

RELIABILITY TESTING AND FAILURE ANALYSIS FOR SPAR STRUCTURE OF HELICOPTER ROTOR BLADE

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Abstract: *In the last years reliability tests represented a widely used method for different life cycle stages of the industrial products – design, manufacturing until service, because on their basis information regarding reliability, lifespan, failure rate etc. can be obtained in the shortest time. In this paper were determined the reliability indicators (reliability function, non-reliability function, failure rate, probability density, mean life) on the basis of the gathered data related to the blades' fatigue testing experiments. Moreover, was done technical expertise concerning a tested blade, with the help of microscopic analysis.*

Keywords: *reliability, fatigue test, blade helicopter, failure, mean life*

1. INTRODUCTION

The helicopter blades are characterised by the aerodynamic airfoil (or the profiles from which is made up), the plan shape, the twisting, the shape of its tip. From the profiles' point of view the blade has to fulfil certain requests [1]:

- high lift coefficient; critical Mach number as big as possible (to lower power loss due to compressibility), which is one of the limitations for the advancing blade;
- the torque coefficient at zero lift to be as low as possible or zero; the drag coefficient, at high lift coefficient and high Mach speeds;
- as reduced as possible variation of the chord's pressure centre.

Modern technology has imposed specific forms of the blade end of aerodynamic considerations, especially in terms of air flow characteristic of this area of the blade. Shaped of the blade tip has a very important role in terms of profile power value and of the rotor noise levels [2].

At helicopters, the loss of a blade immediately leads to the destruction of the rotor and therefore to the immediate loss of the helicopter. For this reason, the blade and the rotor components, and also the supple platinum fall into the vital parts category of helicopter, parts which damaged or lost cause inevitably the destruction the entire aircraft.

A vital piece must meet the following three conditions [3]:

- it is a piece that cannot be duplicated and the breaking of which determines or may determine a serious accident;
- it terms of helicopter operation, the part is subject to important alternating efforts (fatigue stress);
- current technical design of helicopters can not ensure high safety factors.

Some recent studies have been made on aerodynamic performance and mechanical characteristics of helicopters by finite element analysis of the various components [4] and CFD analyses [5,6] on the entire aircraft.

Gathering information on product reliability is typically achieved either watching the behaviour of the products in actual operation, or during the reliability tests. During observations in actual operation all the occurring phenomena are recorded in detail along the use of the product. A study based on this information is, however, a historical study, its value consisting only in the collection of experimental data or detection of factors leading to low reliability of the products.

Information from real operation often concerns obsolete products or equipment, so when arriving at conclusions, it might no longer be of importance to correct issues related to design and products' manufacture, as reliability desideratum. Without excluding tracking products in real operation it is appropriate to use the method of reliability tests. During these tests are sought, where possible, to simulate real service conditions, both through the reproduction of a range of internal stresses and environmental.

Due to the multitude of factors that influence the behaviour of products, reliability's theoretical foundation is the theory of probability and mathematical statistics and the experimental foundation are the reliability tests [7]. A direction intensely researched is the reliability [8] and failure mode analysis [9,10] for blades from the helicopters' structure.

Other studies look on improving flight performance through innovative methods and components deployed on helicopters' structure [11,12]. By implementing composite materials [13] and new blade manufacturing technologies [14] a significant weight reduction is achieved and much higher fatigue strength compared with metal blades. Due to more restrictive noise regulations for helicopters, several current studies have shown the importance of knowing the noise level for helicopter on the ground, during take-off and during manoeuvres [15,16].

2. MATERIALS

Reliability testing, in which the main degradation phenomenon is fatigue, are very important in industrial and especially aerospace industry with applications on components of airplanes and helicopters' structure. Between these components are included: the engines used on different aircraft, rotor blades and compressor blades, landing gear, various avionics equipment, main and anti-torque rotor blades, supple platinum [17].

In this paper it was conducted a constructive and functional study on the rotor blades of IAR 330 Puma helicopter. Anti-torque rotor compensates for the torque generated by the main rotor and serves to control the helicopter's yaw axis.

