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MELBOURNE, VICTORIA

STRUCTURES REPORT 365

CONSTANT-AMPLITUDE AND PROGRAM-LOAD FATIGUE TESTS AT LOW CYCLIC FREQUENCIES ON THICK ALUMINIUM ALLOY PIN JOINTS

by

J. Y. MANN, F. G. HARRIS and G. W. REVILL

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SUMMARY

An investigation has been made of the fatigue behaviour of 32 mm thick 2L.65 aluminium alloy lugs loaded through 19 mm diameter steel pins. It involved constant-amplitude and program-load tests at cyclic frequencies of approximately 1 Hz.

At high alternating stresses, the constant-amplitude test results fall within the relevant data band in ESDU Data Sheet 72020. However, additional data are needed to clarify the fatigue performance of thick lugs for lives exceeding about 5×10^5 cycles.*

Under program-loading, the cycles actually applied at two of the intermediate stress levels exceeded the maximum experimental endurances obtained under constant-amplitude at the same stress levels. In addition, the actual lives of specimens under program-loading were about 10 times those predicted from the constant-amplitude data using the simple Palmgren-Miner hypothesis.

Static tests on about 20 of the fatigued pin-lug joints indicated that fatigue crack geometry may have an important influence on the residual strength of such a connection. A satisfactory theoretical treatment of this problem is thus of practical importance.

* Engineering Sciences Data Unit.

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16. *ABSTRACT*

An investigation has been made of the fatigue behaviour of 32 mm thick 2L. 65 aluminium alloy lugs loaded through 19 mm diameter steel pins. It involved constant-amplitude and program-load tests at cyclic frequencies of approximately 1 Hz.

At high alternating stresses the constant-amplitude test results fall within the relevant data band in ESDU Data Sheet 72020. However, additional data are needed to clarify the fatigue performance of thick lugs for lives exceeding about 5×10^5 cycles.*

Under program-loading, the cycles actually applied at two of the intermediate stress levels exceeded the maximum experimental endurances obtained under constant-amplitude at the same stress levels. In addition, the actual lives of specimens under program-loading were about 10 times those predicted from the constant-amplitude data using the simple Palmgren-Miner hypothesis.

Static tests on about 20 of the fatigued pin-lug joints indicated that fatigue crack geometry may have an important influence on the residual strength of such a connection. A satisfactory theoretical treatment of this problem is thus of practical importance.

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CONTENTS

1. INTRODUCTION

Pin joints are a common method of connecting members in aircraft structures, and a considerable amount of research has been carried out to determine the fatigue characteristics of this type of connection. Some of the resulting information (for aluminium alloy lugs) is summarised in the Engineering Sciences Data Unit Item no. 72020 (Ref. 1).

Most of the fatigue research on pin joints has involved specimens in the thickness range of around 5 mm to 15 mm, and it has been quite common to adopt cyclic frequencies exceeding 30 Hz for the conduct of the fatigue tests. The extensive investigations at the Royal Aircraft Establishment, England (Refs 2–4) and the Nationaal Lucht- en Ruimtevaartlaboratorium, Netherlands (Refs 5–7) typify this research.

Fatigue data for large lugs of aluminium alloy presented in Reference 1, and more recent fatigue investigations on large lugs carried out at the Aeronautical Research Laboratories (Ref. 8) indicate that their fatigue strengths may be much less than those of small lugs. In addition, photoelastic work by Dixon (Ref. 9) and Meek (Ref. 10) has shown that the stress distribution in the lug of a loaded pin-lug connection is affected by the thickness (t) of the lug relative to the diameter (d) of the pin. As the lug thickness (relative to the pin diameter) is increased, pin bending results in a maximum shear stress on the face of the lug at the hole boundary higher than the average maximum shear stress through the lug.

In order to study the fatigue behaviour of thick lugs further, an investigation was undertaken on aluminium alloy lugs of about 32 mm (1·25 inch) thickness with pins of 19 mm (0·75 inch) diameter ($d/t = 0{\cdot}6$): these were tested at cyclic frequencies of about 1 Hz. Both the thickness and frequency are more closely representative of aircraft applications and service loading conditions than most previous tests on pin-lug connections. This investigation included both constant-amplitude and program-load fatigue tests and, together with supporting fracture toughness and residual strength analyses, forms the subject of this report.

2. TESTING PROGRAM

2.1 Test specimens

All specimens used in this investigation—fatigue, tension and fracture toughness—were taken from the gripping ends of 2L.65 aluminium alloy fastener specimens tested in a previous fatigue investigation (Ref. 11) which involved two batches of extruded material designated *BJ* and *CL*. The general plan form of the original specimens, together with the locations from which the smaller specimens were taken, is shown in Figure 1. Details of the pin-joint fatigue specimens and the fracture toughness specimens are given in Figure 2. According to Heywood (Ref. 12) the theoretical stress concentration factor (nett area) for the configuration of loaded pin joint adopted in this investigation is about 2·8. The work of Meek (Ref. 10)—see Appendix—indicates that, because of pin bending, the maximum shear stress at the hole boundary of the lug in this joint would be increased by about 50% relative to a joint in which no pin bending occurred.

The faces of the specimens were not machined further and remained anodised as they had been when originally used in the previous investigation. However, the prior gripping of the fastener specimens caused some surface damage, and to eliminate any effect of this damage on the fatigue performance of the pin-joint specimens, a small chamfer was machined at each end of the lug holes. Surface finish measurements were made as specified in British Standard 2634, Part 1, 1974 in four of the reamed lug holes using a stylus traversing length of 4 mm with a meter cut-off of 0·8 mm. Surface finish values ranged from 0·5 to 1·4 μm (19·8 to 55·2 μinch) CLA with an average of 0·9 μm (35·5 μinch).

2.2 Fatigue tests

Figure 3 illustrates a specimen mounted in a Losenhausen UHS20 hydraulic pulsator which was used for all the fatigue tests. The specimens were assembled dry—without lubrication—using high tensile steel shoulder screws as the pins and with MoS_2 impregnated nylon shims fitted between the specimens and the steel loading links. A slight clearance was maintained between the specimens and the links. New shoulder screws were used for every specimen, the clearance between the holes and the pins ranging from 0·015 mm (0·0006 inch) to 0·07 mm (0·0028 inch) with an average of 0·043 mm (0·0017 inch). The clearances for the individual holes are included in Table 1.

The PL4 control system of the fatigue machine provided a triangular saw-tooth wave shape with a faster rate of unloading per cycle than of loading. All fatigue tests were carried out at constant rates of loading (40 MPa/sec) and of unloading (130 MPa/sec) and, as a consequence, the cyclic frequency of the fatigue tests—expressed in terms of cycles per minute—was greater at the lower stress amplitudes. A constant minimum stress on net area of 23·4 MPa (3,400 psi) was used throughout the tests. At the four alternating net area stresses of ±21·7 MPa (3,150 psi), ±41·4 MPa (6,000 psi), ±70·7 MPa (10,250 psi) and ±96·5 MPa (14,000 psi), the cyclic frequencies were approximately 0·7 Hz (42 cpm), 0·35 Hz (20 cpm), 0·2 Hz (12 cpm) and 0·17 Hz (11 cpm) respectively. In addition to four specimens being fatigue tested under constant-amplitude conditions at each of the above alternating stresses, four specimens were tested under a 'standard' program-loading sequence utilizing the same four cyclic stress levels. This program-loading sequence is illustrated in Fig. 4(*a*). One specimen was tested under the 'modified' three-load-range sequence shown in Fig. 4(*b*).

2.3 Residual strength tests

Complete fracture at one end of the specimens usually terminated the constant-amplitude fatigue tests. The residual strength of the 'unbroken' end of each specimen was subsequently determined by loading it statically in tension through a shoulder screw in a similar manner to that in the fatigue test. For these tests the other end of the specimen was held in serrated wedge grips.

Static residual-strength tests were also made on the program-load specimens which did not fail during the fatigue tests. Each end was loaded successively using the pin joint and wedge grip arrangement referred to above.

2.4 Fracture toughness tests

Fatigue pre-cracking and the determination of the K_{IC} values of the compact-tension fracture toughness specimens shown in Figure 2(*b*) were carried out in accordance with the recommendations of ASTM Standard E399-72. During pre-cracking the maximum load of the fatigue cycle for individual specimens ranged from between 6·3 kN (1,410 lbf) to 7·8 kN (1,740 lbf), with a minimum load of about zero. The first four specimens pre-cracked (nos CL26HS, CL29BS, BJ16JS and CL29BT) were pre-cracked in a 100 kN (10-tonne) Amsler 'Vibrophore' at a cyclic frequency of about 60 Hz. About 70,000 to 105,000 cycles were required to produce satisfactory cracks which, in these four specimens, were monitored optically. The remainder of the specimens were pre-cracked in a 330 kN (75,000 lbf) MTS electro-hydraulic machine at a cyclic frequency of about 30 Hz. For most of these, crack growth was monitored from the output of a crack opening displacement (COD) gauge which also allowed the test to be automatically discontinued when the appropriate crack length was reached. Between 43,000 and 78,000 cycles were required to pre-crack individual specimens.

3. TEST RESULTS

3.1 Fatigue and residual strength tests

Detailed results of the fatigue tests are given in Table 1, and the constant-amplitude data are also presented in the *S/N* diagram, Figure 5. The average *S/N* curve was derived from a least-squares analysis of the data with the assumptions of a log-normal distribution of lives and that the S/N curve could be adequately defined by a polynomial function. The best-fit curve shown is a second-order curve. With the exception of a fifth program-load specimen (no. CL25DB) which failed at 978·5 programs under the modified 3-load-range program, all the "standard" program load tests detailed in Table 1(*b*) were terminated at between 600 and 700 applications of the program. Figure 6 indicates the general method of classifying the various origins and geometries of the fatigue cracks which are listed, for each specimen, in Table 1(*a*).

