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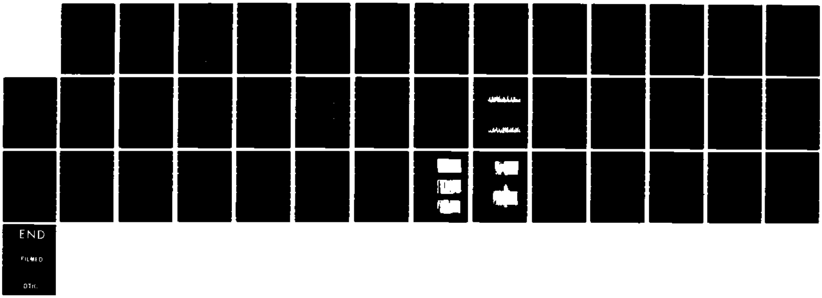

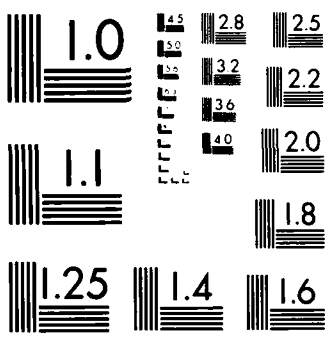


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MELBOURNE, VICTORIA

Structures Technical Memorandum 388

# A COMPARISON OF FATIGUE LIVES UNDER A COMPLEX AND A MUCH SIMPLIFIED FLIGHT-BY-FLIGHT TESTING SEQUENCE

J.Y. MANN and G.W. REVILL



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# A COMPARISON OF FATIGUE LIVES UNDER A COMPLEX AND A MUCH SIMPLIFIED FLIGHT-BY-FLIGHT TESTING SEQUENCE

J.Y. MANN, G.W. REVILL

SUMMARY

Flight-by-flight fatigue tests were carried out on specimens representing part of the front flange of the main spar of the Mirage III wing. Two loading spectra/loading sequences were used, the first being a 200-flight sequence incorporating 24 different types of flight developed by the Eidgenossisches Flugzeugwerk in Switzerland and the second a much simplified 100-flight sequence incorporating only 4 different types of flight developed by Avions Marcel Dassault in France.

The fatigue tests showed that there were no significant differences in the lives to failure between specimens tested under the two sequences, and it was therefore concluded that the use of the simplified stress spectrum/sequence would not have invalidated the findings of a previous investigation to develop life-enhancement procedures for the Mirage wing main spar.



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CONTENTS

## 1. INTRODUCTION

Investigations have been carried out in Switzerland, Australia and France to determine the fatigue behaviour of the Mirage III wing and to develop procedures for increasing the life of the main spar (Refs 1-3).

The loading sequence used during the fatigue testing of the complete structure in Switzerland (at the Eidgenössisches Flugzeugwerk (F+W), Emmen) was a 200 flight flight-by-flight sequence made up of 24 distinct flights. However, most of the fatigue tests at the Aeronautical Research Laboratories (ARL) on specimens representing sections of the spar flange - including those used to develop the rear flange refurbishment techniques (Ref. 3) - were carried out using a 100 flight flight-by-flight sequence of only four different types of flight which Avions Marcel Dassault (AMD) had derived from a much simplified version of the Swiss load spectrum.

In order to demonstrate whether the findings of the various spar life-enhancement investigations might have been invalidated by the use of the simplified spectrum/sequence, a program of comparative fatigue tests was undertaken using the two spectra/sequences. The results of these tests are covered by this report.

## 2. FATIGUE LOADING SPECTRA

The test load spectrum adopted for the full-scale Mirage III fatigue test at the F+W was derived from fatigue meter records and strain measurements on aircraft in the Swiss Mirage fleet (Ref. 4). Various missions were defined and identified by 24 "typical" flights which were then combined to provide the required load spectrum in a test sequence containing 200 flights. The cumulative frequency spectrum of 'g' exceedances is shown in Fig. 1 and the order of occurrence of the 24 distinct flights in the 200-flight sequence is given in Table 1 (Ref. 5). It should be noted that the maximum load of the sequence (+7.5g) occurs twice in each sequence of 200 flights - in flights 48 and 150. Each typical flight consisted of three or four segments (representing, for example, take-off, combat, landing), the actual load sequence in each being appropriate to the particular segment.

During the development of the Mirage III aircraft AMD derived a much simplified version of the Swiss test spectrum which consisted of only four different types of flight arranged into the 100-flight sequence shown in Fig. 2. Each 100-flight sequence included only one occurrence of the maximum load of +7.5g - during flight 42, and adopted a lo-hi-lo sequence of loads within each "flight". The cumulative frequency spectrum of loads for the French sequence is also shown in Fig. 1. Except at low loads, both the Swiss and French load spectra are very similar.

## 3. TEST SPECIMENS AND MATERIAL

Figure 3 illustrates the type of low-shear-load-transfer bolted joint fatigue specimen used in this investigation. It was designed to represent the lower front flange of the main spar of the Mirage III at the position (hole no. 12) at which the major failure had occurred in the first series of full-scale fatigue tests on the structure carried out at the F+W. Although identical to the specimens used in the testing program reported in Ref. 2, only two of the variants of hole treatments and fasteners were used in the current tests namely:

(i) Type C, where the bolt holes were cold-expanded by the Boeing Split-Sleeve process (Ref. 6) by nominally 3% and 0.25 inch clearance-fit bolts used as the fasteners, and

(ii) Type D, where 8.15 mm outside diameter interference-fit bushes of grade 304 austenitic stainless steel were inserted in the holes and 5 mm clearance-fit fasteners used. The bush interference was 0.25 to 0.35%.

Full details of the cold-expansion and interference-fit bushing treatments which were adopted are given in Appendix 3 of Ref. 2.

The fatigue specimens were made from aluminium alloy B.S. L168 supplied in the form of 63.5 mm x 31.75 mm extruded bars. Specification values for the tensile properties and chemical composition together with those derived from ARL tests on the particular batch of material (laboratory code GR) are given in Table 2. Table 2 also includes the results of tests on compact tension fracture toughness specimens taken from offcuts of the extrusions. The notch in these specimens was machined in the long transverse direction.

## 4. FATIGUE TESTS

The fatigue testing program included 22 of the cold-expanded hole specimens (Type C) and eight specimens incorporating interference-fit bushes (Type D). About half of each type were tested under the French and Swiss sequences respectively.

All fatigue tests were carried out in a Tinius-Olsen servo-controlled electro-hydraulic fatigue machine. The French sequence was achieved using an EMR Model 1641 programmable function generator controlled by a punched tape and operating in sine wave mode; while the Swiss sequence was achieved through a DEC PDP 11/20 computer, using a control tape with a strain sequence corresponding to that at hole no. 12 in the Swiss full-scale test. This sequence was deduced from that at a strain gauge (position 1.4T) located near hole no. 12. The computer control provided a quasi-sinusoidal cyclic loading.

Fatigue loads were calculated on the basis that +7.5g corresponded to a gross-section-area stress (not including the skin plates) of 235 MPa (see Appendix), and that for the French sequence there was a single linear stress/g relationship, i.e. the 1g gross-area stress was 31.3 MPa (Ref. 2). The French cumulative frequency stress spectrum for +7.5g = 235 MPa is shown in Fig. 4, and the stress values for individual 'g' values are given in Table 3. Similarly, for the Swiss sequence, the +7.5g load level corresponded to 235 MPa, and stress and 'g' were linearly related. However, because of different loading cases within individual flights in the Swiss sequence (associated, for example, with fuel usage, elevon operation, the use of air brakes), there is not a unique stress/g relationship for every value of 'g'. Consequently, there are some differences between the Swiss cumulative frequency stress spectrum (Fig. 4) and load spectrum (Fig. 1) relative to the respective French spectra and, furthermore, the Swiss stress spectrum incorporates a much greater number of low-amplitude loads than does the French. Some tests were also carried out in which all stresses were scaled upwards by a factor of 1.25, i.e. at +7.5g the corresponding stress was 294 MPa. A trace of the stress sequence under the Swiss spectrum around flights 48 and 150 is shown in Fig. 5.

For tests involving the French sequence, cycles of +6.5g to -1.5g and +7.5g to -2.5g (a total of 39 cycles in 100 flights) were applied at a cyclic frequency of 1 Hz, whereas the remaining 1950 cycles per 100 flights were at 3 Hz. One 100-flight sequence took about 12 minutes to complete. The Swiss 200-flight test sequence (which consisted of about $2 \times 10^4$ cycles) was applied at an average frequency of 9.3 Hz, and took about 36 minutes to complete.

Fatigue test results for all specimens are given in Table 4. The "failure" bolt hole identification is shown on Fig. 3.

## 5. FATIGUE FRACTURES

The fracture surfaces of all specimens broken in this investigation are shown diagramatically in Fig. 6, and photographs of representative fractures are illustrated in Fig. 7. These show that holes nos 2 and 4 predominated as the holes from which the major fatigue crack development occurred, the only exceptions being two of the interference-fit bush specimens where the major crack initiation was close to hole no. 1. However, the actual fracture path in all but one of the 30 specimens tested passed through an adjacent bolt hole and in about half the cases provided evidence of fatigue cracking at these holes.

In the cold-expanded-hole specimens the fatigue fracture developed from multiple crack initiation along the bores of the holes whereas, for the interference-fit bush specimens, initiation by fretting at one or both faces of the specimen was more usual. Of the 22 cold-expanded hole specimens, the fatigue crack development in five approximated a through-the-thickness crack situation. In thirteen of the remainder the major cracking occurred at the end of the hole corresponding to the entrance point of the expansion mandrel, while for the other four specimens, it was at the exit end.

## 6. DISCUSSION

Table 5 summarises the results of the fatigue tests and provides a comparison of the average lives of the three groups of tests covered by the investigation.

The previous investigation (Ref. 2), which included tests under the French sequence only, demonstrated the superiority of the interference-fit bush system compared with hole cold-expansion for fatigue life enhancement. Those findings are supported by the present tests under the Swiss sequence.

Although the numerical values of the mean lives given in Table 5 for groups of specimens tested under the French spectrum are greater than those under the Swiss spectrum, the differences for individual groups are statistically significant* only for the cold-expanded hole specimens tested with +7.5g = 294 MPa. However, a comparison of the French and Swiss sequences based on a two-way analysis of variance and a pooling of the respective results for the two sequences indicated no significant differences in their average lives.

This result is not surprising as tests (Ref. 8) on larger bolted joints under the French sequence indicated that the estimated damage contribution from the lowest load range in the sequence amounted to only about 6% of the total damage. As in the current investigation, the minimum load range was 20% of the maximum load range of the sequence. Other multi-load-level fatigue tests on

---

* At a level of significance of 5%.

multiple-bolted joints of sheet/plate aluminium alloys have also shown that the omission of stress ranges up to and above the fatigue limit (corresponding to 25% of the maximum stress range) have no significant effect on fatigue lives (Ref. 9); and that load ranges of 25% of the maximum range contributed an estimated 10% of the total damage (Ref. 10). Similarly, Broek and Smith (Ref. 11) have shown that the omission of load ranges of up to about 25% of the maximum load range of the spectrum have no significant effects on the crack growth behaviour and fatigue lives of centre-notched panels of 7075-T3 aluminium alloy. These findings support the proposal (Ref. 12) that load amplitudes of up to 20% of the maximum load amplitude in a multi-load-level sequence might be omitted without significantly affecting fatigue lives.