The tail rotor structure comprises of 5 blades. A blade structure shown in Figure 1.a. The main characteristics of tail rotor blade are: profile NACA 0012; chord 186.5 mm; length 1244.3 mm; mass 2.680 kg.

The components of the anti-torque rotor blade, with reference to Figure 1.a, are: NIDA core (1); shell (2); stiffener (3); spar (4); connection parts (5); fixing bushings (6); "salmon" (7); ballast weights (8); balancing rings (9); balancing counterweights (10); extremity rib (11); eyelets (12); trailing edge (13).

Fatigue tests from this paper were carried out on the metal spar (figure 1b), which is part of the tail rotor blade structure of IAR 330 Puma helicopter. The metal spar from the blade's structure is the reinforcing element most stressed and is subject to severe fatigue tests for determining its lifespan.

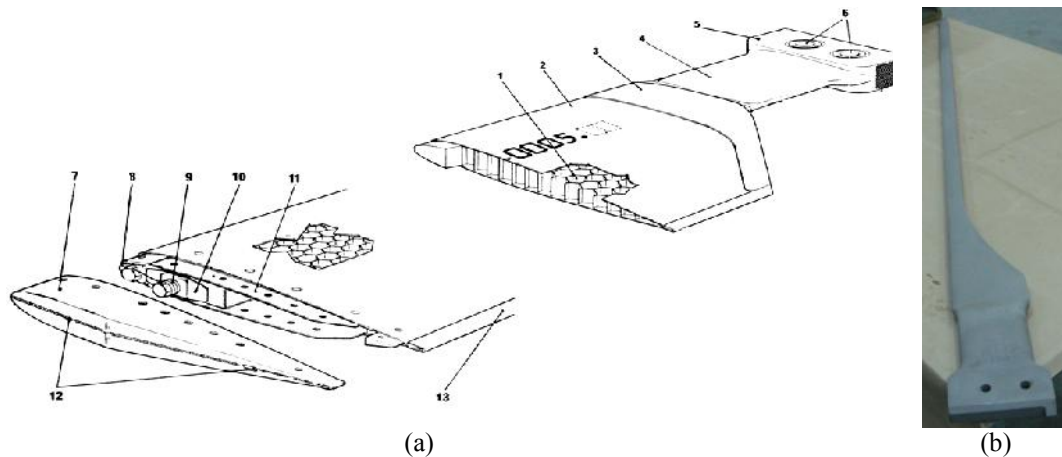


FIG. 1. Anti-torque rotor blade of the helicopter IAR 330 Puma (a) the internal structure of the blade (b) 6061 T6 aluminium blade spar [18]

3. METHODS

In the case study (tail rotor blade) of this paper it will be applied a cyclic mechanical stress. For cyclical stress most commonly used are metal components and systems, and degrading phenomenon most common is fatigue. Fatigue degradation involves a variety of issues: the type of strain; the shape of the part; the surface quality of the worked part; the environment in which the part works. In general, fatigue can be considered as a process in which damage accumulates in a material following stresses with variable characteristic to which it is subjected. Fatigue is a local process, which manifests itself in various materials used in engineering practice such as: metal alloys, polymeric materials and composites, etc. [19,20].

The test bench allows the introduction of stresses according to blade specimen as follows: axial force via an axial cable; lagging dynamic bending moment changes by means of rods that connect to the tensioned blade; flapping dynamic bending moment in the form of an arrow controlled at the end of the blade by means of an eccentric.

To determine the corresponding bending moment of the lagging movement for the blade, use the relation 1:

$$M_{ib} = F_b \cdot b \quad (1)$$

where: F_b - the force in the blade's lagging plan; b - blade's lever arm.

To determine the bending moment corresponding to the flapping movement of the blade is used the relation 2:

$$M_{iB} = F_B \cdot b \quad (2)$$

where: F_B - force in the blade's flapping plan; b - blade's lever arm.

Fig. 2.a and 2.b are the methodologies of blade calibration at lagging and flapping movements. For calibrating the lagging movement (p), the blade is embedded in the rotating frame of the test bed. It is installed a dynamometer (2) with the help of two hooks and joining cable (1). The application, at the blade tip, of the force in the lagging plane is achieved by tightening a screw to the set values for calibration. The values indicated by the dynamometer and the indicated specific strains values are read the strain gauge bridge. For calibrating the flapping movement the blade rotates 90° and the calibration procedure is similar to the sweep movement.