All of the fractures resulting from the static residual strength tests were photographed so that the extent of the fatigue cracking could be accurately assessed. The areas of fatigue cracking

TABLE 1(*a*)
Constant-amplitude results
(S_{min} = 23·4 MPa (3,400 psi))

Specimen number	Pin/hole clearance				Fatigue failure		Fatigue crack classification (Fig. 6)
	End 1		End 2				
	mm	ins	mm	ins	cycles	end	
S_a = 96·5 MPa (14,000 psi)							
S_{max} = 216·5 MPa (31,400 psi)							
BJ10GB	0·033	0·0013	0·043	0·0017	7,086	1	a, d, i, m
BJ16JB	0·051	0·0020	0·028	0·0011	7,607	1	a, e, g, l
CL23GB	0·051	0·0020	0·015	0·0006	7,811	2	a, e, f, i, k
CL21CB	0·066	0·0026	0·051	0·0020	9,229	2	a, d, h, k
log. average life = 7,895							
std. deviation of log. life = 0·049							
S_a = 70·7 MPa (10,250 psi)							
S_{max} = 164·8 MPa (23,900 psi)							
BJ9IA	0·053	0·0021	0·030	0·0012	16,494	1	a, d, h, l
CL29BB	0·023	0·0009	0·033	0·0013	18,571	2	a, h, m
BJ15CB	0·033	0·0013	0·055	0·0022	20,816	2	b, f, h, m
CL29GB	0·043	0·0017	0·048	0·0019	30,971	2	b, d, g, j
log. average life = 21,080							
std. deviation of log. life = 0·119							
S_a = 41·4 MPa (6,000 psi)							
S_{max} = 106·2 MPa (15,400 psi)							
BJ19BB	0·058	0·0023	0·046	0·0018	58,362	2	b, g, l
BJ17DB	0·038	0·0015	0·053	0·0021	65,840	2	b, i, k
BJ10GA	0·033	0·0013	0·036	0·0014	82,440	1	b, h
CL26HB	0·058	0·0023	0·048	0·0019	120,866	1	b, f, h
log. average life = 78,662							
std. deviation of log. life = 0·139							
S_a = 21·7 MPa (3,150 psi)							
S_{max} = 66·9 MPa (9,700 psi)							
CL24HB	0·030	0·0012	0·048	0·0019	268,785	1	c, h
BJ7BB	0·030	0·0012	0·033	0·0013	479,224	1	c, g, k
CL28JB	0·055	0·0022	0·071	0·0028	606,213	2	c, l
CL22EB	0·046	0·0018	0·043	0·0017	682,283	2	c, k
log. average life = 480,433							
std. deviation of log. life = 0·180							

were then carefully traced from 4X enlargements—referring to the original fracture surfaces as required, and these are reproduced in Figure 7. Details relating to the failing loads, areas of fatigue cracking and residual stresses for each specimen are given in Table 2. Three of the four ends without fatigue cracks (and also CL24HB-2 which contained a very small fatigue crack) failed in a way typified by Figure 8. All the other specimens failed essentially across the plane of minimum section through the hole.

3.2 Fracture toughness and tensile properties

Table 3 presents the results of the fracture toughness tests on 14 of the 17 specimens tested. The results from the remaining three specimens were, according to the requirements of ASTM E399-72, invalid.

The tensile properties of the two batches of material (*BJ* and *CL*) are given in Table 4.

4. DISCUSSION

4.1 Constant-amplitude fatigue test results

Table 1(*a*) indicates that, within the limits of the *S*/*N* data, there is a progressive increase in the standard deviation of log. life with increasing mean life. This confirms similar findings of previous investigations (Refs 11, 13). In addition, the number of apparently independent fatigue crack origins decreases from an average of 4 at the highest maximum stress to 2 at the lowest maximum stress, and this observation also supports those made previously (Refs 8, 11, 14).

The broken curves in Figure 5 are taken from Figure 1 of ESDU Data Sheet no. 72020 (Ref. 1) and represent the scatter band enclosing 95% of the experimental results for large hole lugs, *d* greater than 19 mm (0·747 inch), made of solution treated and artifically aged aluminium alloys. It is clear that the current results lie within these bands for the stress limits considered, although most of the data in the ESDU Data Sheet are for *d*/*t* ratios exceeding 1·5. In only

TABLE 1(*b*)
Program-load results
(S_{min} = 23·4 MPa (3,400 psi))

Specimen number	Pin/hole clearance				Fatigue failure	
	End 1		End 2			
	mm	ins	mm	ins	programs	end
Standard program—4 load range (Fig. 4a)						
BJ18IB	0·033	0·0013	0·033	0·0013	605 (unbroken)	—
[Control system malfunction at 461 programs added 7,400 cycles to stage 1 and 9,800 cycles to stage 2 of this particular program]						
BJ13CB	0·020	0·0008	0·055	0·0022	615 (unbroken)	—
BJ9IB	Not measured				654 (unbroken)	—
CL28GB	0·025	0·0010	0·030	0·0012	697 (unbroken)	—
Modified program—3 load range (Fig. 4b)						
CL25DB	0·155	0·0061	0·046	0·0018	978·5	2

one of the sets of data on which the ESDU Data Sheet was based was the thickness of the lug greater than 25 mm (one inch), and this was the only case where the ratio d/t was less than one; i.e. 0·61, which is equal to that adopted in the current investigation. Although these particular ESDU data related to S_a of about 10 MPa (1,400 psi) and fatigue lives of about $1 \cdot 5 \times 10^6$ to 6×10^6 cycles they, and similar results from large lugs given in Reference 8, appear to lie below the projected lower limit of the S/N band shown in the ESDU figure.

Thus, in view of the increasing importance of accurately estimating the effects of low-

TABLE 2
Static residual strengths
(Average uncracked failing stress = 486 MPa (70,500 psi))

Specimen number	End	Failing load		Fatigue cracks				Nominal failing stress		
		kN	lbf	No.	Total area mm²	Total area in²	% of un-cracked	MPa	psi	% of un-cracked
Constant-amplitude										
BJ10GB	2	324	72,800	4	30·4	0·047	3·83	424	61,500	87
BJ16JB	2	298	67,000	4	21·1	0·033	2·66	386	56,000	79
CL23GB	1	285	64,000	3	99·7	0·155	12·56	411	59,500	84
CL21CB	1	339	76,100	3	21·3	0·033	2·68	439	63,600	90
BJ9IA	2	251	56,500	4	167·6	0·260	21·12	401	58,200	82
CL29BB	1	303	68,000	3	59·2	0·092	7·46	412	59,800	85
BJ15CB	1	365	82,000	3	4·7	0·007	0·59	462	67,000	95
CL29GB	1	391	88,000	No fatigue cracks			0	492	71,600	—
BJ19BB	1	217	48,800	2	151·3	0·236	19·07	338	49,100	69
BJ17DB	1	365	82,000	1	10·6	0·016	1·34	466	67,500	96
BJ10GA	2	182	41,000	2	217·6	0·337	27·42	316	45,900	65
CL26HB	2	215	48,400	2	282·8	0·438	35·64	421	61,100	86
CL24HB	2	389	87,500	1	0·7	0·001	0·09	490	71,200	101
BJ7BB	2	367	82,500	1	3·8	0·006	0·48	464	67,400	95
CL28JB	1	365	82,000	2	34·7	0·054	4·37	481	69,700	99
CL22EB	1	235	52,800	2	187·6	0·291	23·64	388	56,200	80
Program load (standard 4 load range)										
BJ18IB	1	378	85,000	No fatigue cracks			0	476	69,100	—
	2	386	86,700	No fatigue cracks			0	486	70,500	—
BJ13CB	1	356	80,000	4	5·5	0·008	0·69	452	65,500	93
	2	390	87,200	No fatigue cracks			0	491	70,900	—
BJ9IB	1	375	84,200	3	1·5	0·002	0·19	473	68,600	97
	2	369	82,900	2	2·6	0·004	0·33	466	67,600	96
CL28GB	1	372	83,700	3	8·5	0·013	1·07	474	68,800	97
	2	220	49,400	3	116·2	0·180	14·64	325	47,000	67
Program load (modified 3 load range)										
CL25DB	1	383	86,000	4	3·7	0·006	0·47	485	70,300	100

TABLE 3
Fracture toughness of material

Specimen number	K_{IC}	
	MPa $m^{\frac{1}{2}}$	ksi $in^{\frac{1}{2}}$
BJ15CS	25·9	23·6
BJ15CT	25·8	23·5
BJ16JS	25·9	23·6
BJ16JT	25·6	23·3
BJ18IS	26·8	24·4
BJ19BS	25·6	23·3
BJ19BT	25·8	23·5
Average	25·9	23·6
Std. dev.	0·41	0·37
Coeff. variat.	0·016	0·016
CL21CS	31·4	28·6
CL21CT	30·0	27·3
CL23GS	31·0	28·2
CL26HS	30·7	27·9
CL26HT	30·9	28·1
CL29BS	31·0	28·2
CL29BT	31·3	28·5
Average	30·9	28·1
Std. dev.	0·46	0·43
Coeff. variat.	0·015	0·015

TABLE 4
Tensile properties of material

Material batch	No. of tests	0·1% PS		0·2% PS		UTS		Elong. (% on 2")	0·1%PS / UTS
		MPa	psi	MPa	psi	MPa	psi		
Specification BS L.65 (minimum)		432	62,700			494	71,700	8	[0·87]
BJ	25								
Average		457	66,300	463	67,200	510	74,000	11·5	0·90
Stand. deviat.		12	1,700	13	1,900	10	1,400	1·0	
Coeff. variat.		0·026	0·026	0·028	0·028	0·019	0·019	0·081	
CL	12								
Average		469	68,000	476	69,100	526	76,300	12·0	0·89
Stand. deviat.		9	1,300	9	1,300	6	900	1·0	
Coeff. variat.		0·019	0·019	0·019	0·019	0·011	0·011	0·076	

amplitude frequently-occurring loads on the fatigue life of aircraft structures, there is a definite need for accurate data on the fatigue properties of thick lugs at low alternating stresses corresponding to fatigue lives exceeding about 5×10^5 cycles.

4.2 Spectrum-load fatigue tests—life estimation

None of the eight pin/lug ends tested under the standard program failed during fatigue testing. Subsequent residual static tests (see Table 2 and Fig. 7) indicated that in three of the ends no fatigue cracks were present, and in four of the remaining five the cracks were relatively small. In only one end (CL28GB-2) was the crack development such that fatigue failure might have been anticipated within, perhaps, the next 50 programs. Thus the *minimum* actual life may have been close to 750 programs.

It is of interest to note, at this point, that even the *shortest* life 'standard-program' specimen (BG18IB)—for which the test was terminated at 605 programs—represented the application of totals of 605, 31,460, 242,000 and 526,350 cycles respectively at each of the four individual alternating stress levels, and that, for the two intermediate stresses, the cycles *actually applied exceeded the maximum experimental endurances* obtained in the constant-amplitude tests at these stress levels—see Table 1(*a*).

An estimate of the *average test life* under program loading can be made by directly using the constant-amplitude test results. For the four constant-amplitude stress ranges the average difference between the log. average lives and the log. minimum test lives is 1·05 times the standard deviation of log. life; and the average standard deviation of log. life for this data is 0·122. If one assumes similar values for these parameters under program loading, then based on a minimum test life of 750 programs under the 'standard' program-loading sequence, the *average* test life would be:

$$\text{antilog}\,[\log 750 + (1{\cdot}05 \times 0{\cdot}122)] \simeq 1{,}000 \text{ programs.}$$

The simple Palmgren-Miner linear cumulative damage hypothesis ($\Sigma n/N = 1$), in conjunction with the calculated log. average lives at each of the four constant-amplitude stress ranges, was used to make an estimate of the average fatigue lives under both of the program-loading sequences. As indicated in Table V, the lives so estimated were 105·4 programs for the standard program and 156·1 programs for the modified program. For the standard program therefore, the average life estimated directly from the test results is approximately 10 times that calculated using the Palmgren-Miner hypothesis. For the single test result under the modified program, the ratio of that life to the calculated average life is approximately 6·5.