Thus, on the basis of this investigation, there is no evidence to suggest that the conclusions arrived at from the Mirage III spar life-enhancement investigation (Ref. 3) would be invalidated because of the use of a relatively simple flight-by-flight loading sequence for that testing program.

## 7. CONCLUSIONS

Flight-by-flight fatigue tests carried out on specimens representing part of the front flange of the main spar of Mirage III wings have indicated:

(i) that there are no significant differences in the lives to failure between specimens tested under a complex flight-by-flight sequence incorporating 24 types of flight and a much simplified flight-by-flight sequence of only four types of flight; and

(ii) that the findings of a previous investigation to develop life-enhancement procedures for the Mirage wing main spar would not be invalidated by the use of the simplified spectrum/sequence.

## ACKNOWLEDGEMENTS

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# APPENDIX

## Derivation of test stresses

The stress at 7.5 g was derived from strains measured at gauge 1.4T during the 1979 strain survey of the left-hand Swiss Mirage test wing. This gauge was located at the inner surface of the lower front flange of the main spar between bolt hole no. 14 and the spar web, and a multiplying factor of 1.2 was used to estimate the strain at the Swiss failure location (hole no. 12). Two different methods were used to estimate the strain at 7.5 g, and the value of 235 MPa adopted for this investigation was an average of the two. The first was determined directly from the actual numerical value of strain at 5 g using the ratio 7.5 (g)/5 (g) and resulted in a strain of 3240 microstrain (stress 237 MPa). The second method was based on the average microstrain per g from the 1 g to 5 g increment (Ref. 7) and resulted in a strain of 3201 microstrain (stress 234 MPa).

TABLE 1 - SEQUENCE OF THE 24 "TYPICAL" FLIGHTS (TF) IN F+W 200-FLIGHT TEST LOADING SEQUENCE (REF. 5)

Flights

| 1 to 40 | 41 to 80 | 81 to 120 | 121 to 160 | 161 to 200 |
|---|---|---|---|---|
| 1 TF14 | 41 TF14 | 81 TF14 | 121 TF9 | 161 TF22 |
| 2 TF10 | 42 TF12 | 82 TF10 | 122 TF5 | 162 TF4 |
| 3 TF6 | 43 TF21 | 83 TF15 | 123 TF5 | 163 TF12 |
| 4 TF11 | 44 TF6 | 84 TF23 | 124 TF16 | 164 TF11 |
| 5 TF15 | 45 TF17 | 85 TF24 | 125 TF13 | 165 TF3 |
| 6 TF16 | 46 TF13 | 86 TF21 | 126 TF17 | 166 TF14 |
| 7 TF17 | 47 TF10 | 87 TF12 | 127 TF21 | 167 TF11 |
| 8 TF21 | [48 TF2] | 88 TF17 | 128 TF22 | 168 TF9 |
| 9 TF23 | 49 TF11 | 89 TF19 | 129 TF15 | 169 TF11 |
| 10 TF13 | 50 TF21 | 90 TF16 | 130 TF17 | 170 TF1 |
| 11 TF11 | 51 TF23 | 91 TF6 | 131 TF21 | 171 TF14 |
| 12 TF22 | 52 TF13 | 92 TF11 | 132 TF12 | 172 TF4 |
| 13 TF24 | 53 TF23 | 93 TF13 | 133 TF24 | 173 TF21 |
| 14 TF5 | 54 TF15 | 94 TF11 | 134 TF14 | 174 TF10 |
| 15 TF12 | 55 TF3 | 95 TF20 | 135 TF13 | 175 TF13 |
| 16 TF18 | 56 TF19 | 96 TF14 | 136 TF24 | 176 TF15 |
| 17 TF14 | 57 TF14 | 97 TF7 | 137 TF7 | 177 TF21 |
| 18 TF5 | 58 TF7 | 98 TF23 | 138 TF23 | 178 TF17 |
| 19 TF23 | 59 TF15 | 99 TF4 | 139 TF16 | 179 TF23 |
| 20 TF13 | 60 TF12 | 100 TF7 | 140 TF22 | 180 TF15 |
| 21 TF3 | 61 TF24 | 101 TF5 | 141 TF14 | 181 TF6 |
| 22 TF8 | 62 TF23 | 102 TF20 | 142 TF10 | 182 TF24 |
| 23 TF21 | 63 TF16 | 103 TF11 | 143 TF21 | 183 TF11 |
| 24 TF17 | 64 TF21 | 104 TF17 | 144 TF4 | 184 TF17 |
| 25 TF11 | 65 TF22 | 105 TF18 | 145 TF15 | 185 TF24 |
| 26 TF13 | 66 TF19 | 106 TF5 | 146 TF5 | 186 TF4 |
| 27 TF15 | 67 TF13 | 107 TF10 | 147 TF15 | 187 TF21 |
| 28 TF24 | 68 TF22 | 108 TF13 | 148 TF24 | 188 TF12 |
| 29 TF21 | 69 TF21 | 109 TF4 | 149 TF12 | 189 TF20 |
| 30 TF11 | 70 TF8 | 110 TF12 | [150 TF2] | 190 TF10 |
| 31 TF23 | 71 TF24 | 111 TF22 | 151 TF11 | 191 TF16 |
| 32 TF22 | 72 TF17 | 112 TF13 | 152 TF23 | 192 TF5 |
| 33 TF7 | 73 TF10 | 113 TF23 | 153 TF8 | 193 TF14 |
| 34 TF11 | 74 TF9 | 114 TF11 | 154 TF11 | 194 TR23 |
| 35 TF22 | 75 TF15 | 115 TF19 | 155 TF23 | 195 TF13 |
| 36 TF6 | 76 TF13 | 116 TF10 | 156 TF13 | 196 TF23 |
| 37 TF10 | 77 TF16 | 117 TF15 | 157 TF9 | 197 TF17 |
| 38 TF14 | 78 TF12 | 118 TF18 | 158 TF22 | 198 TF15 |
| 39 TF16 | 79 TF14 | 119 TF9 | 159 TF17 | 199 TF14 |
| 40 TF8 | 80 TF21 | 120 TF11 | 160 TF8 | 200 TF16 |

The flights containing normal accelerations of 6.5 g and greater are underlined and the maximum values applied in such flights are listed below.

| TF1 | TF2 | TF3 | TF4 | TF5 |
|---|---|---|---|---|
| 6.5 g | 7.5 g | 6.5 g | 7.0 g | 6.5 g |

TABLE 2

PROPERTIES OF TEST MATERIAL

(a) Chemical composition (%)

| Element | British Standard L168: 1978 | Test material GR |
|---|---|---|
| Cu | 3.9-5.0 | 4.29 |
| Mg | 0.2-0.8 | 0.43 |
| Mn | 0.4-1.2 | 0.76 |
| Fe | 0.5 max | 0.23 |
| Si | 0.5-0.9 | 0.74 |
| Ti | 0.15 max | not analyzed |
| Cr | 0.10 max | 0.01 |
| Zn | 0.25 max | <0.20 |

(b) Static tensile

| Property | British Standard L168:1978 | Test material GR |
|---|---|---|
| 0.1% proof stress (MPa) | - | 466 (sd 10) |
| 0.2% proof stress (MPa) | 440 | 474 (sd 12) |
| Ultimate tensile stress (MPa) | 490 | 524 (sd 12) |
| Elongation (%) | 7 | 11 (sd 2) |
| 0.1% PS/Ult | - | 0.89 |

sd = standard deviation

(c) Fracture toughness ($K_{Ic}$) of GR material

| Specimen thickness (mm) | $MPa.m^{1/2}$ | $ksi.in^{1/2}$ |
|---|---|---|
| 25 | 34.5* | 31.5* |
| 19 | 32.0+ | 29.2+ |

* Average of two specimens from the one bar.
\+ Average of five specimens from different bars.

Specimen no.
GR2D

Flights:
26,781

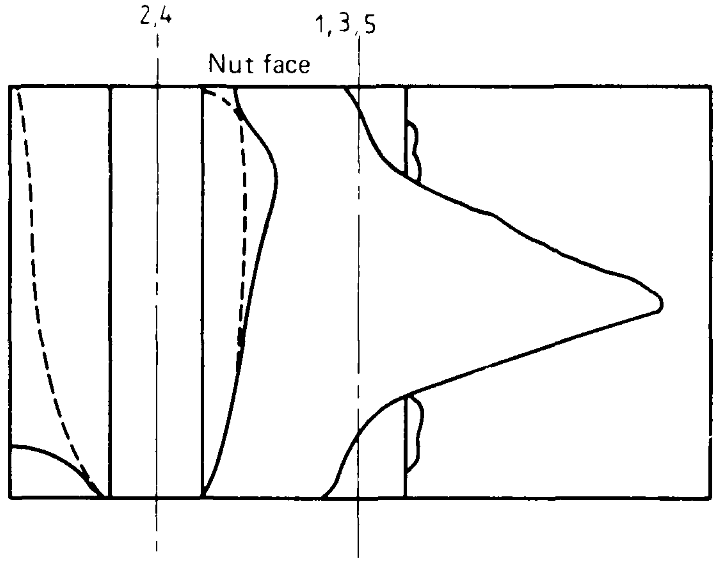
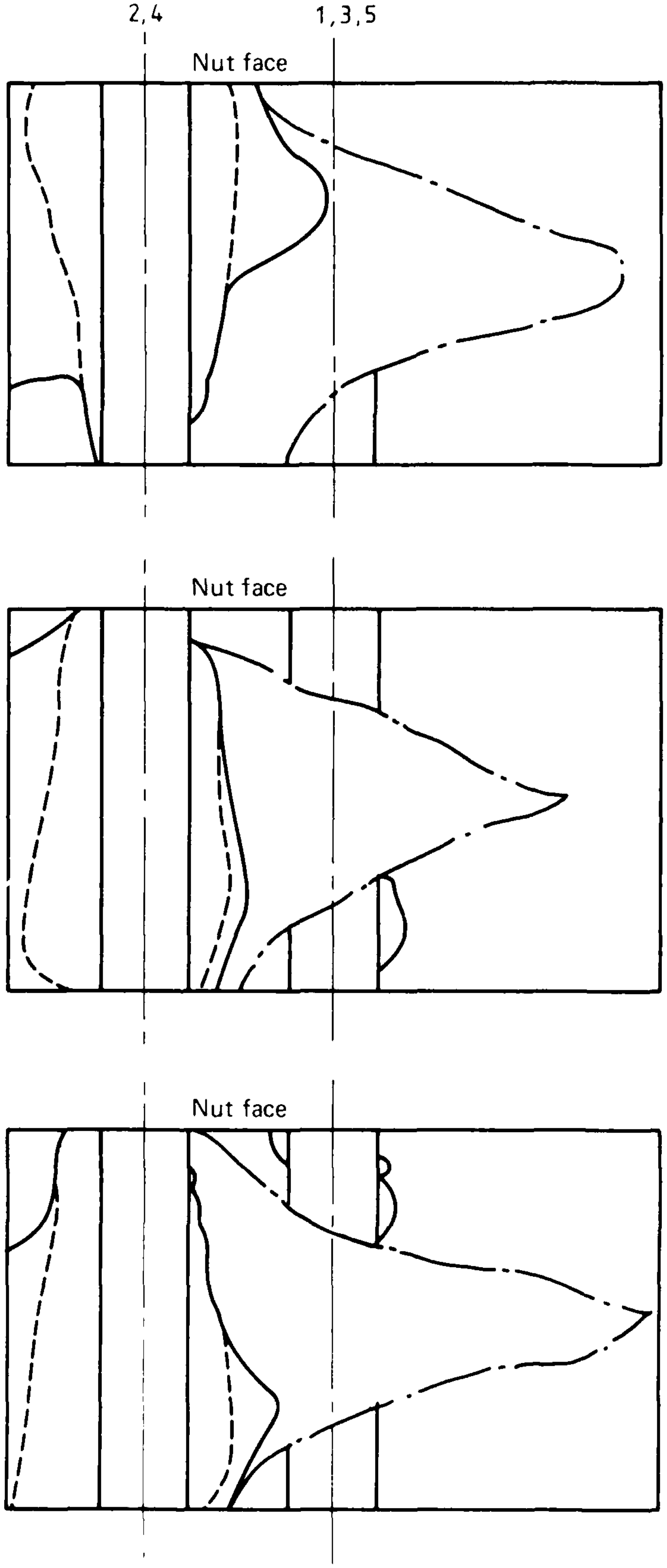



