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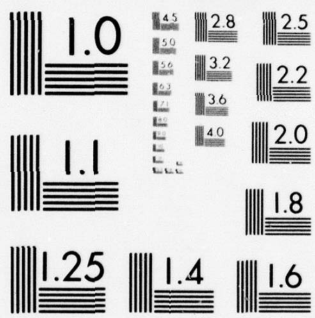
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PROCUREMENT EXECUTIVE MINISTRY OF DEFENCE

BOLTED JOINT FATIGUE PROGRAMME

VOLUME I

STAGE 1 SECTIONS 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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BOLTED JOINT FATIGUE PROGRAMME

VOLUME 1

STAGE 1 SECTIONS 1 TO 6

By

R.H. Sandifer

May 78

166 p.

(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

BOLTED JOINT FATIGUE PROGRAMME STAGE 1

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BOLTED JOINT FATIGUE PROGRAMME

OF THE ROYAL AERONAUTICAL SOCIETY FATIGUE COMMITTEE

STAGE 1

VOLUME I SUMMARY

Some years ago the Royal Aeronautical Society proposed and the then Ministry of Supply agreed to support financially, an extensive programme of research into the fatigue characteristics of bolted joints. As a preliminary to the main fatigue programme, a series of photoelastic tests was conducted at University College, London, on specimens nominally identical in geometry with those to be used for the actual joints, in order to measure the stresses induced under a variety of configurations and loadings. These were completed and reported upon. (Reference 1 to 5).

Meanwhile the manufacture, assembly and testing of the actual bolted joint specimens was undertaken and over a considerable period of time the results were fed back to the Royal Aeronautical Society Fatigue Committee. This Committee has used and is still using the data to produce new, or to modify existing Data Sheets in its Fatigue Sub-series.

Notwithstanding this action, it was thought that the basic data would be of value to designers and research workers. Thus this report presents details of all the tests carried out in the main programme which has become regarded as 'Stage 1' of the Bolted Joint Fatigue Research. (Some nine "Supplementary Investigations" make up 'Stage 2' and are reported in VOLUMES III and IV of this S and T Memo).

In Stage I all the joints were of the single pin form, using aircraft materials, B.S.L.71 for the plates and B.S.S.94 for the pins representing bolts, but without any clamping effects.

A small range of three sizes of specimen was covered, each incorporating three variations in geometry as expressed by the ratio of the diameter of the pin to the width of the plate.

For most of these nine configurations the following three pin/hole combinations were included:- unfilled hole, push fit pin and interference fit pin (two degrees of interference).

Among the pinned specimens the effects of both pin unloaded (i.e. plate loaded) and pin loaded conditions were determined. Finally a few specimens with loose fit pins were included for comparison.

(x)

A range of at least three and often four different mean stresses was covered in the loading, each with at least three but usually four degrees of alternating stress. For each combination of test loading and configuration, three nominally identical specimens were tested. Only in a comparatively few cases were the results nullified, due to a variety of difficulties. For the majority of cases reasonable endurance curves were obtained. The results are tabulated and plotted in detail in Appendix (Volume II of this S and T Memo). In addition, in Sections 3 and 4 the report attempts to analyse these results to determine the effects of the major variables included in the investigation i.e. mean stress, geometry, size of specimen and degree of fit of pin.

Because of the complexity of influence and interdependence of the various parameters involved, some re-grouping of the results has been made in order to produce where possible "Summary Presentations" of the results and it is hoped that these will clarify the findings.

In Section 5 the results of Stage 1 of the research have been compared with a number of existing RAeS Data Sheets. The comparisons are, in general, good and quite encouraging, and the large amount of data now available has enabled the RAeS Fatigue Committee to proceed with the revision, extension or consolidation of a number of these data sheets. The possibility of creating additional data sheets is under consideration.

The main conclusions are given in Section 6 of the Report.

STAGE 1 OF BOLTED JOINT FATIGUE RESEARCH

1. INTRODUCTION

1.1 Historical

Early in 1953, the Structures Committee of the Royal Aeronautical Society put forward proposals for research into the fatigue characteristics and performance of bolted joints. The choice of this particular research was considered justified because,

(i) the bolted joint occurs in a multitude of locations in an aircraft structure,

(ii) the bolted joint is particularly liable to failure from fatigue, and

(iii) notwithstanding the availability of existing ad hoc test data on the subject, the results of a specific programme of correlated tests would prove to be of great value to designers and research workers.

The specific programme consisted of two major parts:-

(a) A photoelastic investigation into the stress distribution and resulting stress concentration factors in a family of simple bolted joints.

(b) 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, (B.S. L71 and B.S. S94 respectively).

The planning of the two parts of the initial programme was completed in 1953 and 1954 respectively. The photoelastic investigation was started early in 1954 at University College London, under Ministry of Supply Contract. Initial results were published in January 1955 and more in August 1955. Further results were published in November 1956 and in May 1958.

In 1955 and 1956 some details of the metal fatigue test programme were reviewed in the light of the photoelastic results to date, and early in 1956 the contract for the manufacture of the specimens was placed by the Ministry of Supply with Plant Machinery and Accessories Ltd, of North Kensington, London W.10. The contract for the initial testing of the specimens was placed by the Ministry of Supply, with the Department of Metallurgy, University of Cambridge, in July 1957. Early in 1959 a similar contract was placed with Short Brothers and Harland Ltd, Belfast to test all the large size specimens.

In 1961, Tiltman Langley Ltd, of Redhill, Surrey, received a contract to test some of the small and medium size specimens, in order to relieve the work load on Cambridge University.

In addition to these contracts, a number of exploratory and special tests were undertaken by National Engineering Laboratory (NEL) East Kilbride, Glasgow, generally to establish techniques or to solve special problems. This laboratory has excellent facilities for, and considerable experience in fatigue investigations.

The relevant Contract Numbers are given below:-

Manufacture of Specimens

Plant, Machinery and Accessories Ltd.

Contract No. 6/P and Eq/17398/CB7 (b)

The pins were made almost exclusively by the Royal Ordnance Factory at Woolwich, and since this factory was part of the then Ministry of Supply, arrangements for manufacture were internal to the Ministry.

Tests

(a) University of Cambridge

Agreements Nos. 7/Gen/1623 and PD/29/030

(b) Short Brothers and Harland Ltd.

Contracts Nos. 6/Exptl/4900/CB38 (b)
and KS/1/0364/CB43 (a)2

(c) Tiltman Langley Ltd.

Contract No. KS/1/036/CB43 (a)2

The work of co-ordinating and monitoring this extensive programme had, by 1955, become considerable and it was decided by the Structures Committee of the RAeS that the time was appropriate to form a separate Fatigue Committee to investigate and develop the programme. This Committee first met in December 1955 and has since continued to deal with the technical administration of the programme, in conjunction with the Ministry of Supply*. The Fatigue Committee does, of course, deal with all other investigations on behalf of the Royal Aeronautical Society, in respect of fatigue.

The testing of the metal fatigue specimens and the analysis of the results of the initial programme have taken a considerable time because often the work had to take second priority to more urgent investigations in the laboratories concerned. Again, staff were not always available to review, analyse and report fully on all the data collected over the years. However, the work has now been completed and is regarded as Stage 1 of the wider programme seen originally in general terms, and subsequently developed to include other variables such as effects of clamping, effects of cold working the surface and effects of chamfering the edges of the holes.

*Later Ministry of Technology and now Ministry of Defence

1.2 Main Objectives of the Programme

1.2.1 The Photoelastic Programme

The photoelastic investigation was originally planned to include multi-bolted joints as well as single bolted joints but so far only single hole tests have been made, with the pin in double shear. Within this limit the following variables were tested:-

Ratio of diameter of hole to width of plate

Ratio of Young's Modulus of the material of the pin to that of the plate, and

Degree of fit between pin and hole.

In addition to testing the plane material in tension the loadings comprised:-

Unfilled hole, plate in tension

Pinned hole, tensile load applied to plate only

Pinned hole, tensile load applied to pin only with the pin in double shear.

In all these configurations and for all the variables listed, the longitudinal and transverse stress distributions were measured on a section through the hole at right angles to the longitudinal axis of the test piece. From these stress distributions, stress concentration factors were obtained. Using these data and a knowledge of the fatigue endurance of the basic material of a joint plate, a first approximation to the endurance of the joint under fluctuating tension could be made (see paragraph 1.3).

The results of the photoelastic investigation are reported in References 1, 2, 3, 4 and 5.

1.2.2 The Fatigue Tests of the Bolted Joints

Notwithstanding the information gained from the photoelastic programme, it was appreciated that such a programme would not include the effects of plastic flow and work hardening which is bound to occur in actual metal joints under load. Moreover, endurances estimated from data obtained from the photoelastic tests could not include the effects of fretting.

Thus the programme of fatigue tests on the metal joints would provide a comparison with and a check on the endurances estimated from the photoelastic tests, and also provide some information on the influence of fretting, if and when it occurred.

To this end the geometrical characteristics and degrees of fit for the metal joints were made the same as those used in the photoelastic programme.

This programme, designated Stage 1, is the subject of the present report.

1.3 Relation to the Fatigue Data Sheets of the Royal Aeronautical Society (Reference 6)

In May 1959 the Fatigue Committee issued a Tentative Data Sheet A.05.02 "Estimation of Endurance of Pin Joints" based upon the results of the photoelastic investigation.

This Data Sheet was revised and re-issued on a more substantial basis in May 1965 when an adequate number of results from the fatigue tests was known. At the present time further data are becoming available from an extension of the current programme and from other research workers, and if necessary a second revision will be made.

The Data Sheet which is of necessity somewhat complex, gives a means of estimating the endurance of pin joints from fatigue data on other types of specimen, by estimating the maximum shear stresses at the critical region (the origin of expected failure) in the pin joint. The choice of maximum shear stress as the criterion is due to the nature of the combined stress system prevailing. Under such a system fatigue endurance is more closely related to the maximum shear stress than to the maximum tensile stress.

The internal stresses due to interference fit pins (where used) are obtained from another Data Sheet - Item 65004 pp53-55 inclusive (or pp57-59 inclusive for interference fit bushes).*

Having obtained the maximum shear stresses for the limits of the fatigue cycle on the bolted joint, these are expressed in terms of an equivalent loading cycle on another type of specimen for which fatigue data are already available.

Two methods of estimating the endurance are given:-

(a) by reference to fatigue data for unnotched specimens, Data Sheet E.07.03 and

(b) by reference to data for single pin joints without interference, Data Sheet E.05.03+

Currently, the results of tests on the actual joints also provide useful supporting data and checks on the Endurance Curves of Data Sheet E.05.01, E.05.03+ and E.05.04, - Endurance of structural joints, Endurance of lugs without interference fits and Endurance of lugs with interference fits.

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*Now revised and issued as Data Item No.71011

+Superseded by Data Item No.72020.

It is hoped that eventually some information on size effect, variation of geometry, fretting and other features will become available from the full results, and that in consequence new or revised Data Sheets will be issued.

2. DESCRIPTION OF THE PROGRAMME

2.1 Outline of the Programme of Fatigue Tests

Turning now to the actual schedule of fatigue tests undertaken, this was as follows. (Including some changes from the original plan noted in paragraph 2.2 below).

2.1.1 The Test Specimens

Like the photoelastic ones, these were of the single hole, flat plate type, with the pin in double shear. It was hoped by choosing three different sizes, defined by the width of the parallel portion, to obtain some information on the effect of size of specimen. The widths chosen were 2 in, 1¼ in and ¾ in, i.e., in the ratios 2.67; 1.67; 1. The essential dimensions are given on Figures 2.1 to 2.5. (For assembly of specimens in the testing machine see Appendix A Figures A.1, A.2 and A.3).

Figure 2.1 for large specimens, 1A to 1D
Figure 2.2 for medium specimens 2A to 2D
Figure 2.4 for small specimens 4A to 4D
Figure 2.3 gives dimensions for the "no hole" specimens which were used for some of the static tests.
Figure 2.5 gives Limits of Manufacture.

The various types of specimen are defined thus:-

Type A for unfilled hole, and pin unloaded tests, i.e. "plate only" loaded. The enlarged ends were an insurance against failures at the jaws of the testing machine.

Type B for "pin loaded" tests, the pin being loaded in double shear.

Type C for similar tests to A, of parallel width, and used for specimens in which the hole size was sufficiently large relative to the width to ensure that failure would not take place at or near the jaws of the testing machine.

Type D of parallel width for similar tests to B.

The choice between A and C of the one loading and between B and D of the other was also influenced by the maximum stress levels involved, the higher levels demanding types A and B.

Suffixes 1 and 2 were originally intended to provide for the inclusion of a few small size specimens to be tested on an alternative machine to the Amsler Vibrophore, namely on a 2 Ton Schenck machine, and this is the reason for the slight difference of dimensions between specimens 4A1 and 4A2, and between 4B1 and 4B2. However, the alternative testing machine was not available at the time and both types were tested on the Amsler Machine. The pin forms and dimensions are also given on Figures 2.1, 2.2 and 2.4.

In each group of specimens, large, medium and small, three values of the ratio

$$\frac{d}{D} = \frac{\text{diameter of hole}}{\text{width of specimen}}$$ were tested.

These three values were:- $\frac{d}{D}$ = 1/4, 3/8 and 1/2, although the number of specimens at d/D = 3/8 was limited. All the plates were manufactured by Messrs. Jas. Booth Ltd, from one melt of aluminium alloy to Specification B.S.L71* (Unclad Aluminium Alloy Sheet, 4.4°/o copper, solution treated and precipitation treated) and all the pins of Steel to Specification B.S.S94* (55 Ton Low Alloy Steel)

2.1.2 Dimensional Tolerances and Pin Fits

Figure 2.5 gives the limits to which the plate specimens were made. It should be noted that all the pin holes were made to a tolerance on the diameter of ±0.0003 in.

The pins were made to a special Schedule of very close limits and then all pins and all holes were measured and selectively fitted in order to provide for the following degrees of fit.

(a) Push Fit Pin (clearance ±0.0003 in) denoted by "P"

(b) 0.4°/o Interference Fit denoted by 'f_1' (to within ±0.0003 in of nominal)

(c) 0.8°/o Interference Fit denoted by 'f_2' (to within ±0.0003 in of nominal)

and a few specimens for comparison to -

(d) Loose or Clearance Fit (clearance +0.004 in / +0.006 in) and denoted by 'L'

For further details of manufacture, see paragraph 2.3.

2.1.3 Testing Machines

In general the large specimens were tested in a standard 20 Ton Schenck Fatigue Testing Machine, the medium specimens in a 6 Ton Losenhausen Fatigue Testing Machine and the small specimens in a 2 Ton Amsler Fatigue Testing Machine.

2.1.4 Load Levels

The objective of the loading programme was to produce for each configuration a family of endurance curves. Each endurance curve would represent a particular

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*For further details see Appendix B

mean stress and would be derived from at least four points representing a range of alternating stresses. Some configurations were omitted because the results that would have been derived would have fallen well outside the useful endurance range.

Finally for each configuration and each combination of mean and alternating stress, at least three nominally identical specimens were tested.

All these configurations and loadings are shown in tabular form in Tables 2.1, 2.2, 2.3 and 2.4.

TABLE 2.1 Stress Levels (on the net area)

Mean Stress (°/o ult.)	Alternating Stress used for fatigue cycling (°/o ult.)					
	22½	15	12½	10	7½	5
50	✓	✓		✓	✓	
40	✓	✓		✓	✓	
25	✓	✓		✓	✓	
15			✓	✓	✓	✓
10					✓	✓

NOTES

1. "°/o ult." signifies "Percentage of Average Tensile Strength" of plain specimens (and some unfilled hole specimens) tested under static loadings. Average Tensile Strength = 31.0 Tons/Sq.in (69400 lb/sq.in)

2. Some combinations were omitted when test results from them began to fall outside the useful range of 10^4 to 10^7 cycles endurance.

3. At least three specimens were tested for each combination of mean and alternating stress, for each configuration.

TABLES 2.2, 2.3 and 2.4 Configurations Actually Tested

NOTES

1. Each group of numbers in the Tables signifies a family of endurance curves one for each percentage mean stress quoted in the group.

2. Specimen Types A and C are for load applied to the plate only.

3. Specimen Types B and D are for load applied to the pin only.

4. 'L' signifies Loose or Clearance Fit Pin

   'P' " Push Fit Pin

   'f_1' " 0.4°/o Interference Fit Pin

   'f_2' " 0.8°/o Interference Fit Pin

5. Three values of d/D were tested for each size of specimen.

See next page for Tables 2.2, 2.3 and 2.4.

(For detailed results see Appendix C paragraph C.1.1).

TABLE 2.2 LARGE SPECIMENS

Plate width -D = 2 in
Plate thickness -t = 1/4 in

Specimen Type (See Fig.2.1)	Hole Diameter (in)	d/D	Endurance Curves at Percentage Mean Stresses Quoted								
			Unfilled Hole	Filled Holes							
				Load on Plate Only				Load on Pin Only			
				L	P	f_1	f_2	L	P	f_1	f_2
1.A	1/2	1/4	50, 40 25, 15		50, 40 15	50, 40 25					
1.B	1/2	1/4						50, 40, 25 15, 10	50, 40, 25 15, 10	50, 40*, 25 15, 10	50, 40
1.C	3/4	3/8	50, 40 25, 15		50, 40 25, 15	50, 40 25					
1.D	3/4	3/8							50, 40 25, 15	50, 40 25, 15	
1.C	1	1/2	50, 40 25, 15		50, 40 25	50, 40 25					
1.D	1	1/2							50, 40, 25	50, 40, 25	50

*2 sets of results, one tested by Short Bros. and Harland and one by NEL.

TABLE 2.3 MEDIUM SPECIMENS

Plate width -D = 1¼ in
Plate thickness -t = 5/32 in

Specimen Type (See Fig.2.2)	Hole Diameter (in)	$\frac{d}{D}$	Endurance Curves at Percentage Mean Stresses Quoted								
			Unfilled Hole	Filled Holes							
				Load on Plate Only				Load on Pin Only			
				L	P	f_1	f_2	L	P	f_1	f_2
2.A	5/16	1/4	50, 40 25, 15	50,40 25	50, 40 25, 15	50, 40 25	50, 40 25				
2.B	5/16	1/4							50, 40 25+	50, 40 25, 15	50, 40 25
2.C	15/32	3/8	50, 40 25, 15		50, 40 25, 15						
2.D	15/32	3/8							Not Tested		
2.C	5/8	1/2	50, 40 25, 15		50, 40	50, 40 25, 15					
2.D	5/8	1/2							50, 40 25, 15	50, 40 25, 15	50, 40 25

+Two sets of results

TABLE 2.4 SMALL SPECIMENS

Plate width -D = 3/4 in

Plate thickness -t = 3/32 in

Specimen Type (See Fig.2.4)	Hole Diameter (in)	$\frac{d}{D}$	Endurance Curves at Percentage Mean Stresses Quoted								
			Unfilled Hole	Filled Holes							
				Load on Plate Only				Load on Pin Only			
				L	P	f_1	f_2	L	P	f_1	f_2
4.A1	3/16	1/4	50, 40 25	50, 40 25	50, 40 25, 15	50, 40 25	50, 40 25				
4.A2	3/16	1/4	15								
4.B1	3/16	1/4							50, 40 25	50, 40 25, 15	50, 40 25, 15
4.B2	3/16	1/4							50, 40 25, 15		
4.C	9/32	3/8	50, 40 25, 15		50, 40 25, 15						
4.D	9/32	3/8								Not Tested	
4.C	3/8	1/2	50, 40 25, 15		50, 40 25, 15	50, 40 25					
4.D	3/8	1/2							50, 40 25, 15	50, 40 25, 15	50, 40 25

2.2 Comparison of Original and Final Test Schedules

It is of interest to note the reasons for some of the more important changes that were made to the original test schedule.

The dominating reasons were that of time consumption, coupled with the fact that in all the testing establishments involved there were other investigations that entailed the use of the testing machines concerned, and that were often of higher priority. The following changes were therefore made:-

(a) Number of Specimens

Originally it had been intended to test ten nominally identical specimens at each load level and for each configuration. Preliminary tests indicated that, possibly because of the care taken in manufacturing and testing the specimens, the scatter was not in general so wide as had been anticipated. It was therefore decided at an early stage to test only three specimens for each configuration and load level. Even so, the programme took a considerable time, fatigue tests requiring more attention to detail than straightforward static tests.

(b) Number of Alloys

It was decided to test only one specification of aluminium alloy plate rather than two or even three as at first considered. The choice of BS.L.71 was made because this material was regarded at the time of the programme initiation as being the most dependable aluminium alloy material, bearing in mind that there were other important properties to be considered, such as notch sensitivity, crack propagation characteristics, ductility and stress corrosion cracking susceptibility, as well as fatigue itself.

(c) Number of Holes in Specimens

In the initial proposals, more than one hole in a row and more than one row of bolt holes were included. This development was set aside, bearing in mind that there were some tests available that gave some indication of the influence of such variations[7].

Another change from the original programme was the addition of a number of load cycles at low stress levels, both for mean and alternating stress*. This was because the endurance at the lower ends of the original stress ranges were not always sufficiently long to provide an adequately useful curve.

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*These tests are now designated "Supplementary Investigation No. 9". The results are given in Stage 2 of this report.

The original programme was drawn up for push fit pins and two degrees of interference fit (0.4°/o and 0.8°/o). Subsequently, loose fit pins were included for a small number of specimens in each of the main groups - large, medium and small.

Again the earlier plan was to initiate the tests only at one level of mean stress, with one or two other levels to follow, but eventually five levels of mean stress were included in order to provide a wider range of investigation. This was easily arranged because of the original large number of specimens per loading per configuration, the excess specimens being used in Stage 2 (The Supplementary Investigations) of the programme, which is fortunate since all will be from the same melt of material.

Finally, a few aluminium alloy pins were made for initial tests but were subsequently discarded as being unrepresentative of practice.

2.3 Manufacture of Specimens

This was carried out by Messrs. Plant Machinery and Accessories Ltd, and in all some 12,000 specimens were made. This total number was built up as follows, (referring to Tables 2.2, 2.3 and 2.4 for guidance). There were three sizes of specimens and for each of these there were:-

7 configurations of pin and hole
3 d/D ratios per configuration
4 mean stresses per configuration
4 alternating stresses per mean stress

and there were originally ten specimens for each combination of configuration and stress cycle.

This led to 10, 080 specimens. The remainder were intended for sundry configurations and for contingencies.

The change from ten to three specimens for each combination provided ample specimens for the subsequent stages of the extended programme.

Each plate was identifiable and a record was kept, identifying each specimen with not only its plate number, but with its position in the plate. (See Tables of results in Appendix C).

It should be noted that the term "plate" was used initially because the large size specimens were 1/4 in thick. The medium and small size specimens were 5/32 in and 3/32 in thick respectively, and therefore may be more commonly termed "sheet".

In this report both terms have been used, but in the context of the report have the same meaning.

Before cutting, a photoelastic study was made of a sample plate marked out to show the positions of the specimens, and the design of the fillet or run-out at the ends of the specimens took into account the stress distribution in the plate. Thus the fillet became a sine curve rather than a simple radius. This refinement proved to be of debatable value but at the time of launching the programme it was thought to be justified.

The final milling cut on the edges of all specimens was held to ±0.001 in and because of this it was agreed that the burrs left along the edges would be negligible and need not be removed by the manufacturer. The testing laboratories were given authority to remove with care any burrs that they considered were excessive in terms of good quality engineering practice. Very few were considered excessive. Any burrs left on the edges of the holes were removed by the use of fine emery paper, grade 0 and then grade 00. The surface of the plate were left "as manufactured".

In regard to the holes, which were required to be to ±0.0003 in limits, some initial difficulties were met in preventing ovality, but eventually a standard reamer was used in a jig borer and the requisite accuracy was achieved.

In order to plan the necessary pin fits, all holes were measured by the manufacturer's Inspection Department and the results recorded to the nearest 0.001 in using a taper plug gauge. This information was invaluable in planning the ranges of pin sizes to be manufactured, and in choosing subsequently by selective assembly combinations of pins and specimens to give the desired fits or interferences. All specimens were treated with a transparent, strippable coating, then wrapped in brown paper, and stored in a heated dry place. All the pins were made by the Royal Ordnance Factory, Woolwich.

In order to facilitate ease of assembly, the pins were made with a 1° included angle taper over half their length and the parallel portion was approximately four times the plate thickness of the specimen so as comfortably to accommodate the fork end applying the load. Both the specimens and the pins were made to a high standard of quality.

2.4 Assembly of Test Specimens, Testing Machines used and Problems Met

This part of the report is most conveniently dealt with by grouping the information under the headings of the Testing Laboratories.

2.4.1 Cambridge University, Metallurgy Department

This was the first centre at which continuous testing was undertaken, although from the start of testing, exploratory work was undertaken by National Engineering Laboratory (NEL) Materials Group (Z). (See paragraph 2.4.3 below).

Assembly

In all cases the protective coating was removed from the holes before assembly, but lanolin grease was applied during testing.

The assembly of the pins in the plates was carried out as follows:-

Push Fit

Small loads were applied axially to the pins. Where necessary a lubricant was used at the discretion of the operator. Loads were measured and recorded.

Interference Fit

Here the same techniques was employed but larger loads were necessary, and a lubricant was invariably employed. Steady pressure was applied through an Instron testing machine. Alternatively a Zwick Machine was used. This method was very satisfactory and there was reasonable correlation between the loads required, the degree of fit and the size of pin.

Detailed loads for individual pins are available but not given in this report. However, the range of loads for each configuration is given at the top of each table of results - See Appendix C.

Alignment

Initially, difficulties were experienced in assembling the specimens in the testing machines because of the problem of eliminating lack of alignment, rotationally, between upper and lower jaws of the testing machine, and to a lesser extent, axially.

A very considerable amount of time and thought were devoted to the problem and how to eliminate it, and an automatic aligning device was eventually developed and produced by the University. This was adopted for both medium and small specimens tested in the Losenhausen and Amsler testing machines. The device enabled the two ends of the specimen to be pre-assembled accurately, quickly and free from strain in the zero load condition. Appendix A, contributed by Metallurgy Department of Cambridge University describes and illustrates this device.

Calibration of Machines

Static and dynamic calibrations were made and found to agree with those of the makers. Strain gauges were applied to sample specimens and used to check the testing machine readings. Although the correlation was fair, there were more errors and less consistency in the strain gauges than in the machine readings. The latter were therefore adopted as the standard load measurement.

Testing Machines

Cambridge University used two types of testing machine. For the small specimens, a 2-Ton Amsler Vibrophore capable of applying a maximum mean load of 1 Ton tension (or compression) and a maximum alternating load of ±1 Ton superimposed on the mean load was employed. The lower practical limit of load was about 0.02 Ton.

The speed of frequency range of this machine was from 2,000 to 12, 000 cycles per minute (c.p.m.), but this range was narrowed for the plate specimens. Initially some tests were made at two speeds, 3,600 and 7,640 c.p.m.* The difference between results was not significant and subsequently all tests were made at between 7,000 and 8,000 c.p.m.

For the medium size specimens a 6-Ton Losenhausen Fatigue Testing Machine was employed. This was capable of applying a maximum mean load of 3 Tons tension or compression, and a maximum alternating load of the same amount (a maximum total load of 6 tons). The test programme load cycles were wholly tensile and therefore tended to require the limit of 3 Ton ±3 Tons. The speed range was from 1,000 to 3,000 c.p.m. and initial tests to explore this range were carried out.*

The resulting endurances at the high speed were somewhat lower than those at the low speed but since the majority of tests with this machine was carried out at 1,500 c.p.m., the overall error was not significant.

Order of Testing

On completion of a number of exploratory tests it was concluded that more reliable results would be obtained if, within a given group of specimens, those which were to be subjected to the highest stress levels were tested first, progressing downwards for the remaining specimens towards the lowest stress levels. Tests of specimens which were still unbroken at an endurance of the order of 10^7 cycles would be discontinued, and if several tests at a given stress level were so terminated, then tests at lower stress levels in that particular configuration would not be carried out.

In respect of configurations, the unfilled hole specimens were tested first, then the push fit pins and finally the interference fit pins. Unloaded pin configurations were tested before loaded pin configurations. This order of testing and the procedure for assembly noted above were maintained in order to minimise scatter of endurances at a given stress level, and although results suggested that this had been a wise precaution there is a feeling that more investigation into the order of testing might prove useful.

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*For details see Appendix C paragraph C.2.

2.4.2 Messrs Short Brothers and Harland Ltd, Testing Laboratory, Belfast

At this centre all the large specimens were tested, except for some exploratory tests by NEL. A number of the problems involved were similar, and their solutions were also similar to those encountered at Cambridge University. Indeed there was continuous co-ordination between the two organisations through the Royal Aeronautical Society. Naturally there were variations in technique due to the larger size of the specimens handled and to different experiences, and these are described below.

Assembly

Because of the larger loads involved, some failures occurred initially at the ends of the specimens, due to the high load concentrations at the grips. To overcome this, the ends of these specimens were coated with a film of Araldite about 1/16 in thick, before insertion in the testing machine. Specimens were protected from corrosion with lanolin as at Cambridge, but nevertheless some corrosion resulted from the use of blue ink used for marking, and was thought to be the cause of some premature failures away from the holes.

Alignment

The special specimen grips used by Cambridge University were not found necessary for the large specimens, and it was established that good alignment could be achieved by selective assembly of suitable end packing pieces that ensured freedom from constraints at zero load. When inserting the pins a grease lubricant was used, and in some cases molybdenum disulphide was added to the grease.

Calibrations

Static and dynamic calibrations were, of course, made and checked satisfactorily before testing began.

Testing Machine

All the large specimens were tested in a 2-Ton Avery-Schenck of the resonant frequency type, with a maximum mean load of 10 Tons and a maximum alternating load of ±10 Tons.

All tests were carried out at a nominal speed of 2,000 cycles per minute.

Order of Testing

In general the high load cycle specimens were tested first and the sequence proceeded downwards in terms of loads, until lives of the order of 10^7 cycles were attained.

2.4.3 National Engineering Laboratory, Materials Group (Z), East Kilbride

As already stated, this organisation carried out some preliminary static tests, and a number of exploratory tests to assist the Royal Aeronautical Society and the Ministry of Technology in planning some of the details of the early stages of the programme, in terms of

- Load cycles to be used
- Degrees of fit
- Geometry of fit
- Testing machine calibrations and
- Methods of assembly

This laboratory did in fact test most of the loose fit pins, and designed the fork end fittings for the 'pin loaded' cases. Later in the programme, NEL studied a representative selection of the occurrences of fretting encountered at the various laboratories and reported on them.

2.4.4 Tiltman Langley Limited, Redhill, Surrey

This organisation assisted in the programme by testing a number of the small and medium size specimens.

Testing Machines

These were all of the NPL Slipping Clutch type with synchronous motors. In general medium size specimens were tested on machines of 6-Ton total capacity and the small size specimens on machines of 2-Ton total capacity.

The actual maximum values of load available were:-

6-Ton Machines	6,000 lb mean load and
	±4,500 lb alternating load
2-Ton Machines	2,500 lb mean load and
	±1,500 lb alternating load.

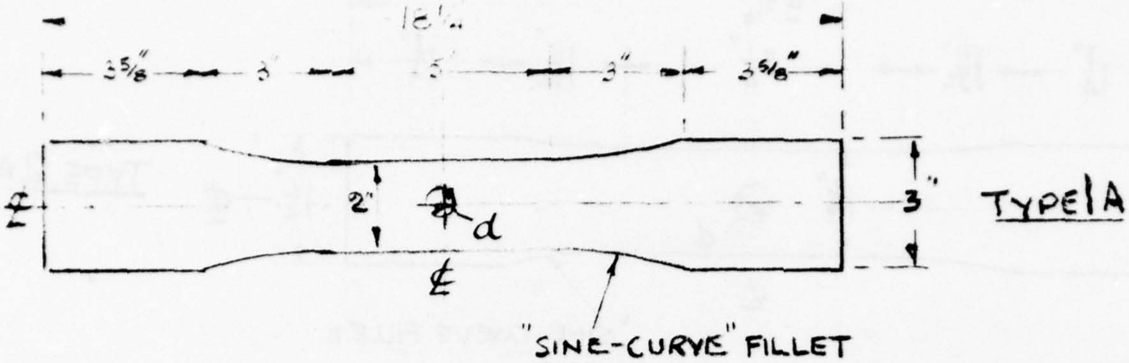
The speeds of testing were between 2,500 and 3,000 c.p.m.

Calibrations

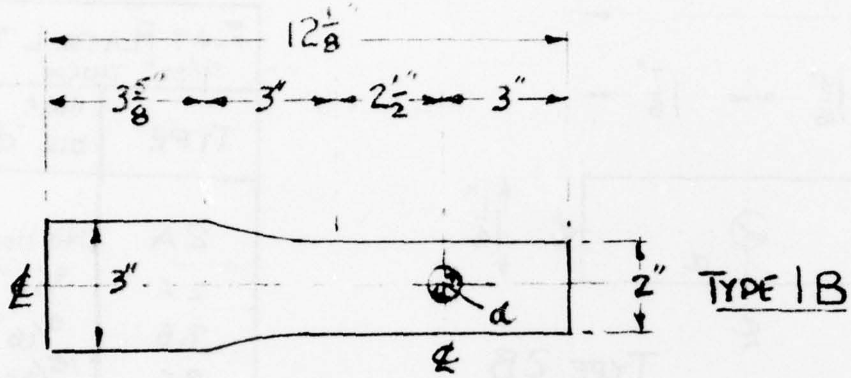
The machines were all calibrated both statically and dynamically at the commencement of the programme, and twice during the working period they were checked statically.

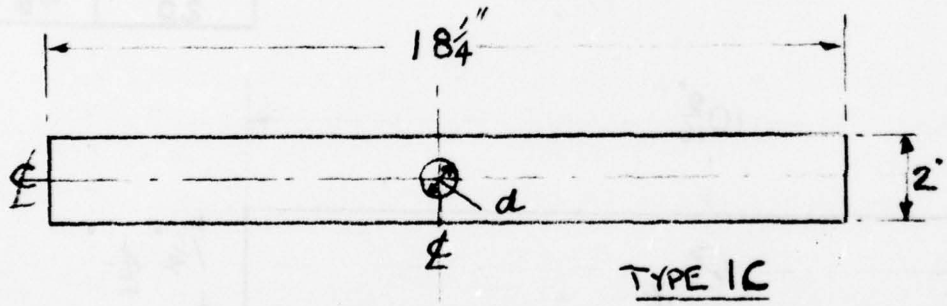
Assembly

Descriptions of the successful methods of gripping the test specimens for this particular programme were sent to Tiltman Langley so that the laboratory could adapt the same methods to their machines, and thus minimise the difficulties of assembly, and accelerate the progress of the work.

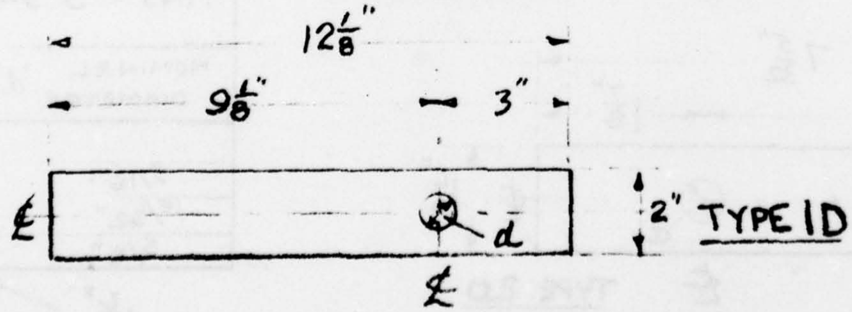


FLAT PLATE L.71 ¼" THICK.	
TYPE	HOLE DIA. 'd'
1 A	No Hole
1 A	½"
1 B	½"
1 C	¾"
1 C	1"
1 D	¾"
1 D	1"





PINS - S.94
NOMINAL DIAMETER 'd'
½"
¾"
1"



PLATES (SCALE 1:4)

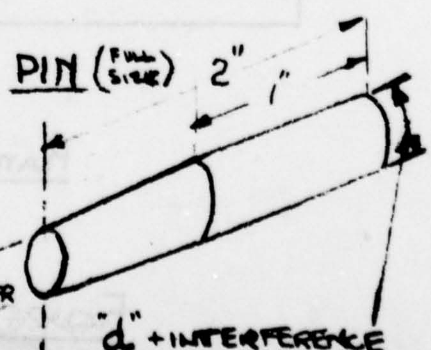
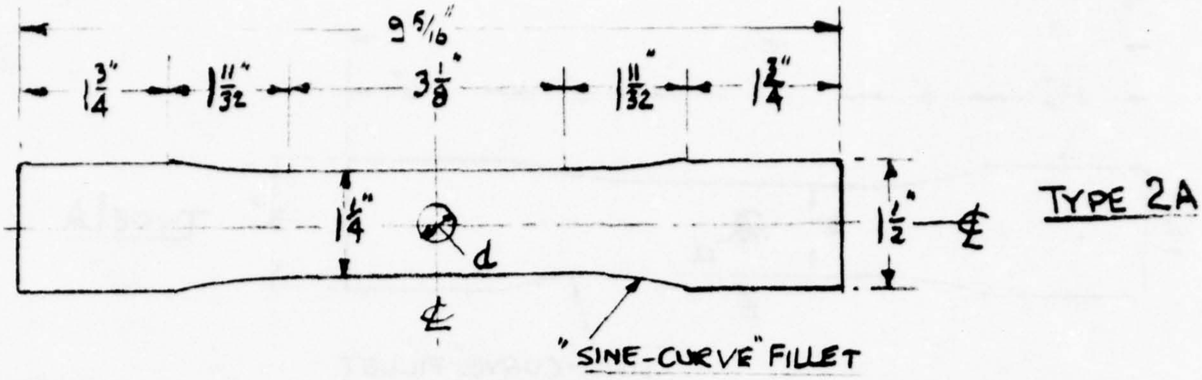
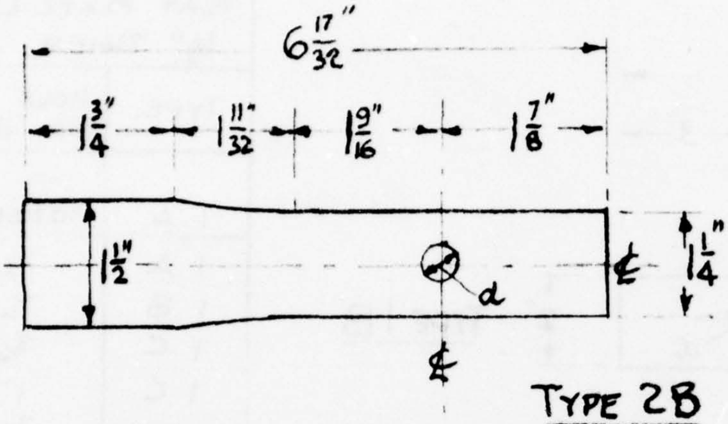
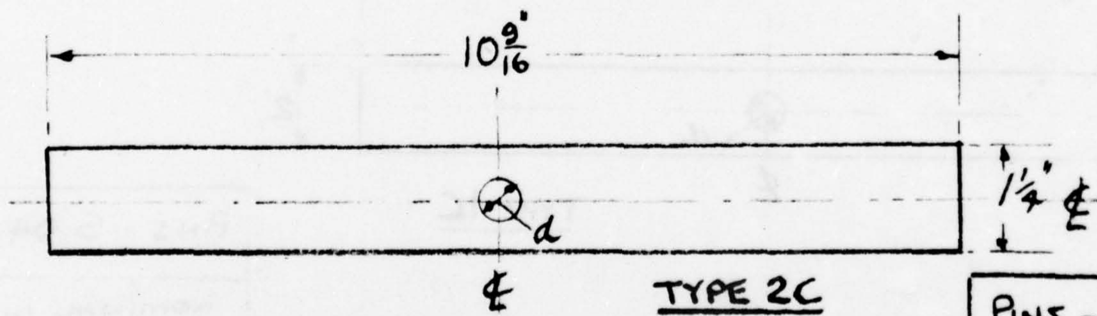


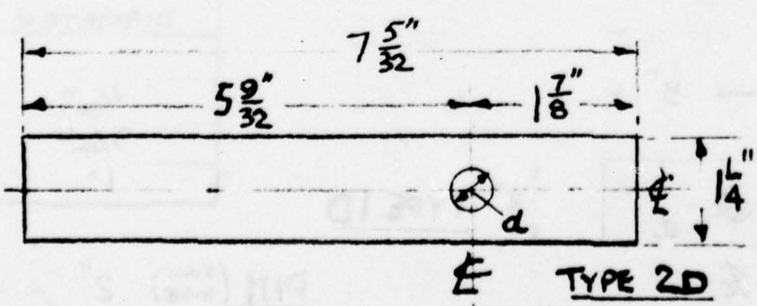
FIGURE 2·1 - LARGE SPECIMENS





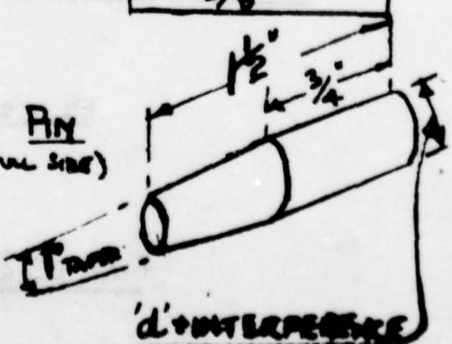
FLAT PLATE L 71 5/32" THICK	
TYPE	HOLE DIA. "d"
2A	NO HOLE
2A	5/16"
2B	5/16"
2C	15/32"
2C	5/8"
2D	15/32"
2D	5/8"





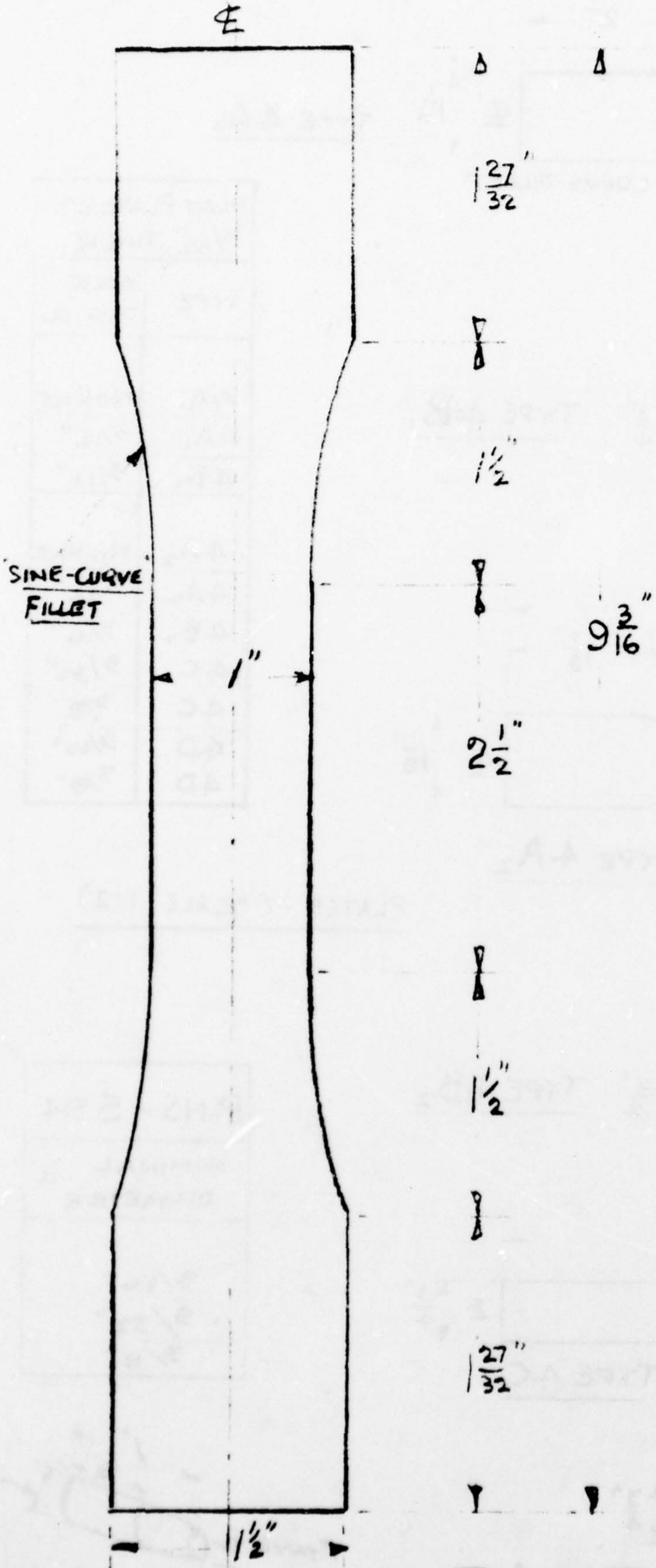
PINS - S.94
NOMINAL DIAMETER 'd'
5/16"
15/32"
5/8"

PLATES (SCALE 1:2)



PIN (FULL SIZE)

FIGURE 2.2 - MEDIUM SPECIMENS

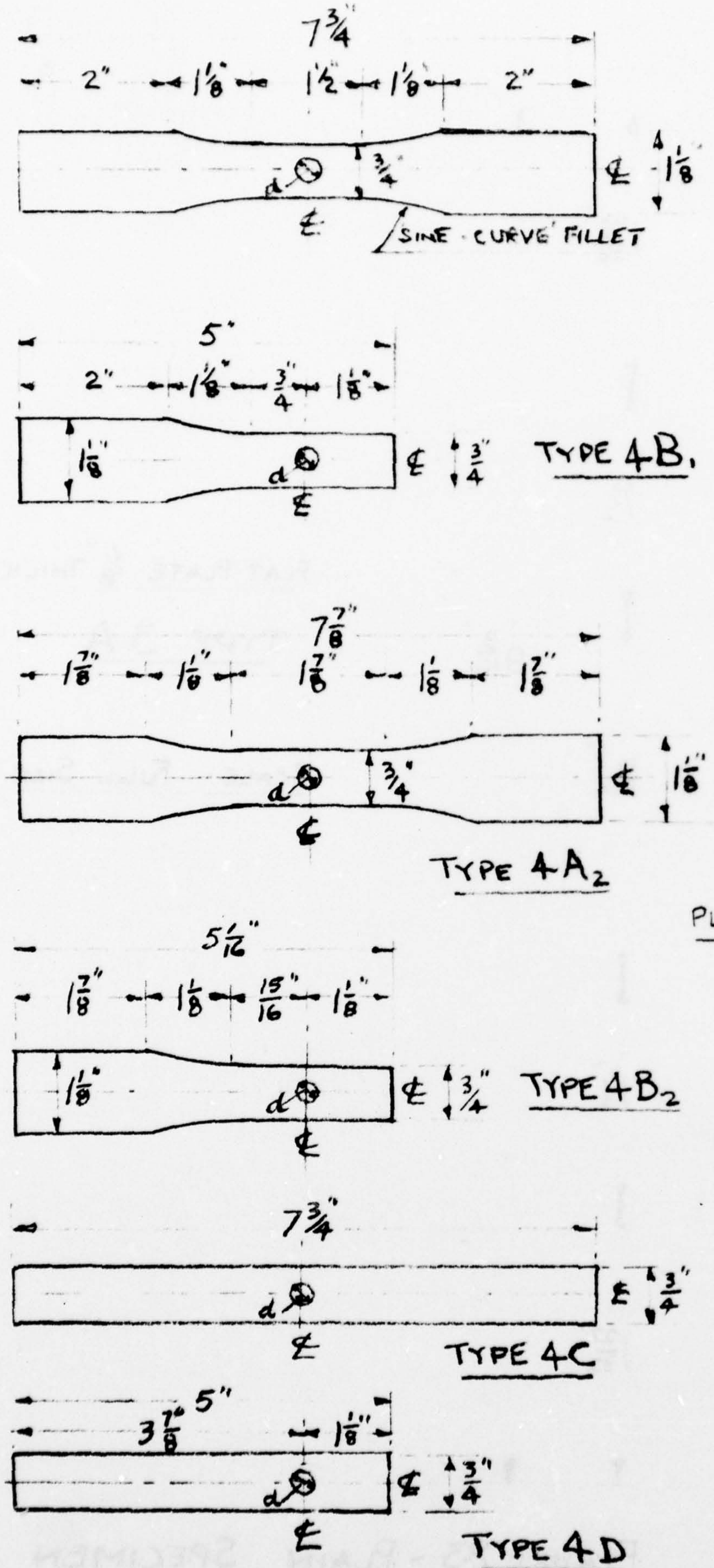


FLAT PLATE 1/8" THICK

TYPE 3A

SCALE - FULL SIZE

FIGURE 2-3 - PLAIN SPECIMEN (NO HOLE)



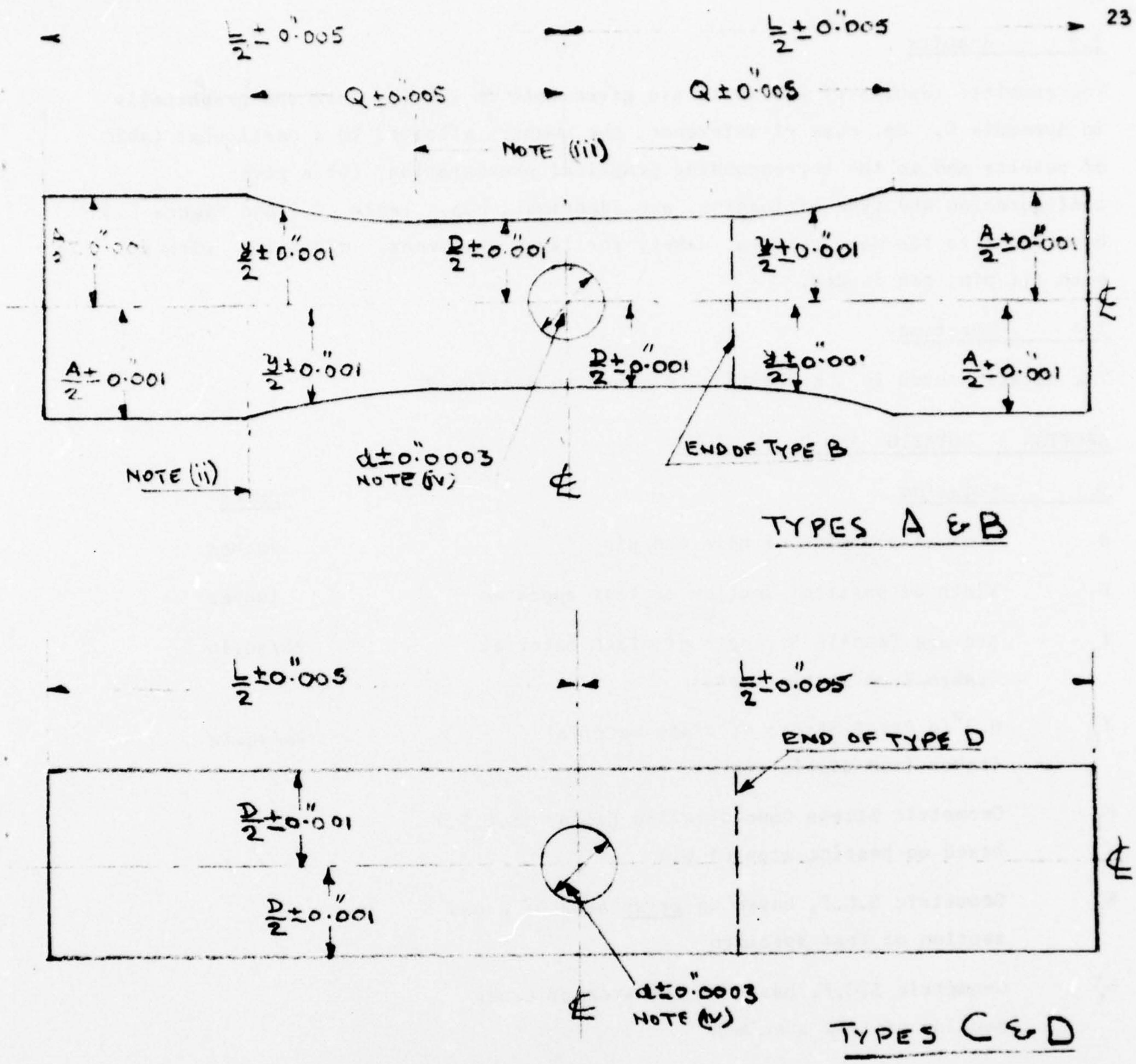
FLAT PLATE L71 3/32" THICK	
TYPE	HOLE DIA 'd'
4A1	No Hole
4A1	3/16"
4B1	3/16"
4A2	No Hole
4A2	3/16"
4B2	3/16"
4C	9/32"
4C	3/8"
4D	9/32"
4D	3/8"

PLATES - (SCALE 1:2)

PINS - S94
NOMINAL 'd' DIAMETER
3/16"
9/32"
3/8"

PIN (FULL SIZE)

FIGURE 2.4 - SMALL SPECIMENS



NOTES:

(i) THE NOMINAL VALUES OF A, D, d, L AND Q ARE GIVEN ON FIGURES 2.1, 2.2, 2.3 & 2.4. THE VALUES OF y/2 FOR THE FILLET ARE TO A PRESCRIBED SINE CURVE.

