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FATIGUE ANALYSIS OF COMPOSITE MATERIALS USING THE FAIL-SAFE CONCEPT

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16. Abstract

A regulation established jointly between SNIAS and the Official French Service requires failure probability for any individual helicopter part below or equal to 10 to the minus 6th power.

In this article, the method used at SNIAS to calculate the global risk of rupture is described.

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FATIGUE ANALYSIS OF COMPOSITE MATERIALS USING THE FAIL-SAFE CONCEPT

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0. INTRODUCTION

The helicopter by design presents numerous sources of vibratory excitation and as a result many components are under stress loads. The main concern of the manufacturer is to produce components that meet highly strict safety requirements while remaining competitive in terms of mass and cost-price considerations. A fatigue regulation established jointly between SNIAS and Official French Services requires that the individual failure probability of a helicopter component must not exceed 10^{-6} during a given lifespan.

The development of composite materials over the past fifteen years has made it possible for Aerospatiale to design new rotors that meet the specifications of the abovementioned regulation.

These materials have a good fatigue life with evident fail-safe characteristics (easily detectable onset of delamination and slow propagation speed).

These properties have made it possible to develop methods of analysis without increasing the risk of failure during flight.

If we let R1 be the probability of having a crack on a flight component and R2 be the probability of seeing this crack propagate between two scheduled inspections, the global failure risk is the product of R1 x R2 and it is this product that must not exceed 10^{-6}.

The objective of this report is to describe the method used by SNIAS permitting the calculation of these two risks R1 and R2.

This method is based on a full study of fatigue characteristics and crack propagation rates in the material used.

1. CALCULATION OF RISK R1 (Risk of Having a Crack During Operation)

The first stage of the study consists of determining the equation of the S/N curve of the material used to manufacture the helicopter component. These equations are generally expressed as shown in figure 1 below:

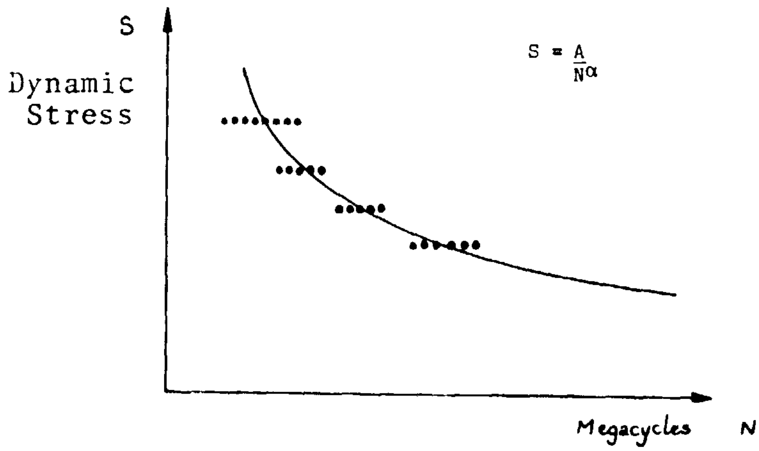
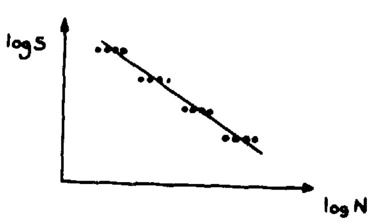


Fig. 1

From the tests of samples performed in fairly large numbers, it is possible to calculate the coefficients A and alpha which are characteristic of a material. The method used is a linear regression along log N as a function of set S (fig. 2):



$$\log N = \frac{\log A}{\alpha} - \frac{\log S}{\alpha}$$

Fig. 2

The second calculation hypothesis consists of assuming that there are S/N curves correlated to the mean curve of the same equation A which follow a normal law of logarithmic probability.

These curves are therefore curves of crack isoprobability (fig. 3):

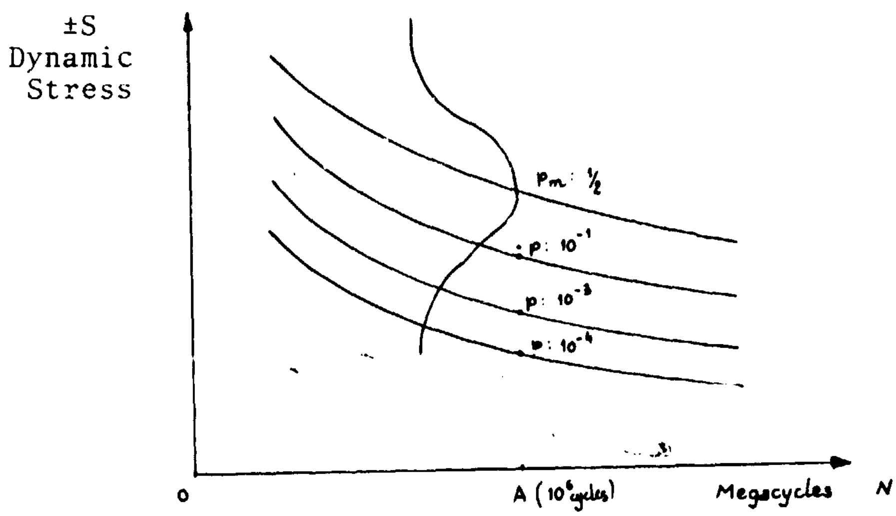


Fig. 3

This hypothesis which may seem arbitrary at first is well verified by the experiment and statistical testing.

