

Kinetics of fatigue cracks in the rotor blades of the Mi-171 helicopter

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Abstract. The rotor blades of the helicopter are operated on the principle of ensuring operability within the assigned resource, which is 2000 flight hours, after which they are subject to decommissioning. However, by the end of this period, as a rule, fatigue damage does not have time to propagate in the blade, so it can be operated on. Thus, the study of the process of nucleation and propagation of fatigue cracks in the blades will allow to determine the period during which the presence of cracks does not threaten the performance of the construction. This will make suggestions for a possible increase in the assigned resource of the blade, which, in turn, will lead to cost savings. The problem of the work is to study the propagation of fatigue cracks in the rotor blades of a helicopter to make recommendations on the possible increase in their assigned resource. Research objectives: development of methodology for full-scale testing of blades; determination of their endurance limit; development of a methodology for processing the results of full-scale tests (videos of the growth of fatigue cracks); assessment of the possibility of extending the assigned resource of the blades. Experimental methods of fracture mechanics and statistical methods for processing data obtained during experiments were used as research methods. As a result, it was found that the appearance and propagation of surface cracks in the blades with the test base of $N = 1.6 \cdot 10^7$ cycles begin after the stresses exceed the level of 76.94 MPa. A fatigue crack in the blades propagates to failure within 150...170 hours, while the subcritical propagation of the crack lasts 130...150 hours. The period of stable slow propagation of cracks can be proposed for inclusion in the assigned resource of the blade.

1. Introduction

Most parts of machines during operation are exposed to time-varying stresses. If the level of these stresses exceeds a certain limit, then microdamages begin to form and accumulate in the material, leading to the occurrence of submicroscopic cracks. These cracks gradually grow and merge, forming a macroscopic crack with a length of 0.1 to 0.5 mm. Stresses are concentrated at the crack front, which facilitates its further propagation. The propagation of a crack gradually weakens the cross section of a part, which leads to its sudden destruction, which can be associated with accidents and severe consequences.



The study of the kinetic behavior of cracks served as the basis for the work of such scientists as A. A. Shanyavskiy [1–3], V. S. Bondar [4], Yu. G. Matvienko [5–6], V. V. Moskvichyov, N. A. Makhutov [7–11], V.N. Shlyannikov [12] and others; a study of the cracks propagation in the rotor blades of helicopters was carried out by A. A. Shanyavskiy [3] based on the testing of samples. To date, scientific work devoted to the study of the kinetics of cracks and based on full-scale testing of machine parts is not enough. This paper presents such a study using the example of the rotor blade of the Mi-171 helicopter, carried out on the basis of full-scale tests of the spars of these blades.

2. Formulation of the problem

There are three basic principles for ensuring the reliability of constructions operating under cyclic loads:

- the principle of ensuring operability within the assigned resource;
- the principle of ensuring operational survivability;
- the principle of operation in technical condition.

The rotor blades of a helicopter are operated according to the first principle. Their assigned resource is 2000 flight hours, after which they are subject to decommissioning. However, by the end of this period, as a rule, fatigue damage does not have time to propagate in the blade, so it can be operated on. Thus, the study of the process of nucleation and propagation of fatigue cracks in the blades will allow to determine the period during which the presence of cracks does not threaten the performance of the construction. This will make suggestions for a possible increase in the assigned resource of the blade, which, in turn, will lead to cost savings. Thus, the problem of the work is to study the propagation of fatigue cracks in the rotor blades of a helicopter to make recommendations on the possible increase in their assigned resource.

3. Experimental results

The object of study is the rotor blade of the Mi-171 helicopter (8AT-2710-00) (figures 1, 2).



Figure 1. Mi-171 helicopter rotor blades.

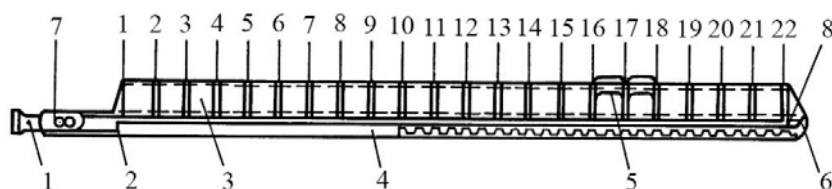


Figure 2. Constructive set of the rotor blade of the Mi-171 helicopter: 1 – blade tip, 2 – spar, 3 – tail compartments, 4 – anti-icing system, 5 – trimmers, 6 – ending, 7 – pressure switch, 8 – mooring unit, 1-22 – ribs.

