DOI: 10.2478/fas-2019-0006
FATIGUE OF AIRCRAFT STRUCTURES
Volume 2019: Issue 11, pp. 56-67

A NEW APPROACH TO MODELLING AND TESTING THE FATIGUE STRENGTH OF HELICOPTER ROTOR BLADES DURING REPAIR PROCESS

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ABSTRACT

The fatigue test was carried out on an element of a rotor blade removed from the Mi-2 helicopter. The purpose of the test was to check the fatigue strength of the repaired rotor blade. Metal composite rotor blades have a metal spar in the form of a box and the trailing sections in the form of metallic honeycomb sandwich panels. The trailing sections are bonded to the spar. The repair had been carried out at the point where the trailing section became debonded from the spar at the Air Force Institute of Technology in Warsaw using a methodology developed for carrying out repairs of rotor blades' damage. All types of the Mi family helicopters are equipped with metal composite rotors blades. Depending on MTOW (Maximum Take-Off Weight) and destination of helicopters, blades differ in dimensions, but their design solutions are practically the same. For this reason, the developed repair methodology can be used for all characteristic rotor blades structures for Mi helicopters. The fatigue test was performed at the Łukasiewicz - Institute of Aviation in Warsaw, using a hydraulically driven fatigue machine. The fatigue test was carried out by performing over 1.1 million load cycles. In repair places, upon completion of fatigue testing, no damage was found.

Keywords: rotor blade, helicopter, fatigue test, repairs, bonding, composites.

DESCRIPTION OF THE ISSUE

Helicopters of the Mi family: Mi-2, Mi-8, Mi-14, Mi-24 are used by the Polish Air Forces. Although differing in airframe design, weight and ways of usage, they share the same rotor blades design solutions.

The front part – leading part is a spar in the form of a single-chamber torsion box made of aluminum alloy on one side it terminates with a steel base allowing installation in the main rotor hub assembly, and on the other side with a plug allowing maintaining pressure inside the spar. The blade trailing section comprises a series of non-connected sections, forming of a metallic honeycomb sandwich structure with a hexagonal core, bonded to the spar (Fig. 1). The leading sections are bonded to the spar with 26 mm wide strips [1]. The place where the section cladding is joined to the spar can be unreliable as it may debond. Disbonds might occur due to a number of factors:

- stresses occurring under the influence of forces during flight operation;
- stresses occurring during helicopter's maintenance and storing;
- influence of various atmospheric conditions (humid environment, temperature variations, etc.).

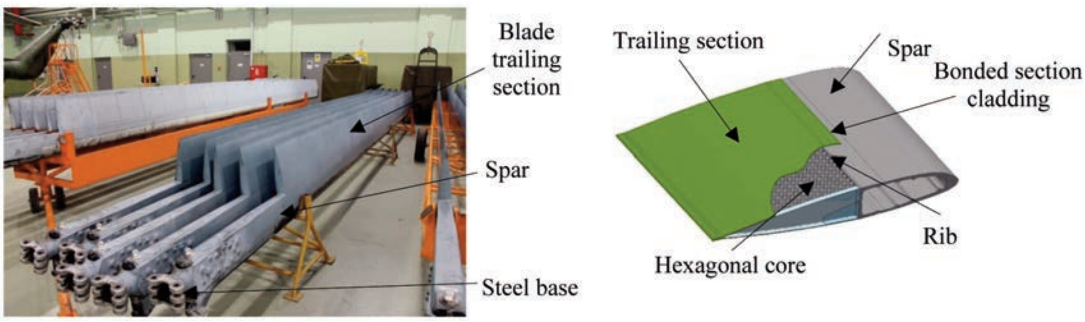

Figure 1. Mi rotor blades: a) removed Mi8 rotor blades during maintenance [2], b) schematic construction of a rotor blade single section.

In usual conditions of operation and storage, blades are exposed to different weather conditions. The impact of water, temperature variability and the aging effect weaken the area where the section cladding is bonded to the spar. The negative impact of water and temperature on the adhesive layer has been confirmed by the single lap joint and wedge tests [3,4]. The weakening of the adhesive layer accelerates the fatigue process of the connection between the spar and the section cladding.

