1 590 600
45.7.B	9 000	1 442 600	6.160	
45.8.B	8 000	10 000 000U	7.000U	>10 000 000
45.8.C	7 000	10 000 000U	7.000U	>10 000 000
3. Type 65004 - Thiokol, Push Fit Pin, Standard Washer				
26.9.D	8 000	4 233 900	6.626	3 795 000
26.2.D	8 000	3 417 600	6.533	
42.6.D	6 000	8 617 100	6.936	6 768 700
27.9.D	6 000	5 318 000	6.726	
26.9.E	4 000	10 000 000U	7.000U	>10 000 000
26.4.D	4 000	10 000 000U	7.000U	
4. Type 65004 - Duralac, Push Fit Pin, Standard Washer				
45.9.D	10 000	3 306 300	6.520	2 183 900
45.1.C	10 000	1 442 800	6.160	
43.4.D	8 000	10 000 000U	7.000U	>8 812 500
45.1.B	8 000	7 765 000	6.880	
45.9.A	6 000	10 000 000U	7.000U	>10 000 000
45.9.C	6 000	10 000 000U	7.000U	

(Table 4 continued on next page)

U denotes unbroken

A denotes specimen cracked through 3 joint plates and both washers

B denotes crack observed at 8 500 000 cycles

NB

There is no specimen No.5 in this group.

× Specimen dismantled and examined after failure

SUPPLEMENTARY INVESTIGATION No.4

TABLE 4 (Contd.) ENDURANCES AT 100°/o BOLT PRE-TENSION FOR ALL TYPES OF SPECIMEN

Reference Figure 4b

All at Mean Stress $S_m = 14\ 000\ \text{lb/in}^2 = 0.20\ f_t$

Specimen Identity	Alternating Stress $\pm S_a$ lb/in^2	Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
6. Type 65005 - Dry, Clearance Fit Pin, Standard Washer				
46.2.D	8 000	1 996 800	6.295	1 788 000
46.2.C	8 000	1 603 300ø	6.205ø	
46.3.D	7 000	8 196 100A	6.912A	4 462 700
46.3.C	7 000	2 430 000	6.385	
46.3.B	6 000	10 000 000U	7.000U	>8 468 000
46.3.A	6 000	7 170 000A	6.855A	
7. Type 65006 - Dry, Clearance Fit, Special Washer				
×46.8.D	10 000	4 240 700A	6.627A	2 779 800
46.8.A	10 000	1 821 000	6.260	
46.7.B	9 000	6 977 000	6.843	6 977 000
46.8.C	8 000	10 000 000U	7.000U	>9 812 800
46.8.B	8 000	9 629 000	6.984	
46.9.B	6 000	10 000 000U	7.000U	>10 000 000

U denotes unbroken

ø denotes slipping at 800 000 cycles and load on specimen required adjustment

A denotes specimen cracked through three joint plates

NB

There is no specimen No.8 in this group.

× Specimen dismantled and examined after failure

SUPPLEMENTARY INVESTIGATION No.4

TABLE 5 COMPARISON OF ENDURANCES - CLAMPED JOINTS (SUPPLEMENTARY INVESTIGATION No.4) v UNCLAMPED JOINTS (STAGE 1)

BOLT PRE-TENSION = 70°/o of 0.2°/o BOLT PROOF STRESS

PIN LOADED

Condition		S_m (lb/in^2)		← 14 000 →		
		S_a (lb/in^2)		10 000	8 000	6 000
Stage 1 Plain Pin UNCLAMPED		Configuration				
		Push Fit Pin Grease	Endurance$^{\phi}$	45 000	65 000	117 000
		0.4°/o Interference Fit Pin Grease	Endurance$^{\phi}$	150 000	320 000	1 550 000
STAGE 2 - S.I. No.4 STANDARD BOLT - CLAMPED	1	Type 65004	Endurance$^{\phi}$	400 000	1 550 000	18 000 000
		Dry *	E.I.R.,P.F.*	8.9	23.8	154
		P.F.Pin,Std.W	E.I.R.,I.F.*	2.65	4.85	11.6
	2	Type 65004	Endurance	650 000	2 550 000	22 500 000
		Grease	E.I.R.,P.F.	14.4	39.3	194
		P.F.Pin,Std.W	E.I.R.,I.F.	4.33	7.95	14.5
	3	Type 65004	Endurance	1 750 000	3 000 000	7 200 000
		Thiokol	E.I.R.,P.F.	38.8	46.2	61.2
		P.F.Pin,Std.W	E.I.R.,I.F.	11.7	9.35	4.65
	4	Type 65004	Endurance	2 000 000	5 600 000	>30 000 000
		Duralac	E.I.R.,P.F.	44.4	86.0	>256
		P.F.Pin,Std.W	E.I.R.,I.F.	13.3	17.5	>19.4
	5	Type 65004	Endurance	4 370 000	-	-
		Duralac	E.I.R.,P.F.	97.0	-	-
		P.F.Pin, Special Washer	E.I.R.,I.F.	29.2	-	-
	6	Type 65005	Endurance	600 000	2 400 000	>30 000 000
		Dry	E.I.R.,P.F.	13.3	37.0	>256
		*C.F.Pin,Std.W	E.I.R.,I.F.	4.0	7.5	>19.4
	7	Type 65006	Endurance	3 550 000	22 500 000	-
		Dry	E.I.R.,P.F.	78.5	346	-
		C.F.Pin, Special Washer	E.I.R.,I.F.	23.6	70	-
	8	Type 65006	Endurance	9 000 000	-	-
		Duralac	E.I.R.,P.F.	200	-	-
		C.F.Pin, Special Washer	E.I.R.,I.F.	60	-	-

Notes

ϕ cycles to failure

* E.I.R. denotes Endurance Increase Ratio

$$= \frac{\text{Endurance of Clamped Joint}}{\text{Endurance of Unclamped Joint}}$$ with respect to P.F. Pin or to I.F. Pin

P.F. Push Fit
I.F. 0.4°/o Interference Fit
C.F. Clearance Fit
Std.W. Standard Washer

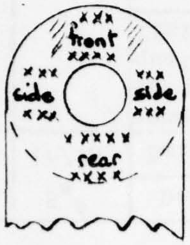
SUPPLEMENTARY INVESTIGATION No.4

TABLE 6a EXAMINATION OF FAILURES (BOLT PRE-TENSION = $70^{o}/o$)

Order No.	Specimen Identity	Bolt Pre-tension	Endurance Cycles	Configuration*	S_a ϕ lb/in^2	Degree of Fretting+		Remarks
						Bore	Faces	
1	28.5.A	$70^{o}/o$	1 471 500	Dry,P.F.Std.W.	8 000	none	Heavy locally under washers at rear region.	Specimen failed through hole from fretted region.
2	45.8.D		6 440 800	Duralac,P.F. Spl.W.	10 000	none	Very light at periphery of washer at extreme front.	×Specimen failed near bolt hole, but not through it. One side plate failed in grip area.
3	28.9.B		3 948 600			none	Light at periphery of washer at "fwd-side" region.	×No crack in test area of specimen, but cracked in grip area. One side plate failed from fretted area.
4	28.8.D		3 274 900			none	Moderate at front, light at rear, both at periphery of washers.	×No crack in test area of specimen, but failed in grip area. One side plate failed in grip area. One side failed near, but not through hole.

(Table 6a continued on next page)

+ key to description of fretted regions: ⟶



× Duralac still liquid on dismantling.

ϕ S_m = 14 000 lb/in^2 throughout.

* P.F. Push fit

Std.W. Standard Wahser

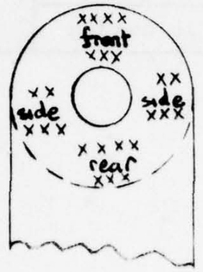
Spl.W. Special Washer

SUPPLEMENTARY INVESTIGATION No.4

TABLE 6a (Continued) EXAMINATION OF FAILURES (BOLT PRE-TENSION = $70^{o}/o$)

Order No.	Specimen Identity	Bolt Pre-tension	Endurance Cycles	Configuration ✱	S_a^{ϕ} lb/in^2	Degree of Fretting$^+$		Remarks
						Bore	Faces	
5	46.5.C	$70^{o}/o$	5 370 000	Dry, Cl.F., Spl.W.	10 000	none - but poor quality finish	Moderate at rear periphery of washer - both faces.	Specimen cracked through fretted region, but not through hole. Finally failed away from hole in grip area.
6	46.6.A		3 175 000			none	Heavy on one face at front, and light at rear. Moderate on other face at rear.	Specimen unfailed, but both side plates failed near, but not through hole.
7	46.7.A		1 511 200			none	Light at rear periphery of washer	Crack in specimen in grip area at one side only
8	44.6.C		7 792 900	Duralac Cl.F., Spl.W.	10 000	none	Moderate at front on one face only; Light on both faces at rear.	*Specimen failed at grip area. One side plate failed near, but not through hole, other side plate failed at grip area.
9	44.6.D		2 397 900	Duralac Cl.F., Spl.W.		Moderate in small area in front	Heavy in rear region.	*Slipping occurred in first few minutes. Small chip of metal missing from rear area after failure in this region, near, but not through bolt hole.

\+ **key to description of fretted regions:-** →



* **Duralac still liquid on dismantling**

ϕ $S_m = 14\ 000\ lb/in^2$ throughout

✱ Cl.F. Clearance fit

Spl.W. Special Washer

SUPPLEMENTARY INVESTIGATION No.4

TABLE 6b EXAMINATION OF FAILURES (BOLT PRE-TENSION = 85°/o)

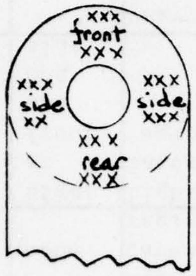
Order No.	Specimen Identity	Bolt Pre-tension	Endurance Cycles	Configuration*	S_a ϕ lb/in^2	Degree of Fretting$^+$		Remarks
						Bore	Faces	
10	46.4.C	85°/o	2 170 800	Dry, Cl.F. Spl.W.	10 000	none	Heavy on both faces at rear	Primary failure of one side plate at grip area. Specimen cracked through fretted area but not at hole.
11	46.5.A		4 466 600		9 000	Small area burnished on one side	Very light on one face around periphery of W.	Primary failure of specimen through rear fretted region, but also failed at grip area. One side plate failed at grip area.
12	46.5.B		2 703 000		9 000	none	Light on both faces in rear region.	Specimen cracked through fretted region but finally failed in grip area. Both side plates cracked.

\+ key to description of fretted regions:- →

ϕ S_m = 14 000 lb/in^2 throughout

* Cl.F. Clearance fit

Spl.W. Special Washer



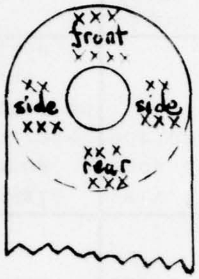
SUPPLEMENTARY INVESTIGATION No.4

TABLE 6c EXAMINATION OF FAILURES (BOLT PRE-TENSION = 100^o/o)

Order No.	Specimen Identity	Bolt Pre-tension	Endurance Cycles	Configuration *	S_a ϕ lb/in^2	Degree of Fretting+		Remarks
						Bore	Faces	
13	28.7.C	100^o/o	8 345 400	Dry, P.F., Std.W.	7 000	none	Light on both faces in rear region	Specimen and both side plates failed through hole at fretted region.
14	28.7.D		4 792 800		7 000	Light at front and one side	Light on both faces in rear region	Specimen and both side plates failed through hole at fretted region.
15	46.8.D		4 240 700	Dry, Cl.F. Spl.W	10 000	none	Heavy on both faces in rear region	Multiple cracks in specimen across fretted area near hole. Both side plates cracked in same area.

\+ key to description of fretted regions:- →

ϕ S_m = 14 000 lb/in^2 throughout



* P.F. Push fit
Cl.F. Clearance fit
Std.W. Standard Washer
Spl.W. Special Washer

SUPPLEMENTARY INVESTIGATION No.4

TABLE 7 SUMMARY OF MEAN ENDURANCES FOR GROUPS OF SPECIMENS EXAMINED FOR DETAILS OF FAILURES

Bolt Pre-tension	Order Nos.	Mean Endurance	Configuration*	S_a lb/in^2
70°/o	1	1 471 500	Dry,P.F., Std.W.	8 000
	2,3,4	>4 367 000	Duralac,P.F.,Spl.W.	10 000
	5,6,7	>2 950 000	Dry, Cl.F.,Spl.W.	10 000
	8,9	>4 320 000	Duralac, Cl.F., Spl.W.	10 000
85°/o	10	2 170 800	Dry, Cl.F., Spl.W.	10 000
	11, 12	3 474 700	Dry, Cl.F., Spl.W.	9 000
100°/o	13, 14	6 324 000	Dry, P.F., Std.W.	7 000
	15	4 240 000	Dry, Cl.F., Spl.W.	10 000

SOME COMPARISONS OF ENDURANCE

(a) Duralac v. dry assembly (other variants being constant)

$$\text{i.e.}\quad \frac{8,9}{5,6,7} = \frac{>4\ 320\ 000}{>2\ 950\ 000} = \underline{1.45\ \text{approx.}}$$

(b) Push fit v. Clearance fit (both with duralac and Spl.washer)

$$\text{i.e.}\quad \frac{2,3,4}{8,9} = \frac{>4\ 367\ 000}{>4\ 320\ 000} = \underline{1.0\ \text{approx.}}$$

(c) 85°/o v 70°/o Bolt pre-tension (with dry assembly, Cl.fit and special washer)

$$\text{i.e.}\quad \frac{10}{5,6,7} = \frac{2\ 170\ 000}{>2\ 950\ 000} = \underline{<0.7}$$

(d) 100°/o v. 70°/o Bolt pre-tension (with dry assembly, Cl.fit and special washer)

$$\text{i.e.}\quad \frac{15}{5,6,7} = \frac{4\ 240\ 000}{>2\ 950\ 000} \ngtr \underline{1.4}$$

* P.F. Push fit

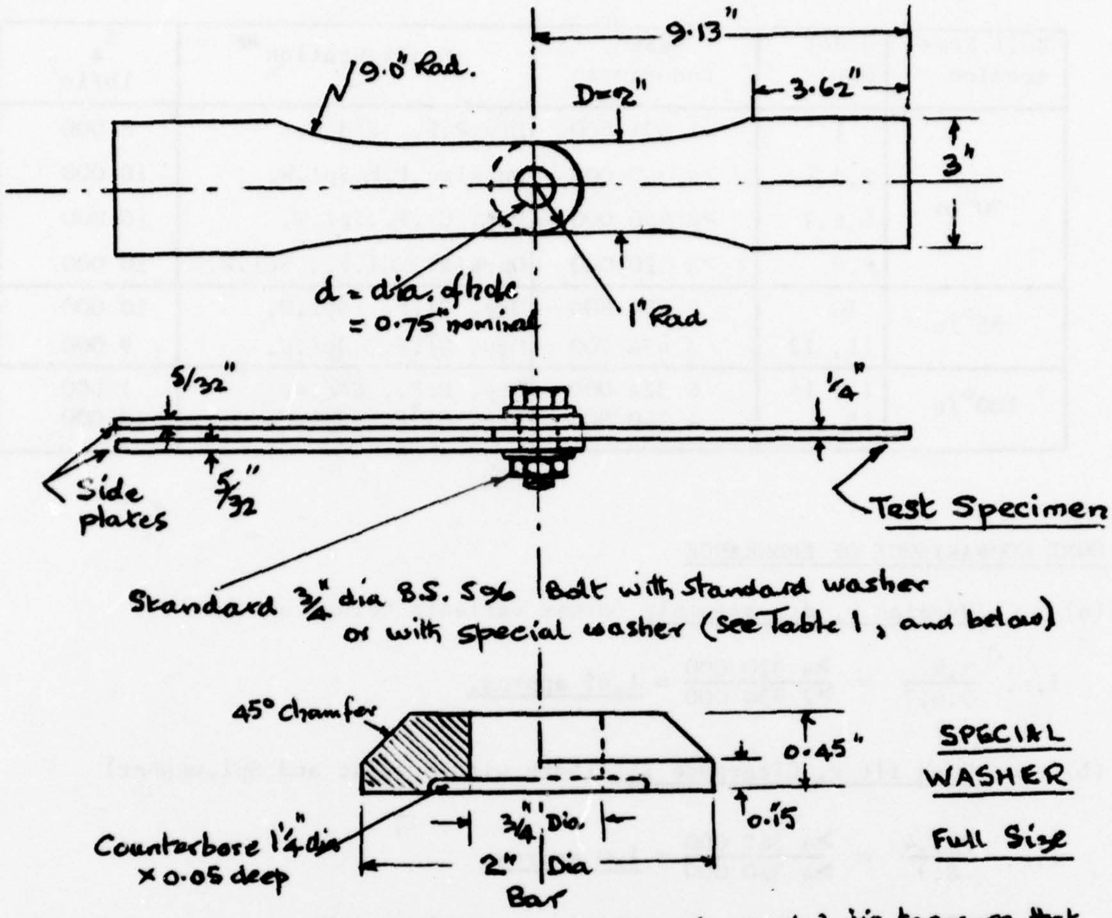
Cl.F. Clearance fit

Std.W. Standard Washer

Spl.W. Special Washer

Sl. N° 4 – TRANSMISSION OF LOAD BY CLAMPING

FIGURE 1 GEOMETRY OF SPECIMEN (1/4 Full size)



Note: All clearance fit specimens assembled in special jig to ensure that bolt is concentric with hole in plate.