FIG. 6(a) FRACTURE SURFACES: SPECIMEN TYPE (C)
COLD - EXPANDED HOLES, FRENCH SEQUENCE,
+7.5g 235 MPa




Specimen no.
GR23D
Flights:
24,413

Specimen no.
GR9D
Flights:
25,813

Specimen no.
GR11B
Flights:
25,842

FIG. 6(a) FRACTURE SURFACES: SPECIMEN TYPE (C)
COLD EXPANDED HOLES, FRENCH SEQUENCE,
+7.5g 235 MPa

Specimen no.
GR6D
Flights:
14,742

Specimen no.
GR19D
Flights:
16,542

Specimen no.
GR3D
Flights:
20,427

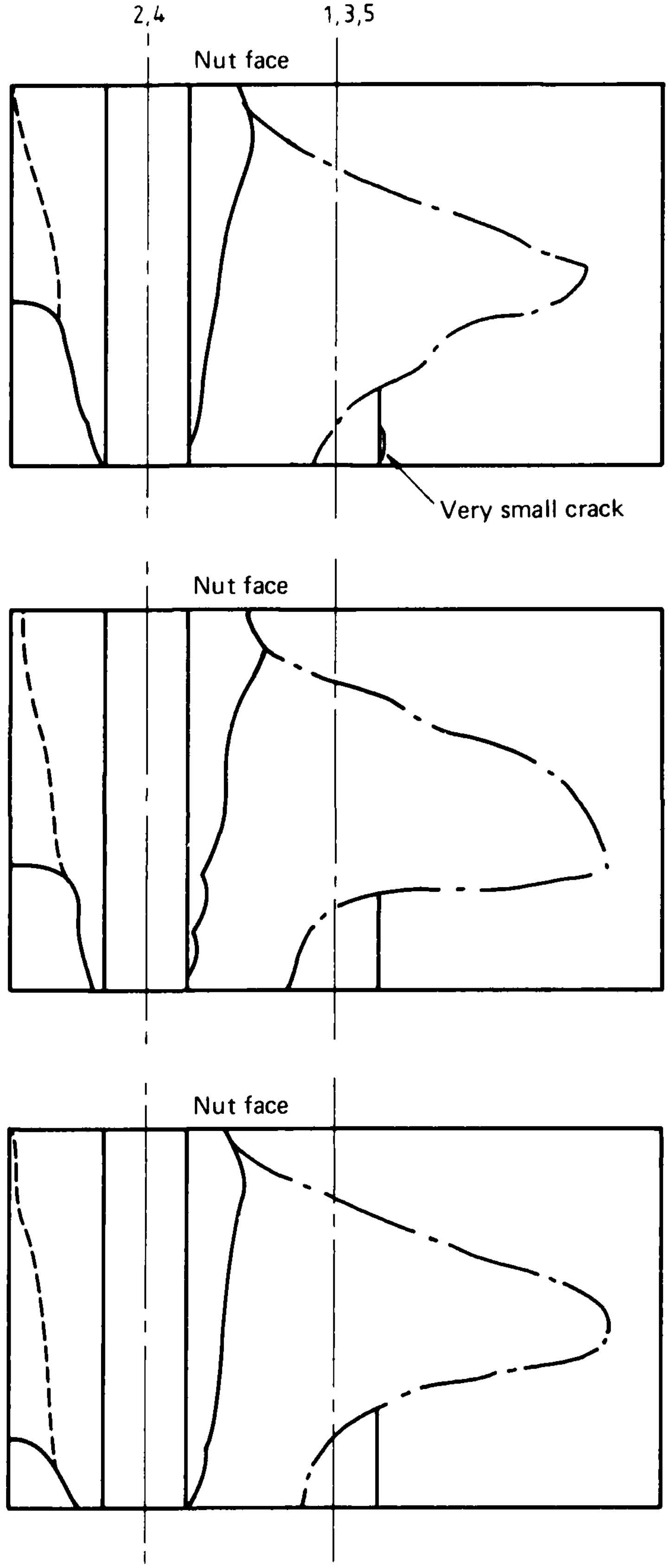
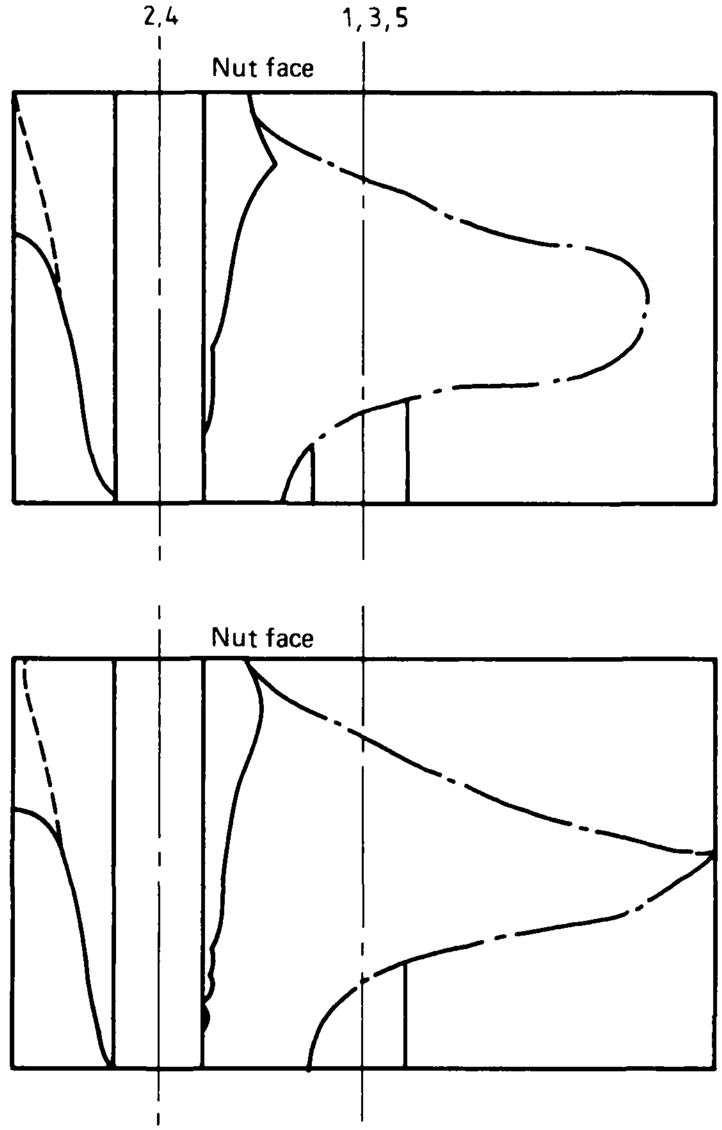



FIG. 6(a) FRACTURE SURFACES: SPECIMEN TYPE (C)
COLD – EXPANDED HOLES, FRENCH SEQUENCE,
+7.5g 235 MPa




Specimen no.
GR8B

Flights:
3,136

Specimen no.
GR12B

Flights:
3,223

(see Fig. 7(a) )

FIG. 6(a) FRACTURE SURFACES: SPECIMEN TYPE (C)
COLD – EXPANDED HOLES, FRENCH SEQUENCE,
+7.5g ≑ 294 MPa

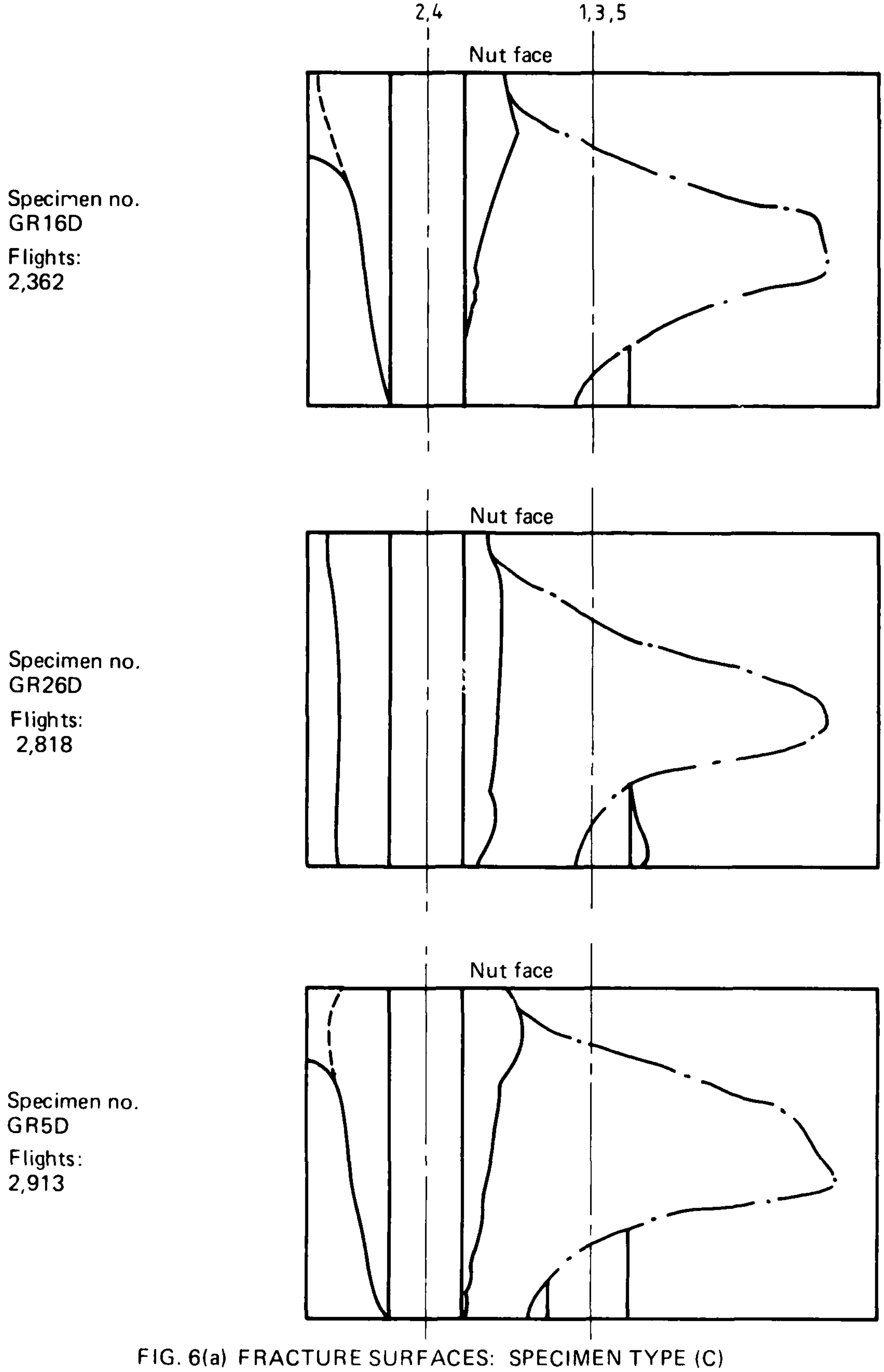



FIG. 6(a) FRACTURE SURFACES: SPECIMEN TYPE (C)
COLD - EXPANDED HOLES, FRENCH SEQUENCE,
+7.5g - 294 MPa

(The full lines indicate the approximate extent of fatigue cracking before final failure, while the small dashed lines represent the approximate boundaries of the 'flat' area of the major crack before the development of shear lips at an advanced stage of the crack propagation. The dot-dash lines represent the approximate boundaries of the shear lips at final fracture.)

