Crack Growth Life Assessment on Turbine Component under Combined Fatigue Loading

Dianyin Hu[1,*], **Rongiqao Wang**[1], **Huawei Liu**[1], **Jiaming Wei**[1]

[1] School of Energy and Power Engineering, BeiHang University, Beijing 100191, China
* Corresponding author: hdy@buaa.edu.cn

Abstract This paper focuses on a crack growth life assessment method for a turbine component under high-low combined cycle fatigue (HLCCF) loading through experimental and numerical methods. Crack growth tests under HLCCF loading on five full scale turbine components, attached to actual turbine discs, were conducted at elevated temperature by using a Ferris wheel combined fatigue system to simulate the stress under HLCCF loading and temperature distributions. Then, the fracture mechanics (FM) analysis was utilized to simulate crack growth of the turbine component to implement crack growth. The experimental life data agrees well with the crack growth life prediction for the turbine component. In summary, this paper provides a new way to estimate the crack growth lifetime criterion of the turbine components under HLCCF loading through experimental and numerical investigations.

Keywords High-low combined cycle fatigue, Crack growth life, Turbine component, Elevated temperature

1. Introduction

The turbine blades of an aero-engine are generally attached to the disc by means of a fir-tree design, a typical multiple load path structure, to allow for different rates of expansion between the disc and the blade while still holding the blade firmly against centrifugal loads. During operation, the fir-tree attachments are subjected to significant tensile stresses due to centrifugal loading and during the flight cycle may experience aerodynamically induced vibrations, leading to additional stresses. The amplitude of the vibrational loading is typically much smaller than that due to centrifugal loading and hence vibration is generally thought to give rise to high cycle fatigue (HCF). In contrast, the effect of centrifugal loading is frequently considered to be low cycle fatigue (LCF). Under the overall high-low combined cycle fatigue (HLCCF) loading, the fatigue damage of the turbine attachments is largely increased[1,2,3,4]. These effects may be responsible for the unscheduled crack failures in service of the mortise on a certain aeroengine second turbine disc.

Conventional life assessment methods of blade-disc connections of gas turbines are almost based on finite element analysis [5] and the experimental data of specimens and component-like specimens instead of actual components so as to reduce experimental costs [6,7,8]. However, the actual crack growth and fracture failure of the mortise teeth are not only determined by the characteristics of the material, but are also affected by the structure, dimension, and the teeth space of the mortise. Furthermore, the differences in crack growth lives between laboratory specimens and full scale components can arise from some characteristics, such as geometry, volume and manufacture process, and therefore influences the accuracy of life assessment. To overcome the above shortcomings, the crack growth life prediction method of the blade-disc connection based on experimental life data of a full scale turbine blade attached to actual turbine disc in conjunction with the fracture mechanics (FM) analysis, is more accurate, since the components own the same manufacture process with real flight turbine components.

The only way to accurately predict the life of a fir-tree contact is to perform fatigue test on a full scale turbine blade attached to an actual turbine disc. For this study, the most challenge work is how to simulate operating conditions of actual turbine attachments in laboratory, especially under

HLCCF loading at elevated temperature.

This paper focuses on a crack growth life assessment method for a turbine component under HLCCF loading through experimental and numerical methods, as shown in Figure 1. Crack growth tests on five groups of full scale turbine components, attached to an actual turbine disc, were conducted under HLCCF loading at elevated temperature. In this study, we have developed a new Ferris wheel combined fatigue system to simulate the stress under HLCCF loads and temperature distributions of a full scale turbine blade attached to a part of actual turbine disk instead of simulated blades at elevated temperature based on our previous test system [9], and the details can be referred to [4]. Then the fracture mechanics (FM) analysis was utilized to simulate crack growth of the turbine component to implement crack growth. The lifetime criterion for withdrawal from service of turbine component was established based on experimental life data and predicted crack growth life.