The two currently existing repair methods are not effective. Both methods are based on bonding the cleaned places of debonding by using non-thixotropic epoxy adhesives. The first way is to deflect the damaged cladding at the place of damage, clean it and bond it (Fig. 2a). In this method, the yield point is exceeded at the place of deflection. Exceeding the yield point causes permanent deformation of the cladding and may also contribute to the propagation of debonding. The second method is to slightly deflecting the damaged cladding, clean the slot as much as possible and bond by injecting epoxy adhesive (Fig. 2b). In this case, the repair involves a high risk of failure, largely due to the inability to thoroughly clean and prepare the surface for the bonding process. In addition, the pressurized adhesive under the cladding is partly ejected by the air compressed in the created chamber. This means that the adhesive does not get to the top of the slot and mixes with the air causing the adhesive to become porous. Most importantly, during the repair, there is no control of what happens under the cover.

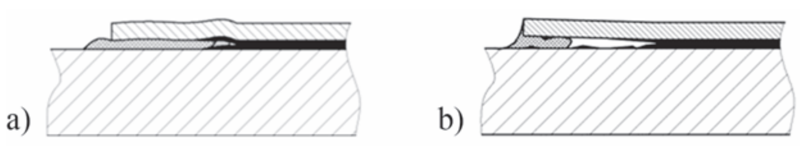

Figure 2. Previous repair methods: a) bonding after deflection and cleaning, b) bonding without deflection.

The new repair method proposed here is invasive - it requires removing a part of the original structure at the place of damage, replacing it with a filling, and restoring the original cladding with a patch. The filling and the patch are joined to the original section cladding with a thermosetting epoxy film (Fig. 3). It was assumed that this solution would allow for accurate surface preparation at the area of repair and control of the repair process, which would contribute to repair repeatability. Most importantly, the use of appropriate materials and surface preparation processes would allow the assumed strength parameters of rotor blades to be permanently restored in a repair process.

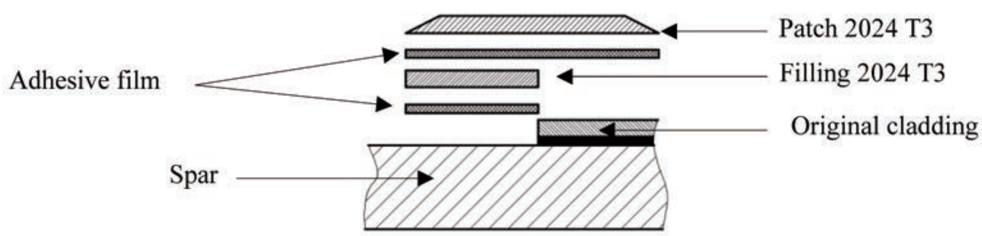

Figure 3. Scheme of the proposed repair package.

This study was one stage of the repair qualification process and consisted in checking the fatigue strength of the blade after repair. The study was comparative – the area of the section with repairs and the undamaged area were considered during the test. The study was conducted on a fragment of a rotor blade – one section long.

As mentioned earlier, the blades are made of a spar and, independently of each other, connected trailing sections bonded to the spar. Between the sections there is a layer of flexible hermetic. Because of that type of construction, each section is loaded independently of the contiguous sections.

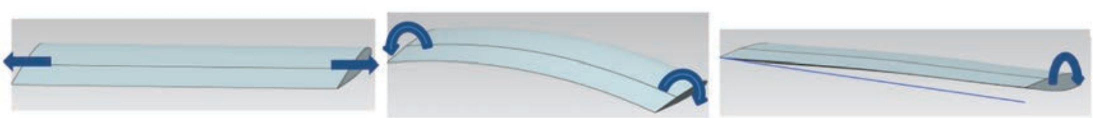

Figure 4. Scheme of blade fragment loads during operation: a) spar stretching caused by centripetal force, b) bending due to aerodynamic force and mass forces, c) torsion caused by aerodynamic force.

Debondings result from exposition to complex loads and moisture (Fig. 4). In order to simplify the test stand, indirectly loaded elements were omitted to focus on the bonding places. The study concept assumed the application of forces causing dominant stresses in the areas where damage occurs in the form of debonding. The highest stresses described were possible to obtain by applying the loads in the form of blade section torsion (Fig. 5).