(ii) THE JUNCTIONS OF THE SINE CURVE FILLETS AND THE WIDENED ENDS ON EITHER SIDE OF THE LONGITUDINAL CENTRE LINE ARE TO WITHIN 0".005 OF EACH OTHER MEASURED LONGITUDINALLY.

(iii) THE PARALLEL TEST PORTION OF NOMINAL WIDTH 'D' DOES NOT TAPER BY MORE THAN 0".001 PER INCH OF LENGTH.

(iv) THE CENTRE OF THE HOLE IS WITHIN ±0".002 OF EACH OF THE TWO CENTRE LINES.

(v) LIMITS FOR THE PIN DIAMETERS ARE CO-RELATED TO THE MEASURED HOLE DIMENSIONS TO GIVE THE PRESCRIBED FITS.

FIGURE 2.5 – LIMITS ON SPECIMEN DIMENSIONS

(DRAWINGS NOT TO SCALE)

2.5 Results

The complete results of all tests are given both in tabular form and graphically in Appendix C. For ease of reference, the numbers allotted to a particular table of results and to the corresponding graphical presentation, for a given configuration and type of loading, are identical, e.g. Table C.5 and Figure C.5 both refer to the same results, namely for large specimens, $d/D = 1/4$ with a push fit pin, pin loaded.

2.6 Notation

The notation used in the analysis is given in Section 3.

SECTION 3 NOTATION AND DERIVATIONS

3.1	Notation	Units
d	Nominal diameter of hole and pin	inches
D	Width of parallel section of test specimen	inches
f_t	Average Tensile Strength of plate material (taken from static tests)	lb/sq.in
f_p	$0.2^{o}/o$ Proof Stress of plate material (taken from static tests)	lb/sq.in
K_B	Geometric Stress Concentration Factor (S.C.F.) based on bearing area of pin	
K_t	Geometric S.C.F. based on gross area of cross section of test specimen	
K'_t	Geometric S.C.F. based on net area of cross section of test specimen	
N	Endurance	cycles
m	Parameter characterising shape of R.M.Diagram	
S_m	Mean Stress on net area	lb/sq.in
S_a	Alternating Stress on net area associated with S_m	lb/sq.in
S_{ao}	Alternating Stress on net area associated with zero mean stress	lb/sq.in
S'_m	$K'_t.S_m$	lb/sq.in
S'_a	$K'_t.S_a$	lb/sq.in
t	Thickness of plate specimen	inches

			Units
L	Loose fit	For limits See Section 2 paragraph 2.1.2	-
P	Push fit		
f_1	0.4°/o Interference Fit		
f_2	0.8°/o Interference Fit		

3.2 Derivations

For the plate Material of these tests (all one batch)

$$f_t = 31.0 \text{ Tons/sq.in} = 69{,}400 \text{ lb/sq.in}$$

$$f_p = 28.0 \text{ Tons/sq.in} = 62{,}500 \text{ lb/sq.in}$$

$$\therefore f_p = 0.90 f_t.$$

When deriving Stress Concentration Factors from RAeS Data Sheets, note that:-

$$K_t' = K_t.\frac{D-d}{D} = K_t(1 - \frac{d}{D})$$

and $$K_t' = K_B.\frac{D-d}{d} = K_B(\frac{D}{d} - 1) .$$

SECTION 4 MAIN FEATURES OF THE EXPERIMENTAL RESULTS

4.1 General Remarks

All the individual results are tabulated and also presented graphically in Appendix C, together with a brief comment for each configuration and size of specimen. This present section attempts to observe the effects of the several variables involved, namely size, mean stress, alternating stress, geometry and the different degrees of fit of the pins in the holes. Where endurances are compared, the mean curves are used rather than actual results at a given stress level. This procedure was considered to present more realistic and effective comparisons than those which would result from comparing extreme values, remembering of course that the actual plotted points are always available in Appendix C, for an assessment of probable scatter.

In searching for the influence of one parameter it is almost certain that one will observe the influence of other parameters, so that groups of "collected curves" will be referred to in more than one of the following paragraphs, as found convenient. These "collected curves" are presented as Figures 4.1 to 4.33 inclusive. However, before discussing the above, a few remarks are made concerning speed of testing, choice of testing machine, variation from sheet to sheet, and location within a given sheet.

4.2 Effect of Speed of Testing

A limited exploration on this feature, within the range of the testing machines used, was carried out by Cambridge University, and the results are described in Appendix C, paragraph C.2 to this report.

A three to one speed range was tested on the 6-Ton Losenhausen and a two to one speed range on the 2-Ton Amsler machine. A range of alternating stresses at one level of mean stress ($S_m/f_t = 0.25$) was used.

The scatter of results was not large, and, for the Losenhausen machine, endurances at the higher speed were somewhat lower than at low speed. For the Amsler however, there was little difference between the endurances at the two speeds tested. It would appear that, within the ranges tested, the effect of speed of testing is not significant.

For convenience of operation, the Losenhausen test programme was carried out at about mid-level of the speed range, and the Amsler tests towards the upper ends of the speed range. Thus the choice of testing speeds was reasonable in the light of the foregoing evidence.

4.3 Effect of Choice of Testing Machine

Unfortunately this particular variable was not really investigated because of the limited number of machines available and of administrative difficulties. There are however two sets of results for the same design of machine, namely a 20-Ton Avery Schenck. Ref. Tables C.6(a) and C.6(b) and Figs. C.6(a) and C.6(b). One machine was at Short Brothers and Harland and the other at the National Engineering Laboratory.

There is a slight difference in the results at $S_m/f_t = 0.25$ and 0.15, those at Short Brothers and Harland being somewhat more favourable, but the total number of results is not sufficient to warrant firm conclusions being drawn.

4.4 Variation from Sheet to Sheet

Refs. Appendix C:-

Table C.19 and Figures C.19, 19a, 19b, 19c and 19d (Unfilled Hole)

Table C.24 and Figures C.24, 24a and 24b (P.F. pin, pin loaded)

Table C.25 and Figures C.25 (0.4^o/o I.F. pin, pin loaded)

Table C.26 and Figures C.26 (0.8^o/o I.F. pin, pin loaded)

In the first reference separate plots for each value of mean stress are presented, sheet numbers being identified. In all cases the scatter is small and well within that expected for nominally identical specimens.

In the second reference eight different sheets were used but all the specimens were cut from one end of each sheet. The two groups tabulated were tested at different times, and are plotted on separate graphs. They each led to quite reasonable curves, although there was not a full range of alternating stress for each mean stress in group (a). It is clear however that variation of sheet has no effect.

Similar remarks apply to the third and fourth configurations.

Thus no effect of sheet variation is evident and this of course is what would be expected from a set of sheets all manufactured from one melt. However, as pointed out in Appendix C, with respect to Table and Figure C.19, it does not necessarily follow that sheets representing the extreme upper and lower permissible limits of mechanical properties and/or chemical composition would conform to the same extent.

4.5 Location of Specimen within a given Sheet

Reference Appendix C, Table C.19, Table C.24, Table C.40 and note (6) of paragraph C.3.1.

With reference to note (6) there were for the small size specimens approximately 21 strips and 15 specimen positions in each strip so that strips 1 and 21 represent edges of sheets and strip 11 represents the centre line. Again, positions A and O represent ends of sheets and position H the centre of length. For the large specimens there were only half the number of strips per sheet and specimens per strip.

A study of the endurances for a given loading and within a given sheet indicates that there is no consistent merit in any given position with regard to endurance.

4.6 Effect of the Presence of an Unloaded Push Fit Pin

Figures 4.1 to 4.9 inclusive show for a given size of specimen and d/D ratio, direct comparisons between the endurance curves for Unfilled Hole and Push Fit Pin, Pin Unloaded. Each figure contains the appropriate references to the original results plotted in Appendix C.

It is important to repeat that in this and the majority of subsequent comparisons the geometric mean curves have been used. It is considered that a comparison of mean curves will give a more representative conclusion than using extreme values. The actual scatter of results can be seen from the graphs in Appendix C and should always be borne in mind when assessing the fatigue performance of a given structure or detail part.

Remembering this fact, one is led to a general conclusion that the effect of an unloaded push fit pin on the resulting endurance is not large and barely affected by the ratio of d/D.

At high alternating stress (order of 14,000 lb/sq.inch or $S_m/f_t = 0.20$) the addition of the pin may increase the endurance by a factor of the order of 2.0 to 2.5. At low alternating stresses (order of 5,500 lb/sq.inch or $S_m/f_t = 0.08$) the addition of the pin may change the endurance by a factor of the order of 0.5 to 1.1. Scatter may increase or decrease individual cases by as much as $50^{o}/o$.

It would appear that the beneficial effect of the support of the pin at the edges of the hole near the ends of the transverse diameter of the hole accounts for the improvement at high alternating stress, whilst the possibility of the occurrence of some fretting at low alternating stresses tends to nullify or even reverse this trend.

This comparatively marginal effect is also supported by the fact that the Stress Concentration Factors for both unfilled hole and for push fit pin, pin unloaded, are virtually the same - see Appendix C, paragraph C.3.1 note (5) and Reference 3. The incidence of fretting and its effects on the test results are discussed in paragraph 4.15.

Two further observations may be made; mean stress has an almost negligible influence, and size has only a small one in favour of the small specimens - see paragraphs 4.10 and 4.11 for more detailed discussion.

4.7 Comparison between Unloaded and Loaded Push Fit Pin

Figures 4.10 to 4.16 inclusive show these comparisons over a range of size and d/D ratio, again with reference to the appropriate original figures in Appendix C. It should be noted that there are no results for d/D = 3/8 for the medium and small specimens.

Endurances for the loaded pins are significantly lower than those for the unloaded pins for a given combination of the other variables. This is, of course, to be expected with the higher stress concentrations for a given applied loading. The reductions in endurance are relatively greater for low d/D (1/4) than for moderate d/D (1/2).

There is also a trend towards greater scatter of results at low alternating stresses, particularly for the medium and small sizes. Again scatter is less for loaded pins than for unloaded pins.

In general mean stress has only a small influence on the results, except at $S_m/f_t = 0.15$.

The influence of the size is even less on the loaded specimens compared with the unloaded ones. In an attempt to suggest very approximate ratios of endurance for loaded pins compared with unloaded pins the following figures are offered.

S_a/f_t	d/D = 1/4	d/D = 1/2
High (0.20)	1/3 to 1/10	1/2 to 1/3
Low (0.08)	1/5 to 1/10	3/4 to 1/5

It should be noted that these are ratios of mean endurances, that size effect is included (but is not large) and that the extreme ratios tend to represent the lowest mean stresses.

4.8 Comparison between Loose Fit and Push Fit Pin

Only a few tests were carried out on loose fit pins. Reference to Tables 2.2, 2.3 and 2.4 of Section 2 shows that these were as follows:-

Large Specimens, Pin Loaded
Medium Specimens, Pin Unloaded — All at d/D = 1/4
Small Specimens, Pin Unloaded

There are corresponding results for push fit pins so that direct comparisons may be made, and these are presented on Figures 4.17, 4.18 and 4.19 respectively.

4.8.1 Loaded Pin (Figure 4.17)

Bearing in mind that for these particular loose fit pins only one result was available at a given level of alternating stress, and that the relevant curves can only be regarded as tentative, there is remarkable agreement between the two sets of curves for loose and push fit pins for all three levels of mean stress plotted. Nevertheless from what has been seen in respect of loaded push fit pins, one would not expect a great deal of difference between a loaded loose fit pin and a loaded push fit pin at a low value of d/D and so regardless of the scarcity of data, Figure 4.17 would appear to indicate a true comparison.

4.8.2 Unloaded Pin (Figures 4.18 and 4.19)

Here there are more results, and for both medium and small size specimens. Again both are at d/D = 1/4.

Allowing for scatter there appears to be no great difference for the small difference in size (1.67:1.0). There is clearly some loss of endurance at high alternating stresses but to a less extent at low alternating stresses.

Approximately the reduction factor is from 1/2 to 1/4 at high S_a and from nil to 1/3 at low S_a (based on mean curves). Another interesting factor is that on comparing the results of the loose fit unloaded pins with the corresponding configuration but with unfilled holes, it is found that there are no significant differences in endurance curves for a given value of mean stress. (Compare Figure C.19 with Figure C.20 and Figure C.35 with Figure C.36).

It may generally be concluded that loose fits do not seriously reduce endurances, but this conclusion is based on limited evidence and there were several examples of fretting. (See paragraph 4.15).

4.9 Effect of Interference Fit

The endurances for two degrees of interference fit are plotted on the same figures as for the push fit pins for the otherwise corresponding configurations, and are presented on Figures 4.20 to 4.26 for unloaded pins, and on Figures 4.27 to 4.33 for loaded pins.

4.9.1 Unloaded Pins

As would be expected, there is a significant gain in endurance for the interference fit pins, because of the induced tensile stress in the material surrounding the pin, which effectively reduces the applied alternating stress. However, if the interference is large enough to cause plasticity this effect will be modified, and for very large interferences, it may even be reversed. Furthermore excessive interference fits in materials which are sensitive to stress corrosion cracking could cause premature failure.

The improvement in endurance is considerably greater for $d/D = 1/2$ than for $d/D = 1/4$, but the improvements for 0.8°/o interference fit compared with those for 0.4°/o interference fit are less for the small specimens than for the medium size specimens. There were no tests for 0.8°/o interference fit in the large size (pin unloaded).

The increases of endurance are less at high values of S_a/f_t than at low values, for both 0.4°/o and 0.8°/o interference fit pins. This is probably due to the greater amount of yielding at high S_a/f_t. The effect of mean stress is more marked for the interference fit pins compared with push fit pins, but the effect of size is less marked.

For the medium size specimens at $d/D = 1/4$ the 0.4°/o interference fit pins show results out of step with the general trend. This could be due to the degree of interference being slightly under normal, as indicated by the relatively small loads required to insert the interference fit pins, combined with a small degree of interference on the push fit pins as indicated by the relatively high loads required to insert the push fit pins of this size and configuration.

Thus some of the interference fit specimens might be regarded as push fit pin specimens and some of the push fit pin specimens as low interference fit specimens.

Adopting the same procedure as for the previous comparisons, the following approximate ranges of factors for increase of endurance of interference fit over the corresponding push fit pin are suggested (both for pin unloaded).

For 0.4°/o Interference Fit

S_a/f_t	d/D = 1/4	d/D = 1/2
High (0.20)	3/4 to 6	7 to 100*
Low (0.08)	3/4 to 9	10 to 100*

For 0.8°/o Interference Fit

S_a/f_t	d/D = 1/4	d/D = 1/2
High (0.20)	4 to 10	no results
Low (0.08)	5 to 10	

It should be noted that the higher factors for a given configuration are usually associated with the lower values of mean stress, and that size effect, such as it is, is accounted for in the comparisons.

4.9.2 Loaded Pins

In general the increases of endurance for loaded interference fit pins compared with push fit pins are not so great as for unloaded pins. The effect of d/D is still considerable as for the unloaded pins, but the effect of mean stress is less marked. Size effect is also small.

It would appear that the reasons for these facts are the greater stress concentrations of the loaded pins, and associated lower scatter of results. Approximate factors for increase of endurance due to interference fit are as follows (pin loaded)

For 0.4°/o Interference Fit

S_a/f_t	d/D = 1/4	d/D = 1/2
High (0.20)	3/4 to 3	2 to 100*
Low (0.08)	3/4 to 3	2 to 100*

---

*Based on limited evidence

For 0.8°/o Interference Fit

S_a/f_t	d/D = 1/4	d/D = 1/2
High (0.20)	1 to 5	10 to 100*
Low (0.08)	1 to 15	20 to 100*

Again the higher factors are usually associated with the lower values of mean stress.

4.10 Effect of Mean Stress

In general, this can be seen from any of the graphs of the initial plots in Appendix C, and from the re-plots on Figures 4.1 to 4.33 of the main report.

However, in order better to demonstrate the effect of this variable, cross plots of S_a against S_m for a series of constant endurances have been derived (see Tables 4.1 to 4.5) and are presented on Figures 4.34 to 4.43 inclusive. These tables and figures cover unfilled Holes, Push Fit Pin - Pin Unloaded, Push Fit Pin - Pin Loaded, 0.4°/o Interference Fit Pin - Pin Unloaded and 0.4°/o Interference Fit Pin - Pin Loaded. For each configuration two values of d/D, namely 1/4 and 1/2, have been considered.

From what has been observed already in respect of size, it does not seem unreasonable to combine results for large, medium and small specimens by using average values for a given configuration and value of d/D. By making this presumption the presentation becomes clearer, and there are more data per point upon which to base conclusions. In paragraph 4.11 which discusses effect of size it is concluded that this presumption is justified.

The resulting curves are effectively R-M diagrams on a basis similar to that of RAeS Data Sheet A.00.02 and may also be compared directly with Figure 3 of Data Sheet E.02.01.

However, the Stage 1 results are available only down to $S_m/f_t = 0.15$, and so the left hand side extensions of the curves for all configurations except the interference fit pins have been predicted from RAeS Data Sheet E.07.01, Figure 3- for artificially aged Al-Cu Alloy. This data sheet gives a mean line for S_{ao}, $K_t' = 1.0$, i.e. plain specimens, and values for S_{ao} for the Stage 1 specimens are obtained simply by dividing the mean line values for a given endurance by the appropriate Stage 1 value of K_t'. See Table 4.6.

This method is not accurate for low endurances, e.g. below 3×10^4 cycles, because the procedure of dividing by K_t' becomes increasingly pessimistic, and so no extension below $S_m/f_t = 0.15$ is given for the curves at 10^4 endurance.

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*Based on limited evidence

In regard to the interference fit pins, for reasons already discussed in Appendix C paragraph C.3.1 note (5) a common value of K_t' cannot be quoted, and hence values of S_{ao} for a given endurance cannot be calculated. Thus the extreme left hand side of the R-M diagram cannot fully be drawn.

Conclusions

(i) For all configurations other than interference fit pins the mean stress has negligible effect on endurance for a given value of S_a, over the range $S_m/f_t = 0.20$ to 0.50. This appears to be due to the occurrence of plastic flow at the region of the maximum stress concentration. It is expressed by the condition:-

$$K_t'(S_m + S_a) \geqslant f_p \quad \text{or} \quad K_t' \frac{S_m}{f_t} \geqslant \frac{f_p}{f_t} - K_t' \frac{S_a}{f_t}$$

and is consistent with the point E H of the curves G E H in Figure 1 RAeS Data Sheet A.00.02.

Below $S_m = 0.20\ f_t$ it is difficult to assess from these tests a definite law of behaviour, but the rough rule that endurance is inversely proportional to mean stress for small variations of S_m appears to be reasonable.

(ii) For the interference fit pins the effect of mean stress is much more marked, particularly at low endurances. Unfortunately, there is only limited evidence at $d/D = 1/2$ and therefore Figures 4.41 and 4.43 should be used with caution. The rough rule noted above could be applied over the full range of mean stress tested, except for very high endurances (above 10^6 cycles).

(iii) The above conclusions apply in general to both $d/D = 1/4$ and $d/D = 1/2$, although the achieved values of S_a for a given endurance are somewhat greater for $d/D = 1/2$ compared with $d/D = 1/4$, especially for loaded pins.

(iv) For all configurations other than interference fit pins there is a slight trend towards a fatigue limit at an endurance of about 10^7 cycles, for mean stresses of $0.25\ f_t$ and greater.

4.11 Effect of Size

From a study of all the results available using mean endurance curves, it is considered that although the effect of size is not large it is of some significance. It might have been greater had the size range exceeded the value chosen, i.e. Large/Small = 2.67 - based on width of specimen. The use of the specimen width as a measure of size is somewhat arbitrary. Alternative bases could be either the ratio of d/D since the amount of material at the side of the hole has an influence on stress concentration factor and hence on endurance, or the basis could be simply the diameter of the hole - 'd'.

It is believed that any one of these bases is an acceptable one, especially as the effect is not large and is of course somewhat masked by general scatter, and so the original basis of width of specimen will be retained.

The smaller the size of the specimen, other variables being constant, the more favourable becomes the fatigue performance. There are two ways of expressing the relative performances

(a) as a ratio of endurances for a given alternating stress, and

(b) as a ratio of alternating stresses for a given endurance.

Because of the general shape of the endurance curves (a) tends to be more reliable at low endurances and (b) tends to be more reliable at high endurances. For convenience both methods will be given.

Method (a)

From paragraph 4.10 it is justifiable to quote average figures for the range S_m/f_t = 0.50 to 0.25 except for interference fit pins for which only average figures for S_m/f_t = 0.50 and 0.40 will be quoted. However, because these are average figures, the results may be considered accurate only to two significant figures.

As in previous comparisons, values at two levels of S_a/f_t are quoted and the results are given in Table 4.7.

Method (b)

Here the data are conveniently available in Tables 4.1 to 4.5 inclusive. Ratios of S_a for small specimen/large specimen can be obtained at stated endurances, again averaging the figures for S_m/f_t = 0.50, 0.40 and 0.25 for all except interference fit, and for the latter averaging only S_m/f_t = 0.50 and 0.40, and quoting the results to two significant figures. These results are given in Table 4.8.

Conclusions

(i) Although only a limited range of size of specimen is covered (2.67 to 1.0) there is definite evidence of a size effect, whether judged by ratio of endurances for a given alternating stress or vice versa. However, the previous decision to average the results of all three sizes of specimens is justified when the size effect is considered in relation to the general scatter of fatigue test results.

(ii) Using method (a) leads to an apparently greater size effect at low alternating stress, but this is not necessarily true (see notes on Table 4.7). By using method (b) which, from the nature of the curves tends to be more reliable at low alternating stress, leads to a more uniform assessment (see Table 4.8). In fact the resulting ratio could be regarded as a general reduction of stress concentration factor of the order of 1.1 to 2.0 for a size reduction of 1/2.67.

(iii) The size effect is somewhat less at $d/D = 1/4$ compared with $d/D = 1/2$. This is consistent with the more powerful effect of the higher stress concentration factor associated with $d/D = 1/4$.

(iv) There appears to be a somewhat larger size effect for push fit pins compared with interference fit pins. This may be partly due to the fact that the loads to insert some of the push fit pins were relatively high. The effect is least for unfilled holes.

4.12 Effect of Geometry

In this broadest sense this variable can be regarded as covering the size and shape of the specimen, and its lack of uniformity, all of which lead to a stress concentration. But because size has been covered separately, in this report 'geometry' will be interpreted by the ratio of d/D. This in turn is expressed in the value of the stress concentration factor, but it should be remembered that stress concentration factor also includes the influence of pin fit.

Figures 4.1 to 4.33 already discussed, and also the original curves in Appendix C enable direct comparisons to be made, for the different configurations tested, and each configuration will be discussed briefly. As previously, in accordance with the findings of paragraph 4.10, results for $S_m/f_t = 0.50$, 0.40 and 0.25 have been grouped together for all but the interference fit pins.

4.12.1 Unfilled Hole (Reference Figures 4.1 to 4.9)

Bearing in mind the general scatter and the fact that the curves are through mean values, it cannot be claimed that there is any significant effect of change geometry in this configuration.

4.12.2 Push Fit Pin - Pin Unloaded (Reference Figures 4.1 to 4.9)

Here again, the differences between high and low d/D are not marked, and to a considerable extent are lost in the general scatter of results. This is better appreciated by further reference to the relevant initial plottings in Appendix C.

4.12.3 Loaded Push Fit Pin (Reference Figures 4.10 to 4.16)

Here there is a definite increase in endurance for the higher values of d/D. This increase in contrast to the two previous configurations is probably due to the greater levels of stress concentration present in the loaded pin configuration. Adopting the earlier procedure, the following figures give an appreciation of the order of the ratio of increase of endurance, assuming the endurance at d/D = 1/4 to be unity

S_a/f_t	d/D = 1/4	d/D = 1/2
High (0.20)	Unity	2 to 5
Low (0.08)	Unity	4 to 10

The higher values in a given range correspond generally with the lower values of mean stress. Size effect has been accounted for, i.e. not included, since the ratios quoted are all for d/D only for a given size.

4.12.4 Unloaded Interference Fit Pin (0.4°/o Interference) (Reference Figures 4.20 to 4.26)

Only the 0.4°/o interference fit can be commented upon as there are insufficient data for 0.8°/o. Even so there is only a limited amount of data for 0.4°/o interference fit especially at $S_m/f_t = 0.25$ and below. The effect of d/D is much greater than for push fit pins, and the range of increase factors for increase of d/D is much wider. Only approximate figures can be quoted as follows:-

S_a/f_t	S_m/f_t	d/D = 1/4	d/D = 1/2
0.20	0.50	Unity	4 to 6
	0.40	Unity	5 to 50
	0.25	Unity	40 to 50
0.08	0.50	Unity	10 to 25
	0.40	Unity	10 to 60
	0.25	Unity	50 to 100

4.12.5 Loaded Interference Fit Pin (0.4°/o Interference) (Reference Figures 4.27 to 4.33)

Here there are similarly large increases in endurance for increase of d/D and because of the limited data only approximate factors can be quoted:-

S_a/f_t	S_m/f_t	d/D = 1/4	d/D = 1/2
0.20	0.50	Unity	3 to 12
	0.40	Unity	10 to 60
	0.25	Unity	150 to 250

S_a/f_t	S_m/f_t	d/D = 1/4	d/D = 1/2
0.08	0.50	Unity	2.5 to 5.5
	0.40	Unity	14 to 65
	0.25	Unity	200 to 500

4.13 Summary Presentations

4.13.1 General

So far in this section, attempts have been made to study the effect of each variable in turn. Some variables have proved to be of little consequence - at least within stated limits. Others have been found to have a significant, but not large effect, and a third group to have considerable influence. An example of the first type is mean stress (excluding joints with interference fit pins). Examples of the second group are size and the ratio of endurance for an unfilled hole and a push fit pin, unloaded.

There are many examples of the third group, such as geometry or stress concentration factor, and the endurance of interference fit pins compared with that for push fit pins under similar conditions of loading.

Often it has been difficult to be precise in stating the magnitude of these influences because of the scatter inherent in fatigue results. To some extent the consideration of mean endurance curves rather than full scatter bands has helped to clarify this particular problem and to avoid making extreme statements, but in assessing the merits of a given design, the effect of scatter must always be considered and reference to the basic curves of Appendix C should frequently be made.

After careful consideration, it was concluded that the preceding findings could be used to present some of the results in summary form, grouping together the non-influential variables and combining some others in a more effective manner, as follows:-

4.13.2 Basis of Presentation

(i) For all configurations except interference fit pins, it is possible to plot $K_t' S_a$ instead of S_a (or $K_t' S_a/f_t$ instead of S_a/f_t) and so include automatically the effect of K_t', whether it be due purely to geometry or to a combination of geometry and configuration.

(ii) Reference to paragraph 4.10 and Figures 4.34 to 4.39 shows that because of the locally steep stress gradient at the seat of a stress concentration, and the consequent plastic flow, the effect of mean stress over the range $S_m/f_t = 0.25$ to 0.50 is virtually negligible, so that all endurances for a given configuration and value of S_a/f_t over this range of mean stresses can be combined and average values used without loss of accuracy.

(iii) In regard to size, this variable can be shown directly by plotting average values in accordance with (ii) above, but with differing symbols for each size, thus:-

Large Specimens +

Medium Specimens ⊙

Small Specimens x

(iv) Paragraph 4.8 has shown that it is justifiable to include in this summary presentation any results for Loose Fit Pin Configurations. These are plotted with an extra ring around each point.

Thus the following tables and figures evaluate and plot the resulting summaries.

Summary Presentations

Table 4.9 and Figure 4.44 - UNFILLED HOLE

Table 4.10 and Figure 4.45 - PUSH FIT PIN - PIN UNLOADED*

Table 4.11 and Figure 4.46 - PUSH FIT PIN - PIN LOADED*

Each Presentation covers:-

Average endurances for Mean Stresses of 0.50, 0.40, and 0.25 f_t.

Values of K_t' appropriate to the particular configuration for three values of d/D namely, 1/4, 3/8 and 1/2.

Separate (average) endurance for Large, Medium and Small sizes.

Figure 4.47 shows a comparison between the three configurations, together with some other interesting data.

4.13.3 Discussion on the Summary Presentations

(i) On each of Figures 4.44, 4.45 and 4.46, band widths of the average results discussed above have been drawn. They cover both the range of sizes tested and the scatter of those average results.

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*Including a few Loose Fit Pins where available.

Although in general the average results for the large specimens tend to be nearer to the lower limit of each band, and those for the small specimens towards the upper boundary of the band, this is not universally so, and hence the width of the band is not a true measure of size effect; indeed it exaggerates the effect. For a more accurate estimate of the influence of this variable see paragraph 4.11.

Bearing in mind the wider scatter of individual results it is considered advisable to work to the lower limit of the band when using these curves for design, or if the middle of the band is used a suitable factor for scatter should be applied.

(ii) Figure 4.47 shows the comparison between the three configurations under consideration.

It is clear that in terms of fatigue endurances, the differences between these three bands, although not negligible, are small, and individual scatter could reduce them to a marginal amount, or even reverse them.

The use of $K'_t S_a$ instead of S_a automatically includes the effect of d/D and leaves one with a clearer picture of the situation as compared with the discussions of paragraphs 4.6 and 4.7.

Considering the same two levels of alternating stress as before ($S_a/f_t = 0.20$ and 0.08) and using an average K'_t of 3.0 these become $K'_t S_a/f_t$ of 0.60 and 0.24. Then taking <u>mean values for each band width</u>, which effectively excludes influence of size, a table of comparative endurances at these two levels of alternating stress has been compiled.

	Relative Endurances		
$K'_t S_a/f_t$	Unfilled Hole	Push Fit Pin Pin Unloaded	Push Fit Pin Pin Loaded
0.60	1.0	2.0	0.9
0.24	1.0	1.5	0.9

Thus under otherwise similar conditions the unloaded push fit pin gives endurances of from 1.5 to 2.0 times those for an unfilled hole while a loaded push fit pin gives endurances which are marginally below those for an unfilled hole.

These figures are of course only approximate but are not significantly at variance with the earlier ones of paragraph 4.6 to 4.7 when one considers that the summary presentation tends to exclude some of the scatter.

(iii) Although comparisons between the results of this programme of research and the existing RAeS Data Sheets are discussed extensively in Section 5 of this report, it is of interest at this stage to compare the test results as presented on Figure 4.47 with an endurance curve derived from Data Sheet E.07.01, Figure 3 coupled with the principles laid down in Data Sheet A.00.02.

The first data sheet gives a mean endurance curve for B.S. L65 unnotched material (i.e. $K'_t = 1.0$) and tested at zero mean stress (S_{ao}). This curve is plotted as curve (1) on Figure 4.47. Data Sheet A.00.02 gives a general relationship between S_{ao} and $K'_t S_a$ for notched specimens, at a given endurance N when subjected to a combination of mean and alternating stresses.

This is $$K'_t S_a = S_{ao}\left[1 - (K'_t \frac{S_m}{f_t})^m\right] \qquad (1)$$

(for Notation see Section 3).

Because for almost the full range of $S_m/f_t = 0.20$ to 0.50 at the values of K'_t of Stage 1, $K'_t S_m/f_t$ under elastic conditions exceeds f_p/f_t, then the true $K'_t S_m/f_t$ (due to plastic flow) becomes:-

$$K'_t \frac{S_m}{f_t} = \frac{f_p}{f_t} - K'_t \frac{S_a}{f_t}$$ (Reference paragraph 4.10 conclusion (i)).

Thus equation (1) becomes

$$K'_t S_a = S_{ao}\left[1 - (\frac{f_p}{f_t} - K'_t \frac{S_a}{f_t})^m\right]. \qquad (2)$$

Assuming f_p = 0.2°/o proof stress = 0.90 f_t (Reference Appendix C, paragraph C.1.2) and m = 1.4 (Reference RAeS Data Sheet E.07.03).

Equation (2) becomes

$$K'_t S_a = S_{ao}\left[1 - (0.90 - K'_t \frac{S_a}{f_t})^{1.4}\right]$$

or $$\frac{S_{ao}}{f_t} = \frac{K'_t S_a}{f_t} \Big/ \left[1 - (0.90 - K'_t \frac{S_a}{f_t})^{1.4}\right]. \qquad (3)$$

Equation (3) gives a particular relationship between $K'_t S_a$ and S_{ao} at a given endurance for notched material of the type used for the test specimens.

Using this equation and assuming values of $K'_t S_a$, values of S_{ao} corresponding to a common endurance have been calculated. A curve of $K'_t S_a$ plotted against N has been added to Figure 4.47 as curve (2), the values of N being obtained directly from curve (1).

It may be noted that alternative assumptions could have been made in regard to the choice of the values of f_p/f_t and m.

For example f_p/f_t could have been chosen as 0.875 or 0.85, and m could have been chosen as 1.5 to 1.6. Curves (3) and (4) on Figure 4.47 show the effects of these alternatives, thus:-

Curve (3) corresponds to both

$f_p/f_t = 0.90$ coupled with $m = 1.5$ and

$f_p/f_t = 0.875$ coupled with $m = 1.4$

whilst curve (4) corresponds to both

$f_p/f_t = 0.90$ coupled with $m = 1.6$ and

$f_p/f_t = 0.85$ coupled with $m = 1.4$.

Clearly the positions of these curves (2, 3 and 4) are sensitive to the choice of f_p/f_t and m, and care should be taken to achieve the most representative choice. Over-estimation of the value of f_p/f_t and under-estimation of the value of m both tend to give a conservative estimate. However, the differences between the three curves are not large in relation to the widths of the scatter bands of the three configurations shown on Figure 4.47. These curves afford a general comparison between the test results and computed endurance curves from Data Sheet E.07.01 coupled with

Data Sheet A.00.02. At first sight the agreement appears to be good. However, the slopes of the computed curves are less than that of the boundary endurance curves for all three configurations and it is considered that this is probably due to the influence of fretting.

If a factor of 1.25 is applied to the values of K_t' for the computed curves at an endurance of 10^6 cycles, reducing to 1.0 at 10^4 cycles, then the computed curves and the endurance curves derived from the test results all have the same slope. For example curve (3) becomes curve (3A). Because the latter are mean curves the factor of 1.25 might be greater in some instances, say up to 1.5. (For a discussion of the examination of fretted specimens, see paragraph 4.15).

4.13.4 Interference Fits

Summary Presentations, plotting endurances against $K_t'S_a$ for Interference Fit Pins are not feasible because, as has already been pointed out, K_t' for interference fit pins varies with the applied loading. However, some re-grouping of results is possible by combining at least those for $S_m/f_t = 0.50$ and 0.40, and plotting S_a against N but this exercise is more conveniently presented in Section 5 paragraph 5.5.

4.14 Occurrence of Failures at Locations Other than at Minimum Cross Section

There were a number of occasions on which this occurred and these were given special consideration. They are indicated in the tables and on the graphs by the letters 'J' and 'F'.

4.14.1 'J' - Indicates Failure at the Jaws or Grips of the Testing Machine

This feature has been mentioned in Section 2, paragraph 2.4.2 in respect of the large specimens but similar failures did occur on some medium and small specimens. It is believed that these failures were due primarily to the local stress concentrations at the grips and to some extent this was eliminated or at least minimised by coating the ends of the specimens with Araldite 1/16 in thick.

4.14.2 'F' - Indicates Failure Above or Below the Hole or at the Fillets

In these instances the reasons for the failures were not immediately obvious. Further photoelastic investigations on some of the relevant configurations helped to clarify the problem and indicated that there could be small areas of stress concentration centrally placed on the specimen axis just above and below the hole. These alone, or possibly combined with slight non-homogeneity of the material could account for this type of failure.

Another cause may have been slight corrosion occasioned by the use of Blue Marking Ink.

Slight imperfections in the profile or finish of the machining of the fillet were considered to be the probable reason for failures at the fillet, but photoelastic studies showed that stress concentrations not associated with the machining were sometimes present.

Non axiality of loading was also considered as a possible cause, but in view of the considerable care taken during assembly of the test specimens, and the fact that some of the failures originated right on the longitudinal axis of the specimen, this cause was ruled out as a probable one, except in isolated cases.

4.14.3 Photographs

Figure 4.48 illustrates some of these types of failure. In the upper photo the two left-hand ones are type 'J' and the right-hand one is believed to be type 'F' since failure was probably due to a stress concentration below the pin. Some similar specimens failed even nearer to the hole. The lower specimen is also type 'F' but was probably due to some local damage at the machined edge since it is clear that the fracture commenced there. On the other hand it is possible that there was some small eccentricity of loading in this case.

4.15 Occurrence of Fretting

The testing laboratories were requested to report on signs of evident fretting as and when it occurred. Initially it was reported that there did not appear to be much fretting on the early tests (with unloaded push fit pins). However, a more searching review, supported by examinations under a microscope revealed that there was fretting on many of the specimens, and to varying degrees.

In order to obtain a uniform assessment of this fretting it was arranged that the testing laboratories would submit typical samples in all configurations to be examined independently by the National Engineering Laboratory.

The actual specimens which were so examined are indicated by the addition of (Fr) against the specimen Identification Number in the Tables C.1 to C.50 of Appendix C.

For convenience, details of these specimens are also presented in Table 4.12. The ranges of all the variables are reasonably well covered and from a glance at the table it is clear that fretting to some degree was present in many pinned configurations, irrespective of size, mean stress, alternating stress and geometry. Perhaps it could be said that fretting was slightly more prevalent at combinations of low mean and alternating stress than at the higher stress levels, but the evidence available is limited.

Again, it is to be noted that the samples considered to be outstanding in terms of fretting were not necessarily those with the lowest endurance for a given stress level.

It is convenient to discuss the findings under headings of Configuration.

4.15.1 Loose and Push Fit Pins, Unloaded (Items 1, 13 to 18 and 30 to 35)

The specimens with loose fit pins showed hardly any fretting and the fractures had commenced at the pin hole surface at 90^{o} from the axis of tension.

Perhaps this freedom from fretting was in part due to the protective lacquer initially used on the test specimen, but this cannot be regarded as a serious influence.

For the push fit pins, all samples examined showed some degree of fretting, albeit not large. The fatigue cracks originated in the fretted areas around the pin hole and were somewhat removed from the 90^{o} position.

4.15.2 Loaded Push Fit Pin (Items 5-7 and 19-21)

(a) General

The incidence of fretting on the pin-loaded specimens was more intense than on those with unloaded pins. The greater intensity was doubtless due to the progressive elongation of the loaded hole, and is what one would expect.

A number of examples from all three sizes of specimen were examined in detail. The large specimens proved to be easiest to deal with. The incidence of fretting on the medium and small specimens was sometimes difficult to determine because in a number of these specimens the protective lacquer inside the holes was not always completely removed, as it should have been. This was a difficult operation on the smaller specimens, remembering that the true hole diameter had to be maintained. The difficulty was resolved eventually by machining away most of the lacquer and then using a solvent.

(b) Large Specimens

A number of examples had been noted by Short Brothers and Harland to possess areas of fretting, and it was reported that the origins of failure were always in these areas.

Three further specimens tested at low stress levels and identified as 21.4.F, 38.2.E and 42.4.E, (all Type 1.B.1/2. d/D = 1/4 and listed on Table C.5) were examined by NEL as a check, because they appeared at first not to have any signs of fretting. Further examination however, revealed heavy fretting at the ends of a transverse diameter of the hole, with the main fractures occurring near the outer edges of the band of heaviest fretting. In each case there were fractures on both sides of the hole, with several fatigue nuclei on a given specimen. Specimens 21.4.F and 42.4.E also had other fairly large cracks within the regions of fretting, whilst Specimens 38.2.E and 42.4.E each had a band of deformation across one side of the hole in the fretted region, which might have been due to local indentation by the pin, perhaps at the moment of fracture.

(c) Medium Specimens

Of the three specimens examined, one did not exhibit any fretting. This was 18.11.F. The other two (25.6.F and 26.12.F) had fatigue cracks originating from the region of fretting (more than one crack per side of specimen). All three specimens gave endurances near the geometric mean value. The fretting and the cracks were somewhat removed from the transverse diameter and towards the loaded end of the pin hole.

(d) Small Specimens

There is no record of the examination of any small specimens in this configuration, although a number of small specimens did show some fretting.

4.15.3 Unloaded Interference Fit Pins (Items 2-4 and 24-26)

All these samples were at 0.4°/o Interference Fit. All samples except 33.9.A had fracture origins at the edge of a fretting band and these fretting bands tended to be at one of four symmetrically disposed positions at about 45° to the transverse centre line through the hole. The fractures were between 30° and 45° to the transverse centre line.

The exception, 33.9.A, had very little fretting and the fracture was not associated with it, but close to the transverse centre line. The fracture faces were liberally striated.

Again, checking with the relevant tables and graphs, these examples of fretting were not associated with one particular value of d/D nor were they confined to a particular stress level. They may therefore be regarded as typical for unloaded interference fit pins ($0.4^{o}/o$).

4.15.5 Loaded Interference Fit Pins (Items 8-12, 22, 23 and 27-29

In this configuration both $0.4^{o}/o$ and $0.8^{o}/o$ I.F. pins were examined, covering large and medium size specimens.

As for the unloaded pins the fractures originated at regions of fretting, sometimes at two separate locations. These locations were at positions ranging from 10^{o} to 45^{o} to the transverse centre line and on the "unloaded" end of hole. They were sometimes at different angles in the same specimen. There was no fretting on the "loaded" end of the hole, probably due to the high contact pressure, resulting from the interference plus the pin loading, minimising or preventing slip.

It was noted that in spite of the higher interference on some specimens ($0.8^{o}/o$) there was still some fretting. This was somewhat unexpected. On one of the $0.8^{o}/o$ I.F. samples (16.12.C) the fracture originated from a fretting mark on the side of the plate, rather than at the hole. This was probably because of contact between the plate and the loading fork.

Photographs

(i) Figure 4.49 shows a section taken through the fretted region of the hole surface parallel to the surface of the plate, and showing fatigue cracks for Specimen 33.5.A, Push Fit Pin - Pin Unloaded (Magnification x 60).

(ii) Figure 4.50 shows three pairs of specimen failures all at the same load but with different relationship between pin and hole.

The 'f_1' fit pins ($0.4^{o}/o$ interference fit pins - pin loaded) show failures largely but not entirely one-sided, with the origins of failure well towards the unloaded end of the hole (see Table C.33).

The push fit pins - pin loaded show failures of a similar nature but either at the end of the transverse diameter or even towards the loaded end of the hole (see Table C.32).

The pre-stressed pin is not in the Stage 1 group of tests, but is of interest inasmuch as the pre-stressing appears to have created a more uniform stress distribution which has led to fractures on both sides of the hole at the ends of the transverse diameter.

(iii) Reference to Appendix C, Figures C.51 and C.52 shows two more photographs of multi-fatigue cracks originating from a fretted region. (Specimen 1.7.A, Table C.38).

4.15.6 Effect of Fretting on Endurance Curves

Reference to the endurance curves for those specimens which were examined and found to exhibit significant fretting shows that in a number of cases the curves were quite steep, especially where S_m/f_t is high. This is consistent with what one would expect, due to the accelerating effect of the fretting on crack initiation. Once the crack has started, the remaining endurance is short, since it depends on total stress rather than on range of stress.

The following is a list of figures which show steep endurance curves indicating the occurrence of fretting. Some are for the examples of Table 4.12 already discussed. They cover a range of configurations.

Figure		S_m/f_t
C. 5		0.50
C. 7		0.40
C.12	0.50 and	0.40
C.14	0.50 and	0.40
C.17		0.50
C.24	0.50, 0.40 and	0.25
C.33		0.50
C.40	0.50, 0.40 and	0.25
C.42	(Group (a) 0.50, 0.40 and	0.25

An attempt has been made in paragraph 4.13.3 (iii) in respect of pins without interference fit, and in paragraphs 5.8.2 and 5.8.3 in respect of pins with interference fit, to evaluate a numerical assessment of the effect of fretting.