The main power element of the blade – the spar – is made of aluminum alloy AVT-1, the mechanical characteristics of which are shown in table 1 [13].

Table 1. Mechanical characteristics of aluminum alloy AVT-1.

E^a (MPa)	σ_t^b (MPa)	σ_v^c (MPa)	δ_5^d (%)	ψ^e (%)	τ_{sh}^f (MPa)	HB ^g (MPa)
69627	294	225	10	20	206	65

^a Elastic modulus.

^b Temporary resistance (tensile strength).

^c Yield strength.

^d Elongation at break.

^e Narrowing at break.

^f Shear stress.

^g Brinell hardness.

The blade tests were carried out on a specially designed bench (figure 3). The scheme of the control and measuring system used in the tests is shown in figure 4.

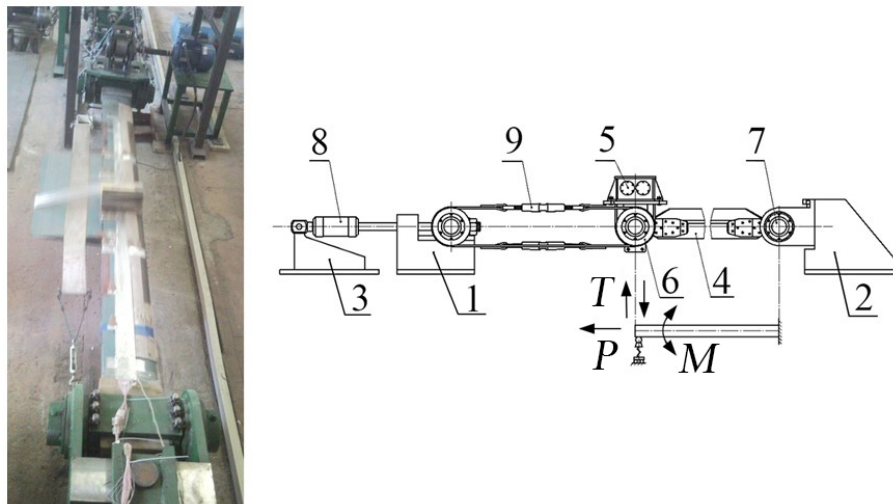


Figure 3. Designed experimental bench for dynamic testing: 1 – tension unit, 2, 3 – brackets, 4 – sample, 5 – exciter, 6 – movable support, 7 – motionless support, 8 – hydraulic cylinder, 9 – rope shroud, P – tensile force, T – pushing force, M – bending moment.

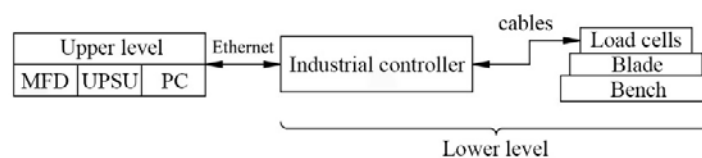


Figure 4. The scheme of the control and measuring system: MFD – multifunction device, UPSU – uninterrupted power supply unit, PC – personal computer.

Cracks in the blade most often occur in the range of its relative radii $\bar{R} = 0.5 \dots 0.7$ (compartments 11...14) (figure 5(a)). As a rule, they arise at the lower radius of the rear wall, the lower inner and upper inner surfaces of the spar (positions 1, 2 and 3 in figure 5(b)).