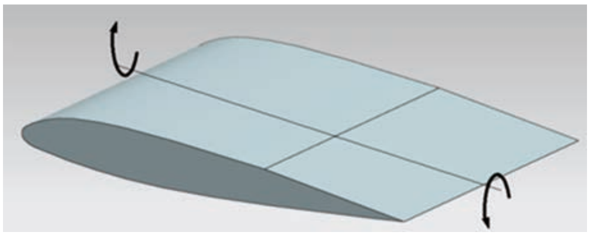

Figure 5. Concept of blade section loading during fatigue test.

NUMERICAL CALCULATIONS

The purpose of numerical calculations was to estimate the value of loads introduced into the examined fragment of the blade during the fatigue test and illustrate the impact of expected stress and strain fields on the blade structure.

The numerical calculations were carried out using the Finite Element Method (FEM), for a sample in the form of a rotor blade fragment – single blade section. For this purpose, a 3D model of the sample was created. The dimensions of individual section elements were determined by the measurements of the original element, using data from the original Mi-2 helicopter manufacturer's documentation and based on the 3D scan of the section (Fig. 6).

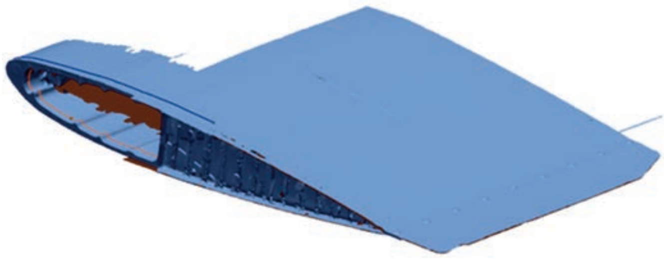

Figure 6. 3D scan of the rotor blade section.

ABAQUS software was used to perform the numerical tests. Due to the qualitative and estimative nature of the calculations, limited information on types of materials used in production of the rotor blades, the strength properties of the aluminum alloy 2024 T3 were used in the calculations. It was assumed that the elements made of this material were: a spar, a cladding of the rotor blade, rib elements and a hexagonal core. The hexagonal core was modeled as a homogeneous structure of mechanical properties equivalent to those of the core.

It was assumed that all the elements of the structure were inseparably connected, including bondings and mechanical joints.

The boundary conditions were introduced in accordance with Fig. 7a. Force P was applied to two places, as a pair of forces, at a distance of 76 mm from the section's symmetry axis. The forces were transferred to the steel overlays located on the surface of the section's trailing edge cladding (Fig. 7), (Fig. 11). The steel overlays were used to convert the point applied forces to the surface forces – to simulate the pressure loading.

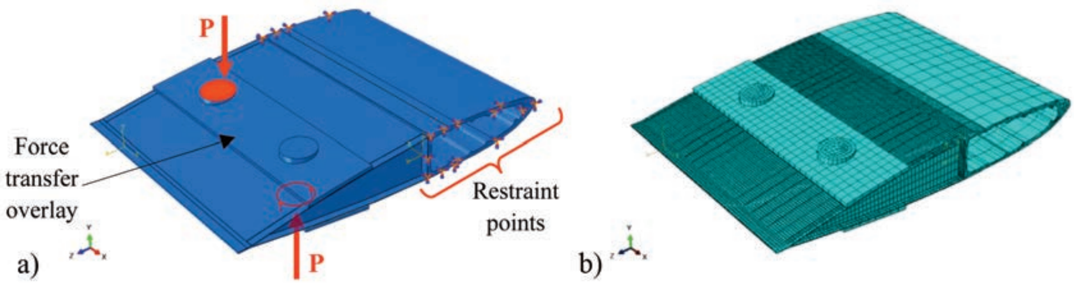

Figure 7. Rotor blade model in ABAQUS software: a) physical model with restraint and load boundary conditions, b) finite elements division – FEM mesh.

The boundary conditions assumed in this way were aimed at introducing the largest and at the same time significant tension at the connection places of the section and the spar. Rotor blades are loaded by several types of loads. One of them is torsion. To check the quality of the conducted repairs, these torsion loads allowed the biggest impact on the bonding between the cladding and the spar.

