AN EXPERIMENTAL METHODOLOGY FOR EVALUATING SURVIVABILITY OF AN AERONAUTICAL CONSTRUCTIONS FROM COMPOSITE MATERIALS

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Abstract

This paper presents the analysis of the survivability of a heavy transport helicopter tail rotor blade made of composite laminated materials after ballistic damage made by the bullet of 7.9 mm calibre shoulder weapons. Penetrating damages made in the root part of the tail rotor blade spar have been analyzed. The test program for the tail rotor helicopter blades has included dynamic testing nondamaged and damaged blades in full-scale. Based on the results of vibratory testing and fatigue testing an assessment is made about the vulnerability and the survivability of the helicopter tail rotor blade after ballistic damage made by the bullet of shoulder weapons.

1 Introduction

The vulnerability, as an element of survivability is one of the most important exploit characteristics of contemporary aircraft. With respect to survivability, composite laminated materials show the best behaviour and results compared to the other materials that are nowadays used in aviation. The survivability program for the military aircraft has been described in References 1 and 2. The requirements and guidelines for the general program are contained in MIL-STD-2069. See also FAR/JAR 25.571. For bird strike requirements, see FAR/JAR 25.631.

By analyzing the dynamic behaviour of damaged constructions one can get the knowledge about the acceptable level of damages and probable chances for the aircraft to survive. The aircraft ability to survive even after being exposed to severe damages on vital and load-carrying parts of the aircraft constructions is imperative not only for combat but also civil aircraft as well [1-8].

Helicopters are given special attention in this analysis as they are rather specific, highly vulnerable and greatly exposed to threats due to their vertical take-off and landing, low speed and flight altitudes etc. This paper presents the analysis of the dynamic behaviour of a heavy transport multipurpose helicopter tail rotor blade (Figures 1 and 2) before and after ballistic damages caused by 7.9 mm calibre shoulder weapons that may occur as a conse-quence of combat as well as terrorist actions (Figures 3-6). First of all a non-damaged tail rotor blade behaviour was analyzed by exposing the blade to static and dynamic loads in extreme flight conditions; after that the blade was exposed to the long-lasting dynamic loads with an aim to define fatigue characteristics; and finally, the blade behaviour suffering penetrating damages was analyzed on its most vital load-carrying part, following the same testing program, i.e. at the root of the spar (Figures. 7 and 8). For each of these tests identical special blades made in the same two-part metal die were used [3 and 9].

In the tail rotor blade the conventional composite materials with epoxy resin matrix, fibreglass filament spar and 18-section laminated fabrics skin of fibreglass filament, some carbon filament embedded along the trailing edge, a foam core, leading edge protection strips polyurethane, etc. were used [3 and 9].

The aim of the tail rotor blade vibratory testing was to determine the basic aeroelastic properties of the blade. The vibratory test program included experimental determination of