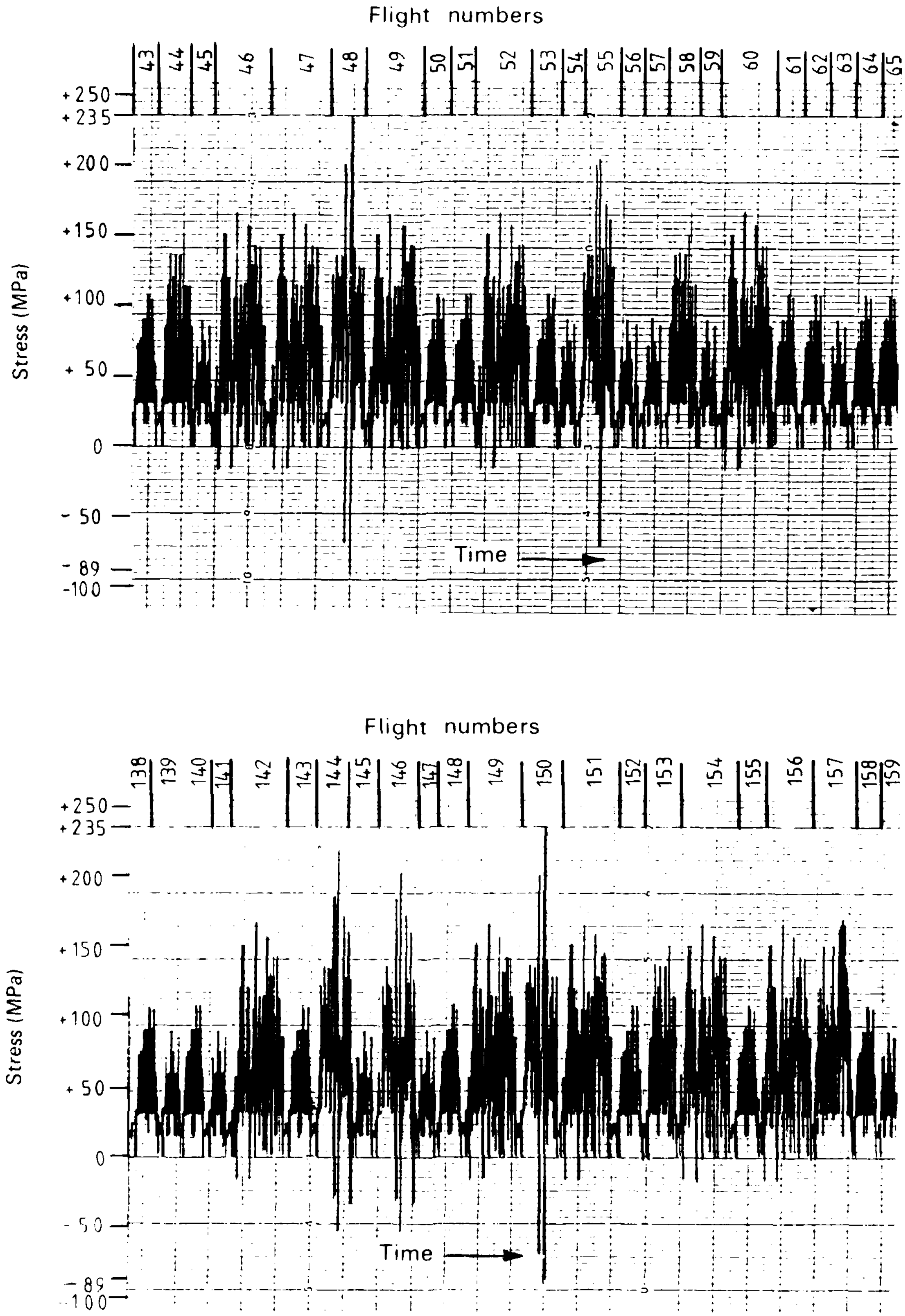



FIG. 5 STRESS SEQUENCE UNDER SWISS SPECTRUM ADJACENT TO FLIGHTS WITH +7.5g LOADS. (+7.5g 235 MPa)

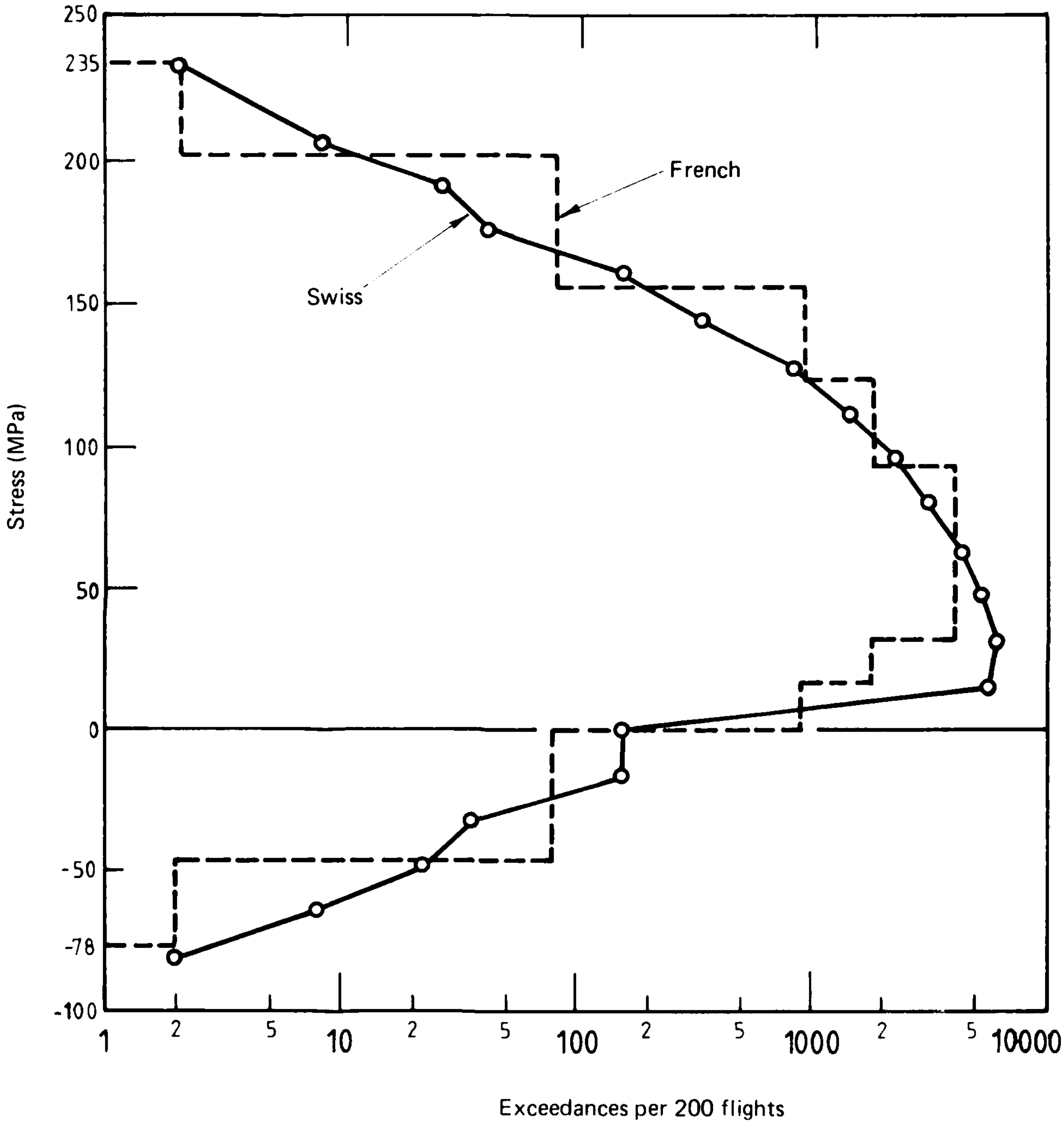
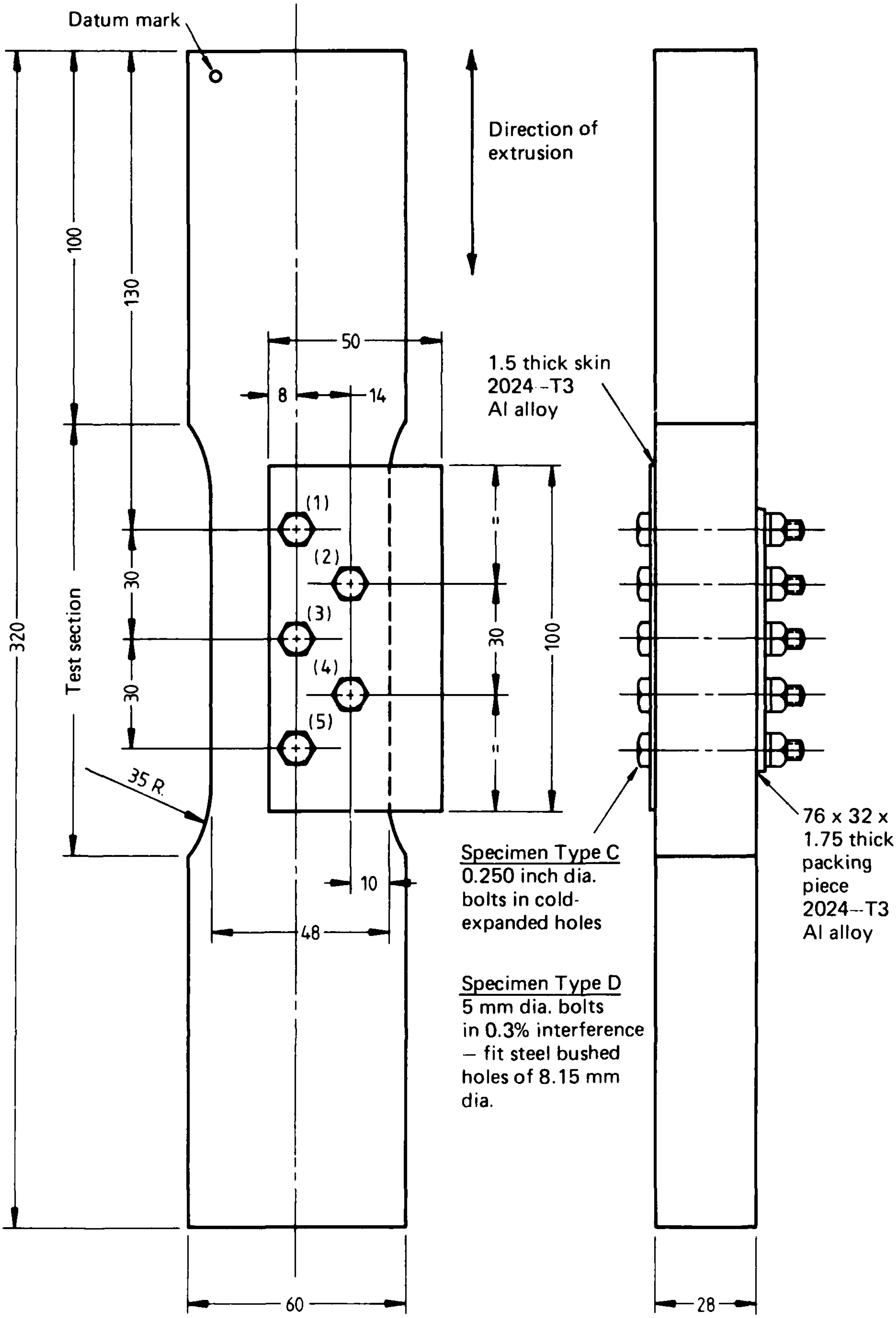



