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EXPERIMENTAL FATIGUE STRENGTH DETERMINATION OF DAMAGED AIRCRAFT ENGINE BLADES

Maciej Masłyk, Wojciech Obrocki,
Amadeusz Setkowicz, Jan Sieniawski

Summary

Paper presents methodology and test results for experimental fatigue strength determination of damaged aircraft engine blades. Research was performed using turboprop TWD-10B/PZL-10S compressor blades. High cycle fatigue test stand was described. Fatigue strength of damaged blade was determined for different damage size. Fatigue strength comparison of damaged and undamaged blades is a result of presented work.

Keywords: compressor blade, fatigue strength, high cycle fatigue, foreign object damage, FOD, blade failures

Eksperymentalna metoda określania wytrzymałości zmęczeniowej uszkodzonych łopatek silników lotniczych

Streszczenie

W pracy opracowano metodykę i prowadzono badania wytrzymałości zmęczeniowej uszkodzonych łopatek silnika lotniczego. W badaniach zastosowano łopatki sprężarki silnika TWD-10B/PZL-10S. Scharakteryzowano stanowisko badawcze do określania wytrzymałości zmęczeniowej dla dużej liczby cykli. Wytrzymałość zmęczeniową łopatek uszkodzonych ustalono dla modelowych ich uszkodzeń o różnych rozmiarach wykonanych na tej samej wysokości pióra łopatki. Przeprowadzono analizy wyników badań – porównano wytrzymałość zmęczeniową łopatek uszkodzonych oraz nowych łopatek nieuszkodzonych.

Słowa kluczowe: łopatki sprężarki, wytrzymałość zmęczeniowa, uszkodzenia łopatek spowodowane ciałem obcym, FOD

1. Introduction

Fatigue strength of compressor blade depends on blade surface condition. During engine operation blades are prone to damage due to foreign object impact (FOD- Foreign Object Damage) – Fig. 1 [1].

Address: Maciej MASŁYK MSc. Eng., Wojciech OBROCKI MSc. Eng. Amadeusz SETKOWICZ MSc. Eng., Prof. Jan SIENIAWSKI, Department of Materials Science, Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, Powstancow Warszawy 12, 35-959 Rzeszow, e-mail: maciej.maslyk@outlook.com

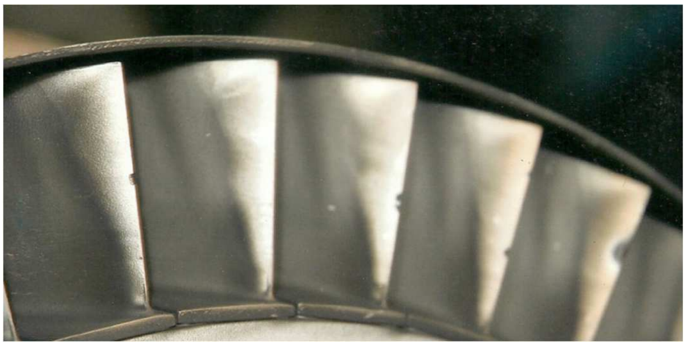

Fig. 1. View of the compressor rotor with both undamaged and damaged blades (FOD) [1]

Compressor blade load analysis confirms that compressor blades are loaded with changing bending and torsional loads. Engine operation on various power level and rotor unbalancing cause a fatigue load condition of the blades. Analysis of failure reports shows that the most exposed area for FOD is blade leading edge, so it might be the area of crack initiation (Fig. 2) [2-4]. Blade damage size depends on foreign object mass, shape and impact dynamic [5].