The experiment that we have just described would be too costly if it were performed entirely on aircraft components. Also, the equation of the S/N curve is determined on specimens and is considered to be applicable to only a few specimens of the components we are testing (6 mini pts) fig. 4:

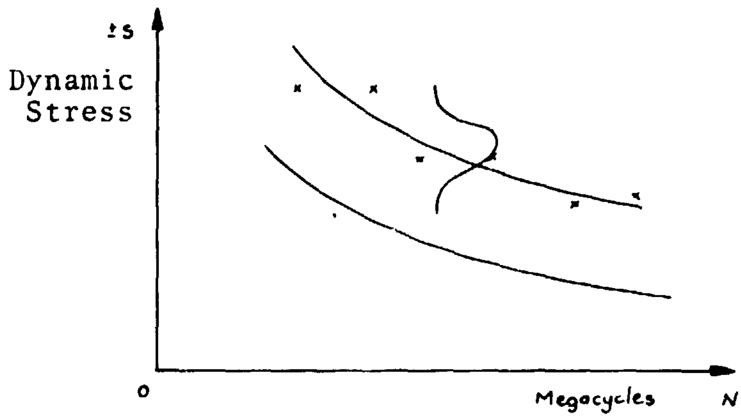


Fig. 4

Formulation of the Calculations

(1) $S = \frac{A_i}{N_i^{\alpha}}$

(2) $|\log A|_m = \frac{\Sigma \log A_i}{\underbrace{n}_{a}}$

a

(3) $\mathrm{loag}\ A_{\underbrace{r}_{b}} = \underbrace{|\log A|_m}_{c} \quad \underbrace{K}_{e}\underbrace{\sigma}_{d} -$

(4) $\sigma = \sqrt{\frac{\Sigma\left[(\log A)_m - \log A_i\right]^2}{n-1}}$

(5) $K = \frac{kr + kq\sqrt{\frac{1}{n}\left[1 - \frac{kq^2}{2(n-1)} + \frac{kr^2}{2(n-1)}\right]}}{1 - \frac{kq^2}{2(n-1)}}$

Key: a-Number of test points; b-risk under consideration; c-Mean fatigue limit at 10^6 cycles; d-standard deviation; e-Normal law coefficient (5).

Fig. 5

kr = margin corresponding to risk r in the simple normal relationship.
kq = margin corresponding to risk q in the simple normal relationship.
q = coefficient of confidence.

Knowing the 6 test results, it is now possible to calculate Am and the Ar's corresponding to different risks r.

Operational characteristics of a helicopter are known, either by recording flight parameters during several hundres of hours or by information obtained from users. We thus have a spectrum giving for each flight configuration the percentage of time corresponding to it. For each of these configurations, the flight stresses are recorded using extensometric gages.

These stresses associated with their percentage serve to calculate the lifespan by applying the MINER relationship (see fig. 6).

Table 1

	CONFIGURATIONS	a % Pourcentage d'utilisation	b Effort de vol	c Limite de fatigue ou risque r	d Nombre de cycles admissible $N = (\frac{A}{F})\%$	e Nb d'h de vol N x t par Mc (t: temps pour 1 Mégacycle)	%/Nbh
f	1. Stationnaire	p_1	$\pm F_1$	A_r	N_1	Nbh_1	p_1/Nbh_1
g	2. Vi transition	p_2	$\pm F_2$	"	N_2	Nbh_2	p_2/Nbh_2
	.						
	.						
	.						
	.						
	.						
	.						
	.						
	.						
h	i-2 Palier	p_{i-2}	$\pm F_{i-2}$	"	N_{i-2}	Nbh_{i-2}	p_{i-2}/Nbh_{i-2}
i	i-1 Approche	p_{i-2}	$\pm F_{i-1}$	"	N_{i-1}	Nbh_{i-1}	p_{i-1}/Nbh_{i-1}
j	i Atterrissage	p_i	$\pm F_i$	"	N_i	Nbh_i	p_i/Nbh_i
							$\Sigma\, p_i/Nbh_i$

k durée de vie : $\dfrac{100}{\Sigma p_i/Nbh_i}$

Key: a-% use; b-Flight stress; c-Fatigue limit at risk r; d-Number of allowable cycles; e-Number of flight hours N x t per Mc (t: time for 1 Megacycle); f-Hovering; g-Vi transition; h-Level flight; i-Approach; j-Landing. k- Mean time between failure