SPECIMEN TYPES (For details of Configurations and Assembly Treatments, see Table 1)

Specimen Type	65004	65005	65006
Material Aluminium Alloy	BS.L71	BS.L71	BS.L71
Bolt 3/4 in dia. BS.S.96 $^{\phi}$	A.59 0.7498 in 0.7493 in	A.25.S	A.25.S
Hole	Push Fit 0.7507 in 0.7495 in	Clearance Fit Drill 0.8125 in	Clearance Fit Drill 0.8125 in
Washer Mild Steel	Standard* Plain	Standard Plain	Special

ϕ Nickel-chrome-molybdenum H.T. Steel

× Configuration No.5 fitted with special washer

FIG. 2a SI. N°4 – 70% BOLT PRE-TENSION – PUSH FIT

CONFIGURATION 1 to 5, ALL STANDARD WASHERS EXCEPT CON. 5
WHICH HAS THE SPECIAL WASHER

Ref. TABLE 2

MEAN STRESS = 14000 lb/in²
= 0·20 ft

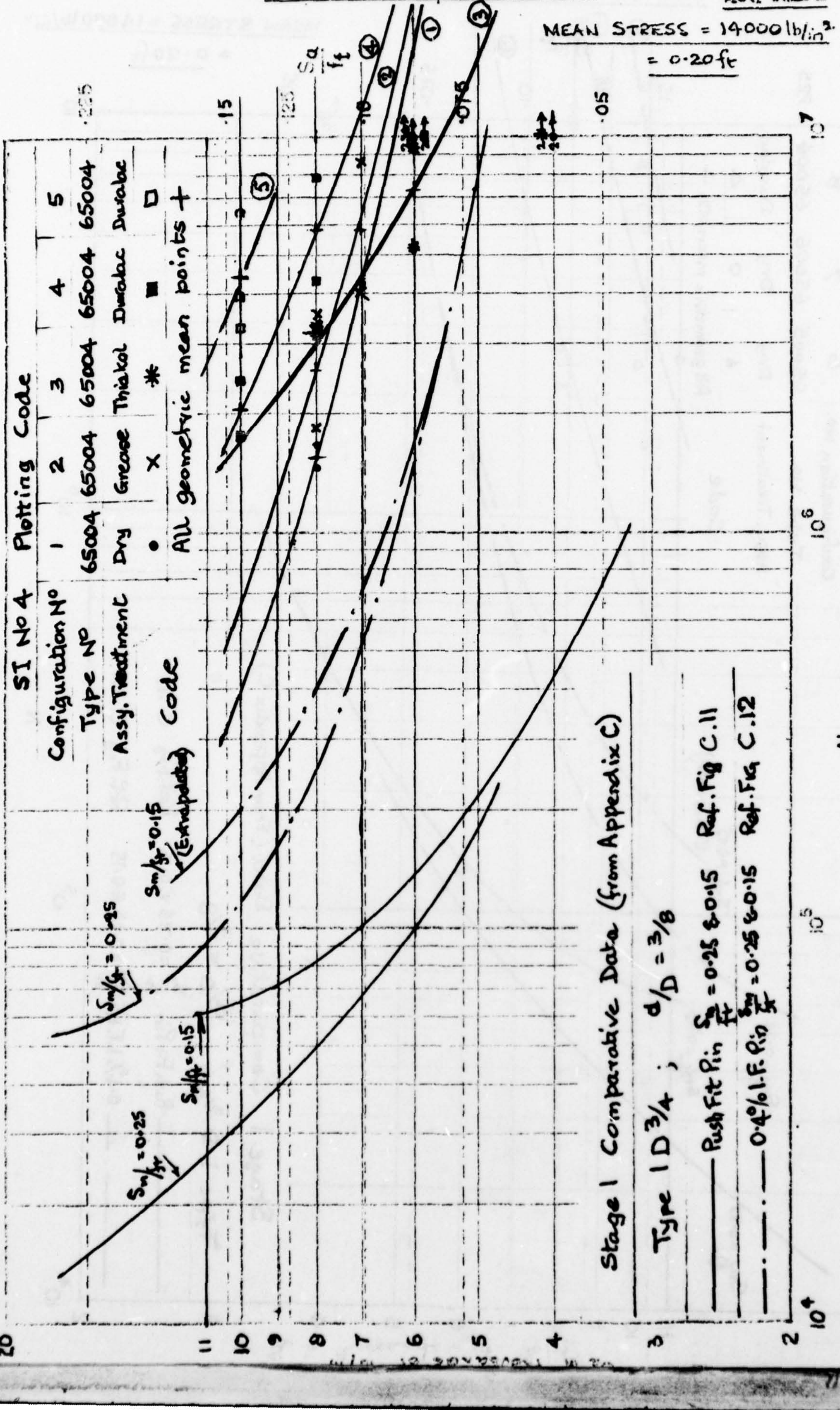


Fig 2b S.I. N°4 - 70% BOLT PRE-TENSION - CLEARANCE FIT

CONFIGURATION 6 - STANDARD WASHER

CONFIGURATIONS 7 & 8 - SPECIAL WASHER

Ref. TABLE 2

MEAN STRESS = 14000 lb/in²
= 0·20 ft

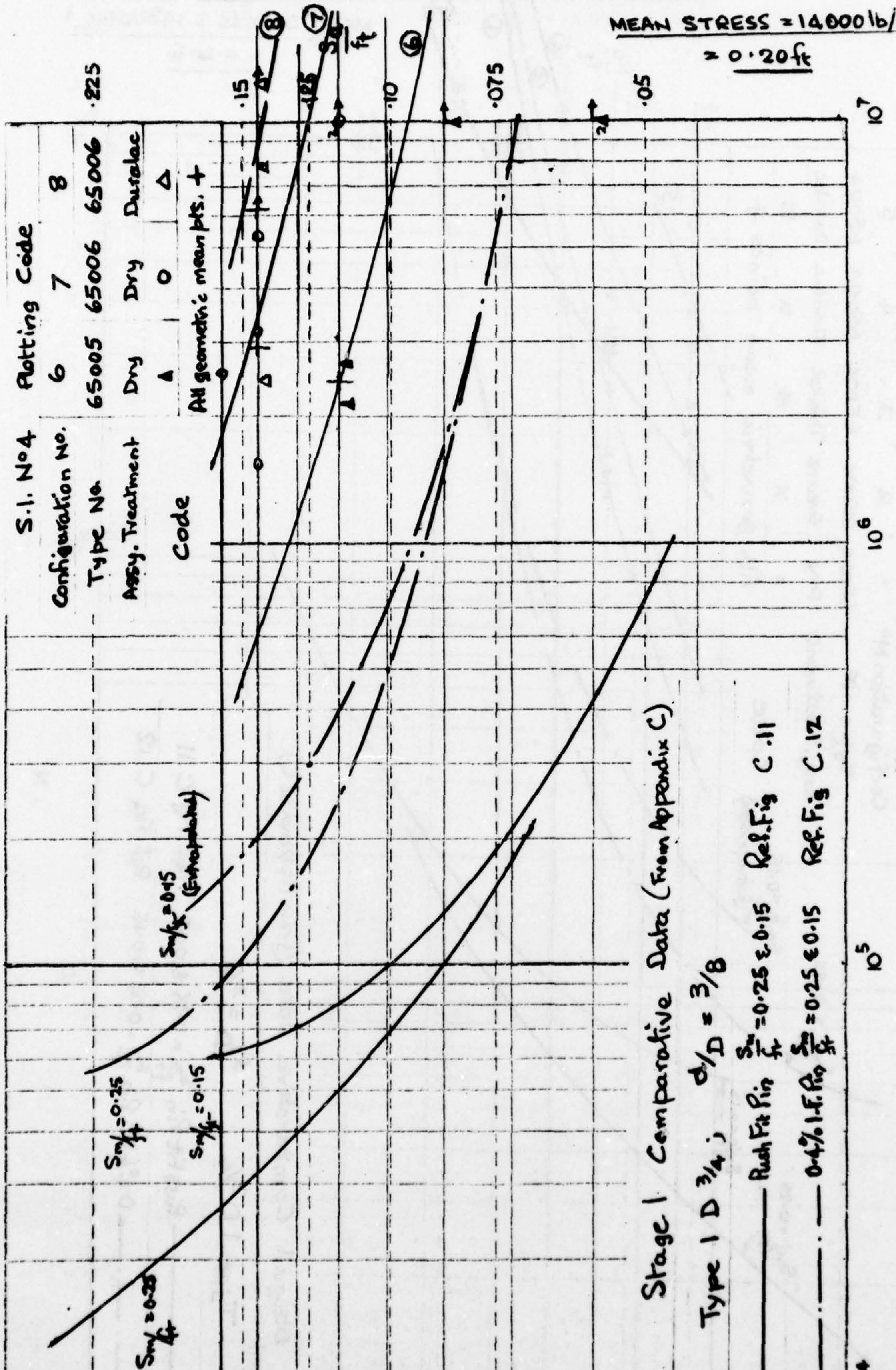


Fig 3a S.I. N° 4 – 85% BOLT PRE-TENSION – PUSH FIT

CONFIGURATIONS 1 to 4; STANDARD WASHER

Ref: TABLE 3

MEAN STRESS = 14000 lb/in²

= 0.20 ft

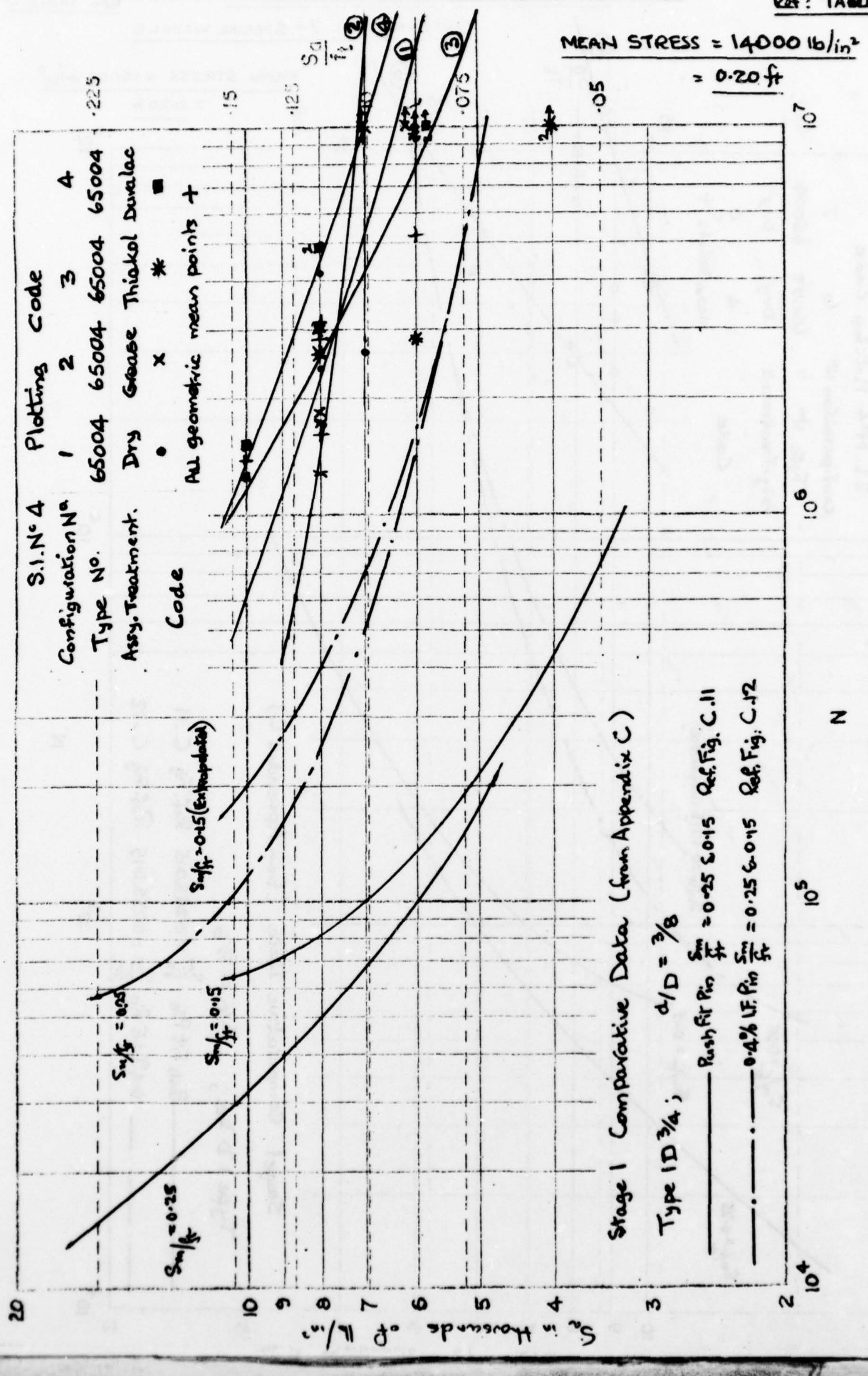


Fig 3b S.I. No4 - 85% BOLT PRE-TENSION - CLEARANCE FIT

CONFIGURATION 6 - STANDARD WASHER

Ref. TABLE 3

CONFIGURATION 7 - SPECIAL WASHER

MEAN STRESS = 14000 lb/in² = 0.20 ft

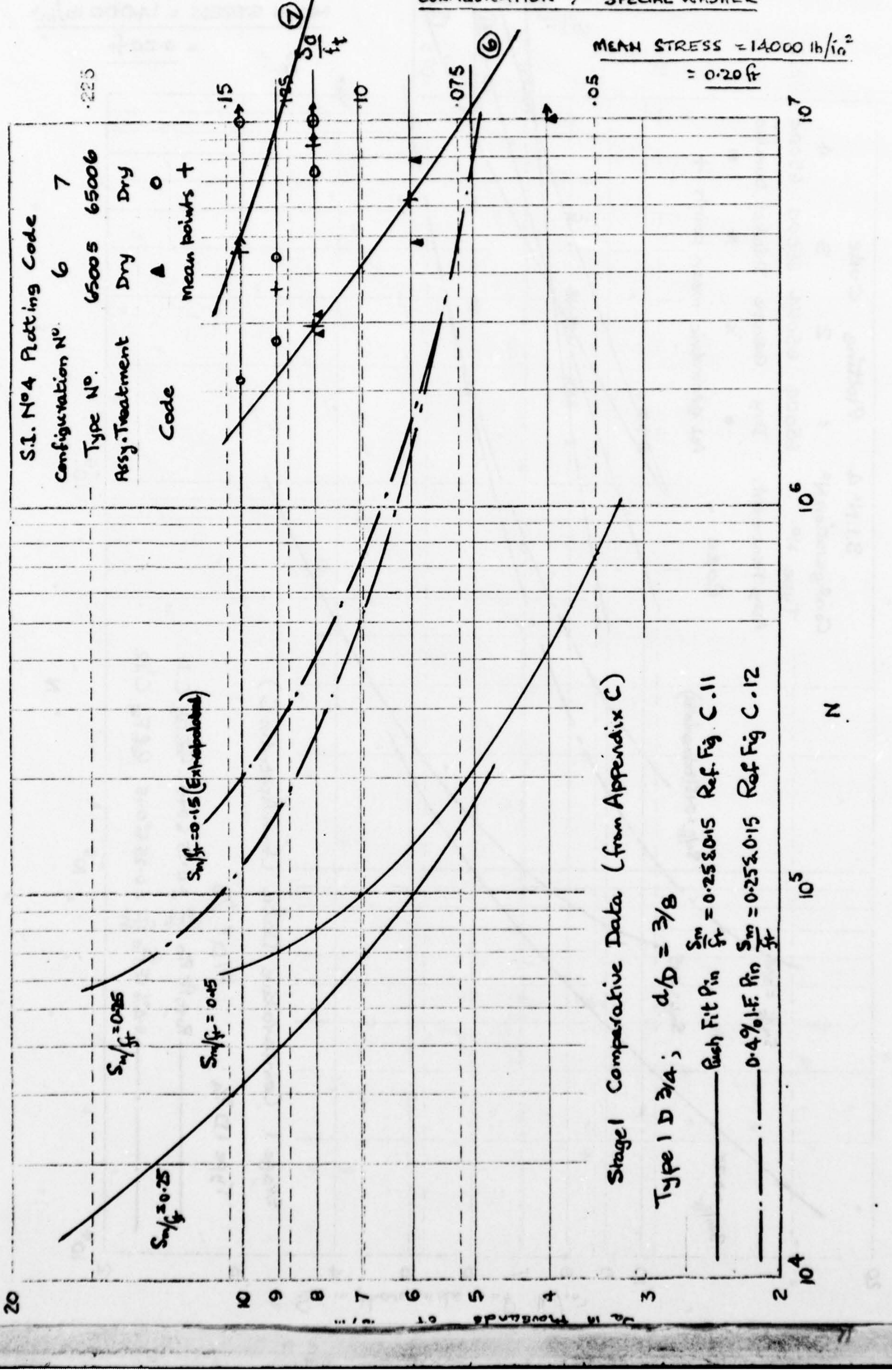


Fig 4a S.I. N° 4 - 100% BOLT PRE-TENSION - PUSH FIT

CONFIGURATIONS 1 to 4; STANDARD WASHER

Ref: TABLE 4

MEAN STRESS = 14000 lb/in² = 0.20 ft.