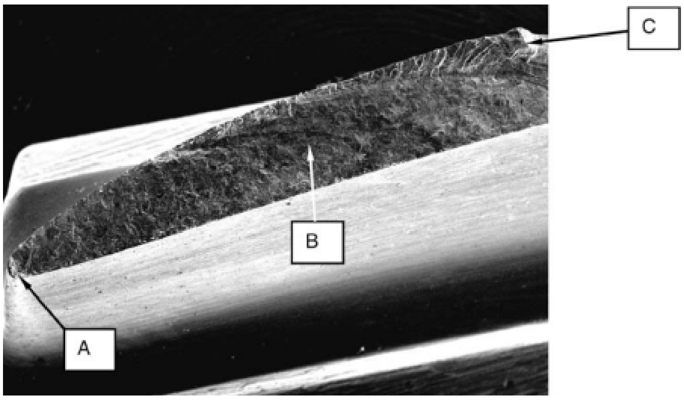

Fig. 2. View of fractured blade with marked crack origin zone (A), fatigue fracture area (B), rupture zone (C) [2]

The blade technical condition is crucial for safe engine operation. Some of the damages don’t effect on blade fatigue strength. Thus experimental research to establish blade damage influence on fatigue strength is a consequence of economy and safety operation analysis [6]. The tests results would be applied by engine manufacturer to determine which blade damage could be allowed for further operation without risking the blade failure and engine damage.

2. Experimental

Research was conducted on TWD-10B/PZL-10S 1st stage compressor blades. This is a turboprop engine powered AN-28 Bryza aircraft.

High cycle fatigue strength was determined by Increasing Amplitude Tests (Step Method) [7] – selected method is applicable for tests with limited specimens amount. To determine fatigue strength using this method, it is required to run test on each specimen until it fails. Test procedure need to define base number of cycle N, initial stress level σ_o and stress increment $\Delta\sigma$. Tested specimen must run successfully through first stress level with defined number of cycle N. After full runout the stress level is increased by $\Delta\sigma$. Specimen is tested on higher stress level to achieve required number of cycle (N). Specimen failure stops the test at highest stress level σ_f. Theoretical fatigue strength of specimen is calculated with formula:

$$\sigma_t = \sigma_f - \frac{\Delta\sigma}{2} \tag{1}$$

Next specimen is tested starting from σ_o stress level independent of previous test result.

Average fatigue strength of the group of n specimens is the average of theoretical fatigue strength of all tested specimens:

$$\sigma_a = \frac{\Sigma_{i=1}^{n}\sigma_{ti}}{n} \tag{2}$$

Presented method allows average fatigue strength determination for group of tested specimens. Considering that new blades manufactured by standardized technology with full quality inspection were used as test specimens, Gaussian distribution theory was applied to estimate the range of fatigue strength for undamaged blade [8]. Standard deviation of results is calculated as:

$$S = \sqrt{\frac{\Sigma_{i=1}^{n}(\sigma_{ti} - \sigma_a)^2}{n-1}} \tag{3}$$

Minimum and maximum fatigue strength was estimated as:

$$\sigma_{\min} = \sigma_a - 3S \tag{4}$$

$$\sigma_{\max} = \sigma_a + 3S \tag{5}$$

Research of high cycle fatigue strength for both damaged and undamaged blades was performed on test stand presented on Fig. 3.

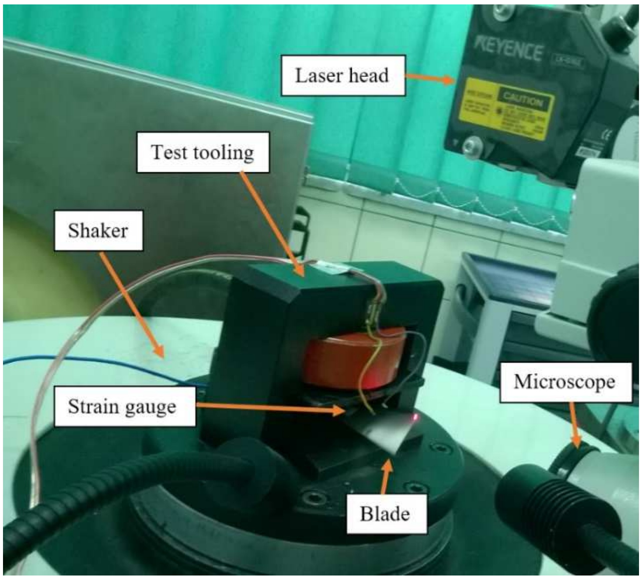

Fig. 3. Fatigue test stand

Test stand consist of:

- Electrodynamic shaker system LDS V830 with dedicated tooling for proper blade clamp and stable grip force during test. Main shaker performance parameters: Sine Force (peak) 6,78 kN, Acceleration (sine peak) 1176 m/s^2 (120g), frequency range 5÷3500Hz [9],
- LDS signal amplifier,
- Shaker control system based on National Instruments^{TM} CompactRIO platform. System was used for setting a required test parameter - control resonant frequency and stress,
- Stress measurement channel with strain gauge sensor. The sensor used for presented tests, had 3 mm measurement base and was installed on the airfoil area of highest stress level (determined for undamaged blade),
- Vibration measurement channel with accelerometer to control shaker table vibration,
- Laser sensor to control vibration amplitude level. Laser was aimed 1 mm from trailing edge and blade tip,
- Microscope for optical verification of vibration magnitude level and setting stress vs strain relationship.

Blade prepared for test is shown on Fig. 4.

Frequency of shaker vibration was equal to blade vibration natural frequency. Blade vibration was kept in resonance condition. Shaker table vibration level was used to set and control proper load (stress) during test.

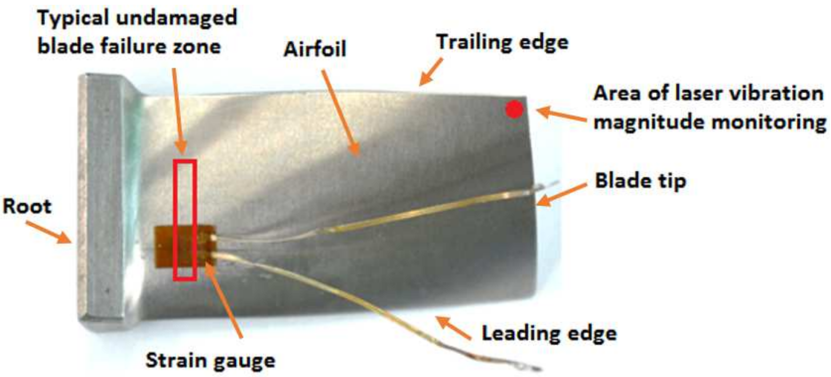

Fig. 4. Blade for High Cycle Fatigue test with strain gauge installed on airfoil

If required stress level exceeds the maximum for strain gauge sensor it is necessary to determine relation for stress vs blade tip vibration magnitude peak – peak (Vm) – Fig. 5. This relation is defined up to 250 MPa and it is used to calculate vibration magnitude at required stress level (linear relation according to Hook's law).