TABLE 4.1 EFFECT OF MEAN STRESS UNFILLED HOLE

d/D=1/4	Ref.Figs C.1, C.19 and C.35					d/D=1/2	Ref.Figs C.13, C.29 and C.45			
	S_m/f_t	0.50	0.40	0.25	0.15	S_m/f_t	0.50	0.40	0.25	0.15
	S_m	34 700	27 700	17 400	10 400	S_m	34 700	27 700	17 400	10 400
		Values of S_a at $N = 10^4$ cycles					Values of S_a at $N = 10^4$ cycles			
L		15 600	23 000	23 500	-		21 500	22 500	25 500	-
M		21 500	23 000	-	-		17 800	18 800	-	-
S		21 000	20 000	-	-		21 500	23 500	-	-
Average		19 370	22 000	23 500	-		20 270	21 330	25 500	-
		$N = 3x10^4$ cycles					$N = 3x10^4$ cycles			
L		11 000	13 600	15 400	-		12 100	12 250	14 300	-
M		14 500	13 200	14 700	-		11 000	11 900	14 000	15 600
S		13 900	13 000	16 000	-		13 300	13 300	22 000	-
Average		13 130	13 330	15 370	-		12 130	12 480	16 770	15 600
		$N = 10^5$ cycles					$N = 10^5$ cycles			
L		7 700	8 100	9 900	-		7 450	7 600	8 500	10 000
M		9 400	8 200	8 800	-		6 950	7 400	7 850	8 500
S		9 800	8 800	-	12 500		8 700	8 300	11 100	-
Average		8 960	8 370	9 350	12 500		7 700	7 770	9 150	9 250
		$N = 3x10^5$ cycles					$N = 3x10^5$ cycles			
L		6 100	6 700	7 800	-		5 100	5 200	6 000	9 100
M		6 300	6 200	7 000	7 000		5 000	5 200	5 200	5 500
S		7 600	6 600	-	9 800		6 500	6 200	7 250	9 700
Average		6 500	6 500	7 400	8 400		5 530	5 530	6 150	8 100
		$N = 10^6$ cycles					$N = 10^6$ cycles			
L		5 500	6 400	7 350	-		-	-	5 200	8 150
M		4 100	5 350	5 600	5 950		-	-	-	3 700
S		6 050	5 400	-	7 900		5 550	5 250	5 750	8 600
Average		5 220	5 710	6 450	6 925		5 550	5 250	5 475	6 820
		$N = 3x10^6$ cycles					$N = 3x10^6$ cycles			
L		5 150	6 200	7 000	-		-	-	5 150	7 350
M		-	4 950	5 400	5 200		-	-	-	-
S		5 400	4 950	-	6 700		5 100	5 000	5 200	7 800
Average		5 275	5 370	6 200	6 450		5 100	5 000	5 175	7 575
		$N = 10^7$ cycles					$N = 10^7$ cycles			
L		4 900	6 000	6 900			-	-	-	6 800
M		-	4 700	4 950	4 950		-	-	-	-
S		5 000	4 650	-	5 700		4 950	4 900	5 000	7 000
Average		4 950	5 120	5 925	5 325		4 950	4 900	5 000	6 900

TABLE 4.2 EFFECT OF MEAN STRESS PUSH FIT PIN - PIN UNLOADED

d/D=1/4	Ref.Figs C.2, C.21 and C.37					d/D=1/2	Ref.Figs C.14, C.30 and C.46			
	S_m/f_t	0.50	0.40	0.25	0.15	S_m/f_t	0.50	0.40	0.25	0.15
	S_m	34 700	27 700	17 400	10 400	S_m	34 700	27 700	17 400	10 400
		Values of S_a at $N = 10^4$ cycles					Values of S_a at $N = 10^4$ cycles			
L		24 500	25 020	-	-		-	-	-	-
M		-	-	-	-		22 500	-	-	-
S		-	-	-	-		22 500	22 500	-	-
Average		24 500	25 020	-	-		22 500	22 500	-	-
		$N = 3x10^4$ cycles					$N = 3x10^4$ cycles			
L		13 000	14 000	-	-		13 900	15 800	26 500	-
M		23 000	-	-	-		14 500	18 800	22 000	-
S		18 000	23 000	26 500	-		15 600	18 000	22 000	-
Average		18 000	18 500	26 500			14 670	18 200	23 500	-
		$N = 10^5$ cycles					$N = 10^5$ cycles			
L		6 450	7 200	-	-		6 400	7 100	9 000	-
M		10 950	14 950	13 950	-		9 250	11 000	15 800	-
S		10 200	11 200	16 000	-		10 800	13 500	16 000	-
Average		9 200	11 120	14 975	-		9 150	10 800	13 600	-
		$N = 3x10^5$ cycles					$N = 3x10^5$ cycles			
L		3 400	3 900	-	-		4 650	4 900	5 100	-
M		7 000	7 650	8 950	10 300		6 150	6 600	-	-
S		6 900	7 350	10 700	-		7 700	10 400	12 000	-
Average		5 770	6 300	9 325	10 300		6 170	7 300	8 550	-
		$N = 10^6$ cycles					$N = 10^6$ cycles			
L		-	-	-	-		-	-	-	-
M		5 500	5 600	6 300	7 150		4 400	-	-	-
S		5 300	5 700	7 700	12 900		5 800	7 800	8 700	-
Average		5 400	5 650	7 000	10 025		5 100	7 800	8 700	-
		$N = 3x10^6$ cycles					$N = 3x10^6$ cycles			
L		-	-	-	-		-	-	-	-
M		5 000	5 150	5 250	5 200		-	-	-	-
S		4 550	5 000	6 400	8 500		4 900	6 000	6 600	9 300
Average		4 775	5 075	5 825	6 850		4 900	6 000	6 600	9 300
		$N = 10^7$ cycles					$N = 10^7$ cycles			
L		-	-	-	-		-	-	-	-
M		-	-	4 750	3 850		-	-	-	-
S		-	-	5 550	6 350		-	4 600	4 950	6 800
Average		-	-	5 150	5 150		-	4 600	4 950	6 800

TABLE 4.3 EFFECT OF MEAN STRESS PUSH FIT PIN - PIN LOADED

d/D=1/4	Ref.Figs C. 5, C.24 and C.40					d/D=1/2	Ref.Figs C.16, C.32 and C.48			
	S_m/f_t	0.50	0.40	0.25	0.15	S_m/f_t	0.50	0.40	0.25	0.15
	S_m	34 700	27 700	17 400	10 400	S_m	34 700	27 700	17 400	10 400
		Values of S_a at $N = 10^4$ cycles					Values of S_a at $N = 10^4$ cycles			
L		9 500	7 500	11 000	14 500		17 500	20 000	25 000	-
M		11 100	12 400	14 000	-		23 500	24 900	25 000	-
S		17 800	22 800	24 000	-		18 700	-	23 000	-
Average		12 800	14 230	16 300	14 500		19 900	22 450	24 300	-
		$N = 3x10^4$ cycles					$N = 3x10^4$ cycles			
L		5 000	-	6 500	8 500		8 250	8 650	11 250	-
M		6 600	7 500	8 400	-		14 700	15 300	15 900	-
S		7 400	8 900	11 900	9 300		12 000	-	17 000	-
Average		6 300	8 200	8 930	8 900		11 650	11 975	14 720	-
		$N = 10^5$ cycles					$N = 10^5$ cycles			
L		-	-	4 300	5 300		5 250	5 400	6 400	-
M		3 750	4 300	5 400	-		8 800	9 250	9 750	12 900
S		4 500	5 100	7 000	5 700		8 250	14 200	12 400	10 400
Average		4 125	4 700	5 570	5 500		7 430	9 620	9 520	11 650
		$N = 3x10^5$ cycles					$N = 3x10^5$ cycles			
L		-	-	3 400	3 700		4 600	4 700	5 100	-
M		-	-	-	-		5 800	6 000	6 800	8 700
S		4 300	4 300	5 100	4 100		6 200	8 700	9 100	7 400
Average		4 300	4 300	4 250	3 900		5 530	6 470	7 000	8 050
		$N = 10^6$ cycles					$N = 10^6$ cycles			
L		-	-	-	-		-	-	-	-
M		-	-	-	-		4 800	4 900	5 200	6 150
S		-	-	-	-		4 900	6 200	6 700	5 000
Average		-	-	-	-		4 850	5 550	5 950	5 575
		$N = 3x10^6$ cycles					$N = 3x10^6$ cycles			
L		-	-	-	-		-	-	-	-
M		-	-	-	-		-	-	-	4 800
S		-	-	-	-		-	5 100	5 300	3 800
Average		-	-	-	-		-	5 100	5 300	4 300
		$N = 10^7$ cycles					$N = 10^7$ cycles			
L		-	-	-	-		-	-	-	-
M		-	-	-	-		-	-	-	4 000
S		-	-	-	-		-	-	-	3 250
Average		-	-	-	-		-	-	-	3 625

TABLE 4.4 EFFECT OF MEAN STRESS
$0.4^{0}/o$ INTERFERENCE FIT PIN - PIN UNLOADED

d/D=1/4	Ref.Figs C.3, C.22 and C.38					d/D=1/2	Ref.Figs C.15, C.31 and C.47			
	S_m/f_t	0.50	0.40	0.25	0.15	S_m/f_t	0.50	0.40	0.25	0.15
	S_m	34 700	27 700	17 400	10 400	S_m	34 700	27 700	17 400	10 400
		Values of S_a at $N = 10^4$ cycles					Values of S_a at $N = 10^4$ cycles			
L		-	-	-	-		-	-	-	-
M		-	-	-	-		-	-	-	-
S		-	-	-	-		-	-	-	-
Average		-	-	-	-		-	-	-	-
		$N = 3x10^4$ cycles					$N = 3x10^4$ cycles			
L		18 000	26 500	-	-		-	-	-	-
M		15 000	20 000	-	-		-	-	-	-
S		21 000	-	-	-		-	-	-	-
Average		18 000	23 250	-	-		-	-	-	-
		$N = 10^5$ cycles					$N = 10^5$ cycles			
L		10 000	15 200	-	-		-	-	-	-
M		8 400	9 700	21 600	-		15 600	17 400	-	-
S		12 000	17 000	20 000	-		20 000	-	-	-
Average		10 130	13 970	20 800	-		17 800	17 400	-	-
		$N = 3 \times 10^5$ cycles					$N = 3 \times 10^5$ cycles			
L		6 150	9 150	17 900	-		11 200	16 600	-	-
M		5 600	6 550	12 500	-		11 700	14 200	-	-
S		8 000	10 600	12 700	-		15 600	-	-	-
Average		6 580	8 770	14 370	-		12 830	15 400	-	-
		$N = 10^6$ cycles					$N = 10^6$ cycles			
L		4 600	5 750	13 800	-		7 400	12 700	-	-
M		4 200	5 600	8 100	-		8 600	11 550	-	-
S		5 700	7 150	8 400	-		12 400	-	-	-
Average		4 830	6 170	10 100	-		9 470	12 125	-	-
		$N = 3x10^6$ cycles					$N = 3x10^6$ cycles			
L		-	5 150	10 900	-		5 800	11 000	-	-
M		-	5 100	6 900	-		6 600	9 500	-	-
S		4 700	5 700	6 600	-		10 000	-	-	-
Average		4 700	5 320	8 130	-		7 470	10 250	-	-
		$N = 10^7$ cycles					$N = 10^7$ cycles			
L		-	4 700	9 100	-		4 900	10 200	-	-
M		-	5 150	6 300	-		5 300	7 700	-	-
S		-	4 950	5 600	-		8 000	-	-	-
Average		-	4 930	7 000	-		6 070	8 950	-	-

TABLE 4.5 EFFECT OF MEAN STRESS
0.4°/o INTERFERENCE FIT PIN - PIN LOADED

d/D=1/4	Ref.Figs C.6, C.25 and C.41					d/D=1/2	Ref.Figs C.17, C.33 and C.49			
	S_m/f_t	0.50	0.40	0.25	0.15	S_m/f_t	0.50	0.40	0.25	0.15
	S_m	34 700	27 700	17 400	10 400	S_m	34 700	27 700	17 400	10 400
		Values of S_a at $N = 10^4$ cycles					Values of S_a at $N = 10^4$ cycles			
L		10 900	11 900	18 400	-		-	-	-	-
M		11 000	12 600	15 000	-		-	-	-	-
S		13 900	16 700	22 000	-		-	-	-	-
Average		11 930	13 730	18 470	-		-	-	-	-
		$N = 3x10^4$ cycles					$N = 3x10^4$ cycles			
L		6 150	6 500	10 900	12 800		-	-	-	-
M		6 350	7 700	9 500	-		16 500	18 300	-	-
S		7 900	9 400	12 600	-		16 000	21 000	-	-
Average		6 800	7 870	11 000	12 800		16 250	19 650	-	-
		$N = 10^5$ cycles					$N = 10^5$ cycles			
L		3 400	3 550	6 100	6 600		5 000	-	-	-
M		3 500	4 500	5 800	9 500		8 400	11 900	-	-
S		5 250	5 900	8 000	8 800		9 500	15 200	-	-
Average		4 050	4 650	6 630	8 300		7 630	13 550	-	-
		$N = 3x10^5$ cycles					$N = 3x10^5$ cycles			
L		-	-	3 650	11 000		-	16 500	-	-
M		-	-	3 700	7 000		4 550	8 000	22 000	-
S		4 300	4 600	6 000	6 000		6 000	11 700	-	-
Average		4 300	4 600	4 450	8 000		5 275	12 100	22 000	-
		$N = 10^6$ cycles					$N = 10^6$ cycles			
L		-	-	-	8 500		-	8 800	19 000	-
M		-	-	-	5 150		-	5 150	17 700	-
S		-	-	5 100	3 900		-	8 500	23 000	-
Average		-	-	5 100	5 850		-	7 480	19 900	-
		$N = 3x10^6$ cycles					$N = 3x10^6$ cycles			
L		-	-	-	6 500		-	5 200	13 600	-
M		-	-	-	4 200		-	-	14 300	-
S		-	-	4 700	4 000		-	6 700	16 600	-
Average		-	-	4 700	4 900		-	5 950	14 830	-
		$N = 10^7$ cycles					$N = 10^7$ cycles			
L		-	-	-	5 200		-	-	9 500	-
M		-	-	-	3 700		-	-	11 500	-
S		-	-	4 500	-		-	5 400	12 200	-
Average		-	-	4 500	4 450		-	5 400	11 070	-

TABLE 4.6 ESTIMATION OF S_{ao} FOR STAGE 1 TEST SPECIMENS FROM DATA ON RAeS DATA SHEET E.07.01 FIGURE 3

ENDURANCE N CYCLES		$^{+}10^4$	3×10^4	10^5	3×10^5	10^6	3×10^6	10^7
S_{ao} PLAIN SPECIMEN (FROM E.07.01) $K'_t = 1.0$		48 500	43 000	37 000	33 000	29 000	26 500	23 500
S_{ao} (lb/in^2) Unfilled Hole and	$d/D = 1/4$, $K'_t = 2.43$	19 900	17 700	16 200	13 600	12 000	10 900	9 650
Push Fit Pin - Pin Unloaded	$d/D = 1/2$, $K'_t = 2.17$	22 300	19 800	17 000	15 200	13 400	12 200	10 800
S_{ao} (lb/in^2) Push Fit Pin -	$d/D = 1/4$, $K'_t = 3.73$	13 000	11 500	9 900	8 850	7 800	7 200	6 300
Pin Loaded	$d/D = 1/2$, $K'_t = 2.22$	21 800	19 300	16 600	14 800	13 000	11 900	10 600

$^{+}$The derived values of S_{ao} for this endurance curve are of doubtful reliability since the procedure tends to be less accurate at low endurances.

TABLE 4.7 EFFECT OF SIZE - EXPRESSED AS ENDURANCE RATIO* FOR STATED STRESS LEVELS

[Averaged for S_m/f_t = 0.50, 0.40 and 0.25 for Unfilled Hole and Push Fit Pin
= 0.50 and 0.40 for Interference Fit Pins]

Configuration	Unfilled Hole				Push Fit Pin - Pin Unloaded				Push Fit Pin - Pin Loaded				0.4% Interference Fit Pin - Pin Unloaded				0.4% Interference Fit Pin - Pin Loaded			
Stress Level S_a/f_t	0.20		0.08		0.20		0.08		0.20		0.08		0.20		0.08		0.20		0.08	
d/D	1/4	1/2	1/4	1/2	1/4	1/2	1/4	1/2	1/4	1/2	1/4	1/2	1/4	1/2	1/4	1/2	1/4	1/2	1/4	1/2
Endurance Ratio*	1.4	1.5	1.7	3.0	2.5	2.2	10.0+	15.0+	2.6	3.0	3.0	9.0	1.5	8.5	3.0	ϕ	1.8	0.6●	3.0	3.5

$$\text{* Endurance Ratio} = \frac{\text{Endurance of Small Specimen}}{\text{Endurance of Large Specimen}}.$$

\+ Large specimen results somewhat low and small specimen results somewhat high.

ϕ Insufficient evidence to permit evaluation.

● Large specimen results unduly high and small specimen results unduly low.

TABLE 4.8 EFFECT OF SIZE - EXPRESSED AS ALTERNATING STRESS RATIO* FOR STATED ENDURANCES

[Averaged for S_m/f_t = 0.50, 0.40 and 0.25 for Unfilled Hole and Push Fit Pins
= 0.50 and 0.40 for Interference Fit Pins]

d/D	Configuration / N cycles Endurance	Unfilled Hole	Push Fit Pin - Pin Unloaded	Push Fit Pin - Pin Loaded	0.4% Interference Fit Pin-Pin Unloaded	0.4% Interference Fit Pin-Pin Loaded
		← ALTERNATING STRESS RATIO* →				
1/4	3×10^4	1.1	1.5	1.6	1.2	1.3
	10^5	1.2	1.5	1.6	1.2	1.5
	3×10^5	1.1	1.6	-	1.1	-
	10^6	1.0	-	-	1.0	-
	3×10^6	0.9	-	-	0.9	-
1/2	3×10^4	1.2	1.0	1.5	-	-
	10^5	1.2	1.8	2.0	-	1.9
	3×10^5	1.2	2.0	1.7	1.4	0.7
	10^6	1.1	-	-	1.7	1.0
	3×10^6	1.0	-	-	1.7	1.3

$$^{*}\text{Alternating Stress Ratio} = \frac{\text{Alternating Stress for Small Specimen}}{\text{Alternating Stress for Large Specimen}}$$

TABLE 4.9 ENDURANCES (CYCLES) FOR UNFILLED HOLE (Plotted on Fig 4.44) SUMMARY PRESENTATION

S_m/f_t = 0.50, 0.40 and 0.25 combined.

d/D = 1/4, 3/8 and 1/2 - K'_t = 2.43, 2.28 and 2.17

Large, Medium and Small sizes

			Geometry	d/D = 1/4, K'_t = 2.43			d/D = 3/8, K'_t = 2.28			d/D = 1/2, K'_t = 2.17		
			Ref.Table	C.1	C.19	C.35	C.8	C.27	C.43	C.13	C.29	C.45
			Size	L	M	S	L	M	S	L	M	S
S_a/f_t	d/D	K'_tS_a/f_t	K'_tS_a									
0.225	1/4	0.547	38 000	18 650	24 000	23 000						
	3/8	0.513	35 600				15 500	41 700	31 600			
	1/2	0.488	33 800							18 500	17 000	27 500
0.15	1/4	0.364	25 300	64 600	61 600	64 600						
	3/8	0.342	23 800				44 700	209 000	89 000			
	1/2	0.326	22 600							50 000	41 700	77 200
0.10	1/4	0.243	16 900	276 000+	295 000+	417 000+						
	3/8	0.228	15 850				170 000	214 000	710 000			
	1/2	0.217	15 100							151 000	135 000	224 000
0.075	1/4	0.182	12 600	-	1 122 000+	3 470 000+						
	3/8	0.171	11 850				1 075 000+	2 090 000+	850 000+			
	1/2	0.163	11 300							417 000+	269 000	1 820 000+

+signifies UNBROKEN FOR SOME OF THE NINE RESULTS

TABLE 4.10(a) ENDURANCES (CYCLES) FOR PUSH FIT PIN - PIN UNLOADED (Plotted on Fig 4.45) SUMMARY PRESENTATION

S_m/f_t = 0.50, 0.40 and 0.25 combined.

d/D = 1/4, 3/8 **and** 1/2 - K'_t = 2.43, 2.28 **and** 2.17

Large, Medium and Small sizes

			Geometry	d/D = 1/4, K'_t = 2.43			d/D = 3/8, K'_t = 2.28			d/D = 1/2, K'_t = 2.17		
			Ref.Table	C.2	C.21	C.37	C.9	C.28	C.44	C.14	C.30	C.46
			Size	L	M	S	L	M	S	L	M	S
S_a/f_t	d/D	K'_tS_a/f_t	K'_tS_a			*						
0.225	1/4	0.547	38 000	22 400	69 200	77 800						
	3/8	0.513	35 600				31 700	76 000	61 800			
	1/2	0.488	33 800							34 000	34 500	56 300
0.15	1/4	0.364	25 300	42 700	166 000	170 000						
	3/8	0.342	23 800				61 800	155 000	170 000			
	1/2	0.326	22 600							60 300	91 300	364 000
0.10	1/4	0.243	16 900	95 000	357 000	603 000+						
	3/8	0.228	15 850				158 500	500 000	870 000			
	1/2	0.217	15 100							107 500	240 000	1 025 000+
0.075	1/4	0.182	12 600	158 500	219 000	1 415 000+						
	3/8	0.171	11 850				331 000	2 515 000+	6 180 000+			
	1/2	0.163	11 300							240 000	427 000	2 820 000+

TABLE 4.10(b) ENDURANCES (CYCLES) FOR LOOSE FIT PIN - PIN UNLOADED (plotted on Figure 4.45)

Additional Points for $d/D = 1/4$, Medium and Small Size Specimens

			Ref.Table	-	C.20	C.36
			Size	L	M	S
S_a/f_t	d/D	$K'_t S_a/f_t$	$K'_t S_a$			
0.225	1/4	0.547	38 000	-	19 100	25 200
0.15	1/4	0.364	25 300	-	52 600	95 600
0.10	1/4	0.243	16 900	-	182 000	257 000$^+$
0.075	1/4	0.182	12 600	-	332 000	1 660 000$^+$

GENERAL NOTES TABLES 4.10(a) and (b)

*Loads to insert pins in this configuration were relatively high - i.e. into the range for 0.4°/o Interference Fit Pins

$^+$Signifies UNBROKEN for some of the nine results.

TABLE 4.11(a) ENDURANCES (CYCLES) FOR PUSH FIT PIN - **PIN** LOADED (Plotted on Fig 4.46) SUMMARY PRESENTATION

S_m/f_t = 0.50, 0.40 and 0.25 combined.

d/D = 1/4, 3/8 and 1/2 - K'_t = 3.73, 2.72 and 2.22

Large, Medium and Small Size Specimens

			Geometry	d/D = 1/4, K'_t = 3.73			d/D = 3/8, K'_t = 2.72			d/D = 1/2, K'_t = 2.22		
			Ref.Table	C.5	C.24	C.40	C.11	-	-	C.16	C.32	C.48
			Size	L	M	S	L	M	S	L	M	S
S_a/f_t	d/D	K'_tS_a/f_t	K'_tS_a			*						*
0.225	1/4	0.840	58 200	4 800	6 600	14 200						
	3/8	0.615	42 500				10 500	-	-			
	1/2	0.500	34 700							13 800	28 800	37 200
0.15	1/4	0.560	38 800	27 000	13 800	25 200						
	3/8	0.410	28 500				20 000	-	-			
	1/2	0.333	23 100							25 700	71 000	155 000
0.10	1/4	0.373	25 900	21 400	39 000	52 500						
	3/8	0.272	18 900				45 800	-	-			
	1/2	0.222	15 400							52 500	214 000	678 000+
0.075	1/4	0.280	19 400	45 700	72 400	182 000						
	3/8	0.205	14 200				110 000	-	-			
	1/2	0.166	11 500							148 000	385 000	1 260 000+

TABLE 4.11(b) ENDURANCES (CYCLES) FOR LOOSE FIT PIN - PIN LOADED

Additional Points for $d/D = 1/4$, Large Size Specimens Only, $K_t = 4.10$

			Ref.Table	C.4	-	-
			Size	L	M	S
S_a/f_t	d/D	K'_tS_a/f_t	K'_tS_a	-	-	-
0.225	1/4	0.925	64 000	4 220	-	-
0.15	1/4	0.615	42 500	14 100	-	-
0.10	1/4	0.410	28 500	29 400	-	-
0.075	1/4	0.307	21 300	28 000	-	-

GENERAL NOTES TABLES 4.11(a) and (b)

*Loads to insert pins in these configurations were relatively high - i.e. into the range for 0.4°/o Interference Fit Pins.

+Signifies UNBROKEN for some of the nine results.

TABLE 4.12 SPECIMENS EXAMINED FOR FRETTING BY NEL

Item	Identification	Configuration*	Size	Type	d/D	S_m/f_t	$\pm S_a/f_t$	Ref.Table
1	33.5.A	PFP-PU	L	1A 1/2	1/4	0.40	0.225	C.2
2	33.7.A	0.4°/oIF-PU	L	1A 1/2	1/4	0.50	0.225	C.3
3	33.9.A	0.4°/oIF-PU	L	1A 1/2	1/4	0.40	0.10	C.3
4	34.3.B	0.4°/oIF-PU	L	1A 1/2	1/4	0.25	0.15	C.3
5	21.4.F	PFP-PL	L	1B/1/2	1/4	0.25	0.05	C.5
6	38.2.E	PFP-PL	L	1B 1/2	1/4	0.20	0.10	C.5
7	42.4.E	PFP-PL	L	1B 1/2	1/4	0.20	0.05	C.5
8	43.6.E	0.4°/oIF-PL	L	1B 1/2	1/4	0.25	0.15	C.6(a)
9	43.8.E	0.4°/oIF-PL	L	1B 1/2	1/4	0.25	0.075	C.6(a)
10	20.9.G	0.4°/oIF-PL	L	1B 1/2	1/4	0.15	0.075	C.6(a)
11	17.4.A	0.8°/oIF-PL	L	IDI	1/2	0.50	0.225	C.18
12	16.12.C	0.8°/oIF-PL	L	IDI	1/2	0.50	0.10	C.18
13	23.16.C	LFP-PU	M	2A 5/16	1/4	0.50	0.225	C.20
14	29.15.B	LFP-PU	M	2A 5/16	1/4	0.40	0.075	C.20
15	30.10.C	LFP-PU	M	2A 5/16	1/4	0.25	0.075	C.20
16	22.13.D	PFP-PU	M	2A 5/16	1/4	0.50	0.225	C.21
17	24.6.B	PFP-PU	M	2A 5/16	1/4	0.50	0.075	C.21
18	30.3.E	PFP-PU	M	2A 5/16	1/4	0.25	0.075	C.21
19	18.11.F	PFP-PL	M	2B 5/16	1/4	0.50	0.225	C.24
20	25.6.F	PFP-PL	M	2B 5/16	1/4	0.40	0.075	C.24
21	26.12.F	PFP-PL	M	2B 5/16	1/4	0.25	0.075	C.24
22	26.1.F	0.8°/oIF-PL	M	2B 5/16	1/4	0.25	0.15	C.26
23	26.18.F	0.8°/oIF-PL	M	2B 5/16	1/4	0.25	0.075	C.26
24	4.18.B	0.4°/oIF-PU	M	2C 5/8	1/2	0.50	0.225	C.31
25	5.1.C	0.4°/oIF-PU	M	2C 5/8	1/2	0.40	0.225	C.31
26	5.2.D	0.4°/oIF-PU	M	2C 5/8	1/2	0.40	0.10	C.31
27	16.14.E	0.4°/oIF-PL	M	2D 5/8	1/2	0.50	0.225	C.33
28	17.7.C	0.4°/oIF-PL	M	2D 5/8	1/2	0.40	0.10	C.33
29	17.10.A	0.4°/oIF-PL	M	2D 5/8	1/2	0.25	0.225	C.33
30	1.4.C	LFP-PU	S	$4A_1$ 3/16	1/4	0.50	0.225	C.36
31	2.6.I	LFP-PU	S	$4A_1$ 3/16	1/4	0.40	0.10	C.36
32	3.16.I	LFP-PU	S	$4A_1$ 3/16	1/4	0.25	0.075	C.36
33	1.19.I	PFP-PU	S	4A 3/16	1/4	0.50	0.225	C.37
34	2.9.J	PFP-PU	S	4A 3/16	1/4	0.25	0.075	C.37
35	2.22.H	PFP-PU	S	4A 3/16	1/4	0.40	0.075	C.37

*KEY

PFP-PU	-	Push Fit Pin - Pin Unloaded
0.4°/oIF-PU	-	0.4°/o Interference Fit Pin - Pin Loaded
PFP-PL	-	Push Fit Pin - Pin Loaded
0.4°/oIF-PL	-	0.4°/o Interference Fit Pin - Pin Loaded
0.8°/oIF-PL	-	0.8°/o Interference Fit Pin - Pin Loaded
LFP-PU	-	Loose Fit Pin - Pin Unloaded

FIG 4·1 EFFECT OF UNLOADED PUSH FIT PIN

LARGE SPECIMENS $a/D = 1/4$ Ref: Figs C.1 & C.2

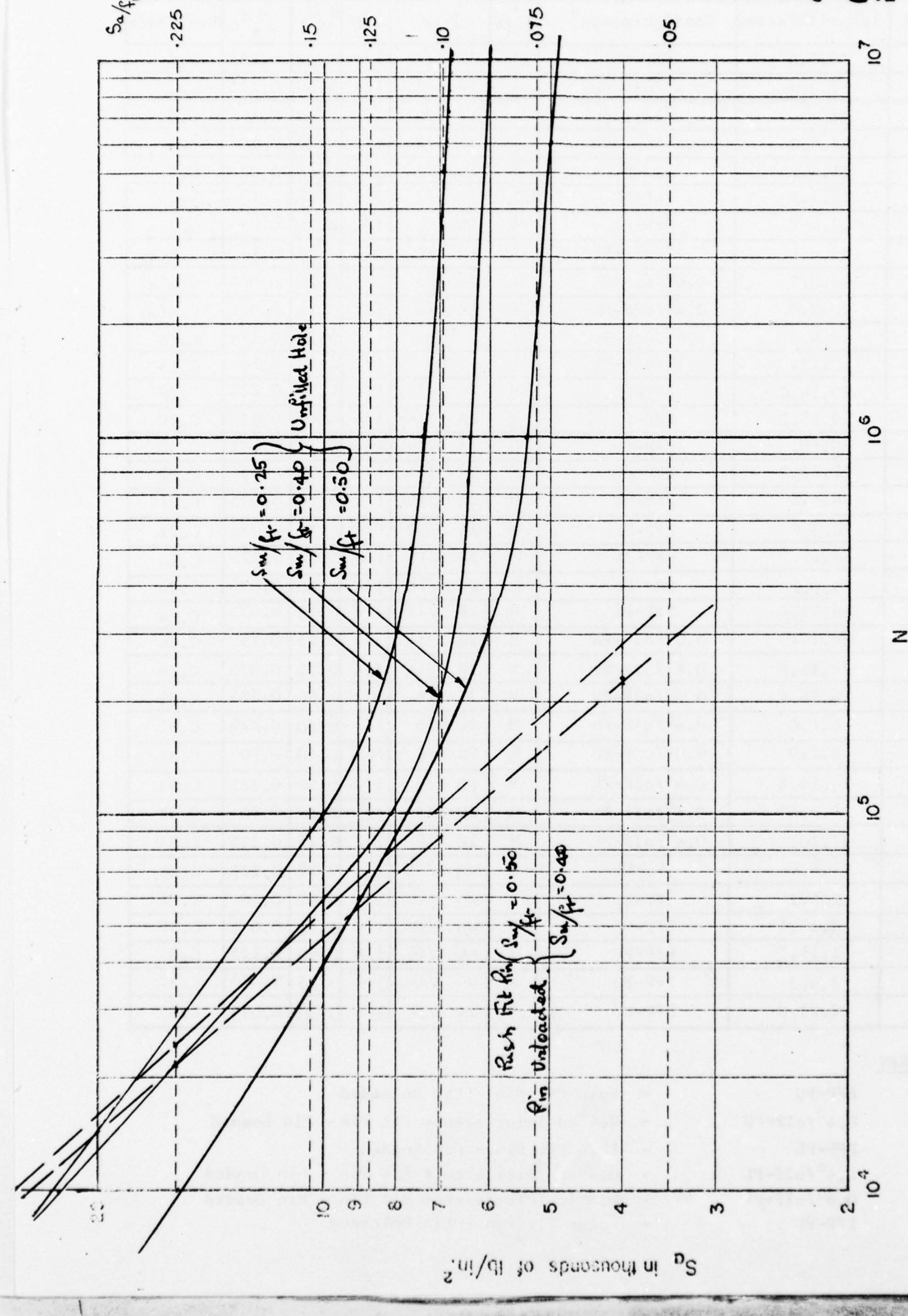


FIG 4.2 EFFECT OF UNLOADED PUSH FIT PIN

LARGE SPECIMENS $d/D = 3/8$ Ref. Figs C.8 & C.9

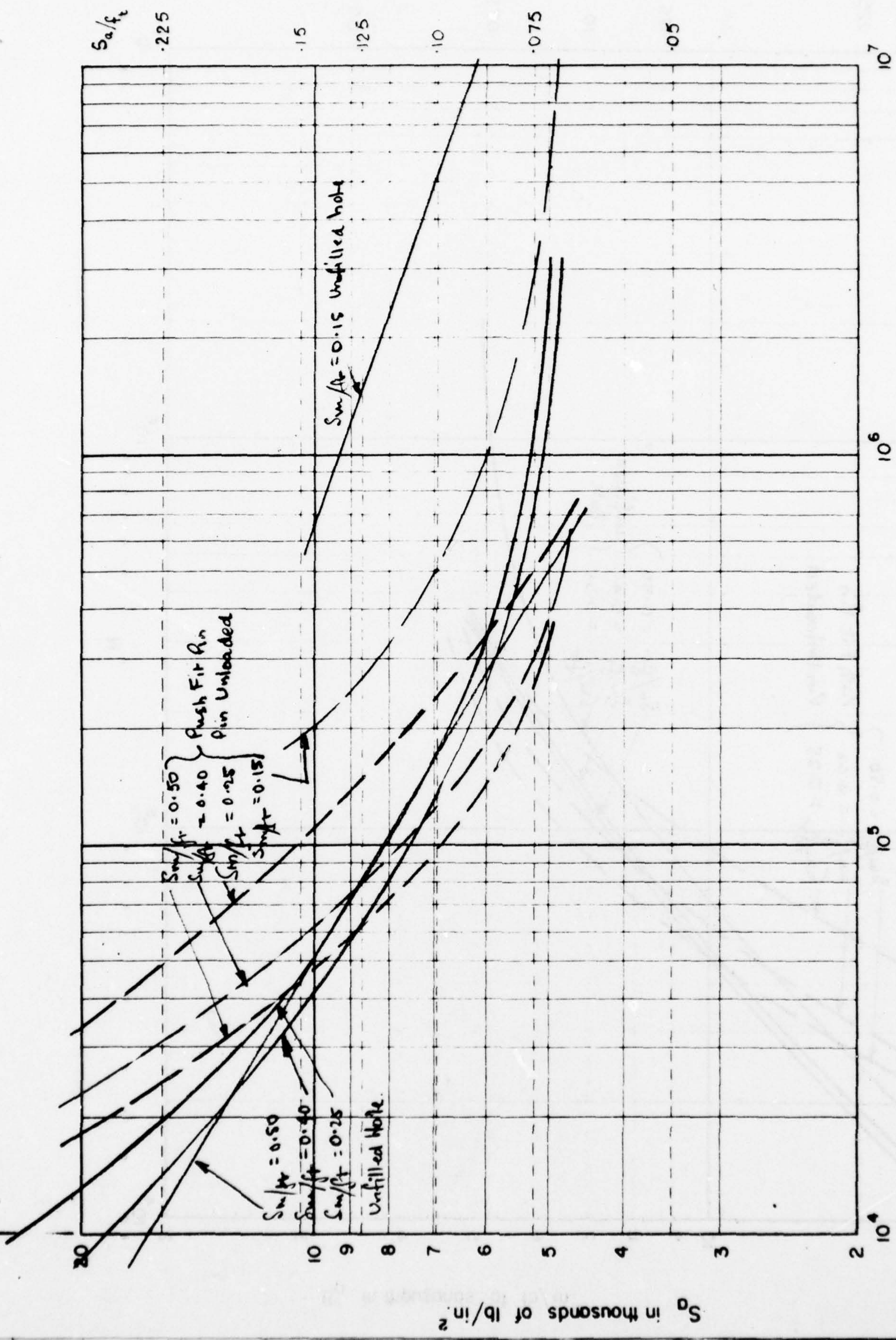


FIG.43 – EFFECT OF UNLOADED PUSH FIT PIN

LARGE SPECIMENS $d/D = 1/2$ Ref. Figs C.13 & C.14

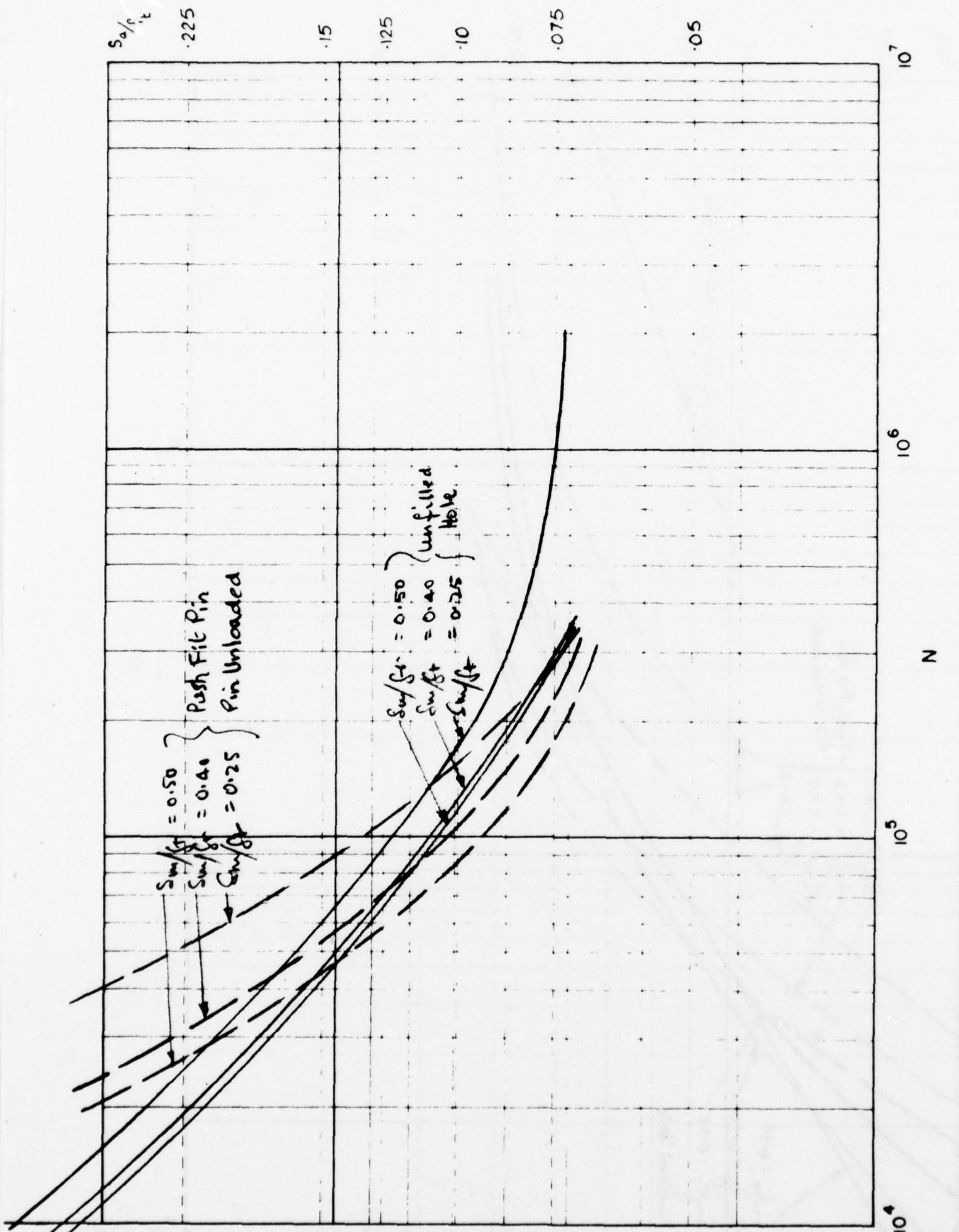
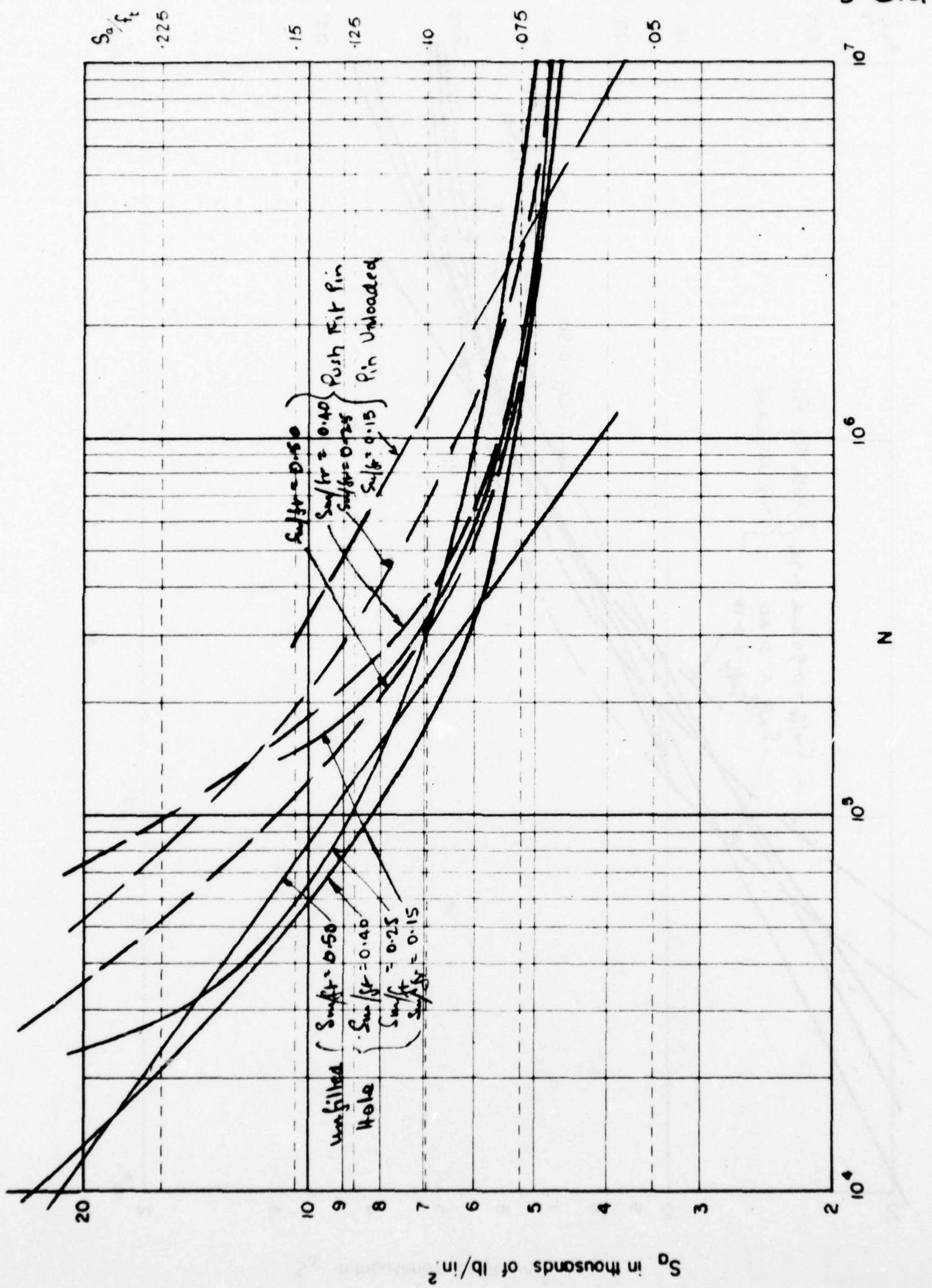


FIG 44 – EFFECT OF UNLOADED PUSH FIT PIN

MEDIUM SPECIMENS d/D = 1/4 Ref Figs C.19 & C.21



66 FIG 4.5 – EFFECT OF UNLOADED PUSH FIT PIN

MEDIUM SPECIMENS   d/D = 3/8   Ref Figs. C.27 & C.28

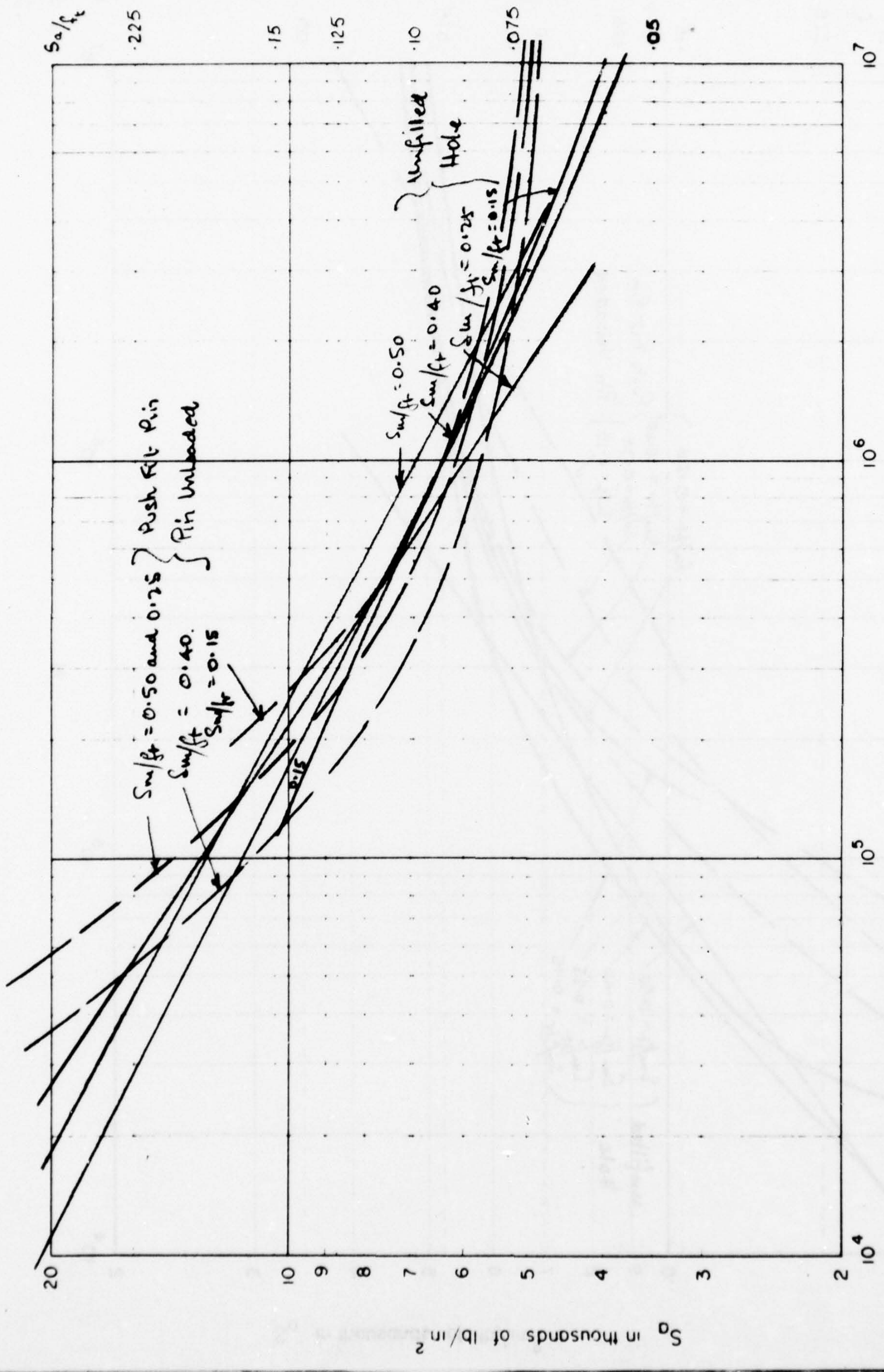


FIG 4·6 – EFFECT OF UNLOADED PUSH FIT PIN

MEDIUM SPECIMENS $d/D = 1/2$

Ref: Figs C.29 & C.30.

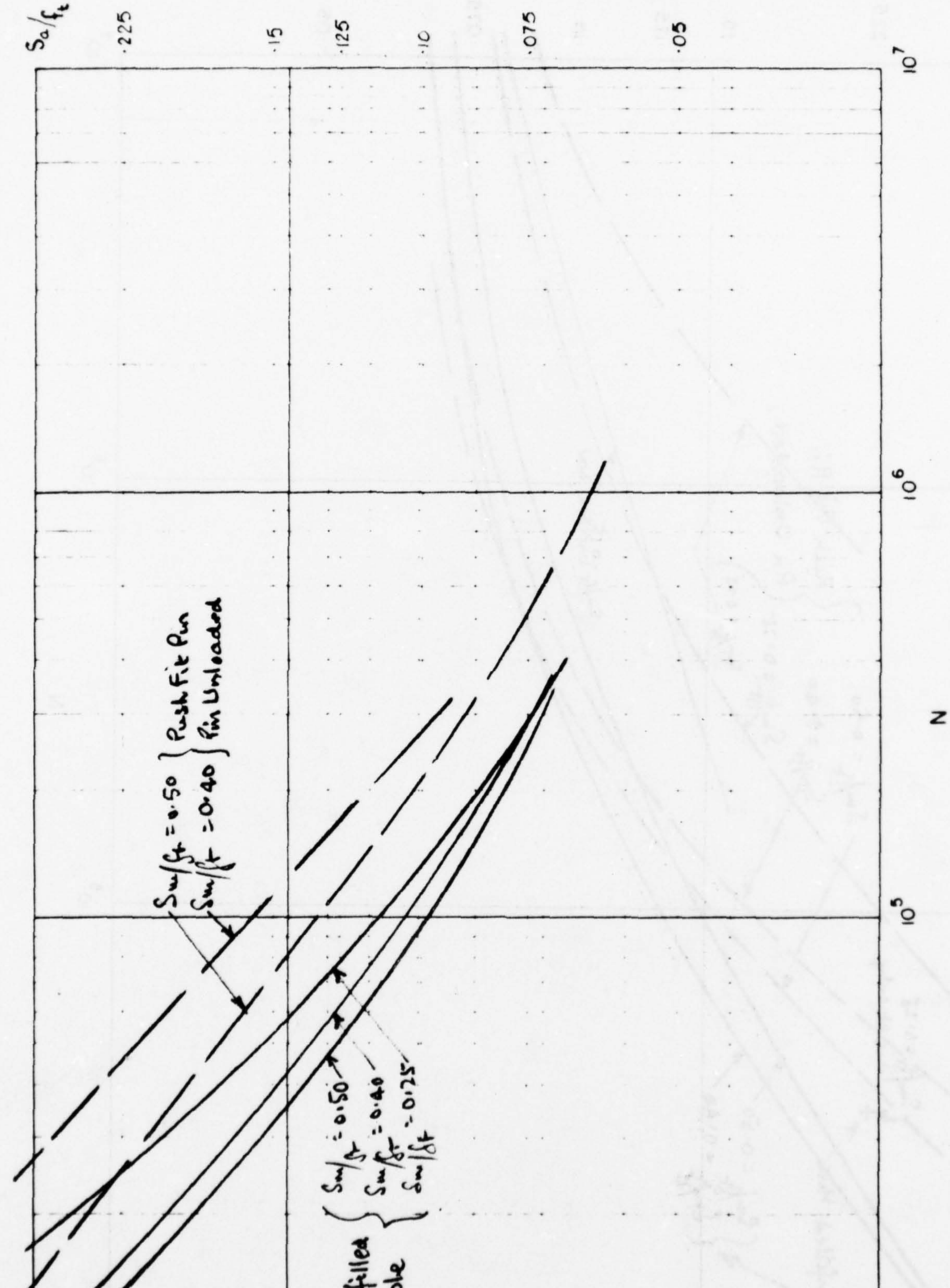


FIG. 4.7– EFFECT OF UNLOADED PUSH FIT PIN

SMALL SPECIMENS $d/D = 1/4$ Ref Figs C.35 & C.37

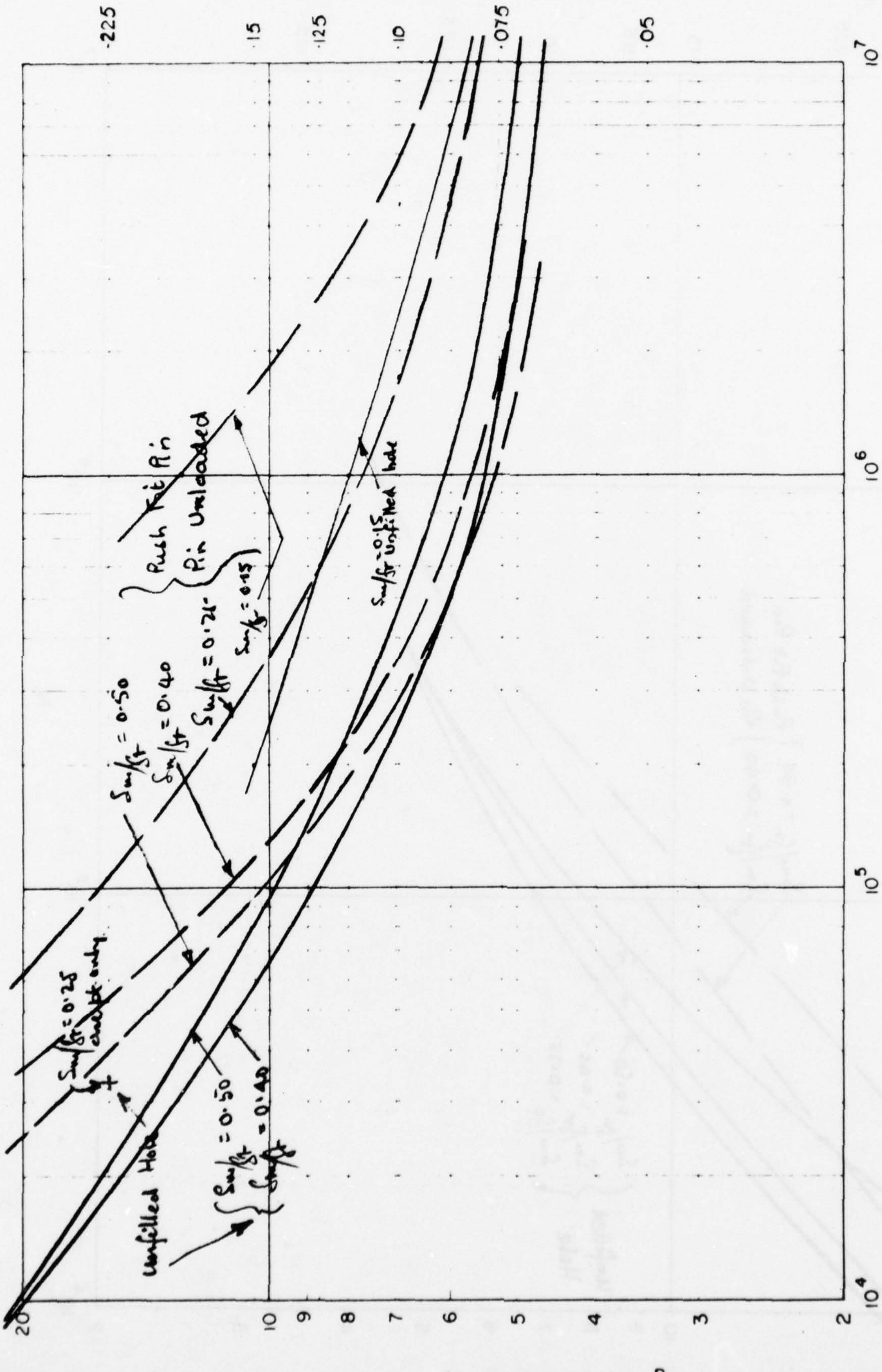


FIG 48 – EFFECT OF UNLOADED PUSH FIT PIN

SMALL SPECIMENS $d/D = 3/8$.

Ref. Figs. C.43 & C.44.