FIG. 4 STRESS SPECTRA FOR SWISS AND FRENCH SEQUENCES
(7.5g 235 MPa)




All dimensions in mm
Bolt hole positions in specimen indicated by number in ( )

Material: BS.L168 Al alloy

FIG. 3 MIRAGE SPAR LOWER FRONT FLANGE FATIGUE SPECIMEN

100 FLIGHTS (1989 CYCLES) REPRESENT 66.6 HOURS OF FLYING

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| FLIGHT A' → | 10 CYCLES +3g/+1g | 5 CYCLES +4g/+0.5g | 2 CYCLES +5g/0g | 1 CYCLE +6.5g/-1.5g | 1 CYCLE +7.5g/-2.5g | 1 CYCLE +6.5g/-1.5g | 2 CYCLES +5g/0g | 4 CYCLES +4g/+0.5g | 10 CYCLES +3g/+1g |
| FLIGHT A → | 10 CYCLES +3g/+1g | 2 CYCLES +4g/+0.5g | 2 CYCLES +5g/0g | 2 CYCLES +6.5g/-1.5g | 2 CYCLES +5g/0g | 2 CYCLES +4g/+0.5g | 5 CYCLES +3g/+1g | | |
| FLIGHT B → | 5 CYCLES +3g/+1g | 5 CYCLES +4g/+0.5g | 9 CYCLES +5g/0g | 4 CYCLES +4g/+0.5g | 5 CYCLES +3g/+1g | | | | |
| FLIGHT C → | 5 CYCLES +3g/+1g | 1 CYCLE +4g/+0.5g | 5 CYCLES +3g/+1g | | | | | | |

CYCLES OF +6.5g/-1.5g AND
+7.5g/-2.5g AT 1 Hz;
REMAINDER OF CYCLES AT 3 Hz

SEQUENCE OF FLIGHTS IN 100 FLIGHTS: 1 FLIGHT A', 18 FLIGHTS A, 36 FLIGHTS B AND 45 FLIGHTS C

| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
| B | C | C | B | C | C | C | A | C | C | B | B | A | C | C | C | B | A | C | B | B | B | A | C | C |
| 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 | 70 | 71 | 72 | 73 | 74 | 75 |
| C | B | C | C | B | C | B | B | C | C | C | A | B | A | C | C | C | B | A | B | B | B | C | B | C |

| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 |
| C | A | A | C | C | B | B | B | C | B | A | B | C | C | B | A | A' | B | C | C | A | A | B | B | C |
| 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 100 |
| C | A | B | C | B | A | B | C | C | B | A | A | B | C | C | B | C | C | B | B | C | B | C | A | C |

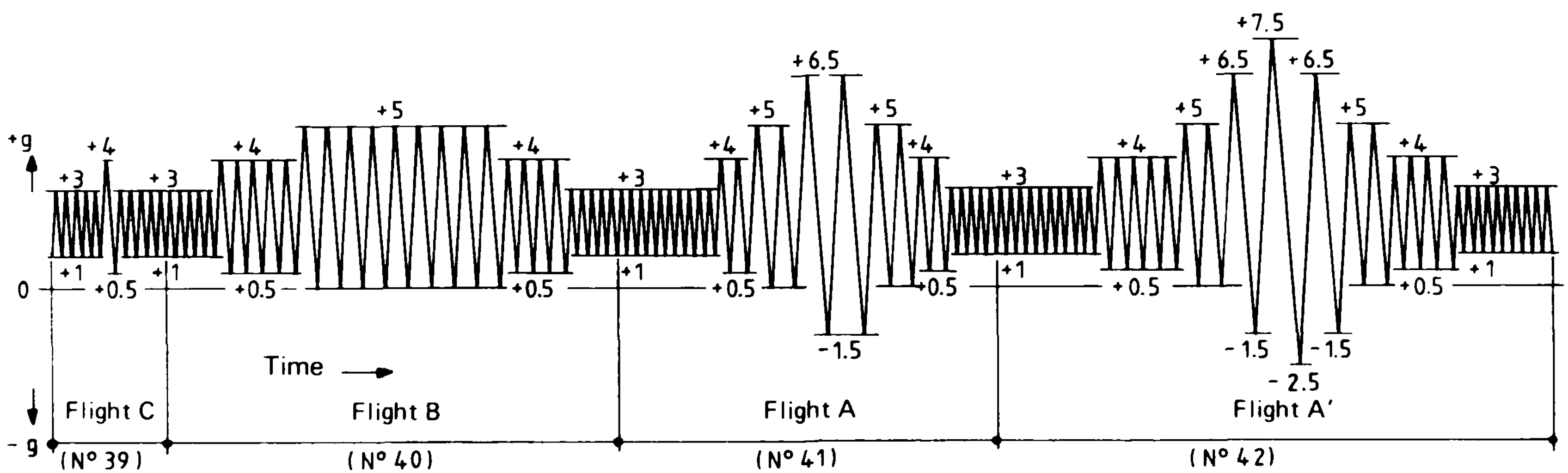



FIG. 2 FRENCH 100 FLIGHT MIRAGE III FLIGHT-BY-FLIGHT SEQUENCE

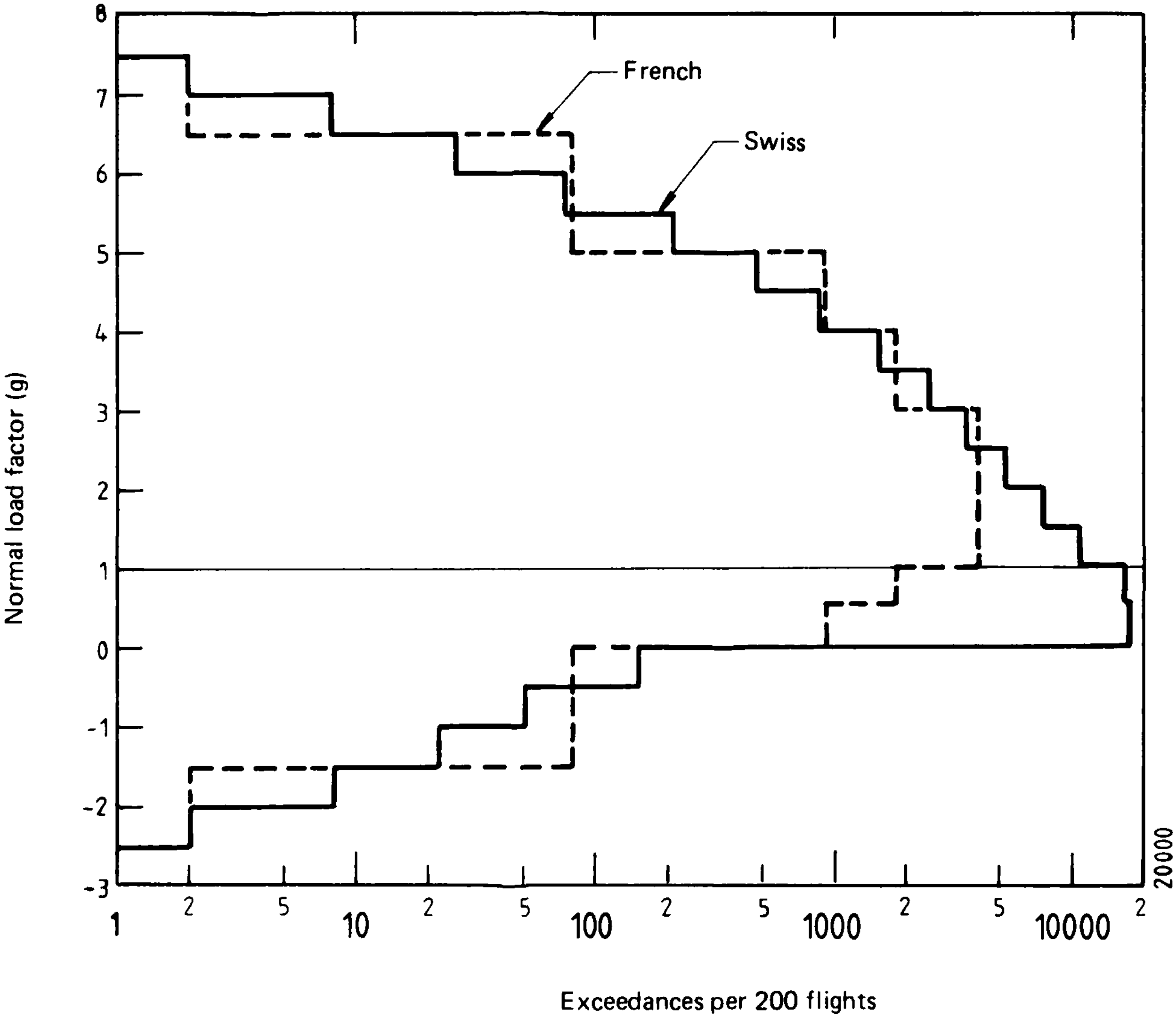



FIG. 1 LOAD SPECTRA FOR SWISS AND FRENCH TEST SEQUENCES

TABLE 5 - SUMMARY OF FATIGUE TEST RESULTS

| Specimen type | 7.5g stress (MPa) | Spectrum | Log. average life (flights) | Ratio French/Swiss |
|---|---|---|---|---|
| Cold-expanded holes | 294 | French | 2874 | 1.28 |
| | | Swiss | 2247 | |
| | 235 | French | 21570 | 1.21 |
| | | Swiss | 17775 | |
| Interference-fit bushed | 235 | French | 38610 | 1.06 |
| | | Swiss | 36354 | |

TABLE 4(b) - TYPE 304 STAINLESS STEEL INTERFERENCE-FIT BUSHED HOLES

| Spectrum | Specimen no. GR | Gross area stress (MPa) at + 7.5 g | Life (flights) | Failure hole no. | Failing Load (kN) |
|---|---|---|---|---|---|
| French | 17E | 235 | 27013 | 2 | 271 |
| | 20E | " | 30227 | 2 | 274 |
| | 23E | " | 41242 | 1 | 292 |
| | 12E | " | 41542 | 1 | 282 |
| | 25E | " | 61342 | 2 | 287 |
| | | Log. average = 38610; s.d. of log. life = 0.139 | | | |
| Swiss | 21E | 235 | 34508 | 2 | 269 |
| | 22E | " | 38298 | 2 | 267 |
| | 19E† | " | 102077 | 4 | 478 |
| | Log. average (21E and 22E) = 36354; s.d. of log. life = 0.032 | | | | |

†Specimen GR19E was inadvertently subjected to a compressive overload of about 400 kN at 24,157 flights. It was unbroken after 102,077 flights, when it was statically loaded in tension and failed through a small fatigue crack at hole 4.