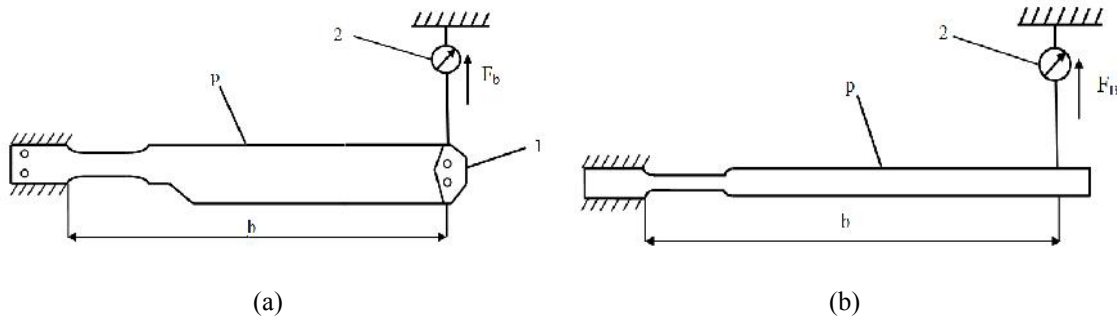


FIG. 2. IAR 330 Puma helicopter blade calibration (a) lagging movement blade calibration (b) flapping movement blade calibration

The test bench for fatigue testing of the IAR 330 helicopter tail rotor blades must allow the blade stress at the following parameters: static force $T = 32000 \text{ N}$; lagging dynamic bending moment $M_z = \pm 1000 \text{ Nm}$; flapping dynamic bending moment $M_y = \pm 200 \text{ Nm}$;

Fatigue helicopter blades testing involves subjecting them to oscillating stresses with a set frequency and amplitude, until cracks in the embedding plan appear. Fulfilling this request is done with the help of the test bed that allows the development in the investigated section – blade's spar neck – of the forces and moments imposed.

This paper is focused on achieving reliability testing techniques on tail rotor blades of the helicopter structure, with the main purpose of determining the reliability indicators and the failure modes.

4. RESULTS AND DISCUSSION

Data obtained from fatigue testing 10 blade-type samples has been introduced in Weibull++ 7 to perform statistical analysis in order to determine and plot the reliability indicators. Weibull++7 is a software specific to the reliability domain which performs data analysis on the lifespan (operation) for thousands of companies worldwide. This software provides all the tools needed in the statistical analysis of experimental data, including working with all data types (complete, suspended, censored) and key statistical distributions [21].

For data of blades' fatigue tests the bi-parametric Weibull distribution is suitable because it is the most appropriate for calculation of the fatigue on mechanical components. Are calculated the two Weibull model parameters by the method of estimation for the maximum likelihood for data from Weibull++7 software. The results are the following values of parameters: shape parameter ($\beta=4.3$); scale parameter ($\eta=2939101.24$).

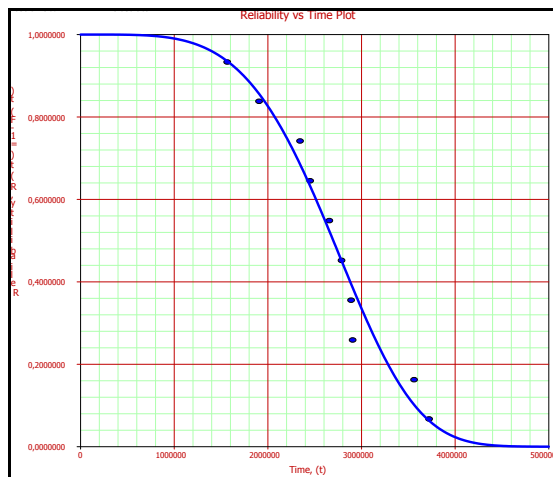
By reliability indicators is understood a measure by which reliability or one of its characteristics is expressed quantitatively. These reliability indicators were determined by relations (Table 1) specific to bi-parametric Weibull distribution. In Table 2 are determined and graphically represented (figure 3.a,b) the main reliability indicators, depending on the number of cycles to failure, resulting from reliability tests with the main degrading factor the fatigue of helicopter blades.