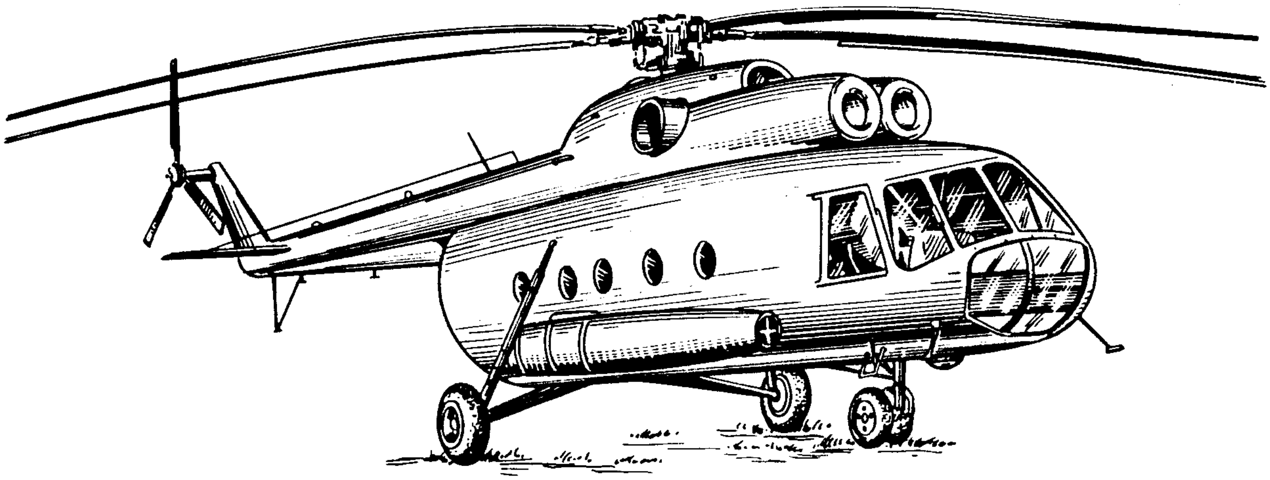

Fig. 1. The heavy transport multipurpose helicopter.

the natural oscillation modes and the tail blade natural frequency as well as its structural damping. The fatigue test program included: interlaminar separation (delamination) testing and geometric deformation of the blade cross-sections following the fatigue tests program during which real tail rotor blade loads were simulated - the same loads to which blade is exposed under extreme flight conditions, before and after ballistic damages of the blade [8-11].

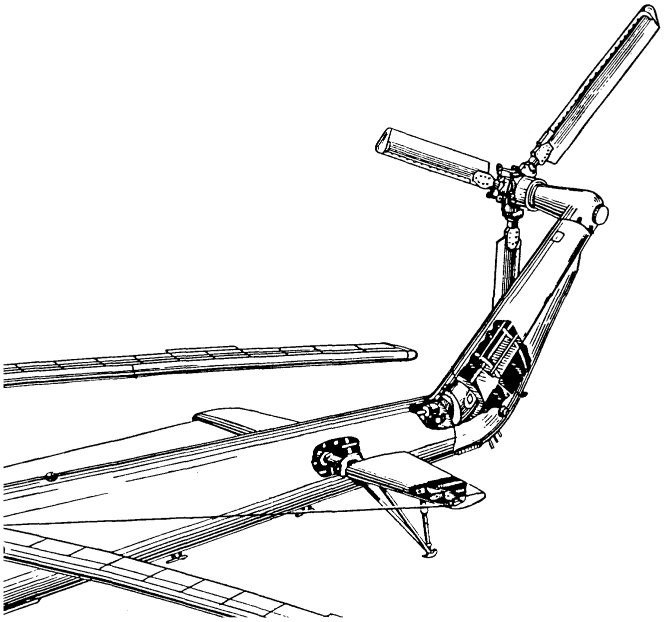

Fig.2. The heavy transport multipurpose helicopter tail rotor.

All the tests on the helicopter tail rotor blade were performed at the Belgrade University, Faculty of Mechanical Engineering, Aeronautical Department Laboratory.

2 Experimental Methodology and Results

The main objective of the testing that was to be done on non-damaged and damaged helicopter tail rotor blade was to verify experimentally the level of the blade survivability which is defined as the degradation degree of its vital mechanical characteristics after ballistic damage. On this occasion only one particular case was analyzed: damages on the most vital load carrying part of the blade, i.e. at the root of the spar (Figure 8).

The resulting damage together with its in-going and out-going penetration presents a vital structural damage on the load carrying part in the area usually exposed to heaviest loads. The investigations were carried out on both tail rotor blades follow a standard practice used by majority of scientific and research aeronautical institutions [12-14].

A very robust facility frame made of steel *U* and *L*-profiles tied together with screws was used in the course of the tail rotor blade attachment vibratory testing program. All the elements used in these testing are shown in References 8 and 9. There it can be clearly seen that all the elements were divided into two

Figure 2. Ballistic damages of helicopter's windshield.

