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A.R.C. Technical Report

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Programme Fatigue Tests on Notched Bars to a Gust Load Spectrum

by

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ROYAL AIRCRAFT ESTABLISHMENT

PROGRAMME FATIGUE TESTS ON NOTCHED BARS TO A GUST LOAD SPECTRUM

by

W.A.P. Fisher

RAE Ref: Structures E.16128/WAPF

SUMMARY

A series of programme fatigue tests in axial loading was made on notched bars machined from extruded alloy to D.T.D.363A. The load spectrum represented a simplified truncated gust spectrum. The alternating load in each programme was steadily increased to a maximum (corresponding to a 27.5 ft/sec gust) and down again. The programme was repeated until failure of the specimen. The average number of programmes to failure was in each case greater than that predicted by the Miner hypothesis $\Sigma \frac{n}{N} = 1$.

Further tests are recommended, in which material, type of specimen, and order of loading are varied.

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1 INTRODUCTION

The type of fatigue test known as "programme loading" was first introduced by E. Gassner[1,2] as a method of simulating in a laboratory test the load fluctuations to which an aeroplane wing is subjected in flight. A "programme" consists of a small fraction (1/10th or less) of the summation of service loads (caused by gusts and manoeuvres) which would eventually bring about fatigue failure. This programme is applied repeatedly until failure occurs. Thus, by the regular mixing of loads of different magnitudes, an approximation to random order of loading is obtained.

In a previous Note[3] results have been given for fatigue tests, under a programme of manoeuvre loads applicable to the tension boom of a fighter wing, on notched specimens made in aluminium alloy to D.T.D.363A (see Appendix). The present tests were made on somewhat similar specimens of the same material specification under loads applicable to a wing spar in a transport aircraft, where the load variations are due mainly to gusts. The specimens were loaded in axial tension.

2 OBJECT OF INVESTIGATION

The tests were made with the object of comparing the test endurances with the endurance computed in accordance with the Miner hypothesis (i.e. $\Sigma \frac{n}{N} = 1$).

3 TEST SPECIMENS

All specimens were made from $3\frac{1}{4}$" x $1\frac{1}{8}$" extruded aluminium alloy supplied by one manufacturer.

A sketch of the test specimen is shown in Fig.1. A severely notched form* was chosen so as to give a strength reduction factor at least as severe as that found for shaped extrusions. Thus the specimen can be regarded as representing, from the fatigue stand-point, a lower wing spar member at a cross section through a geometric stress concentration; but it is not representative of joints, where the initiation of fatigue cracks is usually associated with fretting.

4 TESTING MACHINE AND METHOD OF AUTOMATIC LOAD CONTROL

The testing machine was a Losenhausen U.H.P. 100 hydraulic machine equipped with an automatic programme control.

The load on the specimen is varied cyclically by a hydraulic pulsator with variable stroke, and its limits are controlled by the setting of two pairs of adjustable contacts on the maximum and minimum pressure gauges respectively. The position of these contacts is controlled by a pair of slowly rotating cams. The profile of one cam sets the maximum load in the cycle and that of the other cam determines the minimum load. The machine corrects the maximum load by means of control valves and the load range by variation of the pulsator stroke. Constant mean and alternating load can be set for any desired number of cycles by giving the cams a circular profile for a suitable part of the circumference, and a series of such circular segments can be arranged so as to give appropriate numbers of different predetermined load levels in turn. Alternatively, the cam radii can be gradually increased or decreased, giving a progressive change in alternating load and mean load as desired. On the completion of a programme, the process

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* K_t (theoretical stress concentration factor) was just under 4. Frocht[4] gives 3.95 for a thin specimen, where the stress is essentially 2-dimensional.

is automatically repeated. In the present series of tests, the mean load was maintained constant while the alternating load was varied continuously according to the required programme.

5 LOAD PROGRAMMES

Three different programmes were applied. Fig.2 shows the simplified frequency spectrum, an exponential distribution, from which all three were derived, and diagrammatic representations of the programmes for which the control cams were designed. For practical reasons, it was necessary to limit the maximum alternating stress to 11,500 lb/in^2 corresponding to a 27.5 ft/sec gust. It will be seen from Fig.2 that the same relative gust frequencies obtained for all three programmes, but the programmes differed as follows: in No.2 the number of cycles per programme was halved as compared with No.1, and in No.3, the programme was truncated at 7.5 ft/sec instead of 5 ft/sec. In every programme the alternating load began at the minimum value, increased steadily to the maximum, then decreased again to the initial value, as shown diagramatically in Fig.3. The cycle of loading then started over again and continued until failure of the specimen. In practice the actual programmes were not exactly as designed on account of imperfect control.

6 LOADS AND STRESSES

The loads were computed for a hypothetical aircraft wing in which the stress developed in steady level flight was 14,000 lb/in^2 (on nett area of cross section) and the stress increment for a 10 ft/sec gust was 4,200 lb/in^2. Thus the mean stress for all tests was 14,000 lb/in^2 including the tests to obtain the endurance curve at constant alternating stress shown in Table 1 and Fig.4. Curve B in Fig.4 is a computed 'damage rate' curve found by associating curve A with the basic load spectrum (Fig.2). Tensile control results are recorded in Table 2.