The starting point of the analysis was the value of tensile strength of the aluminum alloy 2024 T3 (regarding the place of damage) [5]. Based on this value, the 2024 T3 alloy fatigue limit value was adopted, with the cycle asymmetry factor R = 0 [6]. The fatigue limit was set at 200 MPa. According to previous studies of rotor blades, for maximum rotational speed loads, in the most adverse environmental conditions, the maximum equivalent stress in the area of bonding is about 120MPa [7]. It was assumed that such stress value would be achieved in the section under the influence of torsional forces. These stress values were the initial ones for the fatigue test (Figs. 7, 8).

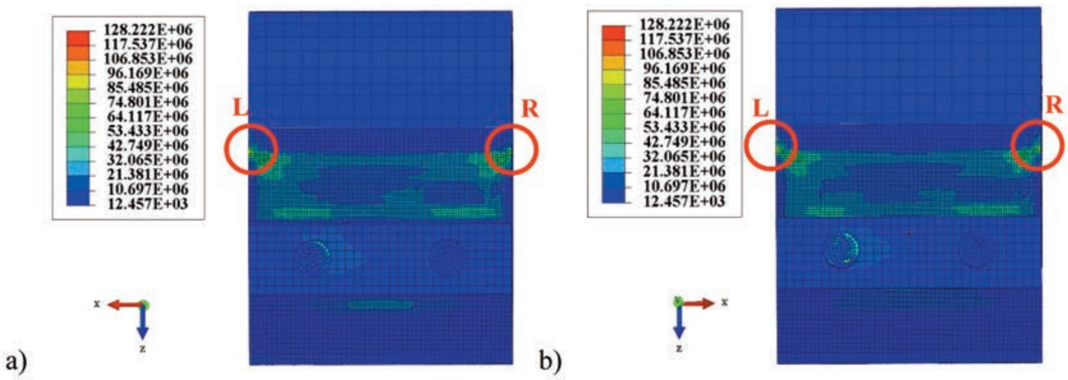

Figure 8. Distribution of equivalent stress , in rotor blade section under the influence of torsion, for the first period of fatigue tests, with marked bonding edges of cladding and spar: a) upper part, b) lower part.

The values of eqivalent stresses for both edges (L) and (R) (Fig. 8) differed and depended on the return of the applied force vector. They also differed for the upper and lower section part, due to the shape of the rotor blade profile. For the upper part: left side (L) MPa, right side (R) MPa (Fig. 8a). For the lower part: left side (L) MPa, right side (R) MPa (Fig. 8b). The stress differences resulted from the return of the applied forces' vector and the way in which the forces influence the rotor blade section bonding. Therefore, the forces applied can be divided into bending (L) and breaking off (R), (Fig. 8).

The purpose of bonding the section cladding and the spar is mainly to transfer shear forces (in the X-Z plane). The transfer of these forces causes stresses in the cladding. The registered maximum shear stress was 29 MPa and the minimum was -33MPa (Fig. 9). The stress difference (edges (L) and (R) at the same side of the section) resulted, as in the case of reduced stresses, from the way in which the forces influenced the bonding and the shape of the rotor blade profile.

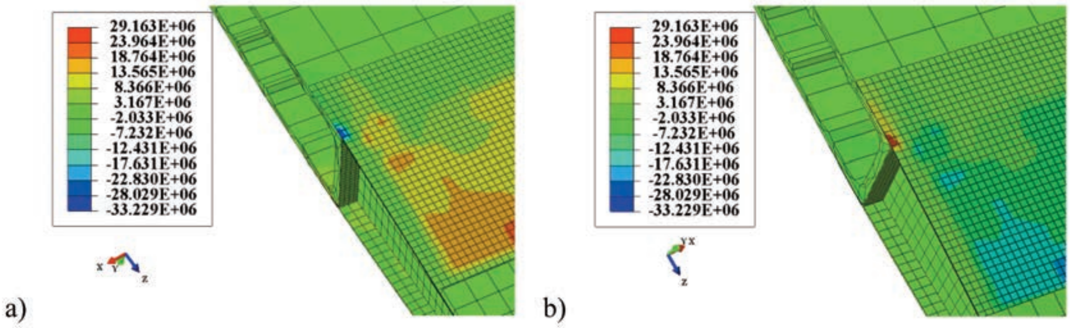

Figure 9. Shear stress on the rotor blade section edges, for loading in the first period of the fatigue test a) upper left side, b) lower left side.