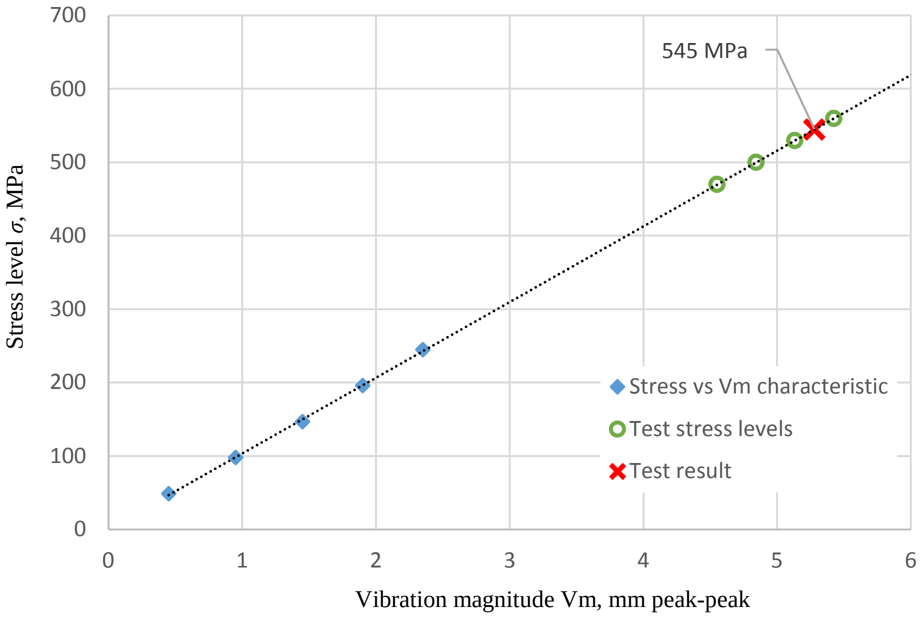

Fig. 5. Stress vs blade tip vibration magnitude relation and test methodology

Increasing amplitude test methodology application is presented on Fig. 5. After stress vs blade tip vibration magnitude relation measurement (blue points) test was started at initial load 470 MPa. After full runout ($N = 10^7$ cycle) stress level was increased by increment of 30 MPa. At 4th stress level failure occurs. As a result, fatigue strength for tested blade was determined as 545 MPa.

Crack initiation was signalized by blade natural frequency drop [10,11]. Test was finished after blade natural frequency decreased by 100 Hz (Fig. 6) and crack was visible on blade surface with the naked eye. Damaged blade crack initiation area was inspected to verify if the failure took place in the middle of airfoil (like undamaged blade) or crack origin was located in the area of prepared damage on leading edge.

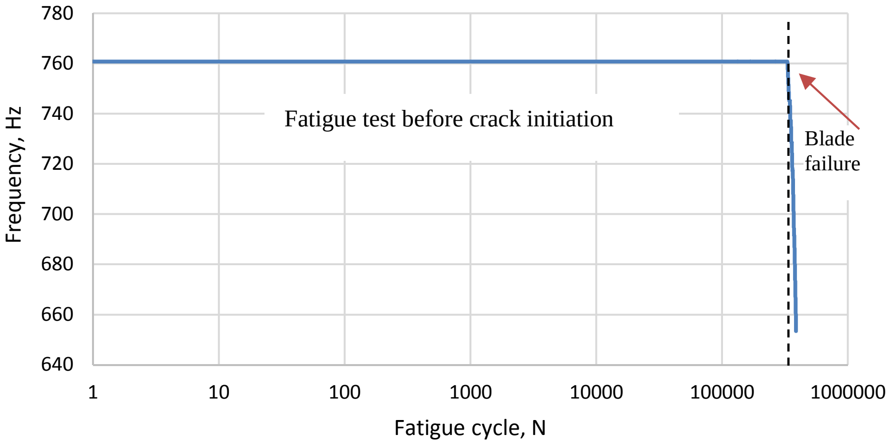

Fig. 6. Shaker table vibration control for blade crack initiation monitoring

Experimental methodology of damaged aircraft engine blades fatigue strength determination requires few main steps:

At first, determining fatigue strength of non-damaged blades is oblige. Test was performed on 10 new blades. According to described procedure of fatigue strength determination, average σ_a, minimum $\sigma_{\min}$ and maximum $\sigma_{\max}$ fatigue strength was estimated. Moreover, natural frequency of each blade was noted.

Secondly, it is necessary to perform specified damage on blades – new blade was damaged to achieve required specimens (Fig. 7). Damages were divided into few size groups (Table 1) to take into account the difficulties of measurements in operation condition as well as damage preparing. Damage size is defined as depth, measured perpendicular to leading edge.