TABLE 4(a) - COLD-EXPANDED HOLES

| Spectrum | Specimen no. GR | Gross area stress (MPa) at + 7.5 g* | Life (flights) | Failure hole no. | Failing Load (kN) |
|---|---|---|---|---|---|
| French | 16D | 294 | 2362 | 2 | 336 |
| | 26D | " | 2818 | 4 | 340 |
| | 5D | " | 2913 | 4 | 338 |
| | 8B | " | 3136 | 4 | 330 |
| | 12B | " | 3223 | 4 | 332 |
| | Log. average = 2874; s.d. of log. life = 0.053 | | | | |
| | 6D | 235 | 14742 | 4 | 303 |
| | 19D | " | 16542 | 4 | 264 |
| | 3D | " | 20427 | 4 | 265 |
| | 23D | " | 24413 | 4 | 271 |
| | 9D | " | 25813 | 4 | 240 |
| | 11B | " | 25842 | 2 | 283 |
| | 2D | " | 26781 | 2 | 267 |
| | Log. average = 21570; s.d. of log. life = 0.104 | | | | |
| Swiss | 25D | 294 | 1971 | 4 | 342 |
| | 10D | " | 2108 | 2 | 364 |
| | 8D | " | 2143 | 4 | 351 |
| | 9B | " | 2505 | 2 | 322 |
| | 14D | " | 2571 | 4 | 366 |
| | Log. average = 2247; s.d. of log. life = 0.050 | | | | |
| | 24D | 235 | 11647 | 2 | 298 |
| | 13D | 247 | 13048 | 4 | Not recorded |
| | | [Life adjusted to stress of 235‡] | (19613) | | |
| | 4D | 235 | 18344 | 2 | 294 |
| | 6A | " | 19743 | 2 | 295 |
| | 12D | " | 21447 | 4 | 303 |
| | Log. average = 17343; s.d. of log. life = 0.119 | | | | |
| | "Adjusted" Log. average = 17775; s.d. of log. life = 0.105 | | | | |

*Nominal machine forces at '+ 7.5 g' load were 316 kN for 7.5 g stress of 235 MPa and 395 kN for 294 MPa.

‡Using relationship given in Reference 2.

TABLE 3 - GROSS AREA STRESS VALUES FOR FRENCH SEQUENCE

| 'g' | stress (MPa) |
|---|---|
| +7.5 | 235 |
| +6.5 | 204 |
| +5 | 157 |
| +4 | 125 |
| +3 | 94 |
| +1 | 31 |
| +0.5 | 16 |
| 0 | 0 |
| -1.5 | -47 |
| -2.5 | -78 |

Maximum load range of sequence, +7.5 g to -2.5 g ≡ 313 MPa

Minimum load range of sequence, +3 g to +1 g ≡ 63 MPa

$$\text{Ratio} \; \frac{\text{minimum range}}{\text{maximum range}} = 0.20$$

Specimen no.
GR25D
Flights:
1,971

Specimen no.
GR10D
Flights:
2,108

Specimen no.
GR8D
Flights:
2,143

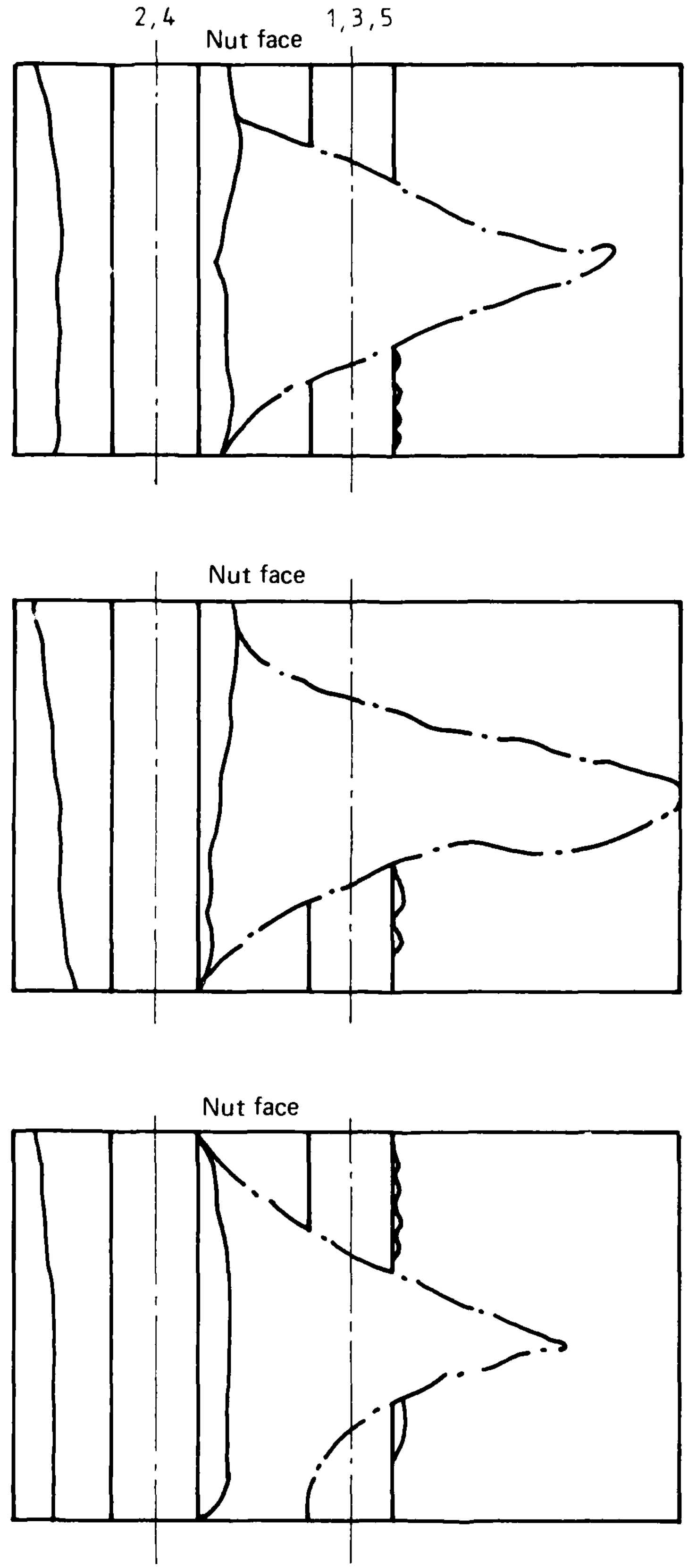



FIG. 6(b) FRACTURE SURFACES: SPECIMENS TYPE (C)
COLD – EXPANDED HOLES, SWISS SEQUENCE,
+7.5g ≈ 294 MPa

Specimen no.
GR9B

Flights:
2,505

Specimen no.
GR14D

Flights:
2,571

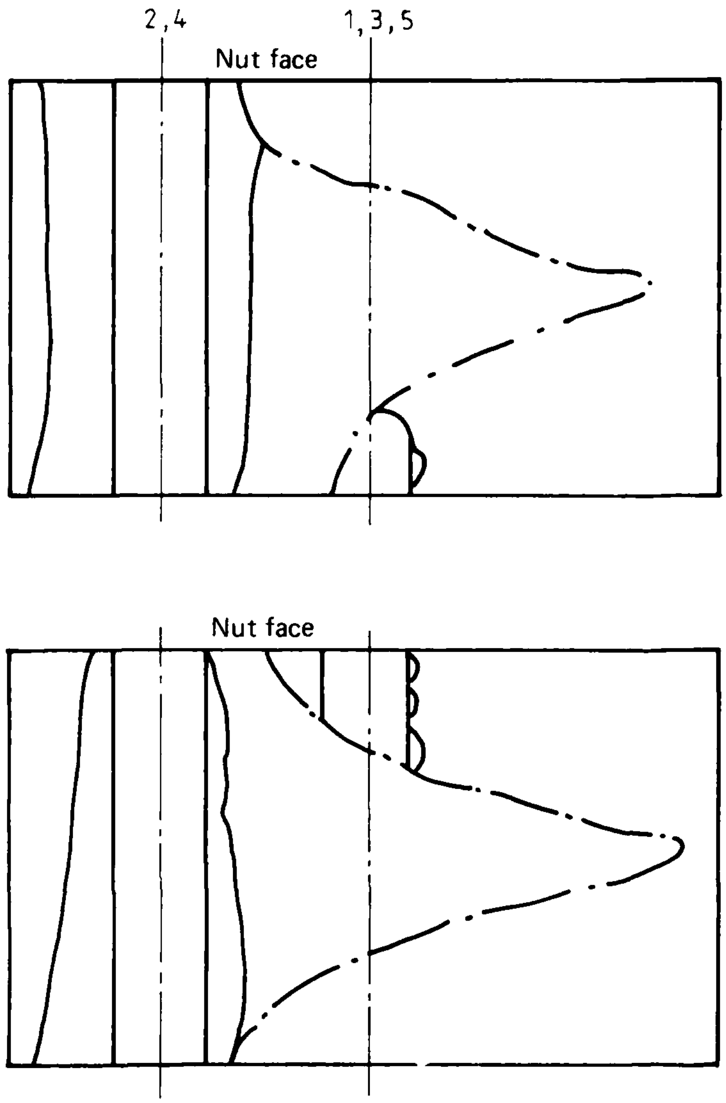



FIG. 6(b) FRACTURE SURFACES: SPECIMENS TYPE (C)
COLD – EXPANDED HOLES, SWISS SEQUENCE,
+7.5g ≡ 294 MPa

Specimen no.
GR 24D
Flights:
11,647

Specimen no.
GR13D
Flights:
13,048
(see Fig. 7(a) )