Table 1. Reliability indicators of the Weibull distribution

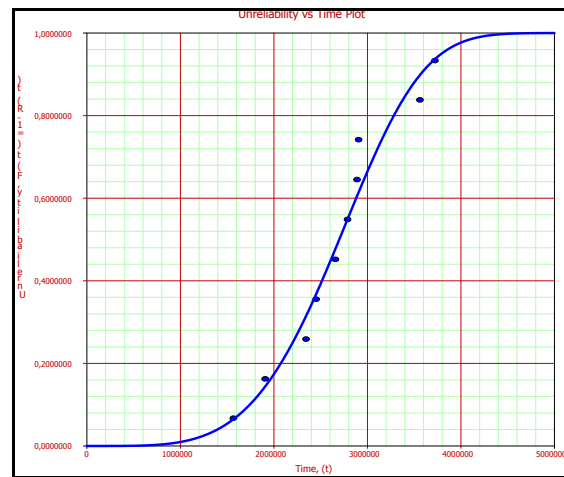
Reliability indicators	Relation
Reliability function	$R(t) = e^{-\left(\frac{t}{\eta}\right)^\beta}$
Unreliability function	$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^\beta}$
Failure rate function	$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1}$
Probability density function	$f(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} \cdot e^{-\left(\frac{t}{\eta}\right)^\beta}$

Table 2. Dependence between the number of cycles to failure and blade's reliability indicators

Cycles to failure	Reliability R(t)	Unreliability F(t)	Failure rate $\lambda(t) \cdot 10^{-6}$	PDF $f(t) \cdot 10^{-6}$
1567825	0.933	0.067	0.488	0.172
1907658	0.837	0.163	0.715	0.301
2345129	0.741	0.259	1.200	0.476
2453217	0.644	0.356	1.381	0.509
2657892	0.548	0.452	1.827	0.549
2789056	0.451	0.549	2.199	0.554
2890756	0.355	0.645	2.542	0.546
2907543	0.258	0.742	2.603	0.544
3562728	0.162	0.838	6.441	0.280
3723620	0.066	0.934	7.932	0.201



(a)



(b)

FIG. 3. Blade's reliability indicators (a) reliability function (b) unreliability function

The probability density function represents the relative frequency of failure times as a function of time. The failure rate function enables the determination of the number of failures occurring per unit time.

It is useful in characterizing the failure behavior of a component, determining maintenance crew allocation, planning for spares provisioning, etc [21]. The graphic representations of functions - probability density and failure rate are shown in Fig. 4.a, b.

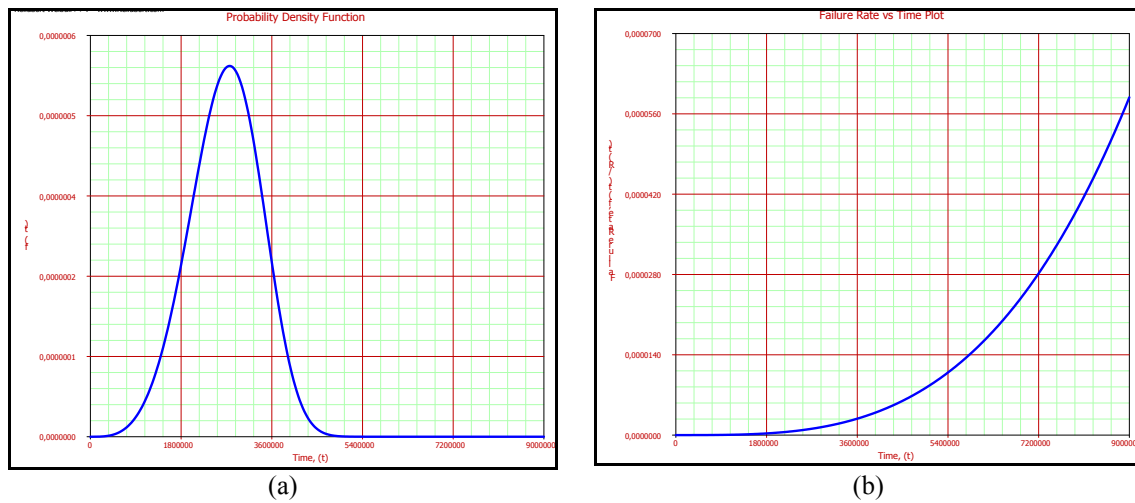


FIG. 4. Blade's reliability indicators (a) probability density function (b) failure rate