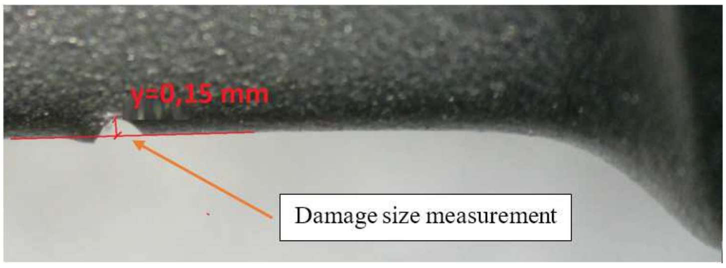

Fig. 7. View of damaged blade with measurements

Damages was performed by impacting the blades with special tooling. Each damage was measured and categorized. During blade damage preparation it was aimed to make maximum damage size, but all damage prepared in defined range was acceptable. Each group of damage size was represented by 4 blades. All blades was damaged on leading edge on the same height (3.5 mm from airfoil base).

Table 1. Damage size groups

Damage size	**Group**				
	I	**II**	**III**	**IV**	**V**
Maximum, mm	0.09	0.199	0.299	0.499	1
Average, mm	0.05	0.15	0.25	0.4	0.75
Minimum, mm	0	0.1	0.2	0.3	0.5

Finally, fatigue test of damaged blades must be performed to assess the influence of damage on blade fatigue strength. Damaged blade was tested with described increasing amplitude method [12]. Average fatigue strength was calculated for each group of damage size. Comparison of average fatigue strength of damaged blade (each damage size independently) with fatigue strength estimated for undamaged blades, provides damage influence on fatigue strength. Moreover, crack initiation zone was inspected.

3. Results

High cycle fatigue strength test results for undamaged blades is presented in Table 2. Concerning described methodology an average and standard deviation for fatigue strength was determined. According to described normal distribution theory, minimum and maximum value for fatigue strength. Results are presented in Table 3.

Results of fatigue tests for damaged blade are presented in Table 4 and Fig. 8.

Table 2. Test result for undamaged blade

Blade number	Fatigue strength σ_t, MPa	Natural frequency f, Hz
L0047	575	753
L0048	485	758
L0049	575	749
L0050	545	800
L0051	575	768
L0053	545	768
L0054	575	768
L0055	605	768
L0056	605	768
L0057	545	768

Table 3. Calculated results for undamaged blades

	Fatigue strength, MPa
Average	563
Minimum	463
Maximum	663

Table 4. Results of HCF tests for damaged blades

Blade number	Damage size, mm	Damage size group	Frequency, Hz	Fatigue strength, MPa	Crack area
L0099	0,064	I	816	515	Chord center
L0100	0,086	I	773	605	Chord center
L0101	0,172	II	804	515	Chord center
L0102	0,174	II	799	485	Chord center
L0103	0,091	I	769	545	Leading edge
L0104	0,148	II	801	515	Leading edge
L0105	0,15	II	799	515	Leading edge
L0106	0,086	I	812	605	Leading edge
L0107	0,221	III	798	455	Leading edge
L0108	0,223	III	813	455	Leading edge
L0109	0,289	III	804	425	Leading edge
L0110	0,267	III	804	365	Leading edge
L0111	0,349	IV	811	395	Leading edge
L0112	0,343	IV	779	395	Leading edge
L0113	0,335	IV	807	305	Leading edge
L0114	0,486	IV	807	305	Leading edge
L0115	0,554	V	809	305	Leading edge
L0116	0,64	V	810	275	Leading edge
L0117	0,659	V	799	215	Leading edge
L0118	0,938	V	802	245	Leading edge