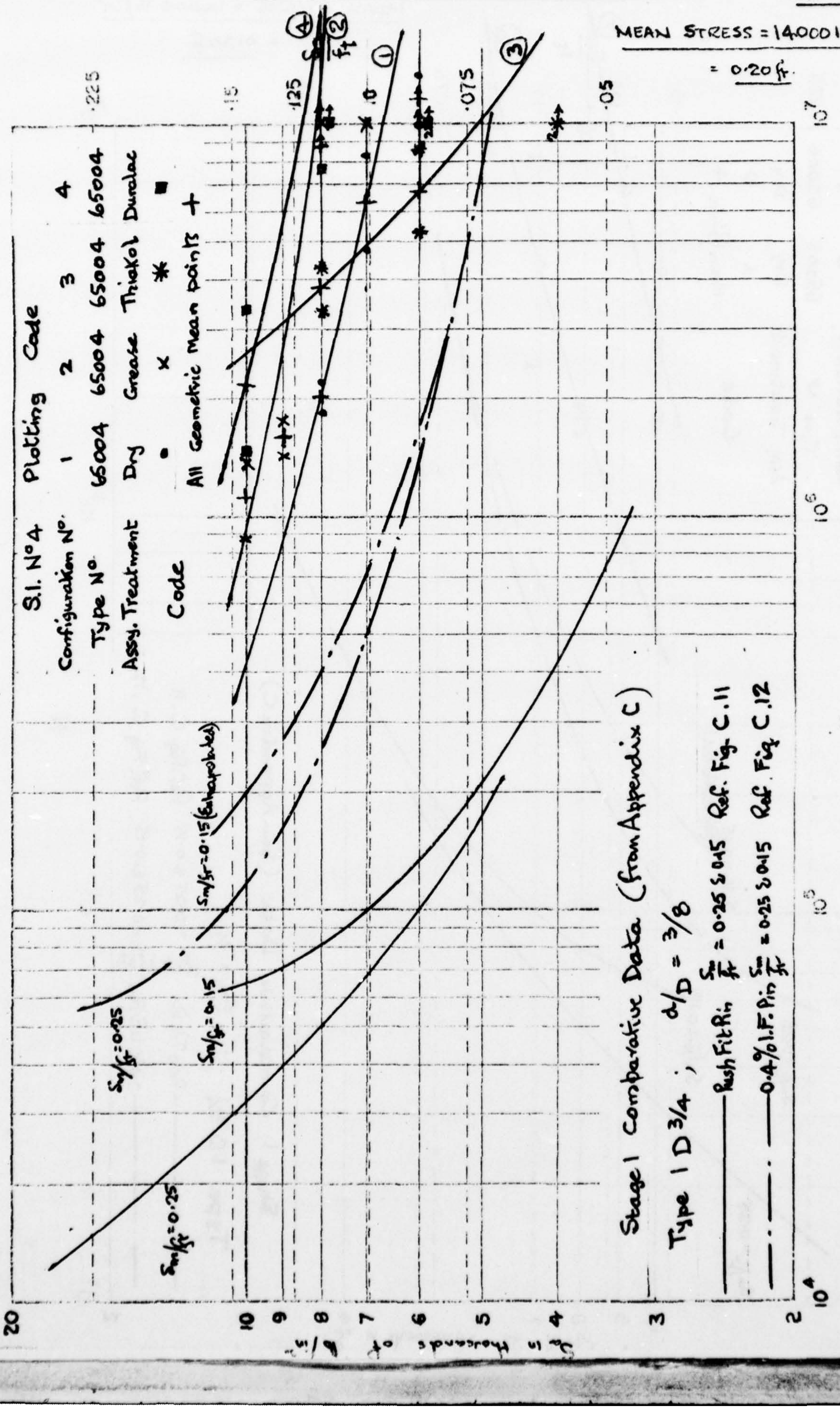


Fig.4-b

S.I. No4 - 100% BOLT PRE-TENSION -- CLEARANCE FIT

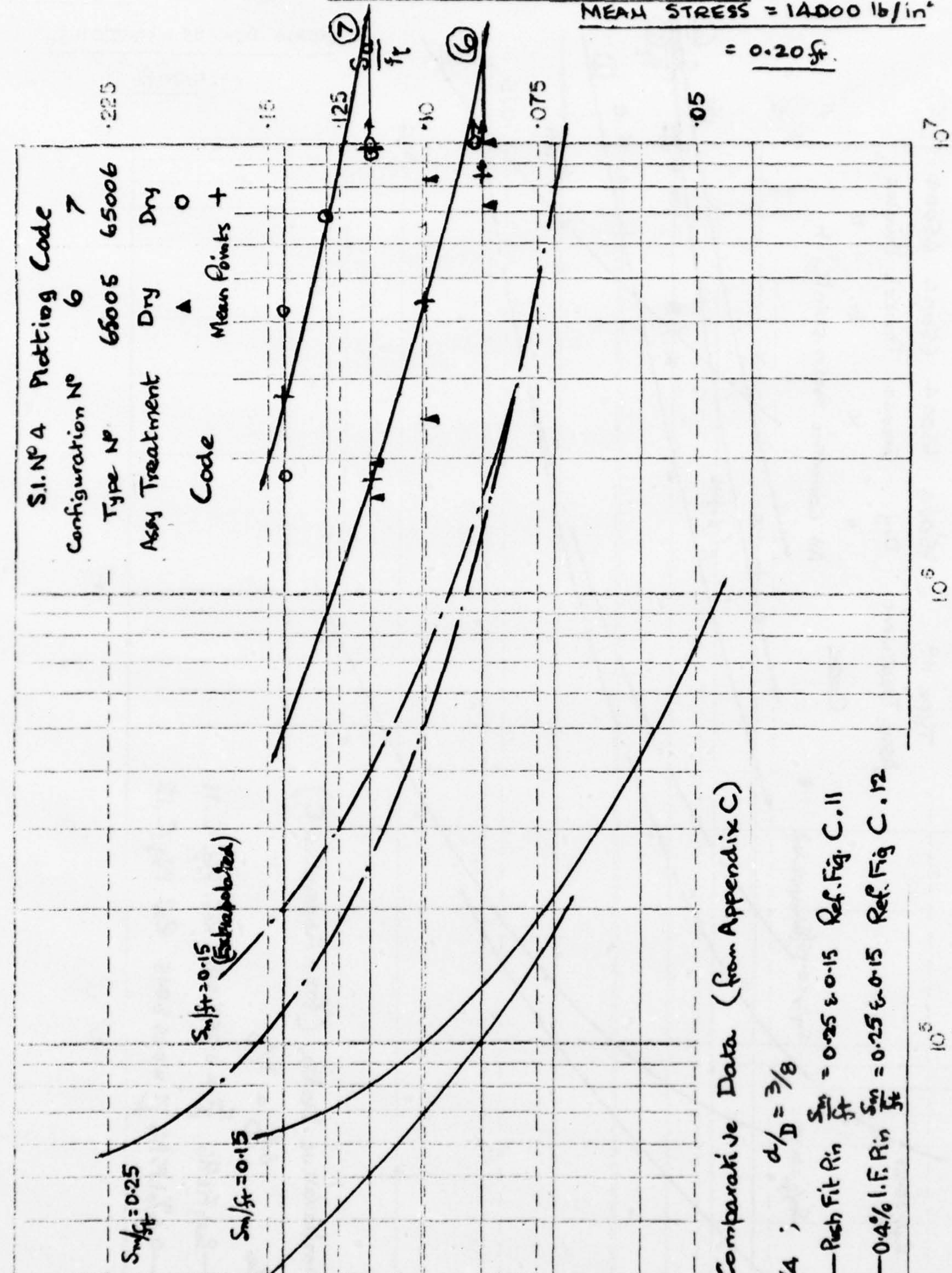
CONFIGURATION 6 - STANDARD WASHER

Ref: TABLE 4

CONFIGURATION 7 - SPECIAL WASHER

MEAN STRESS = 14000 lb/in²

= 0.20 ft.



FIGURES 5a & 5b

S.I. No 4

COMPARISON OF BOLT PRE-TENSIONS

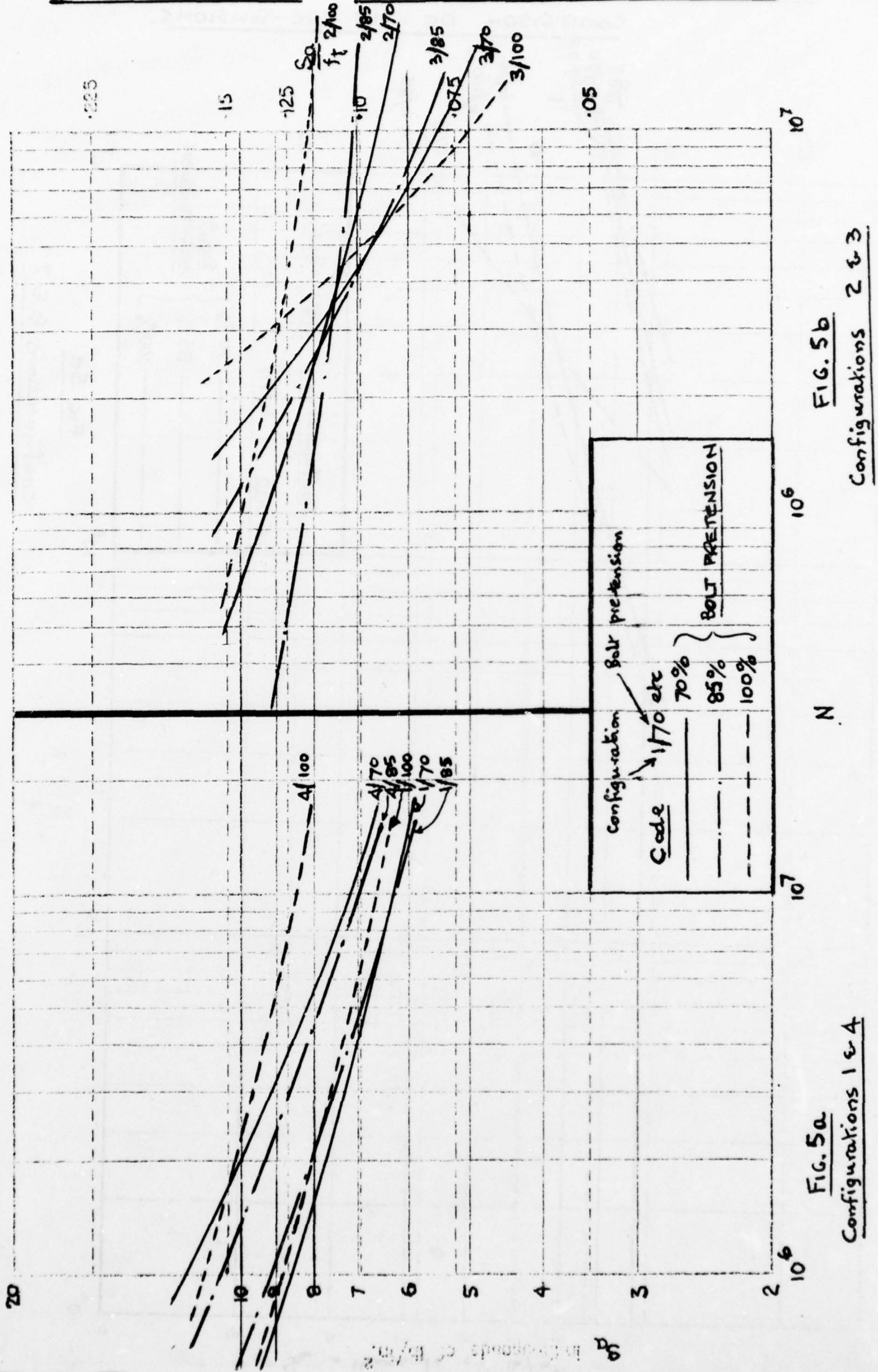


FIG. 5a
Configurations 1 & 4

FIG. 5b
Configurations 2 & 3

FIGURE 5c

S.I. N° 4

COMPARISON OF BOLT PRE-TENSIONS.

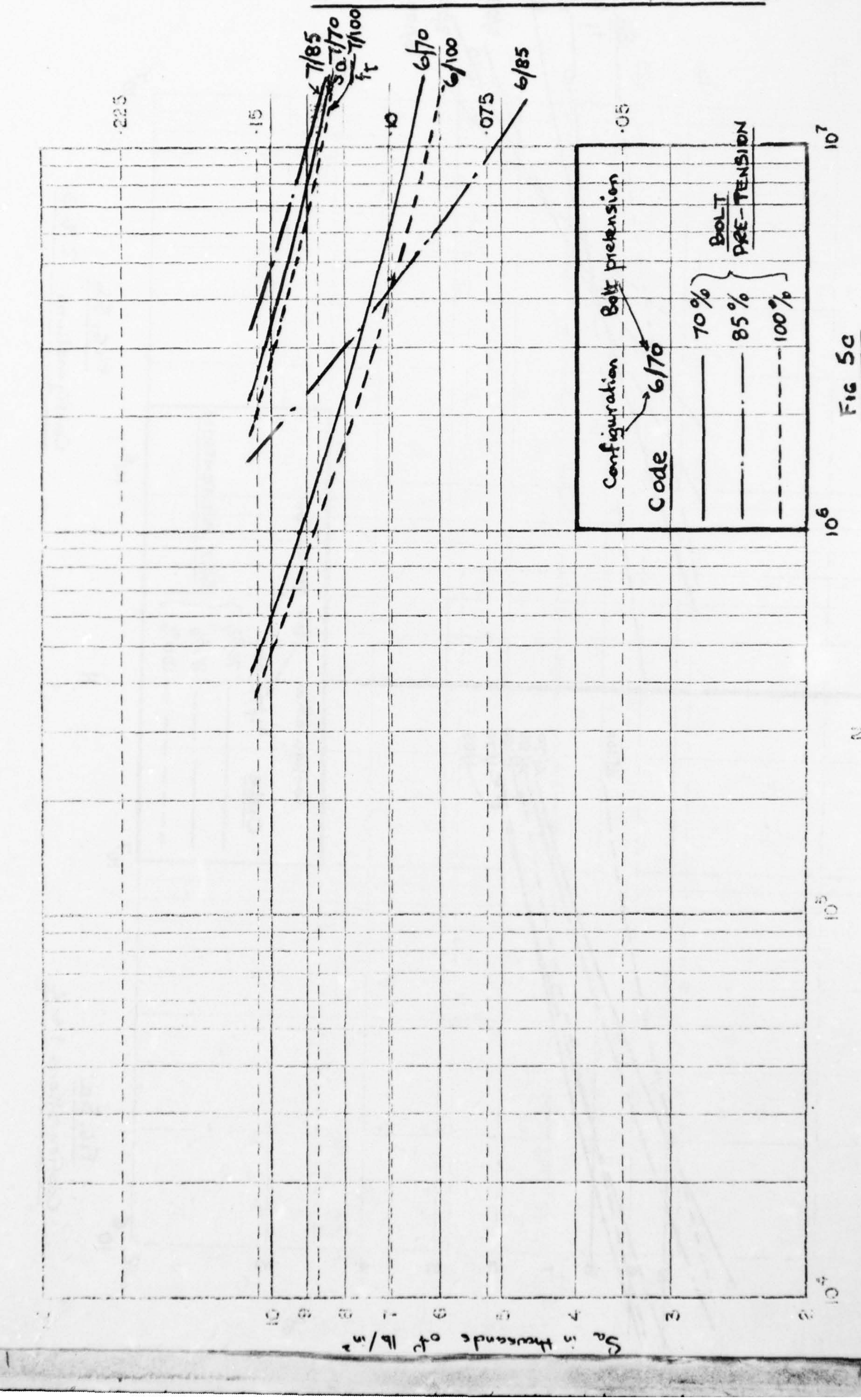


Fig 5c

Configurations 6 & 7

APPENDIX TO SUPPLEMENTARY INVESTIGATION No.4

TENSILE TESTS ON JOINT BOLTS FOR EVALUATION OF THE 0.2°/o PROOF STRESS

(Reference Short Brothers and Harland Test Note No.1091)

These tests were undertaken to establish a reliable and consistent standard of bolt pre-tensioning. The bolts were B.S. - S96, 3/4 in diameter high tensile steel, (f_t = 55 Tons per sq.inch). The bolts used for each type of specimen were obtained from a separate source and so three bolts from each of three sources were tested in tension, to obtain load - extension curves.

The method of loading the bolts is shown on Figure A1. The nut was positioned on the bolt such that the length from the base of the bolt head to the nut face was equal to that required for a particular type of specimen i.e. for Type 65004, 65005 or 65006. These lengths were 0.79 in for types 65004 and 65005, and 1.475 in for type 65006.

Extensions were measured by means of a micrometer on the overall length of the bolt, the ends of which were ground flat to remove irregularities.

RESULTS

Load extension curves for each bolt test were obtained and all the curves were regular, with no abnormal features. The gauge length in finding the 0.2°/o proof loads was taken as the thickness of the appropriate specimen for that particular group of bolts.

A summary of the values of the proof loads are given in Table A1 (see below)

APPLICATION OF RESULTS

It was decided that the safest procedure would be to use the minimum measured value of the 0.2°/o Proof Load namely 18.9 tons, as a common proof load for all bolts. Thus the loads for the three degrees of clamping were:

70°/o	85°/o	100°/o bolt proof stress
13.2	16.0	18.9 tons

The corresponding bolt extensions, taken from the appropriate load extension curves for each of these three loads were used to control the bolt pre-tensions in each of the specimens during assembly.