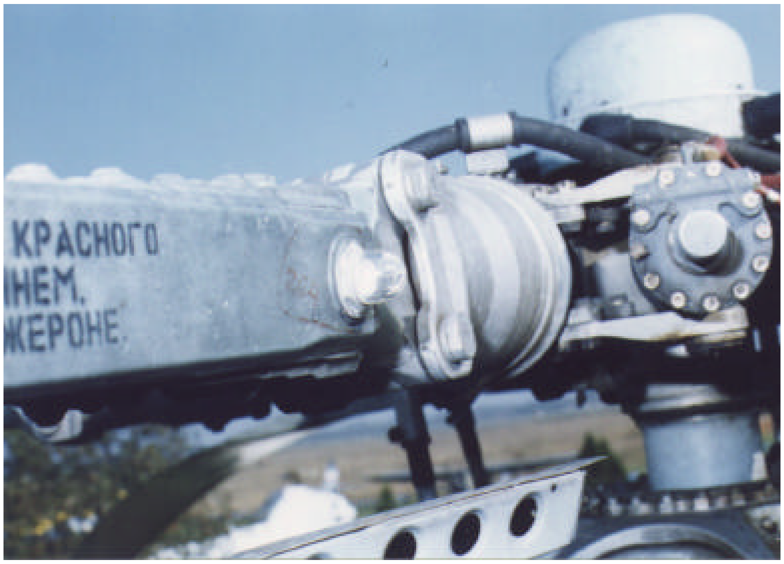

Figure 4. Ballistic damages of transmission and main rotor head.

functional sections. The first one was composed of excitation apparatus while the second one was made of response-detection equipment. Measuring points were placed along the elastic axes of the blade in the same order as shown in Figure 7.

The excitation apparatus consisted of a pulse generator, a signal amplifier, a digital timer and frequency counter, a vibration exciter (shaker) and an airfoil clamp; while the response detection group was made of: piezoelectric accelerometers, oscilloscope with voltmeters and a multichannel *X*-t recorder. The link between the vibration exciter and the rotor blade was formed of a rigidly tied aluminium alloy pipe with adjustable length and by use of a panel airfoil clamp which was shaped so as to fit the rotor blade cross-section at the location of application of excitation.

For displacement measurement in these investigations piezoelectric accelerometers were used and they measured displacements at selected points on the blade as shown in Figure 7.

A special kind of cement was used to provide a close link between the pick-up and the blade in the course of measurement.

Figure 3. Ballistic damage of the main rotor blade.

Figure 6. Ballistic damages of the tail rotor drive shaft and vicinity structure.

As a first step within these investigations a harmonic analysis for both tail rotor blade types was performed.

Having determined the frequencies for the first-four harmonic's natural (resonant) modes of oscillations, displacement vectors for the first-four basic oscillation modes were measured. Some measurement results are shown in Figures 9 and 10. Figure 9 shows the harmonic analysis results of the first-four oscillation harmonics for the non-damaged tail rotor blade, while Figure 10 gives us a comparative presentation of the second oscillation mode for both non-damaged and damaged tail rotor blade.

Tail rotor blades' structural damping was determined from amplitude reduction of free vibrations. At first the blades were excited to vibrate with the first basic (resonant) oscillation mode with gradually decreasing amplitude due to the damping effects of the structure.

The original records obtained from these tests for non-damaged and damaged tail rotor blade at the measured cross-section 10 with time base 1 *s/cm* are shown in Figure 11.

The logarithmic decrement of the free vibrations was utilized to characterize the structural damping diagram (Figure 12). Its value is determined as:

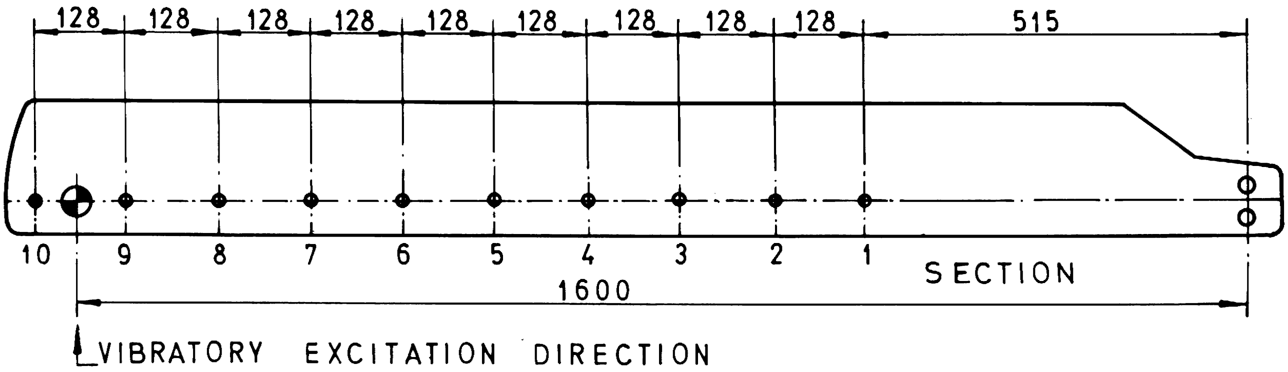

Fig. 7. Measurement points in vibratory testing.

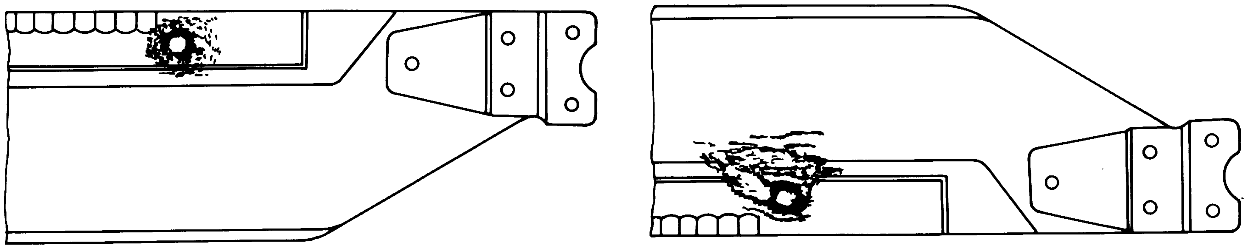

Fig. 8. The helicopter tail rotor blade made of composite laminated materials after ballistic damage made by the bullet of 7.9 *mm* calibre shoulder weapons, in-going (left) and out-going (right) penetration.

$$d = \frac{1}{n} \ln \frac{x_k}{x_{k+n}} \tag{1}$$

where $n=10$ is the number of observed oscillations, x_k is observed initial amplitude in the time interval, whereas the correspondent average value of amplitude is:

$$x_m = \frac{1}{2}(x_k + x_{k+n}) \tag{2}$$

Q-factor is also usually used to define the structural damping and it gives relative energy (*E*) reduction in successive oscillations. *Q*-factor is defined as

$$Q = \frac{E_1}{E_1 - E_2} \approx \frac{1}{2d} \tag{3}$$

The structural damping results for the non-damaged tail rotor blade expressed by the logarithmic decrement and *Q*-factor are given in Figure 12.

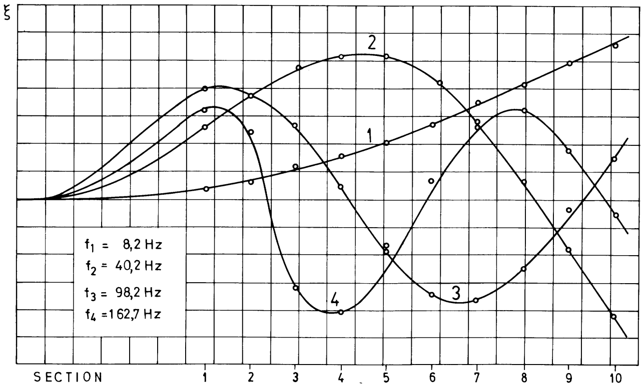

Fig.9. The natural modes of oscillation for the non-damaged tail rotor blade.

Fatigue testing of the root part of the blade spar is one of the most important investigations of the helicopter blades made of composite laminated materials in respect to their load carrying ability and survivability check-ups. These tests are carried out with an aim to define eventual delamination of the composite laminated structure, changes of shape of the root part of the blade and the loss of its load carrying ability after having been exposed to a certain cycle of alternating variable loads, which, on their part, are a consequence of the inflight, combined load influence. The applied test loads include simulated steady centrifugal, vibratory chordwise bending, vibratory flapwise bending, and vibratory torsional pitch motion.