The numerical calculations allowed the researchers to plan the process of the experimental study. Numerical tests made it possible to check the essential correctness of the experiment. The values and distribution of the equivalent stress and shear stress in the rotor blade section, caused by the application of torsional loads, were read. The results of numerical calculations confirmed the occurrence of the expected stress concentration at the place where the section is joined to the spar. It was particularly important to determine the exact loads for the planned experiment in order to obtain stresses at the bonding places, which would be comparable to those occurring in flight. In order to achieve the quantitative parameters, it is appropriate to include the bonding layers in the rotor blade section and the parameters of the adhesive used in the numerical calculations. For qualitative and estimated calculations, it was possible to use perfectly rigid joints between the elements of the rotor blade section.

EXPERIMENTAL STUDY

The purpose of the experimental study was to verify the strength properties of the rotor blade section, after the debonding between the section cladding and the spar had been repaired. This was achieved by carrying out a fatigue test using a sample in the form of a single rotor blade section under the influence of torsional loads. Based on the literature analysis [1,7,8], the experiment was to consider the work of rotor blades during their service life. The type of loads used in the experiment was adopted such as to obtain the maximum stress in the repair place and the minimum in other areas. The process of the experiment assumed continuous monitoring of the repair condition, using a strain gauge. The state of repair after completion of the experiment should determine the final result of the experiment - no damage means correct repair.

Repairs were made in two places of the section - on the upper and lower sides, on the left edges (Fig. 10a, b). In addition, a repair of a lateral crack, initiated at the edge of the section, was carried out (Fig. 10b) but wasn't presented in this paper as going beyond its subject matter.

In order to be able to fix the section in the fatigue machine mounts, reinforcements of the trailing section part were made. The trailing section part was reinforced externally with a layer of carbon-epoxy composite (Fig. 10c). Part of the internal hexagonal core was strengthened by being filled with epoxy resin with the addition of Aerosil 200 filler (Fig. 10a).

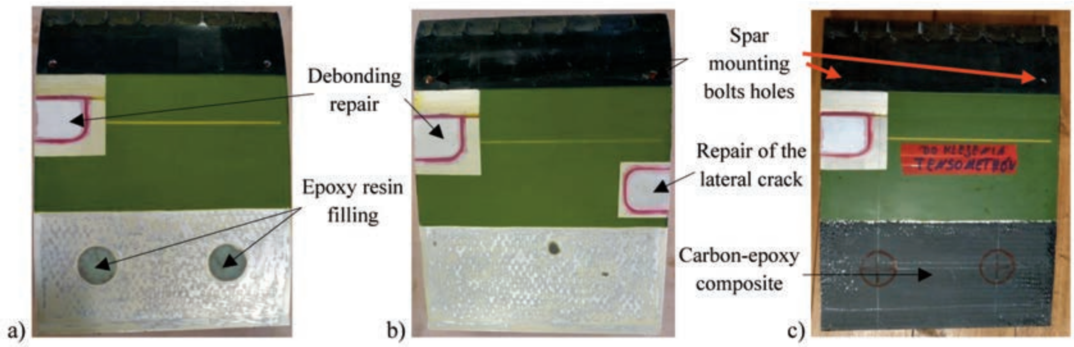

Figure 10. Testing sample, in the form of a single rotor blades section, after repairs: a) lower side, b) upper side, c) section with carbon-epoxy reinforcement.

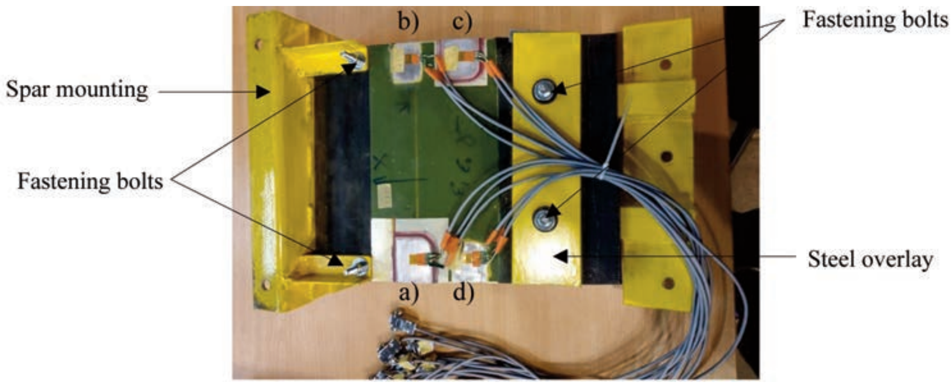

Figure 11. Rotor blade section with fatigue machine mounts and strain gauge installation.