7 SAMPLING CALIBRATION OF PROGRAMMES

Fluctuations of load became evident during work on No.2 programme. A strain gauged specimen was therefore calibrated and a sample record of strain variations for one complete programme was taken, using a Kelvin-Hughes pen recorder. Two such records were taken of programme No.3. In each case, the amplitudes were measured and the numbers of cycles computed, giving the sample load spectra shown in Fig.5. It will be seen that for the most damaging gust range (between 10 and 20 ft/sec) programme No.2 conforms closely to the intended programme, giving one-half as many gusts per programme as No.1. Hence, the predicted number of programmes for No.2 would be approximately double that for No.1.

Programme No.3 as recorded cannot be associated accurately with either No.1 or No.2.

8 NUMBER OF PROGRAMME TESTS

6 specimens were tested under programme No.1
6 " " " " " No.2
5 " " " " " No.3

9 COMPUTATION OF 'PREDICTED LIFE' BY MINER HYPOTHESIS

To compute the theoretical damage, the entire range of alternating stress is divided into a convenient number of intervals and the number of cycles per programme in each interval is treated as if all these cycles were imposed at the middle stress value. If these numbers be designated n_1 n_2 ..n_i and the endurance obtained from the S-N curve for the middle of these intervals are N_1 N_2 ... N_i, then the Miner hypothesis states that

$$D = \Sigma \frac{n}{N}$$

where D is the fractional damage inflicted per programme; i.e. the 'predicted life' is 1/D programmes. This process of computation is illustrated in Table 3, where the theoretical damage and the predicted life are worked out for programme No.1. Tables 4 and 5 show similar calculations for programmes 2 and 3. As the values for N are taken from a mean endurance curve, the predicted lives under programme testing are for average specimens. These lives are:-

Programme No.1	8.5	programmes
" No.2	18.3	"
" No.3	9.3	"

10 RESULTS FOR PROGRAMME TESTS

The programme test results are shown in Table 6. Failures mostly occurred near half way on the rising half of the programmes, i.e. around the 15 ft/sec gust level. Results have been quoted to the nearest complete programme, when, as shown by the markings on the fractured surfaces, the fatigue crack had already severely weakened the specimen.

Photographs of typical fractures are given in Fig.6. Changes in texture of the fractured surface (similar to those often found in service failures) indicate the progress of the crack during the final programmes before failure.

11 DISCUSSION OF RESULTS

Both arithmetic and geometric means have been quoted in Table 6 because there is no strict averaging procedure for this type of test. When scatter is small, as in programme No.2, there is very little difference between the two means. It is shown in footnote 2, Table 6, that if exceptionally high results are disregarded the predicted and the experimental mean lives are in good agreement.

High accuracy of loading cannot be claimed for these tests because a large proportion of the cycles are at low stress range, and because hunting made close control somewhat difficult.

To the degree of accuracy for which the endurance curve (Fig.4, curve A) is definable it can be said that the Miner hypothesis is conservative under these loading conditions, and the worst result (6 programmes in No.3) realised more than 60 per cent of the predicted mean life. It is therefore a fair conclusion - in agreement with the conclusions of Ref.3 - that the Miner hypothesis has been substantiated in these tests as a good engineering rule for estimating the life of a notched aluminium alloy specimen under aircraft load spectra. This does not prove the hypothesis for all types of stress combinations, nor does it validate the hypothesis for similar loading on joints, in which fatigue life is influenced by fretting.

In a comprehensive review of work on cumulative damage, Roylance[5] gives not only a summary of the numerous two-stress-level investigations which have been made, but also a resumé of work by G. Wällgren[6] and by Schiyve and Jacobs[7,8] for programme tests on aluminium alloy 24 S-T alclad, with three different types of specimen. The tests were sufficient in number only to show general trends; but for the majority of cases $\Sigma \frac{n}{N}$ was greater than unity, and the lowest value recorded for a 'notched' type of specimen was 0.90. The ratio of maximum to mean stress was 2.6.

Other investigators, using only two levels of alternating stress, have found that a prior cycle ratio of less than 20% at the higher stress produces a strengthening effect. With the present form of programme, in which the load range was raised and lowered steadily, no such effect is apparent. Corten, Sinclair and Dolan[9], investigating the behaviour of 75 S-T6 alloy (similar in composition and properties to D.T.D.363A), and applying a repeated block stress programme of two levels found that when the major stress was applied for 5% of the total number of cycles $\Sigma \frac{n}{N}$ was greater than unity, whereas if it was applied for 10% or more of the total number of cycles $\Sigma \frac{n}{N}$ was less than unity. On the other hand, Hardrath and Utley[10] found, for 24 S-T4 alloy in rotating bending, that an exponential programme gave $\Sigma \frac{n}{N} = 0.62$ whereas a sinusoidal one (i.e. with a much larger number of high loads) gave $\Sigma \frac{n}{N} = 0.92$.

Clearly it would be unwise to generalise from the present tests. Further investigation is needed into such effects as the order of application of the loads within a programme, the relative frequency of the various loads and the relationship between the stress produced locally and the basic properties of the material.

One further point is the bearing of the present tests on the conclusions of Gassner and of Wällgren that the alternating stresses which would not produce failure under 10^6 cycles in simple testing do in fact cause damage in a programme test. Programmes 1 and 2 of the present tests include a large number of cycles for the gust range 5-7.5 ft/sec, the theoretical damage for which (n/N) is negligible. If the actual damage at this level had been appreciable, it would be expected that mean values of $\Sigma \frac{n}{N}$ less than 1 would have been found. It is suggested, however, that some damage is done by the gusts between 5 and 7.5 ft/sec since the ratio between the realised and predicted numbers of programmes is greatest for programme No.3. This conclusion has to be treated with caution because of the wide scatter of results in programmes 1 and 3.