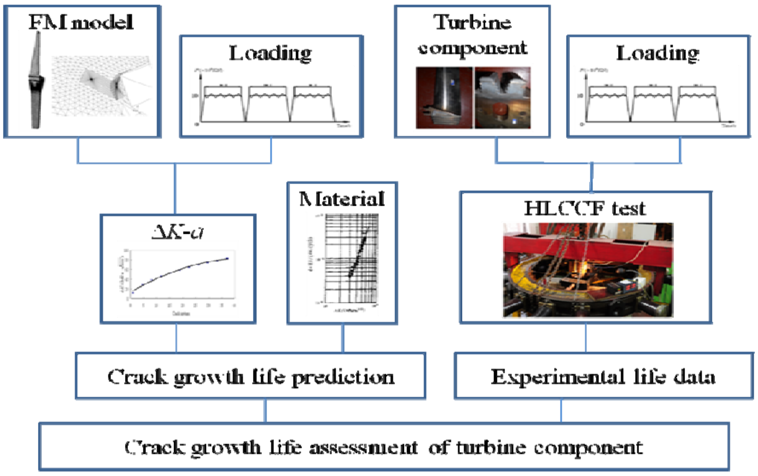


Figure 1. Strategy for crack growth life assessment of turbine component under HLCCF loading

2. Crack growth tests on turbine components

2.1. Experimental system for actual turbine attachment under HLCCF loading

The loading scheme is the key technique of this experiment to achieve failure rendition of the mortise teeth in the laboratory. The diagrammatic sketch of the actual loading is shown in Figure 2. Where, F is the low cycle loading due mainly to the centrifugal force of the blade, and M is the vibration bending moment.

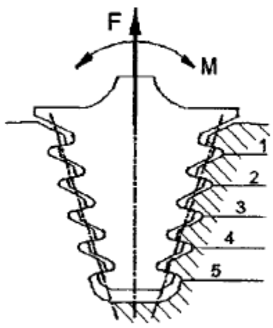
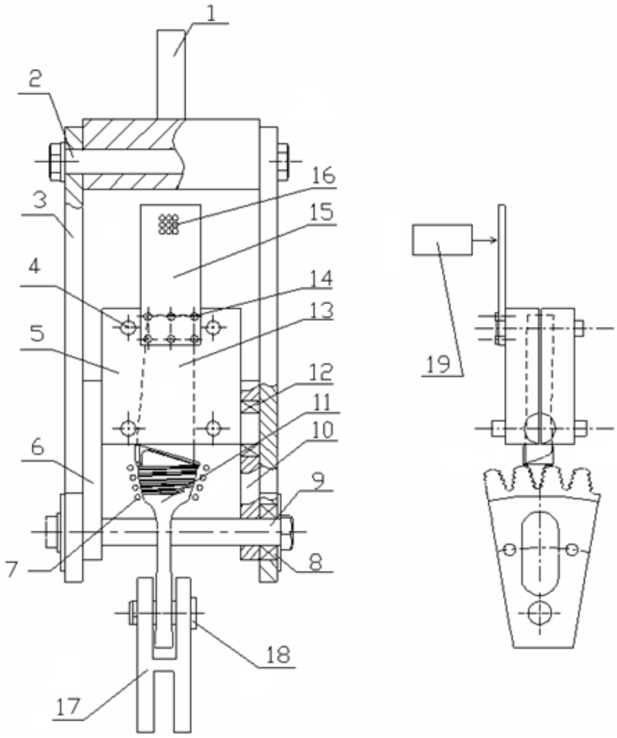


Figure 2. A sketch of an attachment structure and loading

To achieve a rational and noninterfering treatment of the HLCCF loading, a low and high cycle noninterference loading method for a full scale turbine blade attached to a part of the actual turbine disk is presented referred to [4] using a Ferris Wheel (a LCF tester). The sketch is shown in Figure

3. For performing a life test on an actual turbine attachment under HLCCF loading, there are two key techniques including a high and low cycle nointerference loading method and a blade clamp for a full scale turbine blade.