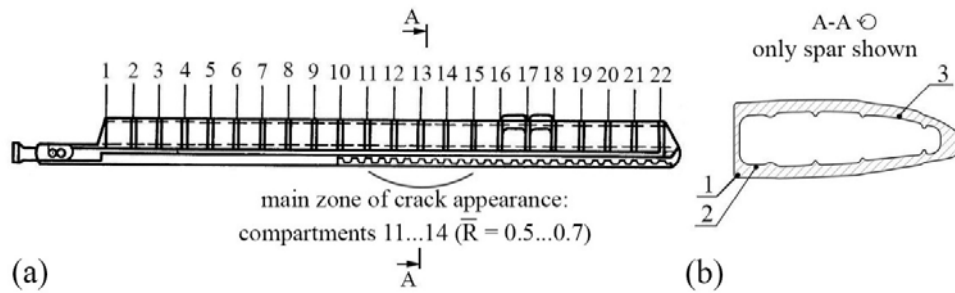


Figure 5. Zones of crack appearance: (a) blade scheme (1-22 – compartment borders), (b) spar cross section.

The values of the fatigue strength characteristics can be obtained either by plotting a fatigue curve (Weller curve) for testing up to 10 samples, or by plotting a full probabilistic fatigue diagram for testing from 50 to 100 samples.

The fatigue curve (Weller curve) was plotted from tests of 8 samples with a symmetrical stress cycle ($R = -1$) and a test base of $N_b = 5.1 \cdot 10^7$ cycles ($\lg N_b = 7.71$) in double logarithmic coordinates $\lg \sigma_{\max} - \lg N$ (figure 6). The corresponding endurance limit σ_{-1} was 56 MPa. The experimental data were approximated by the least square method.

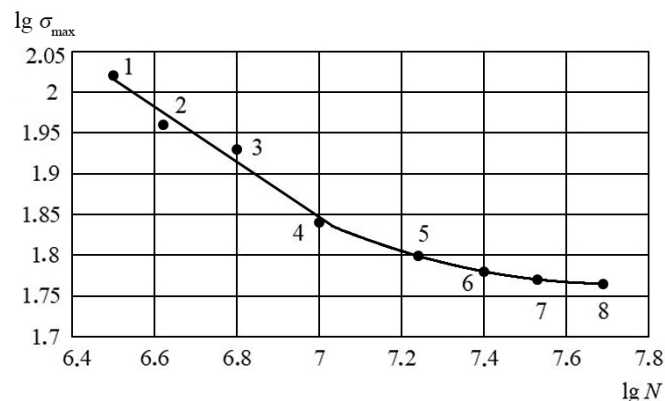


Figure 6. Weller curve for Mi-171 helicopter rotor blade.

The equation of the left portion of the Weller curve corresponding to samples 1...4 has the form:

$$N = 5.272 \cdot 10^{16} \sigma_{\max}^{-5.155},$$

where σ_{\max} is maximum stress (MPa);

N is number of cycles to failure.

The right portion (samples 5...8) is described by the equation:

$$\lg \sigma_{\max} = 0.151 \cdot \lg^2 N - 2.328 \cdot \lg N + 10.746.$$

To plot complete probabilistic fatigue diagrams, 58 blades were tested at 4 stress levels: 100 ± 2 , 85 ± 1.7 , 75 ± 1.5 and 55 ± 1.1 MPa. To determine the average value and the standard deviation of the endurance limit with the test base $N = 1.6 \cdot 10^7$ cycles according to the method described in [14], the following graphs were plotted: a family of durability distribution curves (figure 7), a family of fatigue curves (figure 8), endurance limit distribution curve (figure 9). The letter Q in figures 7, 9 denotes the probability of destruction (accumulated frequency).

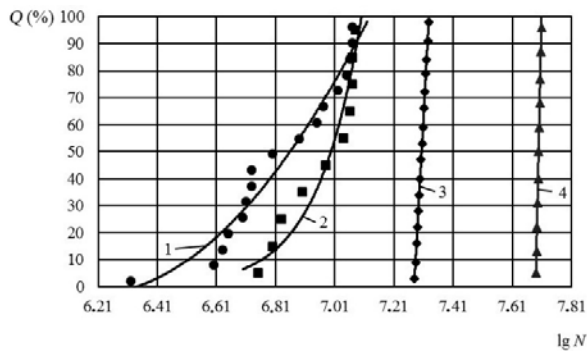


Figure 7. A family of durability distribution curves: 1 – $\sigma_{\max} = 100$ MPa, 2 – $\sigma_{\max} = 85$ MPa, 3 – $\sigma_{\max} = 75$ MPa, 4 – $\sigma_{\max} = 55$ MPa.