The sample was fitted in the fatigue machine using the steel mounts of a trailing section part and a leading section part. The spar mounting (leading section part), as well as mounts of the trailing section part, were connected to the section with bolts (Fig. 11).

For this purpose, holes were made in the spar (Fig. 10b, c) and where the core was filled with epoxy resin (Fig. 10a). In order to simulate the surface load, the steel overlays were placed on the trailing section part, on the upper and lower surfaces. The overlays distributed the forces applied by the fatigue machine evenly (Fig. 11).

The entire experiment was recorded using strain gauges. The rectangular strain gauge rosettes were placed at 4 points on the section sample at the regions of: debonding repairs (Fig. 11a), undamaged (Fig. 11b), lateral crack repair (Fig. 11c), without lateral crack damage (Fig. 11d).

The repair status during the experiment was specified by the strain gauges placed at the repair package. A sudden drop in stress or exceeding the allowable stress of the repair packet material could indicate damage to the repair. To meet the experiment's objective, it was also important to monitor the stress values in places without repair where the section cladding was bonded to the spar. Based on that, it was possible to apply appropriate sample loads to achieve the stress value equal to that resulting from the numerical calculations. The experiment also involved monitoring the sample loading forces. A decrease in forces could indicate damage, occurred in places where the section cladding was bonded to the spar, or in other part of the section.

The fatigue machine stand was made of two beams – stationary and movable (Fig. 12a). The leading section part of the sample was attached to the stationary beam. The movable beam in the middle part was fixed on a perpendicular rod and on both sides to the actuators.

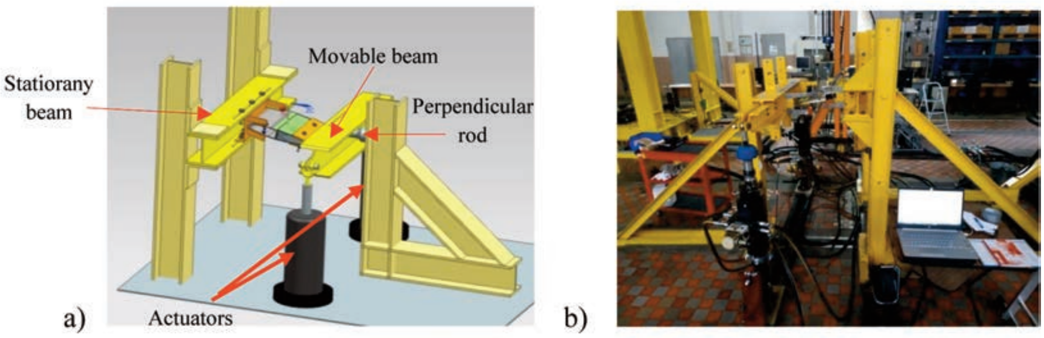

Figure 12. Measuring station – fatigue machine: a) computer model, b) fatigue machine in the Institute of Aviation.

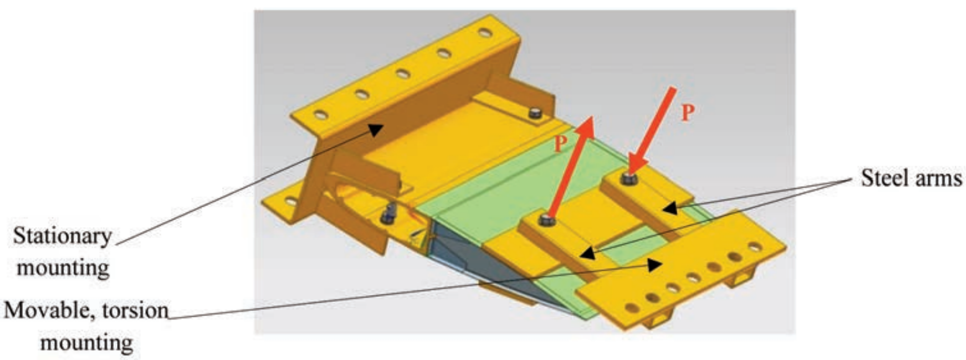

Figure 13. Rotor blade section with fatigue machine mountings.