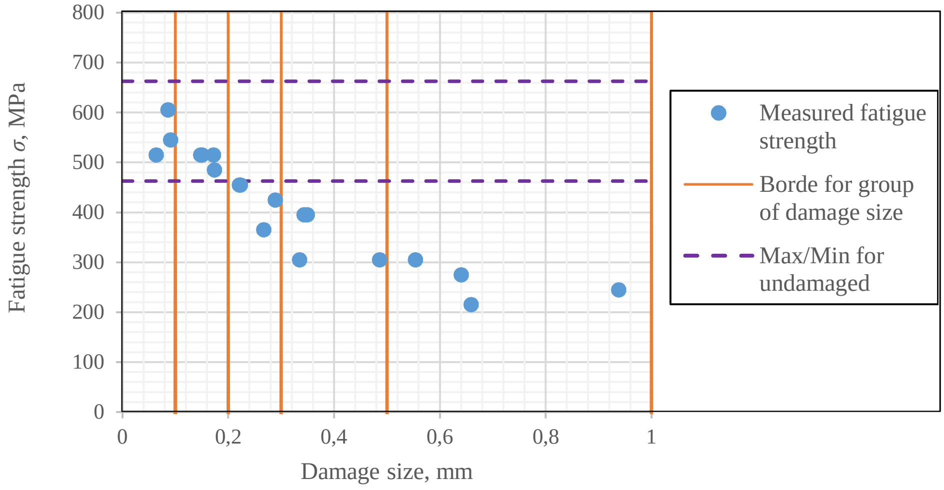

Fig. 8. High Cycle Fatigue strength for damaged blades

4. Conclusion

Blade fatigue strength decline as the size of damage increase (Fig. 8, 9). In the higher damage size, crack initiation is located on the leading edge, the stress level in this area exceeds one in typical crack zone (for undamaged blades). In the presented case (group II-V) damages affects the blade fatigue properties and stress distribution.

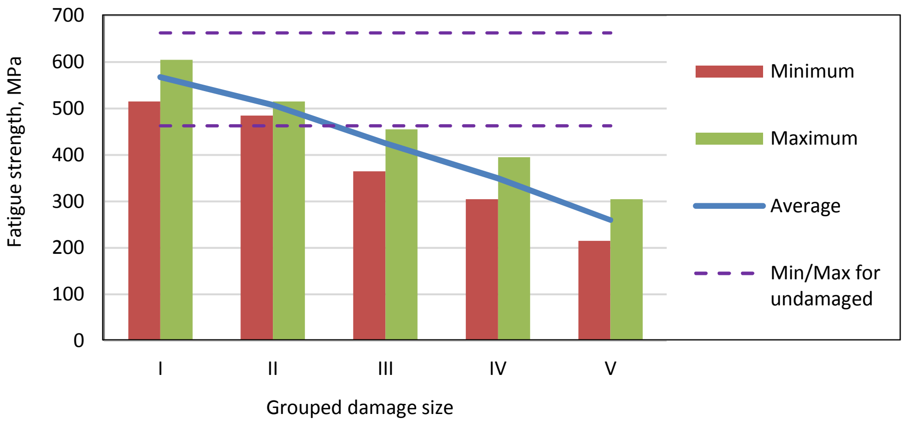

Fig. 9. Statistics for fatigue strength of grouped damaged blade

Minimum, average and maximum values of fatigue strength was determined to represent the statistical assessment for defined groups of damage size. Limited amount of damaged specimens didn't allow to calculate statistical range using normal distribution theory for damaged blades, so presented minimum and maximum values in Fig. 9 represents measured values.

Presented statistic (Fig. 9, Table 5) shows that damage depth up to 0.3 mm (I and II group) doesn't effect on blade fatigue strength. Higher damage provides drop of blade fatigue properties. Average fatigue strength of blades with 0.75 mm damage size (V group) decreased approximately by 50%.

Table 5. Fatigue strength of grouped damage size

Grouped damage	**Fatigue strength, MPa**				
	I	**II**	**III**	**IV**	**V**
Average	568	508	425	350	260
Minimum	515	485	365	305	215
Maximum	605	515	455	395	305

Presented methodology allows determining mechanical properties of damaged blades to compare it with required fatigue strength value to ensure safe operation of the engine with damaged blades.

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