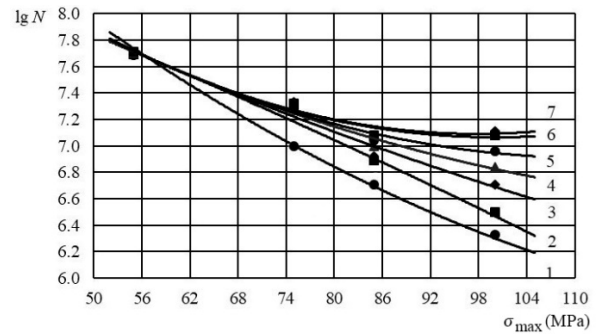


Figure 8. A family of fatigue curves: 1 – $Q = 1\%$, 2 – $Q = 10\%$, 3 – $Q = 30\%$, 4 – $Q = 50\%$, 5 – $Q = 70\%$, 6 – $Q = 90\%$, 7 – $Q = 99\%$.

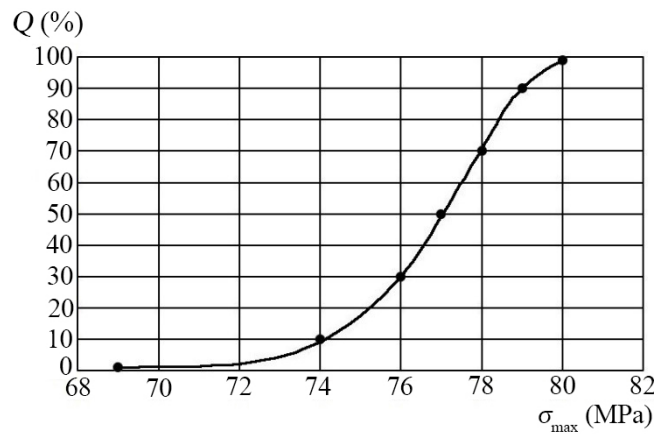


Figure 9. Endurance limit distribution curve with the test base $N = 1.6 \cdot 10^7$ cycles.

To determine the average endurance limit, the interval between its extreme values (68...80 MPa) was divided into 6 equal sections of 2 MPa and calculations were performed according to the formulas:

$$\overline{\sigma_{-1}} = \sum_{i=1}^l \Delta Q_i \cdot (\sigma_{-1})_i; S_{\sigma_{-1}} = \sqrt{\sum_{i=1}^l \Delta Q_i \cdot ((\sigma_{-1})_i - \overline{\sigma_{-1}})^2},$$

where $\overline{\sigma_{-1}}$ is average endurance limit;

$S_{\sigma_{-1}}$ is standard deviation of the endurance limit;

$(\sigma_{-1})_i$ is endurance limit value in the middle of the interval;

l is number of intervals;

ΔQ_i is increment of probability within one interval.

The following values were obtained: $\overline{\sigma_{-1}} = 76.94$ MPa; $S_{\sigma_{-1}} = 2.32$ MPa; the propagation of cracks in the blades begins when the condition $\sigma > \overline{\sigma_{-1}}$ is fulfilled.

The propagation of cracks in the samples of the blades was recorded on a video camera (figure 10, the crack is shown by an arrow).

Next, the resulting record was processed on a computer using specially created software. Each frame of the video was binarized, after which a binary matrix was created on its basis, which was subjected to elementwise processing. Based on the results of processing all the recording frames, a kinetic graph of the crack propagation is plotted (figure 11).

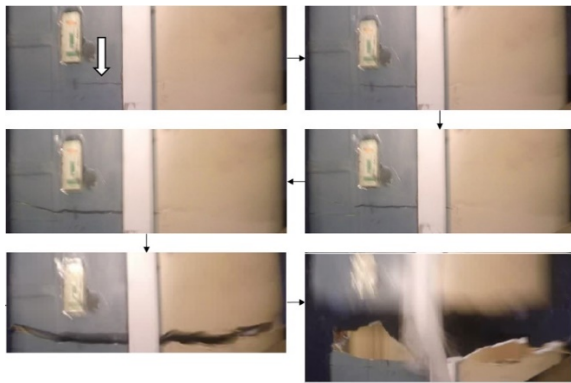


Figure 10. Footage from crack growth video.