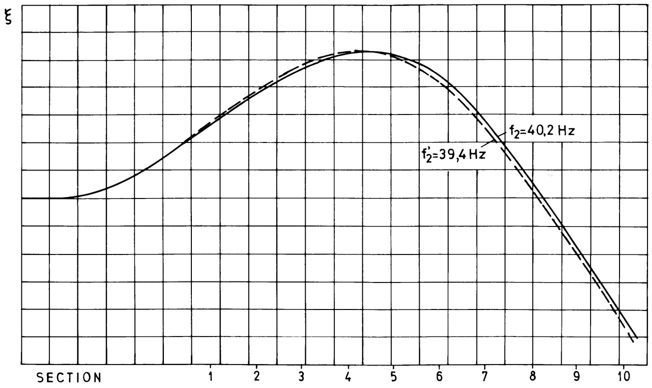

Fig.10. The second oscillation mode for both non-damaged (f_2=*40.2 Hz*) and damaged (f_2=*39.4 Hz*) tail rotor blade.

The simulated forces' values were: the centrifugal force 11350 *daN*, while resulting excitation alternating variable load that was vertical to the rotation plane and originated from vibratory chordwise bending, vibratory flapwise bending and vibratory torsional pitch motion had the value of 500 *daN* at the 6.5 *Hz* (390 *rpm*) frequency and at the angle of attack of 18°. A special facility frame (Figure 13) was constructed to simulate these combined and heavy loads. Facility test frame used in the helicopter tail rotor blade fatigue testing was constructed as a very robust three-dimensional frame made of steel *U* and *L*-profiles and was composed of several basic modules: facility to which tail rotor blade was attached and fixed, the excitation group and modules for centrifugal force simulations (Figure 13).

The excitation group consisted of an electric motor with a rating of 2.2 *kW* and rotation speed of 1420 *rpm*, a belt drive with transmission ratio of 1:3, variable speed drive (variable reduction gear), with a transmission ratio 1-3.25, eccentric mechanism with an adjustable eccentricity of 0-25 *mm* and an eccentric crank arm with bonded strain gages for excitation for selection. The variable transmission ratio enabled the desired excitation force frequency to be adjusted. A stroboscope was used for an accurate detection of excitation force frequency whereas the changeable eccentricity of the eccentric arm allowed adjustment of the excitation force intensity.

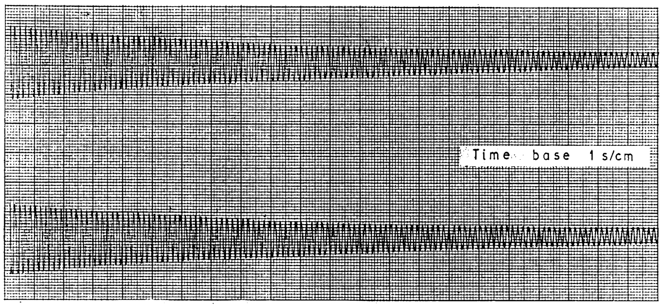

Fig.11. Structural damping for both non-damaged and damaged tail rotor blade.

The module for the centrifugal force simulation included a section for generation of the static load i.e. the centrifugal force, the section that transmitted the force to the blade root section and the blade root attachment fitting at which at one end centrifugal force was applied and at the same time the excitation force at the other end.

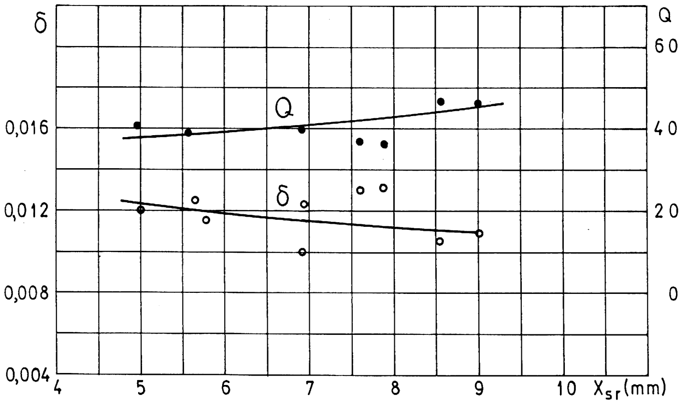

Fig.12. Logarithmic decrement and *Q*-factor of non-damaged tail rotor blade.