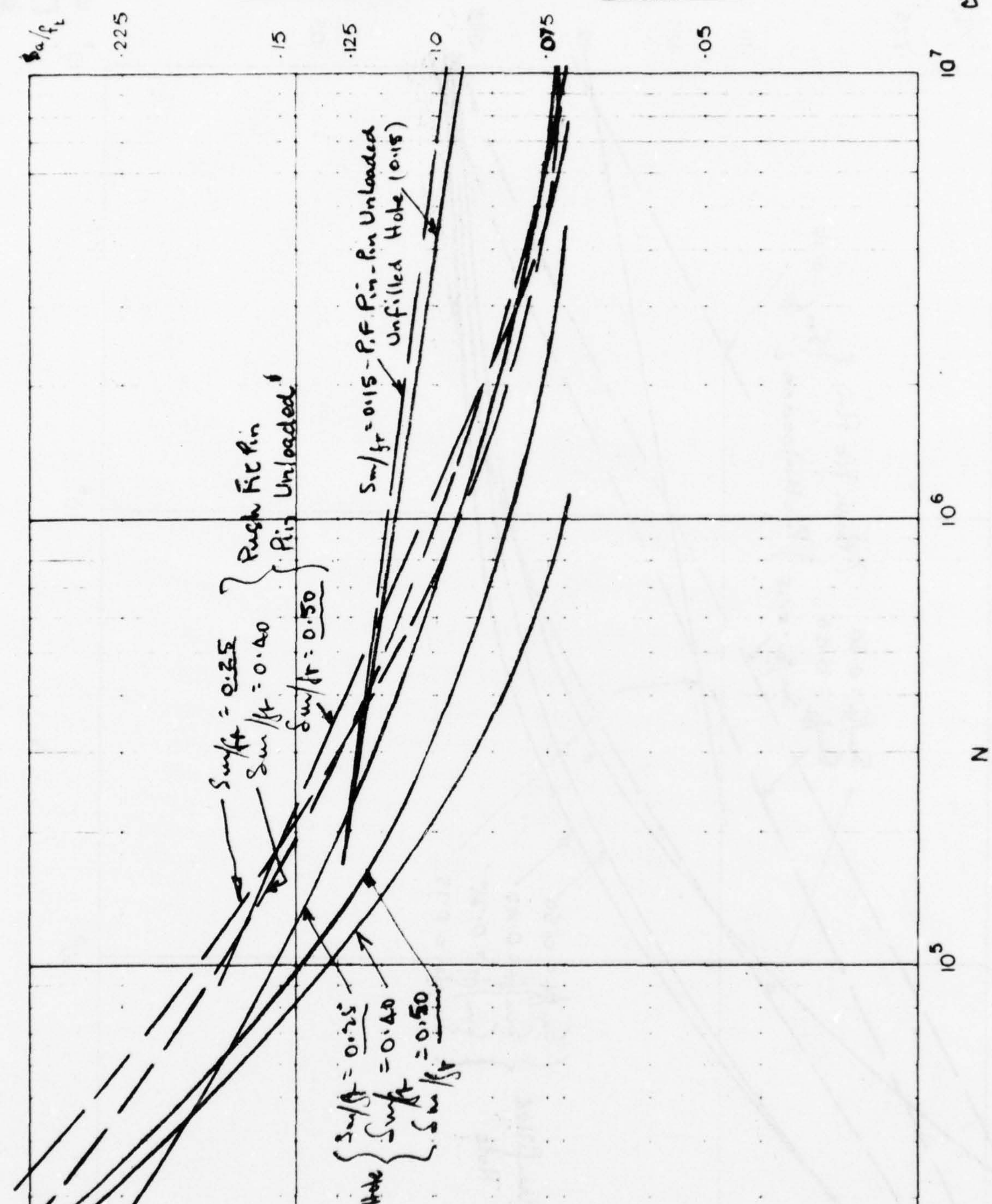


FIG 4.9 – EFFECT OF UNLOADED PUSH FIT PIN

SMALL SPECIMENS $d/D = 1/2$ Ref. Figs C.45 & C.46

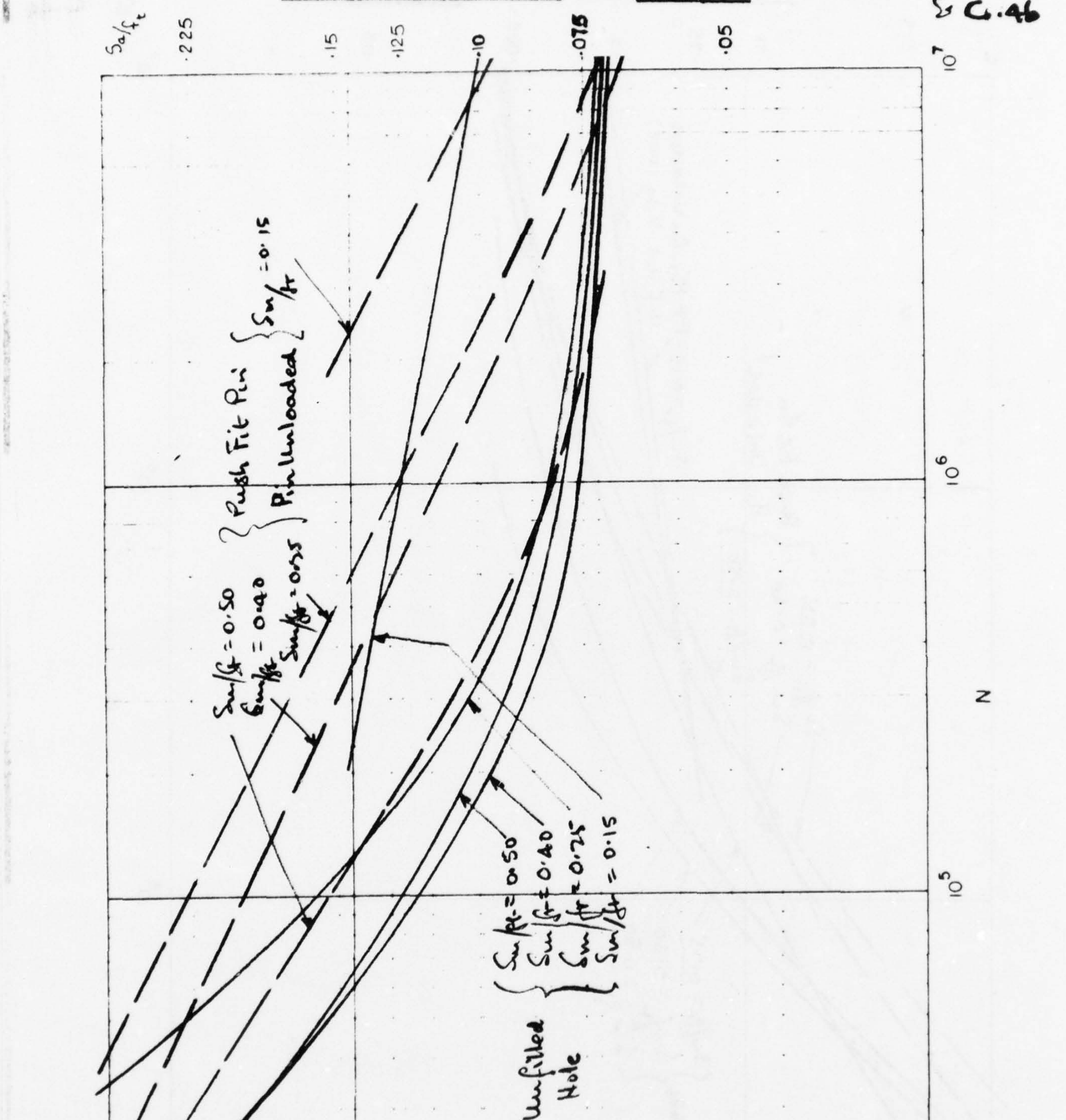


FIG 4.10 COMPARISON BETWEEN UNLOADED & LOADED

PUSH FIT PIN

Ref. Figs C.2 & C.5

LARGE SPECIMENS $d/D = 1/4$

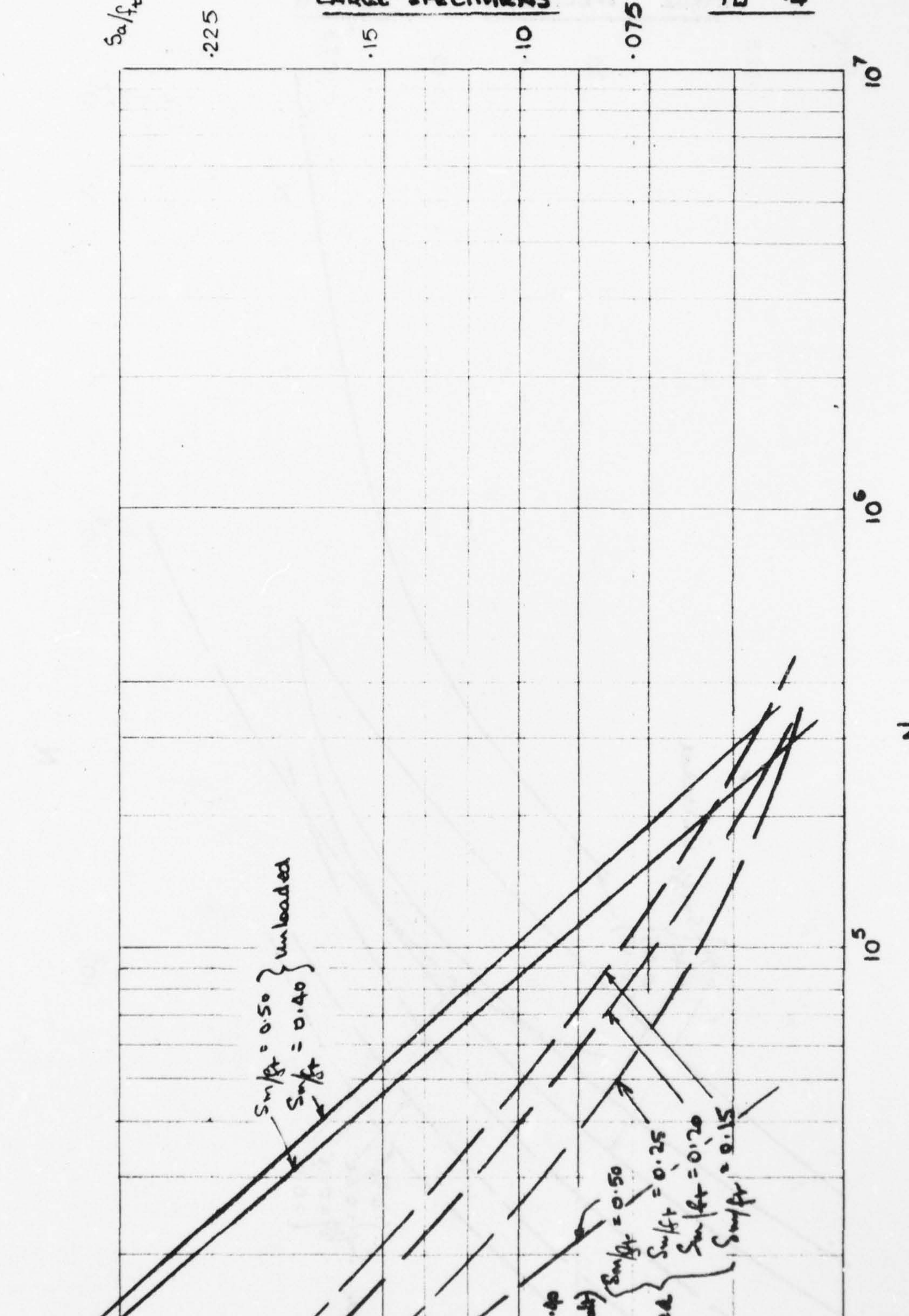


Fig 4.11 Comparison between Unloaded & Loaded Push Fit Pin

Ref: Figs C.9 & C.11

LARGE SPECIMENS $d/D = 3/8$

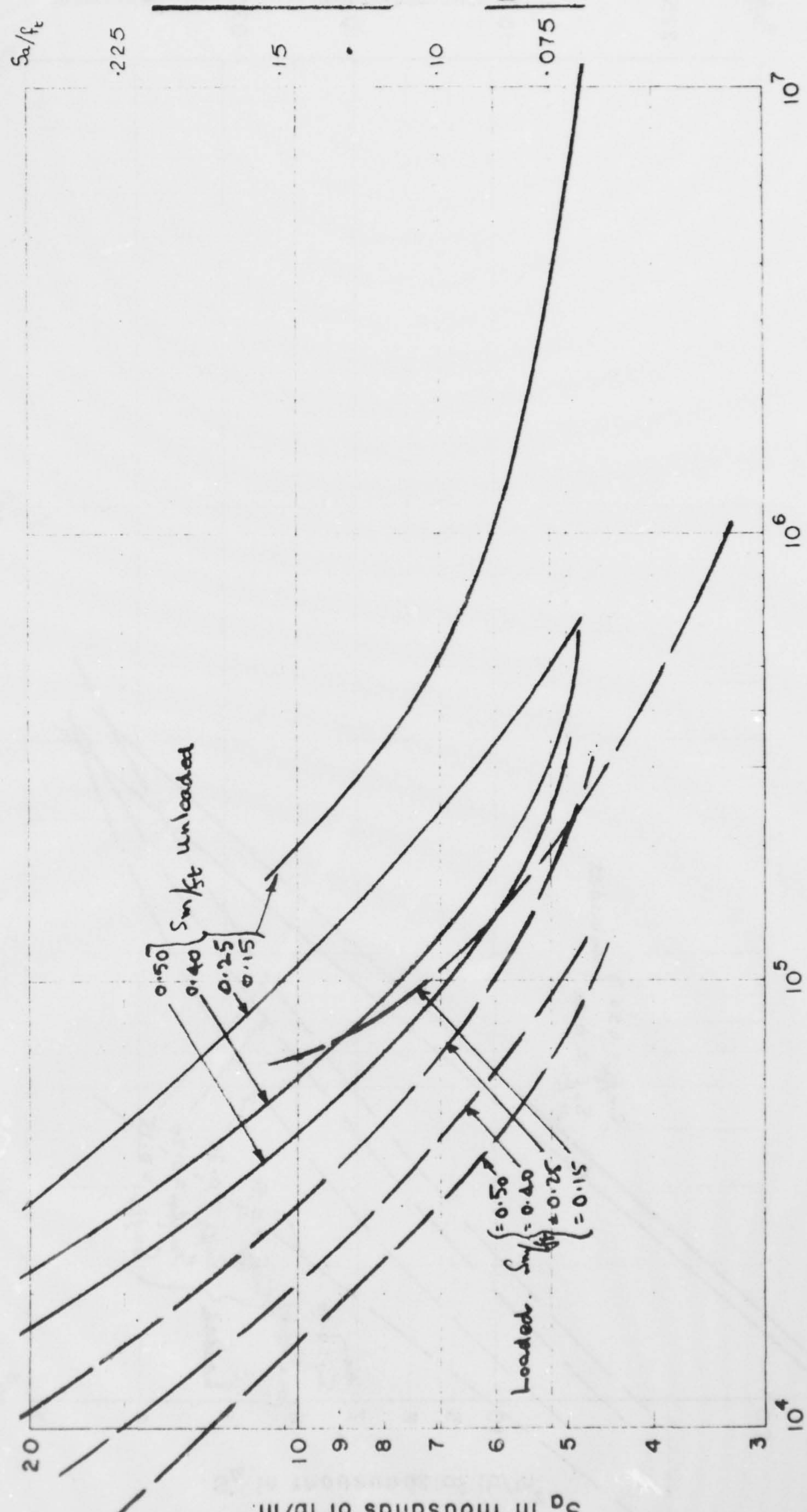


FIG. 4.12 COMPARISON BETWEEN UNLOADED & LOADED

PUSH FIT PIN

Ref. Figs C.14 & C.16

LARGE SPECIMENS

$d/D = 1/8$

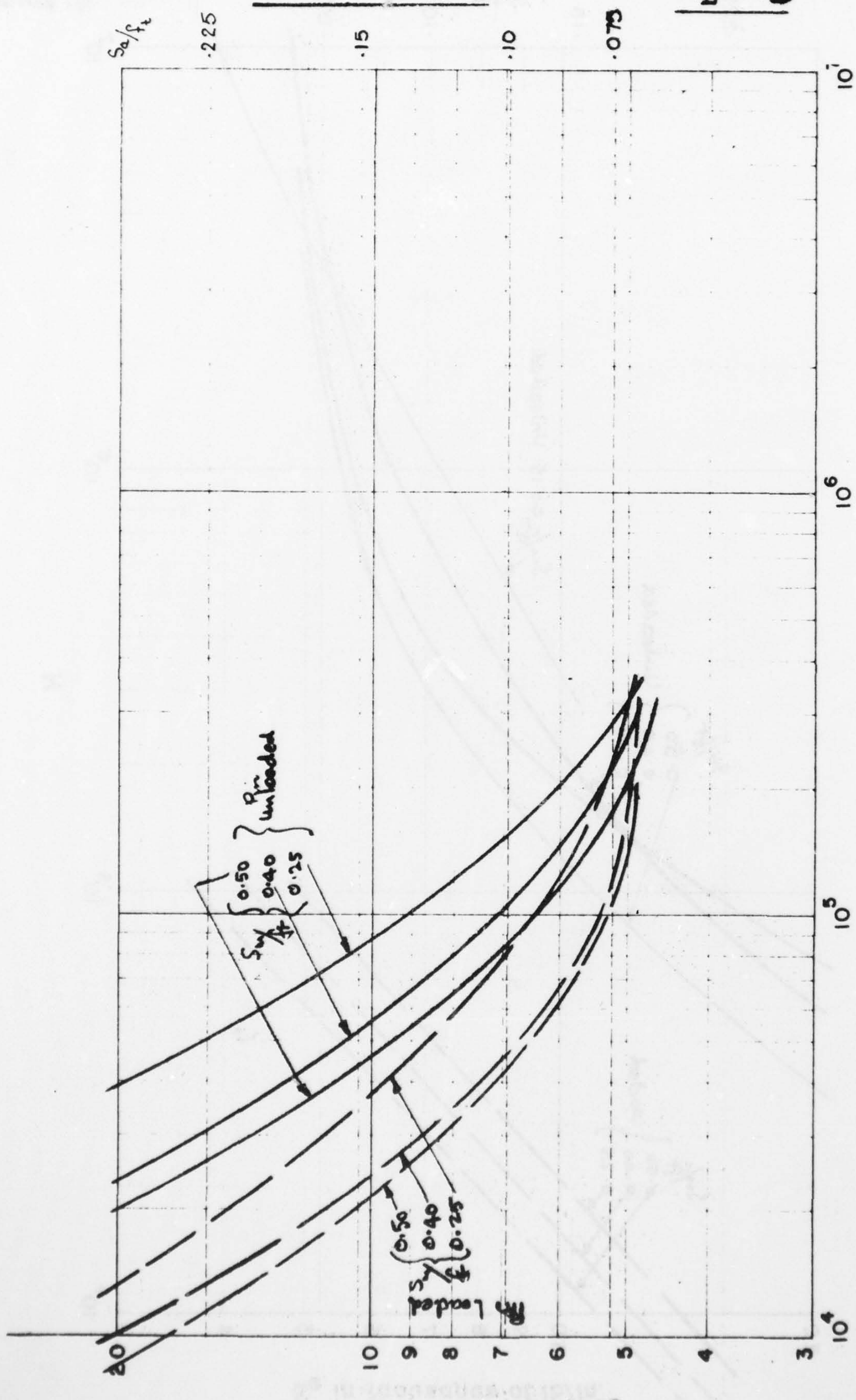


FIG. 4.13 COMPARISON BETWEEN UNLOADED & LOADED

PUSH FIT PIN   MEDIUM SPECIMENS d/D = 1/6

Cf. Fig. C.24

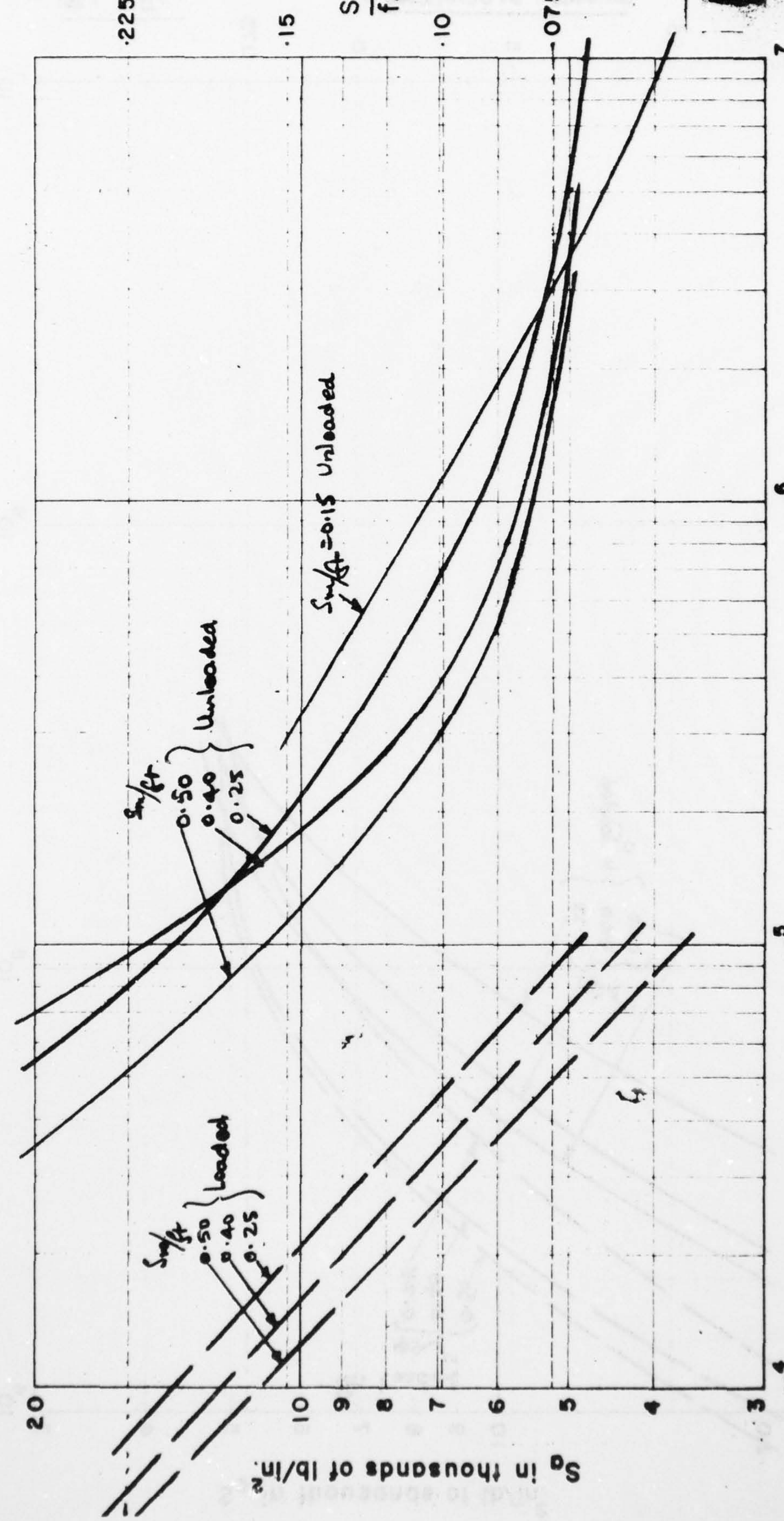


FIG. 4.14 COMPARISON BETWEEN UNLOADED & LOADED

PUSH FIT PIN

Ref. Figs C.30 & C.32

MEDIUM SPECIMENS d/D = 1/2

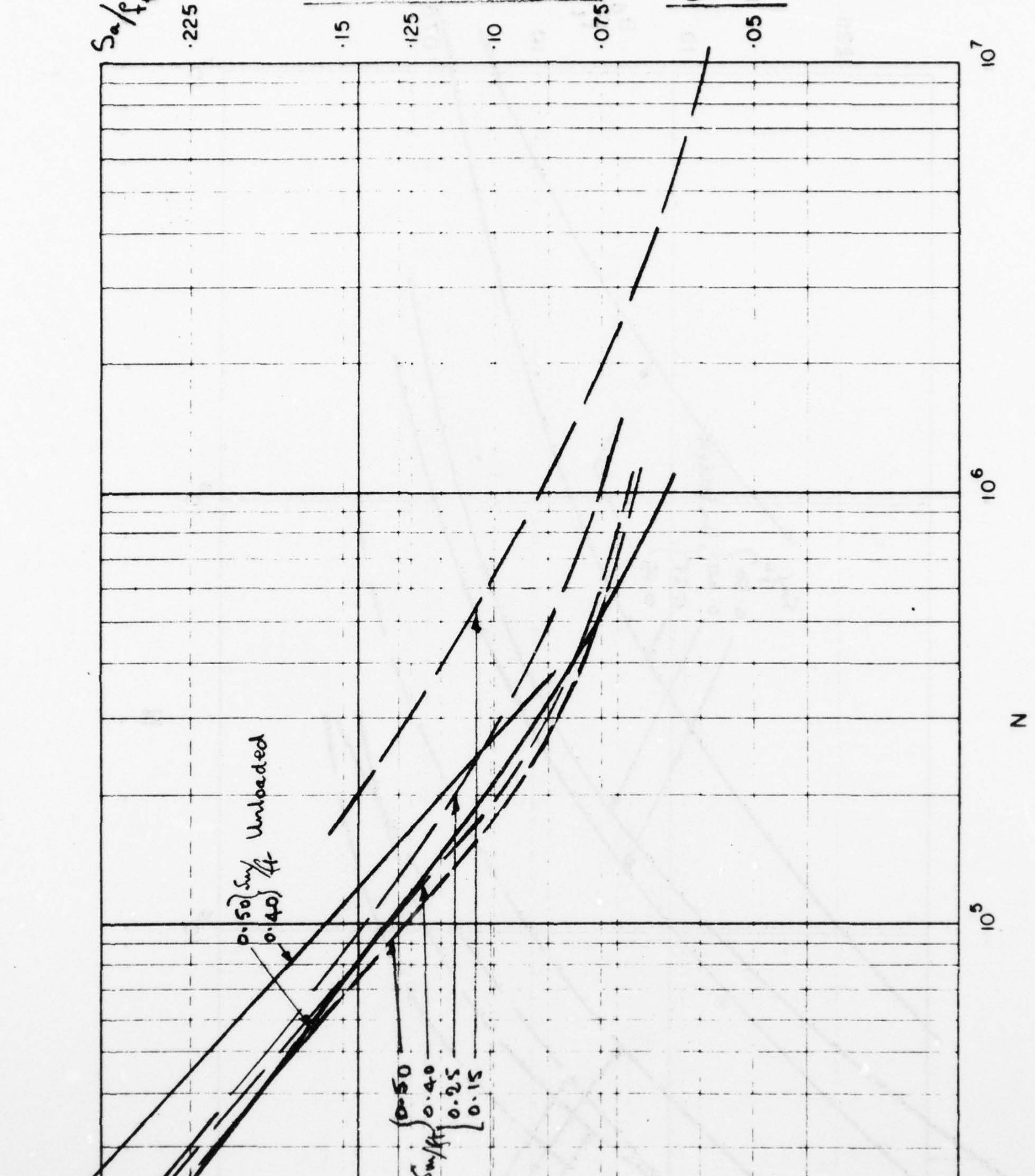


FIG. 4.15 COMPARISON BETWEEN UNLOADED & LOADED

PUSH FIT PIN

SMALL SPECIMENS $d/D = 1/4$

Ref Figs C.37 & C.40

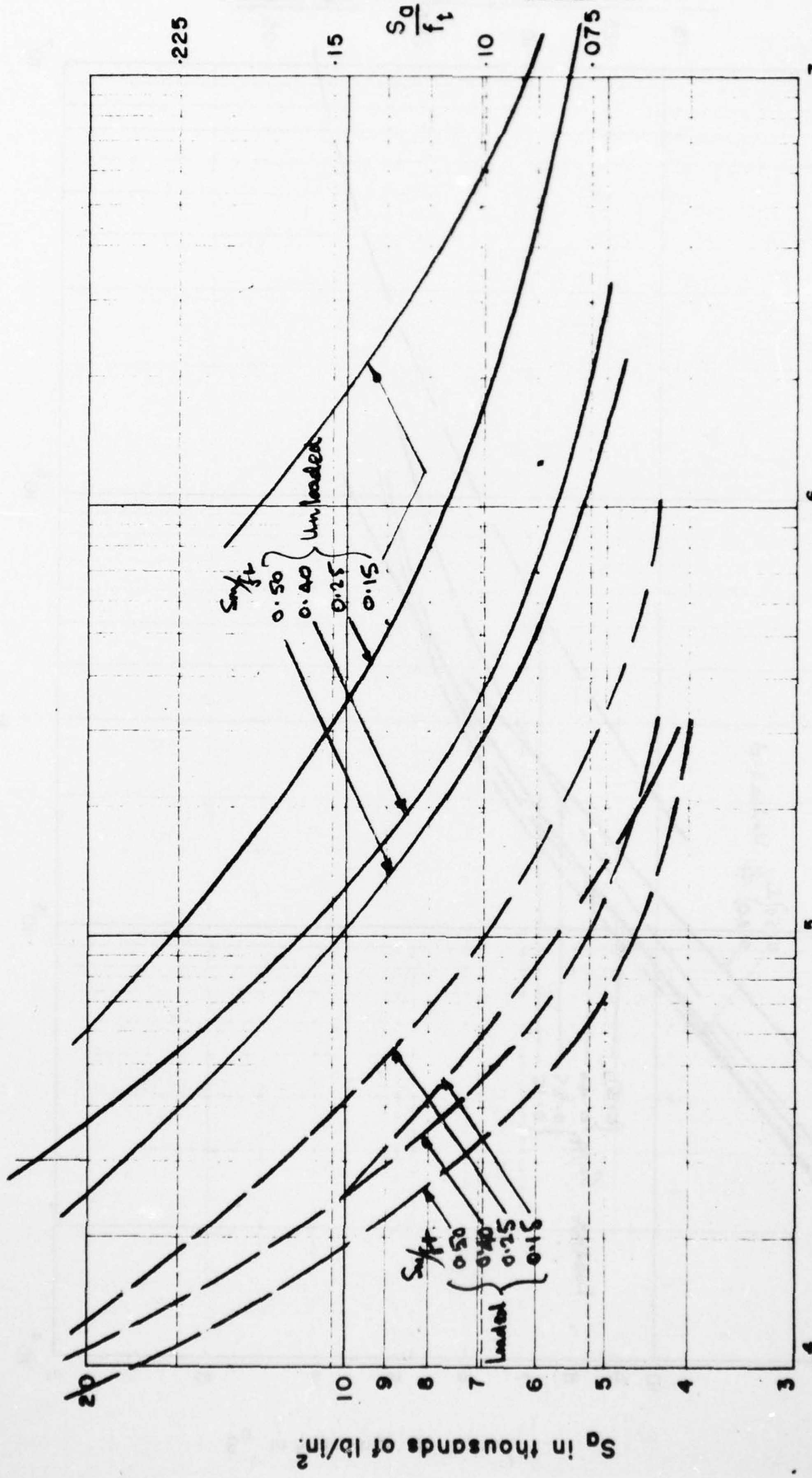


FIG 4.16 COMPARISON BETWEEN UNLOADED & LOADED

PUSH FIT PIN

SMALL SPECIMENS d/D = 1/2

Ref: Figs C.46 & C.48

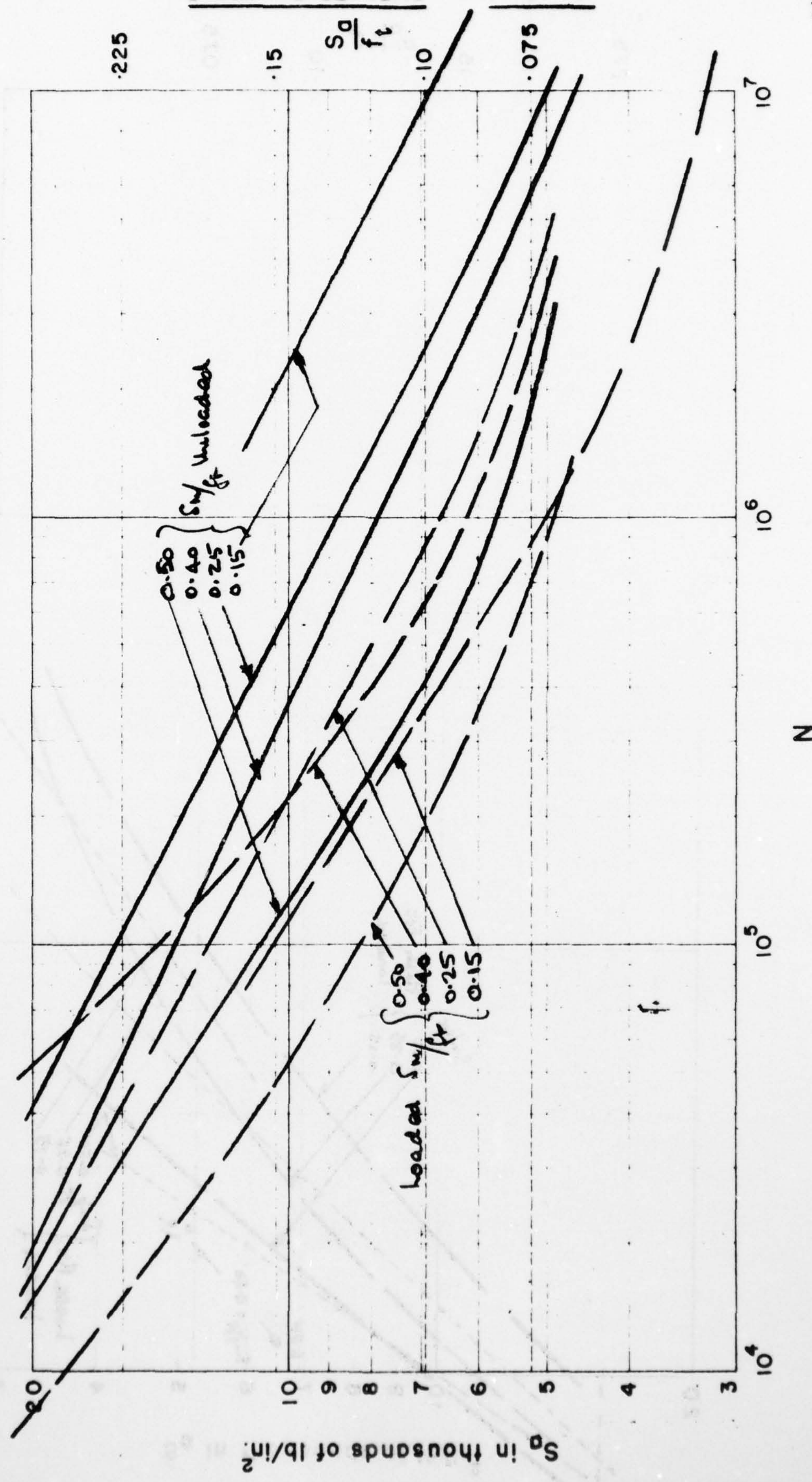


FIG. 4.17 COMPARISON BETWEEN LOOSE FIT & PUSH FIT-LOADED PIN

78

LARGE SPECIMENS $a/D = 1/4$

Ref: Figs C.4 & C.5.