For the particular fatigue testing conditions outlined above—large pin joints in repeated tension under program-loading with a relatively small number of load cycles per program—the simple Palmgren-Miner hypothesis apparently provides a very conservative estimate of fatigue life.

In terms of theoretical fatigue damage, the maximum load range of the program-load sequences makes an insignificant contribution. However, it is well known (Refs 15, 16) that the intermittent application of high tensile loads can cause crack growth retardation and, as a consequence result in an increase in fatigue life. Furthermore Heywood (Refs 17, 18) has reported that, for lug specimens of the same aluminium alloy as that used in this investigation, the application of a high tensile load at regular intervals during an otherwise constant-amplitude fatigue test sequence can cause a substantial improvement in fatigue life. As an example of Heywood's results, when a high load of magnitude equal to about 59 MPa (8,550 psi) greater than the maximum load of the constant-amplitude sequence was applied as follows:

— at commencement of test, and every 20,000 cycles to 500,000 cycles
— then every 50,000 cycles to 1,000,000 cycles
— then every 100,000 cycles to 2,000,000 cycles
— then every 200,000 cycles to 4,000,000 cycles
— then test continued to failure without further overloading,

the life was increased from an average of 124,000 cycles to over 7×10^6 cycles.

For the standard program in the current series of tests, the peak load was applied at intervals of 1323 cycles, the magnitude of the corresponding maximum stress being 51·7 MPa (7,500 psi) greater than the next highest maximum stress of the sequence. The significant increase in fatigue life under program-loading compared with constant-amplitude loading appears to be directly attributable to the effects of this intermittent load application.

The question arises as to the mechanism by which the intermittent application of a high load causes an increased life in a pin joint configuration. Two possiblities which might be considered are stress redistribution associated with preferential strain hardening at the potential crack nucleation sites and, secondly, a modification in the development of fretting damage.

A well-developed pattern of fretting was evident on the surface of all holes at positions corresponding to the bearing areas of the pins. As shown in Figure 9, the fretting was more severe adjacent to the faces of the lugs (where the shear stresses associated with pin bending were a maximum) than at the centre. The origins of the fatigue cracks in every specimen were just inside the circumferential boundaries of the fretted regions. In the constant-amplitude tests the crack initiation sites (Fig. 6) were either at or very close to the faces of the lugs, whereas in the program-load tests they were predominantly within the hole and between 2·5 mm (0·1 inch) and 6 mm (0·25 inch) from the corner.

An apparent consequence of the program-load testing sequence was thus to change the

TABLE 5
Life estimates, standard and modified programs

S_a, MPa (psi)	n	$\bar{N}$	$\Sigma\, n/N$ per program	Damage (%)
Standard program				
96·5 (14,000)	1	7,895	0·0001266	1·33
70·7 (10,250)	52	21,080	0·0024668	26·00
41·4 (6,000)	400	78,662	0·0050850	53·59
21·7 (3,150)	870	480,433	0·0018109	19·08
Totals	1323		0·0094893	100
Estimated average life = 105·4 programs				
Modified program				
96·5 (14,000)	1	7,895	0·0001266	1·98
70·7 (10,250)	52	21,080	0·0024668	38·50
41·4 (6,000)	300	78,662	0·0038138	59·52
Totals	353		0·0064072	100
Estimated average life = 156·1 programs				

initiation sites of the fatigue cracks. Fretting has been postulated (Ref. 19) to result from repeated reversed shearing actions in the surface layers of the materials in contact which leads to the development of fatigue cracking under what are, essentially, high strain conditions. It is conjectured that the occasional high alternating load in a multi-load-level fatigue test sequence could cause actual relative movement (or slip) *between* the contacting surfaces, rather than greater reversed shear *in* the surface layers. Associated with the slip between the surfaces could be a separation of the fretted regions before the extensive development of 'fretting damage', and the elimination or retardation of further damage and crack development in those particular regions. Upon further fatigue cycling at lower loads, the fretting process would need to re-establish itself in the same or in other locations.

Because of the differences in the crack initiation sites under constant-amplitude and program-loading, the relevance of using constant-amplitude data to predict the lives of pin joint assemblies under a multi-load-level sequence is questionable.

4.3 Residual strength of cracked lugs

Reference was made in Section 3.1 to the difference in the fracture paths in specimens which were uncracked and those containing fatigue cracks. The influence of only very small cracks in changing the fracture mode in lug ends of this configuration should be noted.

The residual static strengths of the cracked lugs are summarised in Figure 10, the various points being firstly categorised by the particular batch of material (*BJ* or *CL*) and then by the major fatigue crack development in each case. The differences in fracture toughness between the two batches of material (*BJ:* 25·9 $MPam^{\frac{1}{2}}$ (23·6 ksi $in^{\frac{1}{2}}$) and *CL:* 30·9 $MPam^{\frac{1}{2}}$ (28·1 ksi $in^{\frac{1}{2}}$)) is possibly reflected by a trend toward higher residual strengths for the *CL* material. However, a complicating factor is that there appears to be some correlation between the residual strength and the type of fatigue crack development, in that types 1 and 2 cracking appear to lie on the 'low' side of the data and types 4 and 5 on the 'high' side. This may be associated with differences in the resolved stress situation at the crack fronts for the various configurations of cracks, e.g. comparing cases 2, 4 and 5; but no analytical solution was found in the literature to predict the residual strength of pin/lug connections with cracks covering all of the different shapes and sizes found in this investigation.

Because of the potentially significant effects of crack configuration on the residual strength when a more complex situation than a single corner crack is involved, it would appear that a satisfactory theoretical treatment of this problem is of practical importance.

5. CONCLUSIONS

From an analysis of the tests reported herein, the following conclusions emerge.

1. At high alternating stresses, the constant-amplitude fatigue test results fall within the relevant data band for thick lugs presented in ESDU Data Sheet no. 72020, but additional data are required to clarify the fatigue performance of thick lugs at lives exceeding about 5×10^5 cycles.
2. Under program-loading, the cycles actually applied at two of the intermediate stress levels exceeded the maximum experimental endurances obtained under constant-amplitude at the same stress levels.
3. The actual lives of the specimens under program loading were about 10 times those predicted from the constant-amplitude data using the simple Palmgren-Miner hypothesis, thus indicating that this hypothesis provides a very conservative estimate of life under the particular fatigue testing conditions employed.
4. It is suggested that the long fatigue lives under program loading can be attributed to the application of the peak load at regular intervals during the fatigue test. Two possible mechanisms are firstly, stress redistribution associated with preferential strain hardening at crack initiation sites, and secondly, modifications in the development of fretting damage in which slip between the contacting surfaces at the highest load requires the fretting process to re-establish itself after each such load application.

5. Static strength tests on fatigued pin/lug joints showed that fatigue crack geometry may have an important influence on the residual strength of such a connection. It would appear that the derivation of a satisfactory theoretical treatment of this problem is of practical importance.

ACKNOWLEDGMENTS

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APPENDIX

Stress distribution in lugs

The plan dimensions of the photoelastic specimens used by Meek (Ref. 10) are similar to the aluminium alloy lugs shown in Figure 1, and the ratios *d/D* and *H/d* almost identical. One of the specimens used by Meek had a *d/t* ratio of 0·67 which was also almost identical to that adopted for these fatigue tests. In addition, Meek investigated the effect of radiusing the corners of the hole, and compared the effects of using loading pins of the same modulus of elasticity as the lug material with those having a modulus of three times that of the lug. Both investigations are very relevant to the configuration of the pin/lug assembly used in the present investigation.

Although the work of Dixon (Ref. 9) indicates that pin bending could cause the maximum shear stress at the boundary of the lug in such a joint to be increased by 15%, Meek's work suggests a value closer to 50%. Radiusing the corner of the hole resulted in a further increase of shear stress—estimated to be about 25%—whereas the use of a high modulus pin was estimated to reduce the shear stress by about 20%. Thus, for the configuration of the aluminium alloy/steel pin connection used in the present investigation, it was estimated that the maximum shear stress at the hole boundary in the lug would be about 50% greater than the average maximum shear stress through the lug.