TABLE A1 0.2°/o BOLT PROOF LOADS

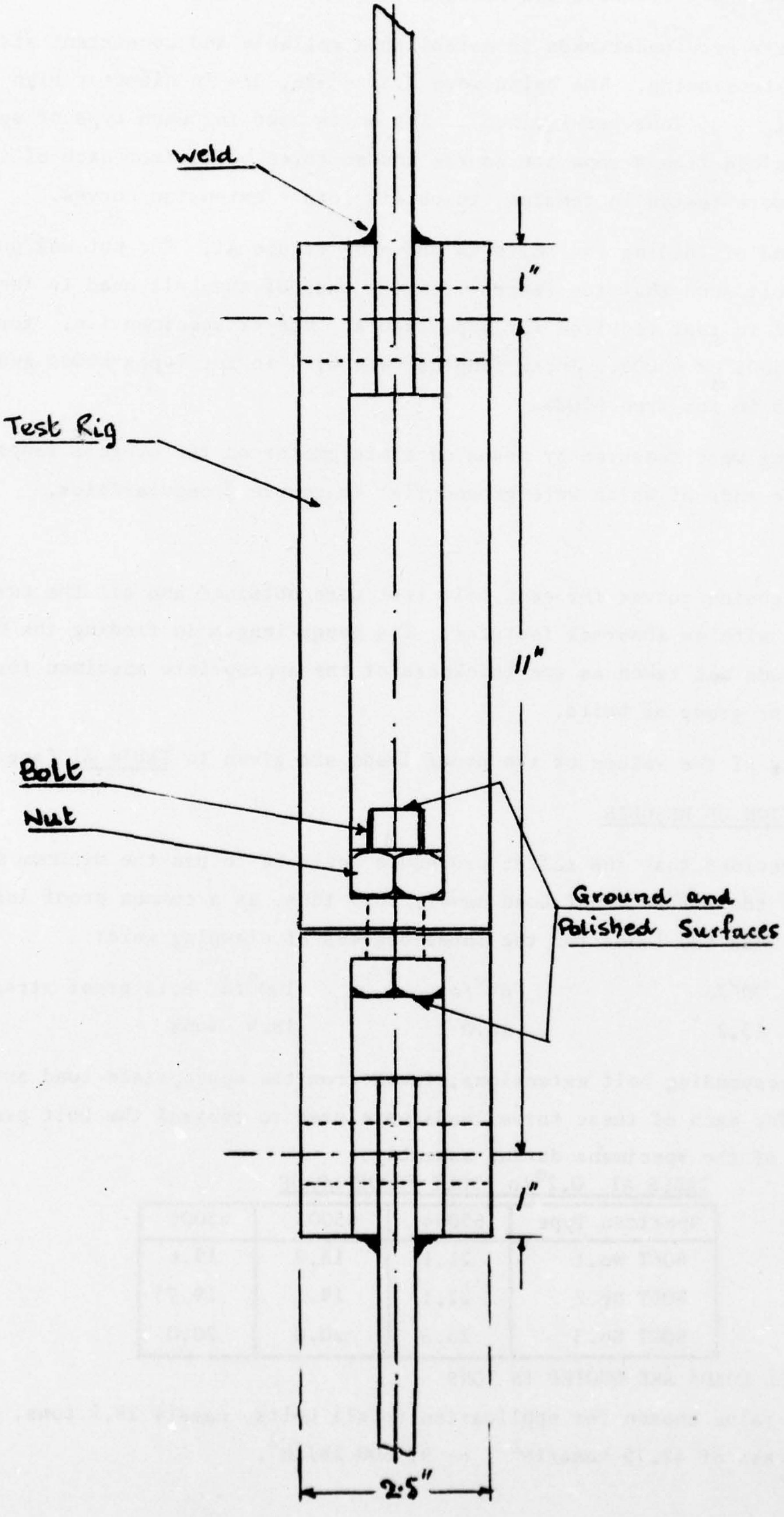
Specimen Type	65004	65005	65006
BOLT No.1	21.1	18.9	19.6
BOLT No.2	22.1	19.1	19.75
BOLT No.3	23.3	20.0	20.0

NOTE ALL LOADS ARE QUOTED IN TONS

Minimum value chosen for application to all bolts, namely 18.9 tons, equivalent to a stress of 42.75 tons/in^2 or 95 500 lb/in^2.

FIGURE A1 BOLT PROOF LOADING TEST RIG

SCALE – ½ SIZE



SUPPLEMENTARY INVESTIGATION No.5

SOME EVIDENCE OF THE INFLUENCE ON ENDURANCE OF SURFACE FINISH AND HOLE EDGE CHAMFERING OF A LOADED PUSH FIT PIN JOINT

1. INTRODUCTION

The majority of aircraft parts made from Aluminium Alloy sheet and some from plate up to say, 1/4 in thick, are completed and fitted in the "as rolled" condition. This investigation was introduced to obtain some evidence of the extent, if any, to which the fatigue life of the part suffered by this practice, as compared with using an average quality machined surface. At the same time, the opportunity was taken to investigate the effect of chamfering the edges of the bolt holes on both sides of the plate.

2. NOTATION (Units are in lb and inches throughout)

The following notation is taken from the Stage 1 Report, and is applicable to the present tests.

d = Nominal diameter of hole and pin

D = Width of parallel section of the test specimen

f_t = Average tensile strength of plate material (from tests)

f_p = Average $0.2^o/o$ proof stress of plate material (from tests)

K_t' = Geometric stress concentration factor based on net area of cross section of test specimen

N = Endurance

S_m = Mean stress on net area

S_a = Alternating stress on net area associated with S_m

t = Thickness of plate specimen

3. TEST PROGRAMME AND STRESS LEVELS

The original plan was to carry out tests on push fit specimens in which half of the specimens would have unloaded pins and half would have loaded pins. Unfortunately the results of the tests on the unloaded pin specimens were inconclusive, and therefore they are not included in this report.

3.1 Loaded Pin Specimens

These tests were carried out by Messrs Short Brothers and Harland Ltd of Belfast. Two levels of mean stress were included and for each of these, two levels of alternating stress were chosen, one comparatively high and one comparatively low. Moreover, four nominally identical specimens were provided for each level of stress.

The programme was repeated to include four different standards of preparation, namely:

(i) the surfaces "as rolled"

(ii) the surfaces machined to a depth of 0.015 in on both faces

(iii) the surfaces "as rolled" and the edges of the holes on both sides chamfered at 45^o to a depth of 0.015 in

(iv) the surfaces machined to a depth of 0.015 in on both faces and the edges of the holes on both sides chamfered at 45^o to a depth of 0.015 in.

When examined by the testing laboratory it was found that some specimens possessed an eccentricity of load line within the plane of the specimen of amounts up to 0.007 in measured at mid length. From a consideration of the effect on life of the bending stresses thus incurred it was agreed to accept specimens with an eccentricity of not more than 0.002 in. Another defect which occurred was that of a slight degree of bowing out of the plane of the specimen, up to 0.017 in. It was decided to accept a maximum bow of 0.010 in. These two defects led to a reduction in the number of specimens tested from 64 to 51.

Table 1 gives details of the test schedule, and
Figure 1 gives details of the test specimens.

3.2 Testing

Great care was exercised, both in the initial set-up of the machine, and in the subsequent installation of each specimen, to ensure axiality of loading and to avoid rotational misalignment of the specimens. Specimens requiring the same dynamic load were tested consecutively where possible, in order to reduce scatter within groups.

Temporary protection of the specimens during testing was accomplished by the application of lanolin grease as in the Stage 1 tests.

4. RESULTS

These are presented in Tables 2 (i) to 2 (iv) and on Figures 2 to 5. Figure 2 also contains the endurance curves for $S_m/f_t = 0.25$ and 0.15 for the same configurations in the Stage 1 tests (Figure C.11).

In order to assess the relative merits of the four standards of preparation, the curves of Figures 2 to 5 are re-presented in summary form on Figures 6 to 7.

Figure 6 covers the four standards of preparation for a mean stress of 0.25 f_t and Figure 7 covers those for a mean stress of 0.15 f_t. The appropriate Stage 1 curves for the "as rolled" condition are also shown on these two figures.

5. DISCUSSION OF RESULTS (See Table 2 and Figures 2 to 7)

Despite the limitation of only two levels of alternating stress and the rejection of a few of the specimens provided, the results are consistent at a given stress level, and in fair agreement with the "as rolled" endurance curves of Stage 1.

On the basis of the limited data there is generally slightly more gain in endurance for surface machning than for hole edge chamfering. In fact for these tests, the hole edge chamfering alone did not produce any significant increase in endurance. Nevertheless, it is clear that the differences between the endurance curves for the four standards of preparation are only marginal and, within the limits of the test coverage, no more than the general order of scatter of fatigue results.

6. METALLURGICAL EXAMINATION OF THE "AS ROLLED" SURFACE

It had been observed that there was some corrosion on the surfaces of the "as rolled" specimens. One typical example was selected, namely 5.8.D. Samples of the surface and a transverse section through the cracked joint plate were extracted as indicated in Figure 8 and prepared for micro-examination as below.

6.1 Surface Sample 1 and Transverse Micro-section

These were polished on a rotating pad with a slurry of γ-alumina for two minutes followed by a light polish on a selvyt cloth with brasso. No change in thickness of the specimen could be detected with a vernier micrometer after this surface preparation.

Subsequent micro-examination revealed three features of the "as rolled" surface which would be absent from the "as machined" surfaces, namely:

(a) embedded surface particles

(b) heavy surface oxidation

(c) Incipient corrosive attack in both pitting and intercrystalline forms.

These features are shown on Figures 9 and 10. The maximum depth of intercrystalline attack exhibited by the transverse section was 0.0015 in. Such attack was very infrequent and the pitting was of negligible depth.

Swabbing treatment with ICI Deoxidine 202 failed to produce a significant change in the surface appearance and the embedded particles resisted a trichloroethylene degreasing treatment.

6.2 Surface Sample 2

This was prepared in a similar manner to surface Sample 1, but with the addition of a short surface grinding treatment prior to polishing. The latter removed most of the surface oxide and some embedded particles, but the intergranular attack persisted since less than 0.0001 inches had been removed. The removal of the oxide layers exposed many more sites of corrosive attack as illustrated by Figure 11.

7. EXAMINATION OF THE SPECIMEN FRACTURES

All except one specimen (3.14.D) indicated a common mode of failure, namely cracks on both sides of the hole in the region of a transverse diameter (at 9 and 3 o'clock notation on Figure 1), which was the location of maximum fretting. The primary fracture faces displayed multi-initiation in the majority of cases with crack initiation at the hole edges and/or in the bore. There were also many cases of secondary cracking, which cracking sometimes joined the primary crack front to produce a stepped fracture face. At the lowest stress level ($0.15 f_t$ to $0.075 f_t$) there was tendency for unequal fatigued areas either side of the pin.

The surface corrosion on the "as rolled" specimens did not appear to play an effective role in the fracture mechanism, as initiation occurred within the bores with comparable frequency.

8. CONCLUSIONS

(i) Axial tension fatigue tests at two levels of mean stress ($0.25 f_t$ and $0.15 f_t$) and at two levels of alternating stress for each level of mean stress yielded results which were consistent at a given stress level, at each of which four specimens were provided.

(ii) The differences between the endurances for the four different standards of preparation were only marginal, and within the general order of scatter of such fatigue tests. For both levels of mean stress there was almost invariably a small increase in endurance when both the surfaces were machined and the hole edges chamfered. At $S_m = 0.25 f_t$ the machined surfaces alone produced a noticeable improvement but this was not so at $S_m = 0.15 f_t$. At neither mean stress did the hole edge chamfering alone produce any significant increase in endurance.

(iii) Comparisons between the "as rolled" condition of these tests and the corresponding results from the Stage 1 tests were fairly good.

(iv) The "as rolled" surfaces displayed shallow intercrystalline corrosion and some embedded particles, and had a surface roughness of 5 to 15 micro-inches CLA. The surfaces of the machined specimens were free from corrosive attack at the critical areas, and gave a comparable surface roughness in the longitudinal direction, which included some machine chatter in the transverse direction. There was no indication that this machine chatter had any adverse effect upon crack initiation. Furthermore, there was no evidence that the surface corrosion on the "as rolled" specimens had influenced significantly the fracture mechanism, since crack initiation frequently occurred within the bores of the holes.

(v) With only one exception all specimens failed with cracks on both sides of the hole in the region of a transverse diameter, which was the location of maximum fretting. These cracks displayed multi-initiation in most cases, with crack initiation at the hole edges and/or in the bore of the bolt holes. There were also secondary cracks, some of which joined the primary cracks leading to stepped fractures.

(vi) The surface machining produced some bowing of the joint plates indicating the presence of residual stresses in the surface layers. Again, some specimens exhibited slight load line eccentricity. The worst examples of these two defects were rejected.

(vii) This investigation was somewhat limited in scope and it is possible that if extended there would have been more definite evidence of some of the trends described herein. It should not be assumed that the effect of machining the surface of a specimen with or without a stress raiser, but without a bolt hole, would be the same as appears to be in the present specimens.

SUPPLEMENTARY INVESTIGATION No.5

TABLE 1 SCHEDULE OF TESTS - LOADED PIN SPECIMENS

All Specimens were of the large size (See Figure 1)

Four standards of preparation were included in the tests which were as follows:

(i) No special preparation, i.e. "as rolled".

(ii) 0.015 in machined from both faces.

(iii) Edges of bolt holes on both sides chamfered at 45° to a depth of 0.015 in, the surfaces being "as rolled".

(iv) Specimen machined to depth of 0.015 in on both faces and hole edges chamfered at 45° to a depth of 0.015 in.

The specimen type, stress levels and numbers of specimens provided at each stress level, applicable to each standard of preparation are given below:

Specimen Type	Mean Stress (S_m/f_t)	Alternating Stress ($\pm S_a/f_t$)	Number of Specimens tested per Standard of Preparation
1.D.3/4 Push Fit Pin Loaded	0.25	0.15	4
	0.25	0.10	4
	0.15	0.125	4
	0.15	0.075	4

NOTE

f_t = Maximum Tensile Stress of plate = 69 400 lb/in^2

Tested by Short Brothers and Harland Ltd, in a 20-ton Avery-Schenck Machine, frequency 1800 c.p.m.

TABLE 2 RESULTS **Reference Figures 2, 3, 4 and 5**

Specimen Type I.D.3/4, d/D = 3/8, Push Fit, Pin Loaded, $K_t' = 2.72$

(i) No special preparation i.e. "As Rolled"

Loads to insert pins ranged from 85 to 833 lb (generally 100-400 lb)

Specimen Identity	Stress Levels Percentage f_t*		Endurance		
	S_m	$\pm S_a$	Cycles	Logarithm Cycles	Geometric Mean Cycles
5.2.C	25	15	26 900	4.430	20 410
3.3.D			22 700	4.356	
3.13.A			18 100	4.257	
5.4.A			15 700	4.194	
5.3.B	25	10	51 200	4.710	46 700
5.2.E			50 500	4.707	
4.4.B			43 400	4.636	
6.6.C			42 400	4.626	
6.6.A	15	12.5	72 200	4.857	50 000
6.7.A			50 100	4.700	
6.5.B			43 600	4.639	
4.10.E			39 600	4.597	
6.2.C	15	7.5	221 400	5.344	153 300
5.8.D+			141 300	5.149	
6.8.C			115 200	5.060	

(ii) Surface machined

Loads to insert pins ranged from 40 to 530 lb (generally 55 to 250 lb)

Specimen Identity	Stress Levels Percentage f_t*		Endurance		
	S_m	$\pm S_a$	Cycles	Logarithm Cycles	Geometric Mean Cycles
4.4.C	25	15	38 100	4.581	37 950
3.12.A			37 900	4.577	
4.5.C	25	10	80 000	4.902	69 630
6.6.B			60 600	4.781	
3.11.A	15	12.5	66 100	4.820	61 310
3.2.A			59 900	4.777	
4.4.A			58 200	4.765	
4.13.A	15	7.5	132 000	5.120	118 400
4.11.A			105 400	5.022	

(continued)

*f_t = Maximum Tensile Stress = 69 400 lb/in^2

\+ Subjected to metallurgical examination (see paragraph 6.0)

TABLE 2 (Continued)

(iii) Hole edges chamfered (Surfaces "as rolled")

Loads to insert pins ranged from 107 to 408 (generally 150 to 220 lb)

Specimen Identity	Stress Levels Percentage f_t*		Endurance		
	S_m	$\pm S_a$	Cycles	Logarithm Cycles	Geometric Mean Cycles
3.2.B	25	15	29 800	4.475	24 280
4.14.D			26 200	4.418	
4.14.A			21 200	4.325	
4.14.B			21 100	4.324	
4.13.C	25	10	50 900	4.706	46 700
6.10.A			50 600	4.703	
3.11.E			48 100	4.682	
4.9.D			38 400	4.584	
3.2.E	15	12.5	70 500	4.848	58 320
5.4.C			66 000	4.820	
5.13.C			51 700	4.711	
3.1.D			48 100	4.682	
6.3.E	15	7.5	140 400	5.149	125 600
3.12.D			139 500	5.144	
3.1.A			113 100	5.052	
6.8.D			112 400	5.050	

(iv) Surfaces machined and Hole Edges Chamfered.