The present tests were limited to one aircraft structural material and to specimens where the fatigue life is uncomplicated by fretting. It is suggested that the next stage of this research should be done with a specimen in the form of a plain bar with a bolted joint at each end. In view of the recent trend in aircraft design (where fatigue life is a primary consideration) to avoid the use of D.T.D.363A in favour of alloys with slightly lower strength but better fatigue properties, the next specimen should be made in material to B.S. L.65, which is of the Al-Cu-Mg type and is still widely used. The tests could be extended later to material having a low proof/ultimate ratio - e.g. L.64 or 24 S-T4 in order to 'bracket' the range of material properties for structural aluminium alloys.

It would be of considerable interest to extend the load spectrum to alternating loads greater than 1g and to vary the order in which the loads are applied.

12 CONCLUSIONS

With this material, type of specimen, and load spectrum it is found that the Miner hypothesis gives a conservative estimate of the average life. This is the same conclusion as was reached in Ref.3 for large notched specimens under a manoeuvre load spectrum.

The form of specimen, the type of material, and the order of the applied loads are variables requiring further investigation.

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4	Frocht, M.M.	A photo-elastic investigation of stress concentrations due to small fillets and grooves in tension. N.A.C.A. Technical Note No.2442 (1951).
5	Roylance, T.F.	A review of cumulative damage in fatigue. Ministry of Supply, S & T Memo. No.8/57 (May, 1957).
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APPENDIX 1

EXTRUDED ALUMINIUM ALLOY BAR TO SPECIFICATION D.T.D.363A (ZINC-BEARING ALLOY)

Specified chemical composition

Zinc	- Not less than 4.0 nor more than 8.0 per cent.
Copper	- Not more than 3.0 per cent.
Magnesium	- Not more than 4.0 per cent.
Manganese	- Not more than 1.0 per cent.
Chromium	- Not more than 1.0 per cent.
Iron	- Not more than 0.6 per cent.
Silicon	- Not more than 0.6 per cent.
Titanium	- Not more than 0.3 per cent.
Aluminium	- The remainder.

Specified heat treatment

Solution treated and artificially aged, i.e. heated to 460°C ±10°C, quenched and aged by heating at 135 ±10°C for requisite period.

Specified minimum strengths

	Test pieces* representing:-	
	Extruded sections greater than 3/8" in thickness.	Extruded sections not greater than 3/8" in thickness.
	Not less than:	Not less than:
0.1 per cent Proof stress	33 tons per sq. in.	30 tons per sq. in.
Ultimate tensile stress	38 tons per sq. in.	35 tons per sq. in.
Elongation	5 per cent	5 per cent

* For bars up to and including 1-1/8" diameter or width across flats, the tensile test piece shall be machined concentrically from the test sample; over this diameter or width, its longitudinal axis shall be not less than 9/16" from the surface of the test sample.

TABLE 1

Results of plain fatigue tests

Alternating stress (lb/in^2)	Cycles to failure
3,000	9,858,300
"	353,400
"	274,500
3,500	100,500
"	548,000
"	393,000
4,000	162,400
"	223,100
4,200	78,630
"	59,920
"	37,510
"	61,400
"	54,800
"	48,600
5,000	73,000
"	81,100
6,300	11,180
"	15,440
"	13,250
7,000	21,600
"	23,370
10,000	7,370
"	12,430
12,600	2,950
"	5,210

TABLE 2

Results of static control tests

Specimen No.	0.1 % P.S.	U.T.S.	Elong. %	R of A %
1 EF 17/16A	37.3	40.4	$5\frac{1}{2}$	5
1 FE 7/15B	37.4	39.6	$7\frac{1}{2}$	6
1 EF 16/7C	37.6	40.0	7	5
* 1 EF 9/4C	37.7	39.8	5	2
* 1 EF 9/4D	37.8	40.2	8	8
7 EF 11/17E	37.2	39.6	7	7

TABLE 3

Computation of theoretical damage per programme

Programme No.1

n is the number of cycles for the gust interval shown in column 1. The average alternating stress is f_A.

N is the endurance determined by the curve given in Fig.4 for the alternating stress f_A.

The fraction D of the total specimen life consumed in one programme is, according to the Miner hypothesis, $\Sigma\, n/N$. The ratio n/N, expressed as a percentage, is given in Col.5. The predicted endurance is 1/D programmes.