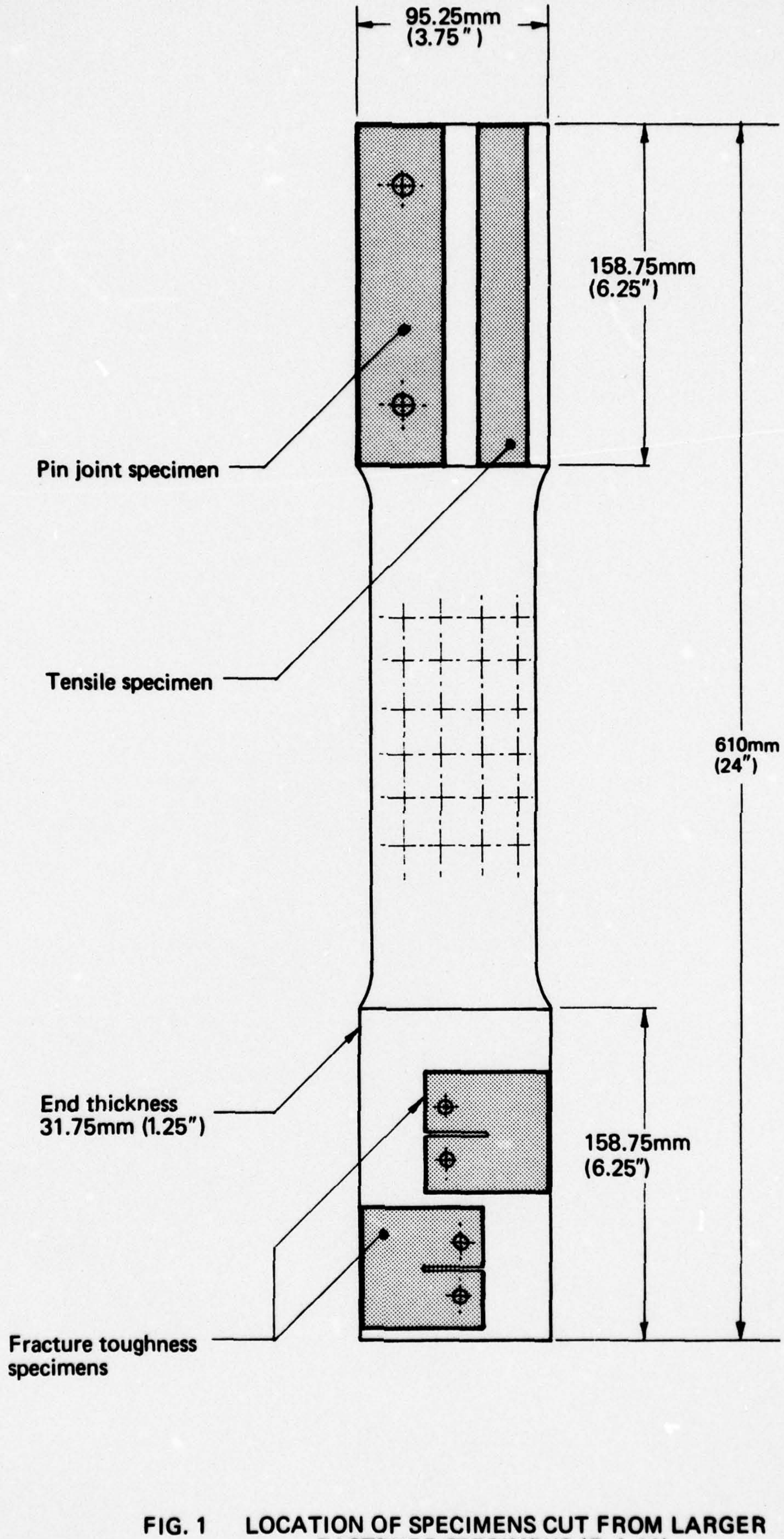
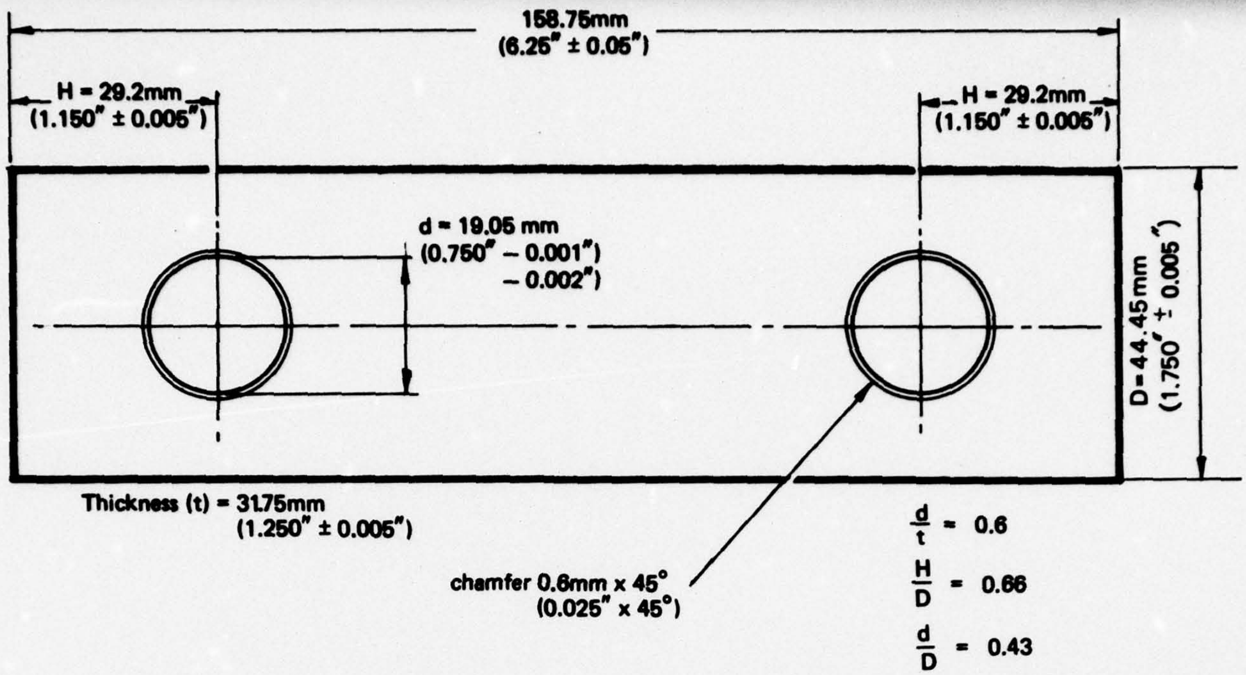
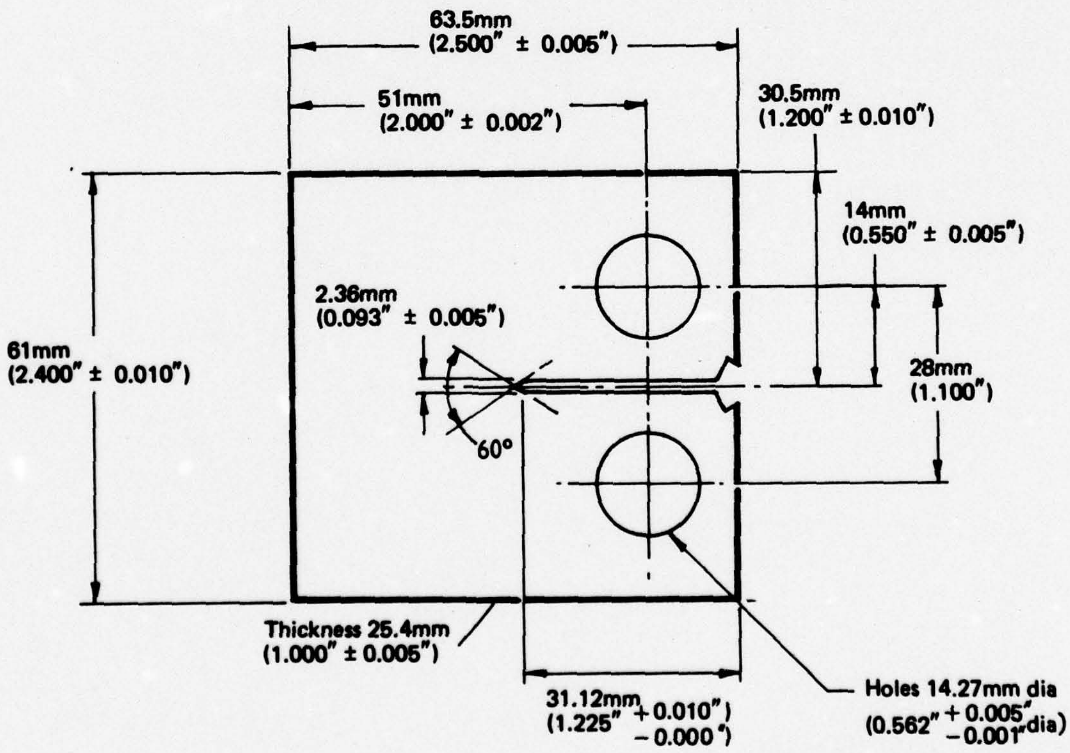


FIG. 1 LOCATION OF SPECIMENS CUT FROM LARGER FASTENER SPECIMENS (Ref. 11)