A hydraulic servo-controlled actuator composed of a hydraulic cylinder, distribution

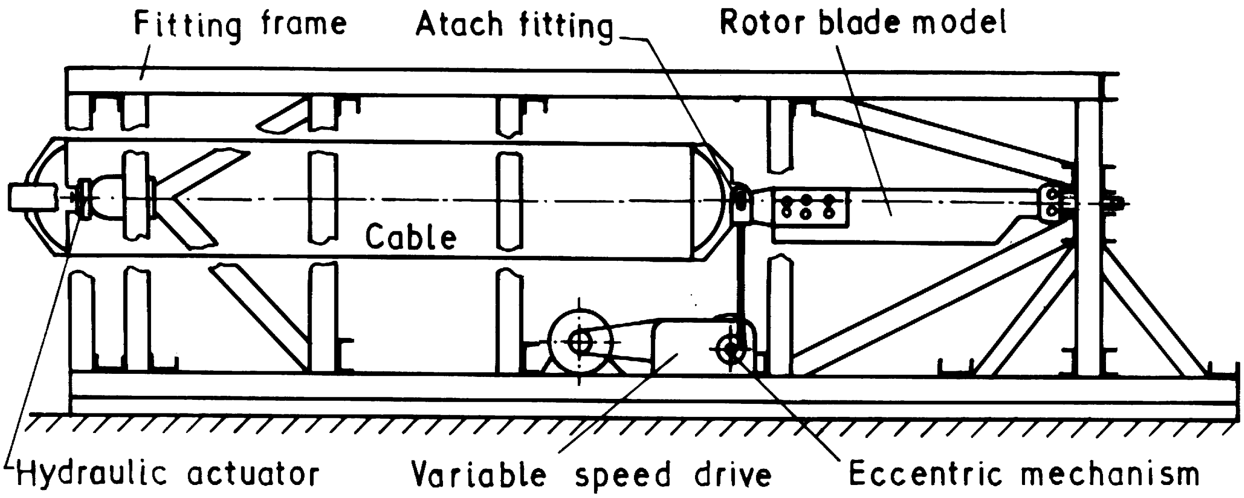

Fig. 13. Tail rotor blade fatigue test facility.

system with oil lines and a pump with a servomotor and control manometer was used as the centrifugal force generator. Its maximum force was 40000 *daN*. Thanks to this system the basic functioning of the facility frame became automatic.

The fatigue testing program of the root part of the tail rotor blade, aimed at the assessment of its load-carrying ability and survivability, included (in accordance with the standards) time fatigue tests together with the simulated centrifugal force-relaxing loading program for both damaged and non-damaged blades [7-12]. The blades were tested for the time fatigue by applying the excitation force at the 6.5 *Hz* frequency with simultaneous application of full-magnitude centrifugal force in duration corresponding to $1.5\text{x}10^6$ *cycles*. After every $3\text{x}10^5$ *cycles* the blade root relaxation was performed by gradually increasing and decreasing the intensity of the centrifugal force in a 0-11350-0 *daN* (Figure 14).

In the course of those investigations the behaviour of the blade, particularly of the damaged parts, was closely followed. No further damages or delamination of the structures, i.e. no further changes were observed at the damaged areas in the course of the testing itself.

When the fatigue testing program was finished on both non-damaged and damaged blades, further detailed check-ups on the deformation and degradation of geometrical shape of the blades and delaminations were carried out. On that occasion no changes were observed on either type of the blade. Also no delamination was observed and the damaged areas of the blades were not expanded in any way.

3 Discussion

The vibratory testing results were surprisingly the same for non-damaged and damaged heavy transport helicopter tail rotor blades. The obtained differences in frequencies and displacement vectors for some basic types of oscillation were within the range 2-5 *%*. The structural damping results coincided to even higher degree and the differences in the logarithmic decrement and *Q*-factor were less then 2 *%* (Figure 12). These minor differences in basic dynamic characteristics of non-damaged and damaged helicopter tail rotor blade made of composite laminated materials cannot significantly change or endanger the helicopter flight security.