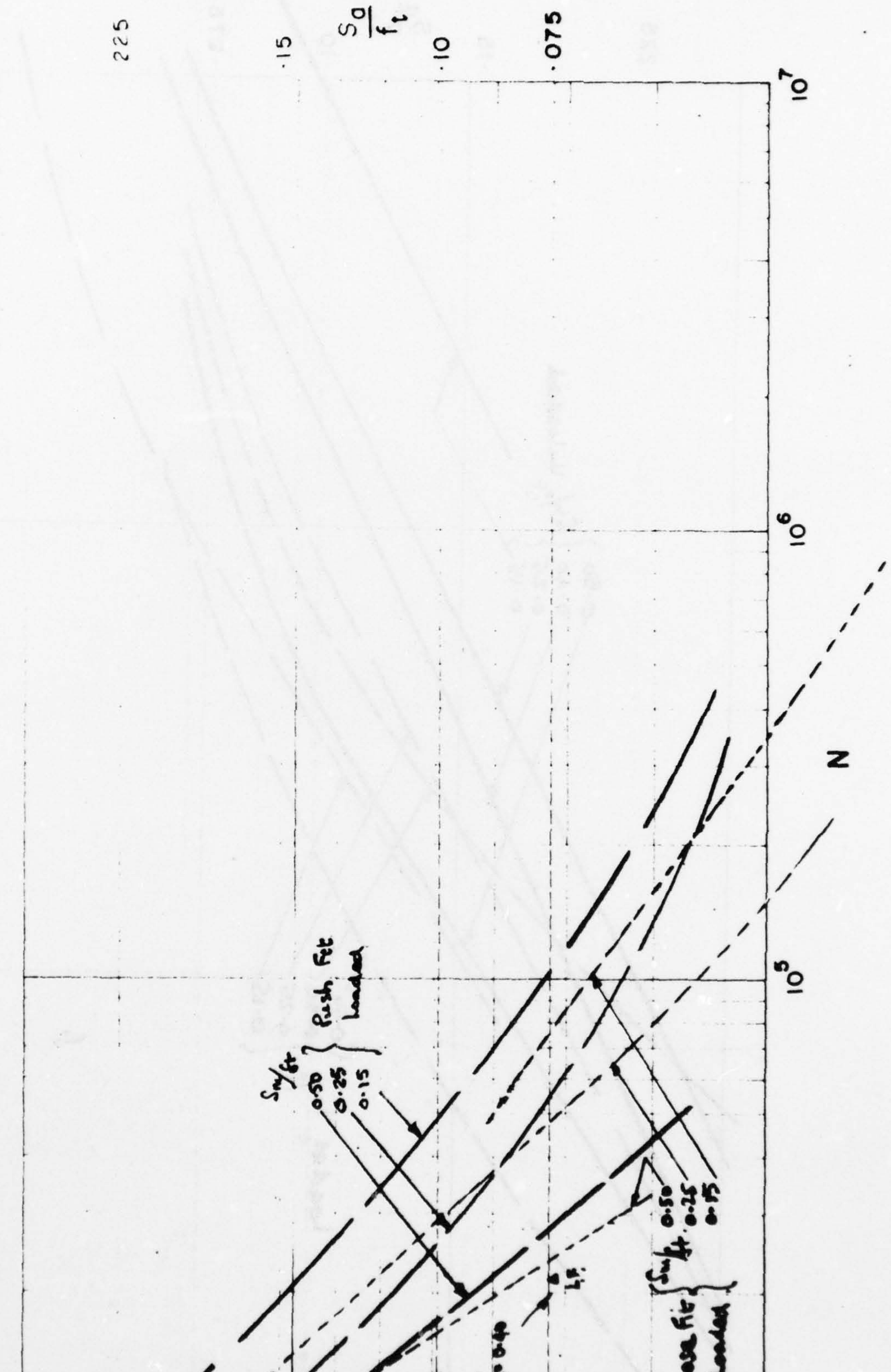


FIG 4·18 COMPARISON BETWEEN LOOSE FIT & PUSH FIT UNLOADED PIN

MEDIUM SPECIMENS $d/D = 1/4$

Ref. Figs. C.20 & C.21

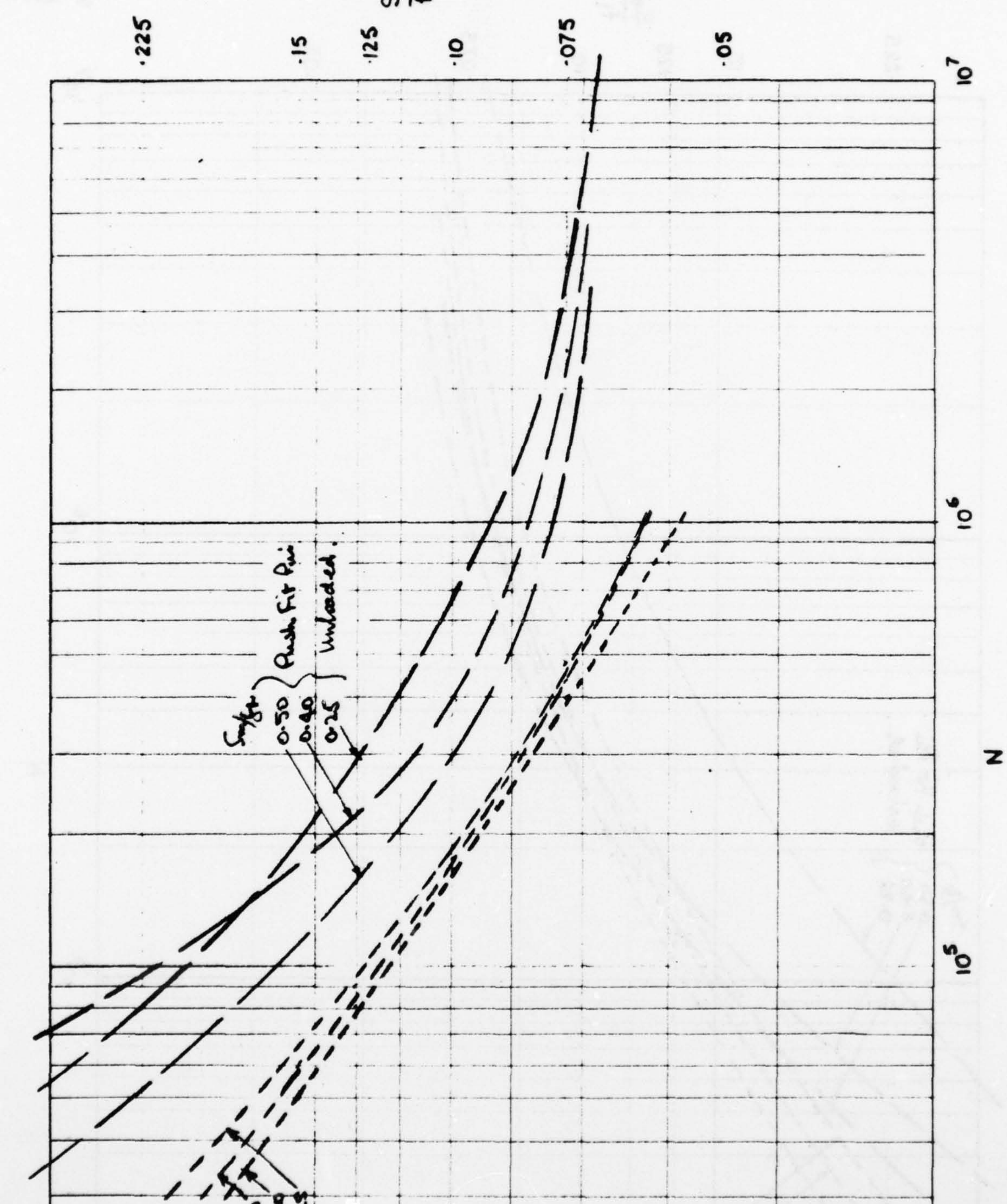


FIG. 4.19 COMPARISON BETWEEN LOOSE FIT & PUSH FIT UNLOADED PIN

80

SMALL SPECIMENS $d/D = 1/4$

Ref: Figs C.36 & C.37

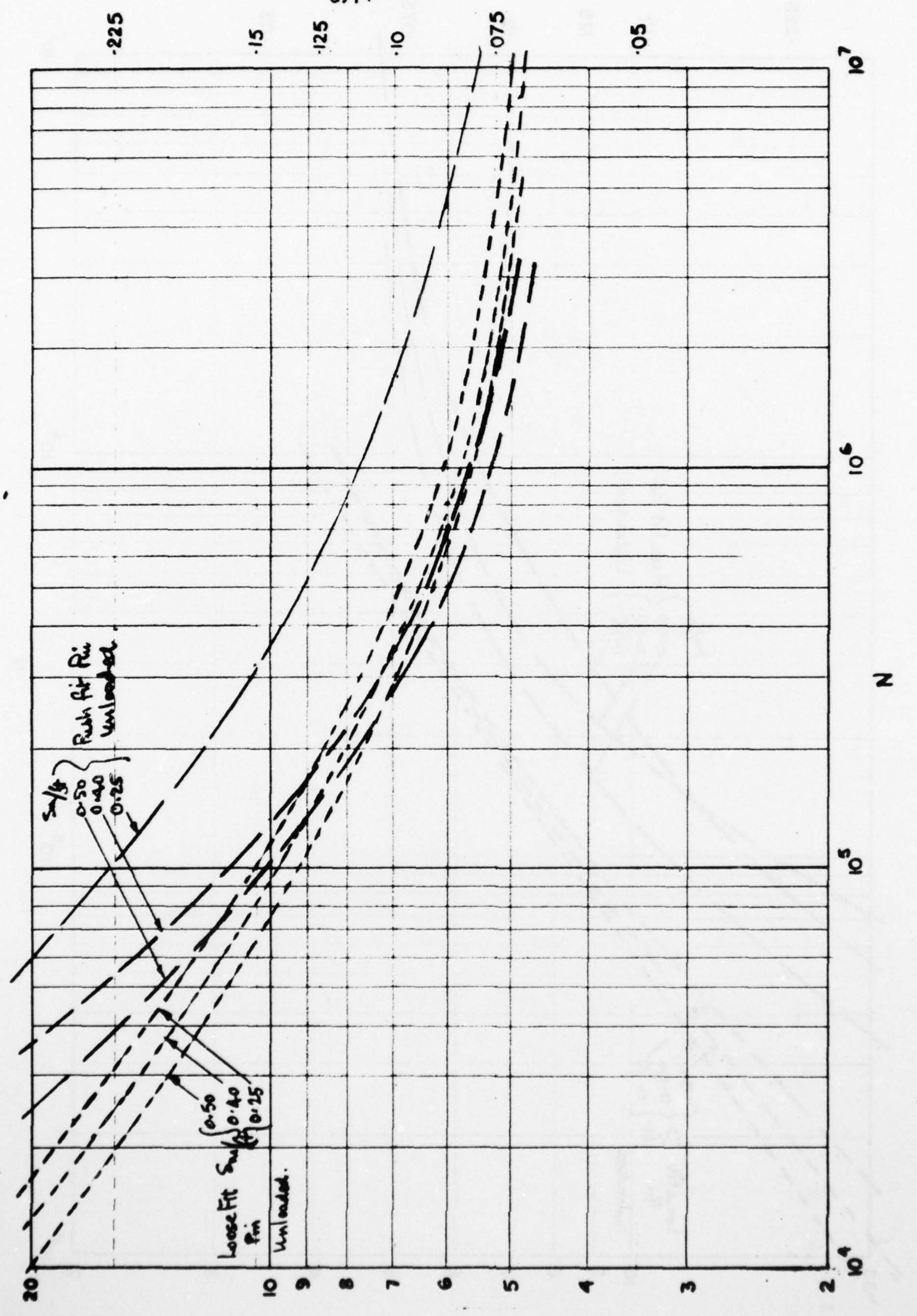


Fig. 4.20 - Comparison between Push Fit and Interference Fit Pin

Pin Unloaded - Large Specimens

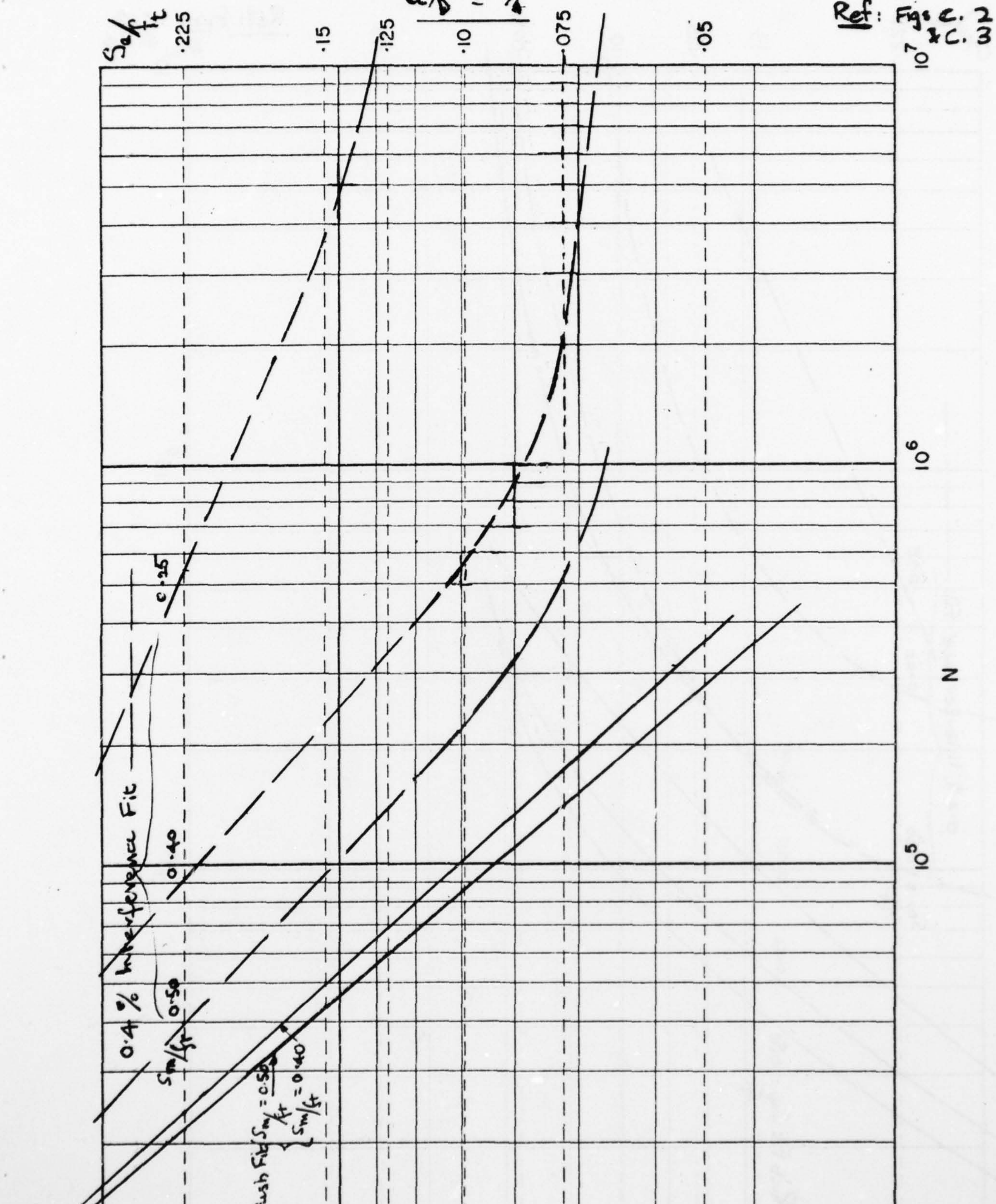


FIG. 4.21 COMPARISON BETWEEN PUSH FIT AND INTERFERENCE FIT PIN

PIN UNLOADED — LARGE SPECIMENS $d/D = 3/8$

Ref: Figs C.9 & C.10

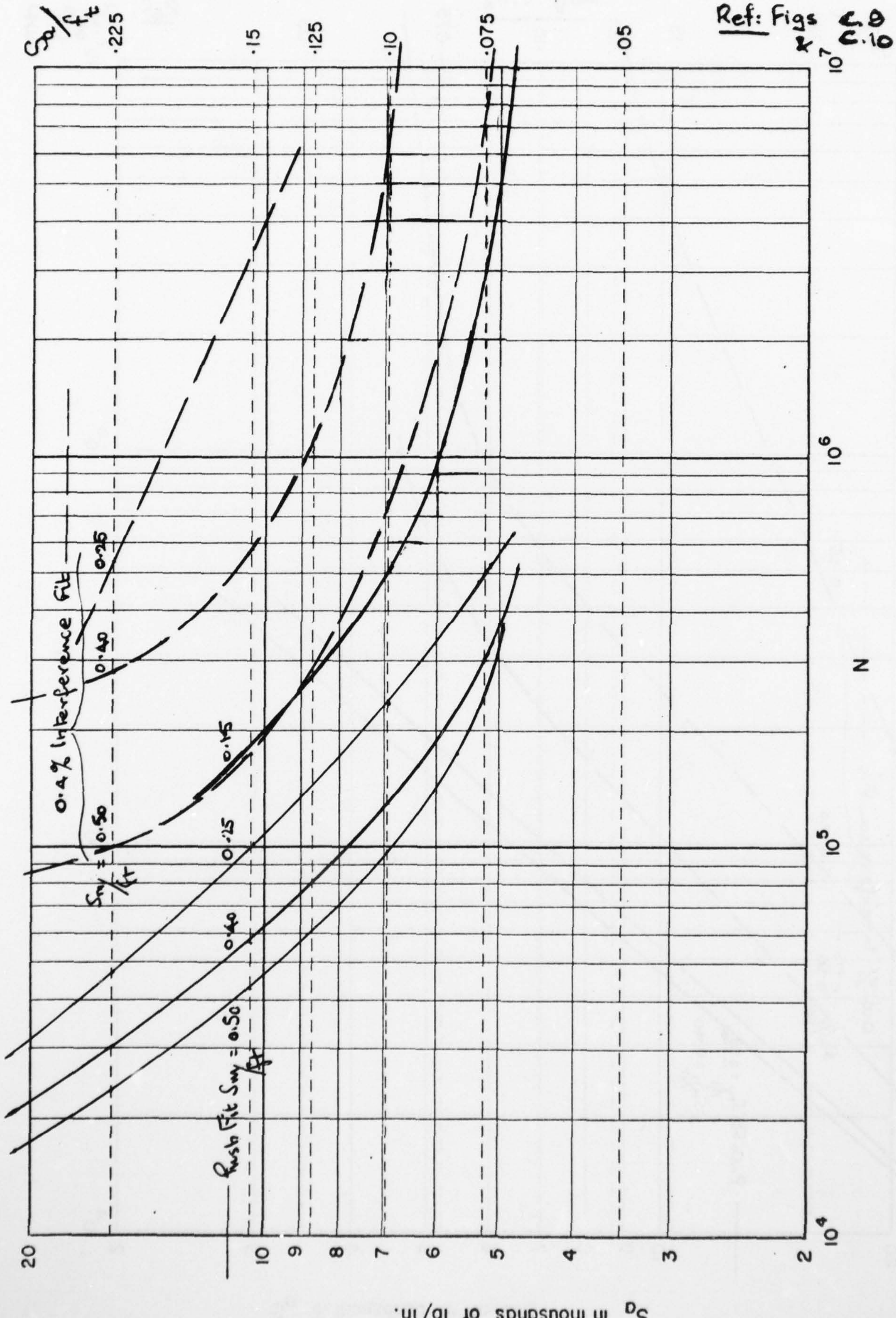


FIG. 4.22 COMPARISON BETWEEN PUSH FIT AND INTERFERENCE FIT PIN

PIN UNLOADED — LARGE SPECIMENS $d/D = 1/2$

Ref: Figs C.14 & C.15

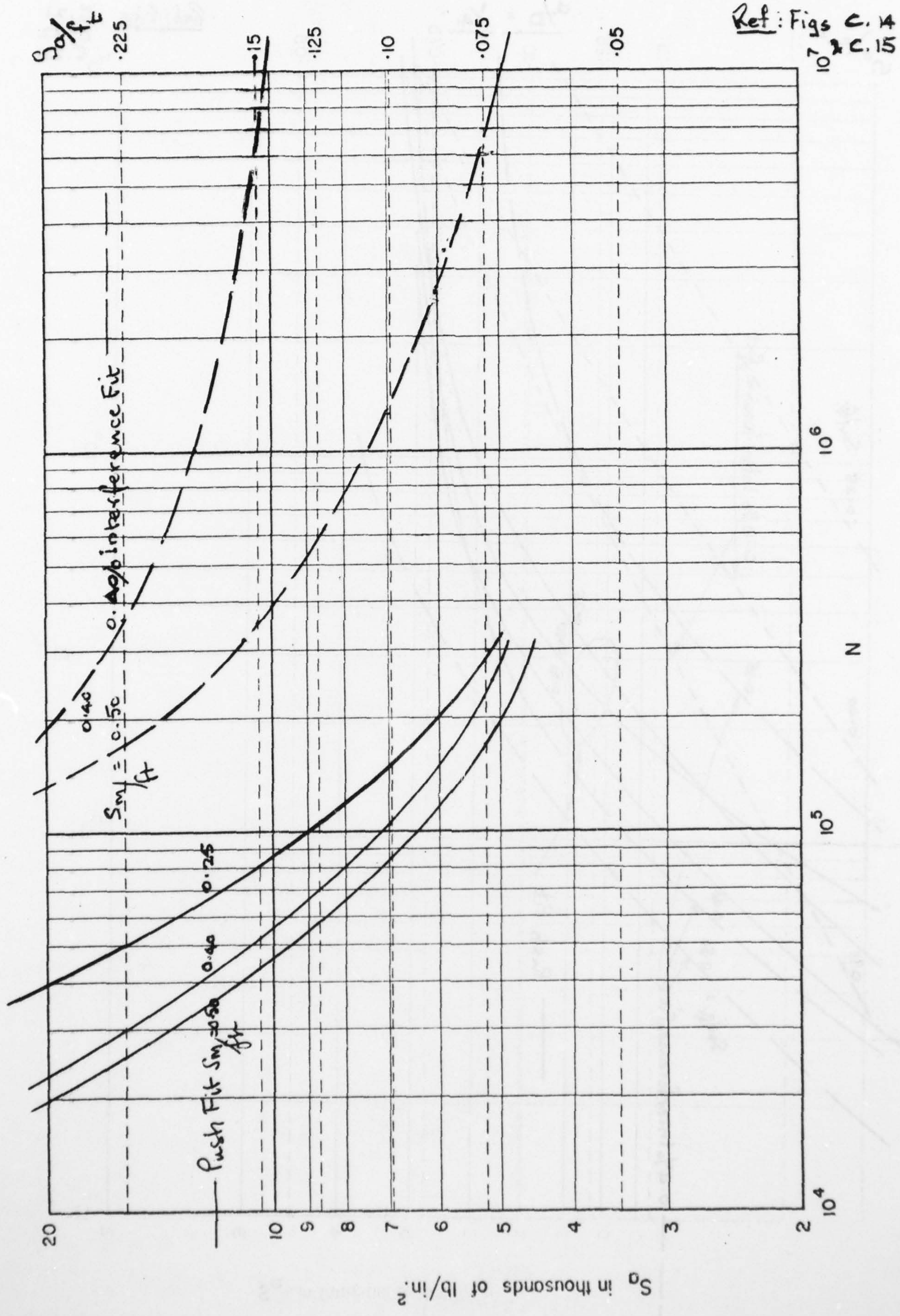


FIG. 4.23 COMPARISON BETWEEN PUSH FIT & INTERFERENCE FIT PIN

84 PIN UNLOADED - MEDIUM SPECIMENS

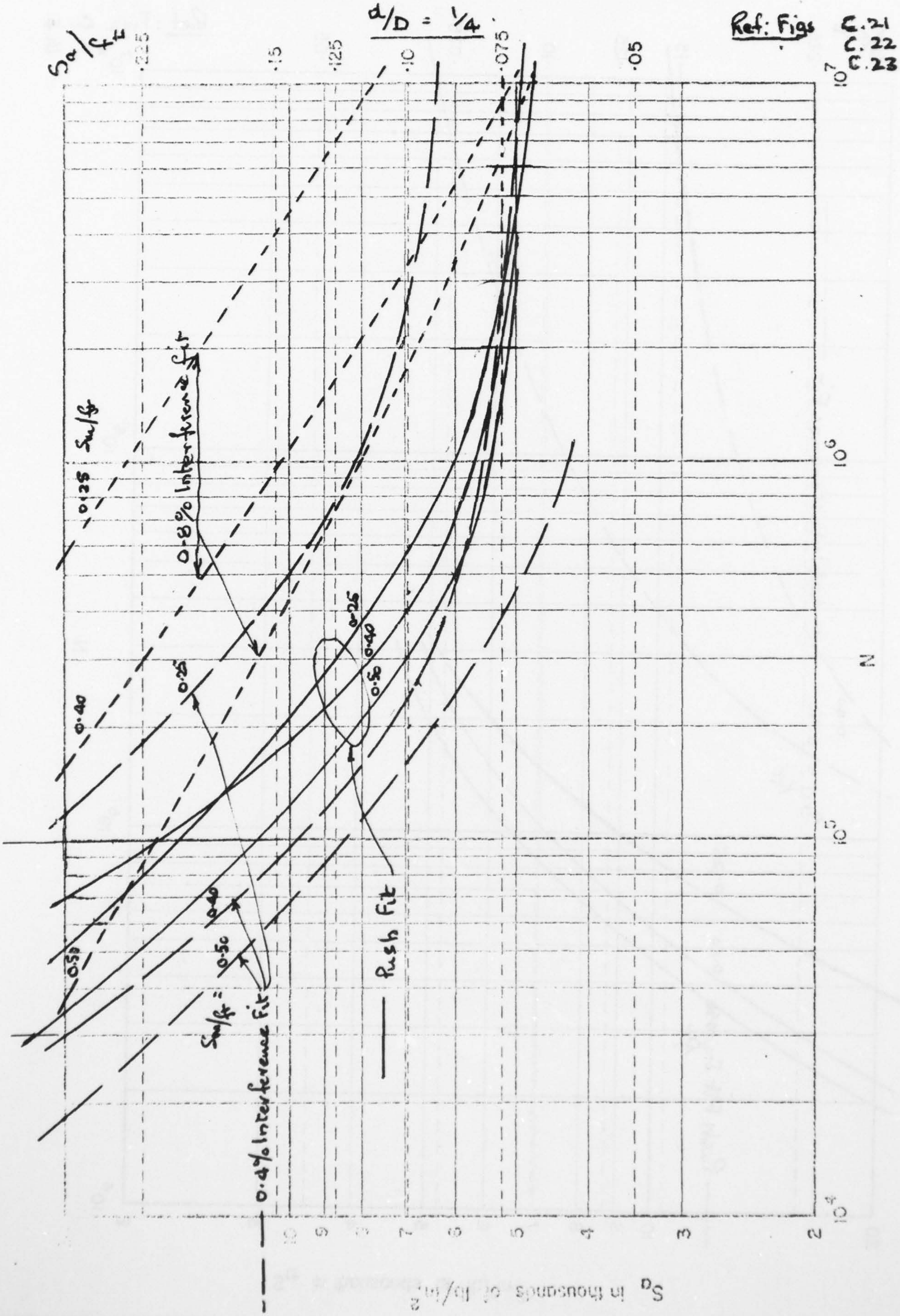
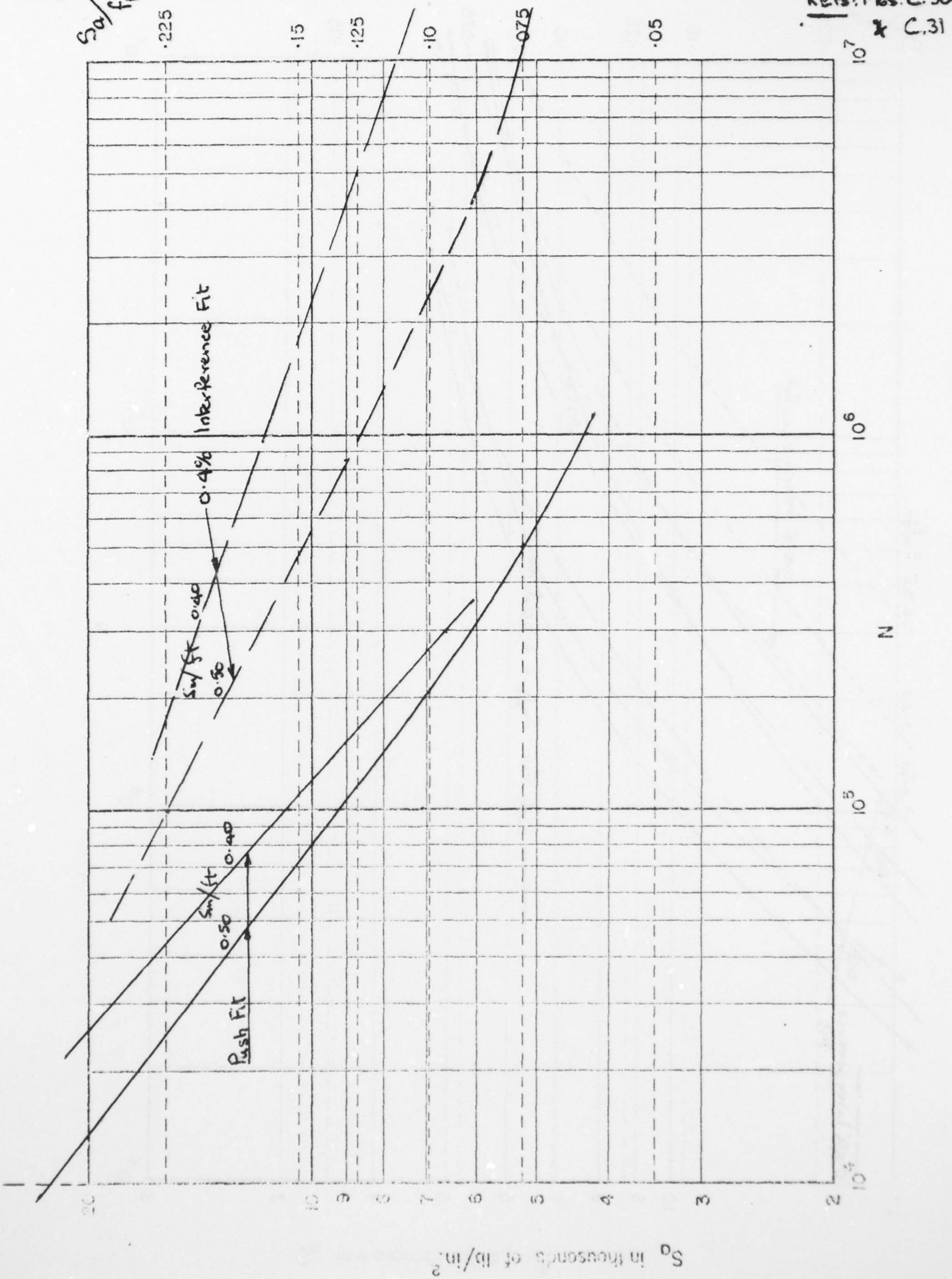


Fig. 4.24 Comparison between Push Fit & Interference Fit Pin

Pin Unloaded – Medium Specimens $d/D = 1/2$

Refs: Figs. C.30 & C.31



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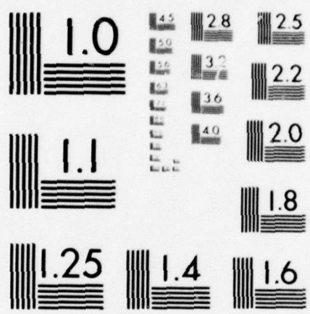

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FIG. 4.25 COMPARISON BETWEEN PUSH FIT AND INTERFERENCE FIT PIN

86

PIN UNLOADED – SMALL SPECIMENS $d/D = 1/4$

Ref: FIGS C.37 C.38 C.39

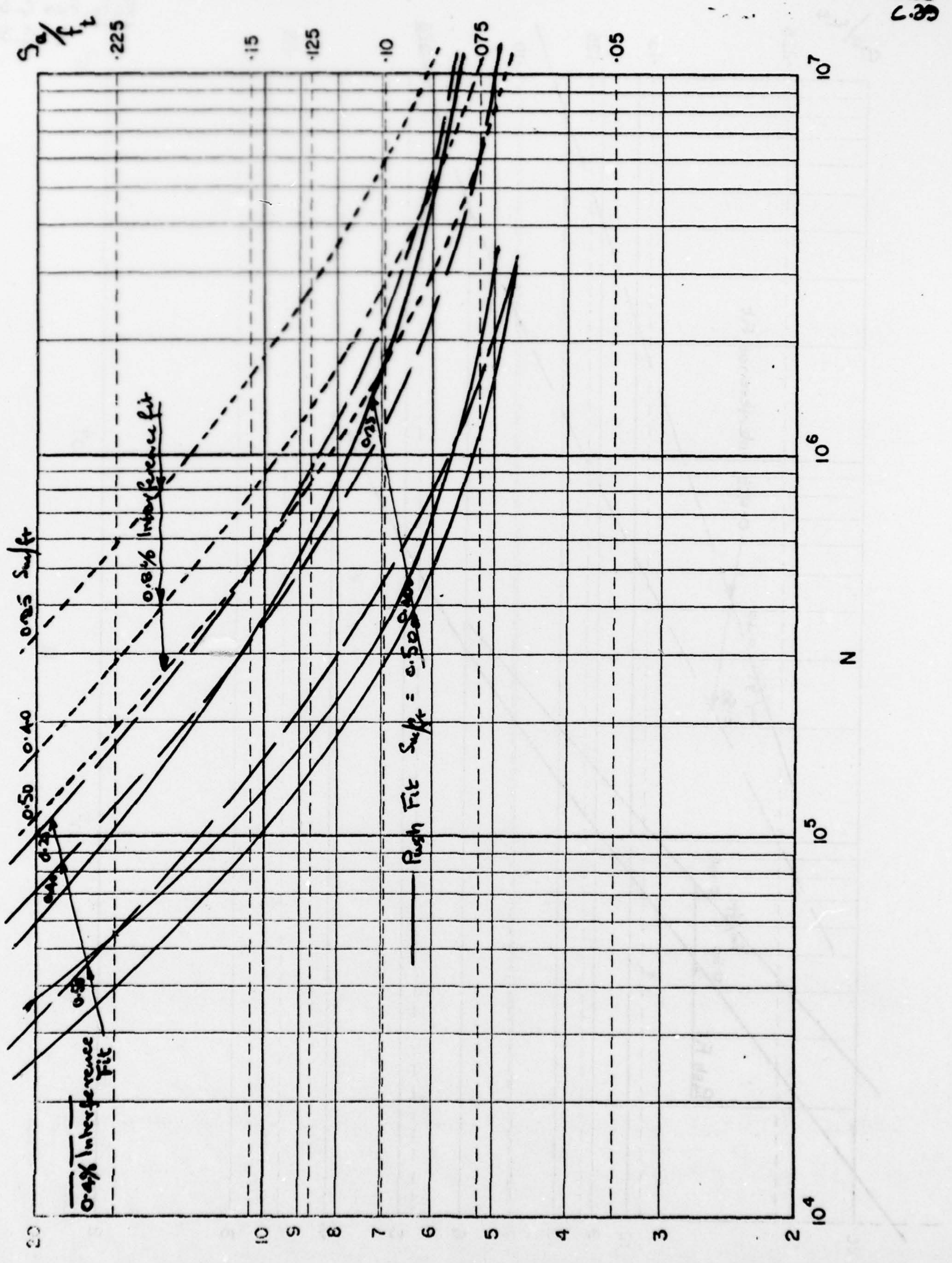


FIG. 4.26 COMPARISON BETWEEN PUSH FIT & INTERFERENCE FIT PIN

PIN UNLOADED - SMALL SPECIMENS. $d/D = 1/2$ Ref. Figs C.46 C.47

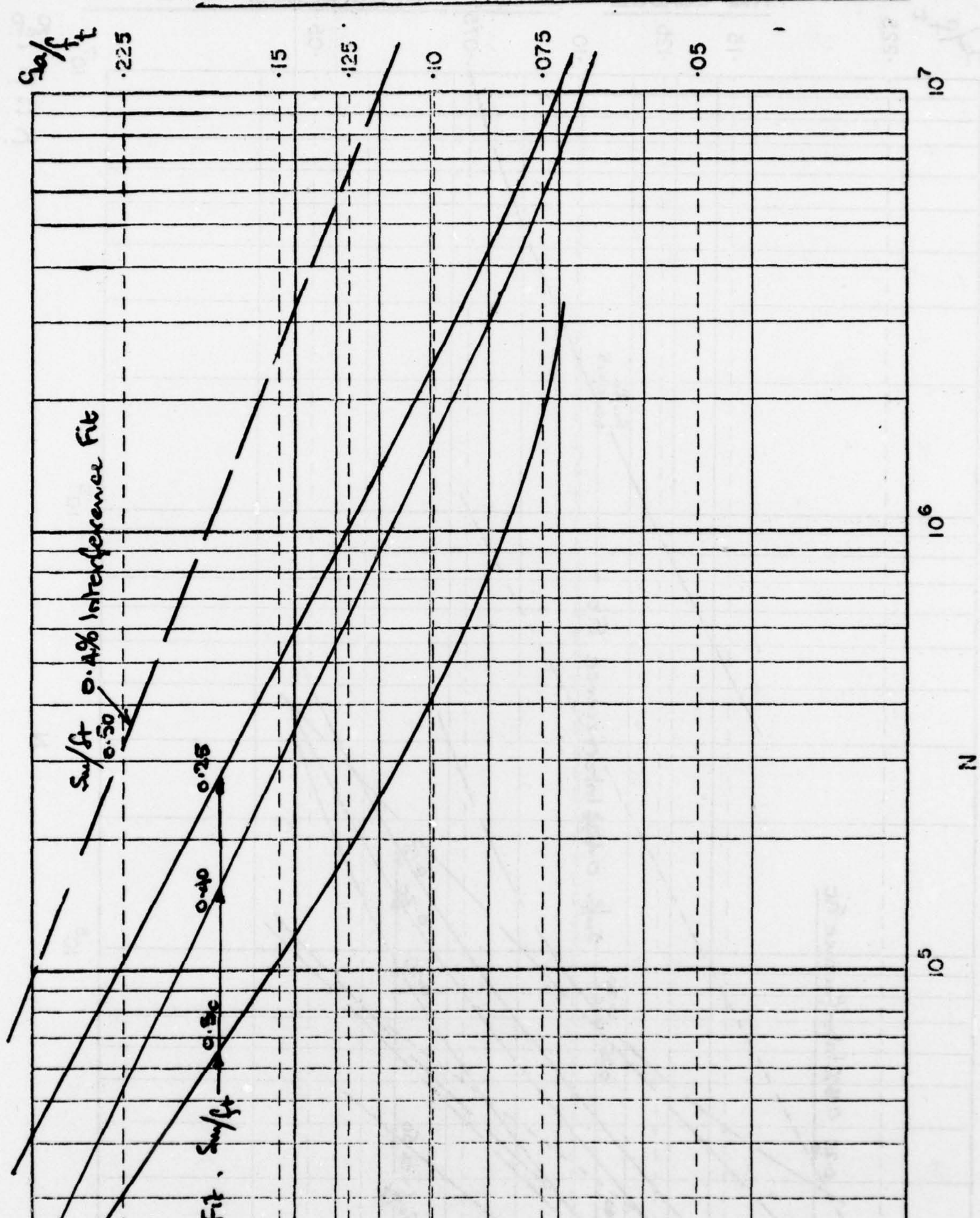


Fig 4.27 Comparison between Push Fit & Interference Fit Pin

88

Pin Loaded - Large Specimens $d/D = 1/4$

Ref. Figs.
C.5
C.6
C.7

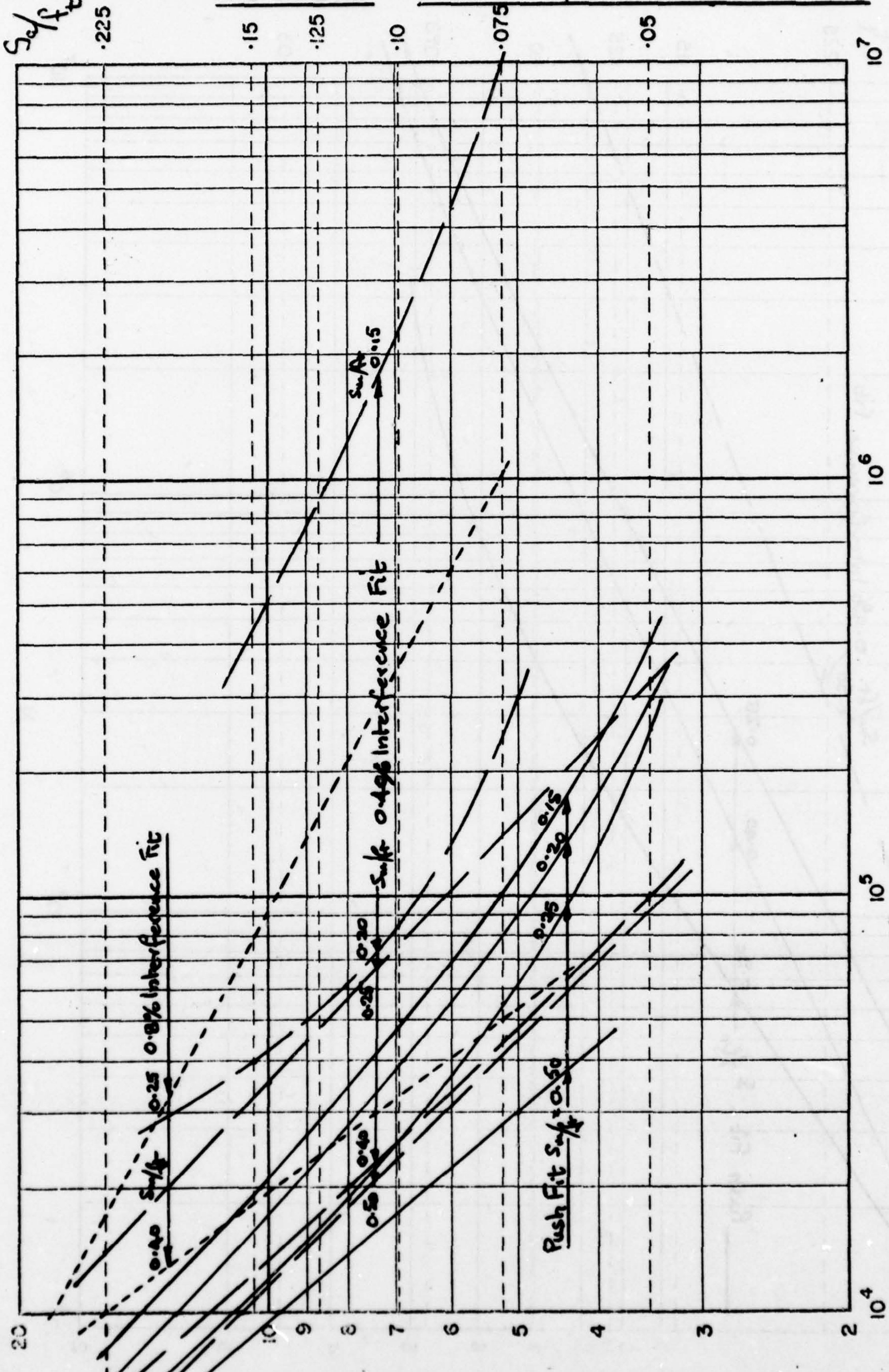


FIG. 4.28 COMPARISON BETWEEN PUSH FIT AND INTERFERENCE FIT PIN

PIN LOADED - LARGE SPECIMENS $d/D = 3/8$

Ref. Figs
C.11
C.12

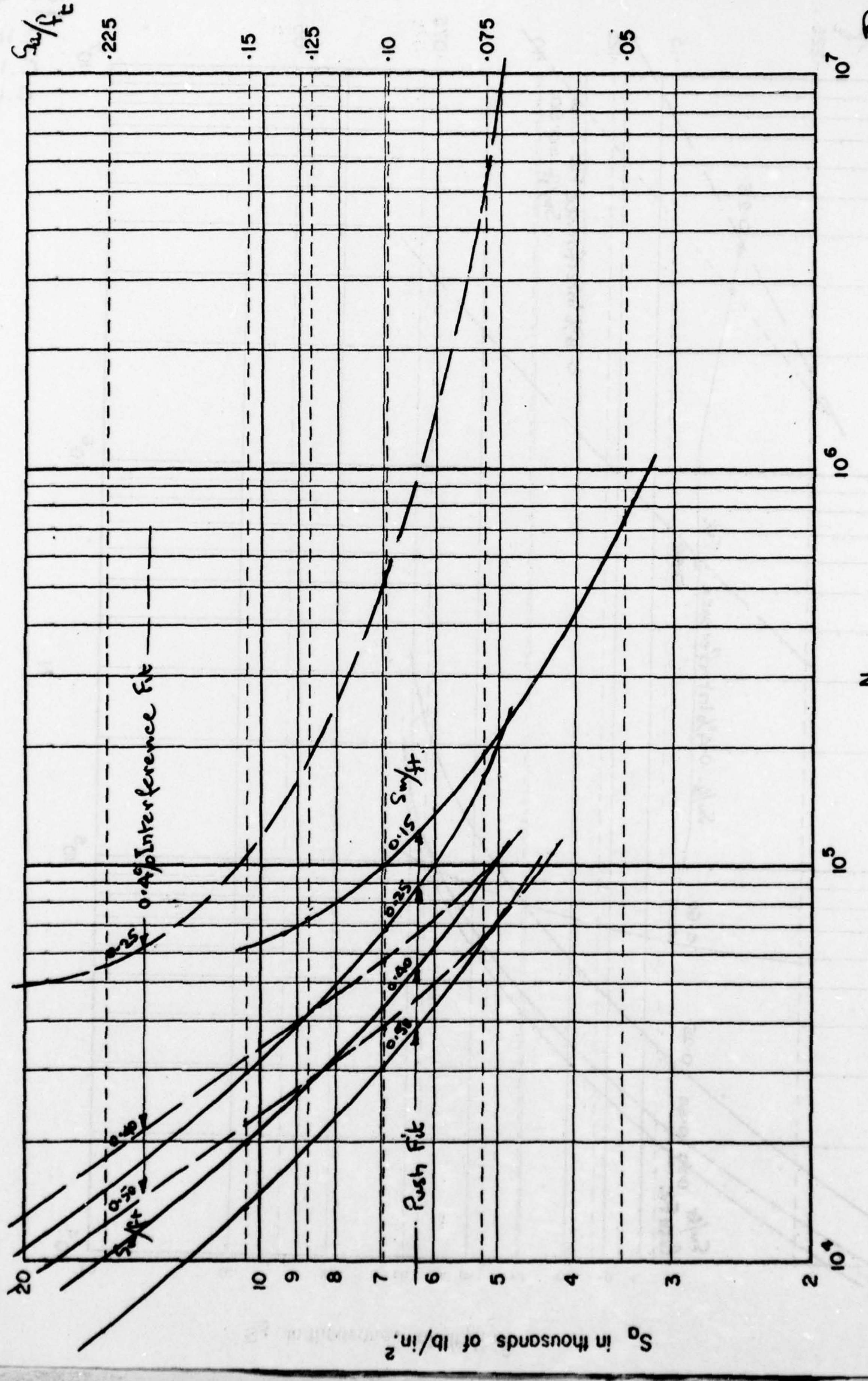


FIG. A-29 COMPARISON BETWEEN PUSH FIT & INTERFERENCE FIT PIN

90

PIN LOADED - LARGE SPECIMENS $d/D = 1/2$

Ref. Figs
C.16
C.17
C.18

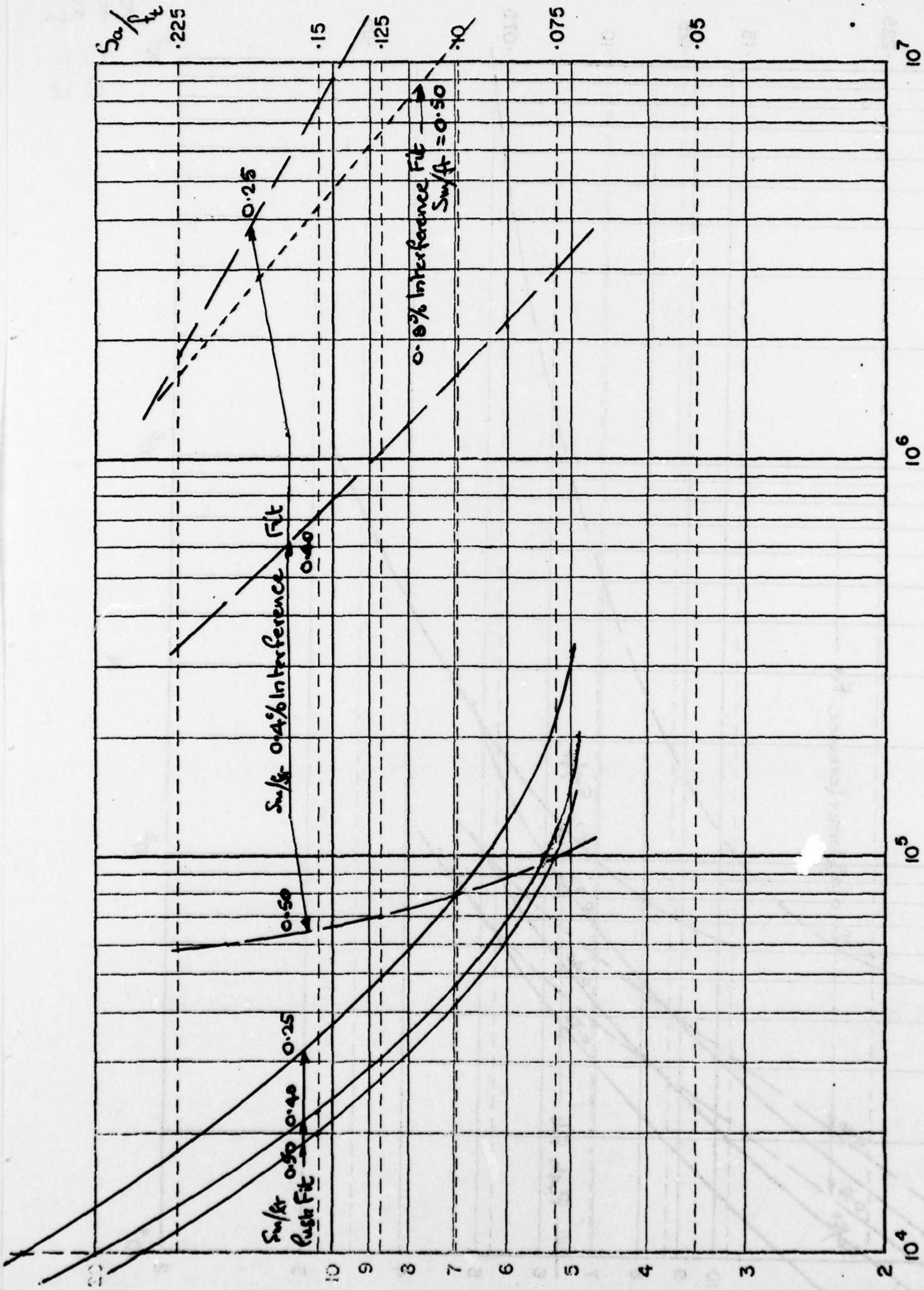


FIG 4.30 COMPARISON BETWEEN PUSH FIT AND INTERFERENCE FIT PIN

PIN LOADED – MEDIUM SPECIMENS $d/D \cdot 1/4$

Ref Figs
C. 24
C. 25
C. 26

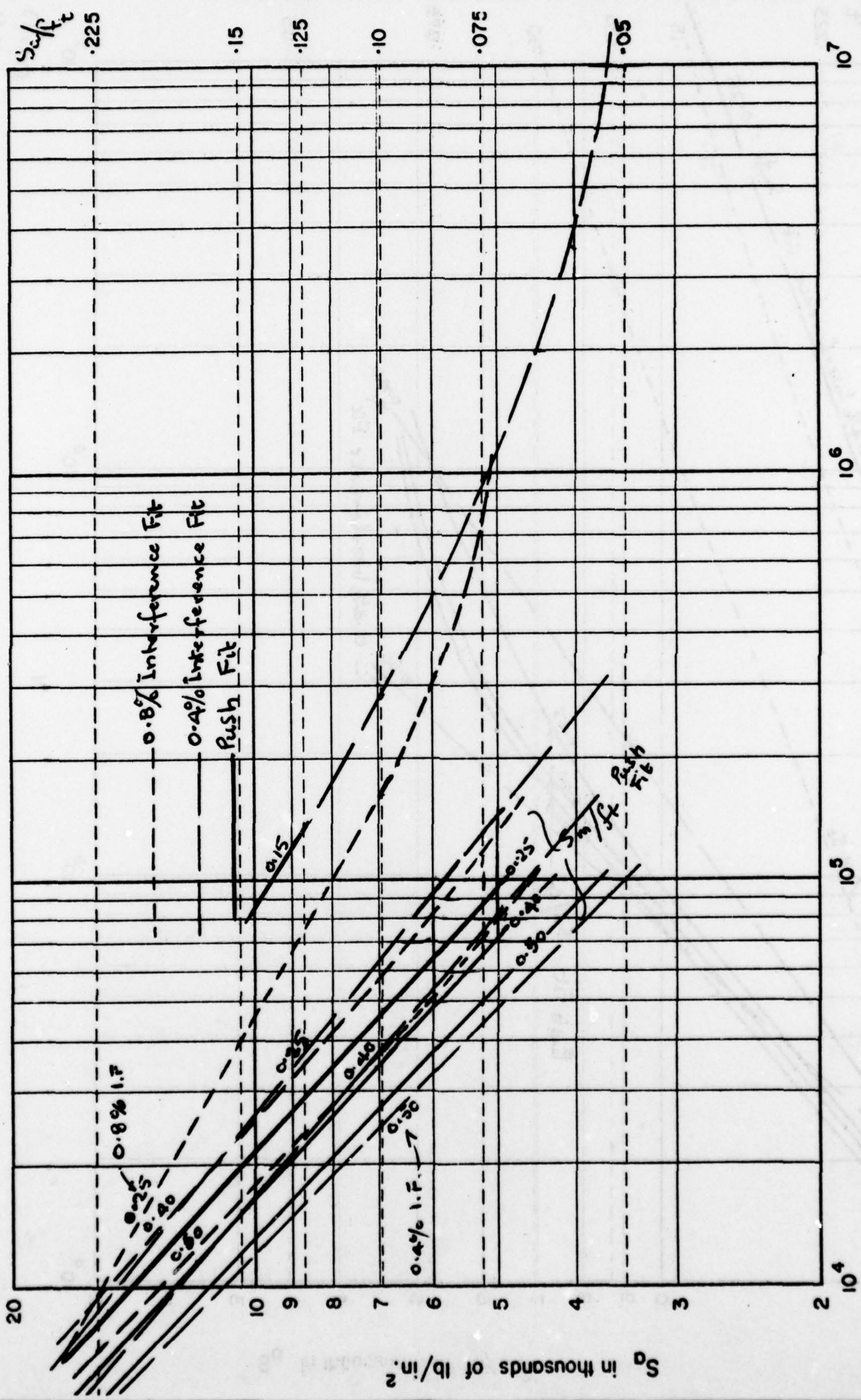


FIG. 4.31 COMPARISON BETWEEN PUSH FIT & INTERFERENCE FIT PIN

92

PIN LOADED - MEDIUM SPECIMENS $d/D = 1/2$

Ref: FIGS
C.32
C.33
C.34

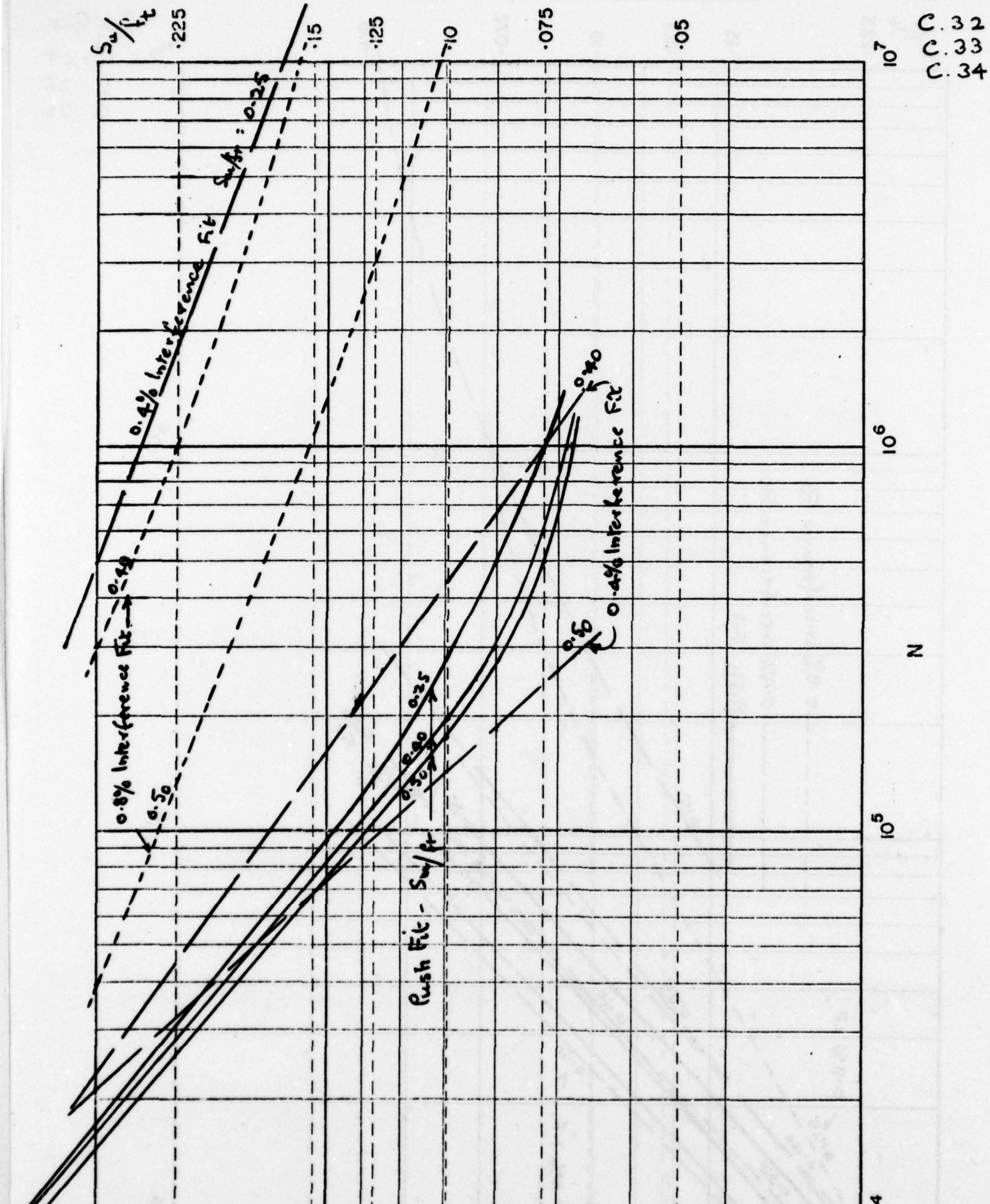


FIG. 4.32 COMPARISON BETWEEN PUSH FIT & INTERFERENCE FIT PIN

PIN LOADED - SMALL SPECIMENS $d/D = 1/4$

Ref. Figs
C.40
C.41
C.42

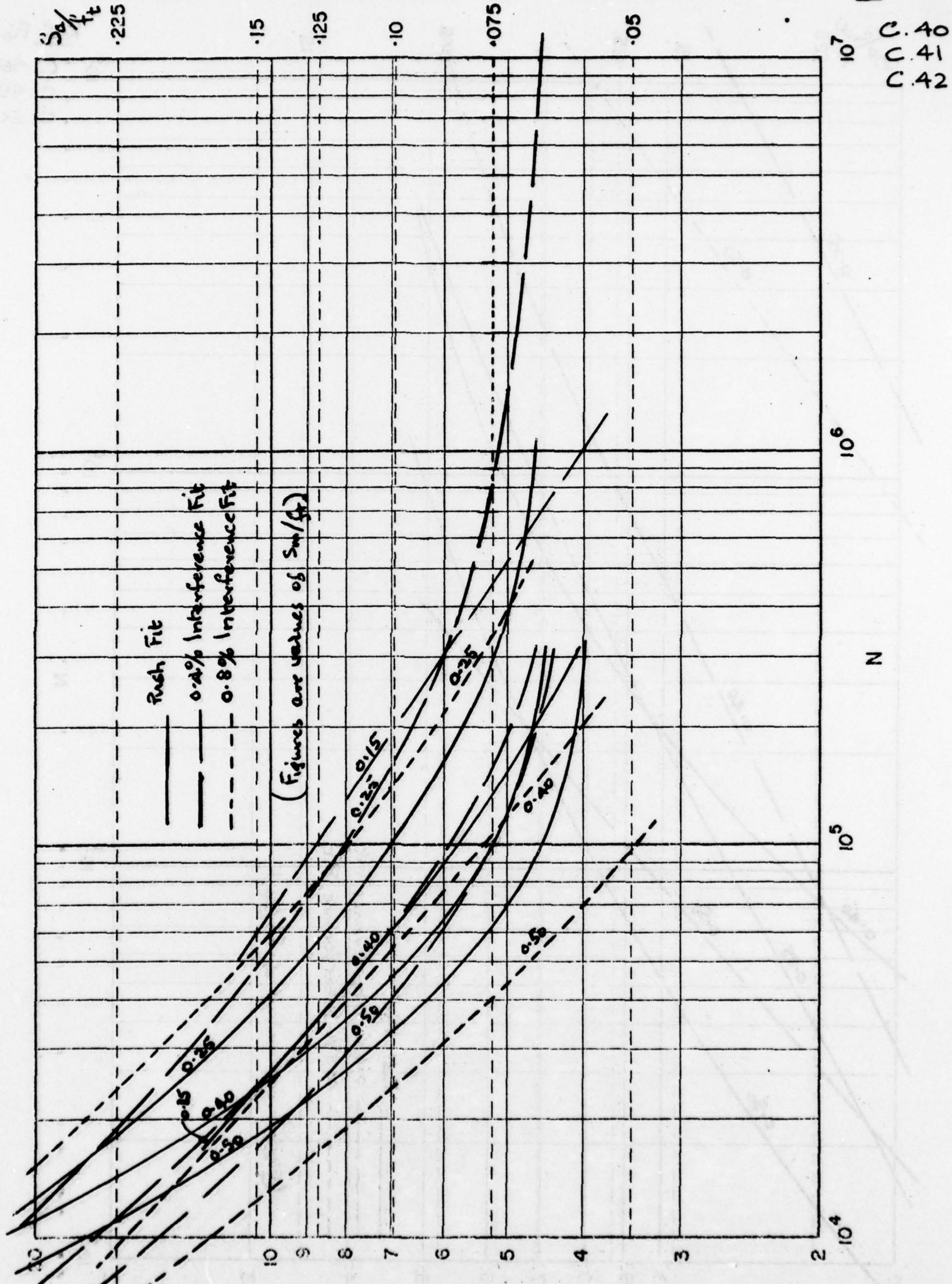


Fig 4.33 Comparison between Push Fit & Interference Fit Pin

94

Pin Loaded - Small Specimens. $d/D = 1/2$

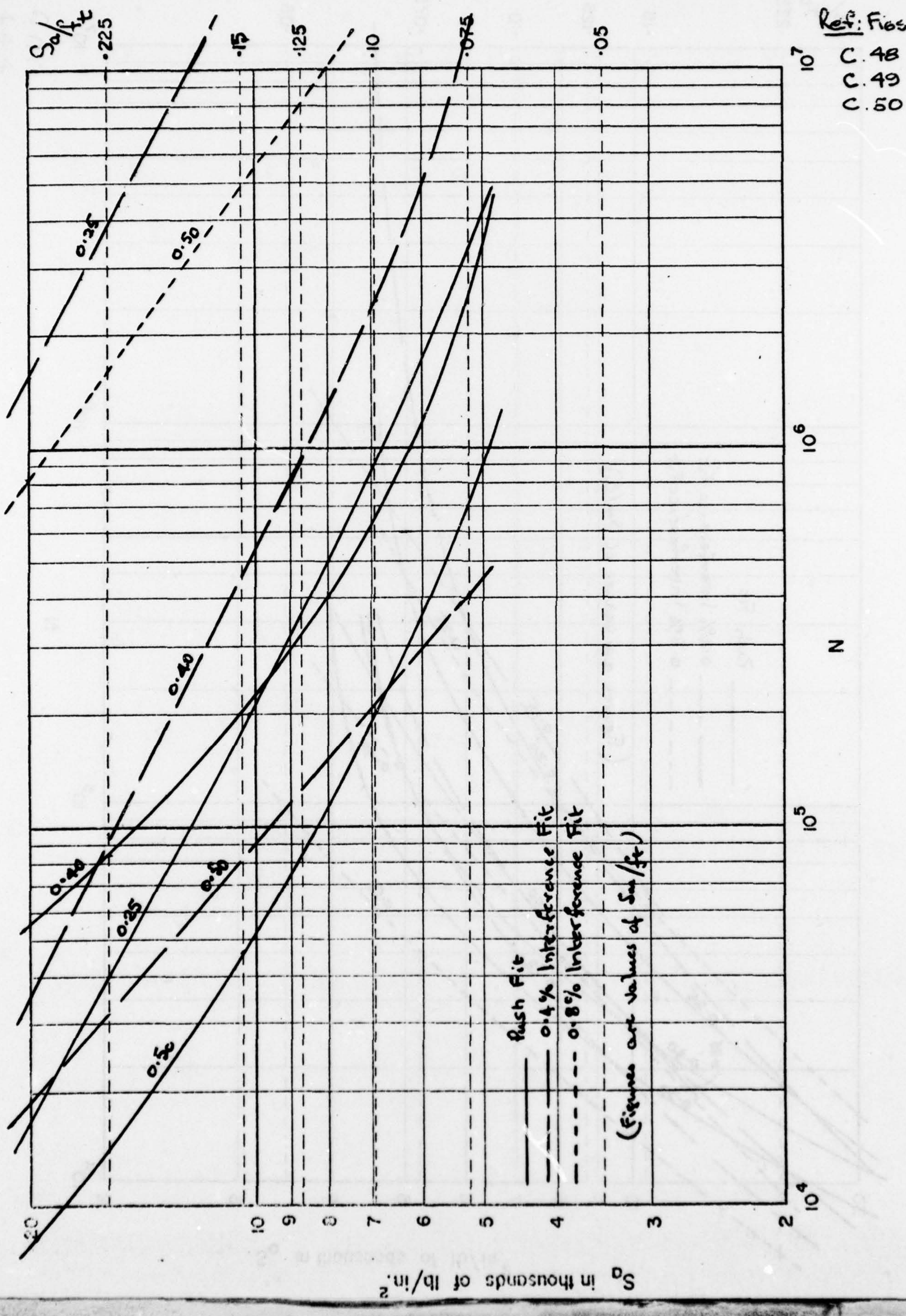


FIG. 4.34 EFFECT OF MEAN STRESS

UNFILLED HOLE d/D = 1/4

Mean Values of all three sizes (Ref Figs C.1, C.19 & C.35)