1.Upper jointer for LCF loading 2.Upper load-transmission pin 3.Drawplate 4.Hold-down bolt 1
5.Blade clamp 6.Left load-transmission plate 7.Heating coil 8.Rolling bearing 1 9.Load-bearing bar
10.Right load-transmission plate 11.Part of actual turbine disc 12.Rolling bearing 2
13.Actual turbine blade 14.Hold-down bolt 2 15.HCF loading transmission plate 16.Vibration point
17.Lower jointer for LCF loading 18.Lower load-transmission pin 19.Electromagnetic vibrator
Figure 3. A sketch of the HLCCF loading method

The HLCCF loading method places the LCF load exerting point from load-transmission pin (see (2) in Figure 3) to the back of the mortise through the drawplate (see (3) in Figure 3), then transmitting the loading using a load-bearing bar (see (9) in Figure 3) and a pair of load-transmitting plates (see (6), (10) in Figure 3) to the bearing ear welded to the blade clamp (see (5) in Figure 3). Meanwhile, there is a pair of rolling bearing (see (12) in Figure 3) between the loading-transmission plates and the bearing ear so as to reduce the friction of vibration transmission. Thus the high cycle vibrating center point moves backward and lengthens the arm of the high cycle vibration. Another pair of rolling bearings (see (8) in Figure 3) is placed between the drawplate and the load-bearing bar to further reduce the friction of vibration transmission. Therefore, the vibrating force can be transmitted to the mortise teeth with no loss.

A clamp to apply LCF loading on the full scale turbine blade (see (13) in Figure 3) to simulate the stress distribution of the fir-tree attachment is designed. The most distinctive characteristic of the clamp is that the load from the hydraulic-servo through the friction force between the clamp and the blade, which causes no damage to the blade. Two interior sides of the blade clamp are CNC(Computerized Numerical Control)-machined into complicated surface shapes just as contrary to the concave surface and convex surface of the turbine blade. The LCF loading is transferred to the turbine blade by means of friction force cause by the normal pressure of four hold-down bolts (see (4) in Figure 3). The full scale turbine blade is attached to a part of actual turbine disc (see (11) in Figure 3) cut from a full size disc.

An electromagnetic vibrator (see (19) in Figure 3) is used to exert the sinusoidal vibration force through HCF loading-transmission plate (see (15) in Figure 3) to the blade clamp, and last to the fir-tree attachment. Through measuring the vibration amplitude on the vibrating point (see (16) in Figure 3) using a BSZ605 vibrating amplitude measure apparatus, the dynamic stress on the turbine attachment can be well controlled.

2.2. Tests and results

2.2.1. Test conditions

HLCCF tests on actual turbine attachment were conducted using a 140KN hydraulic-servo system Ferris Wheel to simulate the centrifugal force of the blade during operation and an electromagnetic vibrator SIMOVERT MM220/3 produced by Siemens company to act the vibration force. Using high frequency induction local heating, the temperature of the experimental turbine attachment can be controlled about 500˚C±5˚C, measured by an electric thermocouple. In this study, a uniform temperature distribution near the turbine attachment was simulated. The load spectrum is shown in Figure 4, with the centrifugal force 100KN, vibration frequency 23.8Hz and vibration amplitude 3.5mm, and duration time 98s at the peak load. Then crack growth tests on five turbine components with pre-cracked size of 0.5×0.5mm in the second teeth (see Figure 5) were conducted under HLCCF loading at elevated temperature. All the tests were not stopped until the turbine components fractured.