The results of the damaged tail rotor blade fatigue testing have proved that even thus severely damaged blade is capable of performing all its vital functions on the helicopter even after 65 working hours in extremely difficult flight conditions.

Very interesting and extremely important conclusion is that the damaged blade survived the whole testing program with all and full loads relevant for the non-damaged blade

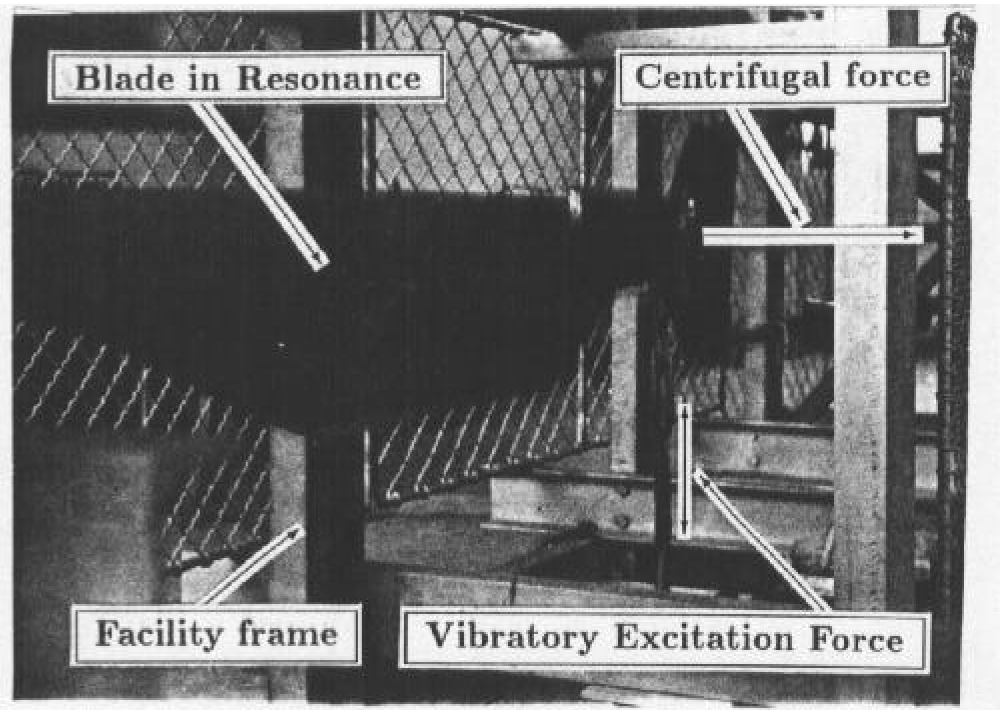

Fig. 14. Rotor blade in fatigue testing.

and that certainly proves the superiority of the composite laminated materials in production of aircraft vital and load-carrying parts.

4 Conclusion

The degradation level of the vital mechanical characteristics after penetrating/ballistic damage (Figure 8) is within such limits that the mission of this heavy transport helicopter (Figure 1) can quite safely be continued and extended much longer than the minimum 30 minutes flight prescribed by standards to reach the emergency landing site. Taking in consideration the results achieved in vibratory testing as well as in fatigue investigations on non-damaged and damaged tail rotor blade made of composite laminated materials, the obtained level of blade survivability is of such a nature that the aircraft could and would survive even considerably worse damages both in the root as well as in the other parts of the blade (Figures 10-12).

Stochastic nature of the impact that ballistic damages produce on the helicopter tail rotor blade prevent us from going into more precise and detailed quantitative analysis of the survivability level, and thus we are only left with the possibility to estimate it. Very low level of differences in the results obtained through the investigation of vibratory characteristics, structural damping and fatigue characteristics (less than 5 %) - all point to low level vulnerability of composite laminated materials to damages. That is why those materials give constructions with exceptionally high level of survivability so important in both military and civil aviation.

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