(a) Pin joint fatigue specimen



(b) Fracture toughness specimen

FIG. 2. TEST SPECIMENS

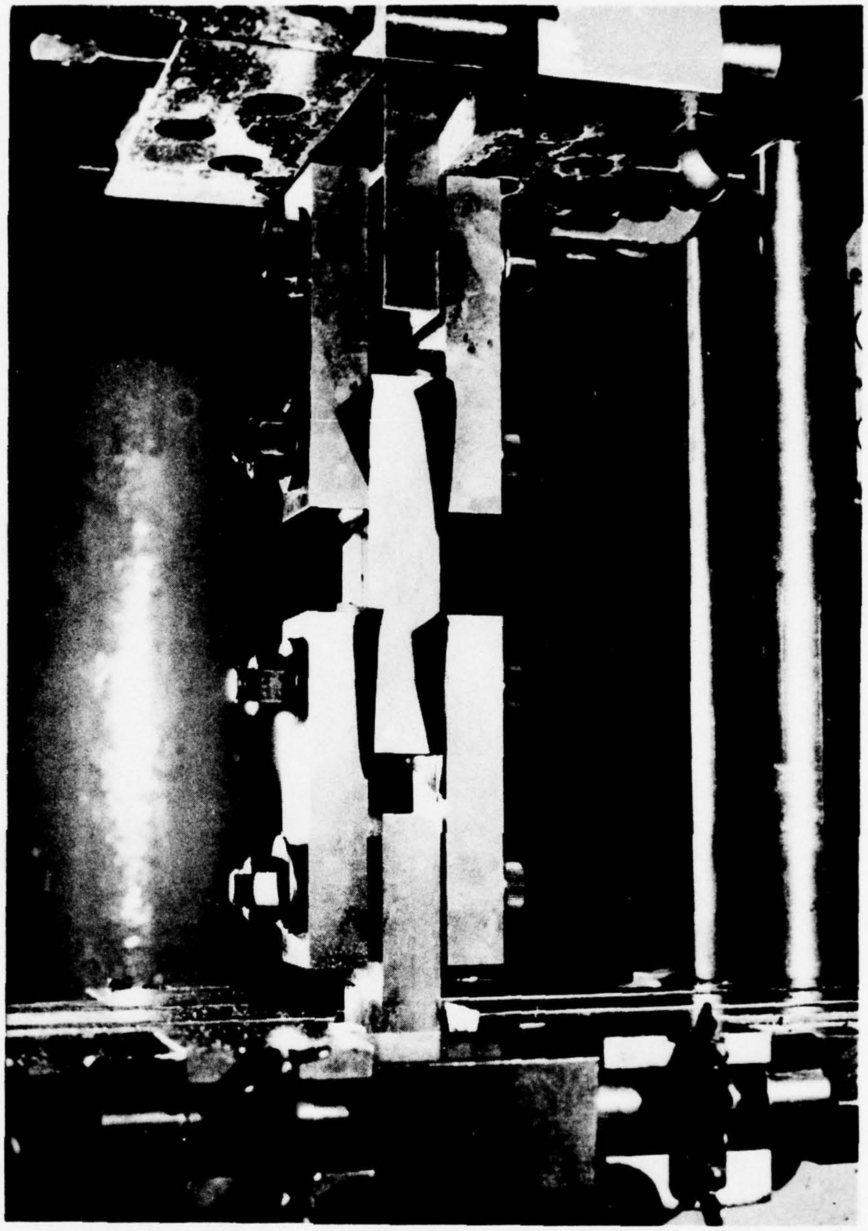


FIG. 3. SPECIMEN MOUNTED IN LOSENHAUSEN PULSATOR

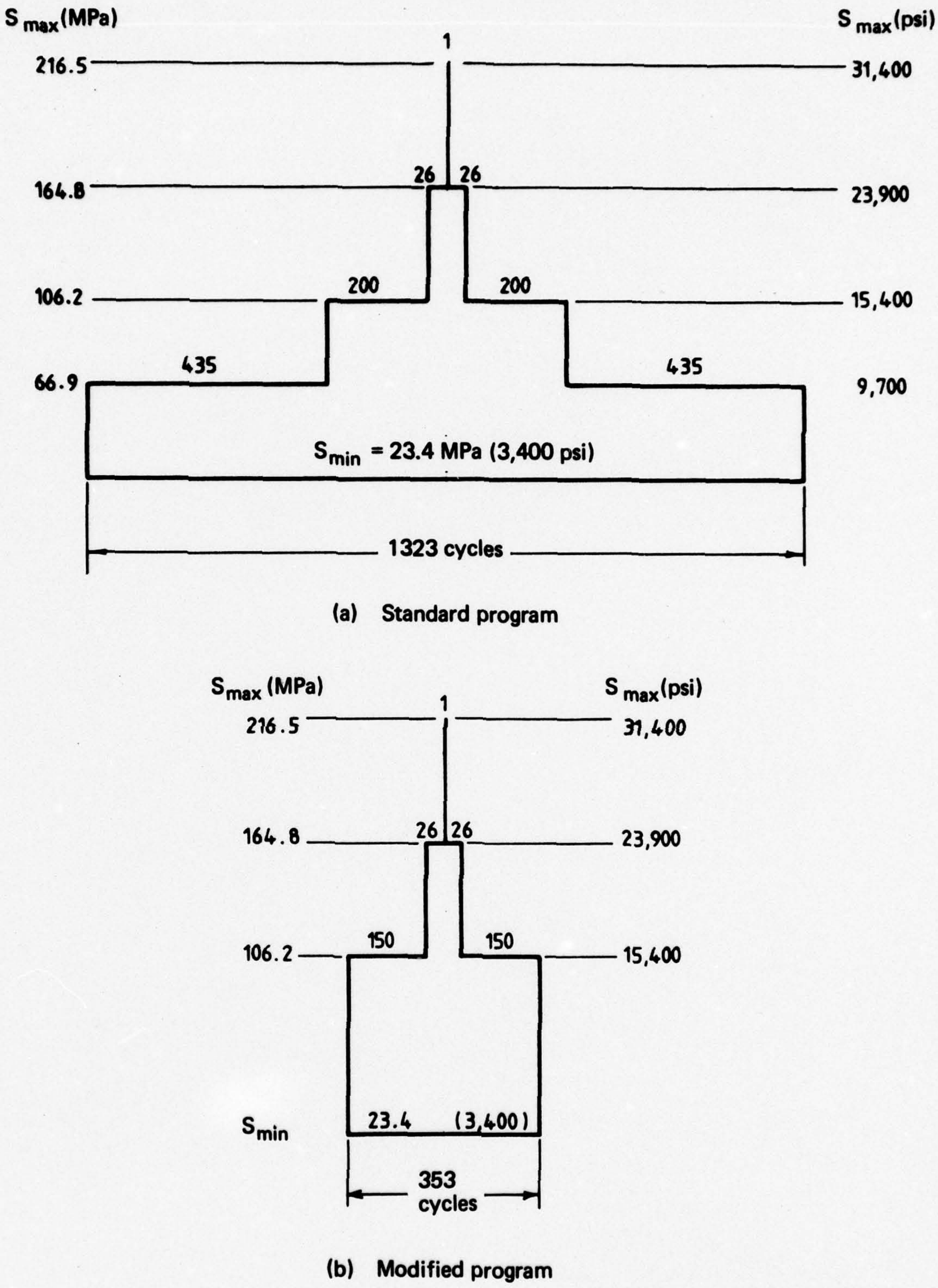


FIG. 4. PROGRAM LOADING SEQUENCES

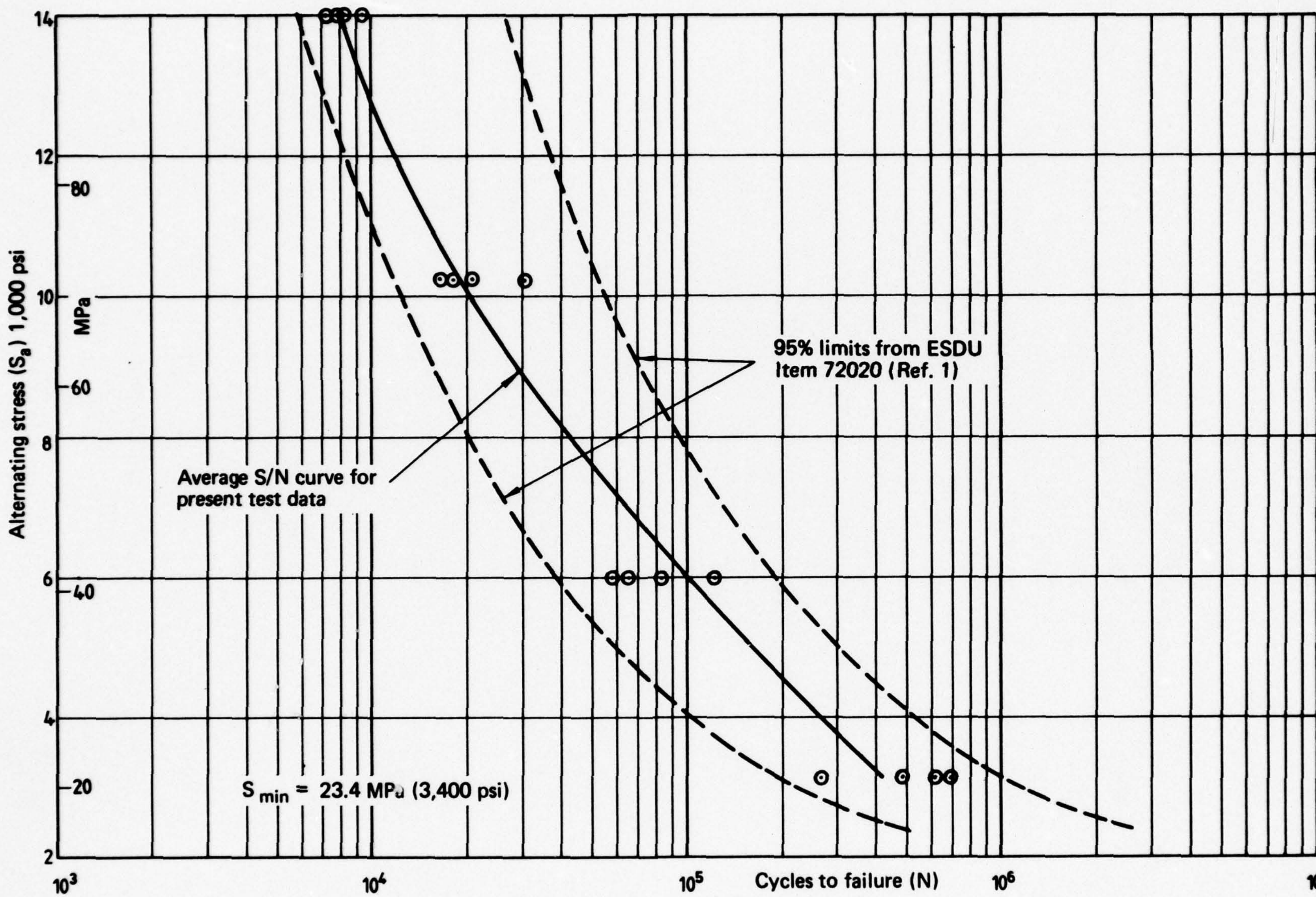


FIG. 5. CONSTANT-AMPLITUDE FATIGUE TEST RESULTS

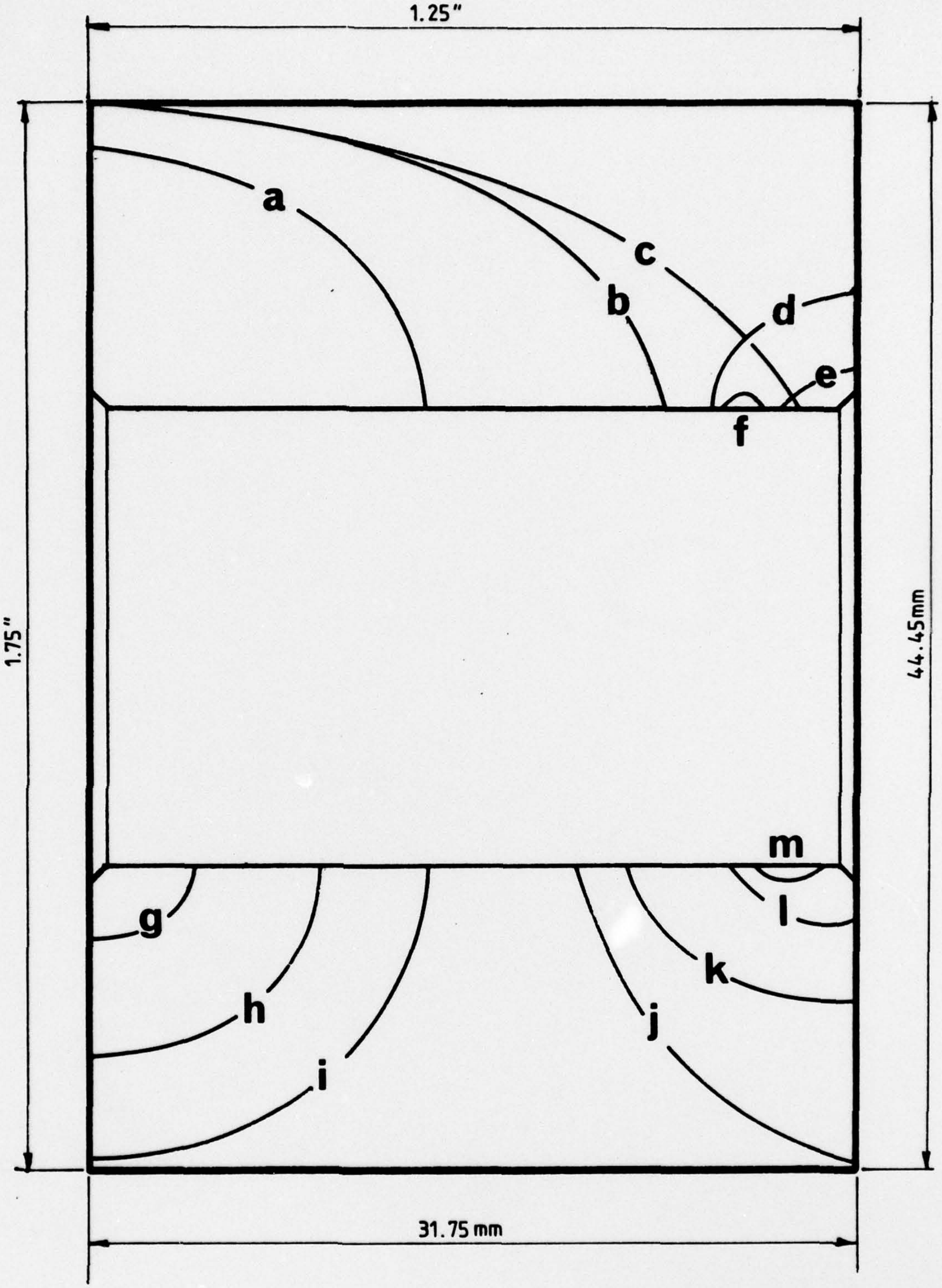


FIG. 6. FATIGUE CRACK CLASSIFICATION – approximate fatigue crack geometries (x 4).