Loads to insert pins ranged from 63 to 432 lb (generally 70 to 180)

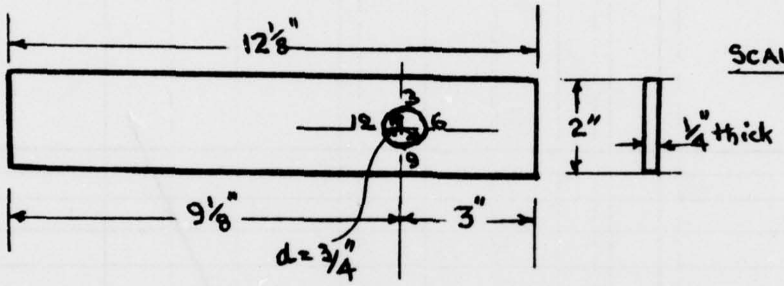
Specimen Identity	Stress Levels Percentage f_t*		Endurance		
	S_m	$\pm S_a$	Cycles	Logarithm Cycles	Geometric Mean Cycles
3.2.C	25	15	42 400	4.626	33 100
4.6.D			33 400	4.522	
3.9.D			25 600	4.408	
3.1.C	25	10	67 700	4.825	64 180
5.4.E			66 300	4.820	
4.13.E			58 900	4.770	
4.13.B	15	12.5	64 300	4.808	60 390
6.13.B			61 500	4.788	
4.14.C			55 700	4.745	
3.1.E	15	7.5	178 800	5.252	174 800
3.14.D			170 900	5.232	

*f_t = Maximum Tensile Stress = 69 400 lb/in^2

FIGURE I DETAILS OF SPECIMENS

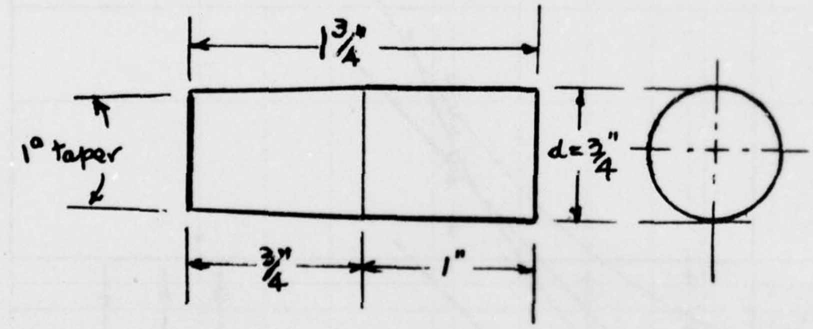
PLATES Aluminium Alloy to Specification B.S. L71

Specimen Type 1 D 3/4 Push Fit Pin - Pin Loaded $d/D = 3/8$



SCALE - 1/4 FULL SIZE

PINS Steel to Specification B.S. S94



SCALE - FULL SIZE

LIMITS Holes to d ± 0.0003"

Pins to d ± 0.0001"

Selective Assembly to give Push Fit Standard 15 $+0.0003"$ $-0.0001"$

S.I. N°5 FIG. 2 - SPECIMEN 1 D 3/4, $d/_D = 3/_8$ PUSH FIT PIN - PIN LOADED

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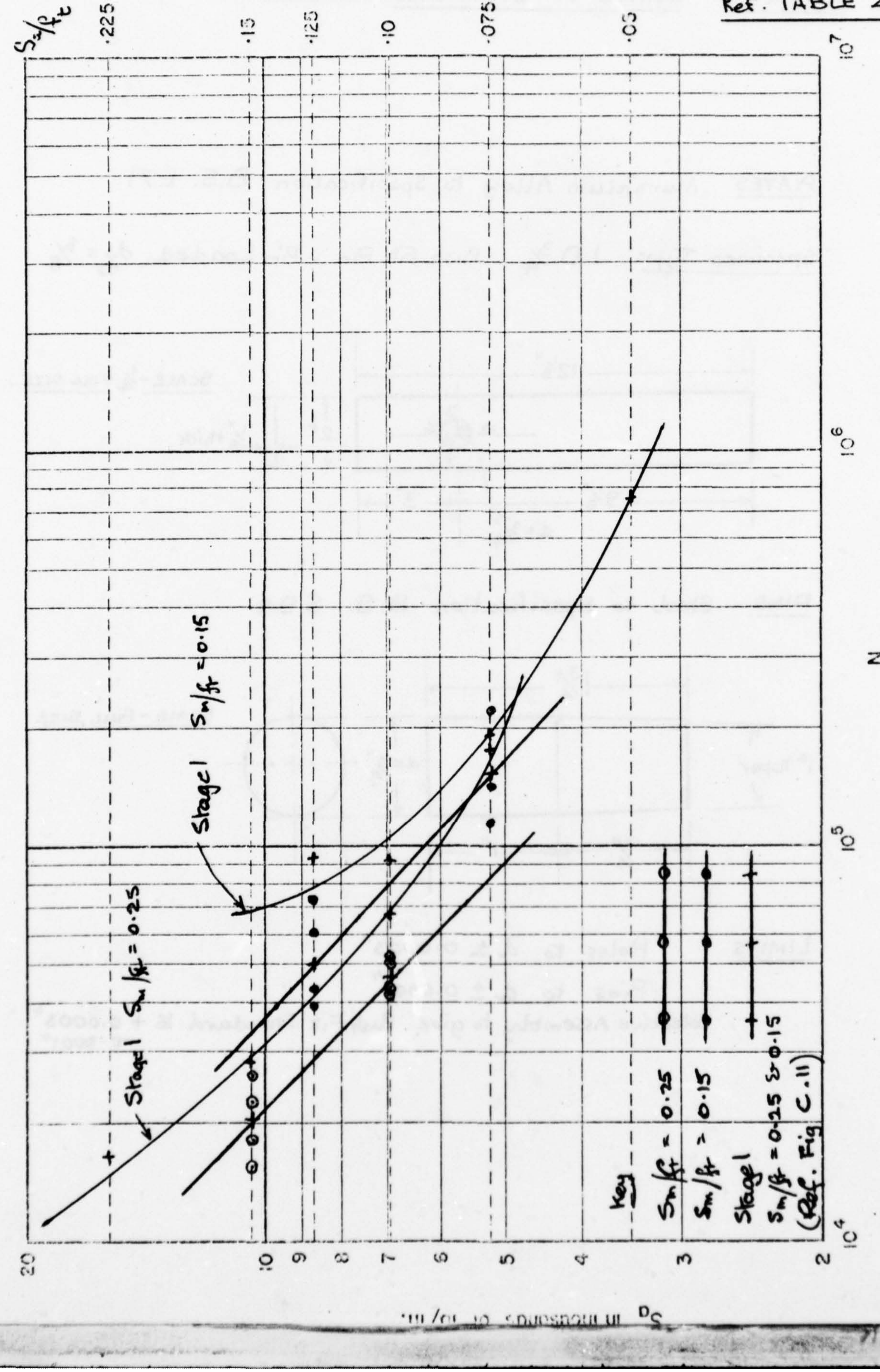
PREPARATION - AS ROLLED $S_m/f_t = 0{\cdot}25$ & $0{\cdot}15$

(& PLAIN HOLES)

Ref. TABLE 2 (i)

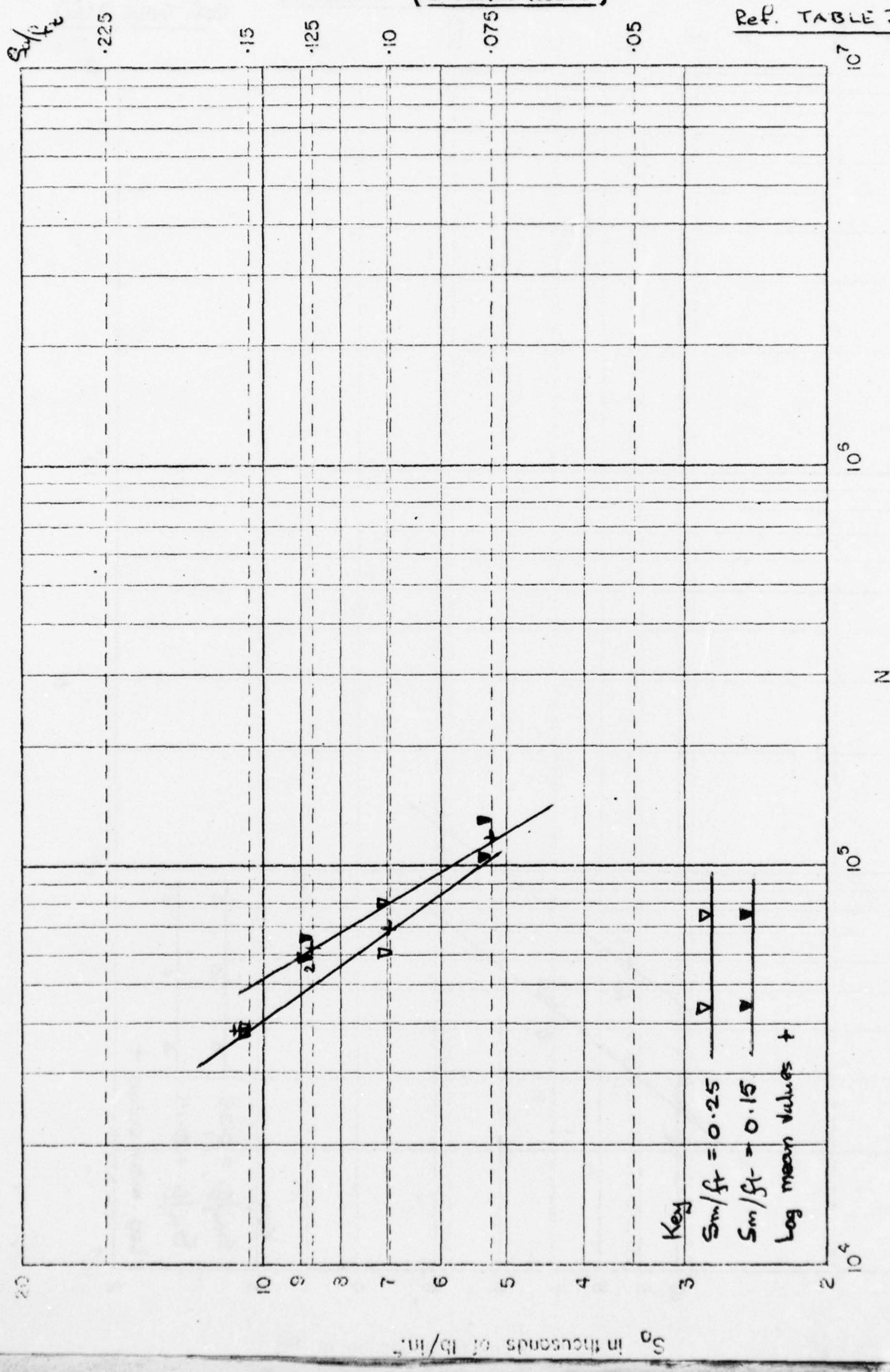


S.I.N°5 FIG.3 - SPECIMEN TYPE I D $3/4$, $d/D = 3/8$ PUSH FIT PIN - PIN LOADED

PREPARATION - SURFACES MACHINED
(6 PLAIN HOLES)

$S_m/f_r = 0{\cdot}25$ & $0{\cdot}15$

Ref. TABLE 2 (ii)



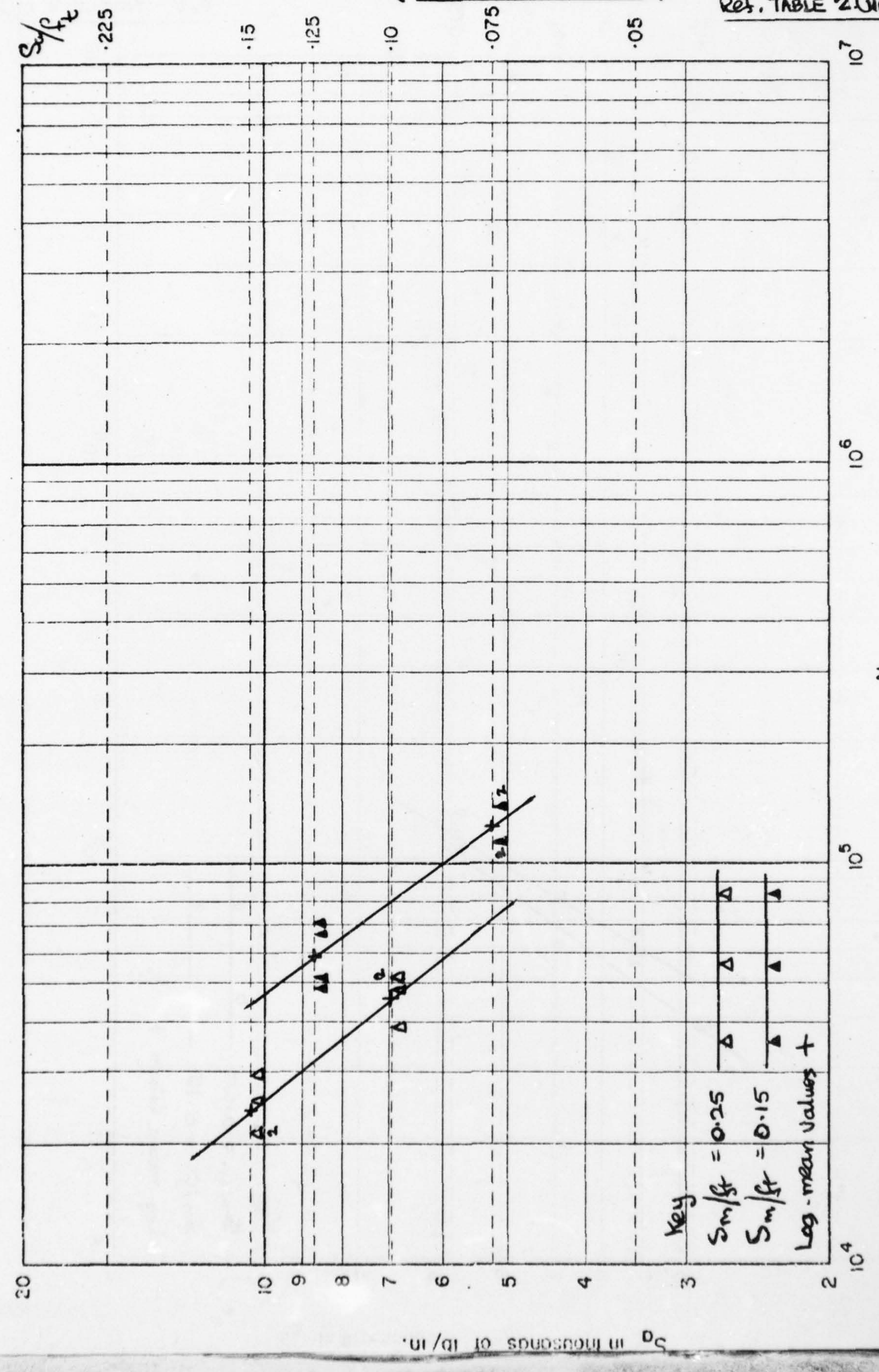
S.I. Nº 5 FIG. 4 - SPECIMEN TYPE 1 D 3/4, $d/D = 3/8$ PUSH FIT PIN - PIN LOADED

PREPARATION - HOLE EDGES CHAMFERED

(& SURFACES AS ROLLED)

$S_m/f_t = 0.25$ & 0.15

Ref. TABLE 2(iii)

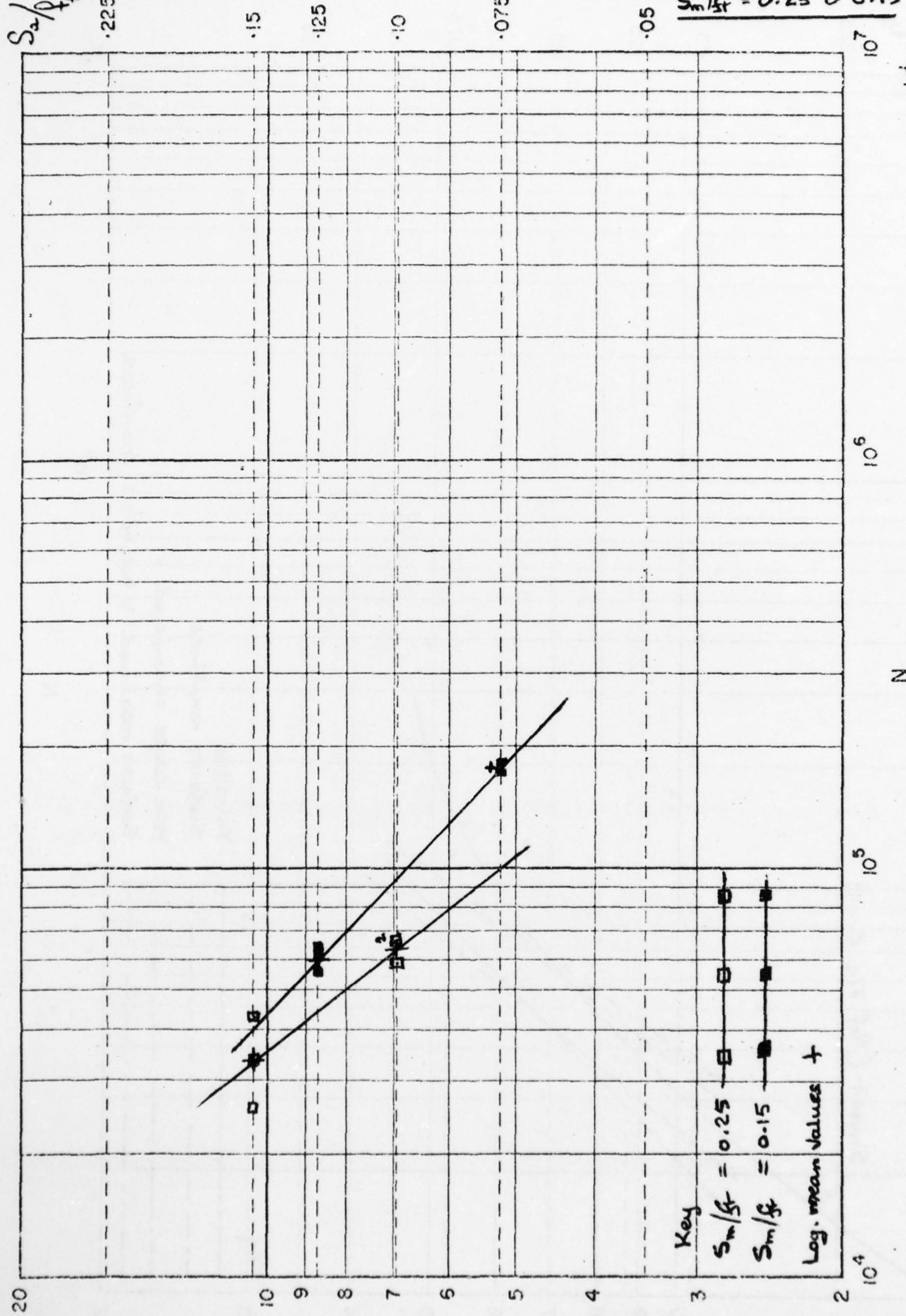


Sl. N°5 FIG. 5 - SPECIMEN TYPE 1 D 3/4. d/D = 3/8 PUSH FIT PIN - PIN LOADED

PREPARATION - SURFACES MACHINED & HOLE EDGES CHAMFERED

S_m/f_t = 0.25 & 0.15

Ref. TABLE 2(iv)