1	2	3	4	5
Gust interval (ft/sec)	f_A (lb/in^2)	n	N (see Fig.4)	100 n/N
5 - 7.5	2,620	7,400	10^7	0.0007
7.5 - 10	3,680	3,100	150,000	1.13
10 - 12.5	4,730	1,500	48,000	3.12
12.5 - 15	5,780	700	26,000	2.80
15 - 17.5	6,840	325	17,000	2.03
17.5 - 20	7,880	150	12,500	1.20
20 - 22.5	8,930	67	9,200	0.71
22.5 - 25	9.980	31	6,800	0.42
25 - 27.5	11,020	15	5,200	0.25
		13,288		11.78

$$D = \Sigma \frac{n}{N} = 11.78\%$$

$$\text{Hence predicted endurance} = \frac{100}{11.78} = 8.5 \text{ programmes}$$

TABLE 4

Computation of theoretical damage per programme

Programme No.2 as recorded

Gust interval (ft/sec)	f_A (lb/in^2)	n	N	100 n/N
5 - 7.5	2,620	4,400	107	-
7.5 - 10	3,680	600	150,000	0.40
10 - 12.5	4,730	700	48,000	1.46
12.5 - 15	5,780	280	26,000	1.08
15 - 17.5	6,840	180	17,000	1.06
17.5 - 20	7,880	66	12,500	0.53
20 - 22.5	8,930	33	9,200	0.36
22.5 - 25	9,980	21	6,800	0.31
25 - 27.5	11,020	13	5,200	0.25
		$\Sigma n = 6,293$		5.45%

$$D = \Sigma \frac{n}{N} = 5.45\%$$

Hence predicted endurance $= \frac{100}{5.45} = 18.3$ programmes

TABLE 5

Computation of theoretical damage per programme

Programme No.3 as recorded

Gust interval (ft/sec)	f_A (lb/in^2)	n	N	100 n/N
5 - 7.5	2,620	810	10^7	-
7.5 - 10	3,680	1,800	150,000	1.12
10 - 12.5	4,730	1,650	48,000	3.44
12.5 - 15	5,780	747	26,000	2.87
15 - 17.5	6,840	193	17,000	1.13
17.5 - 20	7,880	103	12,500	0.825
20 - 22.5	8,930	60	9,200	0.65
22.5 - 25	9,980	27	6,800	0.4
25 - 27.5	11,020	12	5,200	0.23
27.5 - 28	11,600	8	4,000	0.05
		5,410		10.7%

$$D = \Sigma \frac{n}{N}$$

Hence estimated endurance $= \dfrac{100}{10.7} = 9.3$ programmes

TABLE 6

Programme test results

Programme No.	Upper gust limit (ft/sec)	Lower gust limit (ft/sec)	Cycles per programme	Number of complete programmes to failure	Arithmetic mean	Geometric mean	Predicted number	Ratio minimum: predicted endurance	Remarks
1	28	5	13,000	9, 7, 10, 21, 9, 9	11	10	8.5	0.82	
2	28	5	6,290	19, 21, 22, 14, 23, 18	19.5	19.3	18.3	0.765	Programme virtually half No.1 programme.
3	28	7.5	5,530	13, 6, 52, 7, 17	19	13.7	9.3	0.645	

Notes:

1 The predicted endurances for programmes 2 and 3 are computed for the recorded programmes (see Fig.5).

2 The exceptionally high value of 52 programmes, in No.3, seems abnormal. But even if we discount the bias produced by this high result, the means of the remaining four values (Arithmetic 10.75, Geometric 9.8) are slightly higher than the predicted life. Similarly, if the exceptional result (21 programmes) of No.1 is disregarded, the arithmetic mean becomes 8.8.

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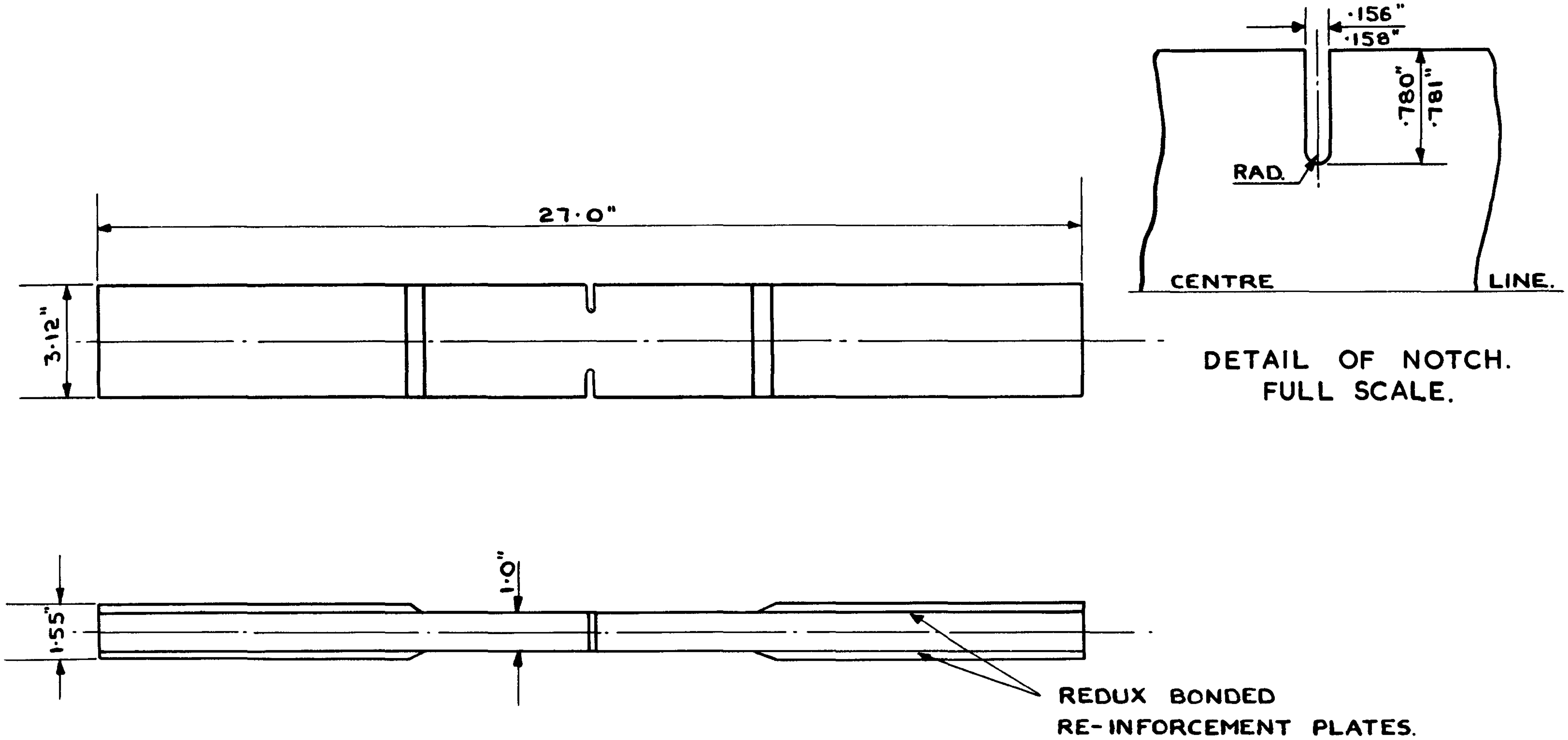