Fig. 6

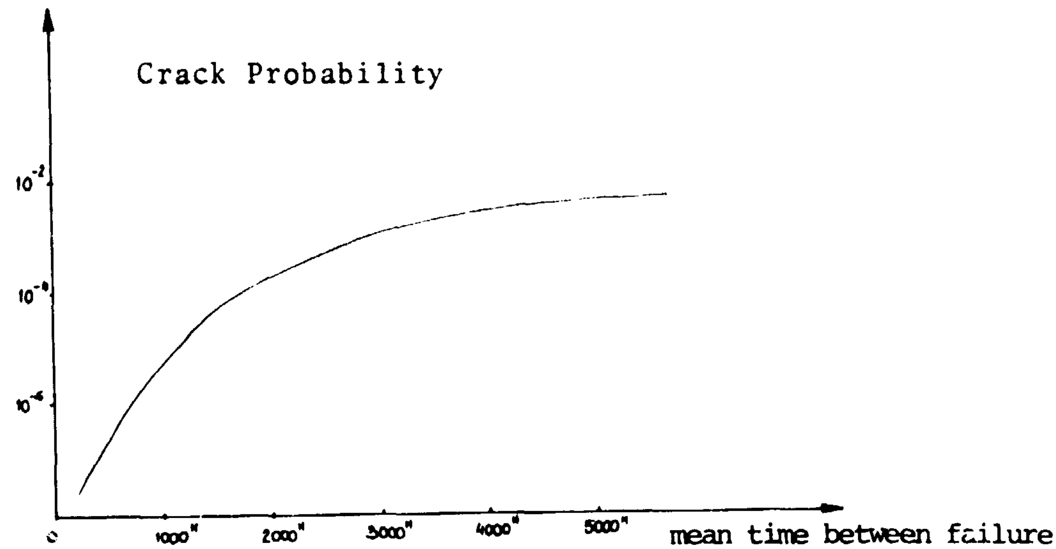


Fig. 7

2 - CALCULATION OF RISK R2 (Risk of having a catastrophic failure between two scheduled inspections)

The tests performed on components to calculate risk R1 are suspended at the first sign of damage and are resumed for flight loads using a program block and taking into account:

- the percentage each configuration is used,
- the chronological order of these configurations (in order to reproduce possible delay effects of the propagation due to changes in stress levels).

(See load spectrum on Table II fig. 8).

These tests were carried out to the failure point with measurements and recording of crack lengths and resistance of the components.

If we call t_{if} the time elapse between time t_i corresponding to the appearance of the first small damage and time t_f corresponding to catastrophic failure, it is possible to match a probability relationship to this random variable t_{if} found during the test.

Table II
Spectrum of Programmed Loads

	Static Flapping	Dynamic Flapping	Static Drag	Dynamic Drag	No. of Cycles
	— 235	0			
a	84	± 79	145.5	± 118	320
b	84	± 168	100	± 170	175
c	83.5	± 69.5	29	± 75	224
d	105	± 149.5	172	± 410.5	64
e	83.5	± 28	100	± 138	465
f	105	± 149.5	172	± 410.5	64
g	83.5	± 28	100	± 138	465
h	105	± 149.5	172	± 410.5	64
i	83.5	± 31.5	258	± 168	384
j	105	± 149.5	172	± 410.5	64
k	90	± 31.5	258	± 168	384
l	74	± 49	201	± 173.5	61
m	96	± 35	158	± 176	4
n	90	± 31.5	258	± 168	384
o	83.5	± 28	100	± 138	465
p	105	± 149.5	172	± 410.5	64
q	83.5	± 69.5	100	± 138	224
r	105	± 149.5	172	± 410.5	64
s	84	± 168	100	± 170	176
t	61	± 109	277	± 140	64
u	84	± 79	145.5	± 118	320
v	74	± 126	132.5	± 201.5	320
w	— 235	0	0	0	

Key: a-Hovering; b-Take-off; c-Minimum cruise speed; d-Turning; e-Economy cruise speed; f-Turning; g-Economy cruise speed; h-Turning; i-Maximum cruise speed; j-Turning; k-Maximum cruise speed; l-VNE; m-VNE turning; n-Maximum cruise speed; o-Economy cruise speed; p-Turning; q-Minimum cruise speed; r-Turning; s-Speed reduction; t-Autorotation; u-Hovering; v-Approach; w-Rotor stop.

Essentially, it seems that the normal logarithmic relationship fits the phenomenon the best.