S.I. No5 FIG. 6 – SPECIMEN TYPE 1 D3/4, $d/D = 3/8$ PUSH FIT PIN – PIN LOADED

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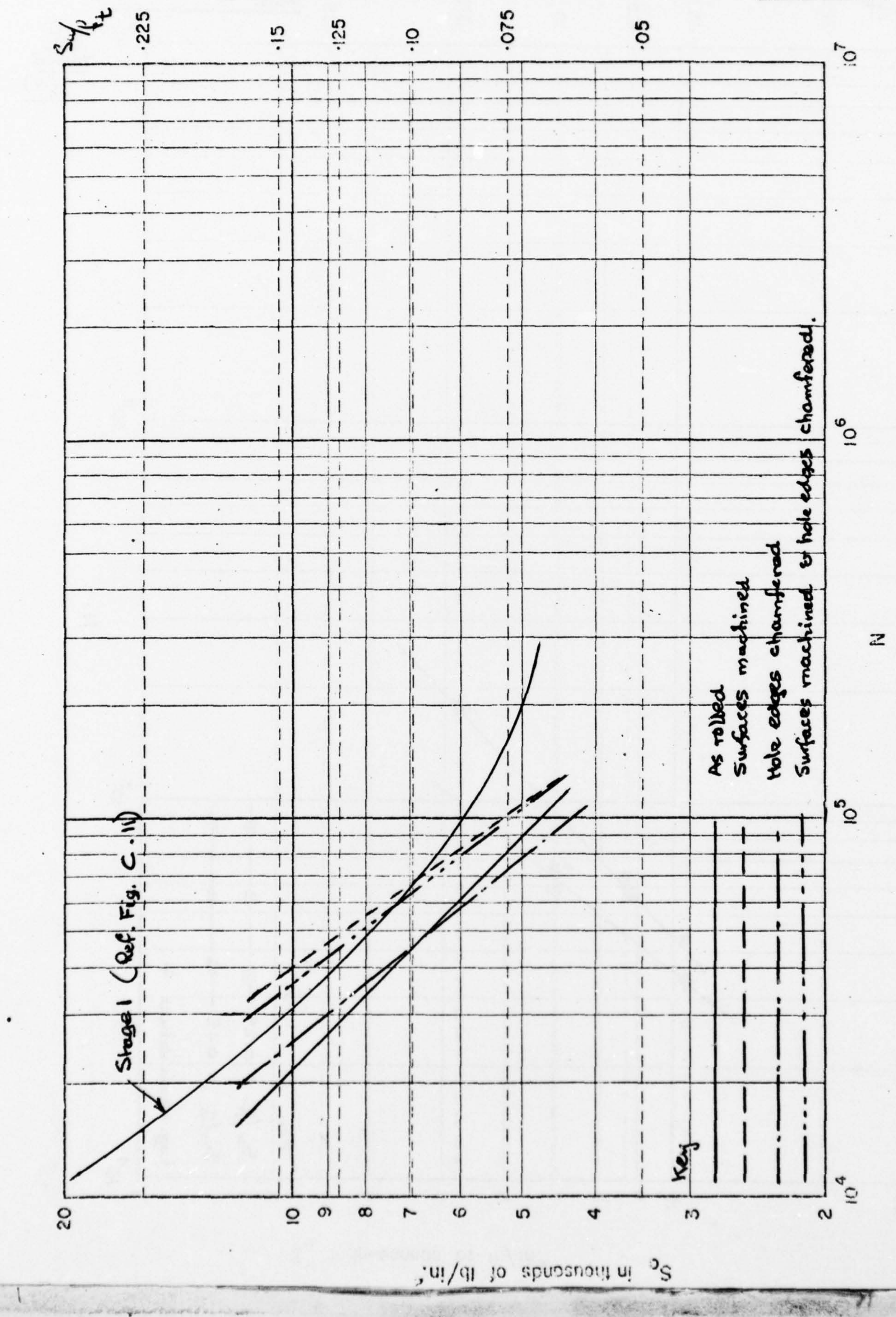
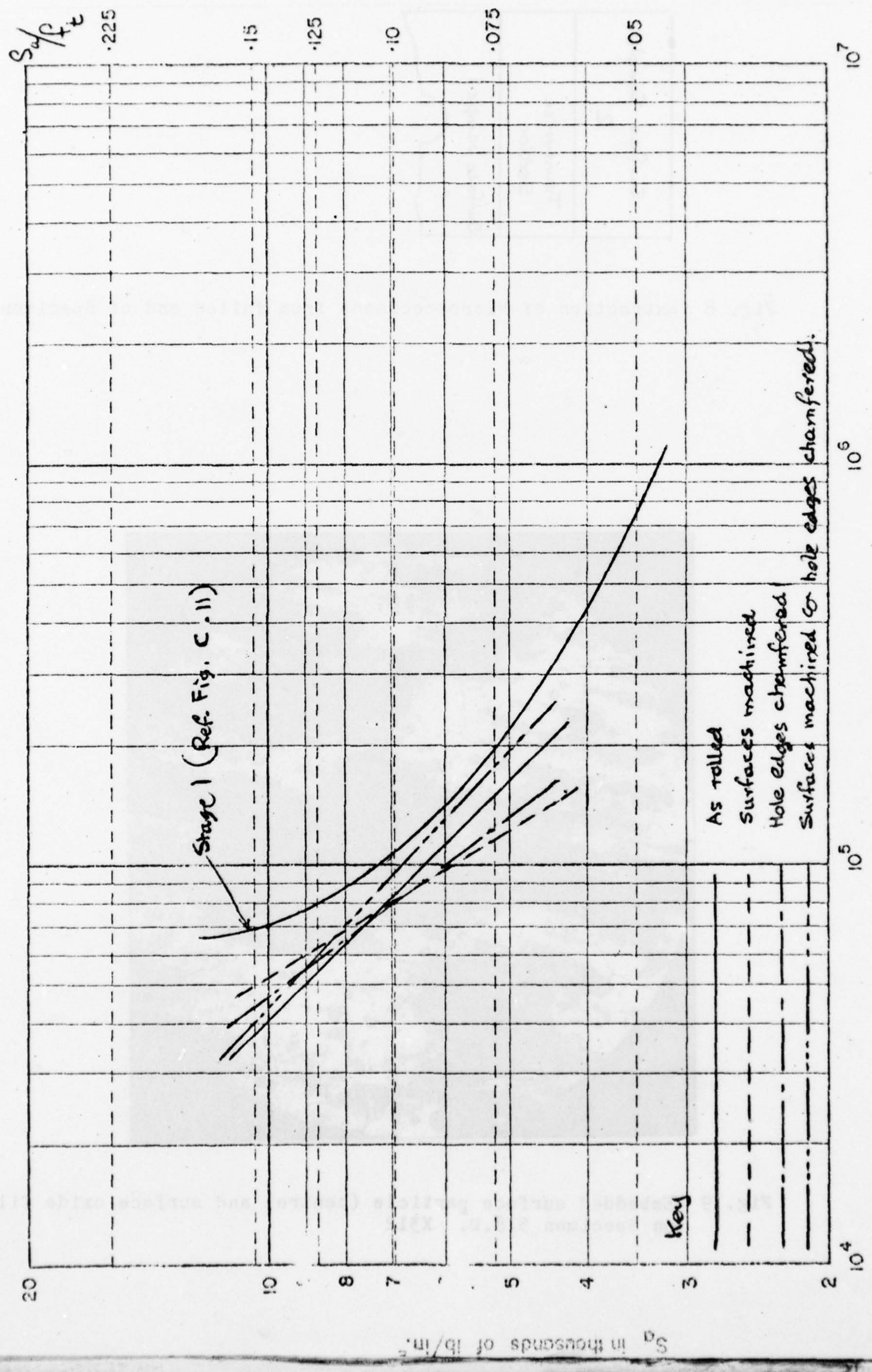
SUMMARY OF FOUR PREPARATIONS $S_m/f_t = 0.25$



S.I. No5 FIG.7 - SPECIMEN TYPE 1 D 3/4. $d/D = 3/8$ PUSH FIT PIN - PIN LOADED

SUMMARY OF FOUR PREPARATIONS $S_m/f_t = 0.15$



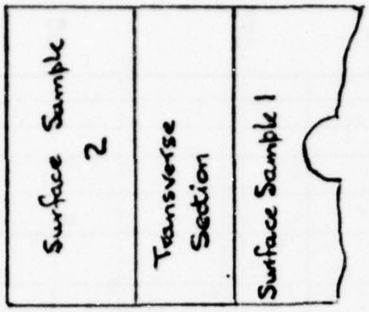


Fig. 8 Extraction of Microspecimens from failed end of Specimen 5.8.D

Fig. 9 Embedded surface particle (centre) and surface oxide films on Specimen 5.8.D. X312

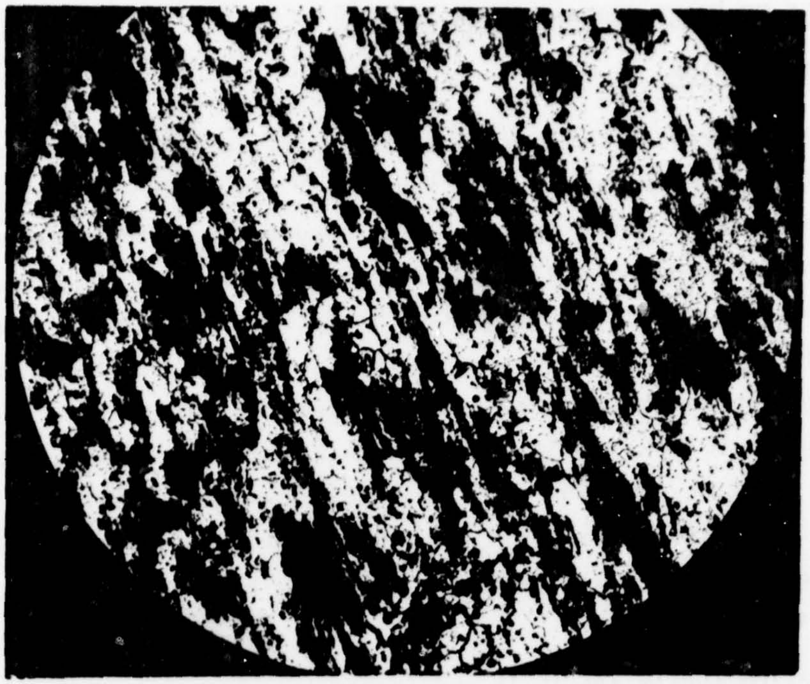


Fig.10 Surface oxide film and intercrystalline corrosion on Specimen 5.8.D X125

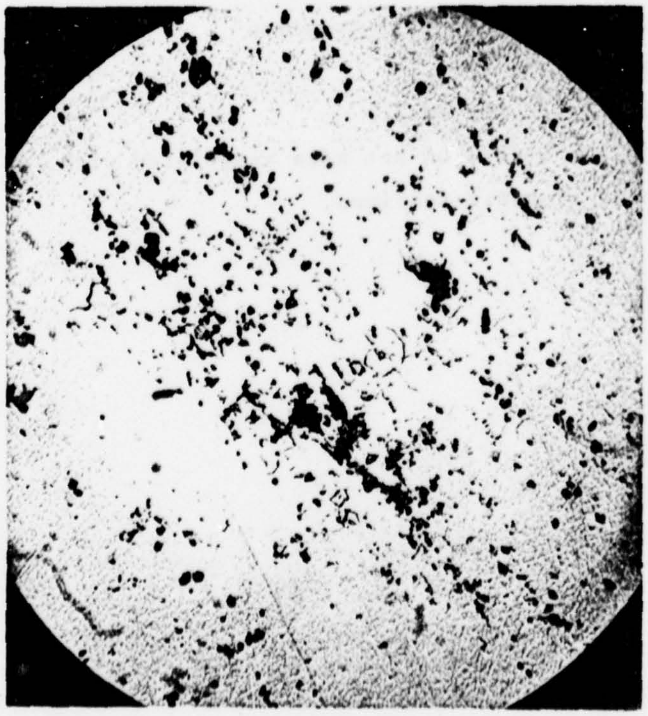


Fig.11 Surface appearance (X125) after light surface abrasion prior to olishing. Remnants of surface oxide and intercrystalline corrosion (unetched)

SUPPLEMENTARY INVESTIGATION No.6

THE INFLUENCE OF SMALL VARIATIONS IN PIN FIT

1. INTRODUCTION

Early in the progress of the Stage 1 tests there was some indication that small variations in the degree of fit of a "push fit" pin might produce significant changes in endurance. Consequently a small programme of tests was arranged, employing small specimens of the 4.C.9/32 type with a push fit pin and the pin unloaded. All the specimens were tested in fatigue at a common stress level. The pins were manufactured to within 0.0001 in of the nominal diameter. The holes in the plates were reamed to the "push fit" requirements of this research programme, namely to ±0.0003 in of the nominal diameter. Subsequently considerable efforts were made to determine the actual hole diameters of all the specimens to an accuracy of 0.00001 in or 0.1×10^{-4} in. These measured variations in pin fit were then considered in relation to the resulting endurances under the common fatigue loading.

2. NOTATION (Units are in lb and inches throughout)

For convenience the relevant Notation from the Stage 1 report is repeated below:

d = Nominal Diameter of hole and pin

D = Width of parallel section of test specimen

f_t = Average Tensile Strength of plate material (from tests)

f_p = Average 0.2°/o Proof Stress of plate material (from tests)

K'_t = Geometric Stress Concentration factor based on net area of cross section of test specimen

N = Endurance

S_m = Mean Stress on net area

S_a = Alternating Stress on net area associated with S_m

t = Thickness of plate specimen.

3. TEST PROGRAMME AND STRESS LEVEL

As already indicated only one type of specimen was employed namely Type 4.C.9/32. This was the small size specimen of Stage 1 with a nominal push fit pin, the pin unloaded; $d/D = 3/8$ and $K_t' = 2.28$.

Figure 1 gives details of the specimen.

Total number of specimens tested = 50.

Common Stress Level: $0.50\ f_t\ \pm 0.10\ f_t$.

4. MEASUREMENT OF THE DEGREE OF FIT

The pins were supplied to an accuracy of ±0.0001 in on the nominal diameter.

The measurement of the hole diameters to the accuracy required, using conventional methods, proved to be very difficult and the testing laboratory (Tiltman Langley Ltd, Redhill), devised an alternative method, using a comparator to measure the variation in height of a pyramid of four 1/8 in diameter hard steel balls, resting on a surface plate, and arranged within the specimen hole. Figure 2 illustrates the arrangement.

In practice it was found convenient to attach the upper steel ball of the pyramid to the stem of the comparator which was spring loaded, thus centralising the upper ball among the other three. The true diameter of the hole could then be calculated from the diameters of the balls and the height of the centre of the upper ball from the centres of the lower balls. Such a calculation would require very accurate measurement of the diameters of the steel balls, but preliminary tests indicated that by using the same four balls in the same relative positions, one could obtain sufficiently accurate records of the positive and negative deviations of the comparator height from a selected standard, and since the nominal diameter of the hole was known to be within the required tolerance this was considered to offer an acceptable compromise. The relation between comparator height and diameter of hole was not linear but nearly so and an approximate estimate gave the change in height to be 1.3 times the change in diameter. The selected standard was not entirely arbitrary, since it was chosen as the median of seven arbitrarily selected samples. The comparator reading was accurate to ±0.0001 in.

Measurements taken in this way were effectively the mean of three diameters at 120° to each other so that the differences between diameters according to the orientation of the specimen were minimal; but it was possible to detect a maximum and a minimum by rotating the triangle of balls in the hole. Both longitudinal and transverse readings were recorded and the mean calculated. It was not possible from the position of the balls to determine the direction of the maximum diameter, but other measurements indicated that this was in the longitudinal direction of the specimen.

The measurements recorded were of course at the point of contact of the balls with the wall of the hole, i.e. at about 0.03 in from one surface. By inserting floors of various thicknesses to carry the balls, (and by reversing the plates) it was found that the walls were sensibly parallel, except that all the specimens had an irregular lip at the surface, which was removed.

The laboratory and the specimens were kept at $60^{\circ} \pm 5^{\circ}$F during the tests. Furthermore, in order to ensure freedom from dust, the holes and balls were washed with trichloroethylene and the balls handled with forceps.

Figure 3 presents the results of these measurements in the form of a histogram, both in terms of change of comparator height and of change of diameter of hole.

5. RESULTS OF ENDURANCE TESTS

These are presented in Table 1, which gives specimen identity, comparator height reading relative to arbitrarily selected "standard" value, corresponding deviation from "standard" diameter of hole, subsequent endurances achieved and group designation (see below). The sign convention chosen is such that for the variation of diameter, positive deviations indicate an increase of diameter of the hole relative to the standard, and negative deviations, a decrease. The reverse is true for the height readings.

Figure 4 presents the same results in graphical form, the endurances being plotted horizontally on a log scale, against deviation from standard comparator height (left-hand vertical scale) and against deviation from standard hole diameter (right-hand vertical scale).

This plot of results shows that the majority of values lie in a central group ("B"), but three values lie well below the central group of endurances, while nine values lie well above (designated groups "A" and "C" respectively).