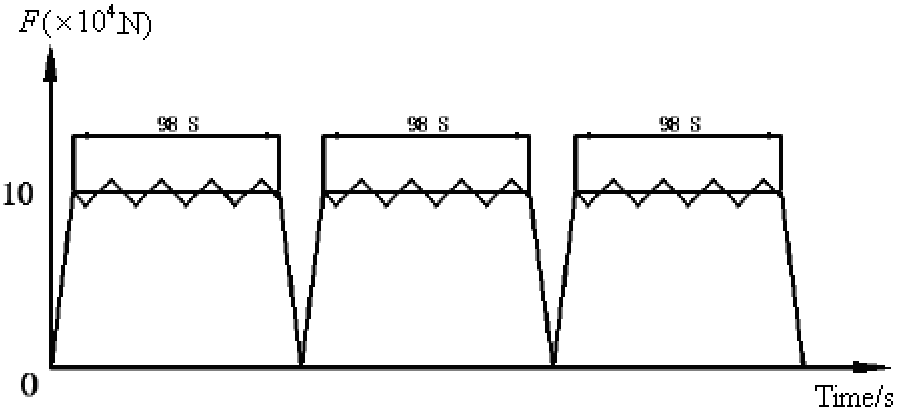


Figure 4. Load spectrum of HLCCF tests

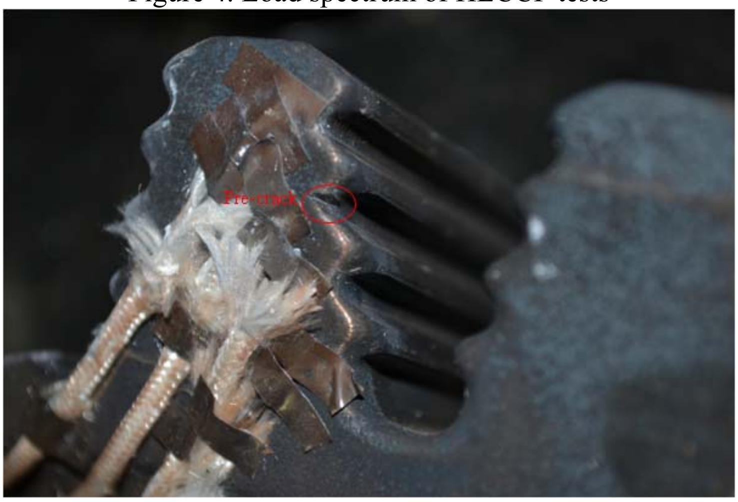
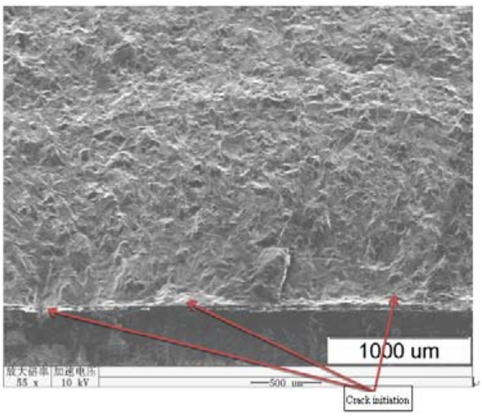


Figure 5. Pre-crack at the second tooth of the turbine disc

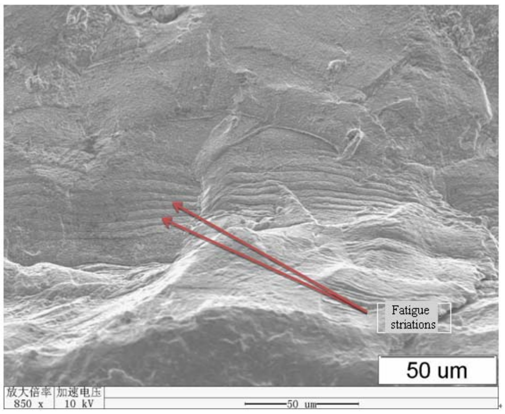
2.2.2. Results and discussions

The macro morphology of the turbine component is shown in Figure 6. It can be seen that crack propagates at the second mortise tooth of the leading edge of the disc. The SEM observations provide further information for understanding the interaction of HCF and LCF. The examination of fracture surfaces shows that fatigue cracks initiate from many positions in Figure 7(a), and there are obvious wide fatigue striations in the crack initiated region (see Figure 7(b), which indicates that stress resulting in crack initiation is large due to LCF loading. The crack propagation area of the fracture surface is dominated by transgranular mode and many thin fatigue striations emerged in Figure 7(c). This implies that HCF loading controls the crack growth. At the same time, oxidation features can be observed at the crack propagation region, as shown in Figure 7(d). The SEM observations reveal that high frequency vibration stress greatly affects the crack growth under HLCCF loading. Thus the effect of HCF damage on LCF damage should be considered for turbine attachments.