Since we know the law of probability, the mean value t_{ifm} and the standard deviation, it is possible to calculate the allowable flight time as a function of risk (see fig. 9)

The curve thus plotted corresponds to the risk of failure by considering that the first damage was noticed right after take-off. The curve of risk R2 should therefore be evaluated by assuming that this first damage may occur at any moment of flight.

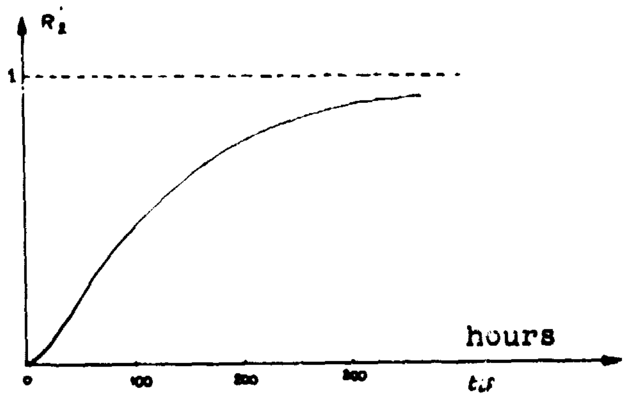


Fig. 9

If we let x be the flight hours between two inspections, we have two possible cases:

(a) No damage appears between two given inspections (this case is not of interest to us since it carries over to case b) during the next inspections:

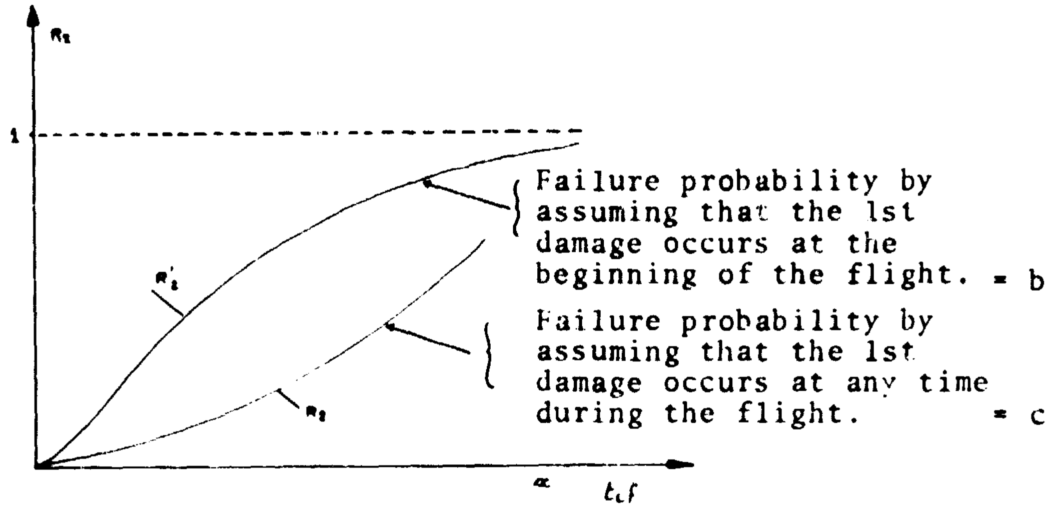
(b) Damage does appear between two inspections. Only this case is of interest to us. We will therefore let the probability of damage appearing be equal to 1. I.e. t_1 is the instant in which the first noticeable damage appears (t counting from zero of the last inspection) and t_2 is the propagation time bringing about catastrophic damage to the component. It should be pointed out that t_1 and t_2 are two independent variables.

Probability $\left\{ x < t_1 < x + dx \right\} = \frac{dx}{x}$
according to the preceding curve = a

Probability $\left\{ t_2 < X - x \right\} = R\ (X - x)$
where $dP = \frac{dx}{X} \cdot R\ (X - x)$

$$P(x) = \frac{1}{X} \cdot \int_0^X R\ (X - x) \cdot dx = R_2$$

This is the mean value from 0 to X of the function R_2' explained previously (see fig. 10).



3 - CALCULATION OF RISK R (Or Risk of Failure During Flight)

As we have already mentioned, this risk is found by multiplying R1 X R2, the calculation method of which we have just described.

R1 and R2 are presented in the form of two curves. The manufacturer therefore has several possible choices, either to assign a long lifespan with frequent scheduled inspections of the component, or, conversely, a short lifespan with very spaced inspections.

What is even better, these curves make it possible to modulate the inspection periods as a function of the component's flight time (fig. 11).

LIFE SPAN	*	R1	R2	R TOTAL
1 000 h	100 h	10^{6}	10^{2}	10^{8}
2 000 h	50 h	10^{5}	10^{8}	10^{8}
5 000 h	10 h	10^{3}	10^{4}	10^{8}

*Periods between inspections

Fig. 11