THEORETICAL STRESS CONCENTRATION FACTOR
IN TENSION $K_T = 3{\cdot}95$
(FROCHT. N.A.C.A. TECHNICAL NOTE Nº 2442.)

MATERIAL: D.T.D. 363 A. SCALE: 1:4

FIG. 1. TEST SPECIMEN.

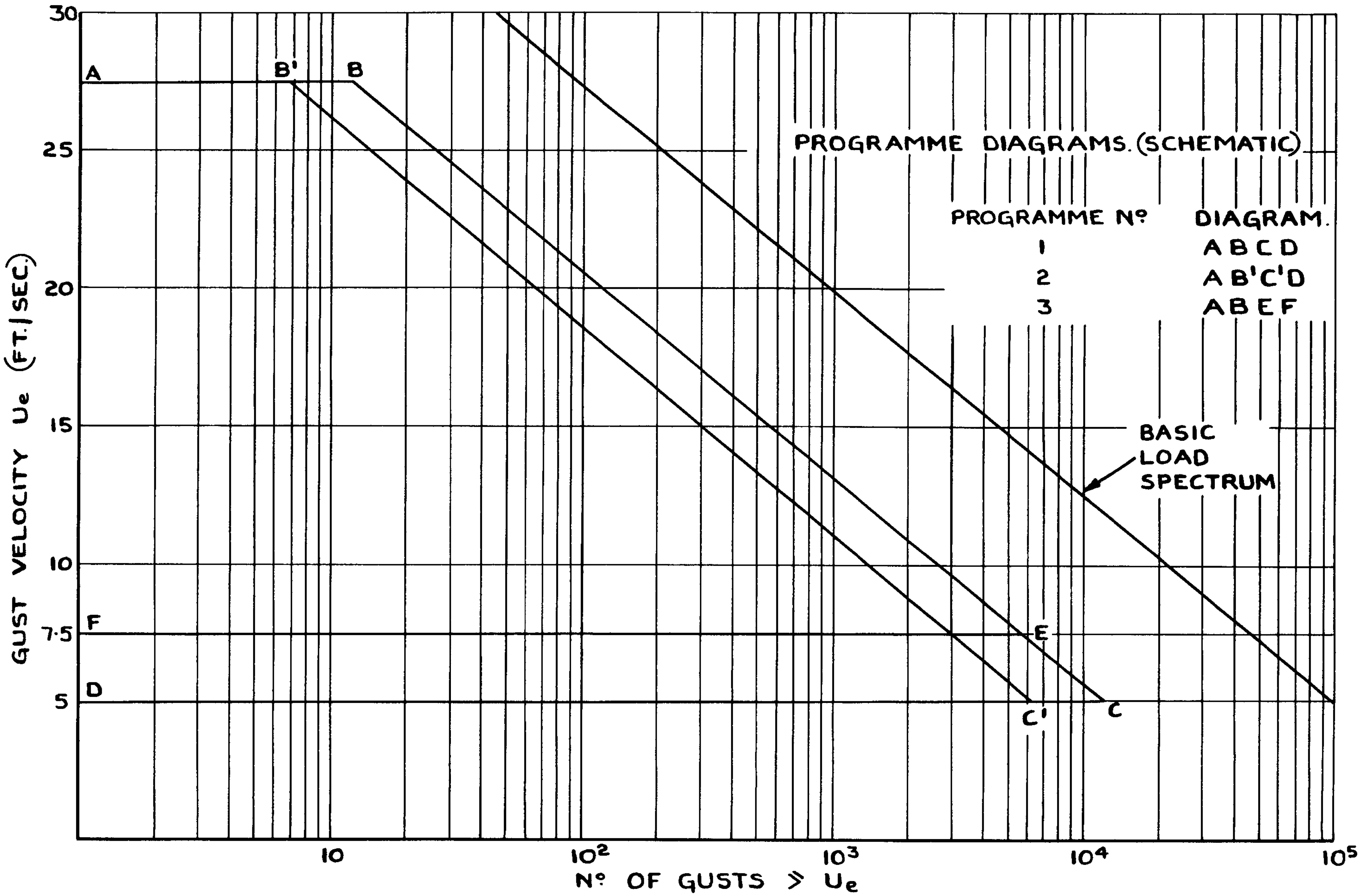

FIG. 2 DESIGN PROGRAMME DIAGRAMS.

