ICAS 2020 SHANGHAI
International Council of the Aeronautical Sciences
32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

Research on Fatigue Strength Prediction Model of Aero-engine Blades Subjected to Foreign Object Damage

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Abstract

The modification of average stress model based on notch types of foreign object damage was studied to improve the prediction accuracy on fatigue strength of damaged compressor blades. The 3-mm-diameter steel ball was impacted to the leading edge of the blade with the velocity of 200 m/s and angle of 0°. Four kinds of notches were induced, which are the semicircular notch, the tearing notch, the V notch and the scratch notch. The fatigue strength of the scratch notch is the highest, that of the semicircular notch is lower, and that of the tearing notch and the V notch are the lowest. The fatigue strength prediction results of damaged blades by the average stress model show low accuracy, and the errors are in the range of -20% and 50%. The prediction accuracy of the modified model is improved, and the errors are reduced to about -20% ～ 0.

Keywords: Foreign object damage; High cycle fatigue; Fatigue prediction; Average stress model; Stress concentration factor

1. Introduction

With the rapid development of aero-engine, the secure access to compressor blades attract increasing attentions [1]. The fatigue fracture of compressor blade tend to impact other blades [2], causing non-containment accident [3], which is one of the major factors leading to engine in-flight shutdown, resulting in disastrous consequences [4]. Engineers have been developing new materials and technologies in the past half century, which have greatly improved the fatigue performance of compressor blades. Small hard objects are often inhaled with the high-speed airflow during aircraft take-off and landing, which inevitably hit blades and cause damage. This accident phenomenon is usually called as foreign object damage (FOD) [5,6]. Under the superposition of low cycle fatigue (LCF) load caused by centrifugal force and high cycle fatigue (HCF) load caused by vibration and short-time resonance, the compressor blade subjected to FOD is prone to crack initiation and rapid propagation, leading to fatigue fracture [7,8]. The fatigue prediction and evaluation method of FOD blade has become a key technology in the process of aero-engine design and use.

The fatigue prediction of FOD blade is based on the study of the fatigue performance of the FOD blade. Scholars have carried out a large number of researches from the perspective of experiment and numerical simulation [9-17]. After decades of experimental researches, air cannon test method has been proved to be the laboratory experimental method which can best reflect the real FOD characteristics [18].The test contents include foreign object sizes [10,13], foreign object types [9], incident velocities [10,12], incident angles [9,13,14], leading edge parameters [11,14] and so on. The results show that the damage size increases with the impact energy and foreign object hardness. The incident angle and the foreign object shape mainly affect the morphology of the damage notch. The main feature of FOD is the loss of material, micro-crack, adiabatic shear band and other micro-damage characteristics caused by high velocity impact. It can introduce serious residual tensile stress at the root of the notch, which significantly affects the fatigue performance [19-23]. The numerical simulation is more used to study the state which is difficult to carry out experiments under laboratory conditions, such as the distribution of residual stress [15-17], and significantly reduces the number of experiments and the cost.

The research on the prediction method of the FOD blade fatigue is always in progress. As early as 1958, Neuber [24] proposed the method of predicting the fatigue notch factor by studying the stress state of notched components, namely the average stress model. After that, Peterson [25] made a modification on the basis of Neuber's research, which simplified the equation form and made it more convenient for engineering application. However, many scholars who study the prediction method of the FOD blade fatigue strength have proposed that the prediction accuracy of average stress model is poor. Ruschau et al. [10] used the average stress model to predict the HCF strength of FOD Ti–6Al–4V specimens at a stress ratio of 0.1, and found that predicted values were significantly higher than tested values. Zhao et al. predicted the fatigue strength of titanium alloy flat plate specimens and stainless steel simulation blades subjected to FOD using neural network method [26] and the worst case notch model [27], respectively. Results show that the accuracy of the two methods was much higher than that of the average stress model. In addition, the Kitagawa – Takahashi (K–T) diagram [22], the theory of critical distance [28], etc. can also be used to predict the fatigue strength of the FOD blade. However, these models with high prediction accuracy all have the problems of complex form and inconvenient use.