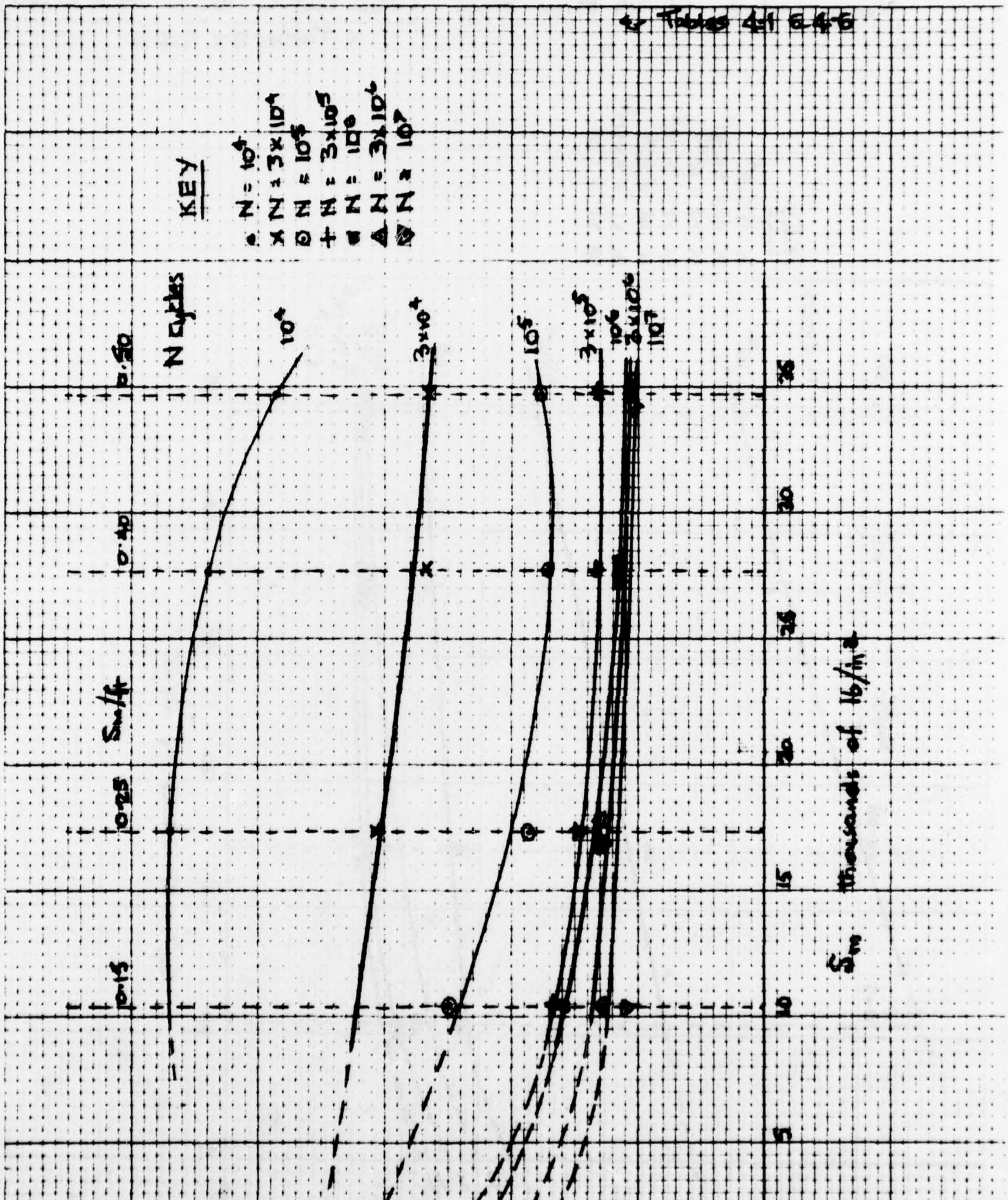


FIG 4.35 EFFECT OF MEAN STRESS

96 UNFILLED HOLE d/D = 1/2

Mean Values of all three sizes (Ref. Figs C.13, C.29 & C.45) & Tables 4.1 & 4.6

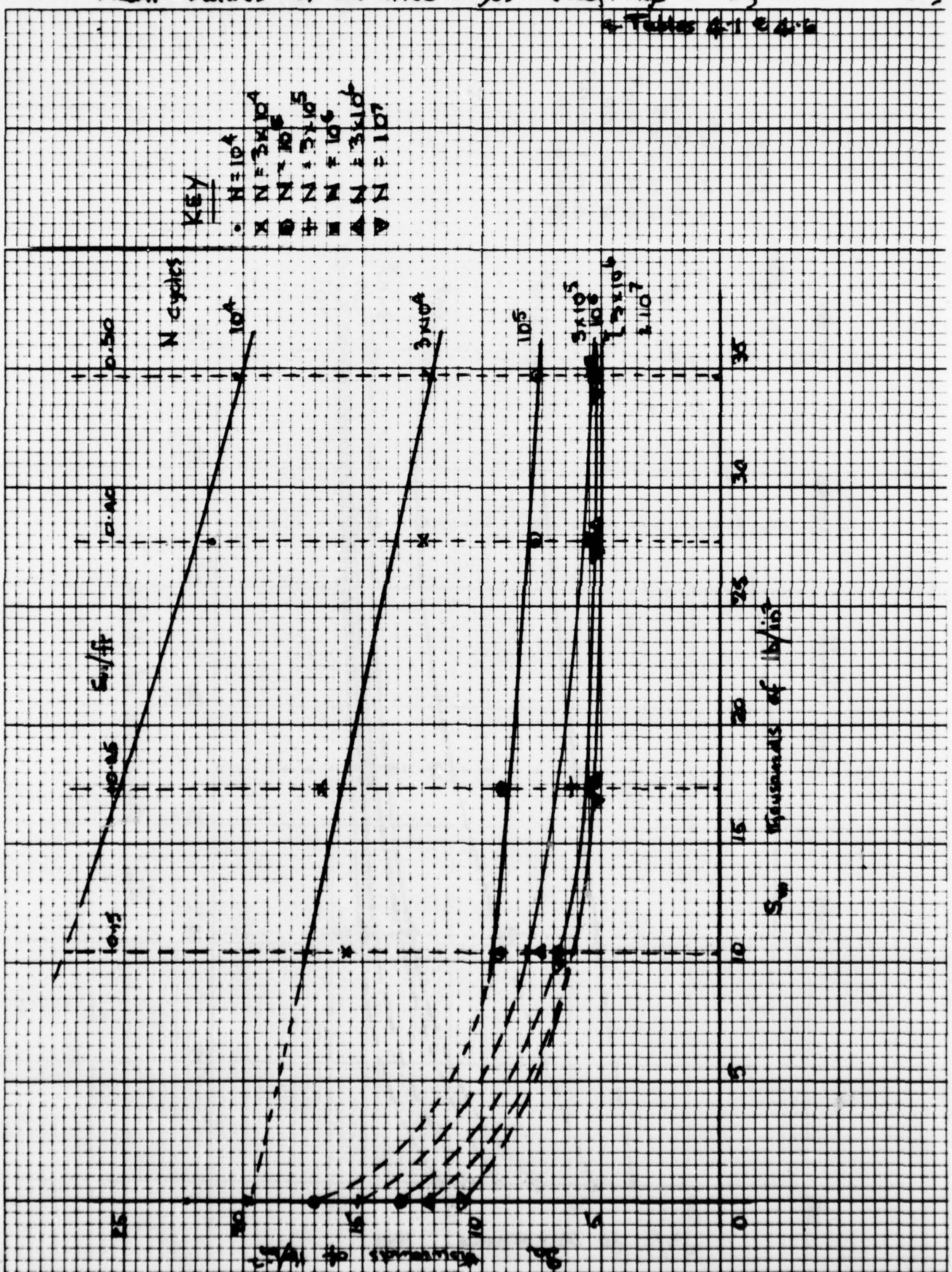


FIG. 4.36 EFFECT OF MEAN STRESS

PUSH FIT PIN – PIN UNLOADED $d/D = 1/4$

Mean values of all three sizes (Ref. Figs C.2, C.21 & C.37)
& Tables 4.2 & 4.6

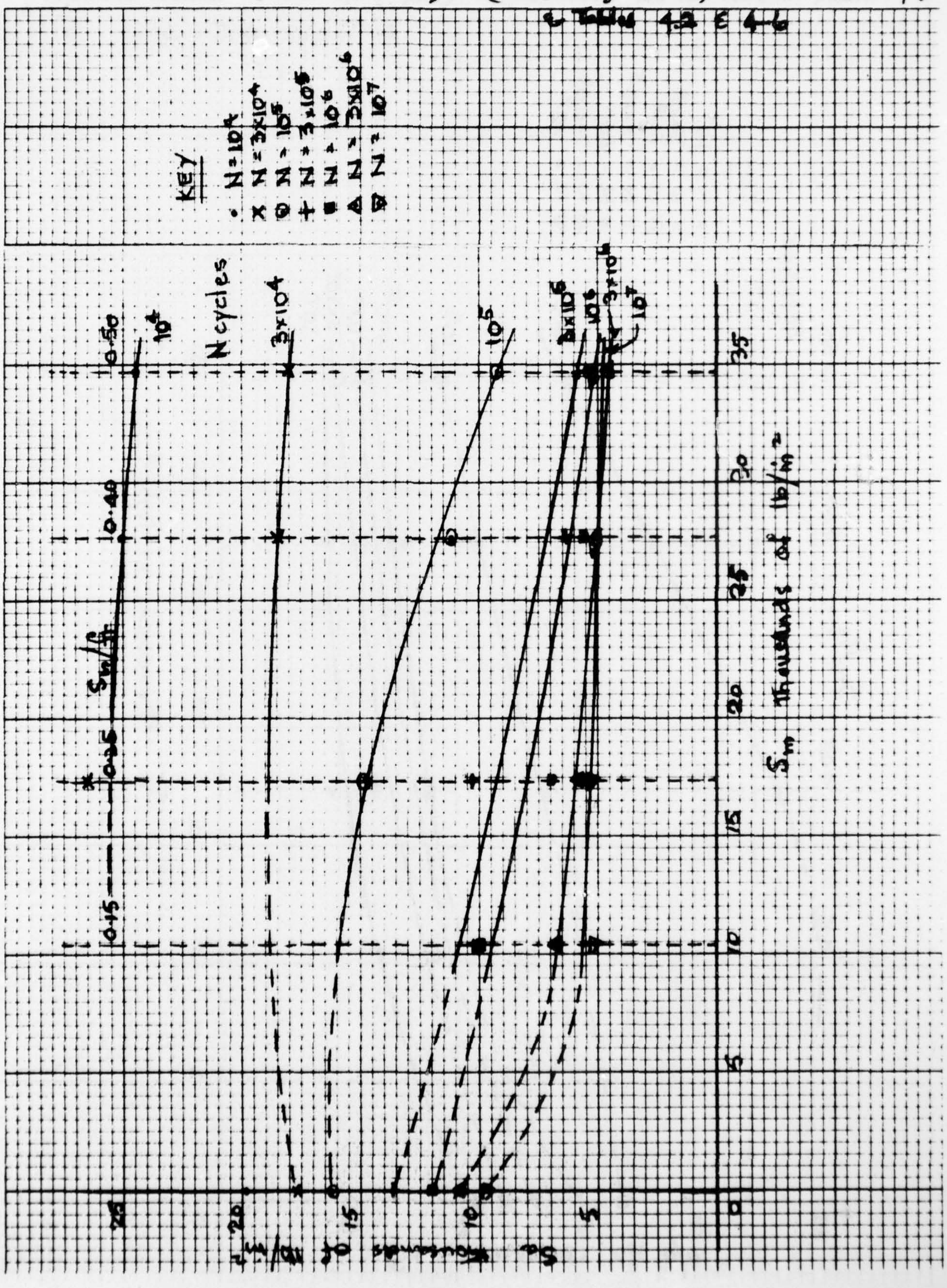


Fig. 4·37 EFFECT OF MEAN STRESS

98 PUSH FIT PIN - PIN UNLOADED $d/D = 1/2$

Mean values of all three sizes (Ref. Figs C.14, C.30 & C.46) & Tables 4.2 & 4.6

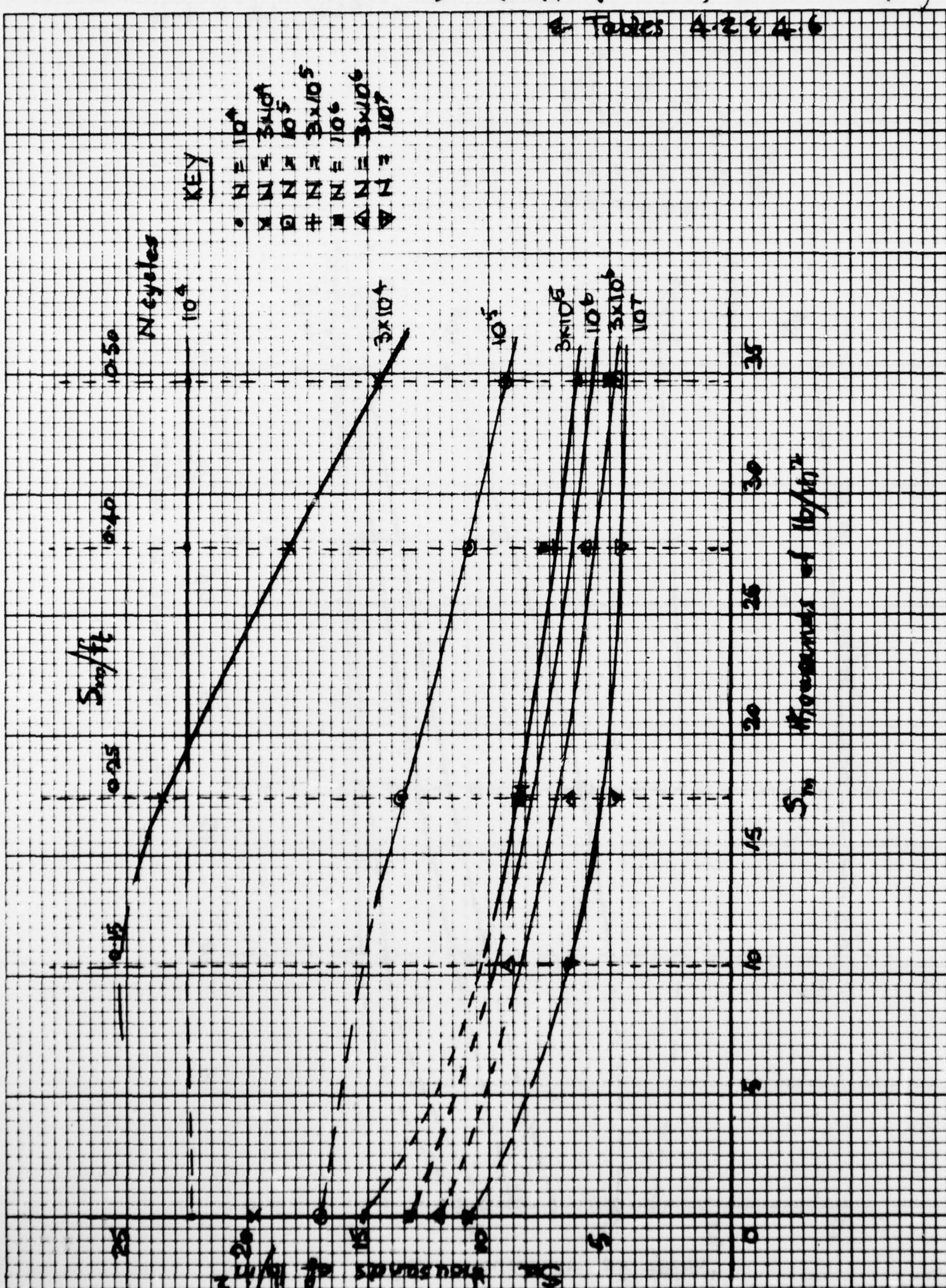
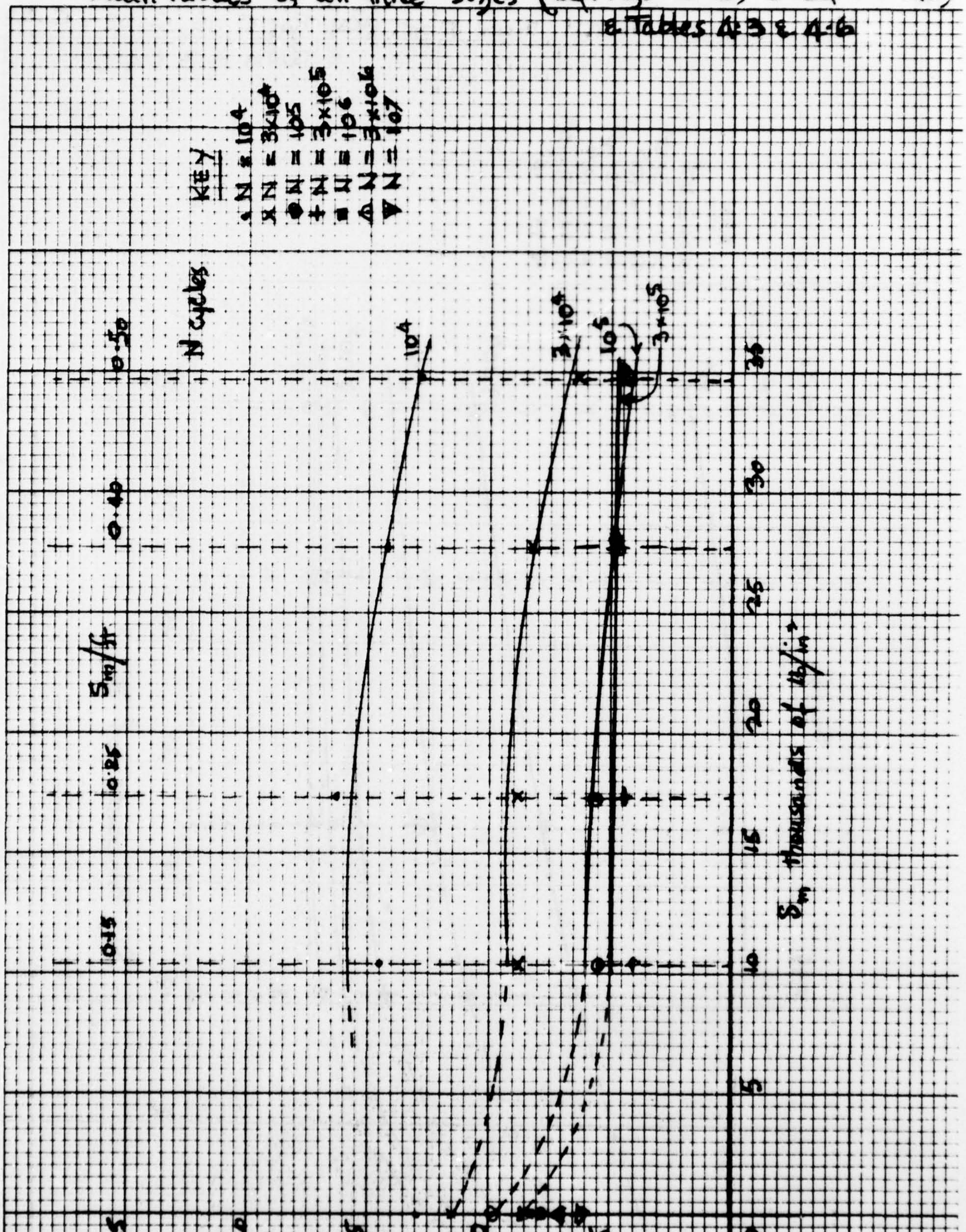


FIG 4.38 EFFECT OF MEAN STRESS

PUSH FIT PIN - PIN LOADED $d/D = 1/4$

Mean values of all three sizes (Ref. Figs C.5, C.24 & C.40) & Tables 4.3 & 4.6



100

Fig 4.39 EFFECT OF MEAN STRESS

PUSH FIT PIN - PIN LOADED $d/D = 1/2$

Mean Values of all three sizes (Ref. Figs C.16, C.32 & C.48) & Tables 4.3 & 4.6

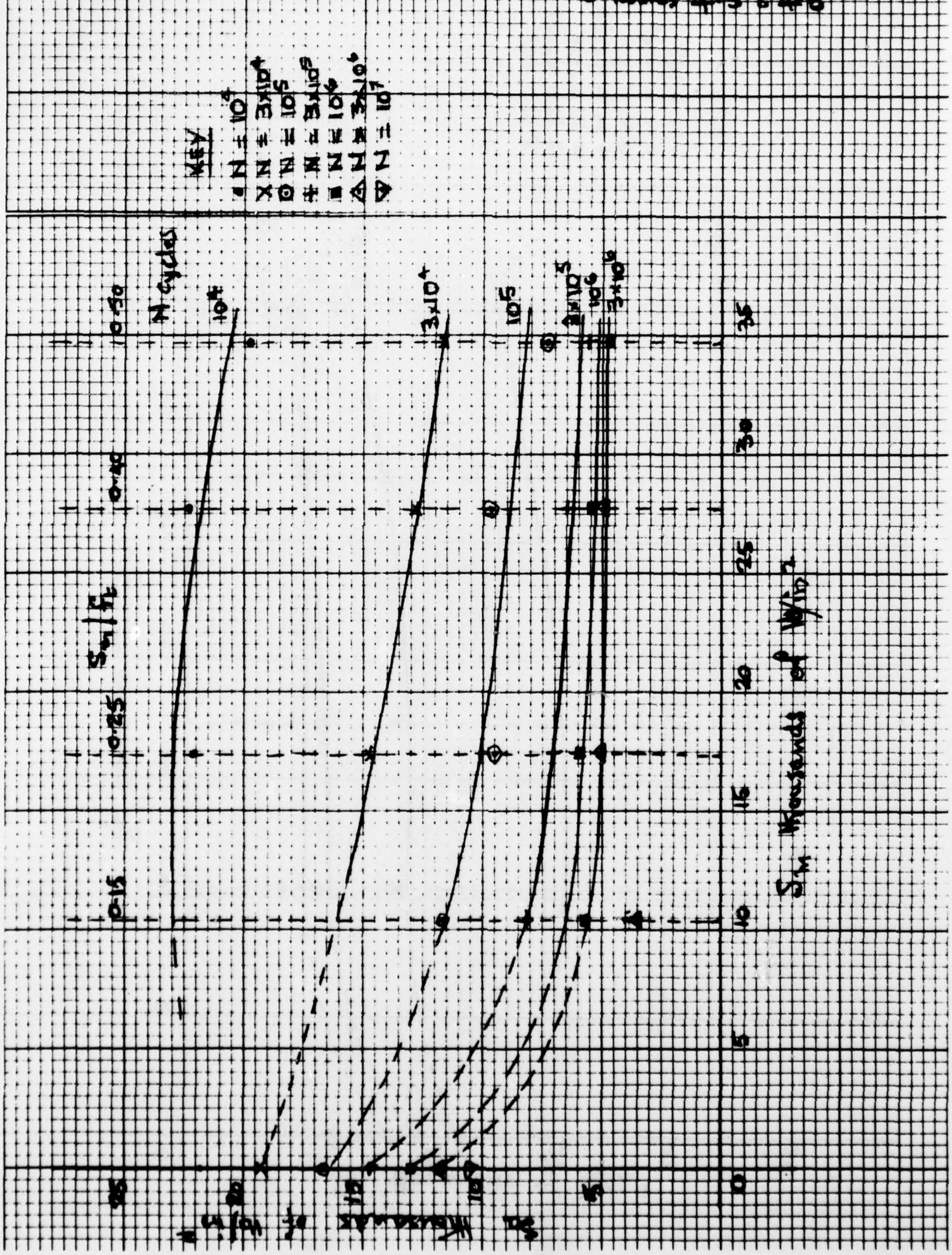


FIG. 4.40 **EFFECT OF MEAN STRESS**

0.4% INTERFERENCE FIT PIN - PIN UNLOADED $d/D = 1/4$

Mean Values of all three sizes (Ref. Figs C.3, C.22 & C.38) & Table 4.4

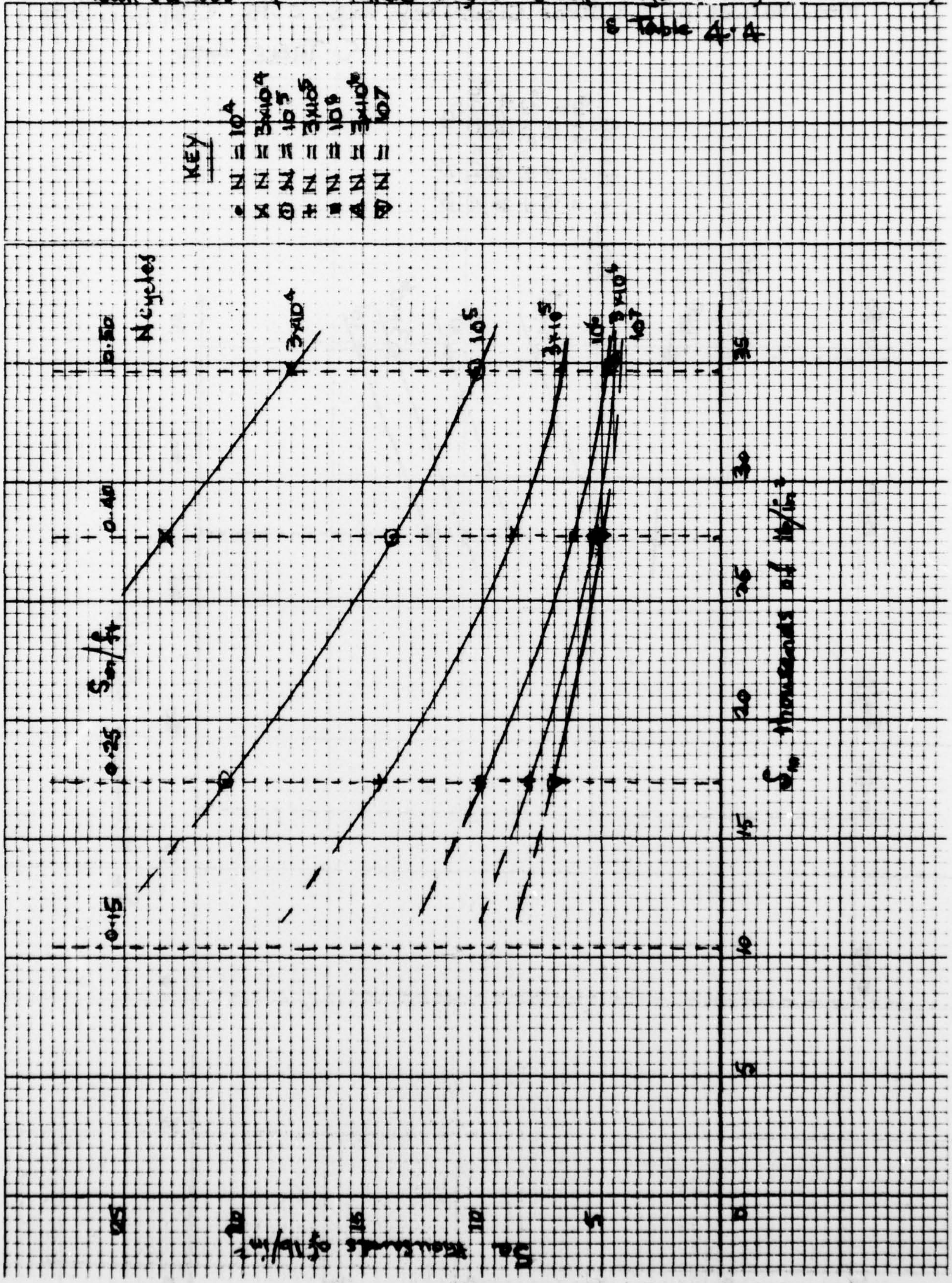


FIG 4.41 EFFECT OF MEAN STRESS

0.4% INTERFERENCE FIT PIN - PIN UNLOADED $d/D = 1/2$

Mean values of all three sizes (Ref. Figs. C.15, C.31 & C.47) & TABLE 4.4

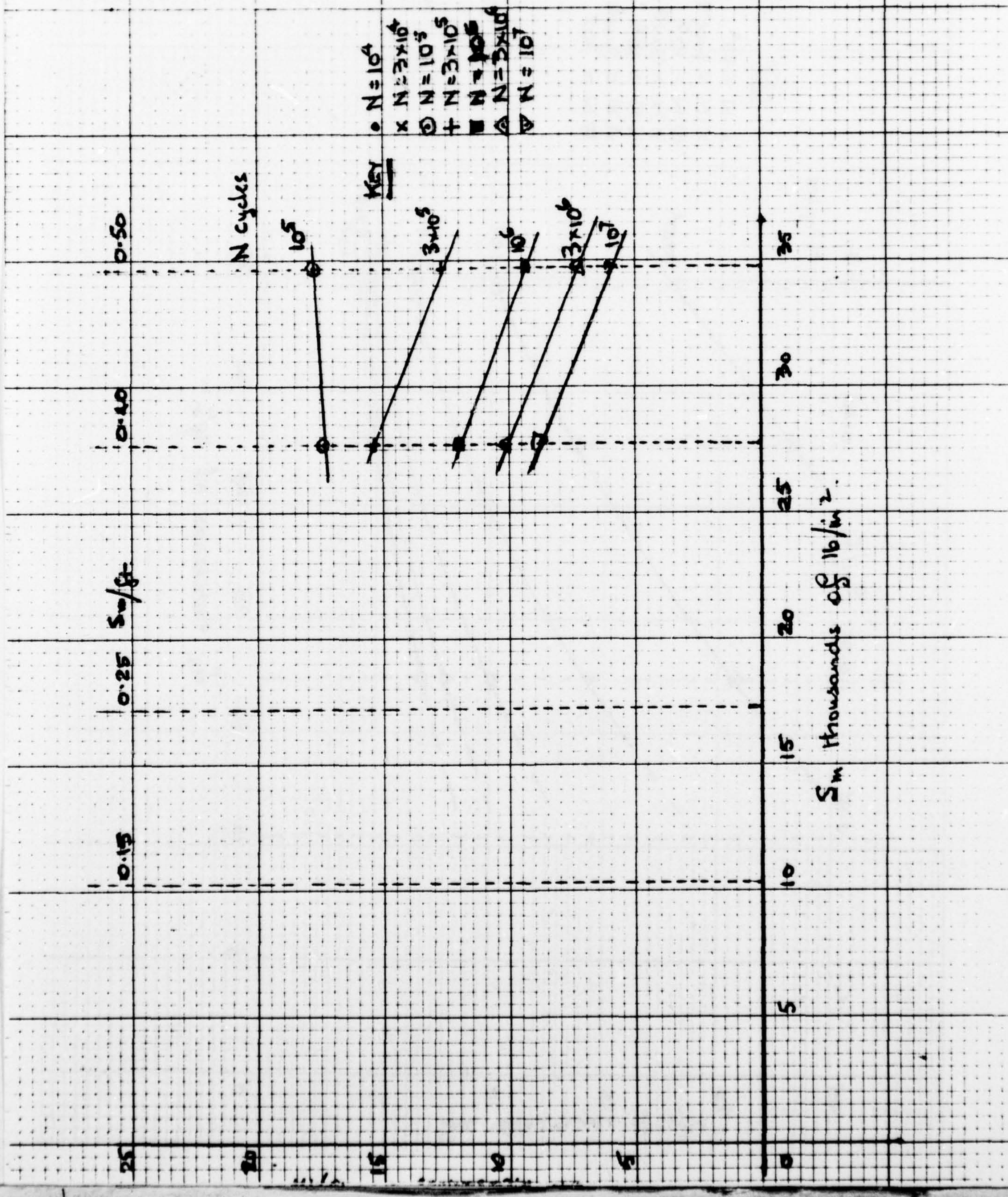
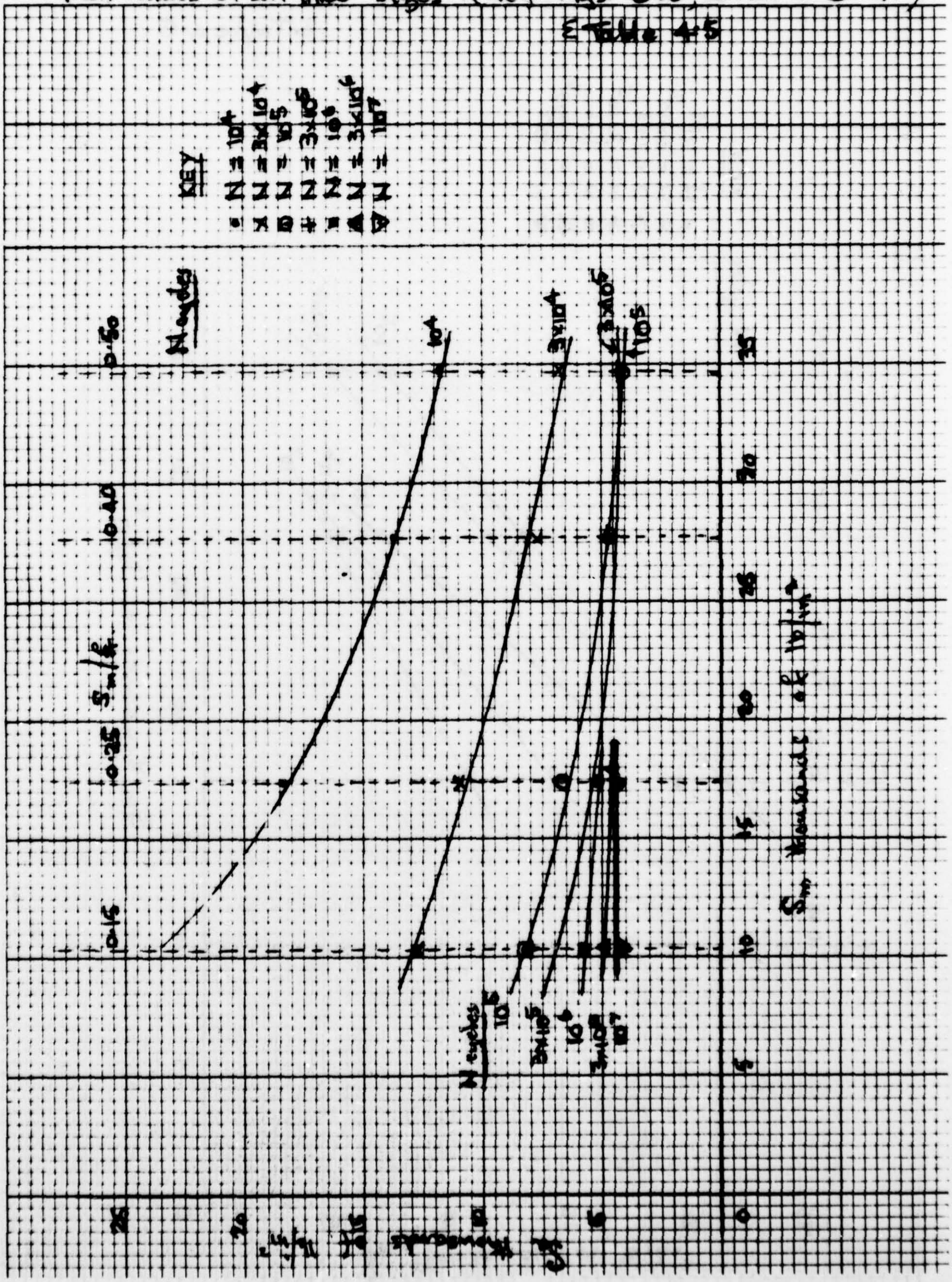


FIG. 4.42 EFFECT OF MEAN STRESS

0.4% INTERFERENCE FIT PIN – PIN LOADED $d/D = 1/4$

Mean values of all three sizes (Ref. Figs. C.6, C.25 & C.41) & Table 4.5



104

Fig. 4.43 EFFECT OF MEAN STRESS

0·4% INTERFERENCE FIT PIN — PIN LOADED $d/D = 1/2$

Mean values of all three sizes (Ref. Figs. C.17, C.33 & C.49) & Table 4.5

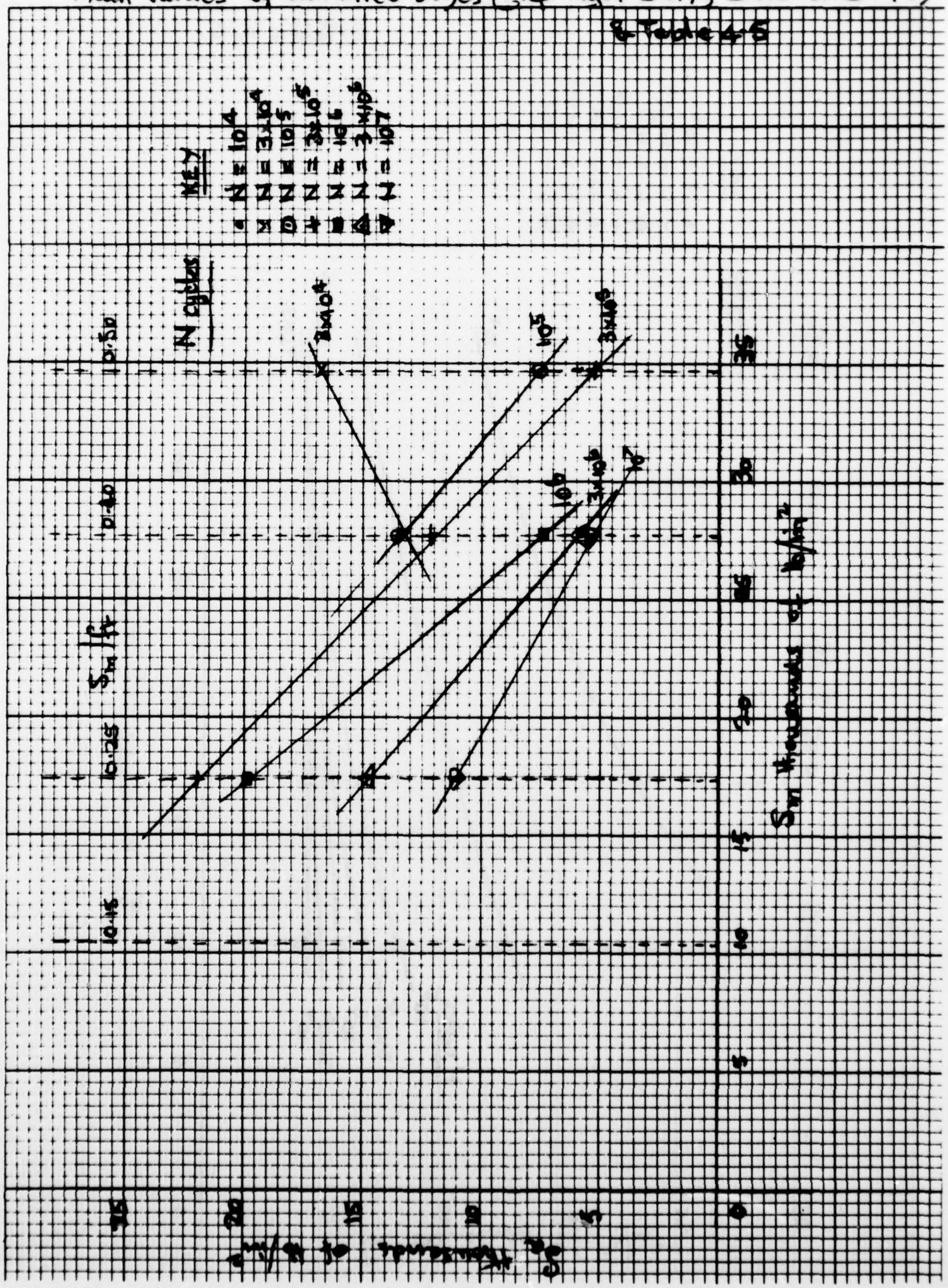


FIG 4.44 UNFILLED HOLE

SUMMARY PRESENTATION

LARGE, MEDIUM & SMALL SPECIMENS.

MEAN STRESSES OF 0.50, 0.40 & 0.25 ft COMBINED

d/D RATIOS OF 1/4, 3/8 & 1/2 — $K_t' = 2.43, 2.28$ & 2.17

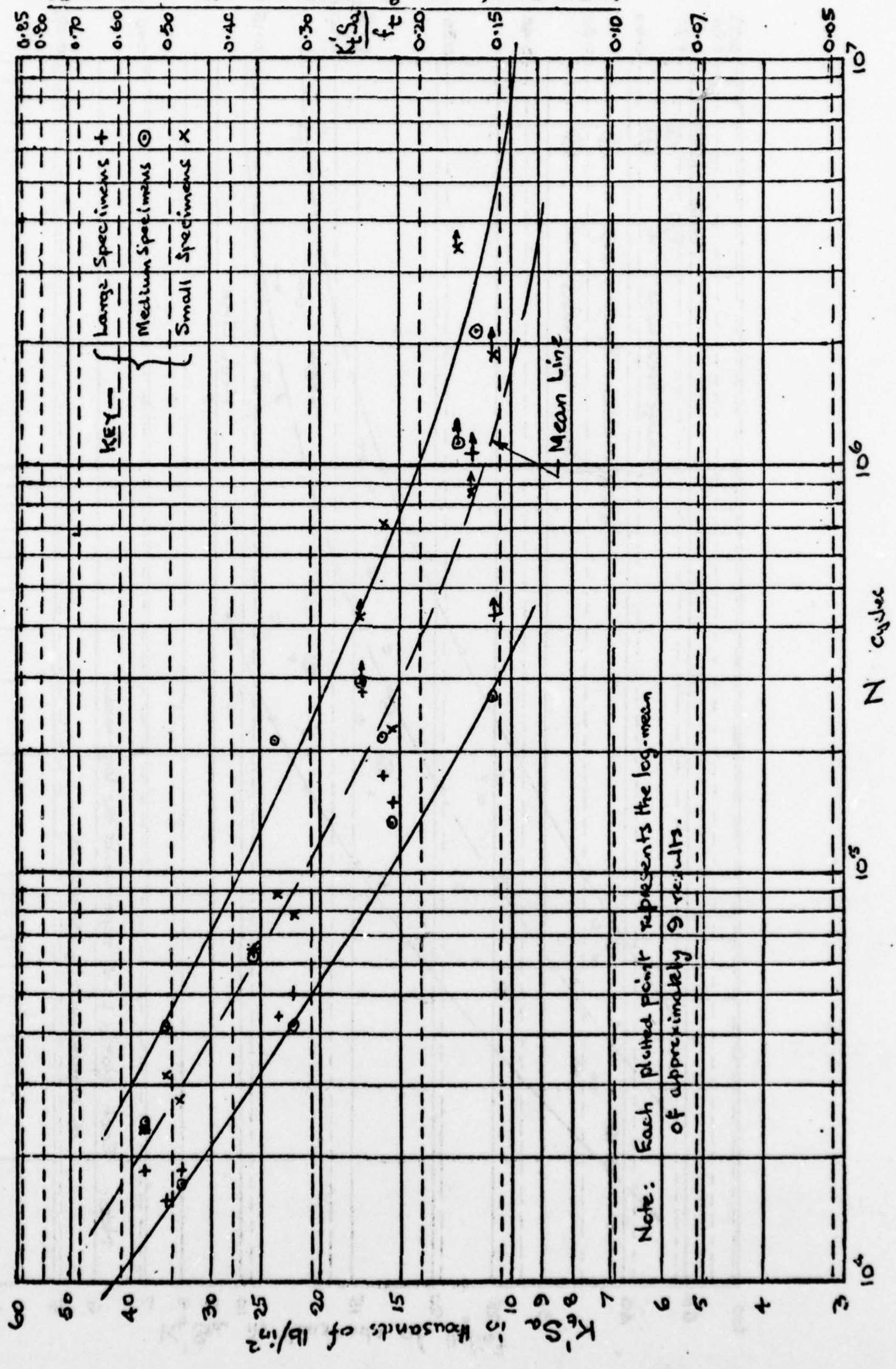


FIG. 4.45 PUSH FIT PIN – PIN UNLOADED (LOOSE FIT PINS ADDED)

LARGE, MEDIUM & SMALL SPECIMENS

MEAN STRESSES OF 0.50, 0.40 & 0.25 f_T COMBINED

d/D RATIOS OF 1/4, 3/8 & 1/2 — $K_t' = 2.43, 2.28$ & 2.17

SUMMARY PRESENTATION

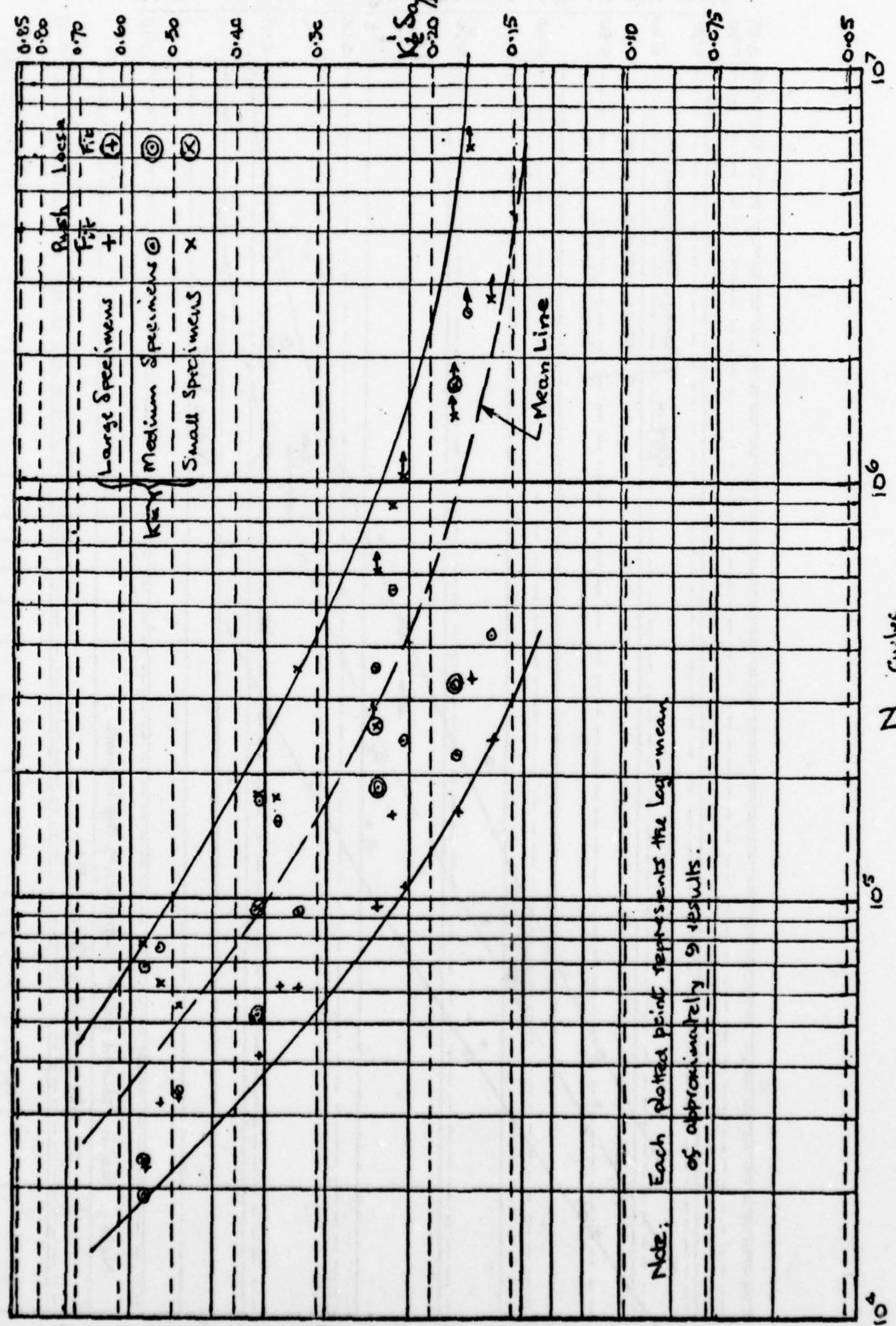


FIG 4.46 PUSH FIT PIN – PIN LOADED (LOOSE FIT PINS ADDED)

LARGE, MEDIUM & SMALL SPECIMENS.

MEAN STRESSES OF 0.50, 0.40 & 0.25 ft COMBINED

d/D RATIOS OF 1/4, 3/8 & 1/2 – $K_t' = 3.73, 2.72$ & 2.22.

SUMMARY PRESENTATION

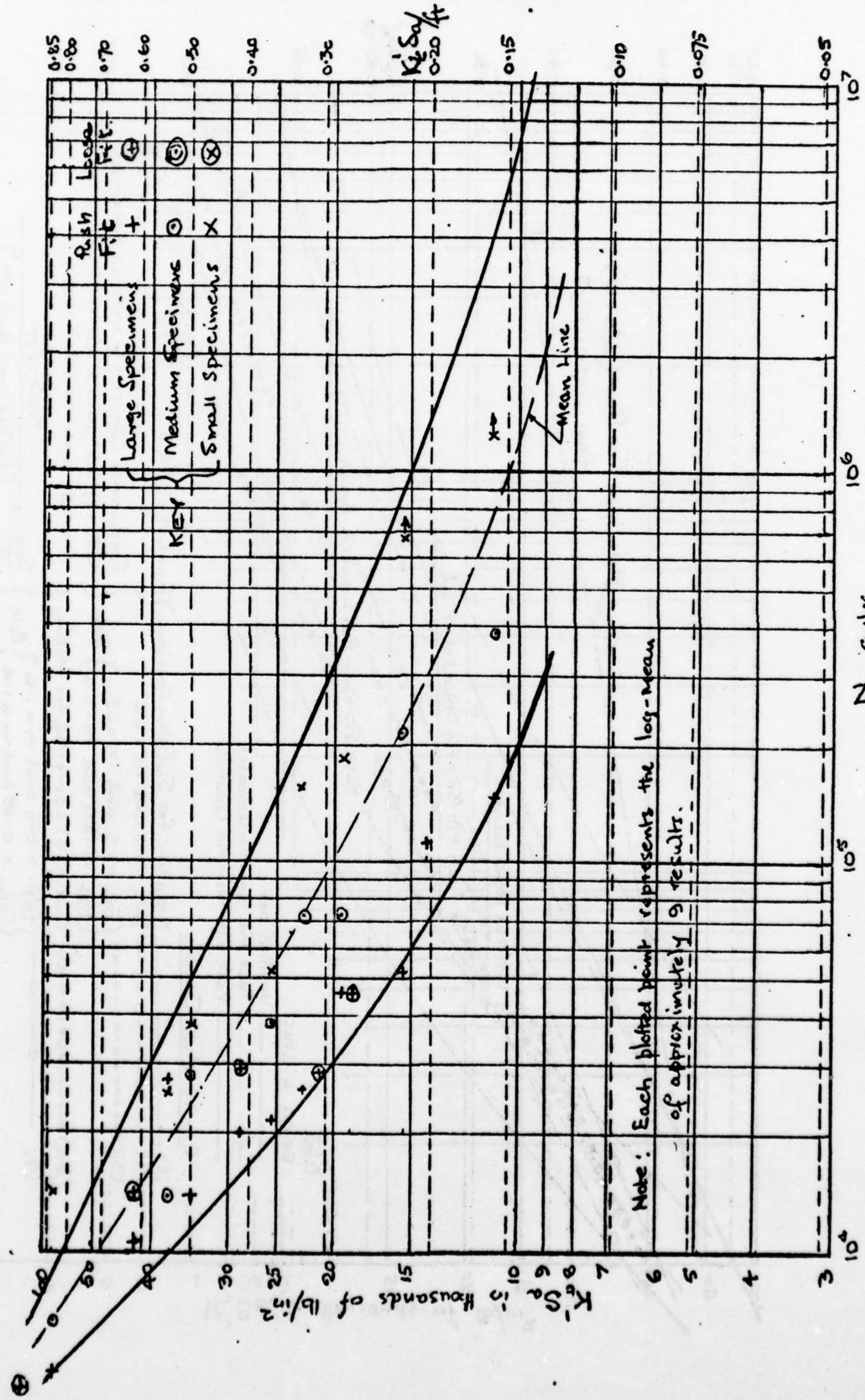
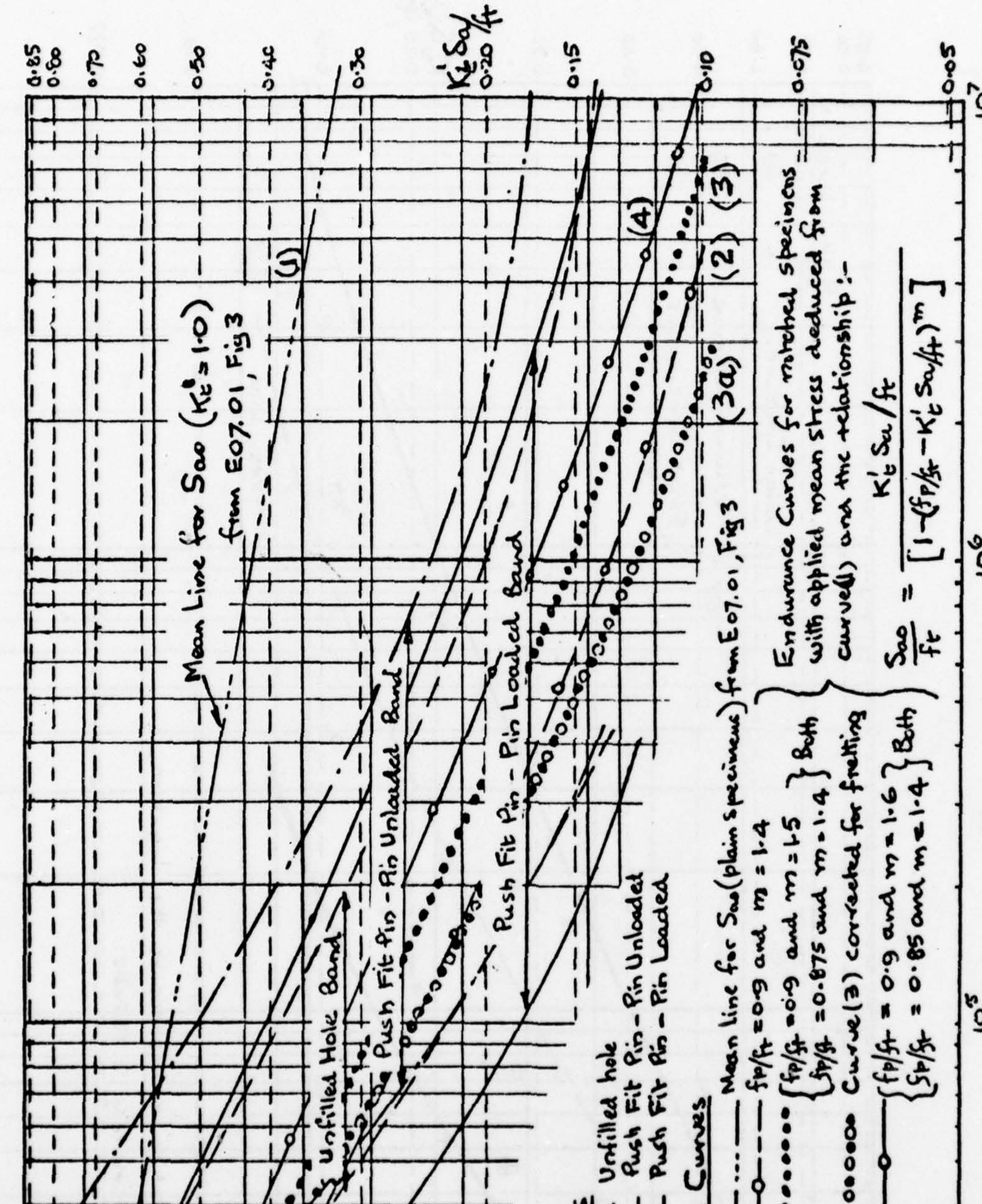


FIG. 4.47 COMPARISON BETWEEN UNFILLED HOLE PUSH FIT PIN - PIN UNLOADED AND PUSH FIT PIN - PIN LOADED

SUMMARY PRESENTATION



(a) Two 'J' Type Failures 'F' Type Failure from centre-line

(b) 'F' Type Failure f Edge

FIG. 4.49 CRACKS FROM FRETTED REGION

SPECIMEN 33.5.A PUSH FIT PIN - PIN UNLOADED

(MAGNIFICATION × 60)

Section through fretted region of hole surface parallel to surface of plate.