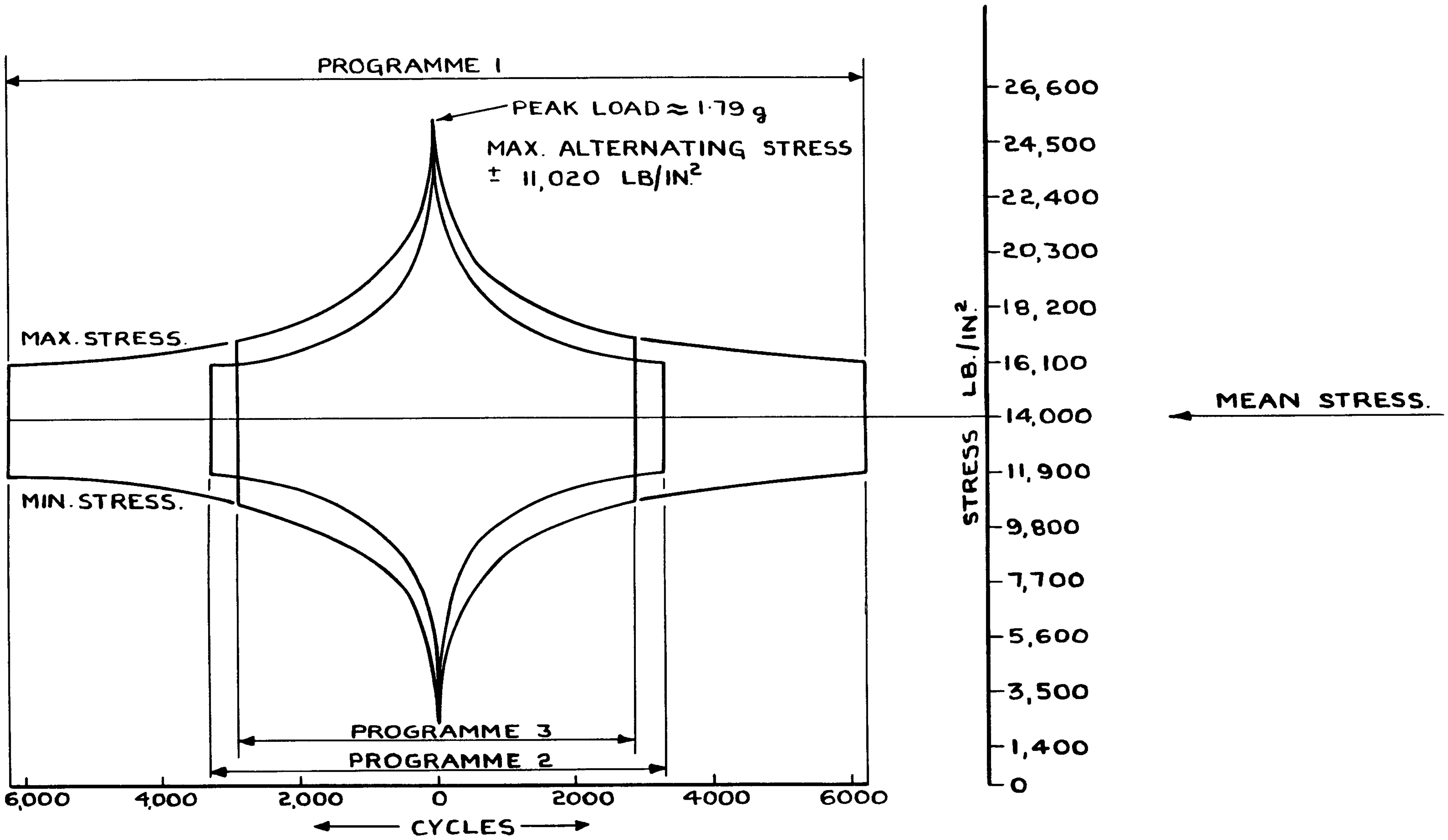

FIG. 3. PROGRAMME STRESS VARIATIONS (DESIGN.)