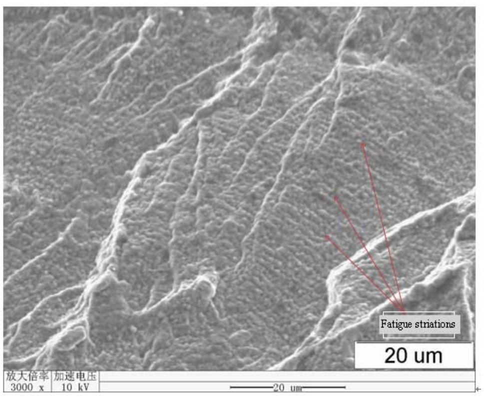
Figure 6. Macro morphology of the turbine component



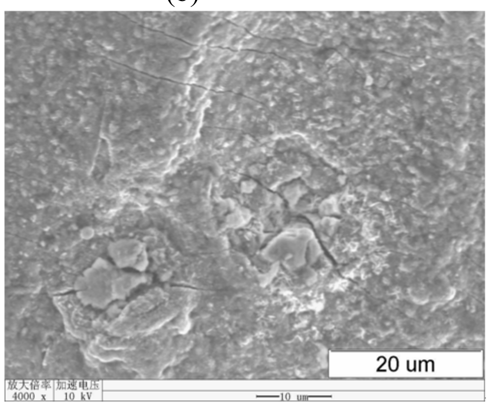
(a)



(b)



(c)



(d)

Figure 7. SEM micrographs. (a)Crack initiation. Arrows indicate the crack initiation zones. (b) Crack initiation. Arrows indicate the fatigue striations. (c)Crack growth at the position 2249μm away from main crack origin. Arrows indicate the fatigue striations. (d)Oxidation features.

Experimental life data of the five turbine components is shown in Table 1. It is shown that crack growth rate increases with flight time at early stage of crack propagation. Then crack growth rate decreases with flight time. The reason is that the fir-tree mortise, a typical multiple load path structure. When the crack propagated at the second tooth, the loading in the fir-tree attachment will be reallocated, which caused the crack growth rates decreased. Based on experimental life data, the relation between flight life and the crack length is shown in Figure 8. According to material's fracture toughness referred to [10], the critical crack growth life Nc is 1017.1hours. If the overhaul period is 300hours and 500hours, the critical crack size are 23.5mm and 17mm respectively. Considering twice overhaul period, we can obtain critical crack size 14.5mm for 300hour-overhaul period and 7.7mm for 500hour-overhaul period.

Table 1. Experimental results

Sample No.	Crack growth life N/hours	Crack size a/mm	$\Delta a/\Delta N$(mm/hours)
1	331.0	13.5	—
2	582.8	16	0.0098
3	762.2	25	0.0510
4	771.8	26	0.1042
5	886.8	31	0.0435

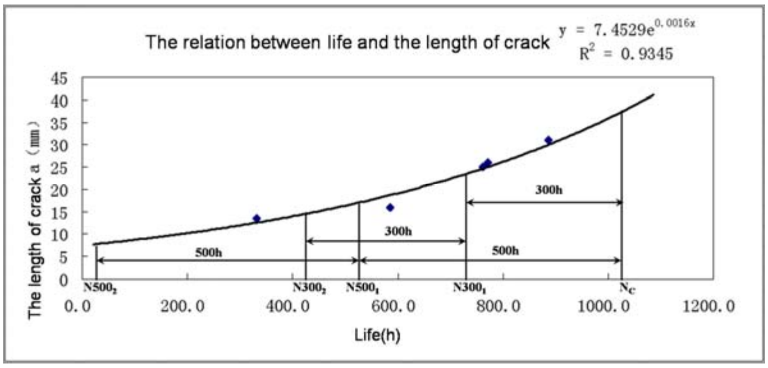


Figure 8. The relation between crack growth life and crack size

3. Crack growth life prediction

A 3-D finite element model of a turbine component including a blade and a sector of the disc was created, as shown in Figure 9. Most of the significant geometric features were modeled and a relatively finer mesh was used for the region of the blade-disc connection. The turbine blade is made of GH4033, a ferrum-base wrought superalloy and the turbine disc is made of GH2036, a nickel-based wrought superalloy. FM analysis was conducted using the commercial code MARC. The singular finite elements at the crack tip are shown in Figure 10. The HLCCF loading spectrum and the temperature distribution are similar to experimental loads.