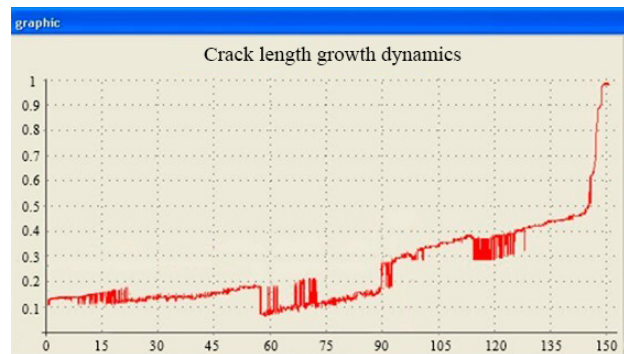


Figure 11. Kinetic graph of the crack propagation (horizontal axis — crack growth time (h); vertical axis — crack growth rate (mm h⁻¹)).

After tracing the graphs in the Mathcad package, the data obtained are interpolated by a cubic polynomial describing the dependence of the crack growth rate (mm h⁻¹) on its growth time (h) (figure 12):

$$v_{\text{length}} = 8.386 \cdot 10^{-7} t^3 - 1.364 \cdot 10^{-4} t^2 + 5.722 \cdot 10^{-3} t + 0.255. \quad (1)$$

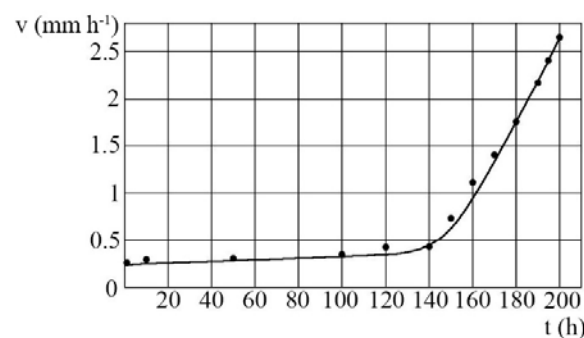


Figure 12. Graph of the dependence of the crack growth rate on the time of its propagation.

Figure 12 shows a graph of the dependence of the crack growth rate on the time of its propagation, from which it can be seen that rapid propagation begins after 140 hours of crack growth.

The critical crack length is determined by integrating polynomial (1) over time with an upper limit of 140 hours; we get the value of 47.5 mm. During the experiments, it was noted that the rapid growth of a crack begins with its length 45...50 mm.

4. Discussion of the results

Scientific results obtained during the study:

- The endurance limit of the spars of the rotor blades of the Mi-171 helicopter is 56 MPa with the test base $N = 5.1 \cdot 10^7$ cycles (the method of plotting the Weller curve), 76.94 MPa with the test base $N = 1.6 \cdot 10^7$ cycles (the method of plotting the endurance limit distribution curve).

- The average time of subcritical growth of the fatigue crack in the spars of the blades is 130...150 hours, of the supercritical is 10...20 hours; the average crack growth rate is 0.5 mm h^{-1} and 2.5 mm h^{-1} , respectively. The critical crack length is 45...50 mm.

The results obtained have sufficient convergence with the studies of A.A. Shanyavskiy, which indicates that the most loaded section of the blade is its interval at relative radii of 0.55...0.7, and also that the subcritical crack propagation rate in the samples averages $1.4 \cdot 10^{-8} \text{ m cycle}^{-1}$, which equals 0.151 mm h^{-1} [3].

5. Findings and conclusion

The period of subcritical propagation of fatigue cracks (130...150 hours) can be recommended for inclusion in the assigned resource of the rotor blade of the helicopter, since there is no damage during this period of time. Thus, a possible increase in the assigned resource of the blade is 5...10% of the existing value in 2000 hours. The potential monetary savings from an increase in the assigned resource will be 77005 rubles for 2000 hours of operation of the blade, which is 6.97% of its cost. The results of the work were applied at CJSC "Ulan-Ude Blade Plant" and introduced into the educational process of the Strength of Materials department of the East Siberia State University of Technology and Management.

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