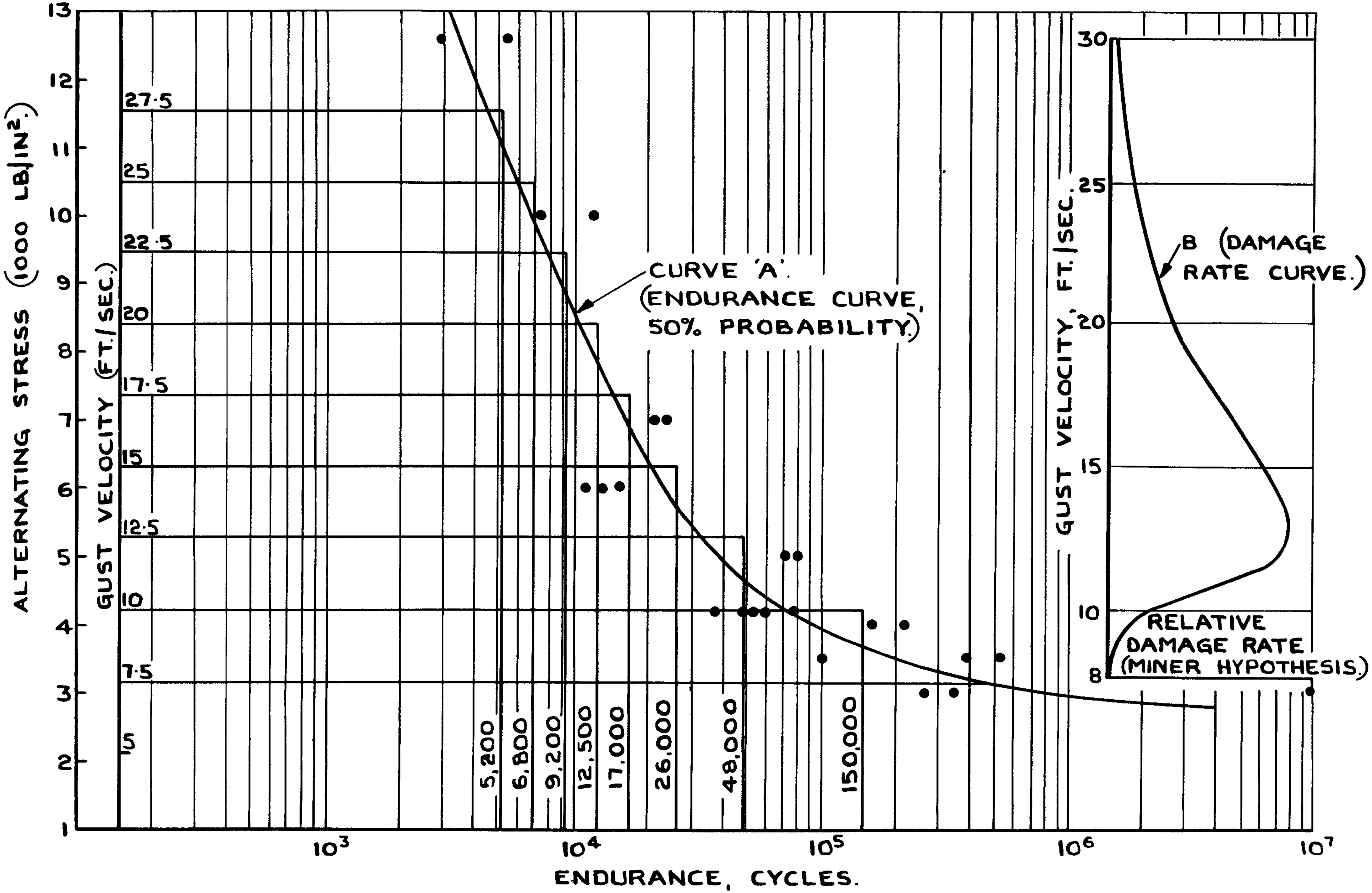

FIG. 4. ENDURANCE CURVE & DAMAGE RATE CURVE.