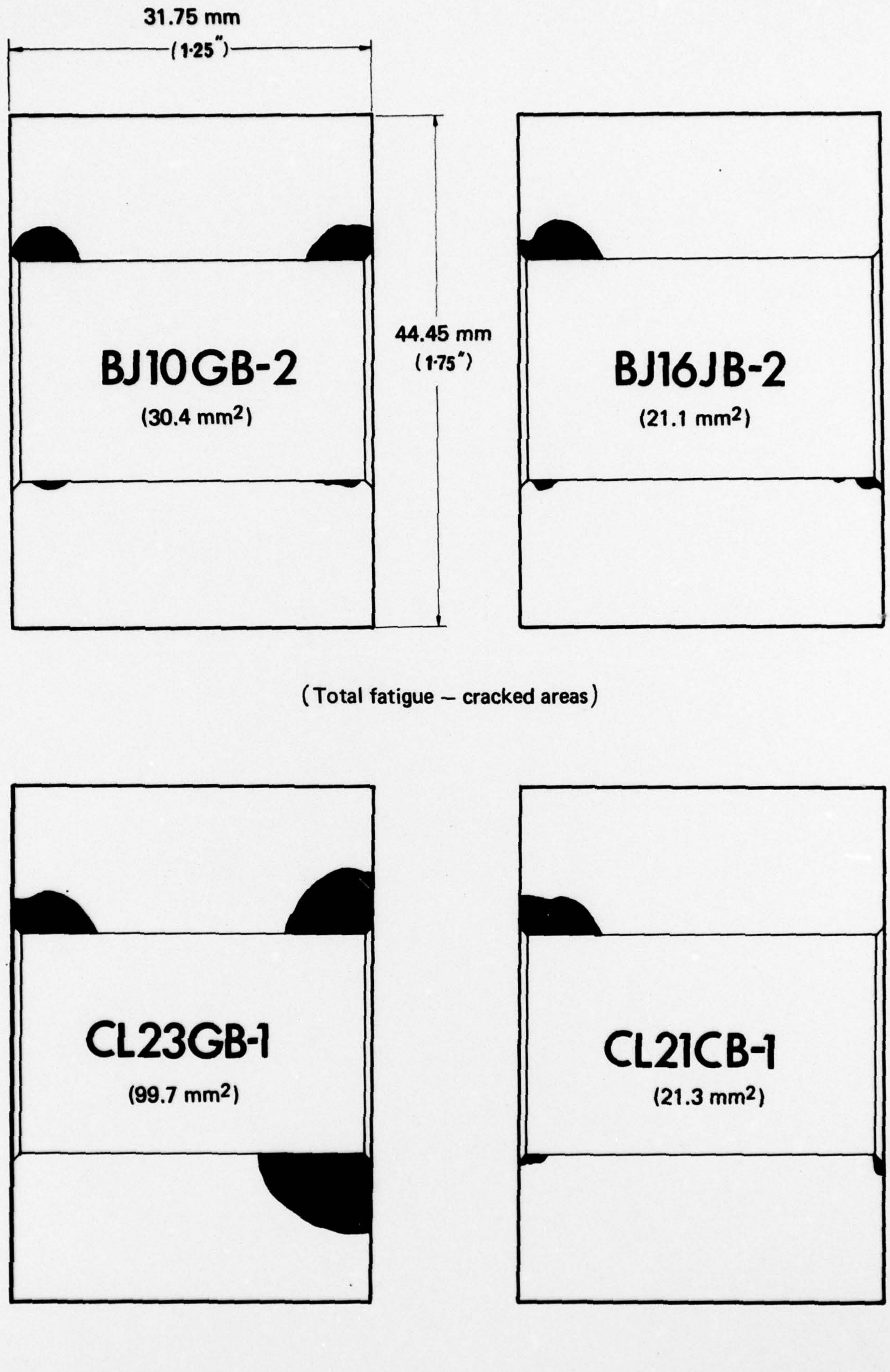


FIG. 7(a) FATIGUE–CRACK AREAS – RESIDUAL STRENGTH TESTS
Constant – amplitude fatigue tests S_a = 96.5 MPa, S_{max} = 216.5 MPa

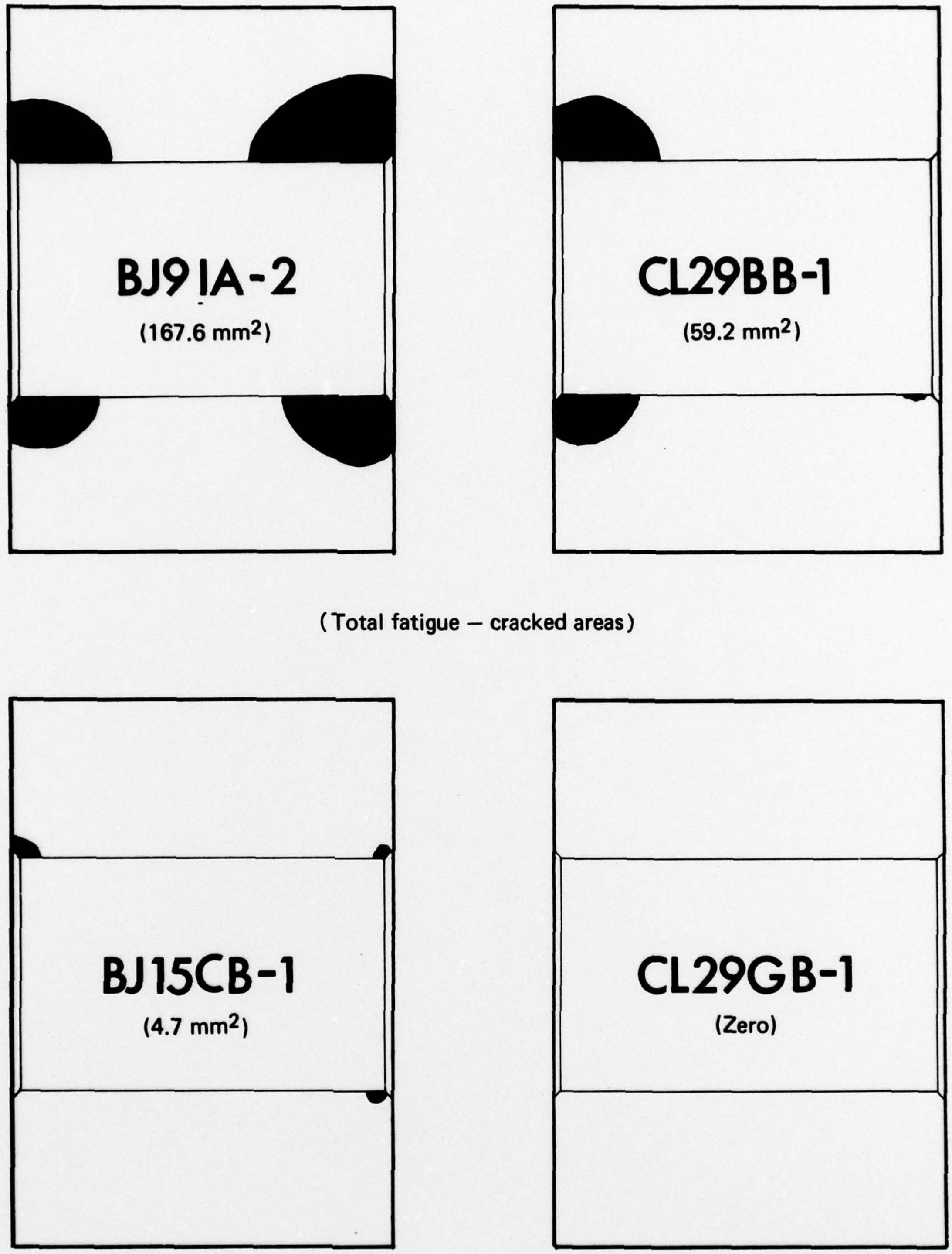


FIG. 7(b) FATIGUE–CRACK AREAS – RESIDUAL STRENGTH TESTS
Constant – amplitude fatigue tests S_a = 70.7 MPa, S_{max} = 164.8 MPa

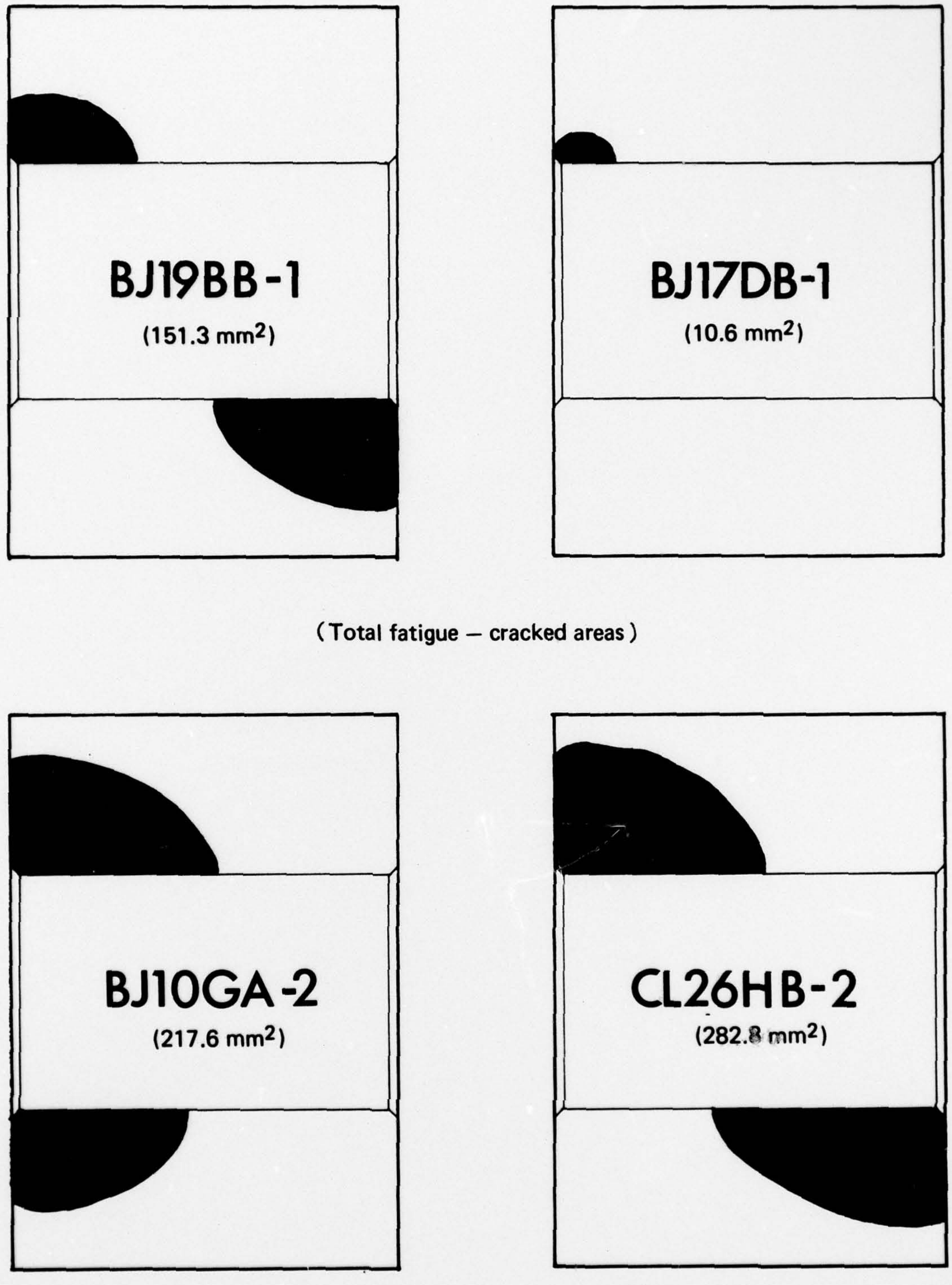


FIG. 7(c) FATIGUE - CRACK AREAS — RESIDUAL STRENGTH TESTS
Constant — amplitude fatigue tests S_a = 41.4 MPa, S_{max} = 106.2 MPa