The sample was loaded by actuators. The forces were transmitted from the actuators to the fatigue machine's movable beam that the trailing section part mount was fastened to. Mounting through two steel arms, fastening bolts and further steel overlays transferred the force in the form of surface load to the section being tested (Fig. 13).

The number of load cycles in the experiment has been planned for 1 million based on the analysis of the operational loads acting on the rotor blade [8], the maximum values of the spar belts structural stresses and the dependencies resulting from the Woehler diagram [7], for the spar materials. The sinusoidal loads were controlled by the actuator pistons distance displacement (Fig. 12a). For the maximum value of their displacement, at the places where the section cladding was bonded to the spar, the equivalent stress value was obtained for about 120 MPa. The load control achieved by controlling the displacement of the pistons made it possible to maintain a constant level of stress in the tested section. The load control achieved by controlling the force of the actuators, in the event of damage occurring anywhere outside of the debonding repair area would prevent further experimental testing. Numerical calculations showed that the assumed stress value occurred at the edge of the cladding-spar bonding area when the stress value at the location of the strain gauges was about 5 MPa. This value of stress in the sample occurred for the actuator pistons' displacement by 3 mm. This value of displacement suited to the force, for each of the actuators, for about 100 N. This suited to forces, at the points of application to the sample, for about 1300 N. In the numerical model, the required stresses values were achieved when the actuators forces of about 200 kN were applied. The same stress value was achieved with displacements at the places of the force application equal to 0.05 mm. Such significant differences resulted from a difference in stiffness between a perfectly rigid numerical model and a real sample of considerable lower stiffness. The tested sample was a fragment of a decommissioned rotor blade. The materials it was made of were subjected to atmospheric aging processes, and there was a loosening of adhesive connection throughout the sample structure. It was also necessary to take into account the looseness at the connections of the sample to the mounts of the fatigue machine.

The static testing of aluminum alloys with WK-3 adhesive [4], used for the production of the original rotor blades, revealed the ability to transfer shear stress 8.7-11.7 MPa. These values depend on the method of preparing the sample's surfaces to be bonded [4,9]. In the case of rotor blades, the spar's surface is prepared for bonding by anodizing. Shear strength for this method is about 10 MPa. This value results from the theoretical formula of the stress-carrying capacity (1):

$$\tau = \frac{P}{A} \tag{1}$$

where:
τ – stress values;
P – tensile force;
A – bonding surface area.

The practical stress distribution in the veneer increases towards the edge of the bonding and depends on the materials' thickness and strength properties as well as on the surface thickness of the adhesive (Fig. 14), [10]. The adequate flexibility and strength allow stresses to be transferred through the bonding.

The stress concentration and the effects of atmospheric factors are responsible for the propagation of debonding. As a result of stress concentration on the edges, in the event of debonding initiation on them, rapid destruction of the entire bonding may occur quickly.

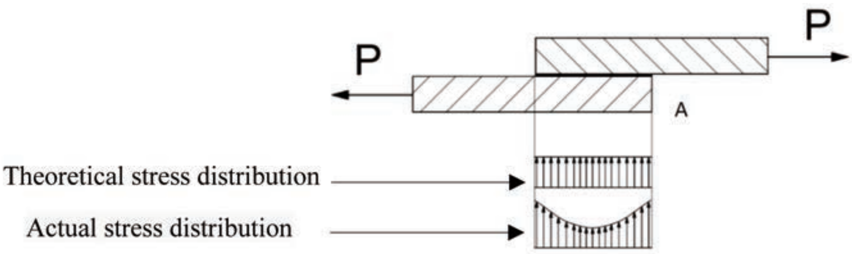

Figure 14. Theoretical and practical stress distribution in the adhesive bond of two monolithic materials.