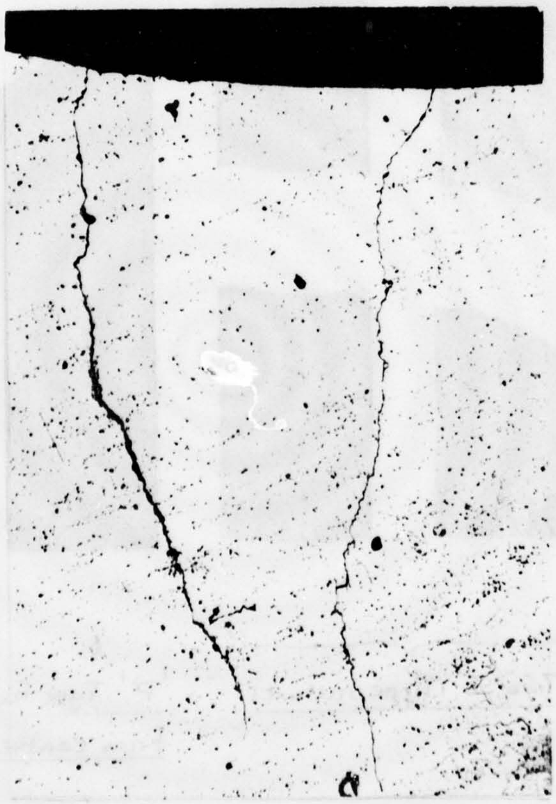
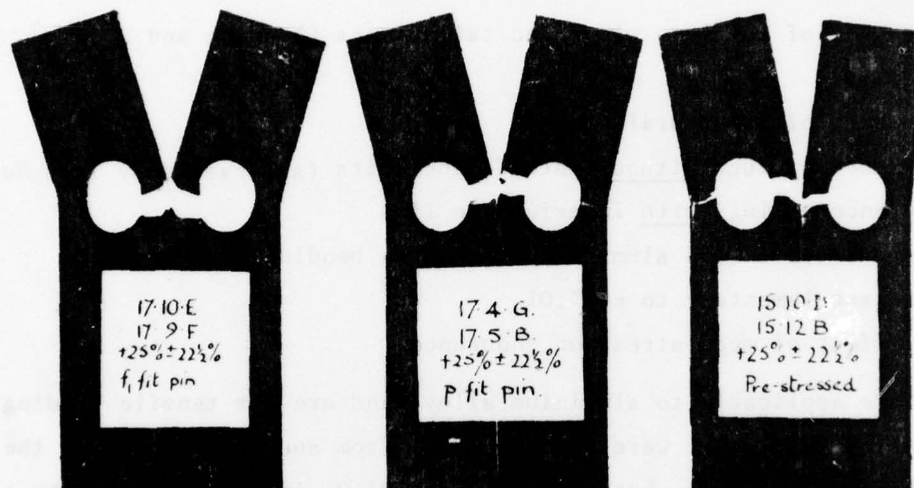


FIGURE 4.50 COMPARISON OF FAILURE ORIGINS



Comparison of failure origin between specimens tested at the same load but with different relationship between pin and hole.

SECTION 5 COMPARISONS WITH RELEVANT RAeS DATA SHEETS

5.1 Introduction

The Fatigue Sub-series of the Royal Aeronautical Society Data Sheets contains a number of sheets dealing with endurance of aluminium alloy structures or detail members and with the prediction of endurances from basic test data.

Some of these data sheets have already been mentioned, but all those which are relevant to this research programme are listed below.

E.02.01	Endurance of complete wings and tail planes (bending and end load)
E.05.01	Endurance of structural joints
E.05.03	Endurance of lugs without interference fits (superseded By Item No.72020)
E.05.04	Endurance of lugs with interference fits
E.07.01	Endurance of unclad aluminium alloys (in bending)
E.07.02	Notes supplementary to E.07.01
E.07.03	The effect of mean stress on endurance

All the above are applicable to aluminium alloys and are for tensile loading unless stated otherwise. All were based on data from sources other than the Bolted Joint Fatigue Research, but E.05.03 and E.05.04 include some of the early results of this research.

A.00.01	The effect of mean stress on fatigue strength (plain test piece)
A.00.02	The effect of mean stress on fatigue strength (test piece with stress concentration)
A.05.02	The estimation of endurance of pin joints (from basic test data)

The first two of these data sheets are based on the work of Gunn - see Reference 9.

The last one is based on the photoelastic work by Jessop, Snell and Holister - see References 2 to 5 inclusive, but was modified in May 1965 as a result of the early results of the Bolted Joint Fatigue Research and of work by Cox and Brown - see Reference 8.

These data sheets have been in use for some years and the completion of Stage 1 of the Bolted Joint Fatigue Research has enabled them to be examined in the light of the results of this research. Indeed, one of the reasons for the research was to provide more information upon which to base such checks, leading where necessary to revision of the data sheets, or even to the issue of new ones. Data Sheet E.05.03 was the first of these to be revised and it is now superseded by Data Item 72020 which incorporates the relevant results of the Bolted Joint Fatigue Research. Nevertheless a comparison between the old data sheet and the present research is still of interest, see paragraph 5.4.

Thus the following paragraphs review each data sheet in the light of the results of the present research.

5.2 Data Sheet E.02.01 - Endurance of Complete Wings and Tailplanes (see Figure 5.1)

In comparing the results of the present research with this data sheet it must be remembered that the basis of the data sheet is full scale fatigue testing on aircraft structures designed in the early 1940's. Both design knowledge and testing techniques have improved considerably since those days and therefore one might expect somewhat better performance from modern designs. Again the failures concerned would cover a wide range of details and therefore of K_t' values, and this is reflected in the considerable scatter reported in the notes on the data sheet.

Perhaps the most useful comparison is to plot Figure 3 of Data Sheet E.02.01 and Figure 4.38 (Push Fit Pin - Pin Loaded, average all sizes, $d/D = 1/4$) on the same diagram, and this is presented on Figure 5.1. The choice of Figure 4.38 gives the most severe of the average results of the three configurations tested (excluding interference fit pins) combined with the highest stress concentration factor for the push fit pins.

The bolted joint specimen results are generally favourable relative to the data sheet curves, for a given endurance, particularly at $N = 10^4$ cycles. However, if instead of plotting average results for all three sizes of specimen, only the large specimen results are plotted (see Table 4.3, $d/D = 1/4$) then these alternative bolted joint curves are generally somewhat less favourable than the data sheet curves.

One exception to these conclusions is for the endurance of 3×10^4 cycles and mean stresses less than $S_m = 0.15\ f_t$. Here the bolted joint curve falls significantly below the data sheet curve, but it must be remembered that this part of the curve is not for true test values, but is assessed from Data Sheet E.07.01, Figure 3 (see Table 4.6) and should therefore be regarded with caution.

From the foregoing, it is concluded that the existing curves of Data Sheet E.02.01 are still reasonable for initial design purposes.

5.3 Data Sheet E.05.01 - Endurance of Structural Joints (see Figure 5.2)

Like the preceding one, this data sheet represents early designs of joints in a number of different aluminium alloys in current use, during and immediately following the Second World War. It covers a range of multiple bolted joints of various qualities of fit (excluding interference fits) and a small range of mean stress from 0.13 f_t to 0.22 f_t. The size of the joints was probably within the same size range of the present research since many were for main spar joints. The data sheet presents three curves:-

A the mean of all joint results

B the upper limit, representing the best practice at the period concerned

and C the lower limit, representing those cases where no special attention was paid to fatigue.

The range of mean stress covered by the data sheet results is small and of low absolute magnitude and so it is appropriate to compare these results with those for $S_m/f_t = 0.25$ to 0.15 in the Bolted Joint Fatigue Research programme - combined to give one set of curves.

The compatible configuration is Push Fit Pin - Pin Loaded, although of course some bolts in the joints were loaded by a combination of pin and plate loading. Since the K_t' values for the joints of the data sheet are not known (and variable) one cannot plot $K_t'S_a$. However, it is possible to show the effect of K_t' by grouping the B.J.F.R. results according to d/D. There are insufficient results at d/D = 3/8 to give a band and so there is but a simple line - for large specimens only. Size of specimen and d/D are indicated by a special key and for d/D = 1/4 and 1/2 band widths are presented. The comparison is presented on Figure 5.2, and is most encouraging. The single line for d/D = 3/8 virtually coincides with the mean line A of the Data Sheet, the band for d/D = 1/4 lies adjacent to, but almost entirely on the lower side of this mean line, and the band width for d/D = 1/2 lies symmetrically about the upper limit line B.

In general, comparing the full band of the B.J.F.R. results with the full band width of the data sheet joints, the B.J.F.R. results appear to be more favourable, and this in spite of the fact that the data sheet joints had tightened bolts and the B.J.F.R. joints were made with pins only, and no clamping of the plates.

However, it must be remembered that the plotted points from the current research are mean results and are averaged for a small range of comparatively low values of S_m/f_t, so that in reality there will be some additional scatter of individual results. In passing it may be noted that if the results for $S_m/f_t = 0.40$ and 0.50 were included, the B.J.F.R. results would be somewhat lower, but not unduly so. For reference, these test results were taken from Appendix C, Tables C.5, C.11, C.16, C.24, C.32, C.40 and C.48.

5.4 Data Sheet E.05.03 - Endurance of Lugs without Interference Fits*

(See Figures 5.3, 5.4, 5.5 and 5.6)

Although this data sheet covers lugs in more than one type of aluminium alloy, no significant influence of choice of alloy was evident. Otherwise the range of the important variables covered was similar to that used for the Bolted Joint Fatigue Research. That is for pin diameter, ratio of d/D, ratio of t/D, range of mean stress and degree of fit. In fact the ratio of t/D extended up to 1.0 compared with 0.5 for the B.J.F.R. and the degree of fit covered by the test specimens of the data sheet was not quite so consistent as for the B.J.F.R. In regard to mean stress range, that for the data sheet was slightly lower than that for the B.J.F.R.

Combined data have already been evaluated for the B.J.F.R. for the range $S_m/f_t = 0.25$ to 0.50 (see Section 4, Table 4.11 - push fit pin - pin loaded) and these will be used for the comparisons.

For clarity each of three values of d/D will be compared on a separate graph; the difference between the three values of d/D of the B.J.F.R. and those of the data sheet are considered virtually negligible. Size of specimen is indicated by separate symbols as before.

Figures 5.3, 5.4 and 5.5 show these comparisons with the three band widths of data sheet E.05.03. Figure 5.4 has only a single line for d/D = 3/8 because only large specimens were tested in this configuration. Being large specimens, this line may be regarded as the lower limit of a band.

In all three cases the lower limits of the band widths shown are in fair agreement with one another, but the B.J.F.R. limits are curves, compared with the straight lines of the data sheet, and are somewhat steeper at low endurances. The increased slopes are probably due to fretting.

The upper limits for d/D = 1/4 and 1/2 of the B.J.F.R. are also curves and somewhat below those of the data sheet. If the results for $S_m/f_t = 0.15$ of the B.J.F.R. had been included in the comparison the upper curves would have been slightly higher but not sufficiently so to reach the data sheet upper

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*This data sheet is now superseded by Data Item 72020, but for consistency the test results will be compared with firstly the old data sheets and secondly the new Data Item.

limits. This can be seen by comparing the upper curves of these three figures with those of Figure 5.2 which are drawn for $S_m/f_t = 0.25$ to 0.15. Nevertheless, the agreement between the present test results and Data Sheet E.05.03 is good, and if the full scatter of results were to be included the B.J.F.R. bands would be somewhat wider.

The full scatter of results has in fact been plotted successfully, but the presentation on a small sheet of the size used in this report is apt to be a little confusing, and so it has been omitted in favour of the clearer "Summary Presentation" curves, using the data from Table 4.11 of Section 4.

Data Sheet E.05.03 has now been revised and improved by combining all the latest results from this research programme with those already used and is now available as Data Item 72020 "Endurance of Aluminium Alloy Lugs with Push Fit Pins (Tensile Mean Stress)". Figure 4 of this new Data Item presents a summary of all the data available for large, medium and small specimens of material with the ratio $f_p/f_t = 0.85$ to 0.91, and therefore incorporates the appropriate results from the Bolted Joint Fatigue Research. Thus one would expect to find good agreement between the two, and this is shown to be so by plotting Figure 4 of Data Item 72020 and Figure 4.46 of this report on the same graph. This is given on Figure 5.6.

5.5 Data Sheet E.05.04 - Endurance of Lugs with Interference Fits (See Figures 5.7, 5.8 and 5.9)

Here the range of data is similar to that for lugs without interference fits, except that there is less information at the lower values of mean stress. More than one degree of interference fit is involved.

Although the effect of mean stress is more marked for interference fit pins than for push fit pins, this is not excessively evident if the pins are loaded, and in any case the number of Bolted Joint Fatigue Research results at $S_m/f_t = 0.15$ is very small. Therefore in the interests of simplification the comparison has been made for the range $S_m/f_t = 0.25$ to 0.50, using average values for this range. The same three values of d/D are examined as before, together with segregation of the three specimen sizes, and the basic endurances are obtained from the appropriate tables in Appendix C as indicated in Tables 5.1 to 5.2.

Table 5.1 gives the derived mean endurances for $0.4^{o}/o$ interference fit pin - pin loaded and

Table 5.2 gives similar information for $0.8^{o}/o$ interference fit pin - pin loaded. The results are plotted on Figures 5.7, 5.8 and 5.9 covering d/D = 1/4, 3/8 and 1/2 respectively, and are compared with the approximately equal d/D ratios of Data Sheet E.05.04.

Considering these three figures, the conclusions are similar to those for push fit pin lugs, namely that the results for the Bolted Joint Fatigue Research fall largely within the corresponding band widths of the Data Sheet E.05.04 and that the agreement is even better if the full scatter of results is plotted. There is however more scatter for the interference fit pin results than for the push fit pin results, at d/D = 1/2. Also the size effect is not so conventional as with push fit pins. These features are partly due to the high endurances achieved, and to the greater number of unbroken specimens. Curves for the test results at d/D = 1/2 have therefore been omitted but the results are plotted.

In Section 4, paragraph 4.15.6 reference has been made to the fact that fretting tends to steepen the slope of the endurance curves, and Table 4.12 gives details of some specimens on which fretting was studied in detail. Some of the results plotted on Figure 5.9 are for these fretted specimens, notably items 8.9, 11, 12, 27, 28 and 29 of Table 4.12 (see also paragraphs 5.8.2 and 5.8.3).

As in the case of E.05.03, it is considered that E.05.04 would be improved if all the Bolted Joint Fatigue Research were to be combined with the present data to produce a revised data sheet for interference fit pin joints.

5.6 Data Sheet E.07.01 - Endurance of Unclad Aluminium Alloys and Data Sheet E.07.02 - Supplementary Notes to E.07.01

The first of these two data sheets presents basic fatigue test data in bending for a range of aluminium alloys. Figure 3 of the data sheet covers L 65 material which is basically the same material as used for the sheet specimens of the present research (L 71). The mean curve of Figure 3 has been used in paragraph 4.13.3 sub-paragraph (iii) to introduce a comparison between this data sheet and the Bolted Joint Fatigue Research results. The comparison is discussed further in paragraph 5.7.

Data Sheet E.07.02 qualified the applicability of D.S. E.07.01 in respect of fatigue strengths in bending and under axial loading; and in respect of quality of surface finish, which in the case of the Bolted Joint Fatigue Research was "as rolled". In Stage 2 of this research a Supplementary Investigation (No.5) has been instigated in order to provide some data on the latter aspect.

5.7 Data Sheet E.07.03 - The Effect of Mean Stress on Endurance and Data Sheets A.00.01 and A.00.02 - The Effect of Mean Stress on Plain and Notched Specimens Respectively

Data Sheet A.00.01 presents and discusses a basic relationship between mean stress S_m, alternating stress S_a in the presence of S_m, and S_{ao} the complementary alternating stress for the same endurance at zero mean stress.

Data Sheet A.00.02 extends this analytical approach from plain to notched specimens based on the expression:

$$S_a = \frac{S_{ao}}{K'_t}\left[1 - (K'_t \cdot \frac{S_m}{f_t})^m\right]$$

and postulates the effect on S_m of plastic yielding at the root of the notch, leading to:

$$S_{m'} = K'_t S_m \quad \text{when} \quad S_{a'} + K'_t S_m < f_p$$

and $$S_{m'} = f_p - S_{a'} \quad \text{when} \quad S_{a'} + K'_t S_m \geq f_p.$$

(For notation see Section 3, and derivation, reference 9 of this report).

Data Sheet E.07.03 applies this analytical approach to the basic fatigue test data for plain specimens as presented in E.07.01, and produces three families of endurance curves for a range of values of S_m/f_t, covering three values of the parameter "m" namely 1.0, 1.2 and 1.4.

The data may then be used for both plain and notched specimens, if the appropriate value of K'_t is included.

These data have already been used in Section 4, paragraph 4.13.3 (iii) for a comparison with the Summary Presentations of Section 4 and have led to reasonably good agreement between the Bolted Joint Fatigue Research and these data sheets where $m = 1.4$ to 1.6 coupled with the appropriate choice of value of f_p/f_t, and provided that some allowance for fretting is made (see paragraph 4.13.3(iii)).

5.8 Data Sheet A.05.02 - Estimation of Endurance of Pin Joints (See Figures 5.10, 5.11, 5.12 and 5.13)

5.8.1 General

The comparisons made here are with Issue 2 of this data sheet, derived as noted in paragraph 5.1. The data sheet is somewhat complex, and is based on the assumption that the endurance of a joint is determined by the values of the maximum shear stresses at the hole boundary corresponding to the maximum and minimum applied stresses of the fatigue cycle.

The data sheet outlines a method evaluating these maximum shear stresses due to the combined effects of interference fit (if any), load applied via the pin at the section under investigation and load passing through the plate but not applied via the pin.

The stresses so determined are then used to calculate an equivalent stress cycle on a simple specimen for which fatigue test endurances are available, e.g. a plain unnotched specimen or a single pin joint without interference.

The curves in this data sheet were originally based on the results of photoelastic investigations, and are therefore strictly valid only for elastic strains, and the use of the data sheet for values of q' much in excess of 0.7 f_p is not recommended.

An assumption implicit in the evaluation of endurance by A.05.02 is that fretting is equally damaging whether the joint has push fit or interference fit pins. In general fretting in the presence of an interference fit pin would be less damaging.

In order to compare this data sheet with the results of Stage 1 of the Bolted Joint Fatigue Research, appropriate predictions will be made via the data sheet, for the endurances for 0.4°/o and if valid for 0.8°/o interference fit pin joints (unloaded and loaded) covering the range of mean stress involved, by using the plain specimen data of E.07.03 for predictions by Method (a) of A.05.02 and the Bolted Joint Fatigue Research results for push fit pins for Method (b) of A.05.02. However, for a number of combinations of interference fit and stress level the value of q' will be in excess of the limit noted above and will therefore be omitted, or if the comparison is included, the text and the appropriate Figures will be annotated accordingly.

Because these predictions are sensitive to the choice of f_p/f_t and m, it has been decided to compare specific combinations of d/D and S_m/f_t. Reasonable coverage will be provided by the following:

> d/D = 1/4 and 1/2 and for each of these, S_m/f_t = 0.50 and 0.25 will be considered.

The successive steps of the calculation follow those given in the example of Issue 2 of the data sheet A.05.02, and therefore only the results are given in this report.

Note

In all these predictions the basic relationship of Data Sheet A.00.02 (Reference 9) is implied, via Data Sheet E.07.03, namely -

$$K'_t S_a = S_{ao} \left[1 - (K'_t \cdot \frac{S_m}{f_t})^m \right]$$

together with the assumption that -

$$S_{m'} = K'_t S_m \quad \text{when} \quad S_{a'} + K'_t S_m < f_p$$

and $$S_{m'} = f_p - S_{a'} \quad \text{when} \quad S_{a'} + K'_t S_m \geq f_p .$$

Also that $f_t = 69\ 400$ lb/in^2 and $f_p = 60\ 500$ lb/in^2

giving $f_p/f_t = 0.875$ coupled with $m = 1.4$.

(Reference paragraph 4.13.3 (iii)).

5.8.2 $0.4^o/o$ Interference Fit Pin - Pin Unloaded (See Figures 5.10 and 5.11)

In this group, the combination of $d/D = 1/4$ and $S_m/f_t = 0.50$ leads to values of q' ranging from $0.8\ f_p$ to $1.0\ f_p$ and therefore comparisons for this combination are not expected to be strictly valid. However the resulting predictions have been included for general information, since they are only slightly in excess of the test results at high endurances.

Predictions are made by Method (a) of A.05.02 using Data Sheet E.07.03 Figure 3, and by Method (b) using the summarised test data of Figure 4.45 of this report, push fit pins, pin unloaded - mean curve.

The predictions are then compared with the appropriate mean endurance curves for the tested specimens with *$0.4^o/o$ interference fit pins pin unloaded*, as given in Appendix C.

Table 5.3 summarises the results of the predictions by both methods for $d/D = 1/4$ and also gives references to the appropriate tables in Appendix C for the comparative test results.

Table 5.4 gives similar information for $d/D = 1/2$.

Figures 5.10 and 5.11 present the same information in graphical form.

Comment

For $d/D = 1/4$, Method (a) predicts lower endurances than Method (b), but even Method (a) leads to endurances generally in excess of the test results, particularly at low values of S_a/f_t. This may be partly due to the high values of q', but the highest values of q' actually occur at the high values of S_a/f_t where the discrepancies are least.

The difference at low values of S_a/f_t could well be due to fretting in the test specimens; three specimens of this group were specifically examined for fretting (Reference Table C.3). Assuming that all of the differences between the endurance curves for Method (a) and those for the test results are due to fretting, then this represents a correction factor on K'_t of from 1.15 to 1.25 for $S_m/f_t = 0.50$ and from 1.25 to 1.35 for $S_m/f_t = 0.25$ (see paragraph 4.15 for a discussion on the examination of fretted specimens).

For $d/D = 1/2$, the predictions by both Method (a) and Method (b) are in good agreement, particularly for $S_m/f_t = 0.50$. For $S_m/f_t = 0.25$ there are insufficient test results to justify drawing curves but the mean results are plotted and indicate that the predictions are of the right order.

<u>5.8.3 0.4°/o Interference Fit Pin - Pin Loaded</u> (See Figures 12 and 13)

The same procedure as used in paragraph 5.8.2 will be followed except that, because of the lower endurances and the greater importance of this configuration, comparisons will be made at three values of S_m/f_t, namely 0.50, 0.25 and 0.15, for $d/D = 1/4$.

The predictions by Method (a) will be made using Data Sheet E.07.03 as before, but Method (b) will use the mean curve of Figure 4.46 of this report (push fit pin - pin loaded).

<u>Table 5.5</u> summarises the results by both methods for $d/D = 1/4$ and

<u>Table 5.6</u> gives the similar information for $d/D = 1/2$.

<u>Figures 5.12 and 5.13</u> present the same information in graphical form.

As for the unloaded 0.4°/o interference fit pins, the combination of $d/D = 1/4$ and $S_m/f_t = 0.50$ leads to maximum shear stresses which are well beyond the recommended limit of 0.7 f_p - ranging from 1.17 f_p to 1.47 f_p. However, for information, the comparisons will be given.

The predictions for $d/D = 1/2$ and $S_m/f_t = 0.50$ and $d/D = 1/4$ and $S_m/f_t = 0.25$ are at best borderline in this respect.

<u>Comment</u>

<u>For $d/D = 1/4$</u> Although predictions by both methods are in reasonably good agreement with one another, they all lead to endurances which are slightly higher than the corresponding test results. This is not surprising for $S_m/f_t = 0.50$, and to a lesser extent for $S_m/f_t = 0.25$, because of the higher shear stresses.

For the group of tests at $S_m/f_t = 0.15$, there appears to be some inconsistency insofar as the endurance curves for small and medium size specimens are significantly lower than those for the large specimens, - a reversal of the usual trend. If the endurance curve for the large size specimen is assumed to be correct, then the agreement between test and prediction is acceptable.

For $d/D = 1/2$ The comparisons for $S_m/f_t = 0.50$ show that the predictions of endurance are too high, presumably because the maximum shear stresses are above the recommended limit. However, the endurance curves for the test specimens are somewhat steep, and it is known that fretting was present on some of the specimens in this group (see Table C.33). Thus the discrepancy is probably partially due to the occurrence of fretting.

The comparisons for $S_m/f_t = 0.25$ are in fairly good agreement with the test curves. There is some evidence of the effect of fretting when comparing the test results with the predicted curve by Method (b), leading to a "fretting factor" of the order of 1.25 at an endurance of 10^7 cycles.

(See paragraph 4.15 for a discussion on the examination of fretted specimens).

5.8.4 0.8^o/o Interference Pin - Pin Unloaded and Pin Loaded

Pins with this high degree of interference are not normally used, and the chief reason for including this degree of interference in the programme was to obtain some information beyond the normal range in order to view the latter in a broader perspective than would otherwise have been possible.

Some provisional comparisons between the test results for 0.8^o/o interference fit pins and the predictions of Data Sheet A.05.02 have been made, but in every case, pin unloaded or loaded, the maximum shear stresses evaluated ranged from a minimum of $0.9\ f_p$ to a maximum of $1.55\ f_p$. Clearly these are well beyond the limit of $0.7\ f_p$ recommended in the data sheet, and reasonable predictions would not be expected. This proved to be the case and so the details have not been included in this report.

5.8.5 Summary Comment on Data Sheet A.05.02 (Issue 2)

Predictions by both Methods (a) and (b) of this data sheet for the endurances of both unloaded and loaded interference fit pins are satisfactory, provided the combination of degree of interference and stress level does not lead to maximum shear stresses much greater than $0.7\ f_p$. In some, but not all of the combinations examined, satisfactory predictions were also obtained when the maximum shear stress was as high as $0.8\ f_p$. Above this value of $0.8\ f_p$ the predictions for endurance became increasingly in excess of those of the corresponding test results.

Combinations of 0.4°/o interference and $S_m/f_t = 0.50$ at $d/D = 1/4$, unloaded and loaded fell into the same category, but at $S_m/f_t = 0.25$, 0.4°/o interference and $d/D = 1/4$ all predictions were satisfactory.

At $d/D = 1/2$ and 0.4°/o interference fit, all predictions at $S_m/f_t = 0.50$, pin loaded were satisfactory.

For 0.8°/o interference fit none of the combinations led to a satisfactory prediction largely because of the high resulting maximum shear stresses.

Notwithstanding the above comments, there was a general falling away of the test curves relative to the predicted endurance curves, at low values of S_a/f_t, and this is believed to be due chiefly to the occurrence of fretting. The correction factor in terms of K'_t for a given endurance ranged from 1.15 to 1.35, which is somewhat smaller than was expected. The small effect of the fretting may be due to the presence of the interference fit pin.

In using this data sheet, it was found that at low values of f_{nom}/q'_o where the curves of Figure 1 converge towards $q'/q'_o = 1.0$ it is not easy to maintain accuracy and a larger scale re-plot of this area would be helpful. Also additional curves for $d/D = 0.15$ and 0.25 would make for more rapid evaluations.

The procedure is complex and sensitive to the choice of f_p and m. Some amplification and clarification of the text would be welcome, although most of the problems become clearer from a close study of the example.

5.9 General Comment on the RAeS Data Sheets

In so far as they are affected by the results of the current Bolted Joint Research Programme.

(i) None of the existing relevant data sheets when considered within their range of validity has been found to be seriously at variance with the test results; indeed most of them are in good agreement, but a few would be improved by the inclusion of the Bolted Joint Fatigue Research test results where applicable.

These are E 05.03* Endurance of Lugs without Interference Fits

E 05.04 Endurance of Lugs with Interference Fits and

A 05.02 The Estimation of Endurance of Pin Joints

(See detailed comments in the preceding paragraphs).

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*Now revised and issued as Data Item 72020

(ii) The importance of the effect of local plastic yielding at a stress concentration must always be borne in mind. In addition to the information already incorporated from Data Sheet A.00.02, Data Sheet E.07.03 would be enhanced if the condition $K'_t(S_m + S_a) \geqslant f_p$ could be shown for a small range of proof stresses, e.g. $f_p/f_t = 0.80$ to 0.90, for guidance when this data sheet is used for notched specimens - i.e. S_a and S_m being treated as $K'_t S_a$ and $K'_t S_m$. On reflection, it is realised that this proposal is a little difficult because the data plotted thereon are applicable to a range of stress concentration factors. An alternative presentation for Data Sheet E.07.03 has been suggested in which S_{ao}/f_t would be plotted against $K'_t S_a/f_t$ for a range of values of f_p/f_t and m, as related by equation (3) of paragraph 4.13.3 (iii),

i.e. $S_{ao}/f_t = K'_t S_a/f_t \Big/ \left[1 - (f_p/f_t - K'_t S_a/f_t)^m\right]$,

applicable for $K'_t(S_m + S_a) \geqslant f_p$, and the values of m ranging from 1.0 to 1.6.

(iii) The essence of the Summary Presentations for Unfilled Holes and Push Fit Pins - Pin Unloaded might well be included in the Data Sheets (in addition to Push Fit Pins - Pin Loaded).

NB

The Engineering Sciences Data Unit of the Royal Aeronautical Society is fully aware of the findings of this Report, and appropriate action is already in hand.

TABLE 5.1 COMPARISON OF TEST RESULTS WITH DATA SHEET E.05.04

(LUGS WITH INTERFERENCE FIT PINS - PIN LOADED) (Ref.Figures 5.7, 5.8 and 5.9)

0.4°/o INTERFERENCE FIT - PIN LOADED

S_m/f_t = 0.50, 0.40 and 0.25 combined

d/D = 1/4, 3/8 and 1/2 Large, Medium and Small Specimens

Geometry		d/D = 1/4			d/D=3/8	d/D = 1/2		
Size		L	M	S	Large only	L	M	S
Ref.Table		C.6 a and b	C.25	C.41	C.12	C.17	C.33	C.49
S_a/f_t	S_a							
0.225	15 600	3 700	4 920	14 000	24 500	1 390 000+	139 000	340 000+
0.15	10 400	30 500	35 300	27 600	34 200	650 000+	550 000+	935 000+
0.10	6 940	48 500	41 800	66 700	119 000	485 000	272 000	1 700 000+
0.075	5 200	135 000+	74 500	380 000+	238 000+	660 000+	298 000	2 180 000+

TABLE 5.2 0.8°/o INTERFERENCE FIT - PIN LOADED

S_m/f_t = 0.50, 0.40 and 0.25 combined

d/D = 1/4 and 1/2 Large, Medium and Small Specimens

Geometry		d/D = 1/4			d/D=3/8	d/D = 1/2		
Size		L	M	S	-	L	M	S
Ref.Table		C.7	C.26	C.42	NO RESULTS	C.18	C.34	C.50
S_a/f_t	S_a							
0.225	15 600	12 000	8 200	14 800		1 467 000+	656 000+	5 000 000+
0.15	10 400	98 500	30 000	32 000		3 426 000+	4 450 000+	13 400 000+
0.10	6 900	159 500	68 000	63 600		6 536 000+	9 810 000+	14 450 000+
0.075	5 200	-	197 000	103 500		-	-	17 000 000+

+signifies at least ONE of the specimens was UNBROKEN.

TABLE 5.3 COMPARISON WITH RAeS DATA SHEET A.05.02 (ISSUE 2) (Ref.Fig 5.10)

0.4°/o INTERFERENCE FIT PIN - PIN UNLOADED

d/D = 1/4

S_m/f_t	S_a/f_t	Predicted $N/10^6$ cycles		Compare with Fig. Ref in Appendix C		
		Method (a)	Method (b)	L	M	S
0.50	0.225 0.15 0.10 0.075	0.024 0.09 0.27 1.10	0.058 0.145 0.40 2.5	C.3	C.22	C.28
0.25	0.225 0.15 0.10 0.075	0.15 1.0 20.0 >100	0.35 10.0 >100 >100	C.3	C.22	C.28

TABLE 5.4 COMPARISON WITH RAeS DATA SHEET A.05.02 (ISSUE 2) (Ref.Fig 5.11)

0.4°/o INTERFERENCE FIT PIN - PIN UNLOADED

d/D = 1/2

S_m/f_t	S_a/f_t	Predicted $N/10^6$ cycles		Compare with Fig. Ref in Appendix C		
		Method (a)	Method (b)	L	M	S
0.50	0.225 0.15 0.10 0.075	0.055 0.16 0.70 2.3	0.088 0.24 1.25 10	C.15	C.31	C.47
0.25	0.225 0.15 0.10 0.075	0.75 5.5 >100 >100	1.10 10 >100 >100	C.15	C.31	C.47

TABLE 5.5 COMPARISON WITH RAeS DATA SHEET A.05.02 (ISSUE 2) (Ref.Fig 5.12)

0.4°/o INTERFERENCE FIT PIN - PIN LOADED

d/D = 1/4

S_m/f_t	S_a/f_t	Predicted $N/10^6$ cycles		Compare with Fig.Ref in Appendix C		
		Method (a)	Method (b)	L	M	S
0.50	0.225 0.15 0.10 0.075	0.005 0.02 0.065 0.14	0.009 0.026 0.075 0.15	C.6	C.25	C.41
0.25	0.225 0.15 0.10 0.075	0.018 0.065 0.20 0.55	0.027 0.072 0.225 0.55	C.6	C.25	C.41
0.15	0.15 0.125 0.10 0.075 0.05	0.30 1.20 3.00 20.0 >100	0.30 1.0 10.0 >100 >100	C.6	C.25	C.41

TABLE 5.6 COMPARISON WITH RAeS DATA SHEET A.05.02 (ISSUE 2)(Ref.Fig 5.13)

0.4°/o INTERFERENCE FIT PIN - PIN LOADED

d/D = 1/2

S_m/f_t	S_a/f_t	Predicted $N/10^6$ cycles		Compare with Fig.Ref in Appendix C		
		Method (a)	Method (b)	L	M	S
0.50	0.225 0.15 0.10 0.075	0.075 0.20 1.0 4.0	0.075 0.20 0.85 5.0	C.17	C.33	C.49
0.25	0.225 0.15 0.10 0.075	1.0 6.0 >100 >100	1.0 100 >100 >100	C.17	C.33	C.49

NB

There are no Bolted Joint Fatigue Research test results at $S_m/f_t = 0.15$ and $d/D = 1/2$ with which to compare predictions. In any case the predictions would be at $N > 10^8$ cycles.

Fig. 5.1 Comparison of Test Results with Fig. 3 of RAeS Data Sheet E 02.01

Ref: Fig. 4.38 & Table 4.3

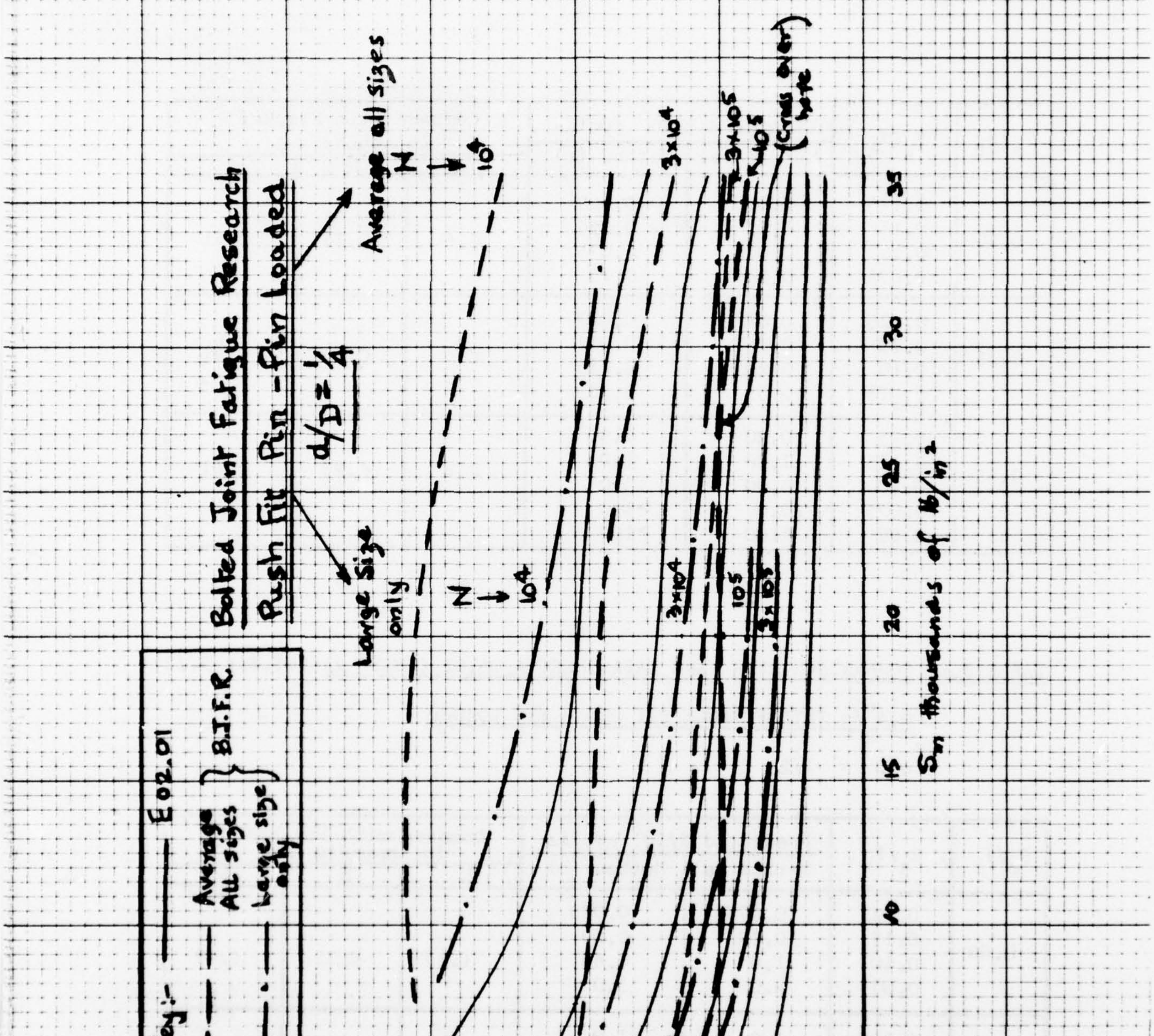


FIG. 5.2 COMPARISON OF TEST RESULTS WITH RAeS. DATA SHEET E05.01

(TEST RESULTS FOR PUSH FIT PIN – PIN LOADED $d/D = 1/4, 3/8 \& 1/2$)

(S_m/f_t 0·25, 0·20 & 0·15 COMBINED)

Ref. Para. 5.3

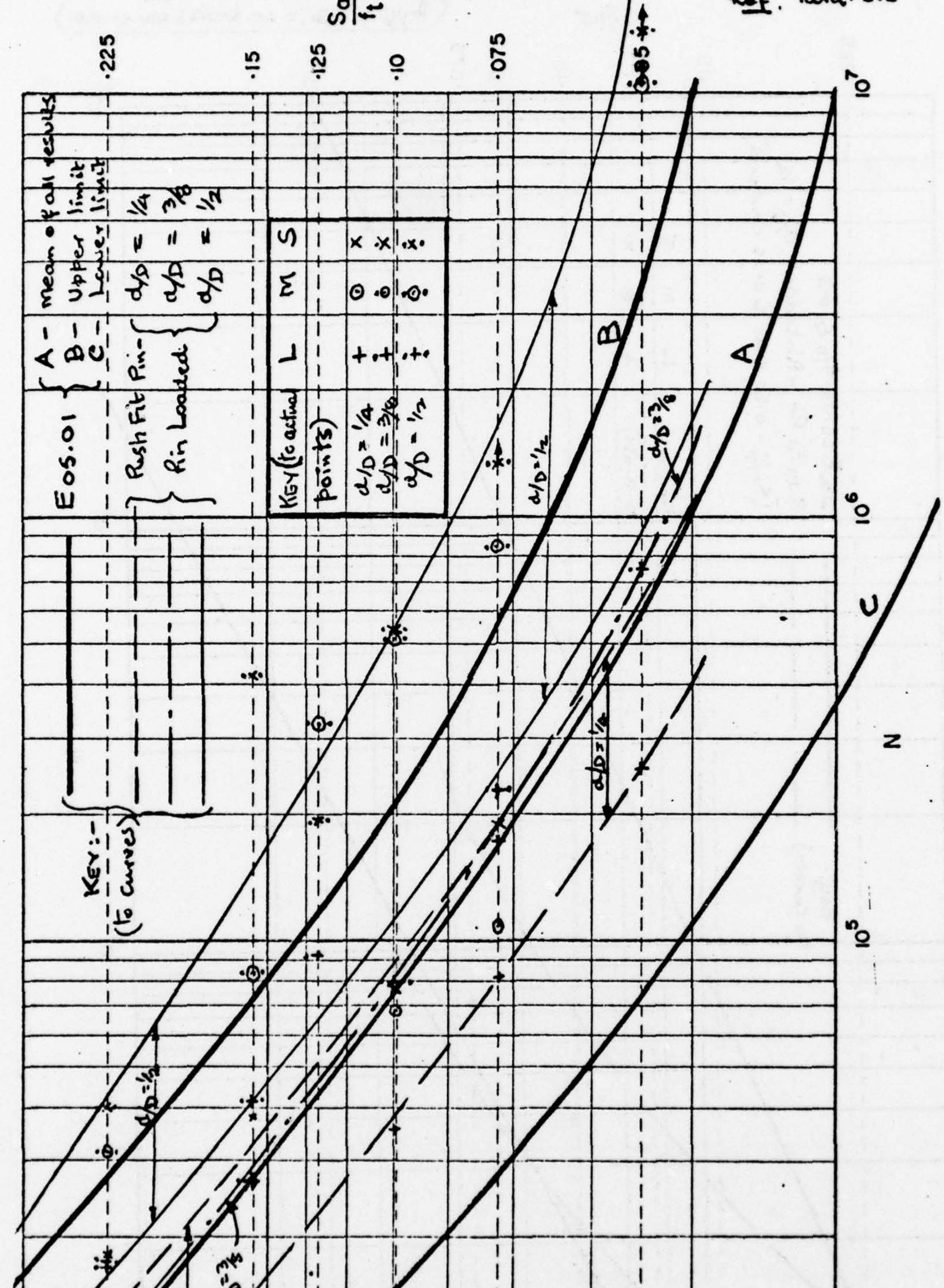


Fig 5.3. Comparison of Test Results with RAeS. Data Sheet E 05.03

Ref: Table 4.11

(Test Results for Push Fit Pin – Pin Loaded, $d/D = 1/4$)

(S_m/f_t = 0.50, 0.40 & 0.25 combined)

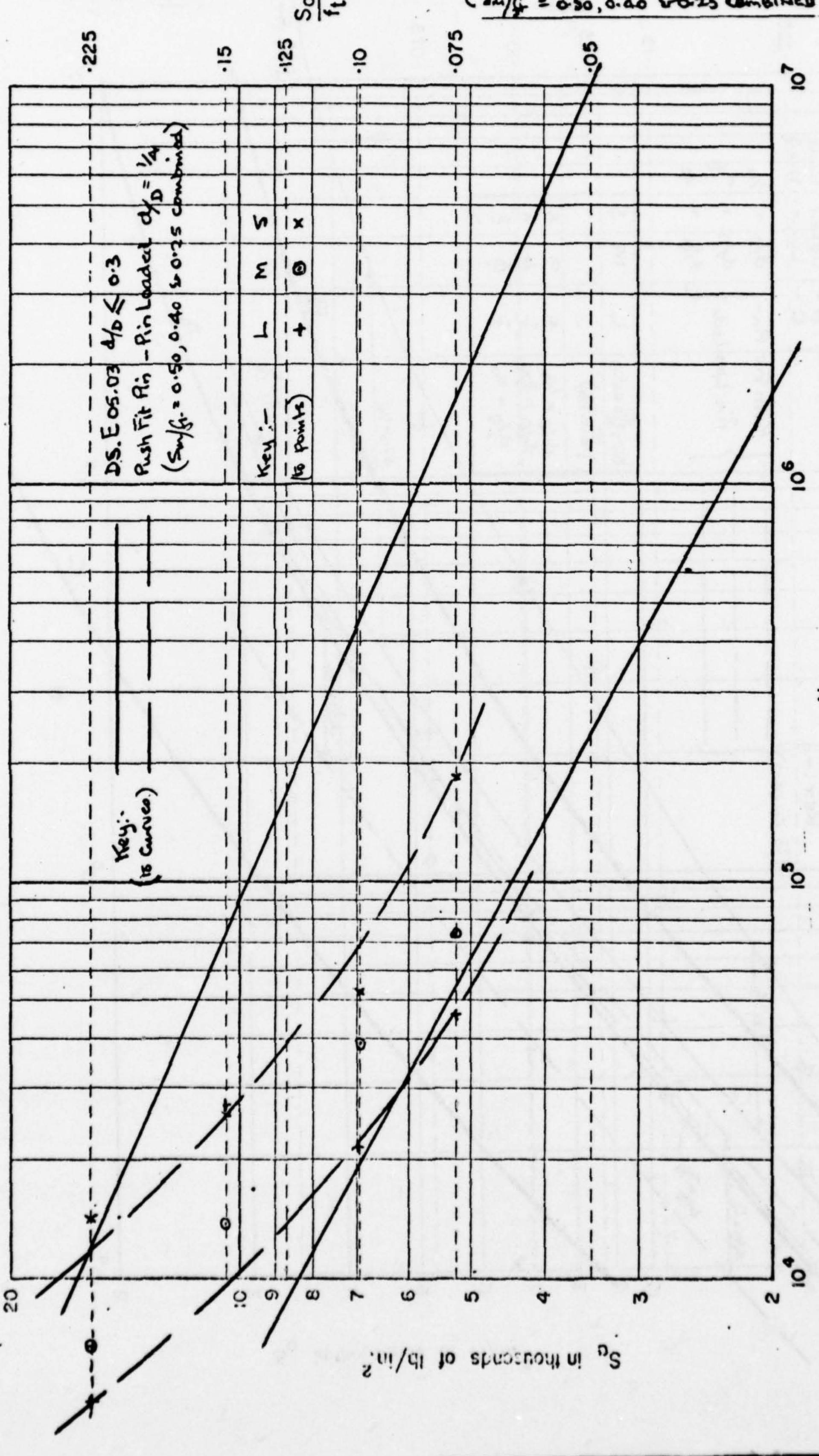


FIG 5.4 COMPARISON OF TEST RESULTS WITH RAeS DATA SHEET E05.03

Ref: Table 4.11

(TEST RESULTS FOR PUSH FIT PIN – PIN LOADED. d/D = 3/8)

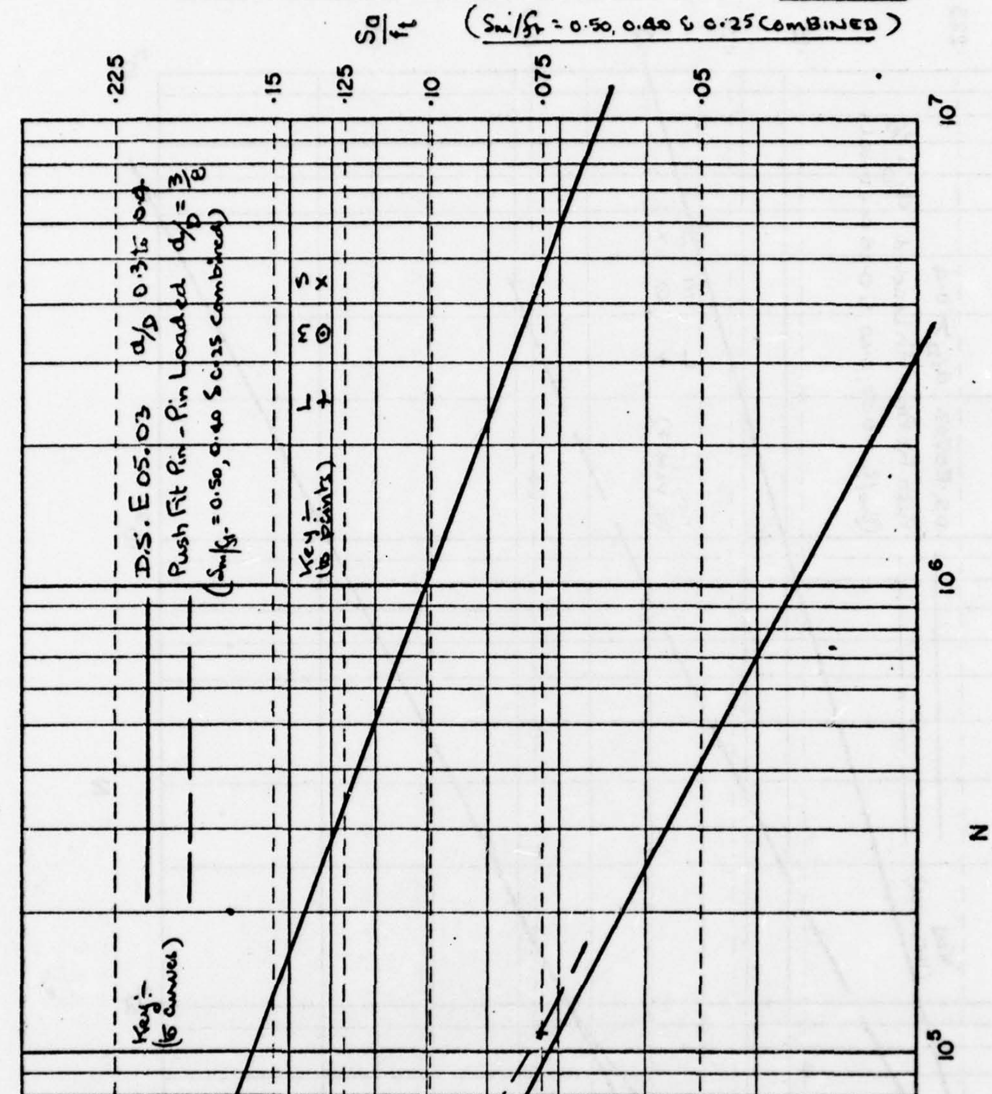


FIG 5.5 COMPARISON OF TEST RESULTS WITH RAeS DATA SHEET E05.03

Refr Table 4.11

(TEST RESULTS FOR PUSH FIT PIN – PIN LOADED, $d/D = 1/2$)

(S_m/f_t = 0.50, 0.40 & 0.25 COMBINED)

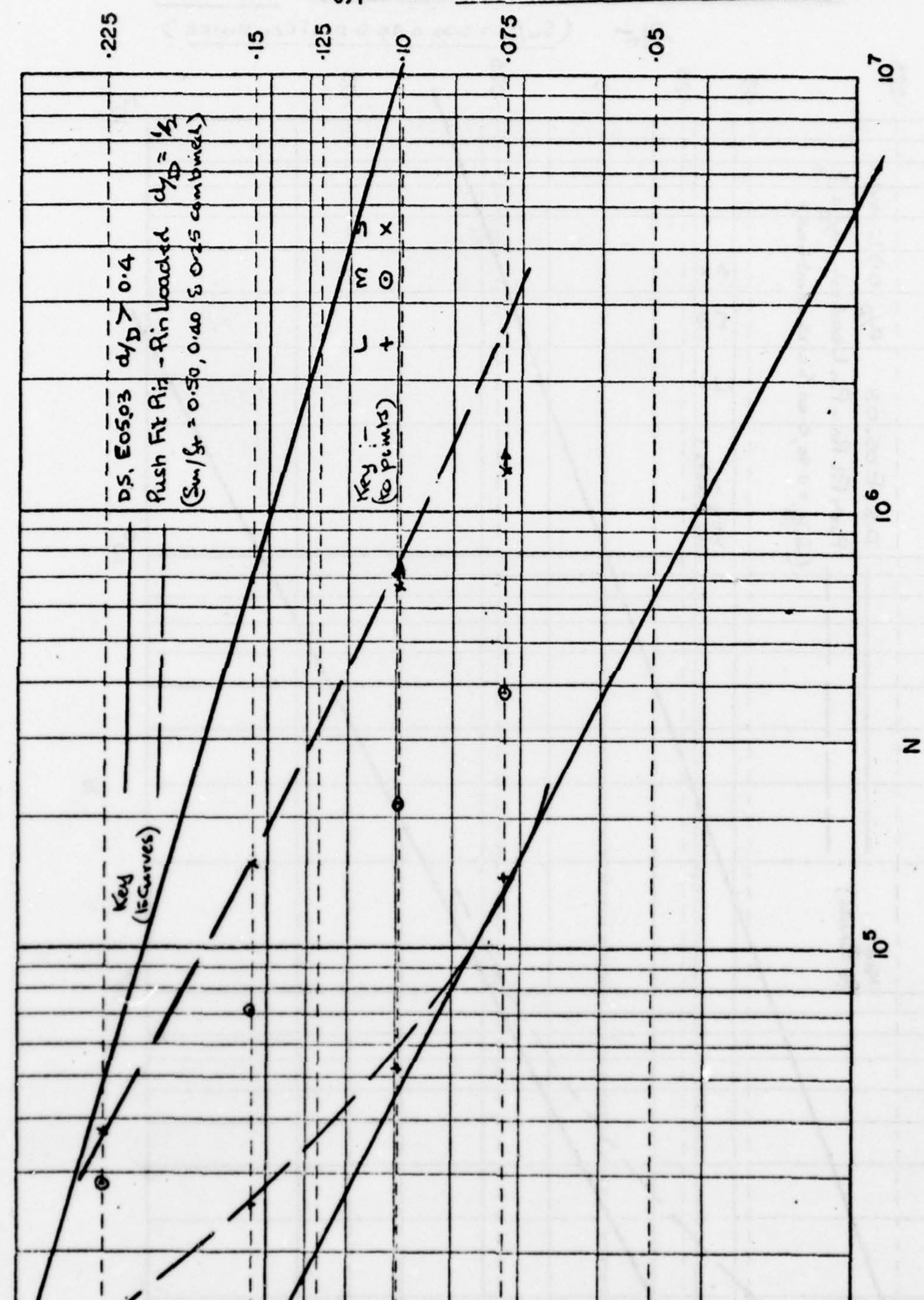


FIG. 5.6 COMPARISON OF TEST RESULTS FOR PUSH FIT PIN - PIN LOADED WITH FIGURE 4 OF DATA ITEM 72020 USING FIG 4.46 OF SECTION 4.