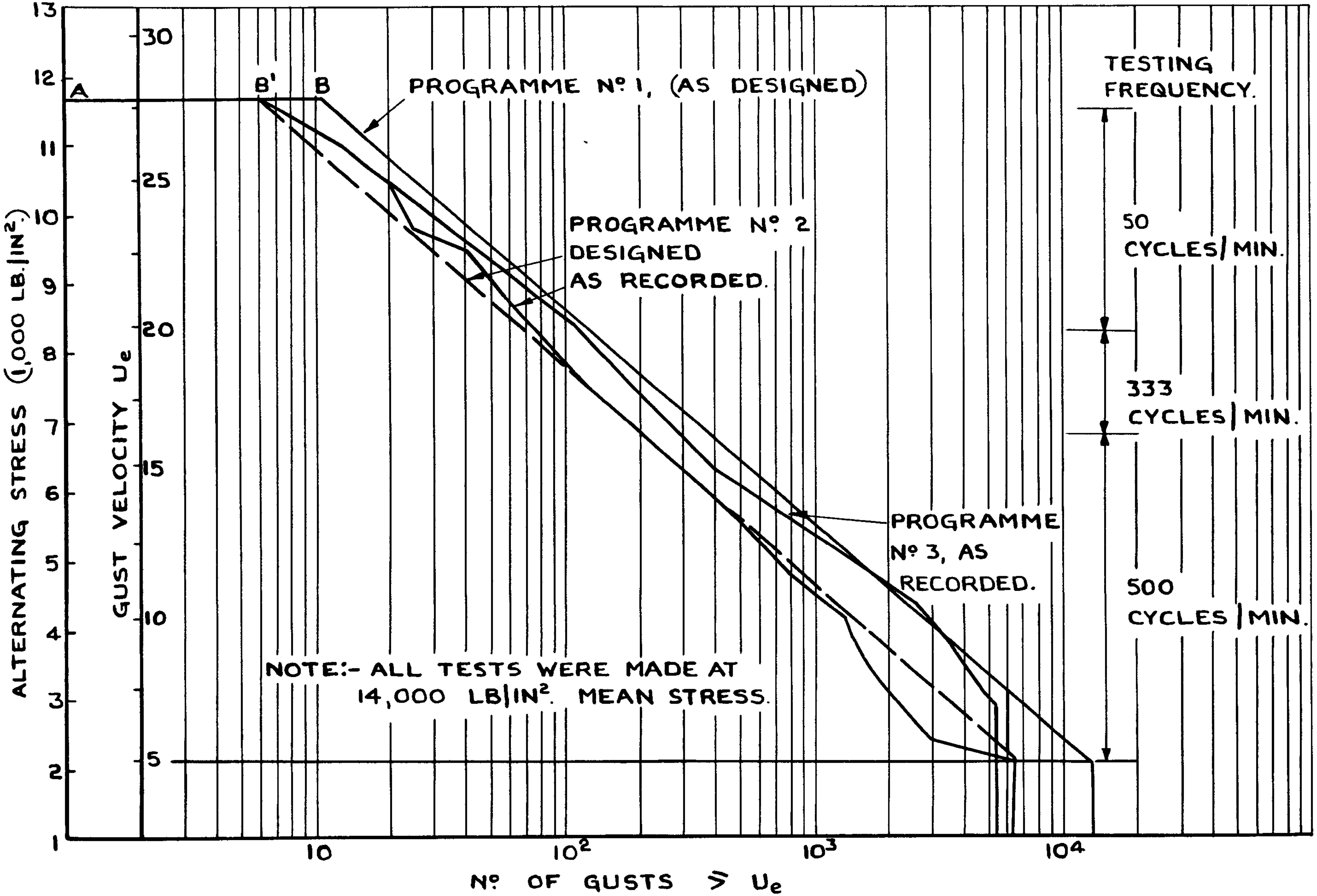

FIG. 5. COMPARISON BETWEEN ACTUAL AND DESIGN PROGRAMMES.

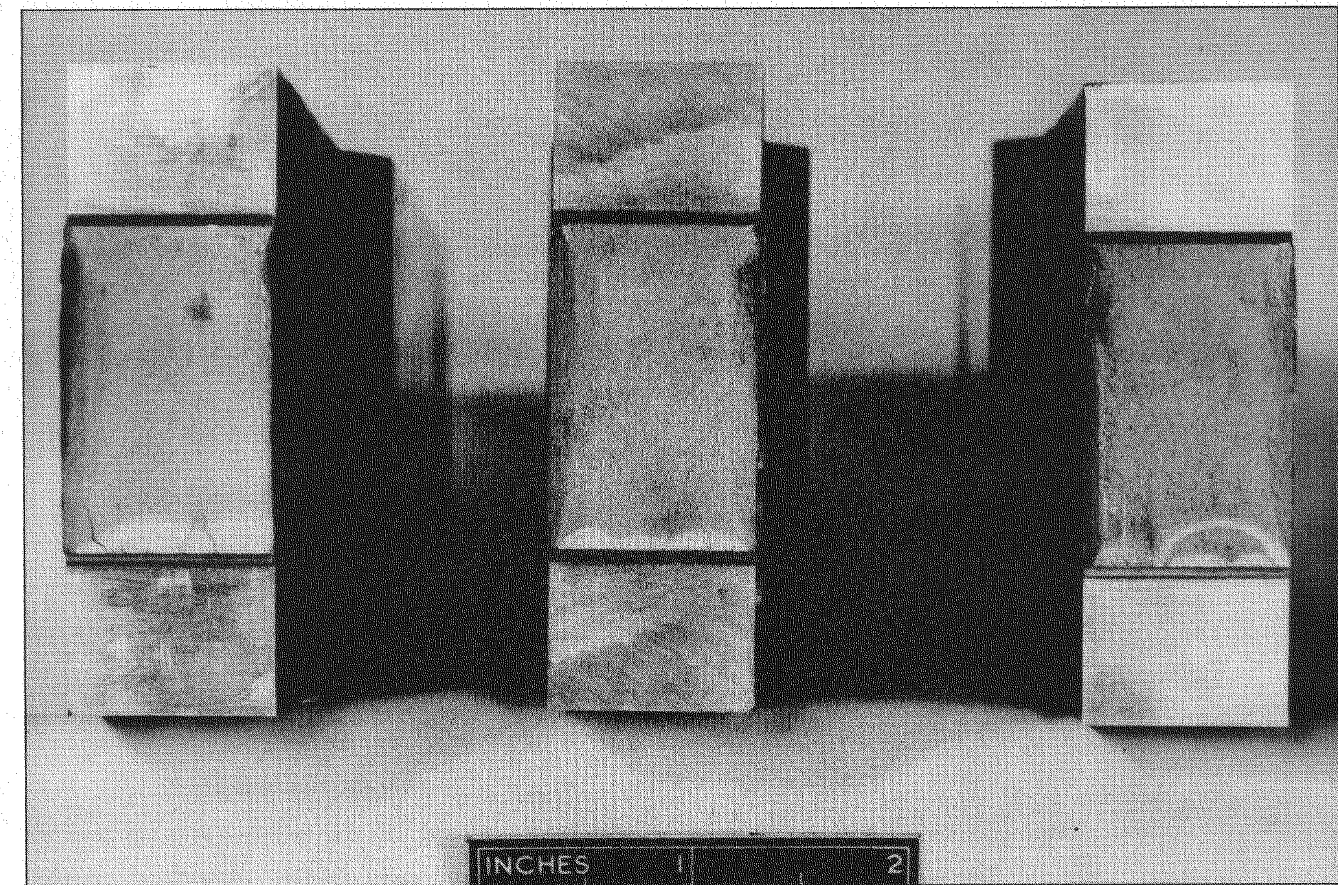

FIG.6. SPECIMENS OF FRACTURES

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