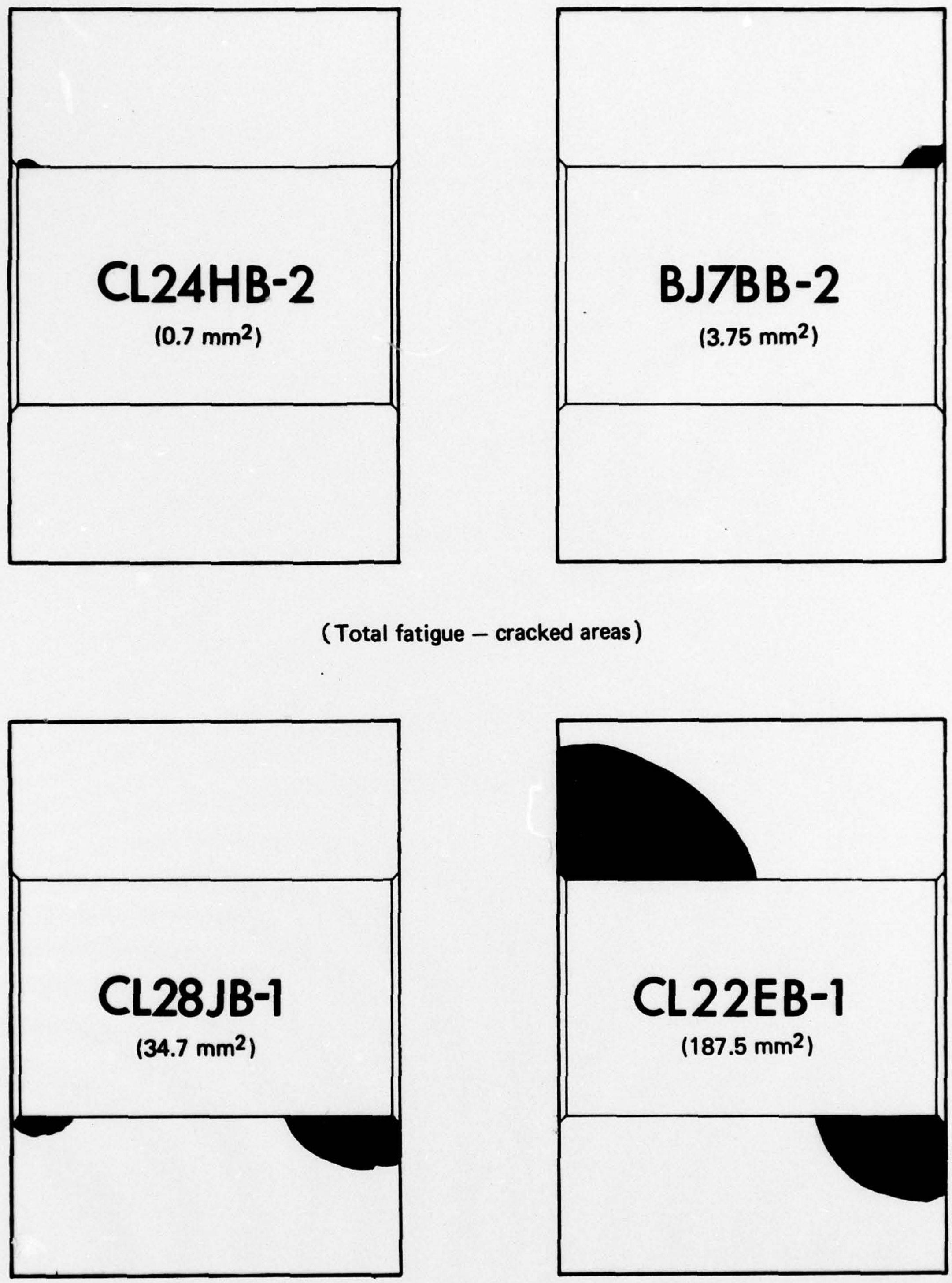


FIG. 7(d) FATIGUE – CRACK AREAS – RESIDUAL STRENGTH TESTS
Constant – amplitude fatigue tests S_a = 21.7 MPa, S_{max} = 66.9 MPa

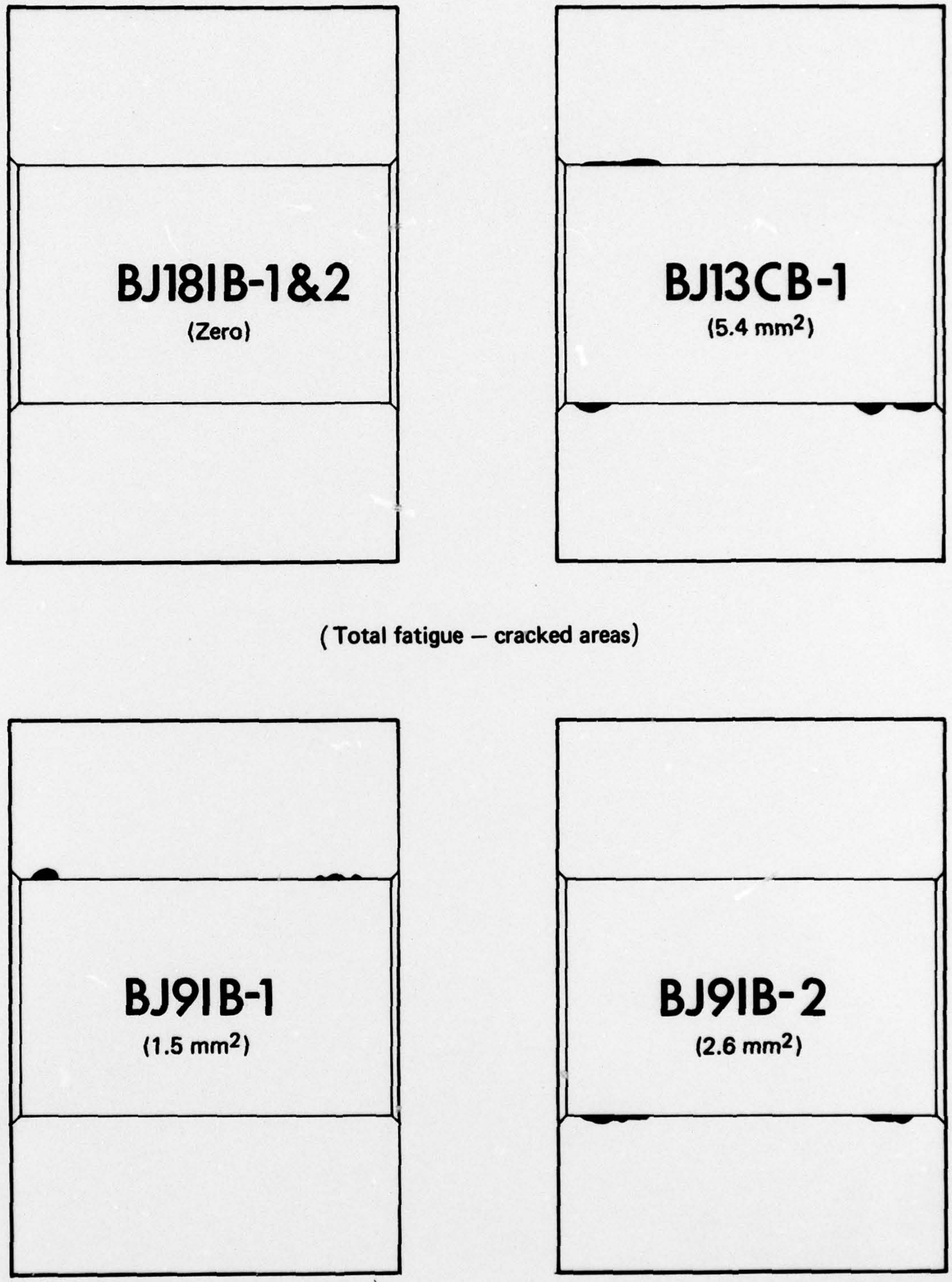


FIG. 7(e) FATIGUE–CRACK AREAS – RESIDUAL STRENGTH TESTS
Program – load fatigue tests