The failures/suspensions timeline diagram (figure 5.a) represents the values of the failures and suspensions are plotted on the y-axis and the time periods are on the x-axis [21]. The mean number of cycles to failure is determined by the mean relationship for Weibull distribution. Mean life is the most important reliability indicator and is determined using the Weibull software through a Quick Calculation Pad, and its value is 2675127 cycles at a confidence level of 0.95 (Fig. 5.b).

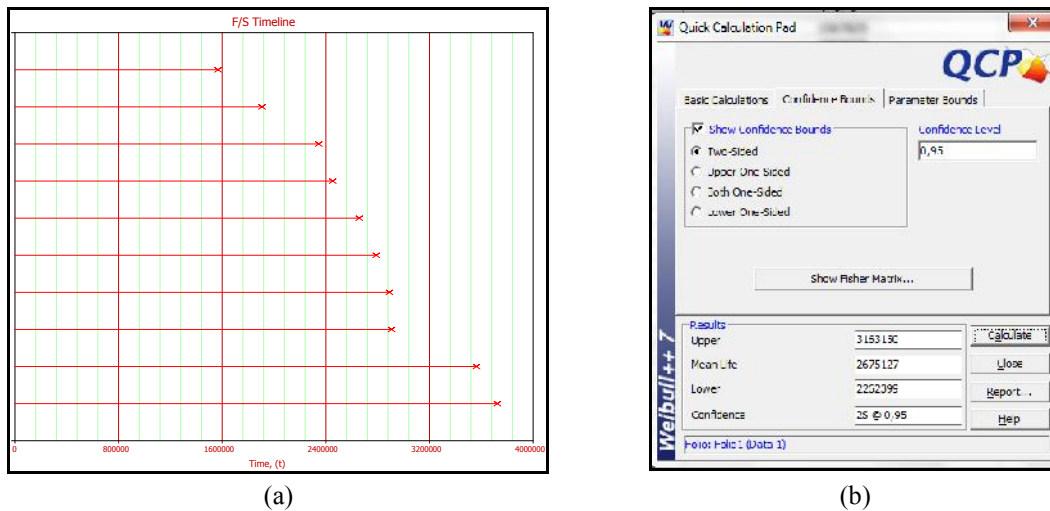


FIG. 5. Blade's reliability indicators (a) the failures/suspensions timeline diagram (b) mean life

5. FAILURE ANALYSIS OF A HELICOPTER ANTITORQUE ROTOR BLADE

The 10 blades fatigue tested have failed in the spar area (figure 6.a). For a helicopter blade there was a microscopic examination with optical stereo microscope IOR and with the electron microscope Philips SEM-515, with magnifications ranging between x10 - X3000. Microscopic appearance of the fracture surfaces is illustrated in Figure 6.b.

The arrow indicates the fatigue crack priming area that has propagated around the entire section of the blade near to the opposite edge, where the final tearing of the product when it reached the critical section took place.

In Fig. 7.a there is a fragile area (marked with the letter F), fatigue striations characteristic to the fatigue phenomenon occur within the broken surface. The material from which the helicopter blade was made contains oxide type inclusions, oxide film, mainly delivered in the breaking priming area. Some of these inclusions are visible to the naked eye breaking the surface in the form of dark spots of colour. Microscopy image of Fig.7.b shows such an inclusion that is contaminated in the electron beam. In the rupture of the surface more oxide inclusions can be seen, oxide film, indicating an impure material. Some of these inclusions are visible to the naked eye. Fatigue tear propagation outlines characteristic aspects, normal for such a breaking for an aluminium alloy blade.