The stress intensity factor range (SIF) ΔK_{block} under HLCCF loading can be expressed as [11]

$$\Delta K_{block} = \Delta K_{LCF} + n \cdot \Delta K_{HCF} \tag{1}$$

where ΔK_{LCF} is the SIF range under LCF loading, ΔK_{HCF} is the SIF range under HCF loading, n is the number of HCF cycles at a period.

With varying the crack size, the corresponding ΔK_{block} can be obtained by the use of J-integral method[12], as shown in Table 2. The ΔK_{block} is fitted by a least square method as follow:

$$\Delta K_{block} = -0.0724a^2 + 4.131a + 26.198 \quad (2)$$

where the correlation coefficient R^2=0.9934.

The crack growth life prediction under HLCCF loading is based on Paris crack growth law which gives the expression between the crack growth rate da/dN and the stress intensity factor range ΔK:

$$da/dN = C(\Delta K)^m \quad (3)$$

where the two parameters of C and m can be obtained experimentally. Referred to [10], the values of C and m in equation (3) are 1.0527×10^{-8}, 3.1826 respectively. Then crack growth life is derived by integrating Paris equation (3) over the crack length. Substituting equation (2), we can get

$$N = \int_{a_0}^{a} \frac{1}{1.0527\times10^{-8}(\Delta K_{block}(a))^{3.1826}} da \quad (4)$$

The crack growth life for the turbine component is 7691cycles, which is equal to flight life 2673.8 hours . If the safety factor is set as 2.0 referred to [13], then the life prediction is 1336.9hours which agrees well with the experimental result.

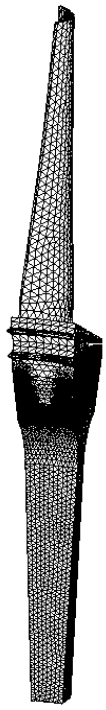


Figure 9. Mesh of turbine component

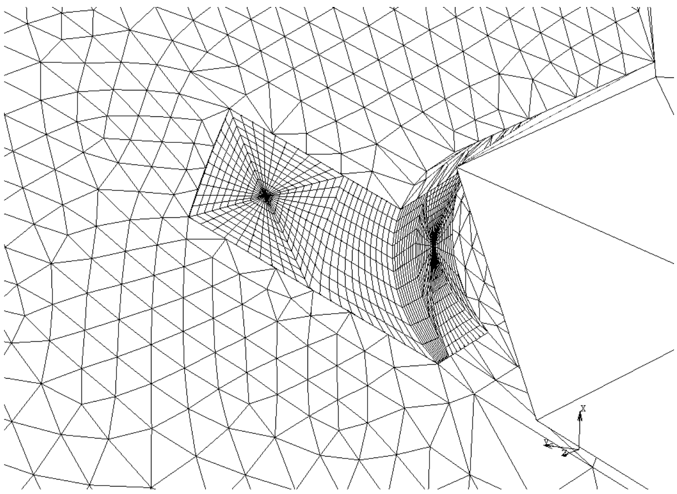


Figure 10. Singular finite elements at the crack tip

Table 2. Stress intensity factor value through FM analysis

Crack size a/mm	Stress intensity factor range ΔK/(MPa√m)
0.8	24.04
4.5	45.61
8.2	59.00
11.9	67.99
15.6	74.31
19.3	78.71
23	81.63

26.7	81.01
30.4	81.50
34.1	82.66
37.8	82.95

Therefore, based on experimental and numerical investigations, a new criterion for withdrawal from service of this type of turbine component to assure the structural integrity of this aeroengine is established by the industrial corporation, that is, if the overhaul period is 300hours and 500hours, the critical crack size are 23.5mm and 17mm respectively. And considering twice overhaul period, we can obtain critical crack size 14.5mm for 300hour-overhaul period and 7.7mm for 500hour-overhaul period.

4. Conclusions

This paper studied the crack growth life of a full scale turbine component at elevated temperature under HLCCF loading through experimental and numerical methods. The experimental system achieves HLCCF loading of the full scale turbine component, and a special design of the blade clamp successfully simulates the stress field of the turbine blade.

A new reliable crack growth life assessment strategy for turbine component is developed based on experimental and numerical investigations under HLCCF loading. In summary, this paper provides a new way to establish a lifetime criterion for withdrawal from service of turbine components.

Acknowledgements

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