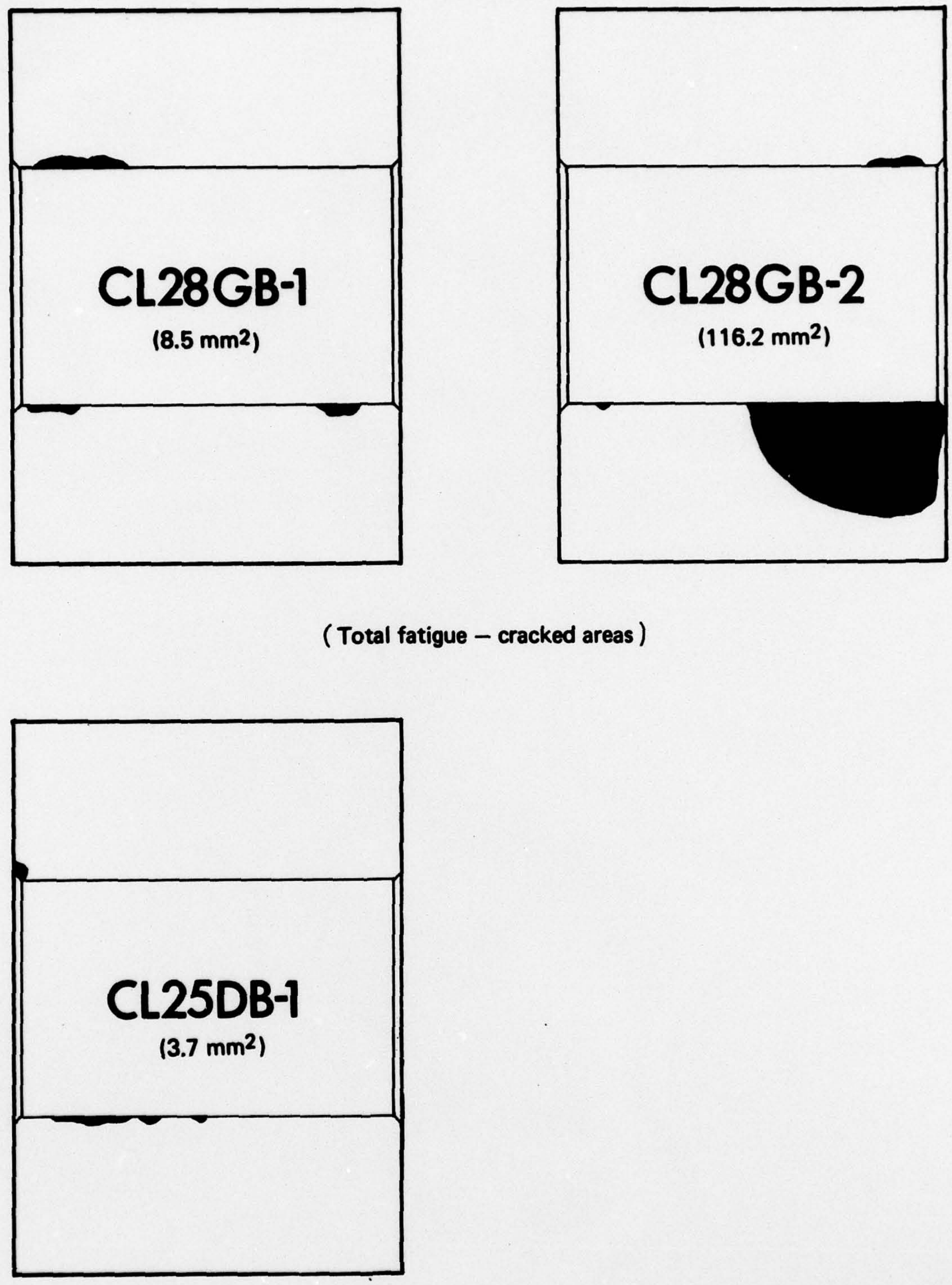


FIG. 7(f) FATIGUE–CRACK AREAS – RESIDUAL STRENGTH TESTS
Program – load fatigue tests

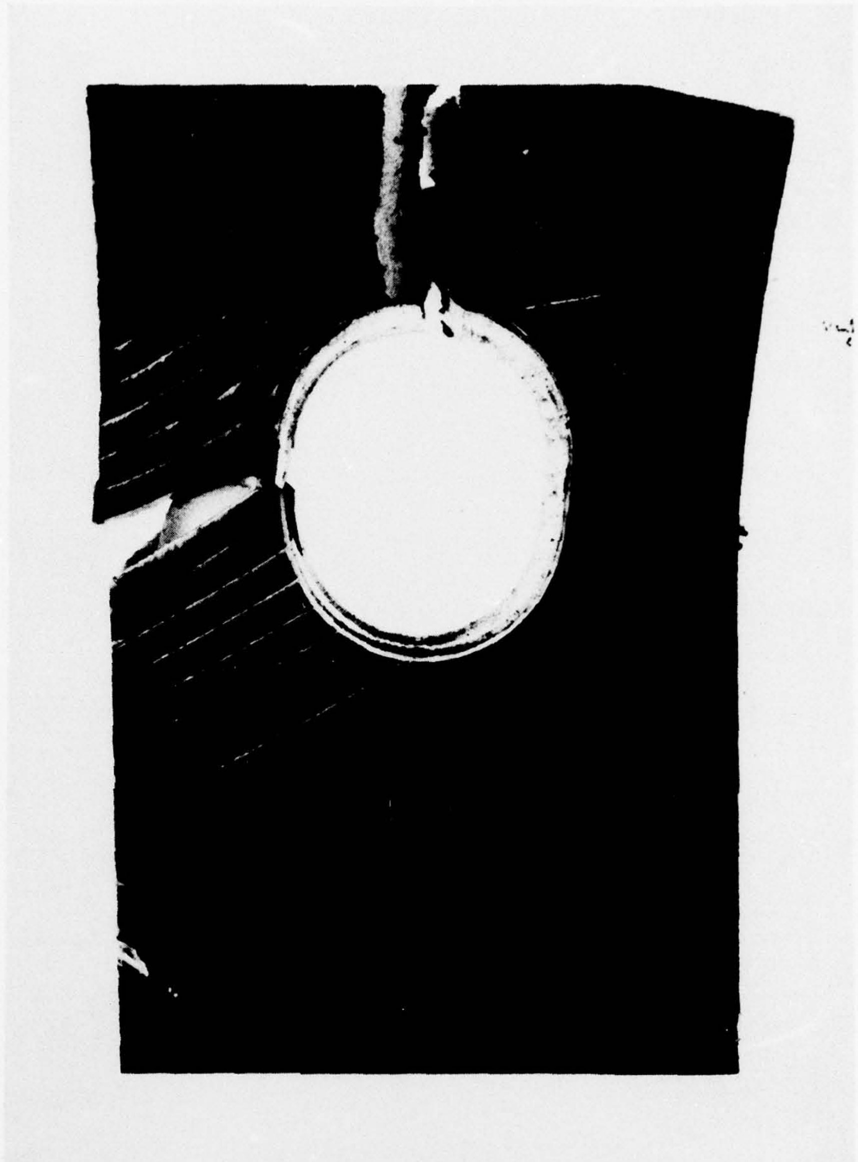
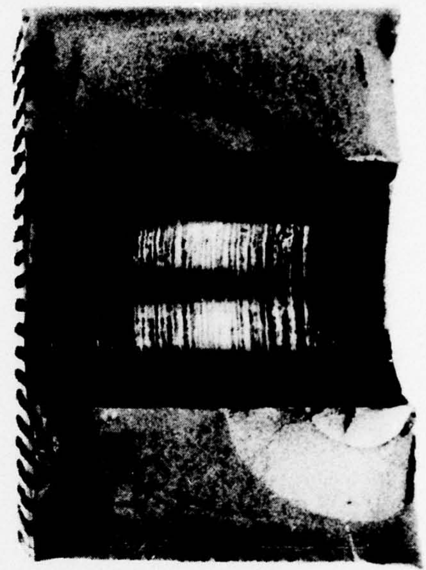


FIG. 8   PULL–OUT TYPE STATIC TENSILE FRACTURE

(a)



(b)

FIG. 9 FRETTING PATTERNS IN LUG HOLES
(a) Constant amplitude, specimen no. BJ10GA (end 2)
(b) Program load, specimen no. CL28GB (end 2)

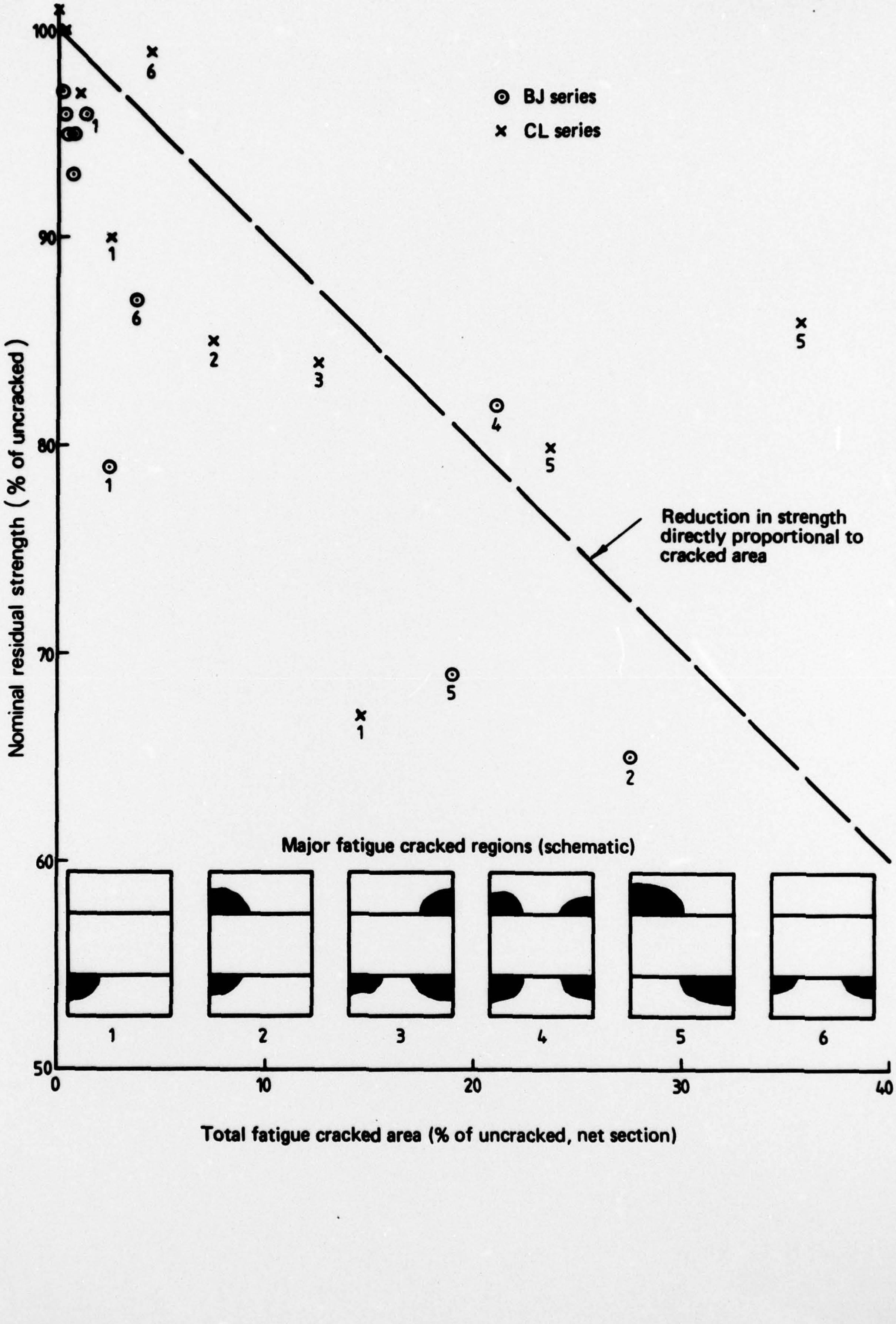


FIG. 10 RESIDUAL STATIC STRENGTHS OF CRACKED LUGS

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