This paper focuses on the modification method of the average stress model according to the FOD notch types to improve its accuracy. FOD and HCF tests were carried out to analyze the effect of FOD on the HCF performance of compressor blades. The modified equation of theoretical stress concentration factor was established, which is used in the calculation of the average stress model. The prediction errors before and after the modification were compared. This work can provide judgment basis for repair and maintenance of FOD aero-engine blades.

2. Experimental procedures

2.1 Specimen details

The material of test samples is 1Cr15Ni4Mo3N stainless steel, which is a kind of precipitation hardening stainless steels. It is now widely used in the manufacture of aero-engine fan shaft, compressor blade and some other components working at a temperature lower than 550 °C. The mechanical properties at room temperature are shown in Table 1. The compressor blades of a turbine-shaft engine was chosen as test samples, as shown in Fig. 1.

Figure 1 A compressor blade of turbine-shaft engine.

Table 1 Mechanical properties of 1Cr15Ni4Mo3N and GCr15 steel at room temperature

Material	Density / (kg/m^3)	Elastic modulus / GPa	Poisson's ratio
1Cr15Ni4Mo3N	7870	194.2	0.33
GCr15	7850	210	0.3

2.2 FOD tests and measurement

The FOD tests were promoted by impacting a GCr15 steel ball with a diameter of 3 mm onto the leading edge of the test sample at the incident velocity of 200 m/s using an air cannon test system. Mechanical properties of GCr15 hardened steel at room temperature are shown in Table 1. The air cannon test system consists of gas cylinder, a gas storage tank, a loading mechanism, solenoid valves, a pressure sensor, a target chamber and other components, as shown in Fig. 2. The maximum stress position of the leading edge under the first-order vibration mode was selected as the impact position of the compressor blade during the FOD test, which is 6.5 mm away from the blade root. The radius of leading edge on the FOD test position is 0.1 mm.

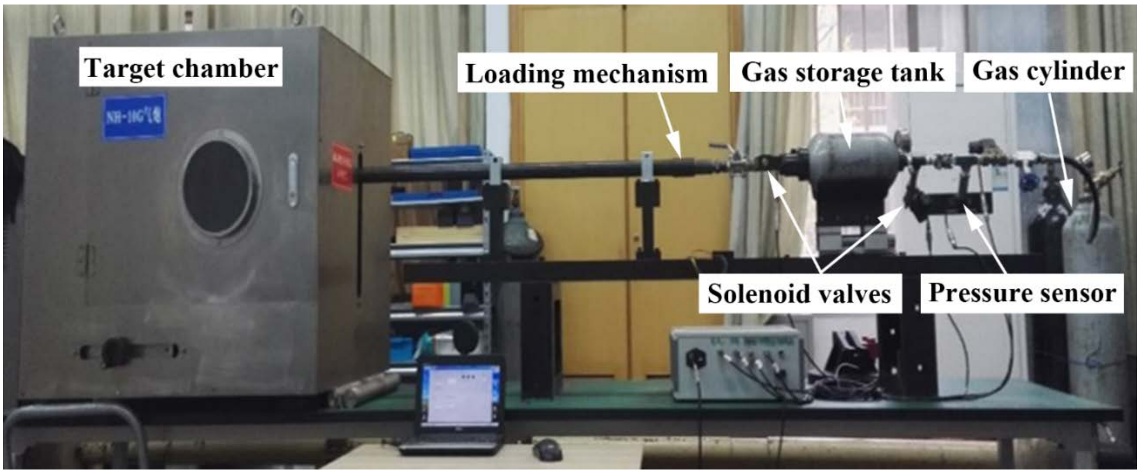

Figure 2 The air cannon test system [26].

The damage notch sizes and shapes were measured and observed by the KH-7700 three-dimensional stereomicroscope (HIROX, Japan) after the FOD test, whose highest measurement accuracy is 1 μm.