5.1 Group "B"

Considering first the central group, the scatter of endurance does not appear to be directly related to the magnitude of the deviation from the selected standard. However, a mean line has been drawn through the points, which shows a small, but significant trend towards an increase of endurance as the diameter of the hole decreases.

For comparison, the endurances for the Stage 1 results for this configuration, and at the same stress level as the present investigation, are plotted just above the graph of Figure 4 (Stage 1, Figure C.44). It will be seen that the scatter of endurances for Stage 1 is approximately the same as that for group "B" as a whole, whilst the possible range of deviation of hole diameter in Stage 1 was $\pm 3\times10^{-4}$ ins as compared with the present total range of 4×10^{-4} ins.

It would appear therefore, that the scatter of endurance for this present investigation is of the same order as that for a larger number of results taken from Stage 1 tests with approximately one and a half times the range of deviation of hole diameter.

5.2 Groups "A" and "C"

Clearly the number of results in each of these two groups is too small and their scatter too great, to enable them to be considered in the same way as group "B". However, this still leaves the question, - why are these results significantly out of line with the central group? A number of possible reasons have been explored, and these are noted in the following sub-paragraphs.

5.3 Non-homogeneity of Material

All the specimens were taken from one sheet, No.17, of the original 45 to 50 sheets of Stage 1, all from one melt. This leaves the possibility of variation of quality due to position of specimen within the sheet. Figure 5 shows the positions of the specimens from each of the three groups, and further sub-divides group "B" into approximately three numerically equal sub-groups of low, medium and high endurance within the "B" range.

A study of Figure 5 shows that the three group "A" specimens lie in a diagonal line across the lower half of the sheet (as drawn) whilst the somewhat larger number of "C" group specimens lie generally scattered about the upper half of the sheet, but not in any particular pattern.

The distribution of the "B" group suggests that there are areas of high endurance within the group (e.g. a considerable number of B or B_C in the lower third of the sheet). On the other hand there are B_A and B_C specimens adjacent to one another in the central region of the sheet, and indeed to some extent in the upper third of the sheet.

Thus non-homogeneity could account for some of the divergence of endurances, but there was no evidence to support this in the Stage 1 comparisons (Section 4 paragraph 4.5).

5.4 Variation of Pin Size

It has already been stated that the pins were manufactured to within ± 0.0001 in of the nominal diameter. Subsequently a sample of the pins was measured accurately, and found to be within ± 0.00005 in. Variations of this order could account for some of the scatter within the "B" group, but from an extrapolation of the mean line for the "B" group it is estimated that a variation of ±0.001 in would be required to account for the differences between the "B" group and either of the "A" or "C" groups.

5.5 Variations in Preparation of the Specimens

Two of the three specimens which gave very low endurances were found to be badly burred along the edges, but several of the specimens which achieved much higher endurances were also burred.

5.6 Variation in Atmospheric Conditions in the Laboratory

This feature was considered initially in the analysis, but apart from the special care taken, as described in paragraph 4, the distribution of the results with respect to time was checked and did not bear any relationship to the distribution of endurances.

5.7 Variation between Testing Machine used

Several testing machines of the same type and loading capacity were used for this investigation, but there was no co-relation between these machines and the extremes of endurance.

5.8 Possibility of a Discontinuous S-N Curve for the Material

Supplementary Investigation No.9 has shown that it is possible to find that at low values of S_a/f_t there is a discontinuity in the slope of the endurance curve. (See Figures 5a, 7a, 8a and 10a of that report). These discontinuities occurred at values of S_a/f_t in the range 0.045 to 0.095 whereas the present tests were at an alternating stress level of 0.10 f_t. Such discontinuities are believed to occur as a result of two different mechanisms of fatigue, one of which becomes ineffective in promoting failure at stress levels below a critical value, so that failure below the critical stress level occurs by the second mechanism. It is possible that this feature could account for some of the anomolies of groups "A" and "C", in relation to group "B".

6. EXAMINATION OF A NUMBER OF FAILED SPECIMENS

The rather inconclusive result of the preceding discussions led quite logically to a detailed examination of the nature of the failures of a selected number of specimens. This examination was made by the Structures Fatigue Laboratory of the Royal Aircraft Establishment at Farnborough, Hants. Their examination and subsequent report were made without prior knowledge of the endurance achieved. These endurances have been added later to the summary table which follows.

Thirteen specimens were examined, numbered as follows, all with the prefix 17, denoting the sheet number:
18D, 18F, 19A, 19I, 20E, 21E, 22H, 23C, 23E, 23I, 24D, 24F and 24H.

Reference to Figure 5 will indicate the location of these specimens within the sheet.

Of these specimens -

24F was unbroken

22H had failed away from the hole from a fatigue crack at one edge and the wedge grip marks suggested that the axis of load was displaced towards this edge.

The remaining specimens in which failure was from the central hole can be placed in one of the following three categories (See Figure 6).

(a) One principal fatigue crack from line of fretting.

This failure can be regarded as normal, and occurred consistently in 8 specimens. Bearing between the pin and the bore of the hole was apparent over an arc of about 60° on each side of the hole as indicated in Figure 6a. At the edges of these bearing areas (A-B, and C-D), the movement between the pin and the bore produced lines of fretting damage in the bore, and the principal fatigue crack emanated from one of these lines. In some cases a small secondary crack had developed at a fretting line on the opposite side of the hole.

(b) Symmetrical fatigue cracking on each side of hole, from lines of fretting at the edge of the bearing area.

This type of failure was found on only one specimen (23I), and the fatigue cracks emanated from the edge of the fretted area in the bore (See Figure 6b). There were circumferential marks in the bore and this feature together with the symmetrical fatigue cracking suggest a low fatigue endurance. (It was in fact among the lowest endurances of group "B").

(c) Fatigue cracks from the centre line on both sides.

There were two specimens which failed in this manner (See Figure 6c) and the origins of the crack were not influenced by fretting, which was either slight or negligible. These were the only specimens in which the fractured surfaces were damaged by impact of the failure.

Summarising this examination, and adding the appropriate endurances and associated group letters, we have:

Specimen Identity	Description of Failure	Group	Endurance (Cycles)	Figure Number
17.24.F	Unbroken	C	10 000 000	-
17.22.H	Failed at edge, away from hole due to off centre loading	B	960 000	-
17.18.D	One fatigue crack from line of fretting	C	4 200 000	6a
17.18.F		A	98 000	
17.20.E		C	4 200 000	
17.24.H		A	580 000	
17.19.A	One fatigue crack from line of fretting, plus small secondary crack on opposite side of hole	B	730 000	6a
17.21.E		B	780 000	
17.23.E		B	720 000	
17.24.D		C	4 200 000	
17.23.I	Symmetrical fatigue crack on each side of hole, from edge of fretted area. Poor finish in bore.	B	540 000	6b
17.19.I	Fatigue cracks from centre line on both sides, not influenced by fretting.	B	890 000	6c
17.23.C		B	420 000	

A study of this table shows that there is no relationship between endurance and type of failure.

7. CONCLUSIONS

(i) In a limited attempt to investigate the effect on endurance of small variations of pin fit a discontinuous distribution of endurance was obtained, leading to three separate groups of results. Notwithstanding this feature, $76^{o}/o$ of the results lay in a central group and a mean line through this group showed a small but significant increase in endurance as the degree of fit improved, i.e. as the diameter of the hole decreased. This effect is not of great importance because the scatter of results about the mean is of the same order as the general scatter of corresponding results of Stage 1 tests (see Figure C.44 of Stage 1), which were for a range of deviation of hole diameter of $\pm 3x10^{-4}$ ins. from the nominal compared with the present total range of $4x10^{-4}$ ins.

(ii) One probable cause of the discontinuity of distribution of results in respect of endurance is the non-homogeneity of the material within the particular sheet used, with patches of material a few inches across giving consistently high or consistently low endurance. This variation in material quality was not found in the Stage 1 tests.

(iii) It is known that some materials, including B.S. L71 Aluminium Alloy from which these specimens were made, exhibit a discontinuity in the endurance curve in the form of a sudden change of slope of the curve at a relatively low alternating stress level. Such a discontinuity is believed to be due to two different mechanisms of fatigue, one of which becomes ineffective in promoting failure at alternating stress levels below a critical value. This feature could have had some influence upon the results of this test programme, since the test alternating stress was approximately of the order of this critical level.

(iv) Other possible causes of the discontinuities observed were studied; namely:

(a) Range of pin size used.

(b) Variation in standard of preparation of specimen.

(c) Atmospheric conditions in the laboratory.

(d) Variation between testing machines used,

- but none was considered to have had any effect upon the results obtained.

(v) An examination of a selected number of failed specimens showed no relationship between endurance and nature of failure. 60°/o of the failures examined were very similar in form, but included some of the greatest and some of the least of the endurances achieved.

(vi) In retrospect, it is thought that the conclusions might have been more decisive if this investigation had included some of the large size specimens as well as some of the small size. Furthermore a second (lower) value of mean stress would have helped, together with a range of alternating stresses, but this would have required more specimens than were available and a much longer time to complete the testing.

TABLE 1 ENDURANCES IN RELATION TO DEVIATION FROM STANDARD COMPARATOR READING AND CORRESPONDING DEVIATION FROM STANDARD HOLE DIAMETER

Specimen Identity	Deviation from "standard" comparator height (ins^{-4})*	Deviation from "standard" Hole diameter (ins^{-4})ϕ	Endurance (Cycles)	Group
17.21.B	-3.50	2.7	4 000 000	C
17.21.C	-3.50	2.7	480 000	B
17.18.D	-3.25	2.5	4 200 000	C
17.19.J	-3.25	2.5	500 000	B
17.24.H	-3.25	2.5	80 000	A
17.23.H	-3.00	2.3	620 000	B
17.21.D	-3.00	2.3	480 000	B
17.20.F	-3.00	2.3	620 000	B
17.22.J	-2.75	2.1	580 000	B
17.22.D	-2.75	2.1	470 000	B
17.17.I	-2.75	2.1	500 000	B
17.23.A	-2.75	2.1	530 000	B
17.24.E	-2.50	1.9	1 000 000	B
17.22.A	-2.50	1.9	460 000	B
17.22.C	-2.25	1.7	290 000	B
17.24.G	-2.25	1.7	310 000	B
17.20.G	-2.25	1.7	48 000	A
17.21.A	-2.00	1.5	510 000	B
17.23.I	-1.75	1.3	540 000	B
17.24.F	-1.75	1.3	10 000 000U	C
17.19.G	-1.75	1.3	410 000	B
17.18.C	-1.75	1.3	550 000	B
17.18.F	-1.50	1.2	98 000	A
17.19.I	-1.50	1.2	890 000	B
17.23.B	-1.00	0.8	800 000	B
17.24.D	-1.00	0.8	4 200 000	C
17.24.[illegible]	-1.00	0.8	630 000	B
17.18.E	-1.00	0.8	5 800 000	C

Continued..

*
ϕ } see next page

SUPPLEMENTARY INVESTIGATION No.6

TABLE 1 (Continued)

Specimen Identity	Deviation from "standard" comparator height (ins^{-4})*	Deviation from "standard" Hole diameter (ins^{-4})ϕ	Endurance (Cycles)	Group
17.20.E	-0.75	0.6	4 200 000	C
17.21.E	-0.50	0.4	780 000	B
17.22.B	-0.50	0.4	910 000	B
17.20.B	-0.25	0.2	5 000 000	C
17.22.G	-0.25	0.2	420 000	B
17.23.C	-0.25	0.2	420 000	B
17.19.A	0	0	730 000	B
17.21.J	0	0	1 800 000	B
17.19.F	0	0	680 000	B
17.19.B	0	0	5 400 000	C
17.23.E	0.25	-0.2	720 000	B
17.22.H	0.50	-0.4	960 000	B
17.24.H	0.50	-0.4	580 000	B
17.19.H	0.75	-0.6	1 100 000	B
17.19.C	0.75	-0.6	10 000 000U	C
17.17.J	0.75	-0.6	1 500 000	B
17.24.J	1.00	-0.8	870 000	B
17.23.D	1.00	-0.8	920 000	B
17.22.E	1.50	-1.2	800 000	B
17.17.G	1.50	-1.2	840 000	B
17.20.J	2.00	-1.5	1 700 000	B
17.22.F	2.00	-1.5	750 000	B

*Quoted to nearest 0.25x10^{-4} ins. - Arbitrarily selected "standard" comparator height was that for specimens 17.19.A, 17.21.J, 17.19.F and 17.19.B.

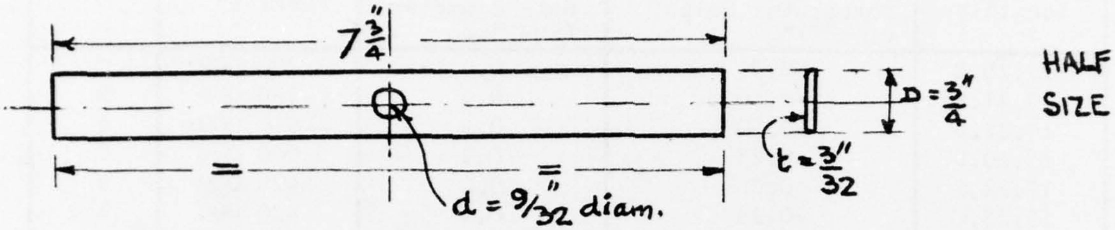
ϕQuoted to nearest 0.1x10^{-4} ins. - selected "standard" corresponds to that chosen for comparator height

Sign Convention

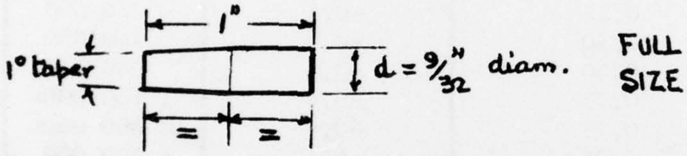
Negative deviations from standard comparator height Positive deviations from standard hole diameter	both denote an increase in hole diameter.

FIGURE 1 DETAILS OF SPECIMENS - TYPE 4 C 9/32

PLATE - Aluminium Alloy to Specification B.S. L71



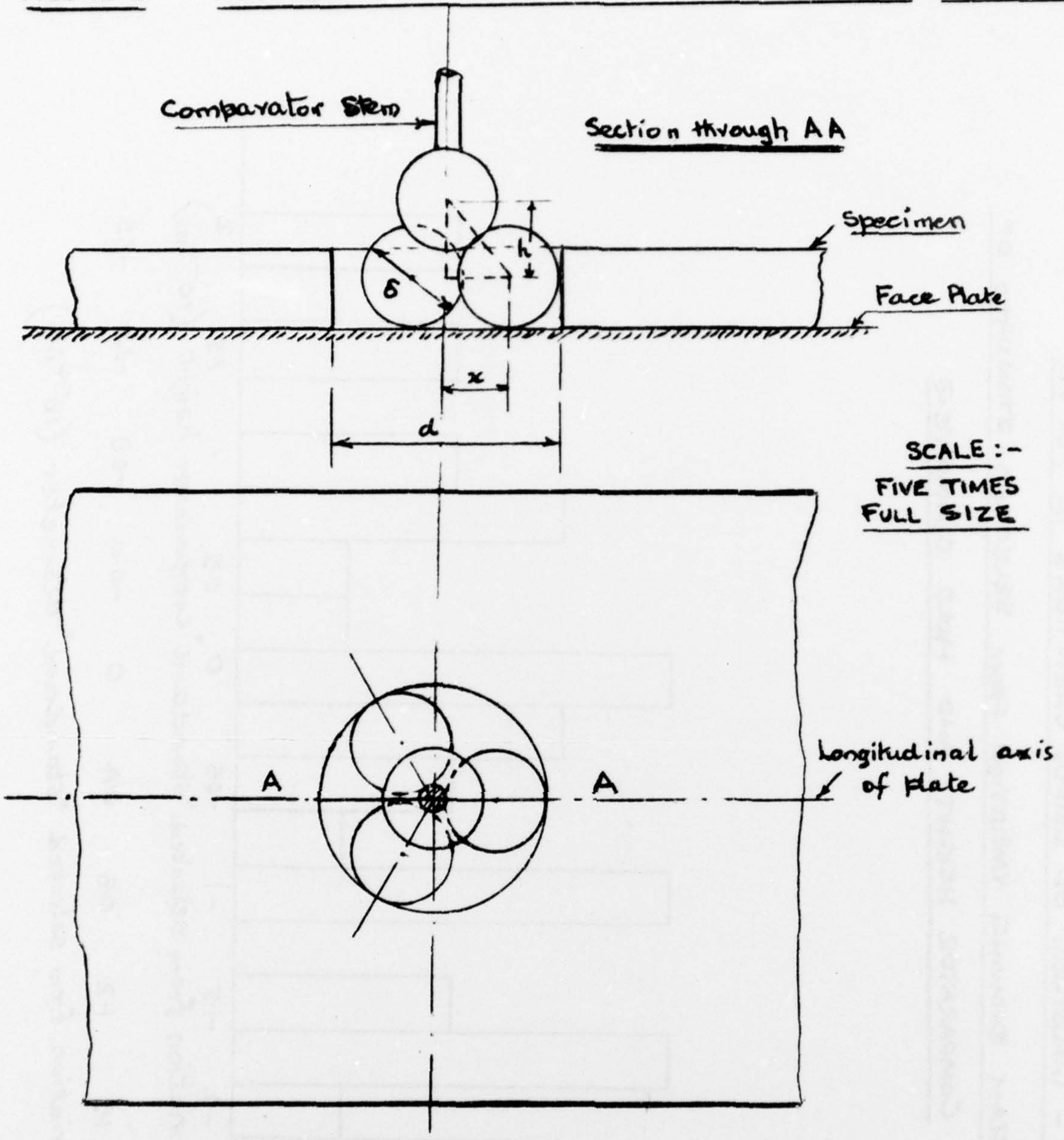
PIN - Steel to Specification B.S. S 94



LIMITS - Hole Diameter: Manufactured to ± 0.0003" but individual hole diameters were computed from actual measurements of the height of a pyramid of 4 steel balls, using a comparator, and found to range from + 0.00027" to − 0.00015" relative to an arbitrarily selected 'standard'.