Specimen no.
GR 4D
Flights:
18,344

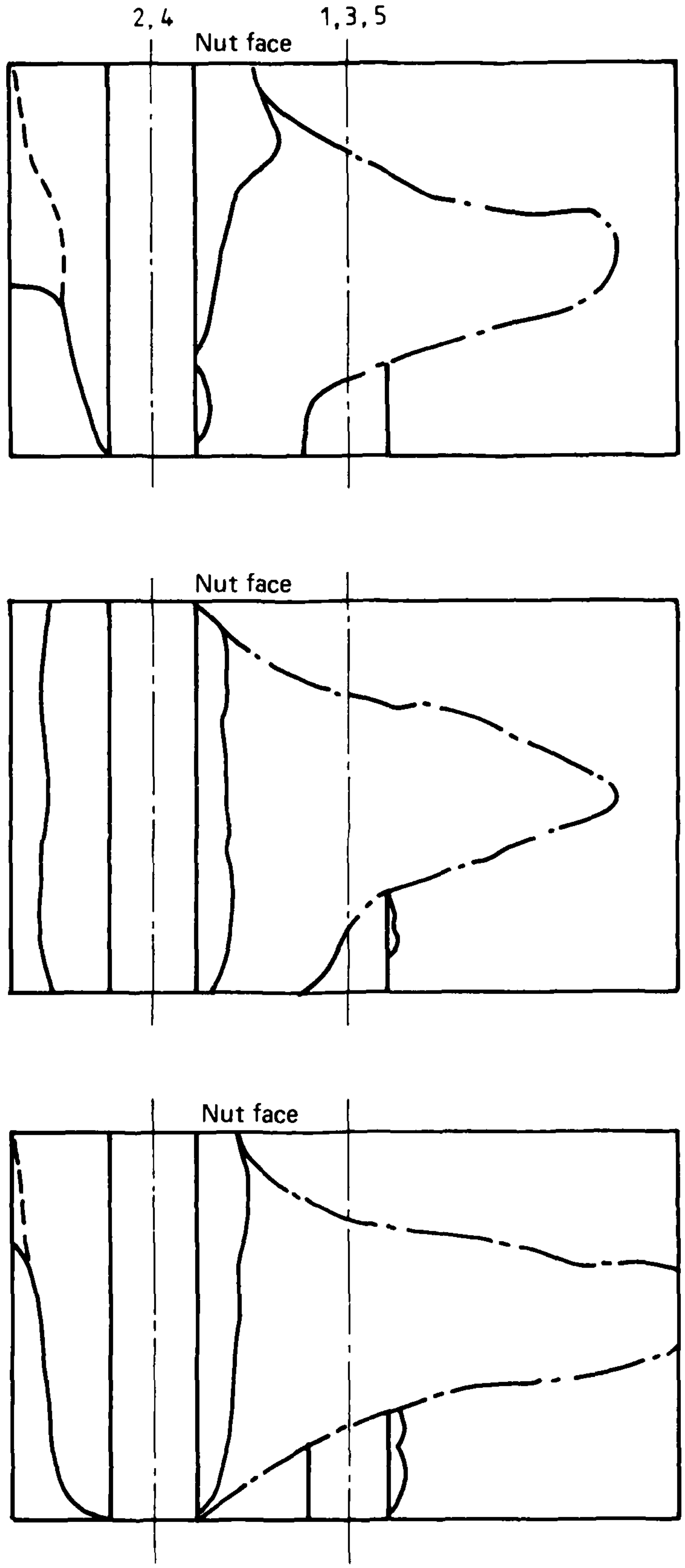
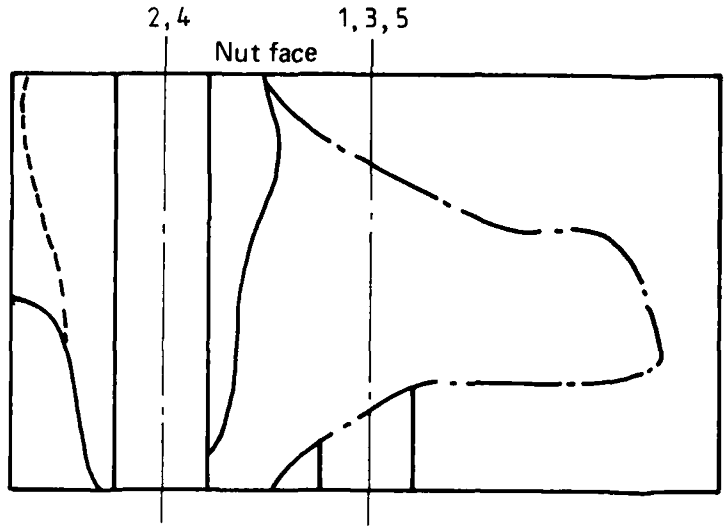



FIG. 6(b) FRACTURE SURFACES: SPECIMENS TYPE (C)
COLD – EXPANDED HOLES, SWISS SEQUENCE,
+7.5g ≙ 235 MPa

Specimen no.
GR 6A

Flights:
19,743




Specimen no.
GR12D

Flights:
21,447

(see Fig. 7(a) )

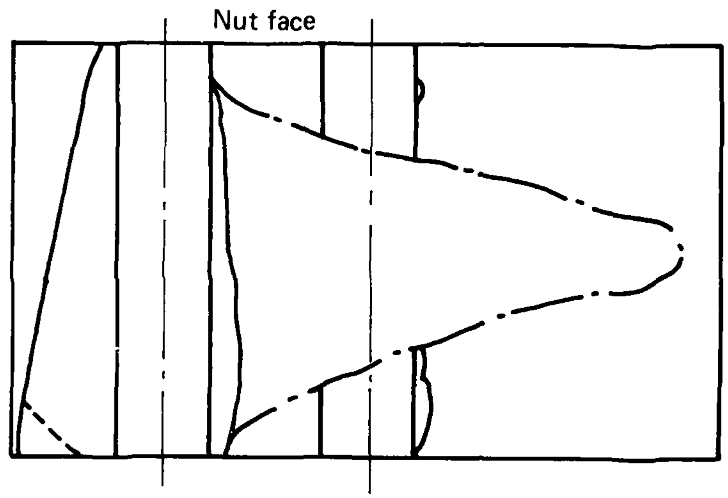



FIG. 6(b) FRACTURE SURFACES: SPECIMENS TYPE (C)
COLD -- EXPANDED HOLES, SWISS SEQUENCE,
+7.5g ≡ 235 MPa

Specimen no.
GR17E
Flights:
27,013

Specimen no.
GR20E
Flights:
30,227

Specimen no.
GR23E
Flights:
41,242

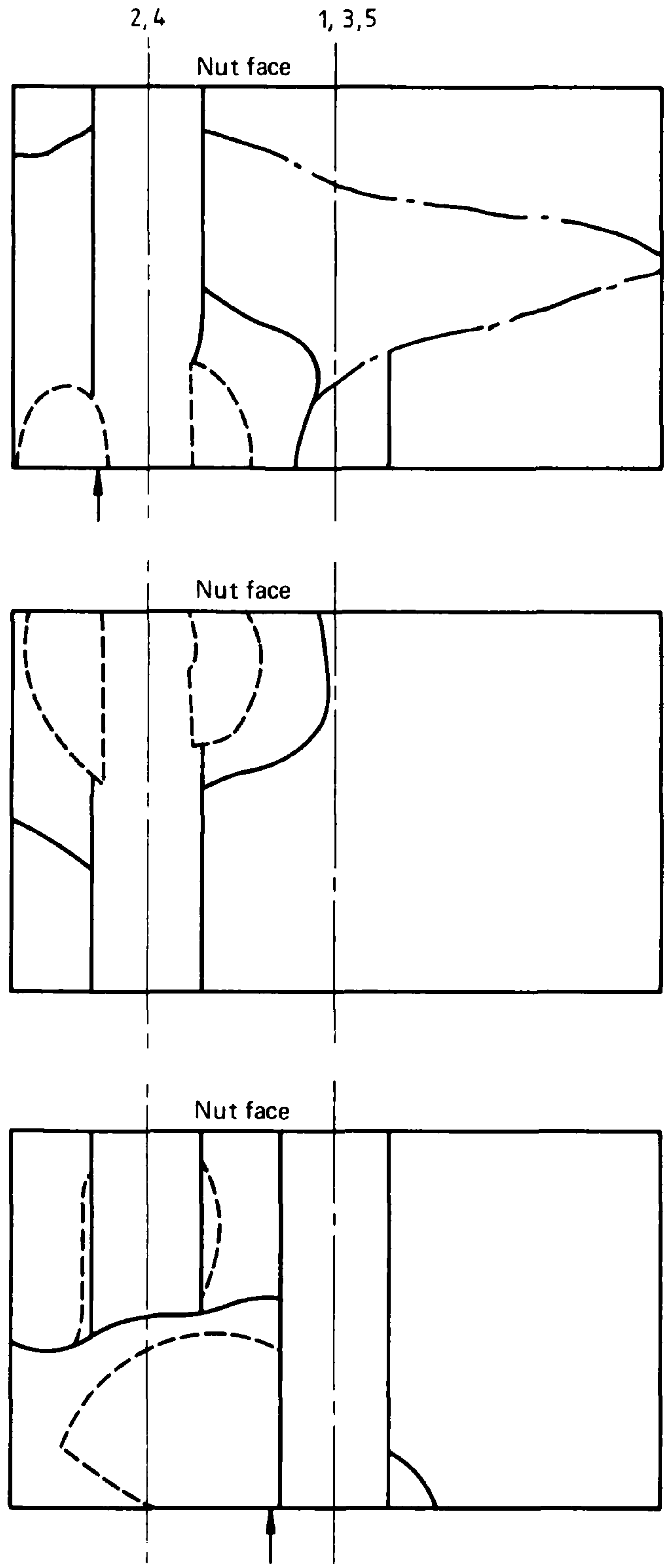



FIG. 6(c) FRACTURE SURFACES: SPECIMEN TYPE (D)
INTERFERENCE – FIT BUSHES, FRENCH SEQUENCE
+7.5g ≡ 235 MPa

Specimen no.
GR12E

Flights:
41,542
(see Fig. 7(b) )