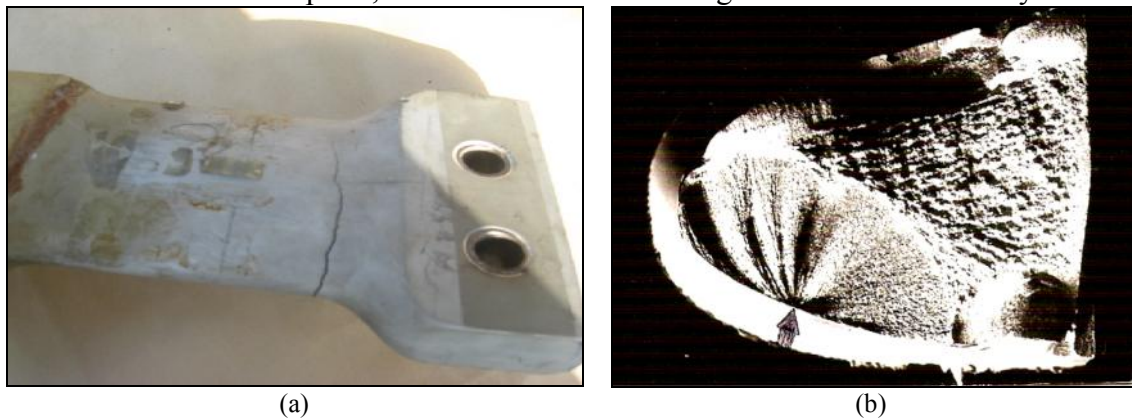


FIG. 6. (a) Defects shown in the blade's spar area (b) the microscopic appearance of the break surface

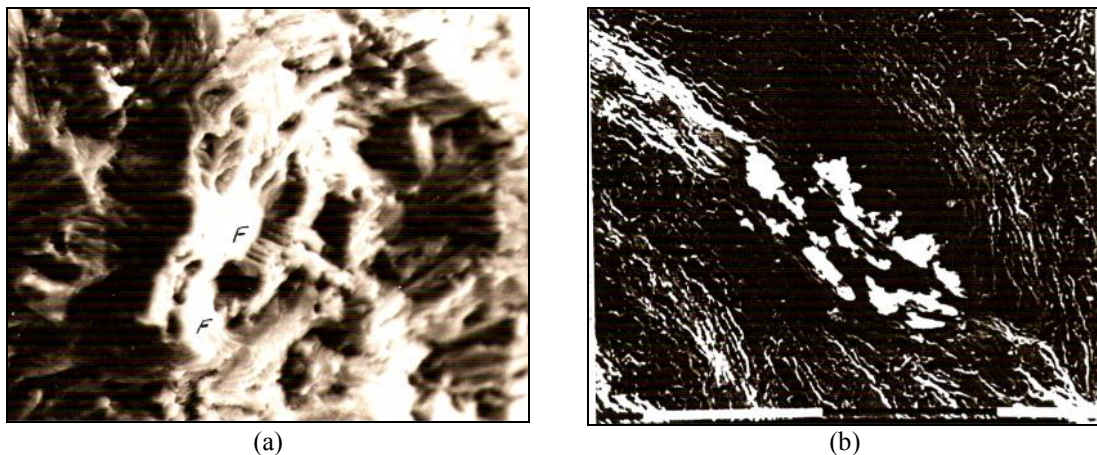


FIG. 7. (a) Microscopic appearance of the fragile breaking area (b) oxide type inclusion highlighted in the breaking surface

CONCLUSIONS

Product and service quality is the basic indicator of an industry or economy. Reliability being a component along with other indicators of quality, it must stay in the attention of all the factors determining the smooth running of society. In this paper the main indicators of reliability (reliability function, non-reliability function, failure rate, probability density, and mean life) were determined and plotted using statistical analysis and processing of experimental data. Although the tests are in a complex reliability program the most expensive component, when well designed and properly deployed they determine the lasting economic effects at all negligible.

In conclusion, the helicopter tail rotor blade breaking was produced due to priming and propagation of a fatigue crack. The stress concentrator that favoured the priming was the oxide inclusion, oxide film, located at the outer edge, to one of the blade's edges.

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