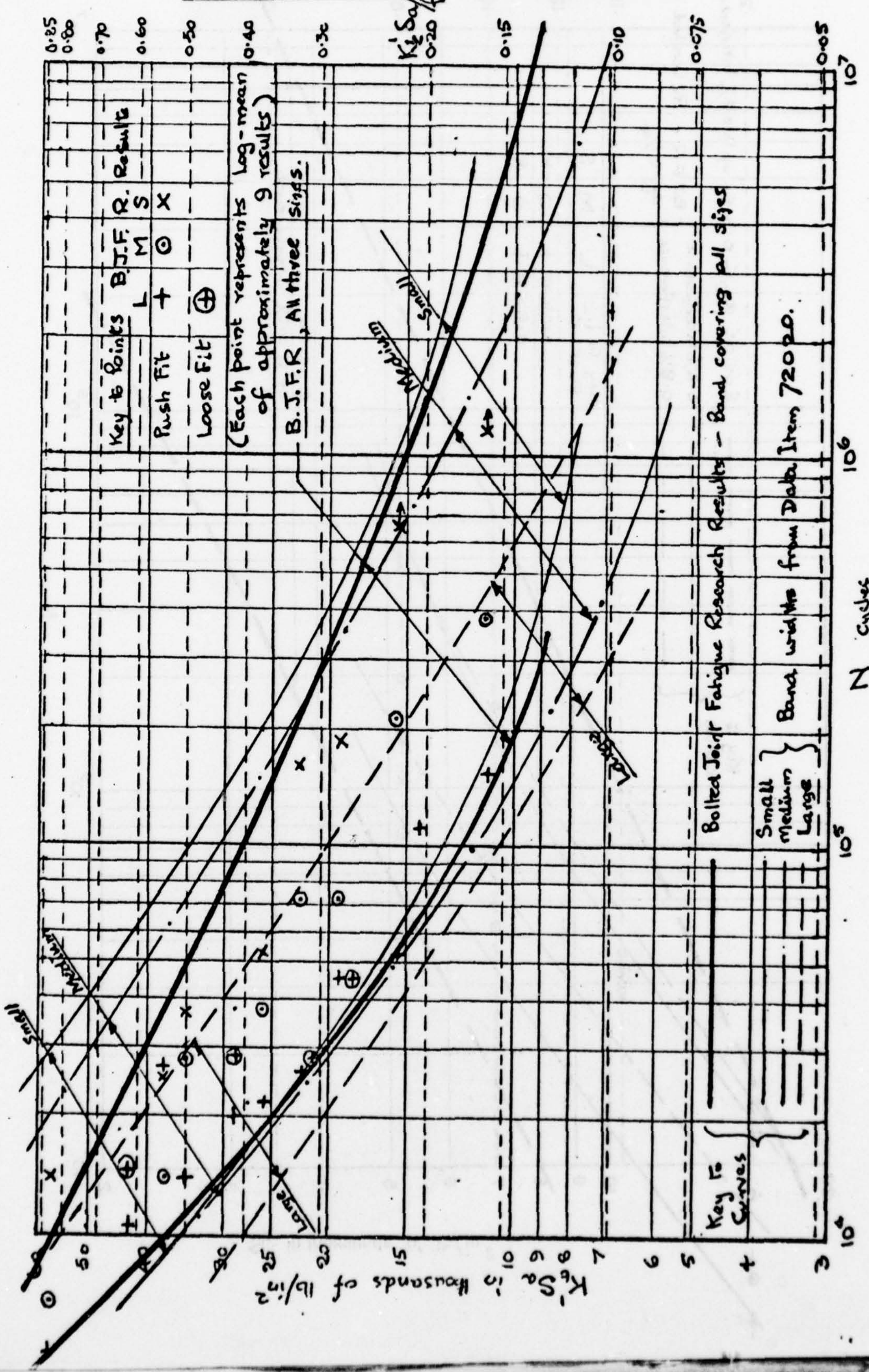


FIG 5.7 COMPARISON OF TEST RESULTS WITH RAeS DATA SHEET E05.04

Ref:- TABLES 5.1 & 5.2

(TEST RESULTS FOR 0.4% & 0.8% INTERFERENCE FIT PIN-PIN LOADED)
(d/D = 1/4 - S_m/f_t 0.50, 0.40 & 0.25 f_t COMBINED)

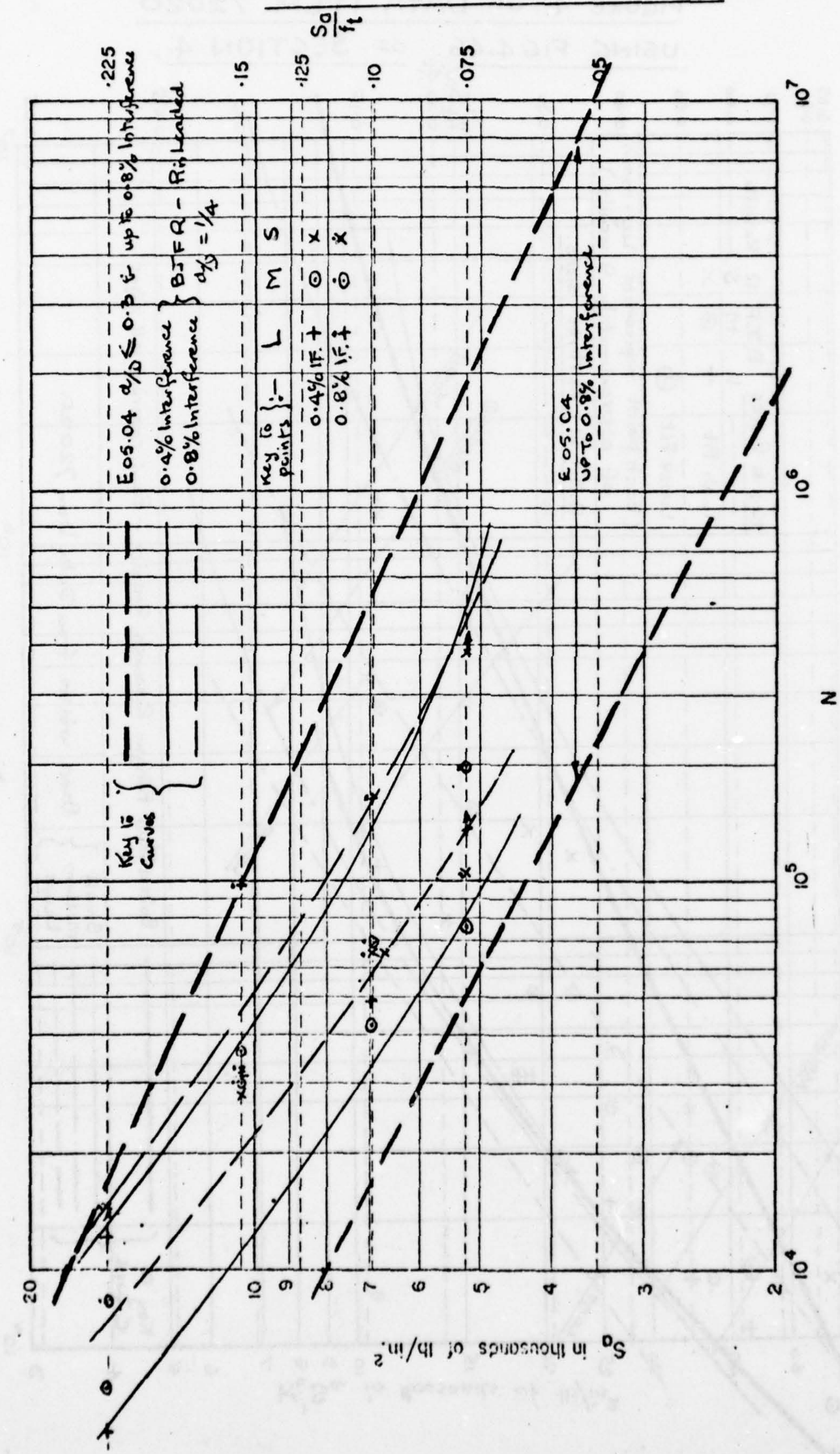
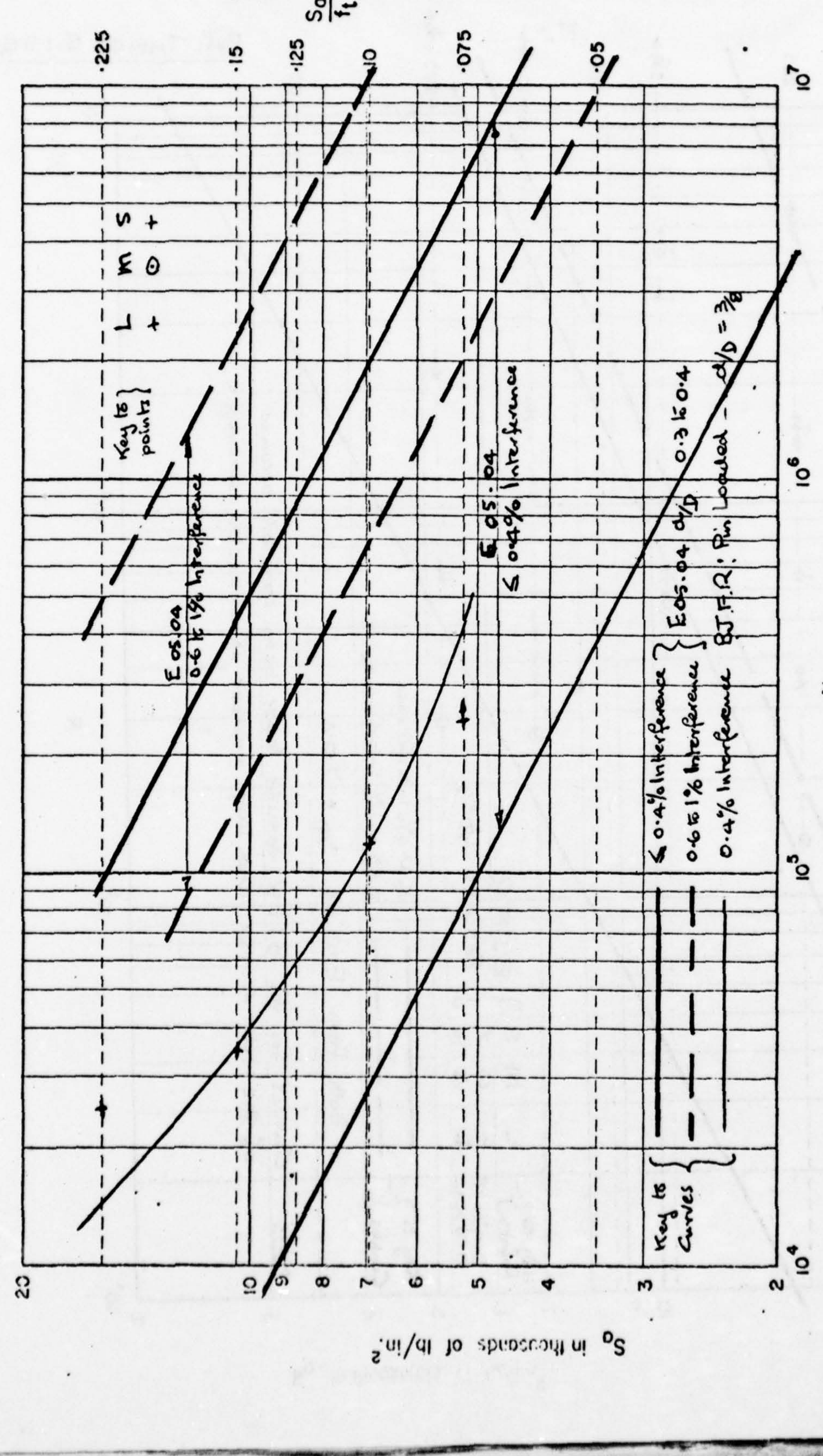


FIG 5.8 COMPARISON OF TEST RESULTS WITH RAeS DATA SHEET E05.04 Ref: Table 5.1

(TEST RESULTS FOR 0·4% INTERFERENCE FIT PIN – PIN LOADED)
(d/D = 3/8 – Sm/ft 0·50, 0·40 & 0·25 COMBINED)



136 FIG. 5.9 COMPARISON OF THE TEST RESULTS WITH RAeS. DATA SHEET E 05. 04

TEST RESULTS FOR 0·4% & 0·8% INTERFERENCE FIT PIN - PIN LOADED

$d/D = 1/2$ S_m/f_t = 0·50, 0·40 & 0·25 COMBINED

Ref: TABLES 5.1 & 5.2

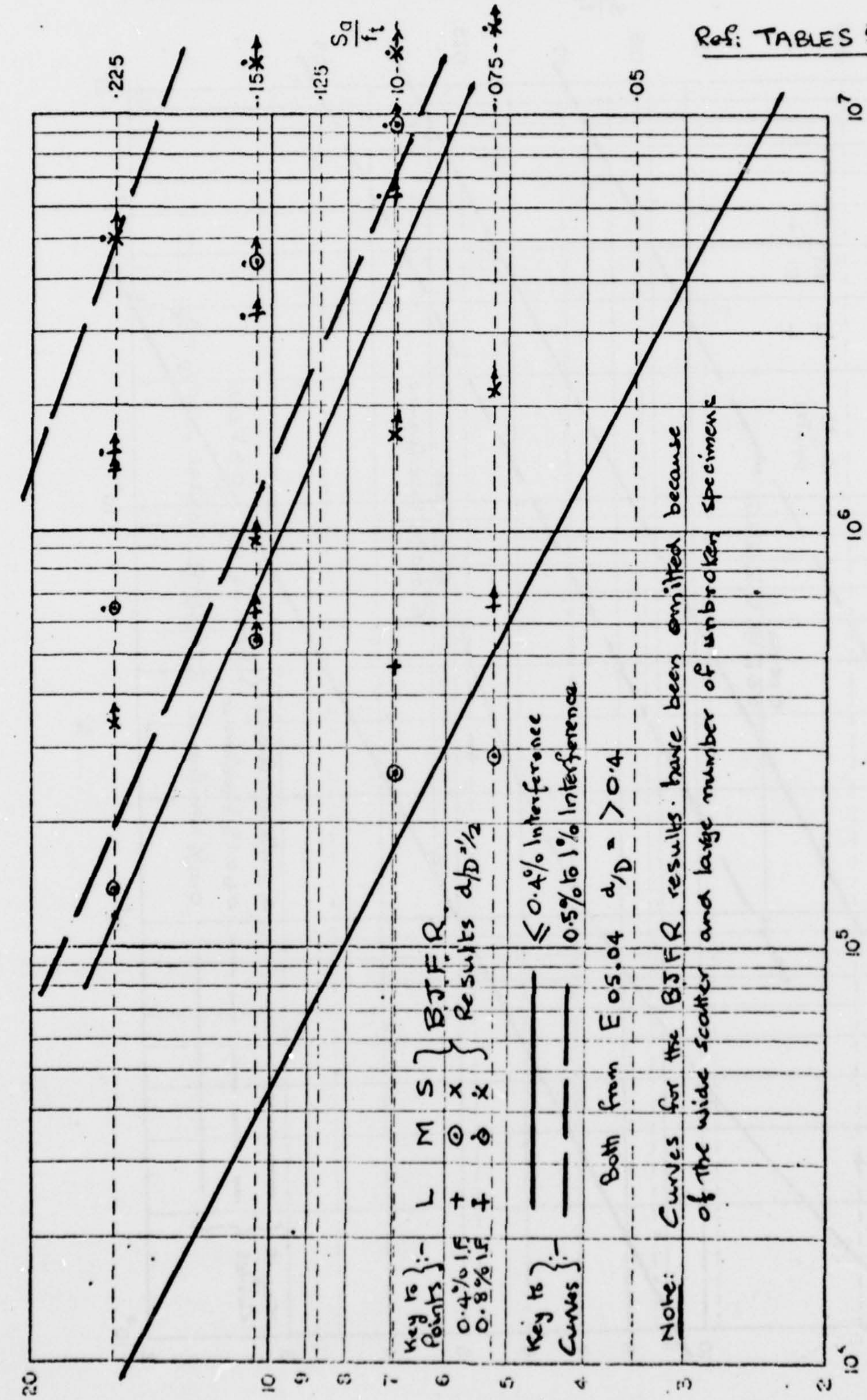


FIG. 5.10 COMPARISONS WITH RAeS DATA SHEET A05.02 (ISSUE 2)

0·4% INTERFERENCE FIT – PIN UNLOADED

d/D = 1/4

Sm/ft 0.50 & 0.25

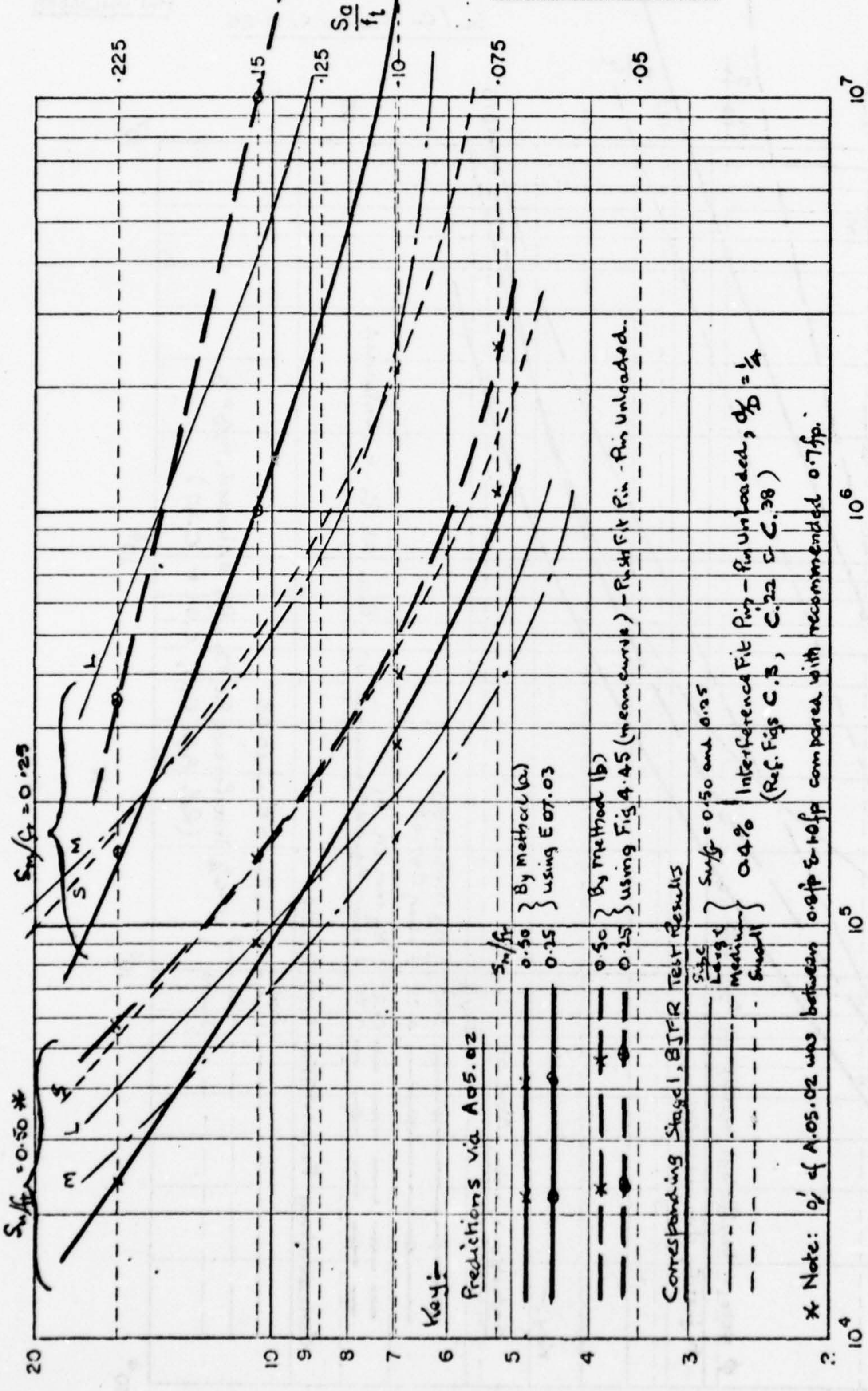


FIG 5.11

COMPARISONS WITH RAeS DATA SHEET A05.02 (ISSUE 2)

$d/D = 1/2$ 0.4% INTERFERENCE FIT PIN PIN UNLOADED

$S_m/f_t = 0.50$ & 0.25

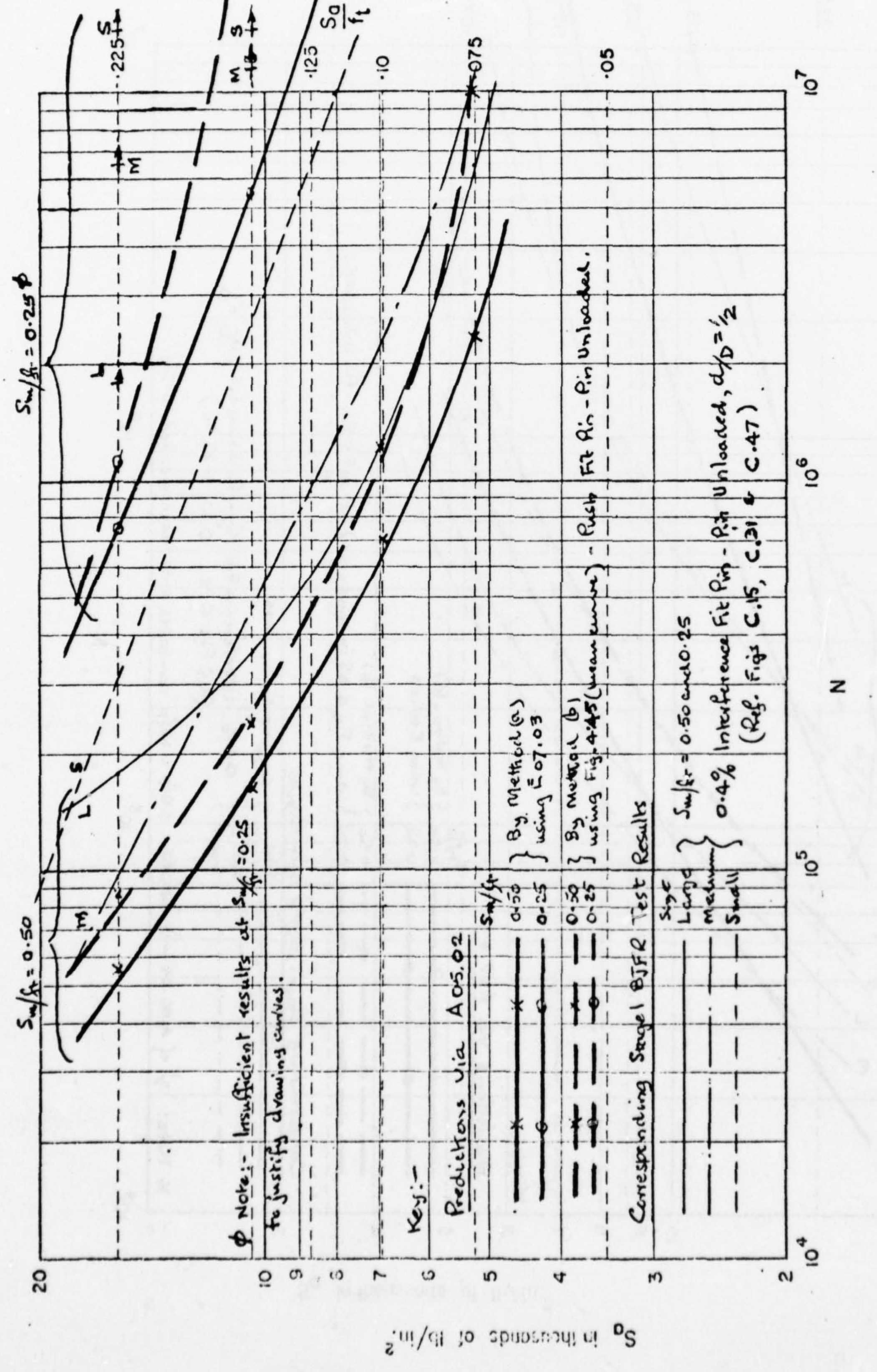


FIG. 5.12 COMPARISONS WITH RAeS DATA SHEET A05.02 (ISSUE 2)

0.4% INTERFERENCE FIT — PIN LOADED $d/D = 1/4$

$S_m/f_t = 0.50,\ 0.25\ \&\ 0.15$

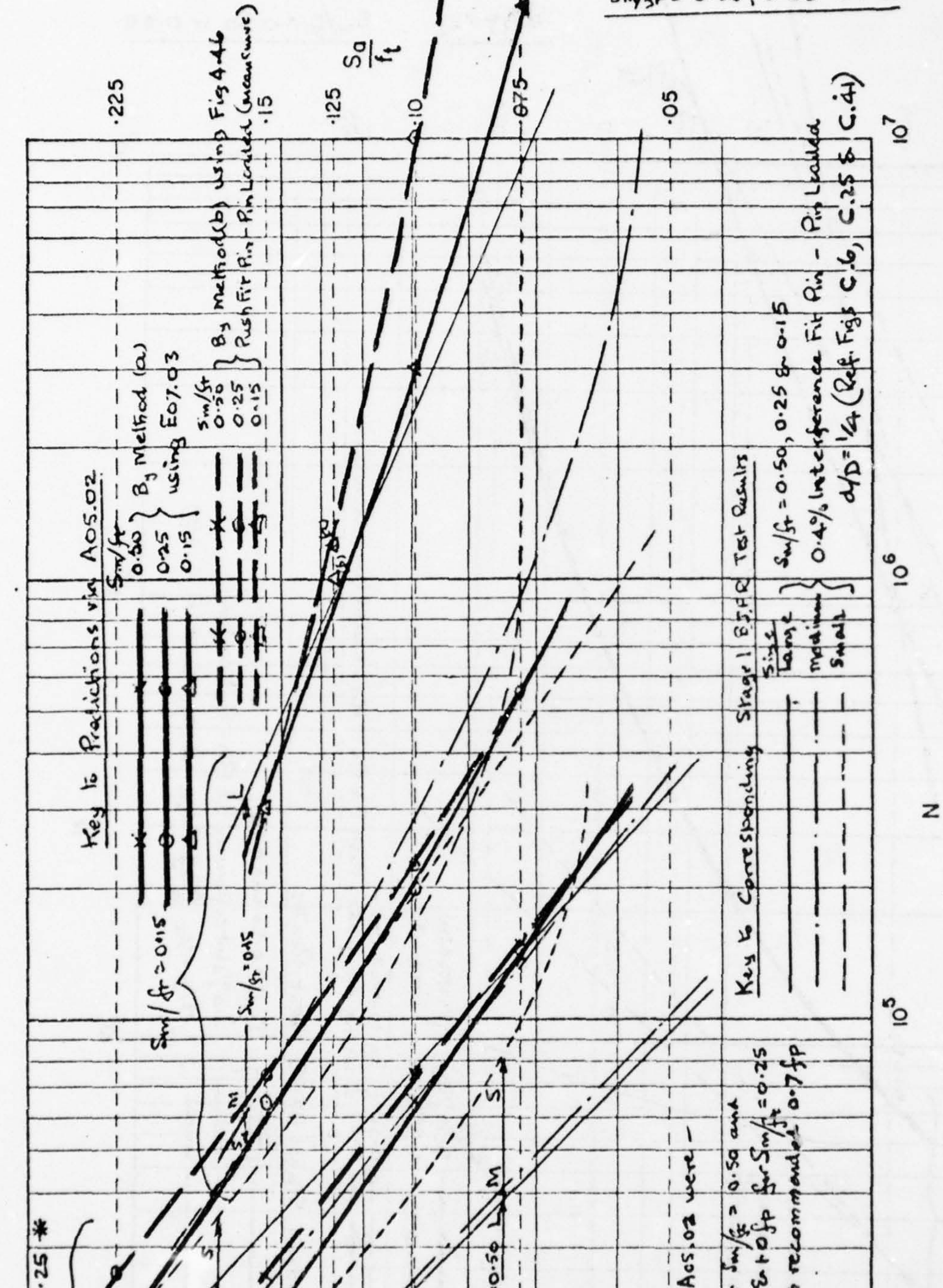
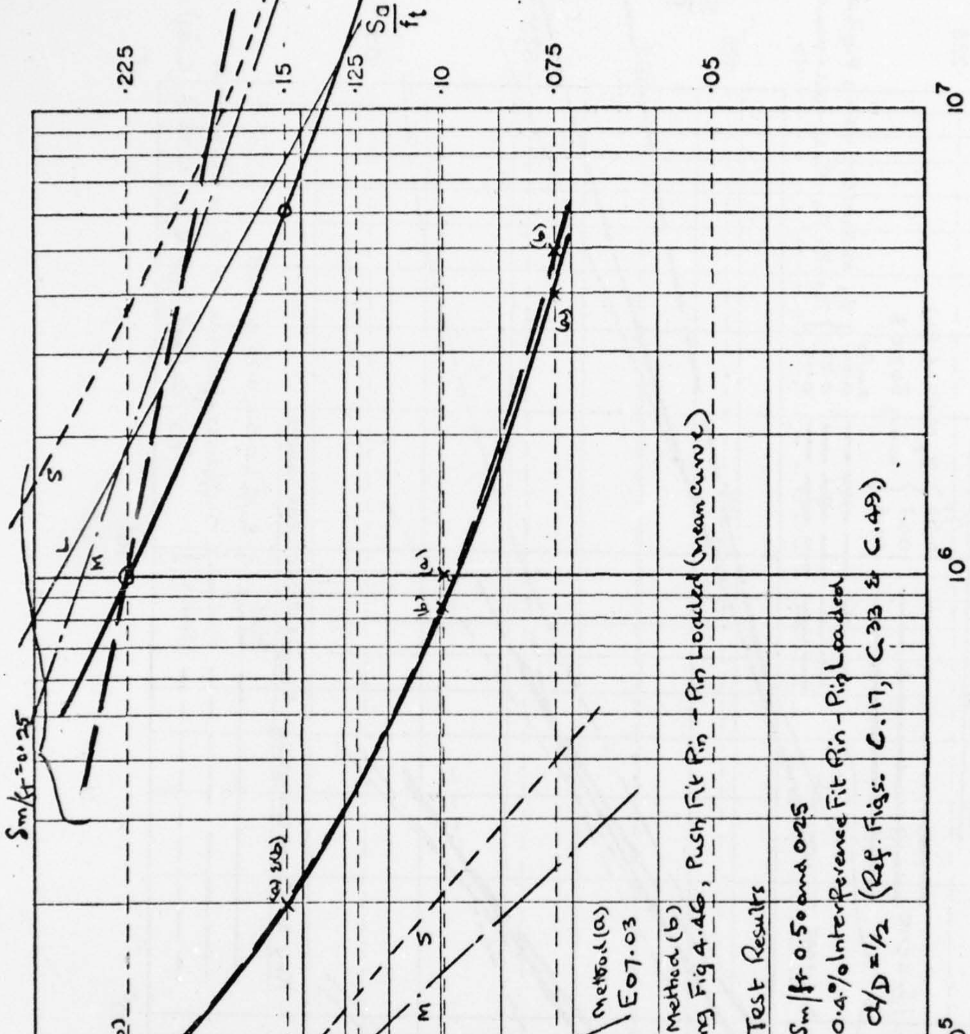


FIG. 5.13.

COMPARISONS WITH RAeS DATA SHEET A05.02 (ISSUE 2)

0.4% INTERFERENCE FIT – PIN LOADED

$d/D = 1/2$ $S_m/f_t = 0.50$ & 0.25



SECTION 6 CONCLUSIONS

6.1 General

When this programme of research was planned, the limits laid down for the manufacture of the specimens were considered to be fairly close, but not extreme by the current standards. The close limits were considered to be necessary in order to minimise the scatter of results and to give a reasonable chance of detecting the influences of the numerous variables included in the programme. A study of the results now available fully justifies this provision.

Despite this provision, it is clear that there is still a significant and sometimes considerable scatter of endurance of nominally identical parts, the magnitude of which can be observed from the tables and graphs of Appendix C. Frequently this scatter causes overlapping of the scatter bands representing related configurations, or representing increments in the value of a given parameter, and may tend to confuse conclusions.

For this reason, much of the analysis in this report has been made by using mean endurance curves rather than scatter bands, and it is felt that the results achieved have justified the procedure adopted, provided that the existence of the scatter and its possible range for a specified set of conditions are kept in mind constantly. The range of the scatter is greatest at low alternating stresses and/or high d/D, and lowest when the alternating stresses are high and/or d/D is low. It can be as low as the equivalent of a scatter of 1.25:1 between the mean and the minimum endurances, or as high as the equivalent of a scatter factor of 10:1 between the mean and the minimum endurances. However, more normal scatter factors (mean to minimum endurances) for a given configuration and loading are of the order of 3:1 for high alternating stress and 5:1 for low alternating stress.

Throughout this research it has often been evident that the influence of one parameter is combined with that of another, and assumptions have had to be made in order to eliminate, at least partially, one variable, in order to examine another. Similarly the variety of configurations (degree of pin fit and type of loading) have complicated the analysis. On balance it is considered that the optimum order in which to discuss these matters is to deal with the parameters of mean stress, size and geometry (K'_t) first and then to discuss the configurations.

6.2 Effect of Mean Stress (Ref.paragraph 4.10 and Figures 4.34 to 4.43 inclusive)

In normal configurations, i.e. excluding pins with interference fit, in the regions of high stress concentration, the material is sufficiently ductile to enable plastic flow to occur which reduces the maximum local stress from the theoretical figure to a value approximating to f_p, the 0.2°/o proof stress. Therefore $K'_t\ (S_m + S_a)$ is reduced to f_p locally.

The effect of mean stress is thereby reduced and is virtually negligible above an applied mean stress of approximately $0.20\ f_t$. This enables all results except those for $S_m/f_t = 0.15$ or less to be grouped together into one population (for a given size and configuration), thus simplifying analysis.

As S_m is reduced below $0.20\ f_t$ there is a gradual increase in endurance for a given alternating stress; alternatively, there is an increase in alternating stress for a given endurance. (The present research has not produced enough evidence to warrant a more precise conclusion).

The foregoing behaviour is modified when interference fit pins are used. In these circumstances it would appear that endurance is inversely proportional to the applied mean stress over the whole range of the tests, except that for very high endurances (above 10^6 cycles) and $d/D = 1/4$ (i.e. high K'_t) there is a slight trend towards the reduction of mean stress influence, though not to the same degree as for normal configurations.

6.3 Effect of Size (Reference paragraph 4.11 and Tables 4.7 and 4.8)

The range of size covered by the Bolted Joint Fatigue Research was limited to 2.67:1.0 and the conclusions concerning this effect do not necessarily apply to changes of size which are markedly beyond this range.

The size effect from these tests is not large, but is of some significance. The smaller the size of specimen, other variables being kept constant, the more favourable becomes the fatigue performance. There are two ways of expressing the relative performances.

(a) As a ratio of endurances for a given alternating stress

and

(b) as a ratio of alternating stresses for a given endurance.

Because of the general shape of the endurance curves, (a) tends to be more reliable at low endurances and (b) tends to be more reliable at high endurances. However, method (b) gives more consistent comparisons over the full range of tests (see Table 4.8). These comparisons lead to the conclusion that there is an increase in permissible alternating stress for a given endurance, ranging from a factor of 1.1 to 2.0, for a reduction in size in the ratio of 1:2.67. The configuration of an unfilled hole lies strongly towards the lower end of this range, while the push fit pin tends to lie towards the upper end of the range. Interference fit pin joints show factors near the middle of the range.

This size effect expressed as a ratio of alternating stresses for a given endurance can be regarded as a ratio of stress concentration factors - a reduction of factor for a reduction of size.

Size effect is somewhat less at $d/D = 1/4$ compared with that at $d/D = 1/2$, possibly due to the higher stress concentration factor at $d/D = 1/4$.

6.4 Effect of Geometry (Reference paragraph 4.12, Figures 4.1 to 4.33)

For the purposes of this report, "geometry" signifies a change in the ratio of d/D, which in turn is expressed adequately as a change in the value of K'_t.

For unfilled holes and unloaded push fit pins, geometry has but little influence. For the other configurations there is a significant effect, there being a definite increase in endurance for an increase in d/D (i.e. for a reduction of stress concentration factor).

For convenience the ratios of increase of endurance for increase of d/D from 1/4 to 1/2 are repeated here (and taken from paragraphs 4.12.3, 4.12.4 and 4.12.5).

Data are given for two convenient values of S_a/f_t namely 0.20 and 0.08, i.e. high and low in the context of this programme of tests.

Because of scatter, it is necessary to quote ranges of these endurance ratios. For the push fit pins, because change of mean stress has but little effect, only one range for a given S_a/f_t is quoted, although the higher ratios in the range tend to apply to the lower values of S_m/f_t. Size effect has been eliminated from these figures.

For the interference fit pins separate ranges are given for each value of S_a/f_t.

EFFECT OF GEOMETRY IN TERMS OF:		Range of Endurance for Increase Ratio for $d/D = 1/2$ / $d/D = 1/4$
S_a/f_t	S_m/f_t	
6.4.1 Push Fit Pin - Pin Loaded		
0.20	0.50 to 0.25	2 to 5
0.08	0.50 to 0.25	4 to 10

6.4.2 0.4°/o Interference Fit Pin - Pin Unloaded

0.20	0.50	4 to 6
	0.40	5 to 50
	0.25	40 to 50
0.08	0.50	10 to 25
	0.40	10 to 60
	0.25	50 to 100

6.4.3 0.4°/o Interference Fit Pin - Pin Loaded

0.20	0.50	3 to 12
	0.40	10 to 60
	0.25	150 to 250
0.80	0.50	2.5 to 5.5
	0.40	14 to 65
	0.25	200 to 500

NB

There are insufficient results to enable reliable endurance increase ratios to be obtained for 0.8°/o interference fit, but they are certainly greater than those for 0.4°/o interference fit and probably of the order of 50°/o greater.

6.5 Unfilled Hole, Loose Fit and Push Fit Pin, Loaded and Unloaded

(Reference paragraph 4.13 and Figure 4.47)

Relative Endurances

Having considered the influence of parameters applicable to all configurations it is now convenient to compare the configurations themselves, and in so doing it has been established that they fall into two groups - those without and those with interference fit pins.

Considering the first group and studying Figure 4.47, coupled with Figures 4.44, 4.45 and 4.46, it is clear that the endurance bands for each of these configurations can justifiably be embraced by one rather broad scatter band, if plotted in terms of $K'_t S_a$ instead of S_a, using average values for the range of mean stresses from 0.25 f_t to 0.50 f_t. The effect of size is also included in this broad band.

Figure 4.47 also shows some computed mean endurance curves for notched specimens ($K'_t S_a$ versus N) derived from the basic data of Data Sheet E.07.01 (Figure 3) coupled with the theoretical relationship given in Data Sheet A.00.02.

These curves are slightly sensitive to the choice of f_p and m and three such choices are given.

In comparing the computed endurance curves with the boundary endurance curves (or with the mean curves) of the broad scatter bands, it appears that the computed curves have less slope than the boundary curves. This general difference is probably due to the effect of fretting. Taking curve (3) as a representative computed curve, a factor of 1.25 on K'_t at an endurance of 10^6 cycles reducing to 1.0 at 10^4 cycles would change this to curve (3a) and bring it into line with the common slope of the endurance of the test results. Allowing for scatter about the mean values the factor of 1.25 could well be 1.5. This is not as large a factor for fretting at high endurances as might have been expected. (See also paragraph 4.13.3 (iii)).

Turning to the finer differences between one configuration and another in this group, they are briefly represented by the following table of relative endurances of the mean curves of Figures 4.44, 4.45 and 4.46, taken at two levels of alternating stress (Reference paragraph 4.13.3 (ii)).

	Relative Endurances		
$K'_t S_a / f_t$	Unfilled Hole	Push Fit Pin Pin Unloaded	Push Fit Pin Pin Loaded
0.60 0.24	1.0 1.0	2.0 1.5	0.9 0.9

Thus under otherwise similar conditions the unloaded push fit pin gives endurances of from 1.5 to 2.0 times those for an unfilled hole while a loaded push fit pin gives endurances which are marginally below those for an unfilled hole.

6.6 0.4°/o and 0.8°/o Interference Fit Pins, Loaded and Unloaded

(Reference paragraphs 4.9.1 and 4.9.2)

There is a significant gain in endurance for an interference fit pin compared with that of the corresponding joint with a push fit pin, because of the induced tensile stress in the material surrounding the pin which effectively reduces the applied alternating stress.

Joints with 0.8°/o interference fit pins are not always much superior in endurance to those of 0.4°/o interference fit pins, especially under high loading because the plastic deformation in the regions of high stress, which reduces the effective mean stress, also reduces the degree of interference.

The influence of mean stress, size and d/D have already been discussed and in general the effects of these parameters are more marked with interference fit pins than with push fit pins. There is also more scatter of results at long endurances compared with that for push fit pins.

The improvement in endurance is considerably greater for d/D = 1/2, than for d/D = 1/4, when comparing interference fit pin joints with push fit pin joints and also when comparing 0.8°/o interference fits with 0.4°/o interference fits.

The results for interference fit pins are not amenable to the same form of Summary Presentation as were the normal configurations because of the effect of applied load on the resultant stress concentration factor.

It is therefore appropriate to consider the values of the Endurance Increase Ratio, i.e. the ratios of actual endurances of interference fit pin joints to the endurances of the corresponding push fit pins. Here it is necessary to quote ranges for these ratios because of the scatter, and although this was at first examined for each values of S_m/f_t, it became clear that there was not a great deal of difference in the ratios with change of S_m/f_t. The highest factors were usually associated with the lowest values of mean stress. Therefore, in the interest of simplification one range is given for each value of S_a/f_t and d/D, which may be considered applicable to all values of mean stress. These are given in paragraphs 4.9.1 and 4.9.2 and for convenience are repeated here.

$$\text{ENDURANCE INCREASE RATIO} = \frac{\text{Endurance of Interference Fit Pin Joint}}{\text{Endurance of Push Fit Pin Joint}}$$

Unloaded Pins

For 0.4°/o Interference Fit

S_a/f_t	d/D = 1/4	d/D = 1/2
0.20	3/4 to 6	7 to 100*
0.08	3/4 to 9	10 to 100*

For 0.8°/o Interference Fit

S_a/f_t	d/D = 1/4	d/D = 1/2
0.20	4 to 10	Insufficient
0.08	5 to 10	results

Loaded Pins

For 0.4°/o Interference Fit

S_a/f_t	d/D = 1/4	d/D = 1/2
0.20	3/4 to 3	2 to 100*
0.08	3/4 to 3	2 to 100*

*Based on limited evidence.

For 0.8°/o Interference Fit

S_a/f_t	d/D = 1/4	d/D = 1/2
0.20	1 to 5	7 to 100*
0.08	1 to 15	20 to 100*

It is also of interest to consider the comparison between 0.4°/o interference and 0.8°/o interference.

Endurance Increase Ratios for 0.8°/o interference/0.4°/o interference have been evaluated for each level of mean stress (where sufficient data are available), for unloaded pins at d/D = 1/4, and for loaded pins at both d/D = 1/4 and d/D = 1/2. Two levels of S_a/f_t have been considered as before. There is no significant difference in the range of ratios evaluated at the various mean stresses and therefore a common range applicable to all mean stresses is quoted.

The results are as follows:

$$\text{ENDURANCE INCREASE RATIO} = \frac{\text{Endurance of 0.8°/o Interference Fit Pin Joint}}{\text{Endurance of 0.4°/o Interference Fit Pin Joint}}$$

Unloaded Pins — d/D = 1/4 only

S_a/f_t	
0.20	2 to 7
0.08	2 to 10

(Ratios for d/D = 1/2 would probably be of the same order as for loaded pins at d/D = 1/2 - see below)

S_a/f_t	d/D = 1/4	d/D = 1/2
0.20	1 to 2	4 to 50*
0.08	1 to 5	10 to 100*

6.7 Occurrence of Fretting (Reference paragraph 4.15)

Fretting occurred in a considerable number of specimens and in all configurations, except of course the unfilled hole configuration. A representative selection was examined by the National Engineering Laboratory, in addition to those examined and photographed by the testing laboratories. The former are listed in Table 4.12, and are also indicated in the tables of results in Appendix C.

The study of these fretted specimens showed that there was only a little coordination between fretting and stress level, inasmuch as there were somewhat more specimens with fretting at combinations of low mean and low

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*Based on limited evidence.

alternating stress. For a given mean and alternating stress level specimens exhibiting fretting were often not those with the lowest endurance.

In regard to d/D there were more fretted specimens at d/D = 1/4 than at d/D = 1/2, roughly in the ratio of 3 to 1.

There was less fretting in the small size specimens.

In regard to configurations, as was expected, there was only minor fretting with the unloaded loose and push fit pins, and the majority of the fractures occurred at the hole edge at 90° to the axis of tension.

For the unloaded interference fit pins some fretting occurred and the fretting bands tended to be symmetrically disposed at about 45° to the transverse centre line through the hole. The origins of fracture were at the edges of the fretting bands, and a little nearer to the transverse centre line.

Turning now to the loaded push fit pins, the fretting was more intense than with the unloaded pins, as would have been expected. The fretting was generally in bands at or near the transverse axis of the hole but generally towards the loaded side of the hole. Often there was more than one fracture, the fractures being disposed towards the loaded side of the hole.

It was a little surprising to find that fretting occurred in the $0.4^{\circ}/o$ and even in the $0.8^{\circ}/o$ interference fit specimens. This was located towards the unloaded side of the hole, possibly because the combination of interference and load had failed to prevent slip. Fractures were found between 10° and 45° from the transverse diameter, towards the unloaded side of the hole.

The fretting often caused the endurance curves to assume a steeper slope than would have occurred otherwise. These are discussed in paragraph 4.15.6.

From comparisons between test results and endurance curves which had been computed from basic fatigue data sheets it appears that the numerical effect of fretting in the tests of this research can be expressed as a reduction factor ranging from 1.15 to 1.5 on alternating stress for a given endurance, this factor applying mainly to endurances of the order of 3×10^5 and greater. This is somewhat less than was expected. (See also paragraphs 6.5 and 6.8).

6.8 Comparisons with Relevant RAeS Data Sheets and Consequent Recommendations

Comparisons have been made between the results of the tests described herein and the relevant data sheets — essentially those dealing with the fatigue endurance of aluminium alloys with and without pin joints.

No serious disagreements have been found. The understanding of a number of features of bolted joints has been clarified and information has been acquired which will enable several data sheets to be reinforced, extended or revised. This process is currently progressing and new issues being made as and when available.

The main conclusions from these comparisons are as follows:

6.8.1

Data Sheets E.02.01 and E.05.01 are well substantiated by the results of the present research.

6.8.2

Data Sheet E.05.03 has already been revised and extended by the inclusion of all the data on the loaded push fit pin joints of the present research, and re-issued as Data Item 72020.

6.8.3

Data Sheet E.05.04 (Endurance of Lugs with Interference Fit Pins) would be improved considerably by the inclusion of the relevant data from Bolted Joint Fatigue Research.

6.8.4

Data Sheets E.07.01 and E.07.02 give adequate basic data on plain and notched aluminium alloy material. When used in connection with bolted joints the possible influence of fretting should not be overlooked.

6.8.5

The effect of geometry and mode of loading are adequately represented by the stress concentration factors given in the current data sheets and endurances can be related to $K'_t S_m$ and $K'_t S_a$ in all instances.

6.8.6

Data Sheet E.07.03, coupled with the two data sheets A.00.01 and A.00.02 provide adequate information regarding the influence of mean stress provided that where stress concentrations occur allowance is made for the reduction in mean stress which results from plastic deformation in these regions.

It should be noted that in Data Sheet E.07.03 the resulting deductions from the families of curves therein are somewhat sensitive to the choice of the values of f_p/f_t and m.

For the present research the best values appear to be $f_p/f_t = 0.875$ and $m = 1.4$, but due allowance for fretting must be made.

Consideration might be given to an alternative presentation of the data in E.07.03 by plotting S_{ao}/f_t against $K'_t S_a/f_t$ from the relationship between these two quantities, given in Data Sheet A.00.02, assuming

$$S_{m'} = K'_t S_m \quad \text{when} \quad S_{a'} + K'_t S_m < f_p$$

$$\text{and } S_{m'} = f_p - S_{a'} \quad \text{when} \quad S_{a'} + K'_t S_m \geqslant f_p.$$

6.8.7

Data Sheet A.05.02 provides an adequate method of estimating the endurance of pin joints with interference fits provided that the combination of degree of interference and loading is moderate. Where this is not so the resultant maximum shear stress will exceed the recommended limit of applicability, namely, $q' \not> 0.7\ f_p$, and the validity of the curves given in Figure 1 of the data sheet becomes increasingly doubtful. Furthermore, the resulting predictions will tend to over-estimate the true endurances. Under such high loading the plastic deformation in the regions of high stress, which reduces the mean stress there, also tends to reduce the degree of interference. Thus the benefit from interference fit under high loading proves to be slight and particularly so with a high degree of interference.

Notwithstanding the agreement between Data Sheet A.05.02 and the results of the Bolted Joint Fatigue Research, this data sheet would be of great value if the text were revised to expand and clarify some of the steps involved therein. Moreover Figure 1 would be improved by the addition of curves for $d/D = 0.15$ and 0.25 and a large scale replot of the area in which all the main curves converge towards $q'/q'_o = 1.0$.

6.8.8

Predictions of endurances from basic data sheets such as E.07.01, E.07.03 and A.05.02 should be accompanied by some consideration of the possibility of the occurrence of fretting. Data Item No. 67012 gives some guidance. In the present research, although many of the specimens exhibited fretting, the influence of this fretting upon the fatigue endurances was not as large as would generally be expected.

6.8.9

Although many of the comparisons noted above have been made via individual mean endurance curves, some have been made via scatter bands which have been established by up to 30 values at a given stress level. This has been possible because of the small influence of mean stress and of the acceptable grouping of the results of the three sizes of specimens tested. Again, the scatter about the mean values so established was of the same order for each sub group whether for loaded pins or even for unfilled holes. Thus the validity of the general conclusions drawn from these comparisons and from this research is substantiated.

6.9 ACKNOWLEDGEMENTS

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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.

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