Specimen no.
GR25E

Flights:
61,342

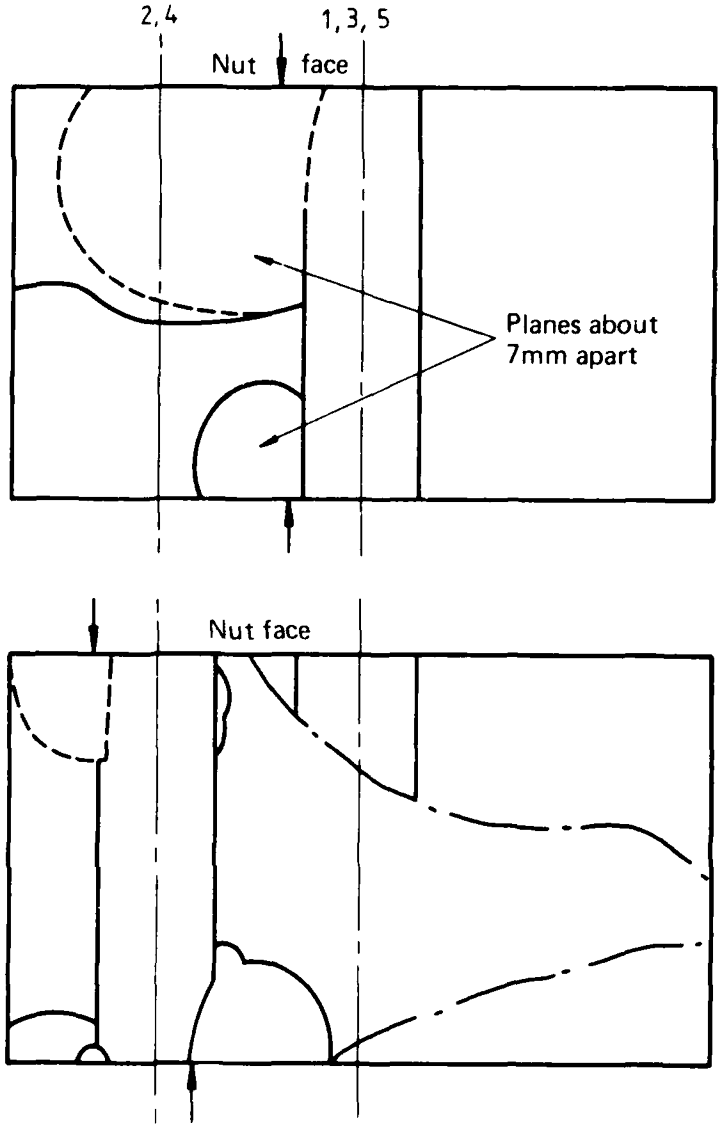



FIG. 6(c) FRACTURE SURFACES SPECIMEN TYPE (D)
INTERFERENCE FIT BUSHES FRENCH SEQUENCE,
+7.5g 235 MPa

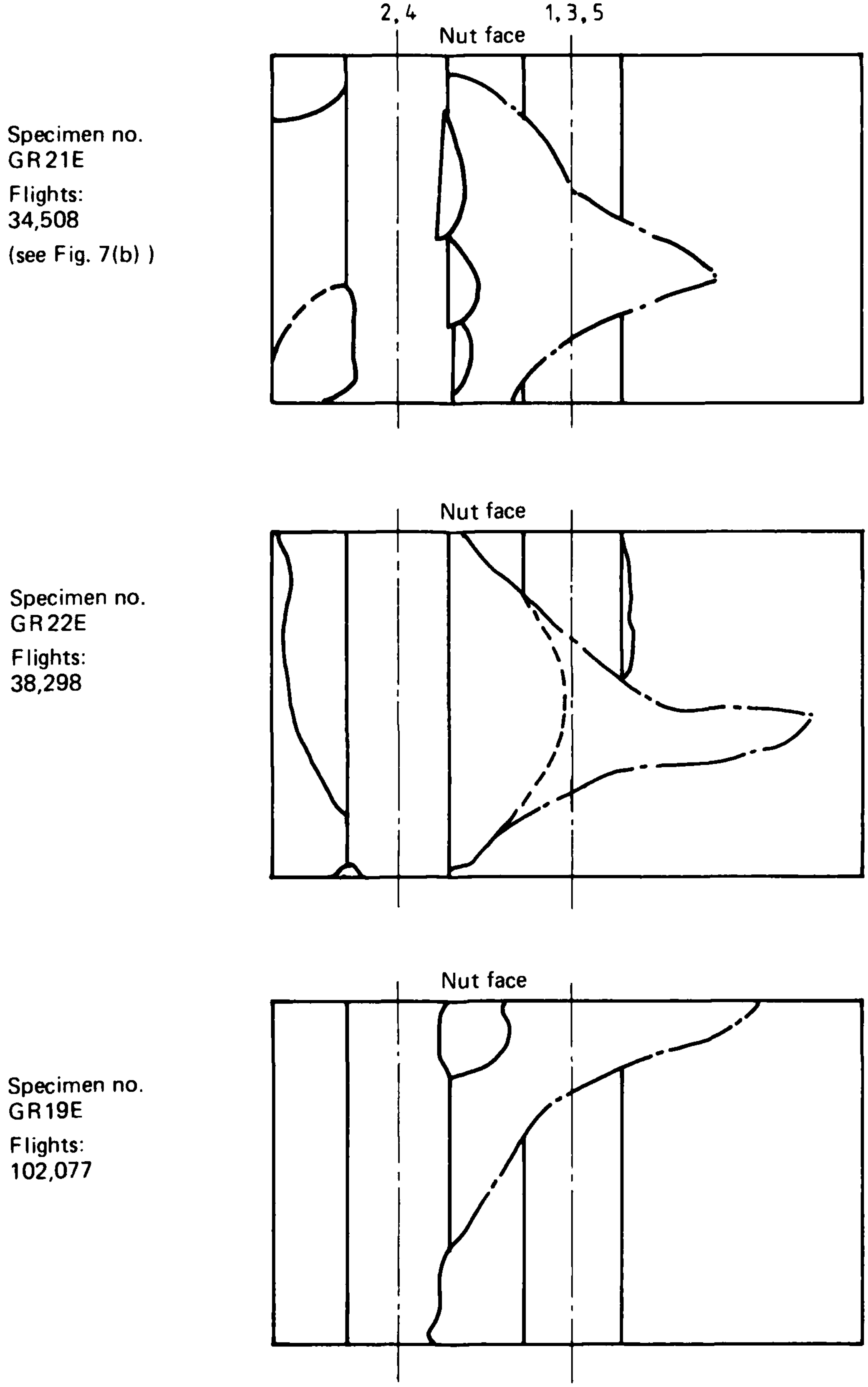



FIG. 6(d) FRACTURE SURFACES: SPECIMENS TYPE (D)
INTERFERENCE – FIT BUSHES, SWISS SEQUENCE,
+7.5g = 235 MPa

Nut face

Specimen no.
GR 12B

French sequence
+7.5g ≡ 294 MPa

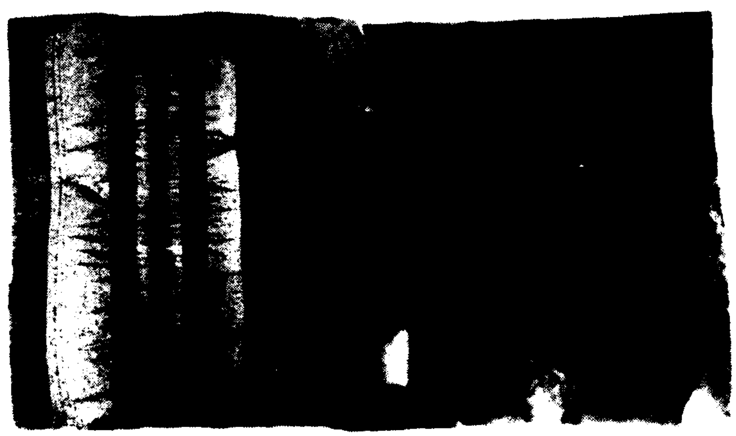
Flights:
3,223

Nut face

Specimen no.
GR 13D

Swiss sequence
+7.5g ≡ 235 MPa

Flights:
13,048



Nut face

Specimen no.
GR 12D

Swiss sequence
+7.5g ≡ 235 MPa

Flights:
21,447

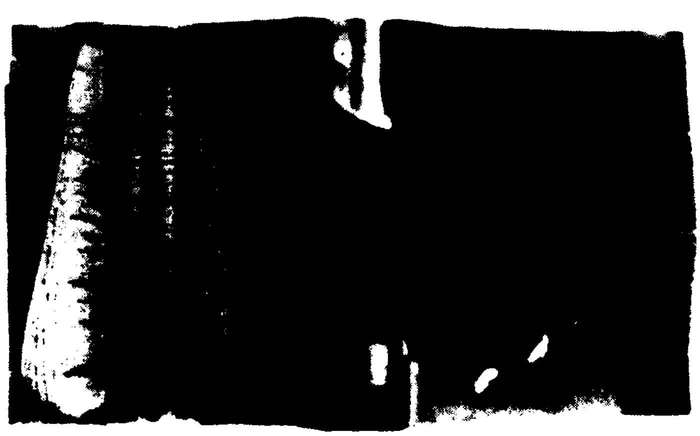
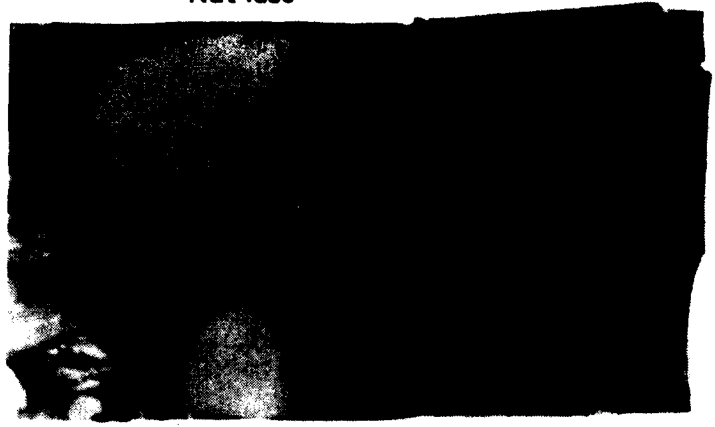


FIG. 7(a) FRACTURE SURFACES: SPECIMEN TYPE (C)
COLD – EXPANDED HOLES

Specimen no.
GR12E

French sequence
+7.5g ≡ 235MPa

Flights:
41,542




Specimen no.
GR 21E

Swiss sequence
+7.5g ≡ 235 MPa

Flights:
34,508

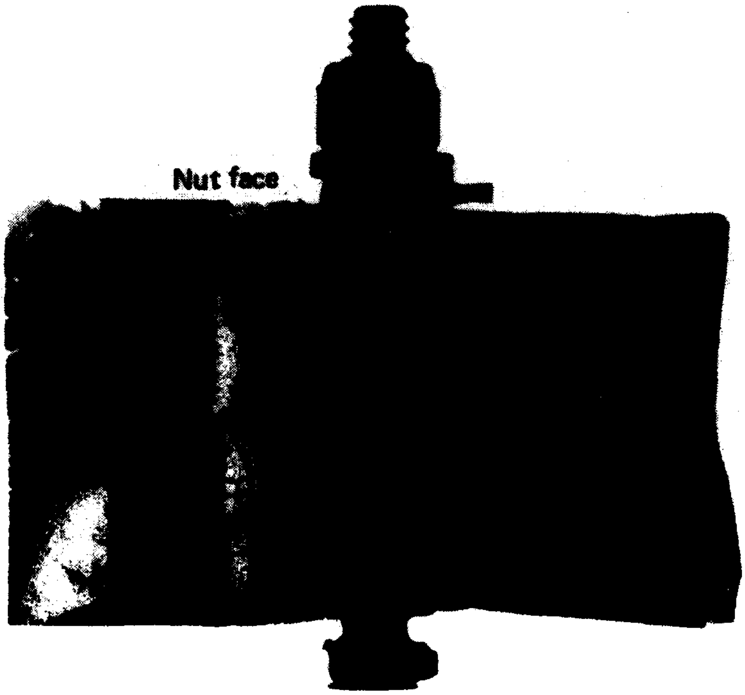



FIG. 7(b) FRACTURE SURFACES: SPECIMEN TYPE (D)
INTERFERENCE – FIT BUSHES

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| Bolted joints | Load spectra | 01030 |
| Cold working | | |
| Fasteners (interference) | | |

16. Abstract

Flight-by-flight fatigue tests were carried out on specimens representing part of the front flange of the main spar of the Mirage III wing. Two loading spectra/loading sequences were used, the first being a 200-flight sequence incorporating 24 different types of flight developed by the Eidgenössisches Flugzeugwerk in Switzerland and the second a much simplified 100-flight sequence incorporating only 4 different types of flight developed by Avions Marcel Dassault in France.

The fatigue tests showed that there were no significant differences in the lives to failure between specimens tested under the two sequences, and it was therefore concluded that the use of the

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**16 Abstract (Contd)**

simplified stress spectrum/sequence would not have invalidated the findings of a previous investigation to develop life-enhancement procedures for the Mirage wing main spar.

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