The initial assumption was to transfer the maximum section cladding stress values, that may occur in flight. The first load period assumed the execution of 500 000 load cycles. During the first load period the actuator piston's displacement was set at 3 mm. The forces registered on the actuators, at the time of maximum displacement, were about 100 N. The subsequent load periods with characteristic parameters estimated based on numerical calculation and strain gauges values records are included in the table below (Table 1):

Table 1. Quantitative characteristics of the conducted fatigue test.

No.	Piston displacement [mm]	Number of load cycles × 10^3	Average maximum force on actuators [N]	Estimated maximum equivalent stress at the edge of the bonding area [MPa]	Estimated maximum shear stress at the edge of the bonding area [MPa]
1.	3	586	100	120	37
2.	4	27	150	147	49
3.	5	100	200-98	342	113
4.	7	400	116	475	157

The total number of load cycles was over 1.1 million, for increasing load values. During the test, damage did not appear in the area of repair. After the beginning of the third load period, the value of registered forces on the actuators dropped sharply (Fig. 15). This was probably caused by an internal structure damage of a sample. However, no damage occurred in the area of repair. As a result of controlling the load cycles by the actuator piston's displacement, the stresses in the debonding repair area and in the places free of damage did not change significantly. This enabled further experimentation with the assumed stresses.

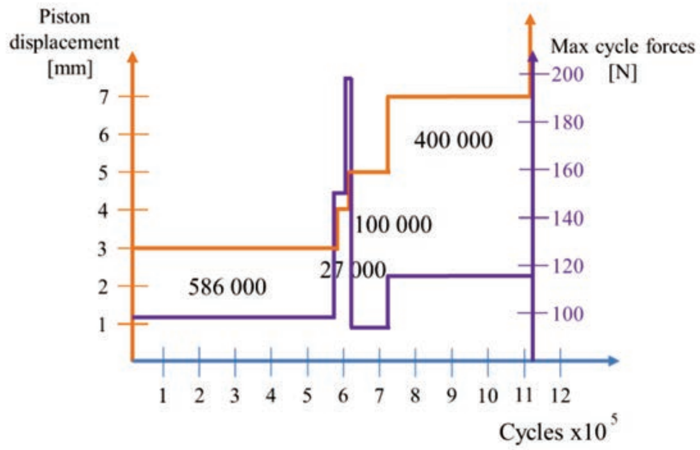

Figure 15. Diagram of torsion course forces and displacement of the fatigue machine's actuator piston.

After the fatigue test was completed, to destroy the sample, maintaining the load method, a static test was carried out. The sample was loaded with an increasing load, controlled by the actuator's piston displacement at a speed of 2 mm/min. As a result, the sample was destroyed by the deformation of the section ribs (Fig. 16). The repair areas were not damaged. The static test was interrupted when the strain gauge at the place without a lateral crack damage exceeded the measuring range (Fig. 11 d). The sample's deformation didn't result in any increase in was stress in the area where the cladding debonded from the spar.

Figure 16. Section side view after static destruction.

SUMMARY

During the fatigue test, over 1.1 million load cycles were performed. In the conducted experiment, a new solution to repairing a spar-cladding debonding was tested. The fatigue test was preceded by the FEM tests, in order to plan the experimental test and check the stress distribution under the influence of torsional loads. Torsional loads were applied to maximize the stress in the area of the bonding of rotor blade section cladding and the spar. The maximum values of shear stress transmitted through the connection in the analyzed repair areas were equal to 37 MPa. During the fatigue test, strain gauges located on the surface of the tested section measured loading forces on the actuators, displacement of the actuator pistons and cladding stresses. Following the fatigue test, a static sample load test was performed. After completing the static test, the section was destroyed. The places where the section cladding was bonded to the spar were not damaged, despite the large number of load cycles, at values significantly larger than those occurring during operation of helicopters. No damage in the places of repair suggests its proper performance and restoration of the element functioning. As suggested by static tests of the adhesives, weather conditions have a significant impact on adhesives' durability, especially temperature (variation in thermal expansion) and humidity [4]. Therefore, it is important to take into account potential hazards resulting from the atmospheric conditions in which repaired rotor blades are operated. Periodic inspections of repairs should be carried out.

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