Pin Diameter: Manufactured to ± 0.0001" but a selected number of the pins used were measured and found to be within ± 0.00005" of the nominal diameter.

FIGURE 2 ARRANGEMENT OF PYRAMID OF STEEL BALLS (1/8" DIAMETER)



d = diameter of hole = 9/32" nominal

δ = diameter of steel balls = 1/8"

h = deduced height of centre of upper ball from centre of lower ball.

Then $x^2 = \delta^2 - h^2$ or $x = \sqrt{\delta^2 - h^2}$

$$\therefore \underline{\text{True } d} = 2\left(x + \frac{\delta}{2}\right) = \underline{2\left(\sqrt{\delta^2 - h^2} + \delta/2\right)}$$

SJ. No. 6 – INFLUENCE OF SMALL VARIATIONS IN PIN FIT

FIGURE 3 – HISTOGRAM SHOWING VARIATION FROM SELECTED STANDARD OF COMPARATOR HEIGHT AND HOLE DIAMETER

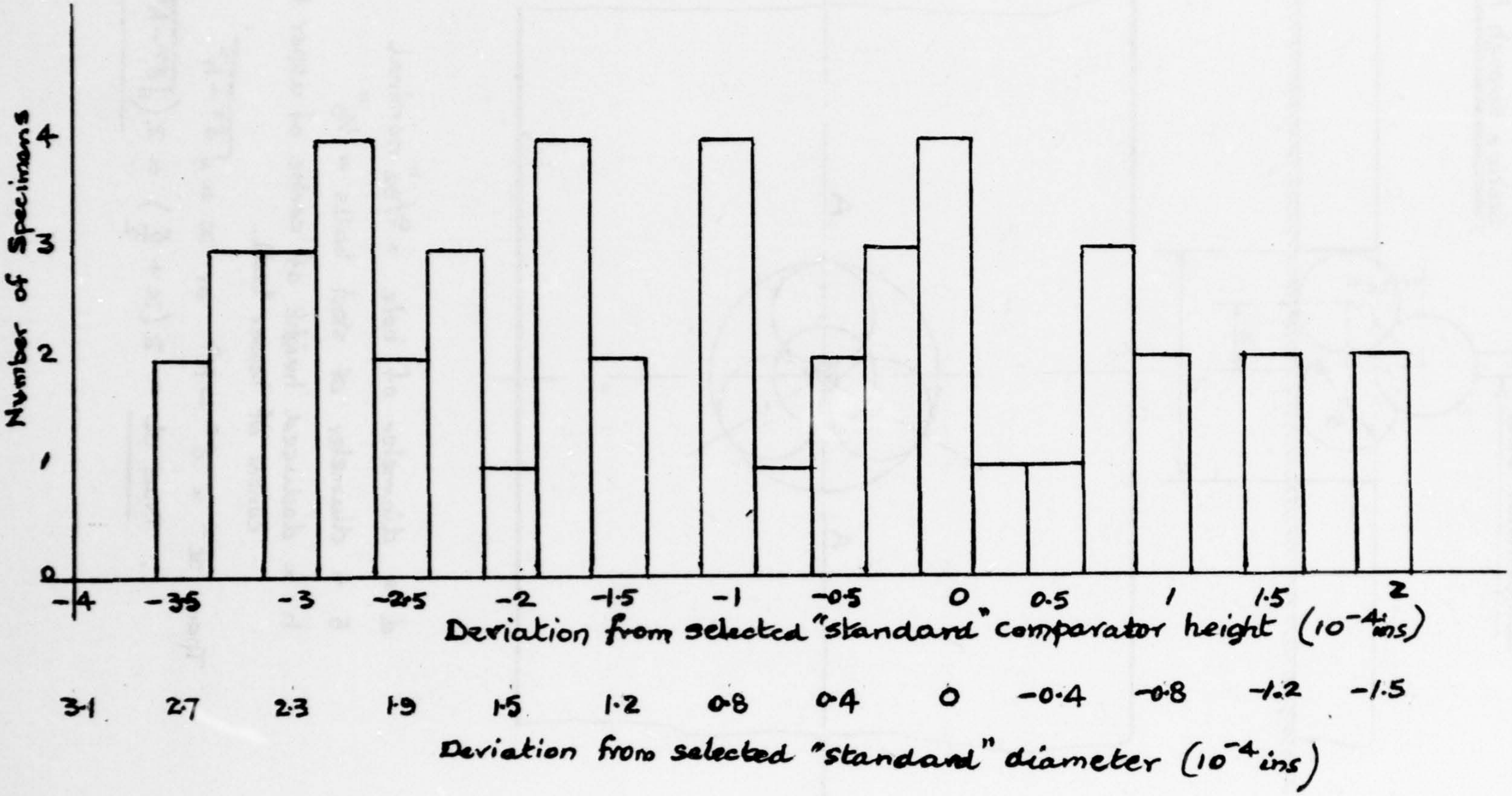


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FIGURE 4 ENDURANCES V. HOLE DIA. DEVIATION

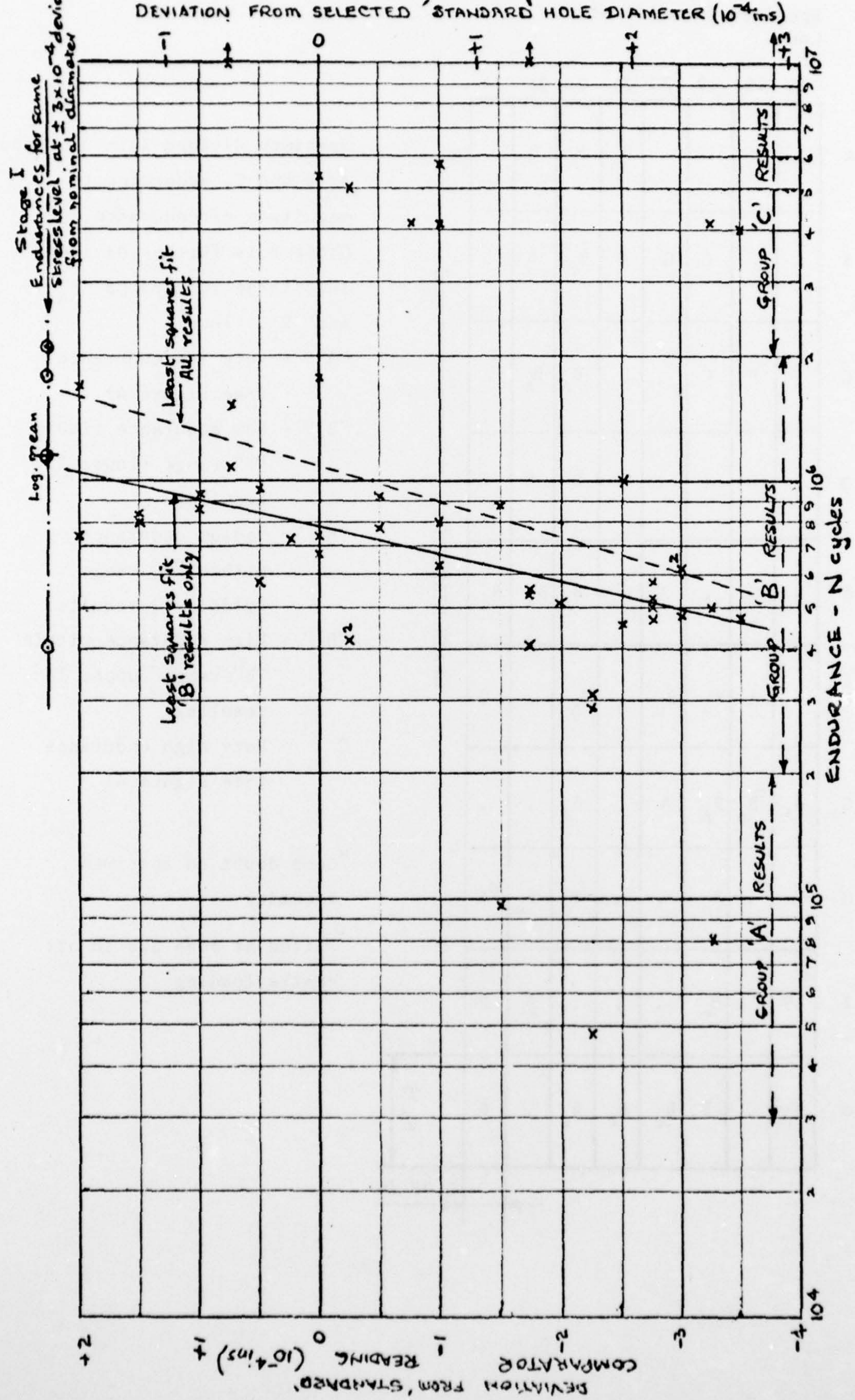
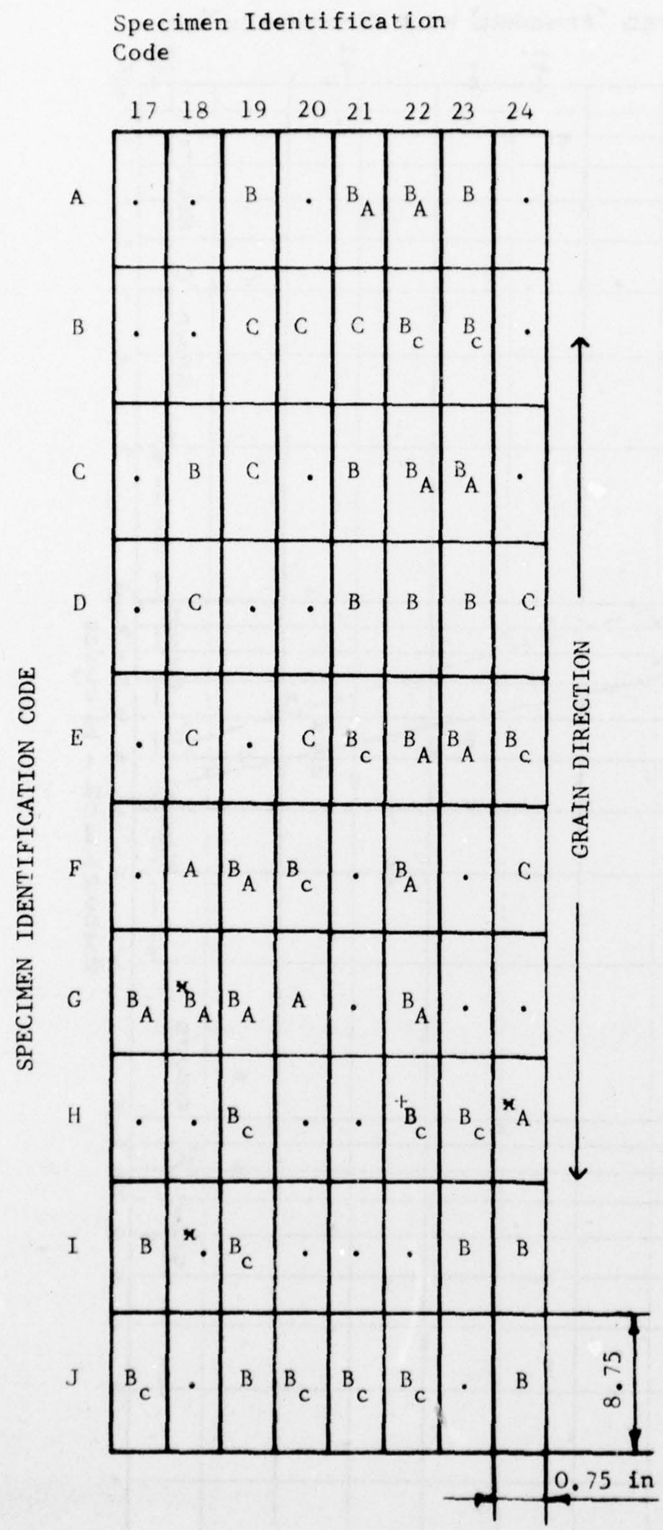


FIGURE 5 LOCATION OF SPECIMENS WITHIN SHEET No.17



	17	18	19	20	21	22	23	24
A	•	•	B	•	B_A	B_A	B	•
B	•	•	C	C	C	B_C	B_C	•
C	•	B	C	•	B	B_A	B_A	•
D	•	C	•	•	B	B	B	C
E	•	C	•	C	B_C	B_A	B_A	B_C
F	•	A	B_A	B_C	•	B_A	•	C
G	B_A	×B_A	B_A	A	•	B_A	•	•
H	•	•	B_C	•	•	+B_C	B_C	×A
I	B	×•	B_C	•	•	•	B	B
J	B_C	•	B	B_C	B_C	B_C	•	B

Specimen divided into 3 Groups, A, B and C, according to magnitude of endurance. Group B is further divided into three sub-groups B_A, B and B_C. Thus:-

"A" - very low endurance (See Figure 4)

"B_A" - Low endurance within "B" range (lower 13 results)

"B" - Medium endurance within "B" range (middle 12 results)

"B_C" - High endurance within "B" range (upper 13 results)

C - Very high endurance (See Figure 4)

×Some doubt on specimen identity

+Failed at edge due to off centre loading

S.I. Nº 6 INFLUENCE OF SMALL VARIATIONS IN PIN FIT

FIGURE 6 NATURE OF FAILURES OF SELECTED SPECIMENS

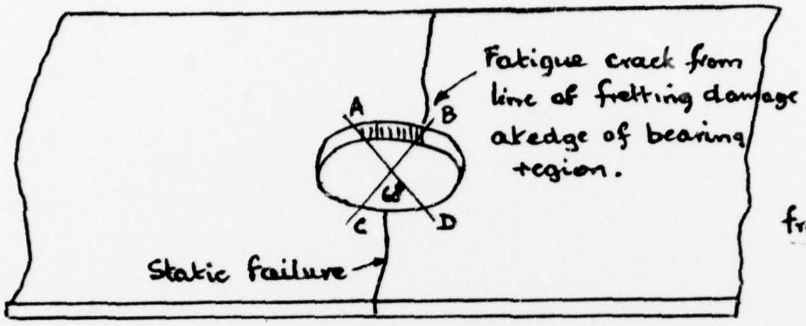


FIG. 6(a)

One fatigue crack from line of fretting.

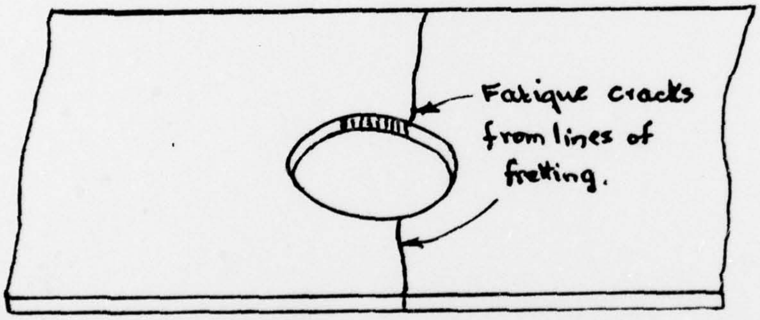


FIG. 6(b)

Two fatigue cracks from lines of fretting.

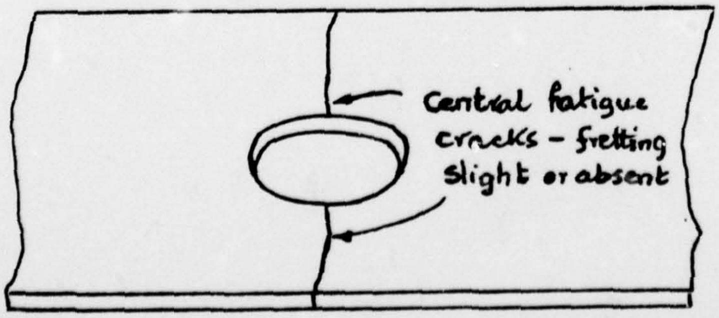


FIG. 6(c)

Central fatigue cracks

REPORT DOCUMENTATION PAGE

(Notes on completion overleaf)

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DRIC-BR-60446		S&T-MEMO-1-77	UNLIMITED

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3134000R	ENGINEERING SCIENCES DATA UNIT, LONDON, UK

5a. Sponsoring Agency's Code (if known)	6a. Sponsoring Agency (Contract Authority) Name and Location
7248000N	PROCUREMENT EXEC., MIN. OF DEFENCE, DR AIR, UK

7. Title

BOLTED JOINT FATIGUE PROGRAMME, VOLUME 3, STAGE 2, SUPPLEMENTARY INVESTIGATIONS 1 TO 6

7a. Title in Foreign Language (in the case of translations)

7b. Presented at (for conference papers). Title, place and date of conference

8. Author 1. Surname, initials	9a Author 2	9b Authors 3, 4...	10. Date	pp	ref
Sandifer, R.H.			5.1978	171	2

11. Contract Number	12. Period	13. Project	14. Other References

15. Distribution statement

Descriptors (or keywords)

*Bolted joints, *Fatigue (materials), Aluminium alloys, Fatigue tests, Photoelasticity, Steels, Stress corrosion

Abstract The programme consisted of two major parts - a photoelastic investigation into the stress distribution and resulting stress concentration factors in a family of simple bolted joints, and a correlated series of fatigue tests on bolted metal joints having the same geometrical form as the photoelastic ones using a commonly employed aluminium alloy for the plates and a steel in current use for the pins.

MC

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