2.3 HCF tests

The HCF tests at 10^7 cycles of compressor blades were carried out on a vibration table under the first-order bending vibration mode. All samples were clamped by the combined action of the top pressing block and the back pushing block, as shown in Fig. 3. The HCF tests were promoted using step-loading method (Maxwell and Nicholas [29], 1999), which can be described as follows. If a given sample survives the initial stress level at 10^7 cycles without fatigue failure, the stress level will be increased by 10% and the test is repeated. This will continue until the sample fails in less than 10^7 cycles. It is assumed that the fatigue damage accumulates linearly in the stress level that the sample fails, the fatigue strength at 10^7 cycles can be calculated according to the following equation:

$$\sigma_{\mathrm{e}} = \sigma_{\mathrm{p}} + \frac{n}{10^7} \cdot \left(\sigma_{\mathrm{f}} - \sigma_{\mathrm{p}}\right) \tag{1}$$

where σ_e is the fatigue strength at 10^7 cycles, σ_p is the stress level before the final loading step, σ_f is the stress level of the final loading step, and n is the number of cycles when the test sample fails.

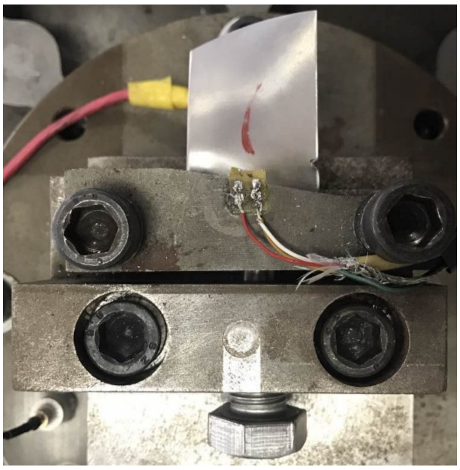

Figure 3 The fixture and compressor blade.

An example of load spectrum for step-loading method is shown in Fig. 4. For different notch type of test samples, the initial stress level was changed appropriately.

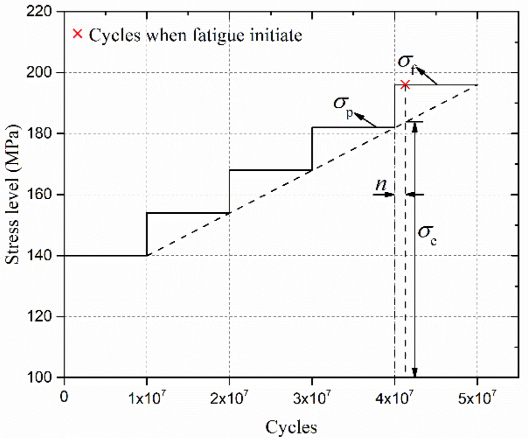

Figure 4 A load spectrum for HCF test.

The stress at the FOD notch of the test sample is obtained by converting the test value of the strain gauge pasted on the surface of the blade with the nominal stress of each characteristic point under the first-order bending mode numerical calculated by the finite element method. DH5981 dynamic signal testing and analyzing system is used to collect strain data, and the sampling rate is 15 kHz. The sticking position of the strain gauge on the surface of the sample is defined as point P. The test value of the strain gauge is ε_P and the nominal stress of numerical simulated element value at this point is σ_{P0}. The root of FOD notch is defined as point N and the nominal stress of numerical simulation at this point is σ_{N0}. The fatigue strength of the test sample is σ_N. The relationship between these parameters can be calculated by the following equation. Where all simulation stresses were taken as element values.

$$\frac{\sigma_{P0}}{E.\varepsilon_{P}} = \frac{\sigma_{N0}}{\sigma_{N}} \tag{2}$$

3. Results and discussions

3.1 FOD characterization

FOD tests were conducted on 10 compressor blades. The size and shape of damage notch due to high speed impact of steel ball was measured using optical microscopy. The damage size along the leading edge direction is defined as the notch width and the damage size perpendicular to the leading edge direction is defined as the notch depth, as shown in Fig. 5. According to the shape of the damage notch, it can be divided into four types, which are the semicircle notch (Fig. 5 a), the scratch notch (Fig. 5 b), the tearing notch (Fig. 5 c) and the V notch (Fig. 5 d). Among them, the average depth of the V notch is the largest, the average depth of the semicircle notch and the tearing notch is in the middle, and the average depth of the scratch notch is the smallest, as shown in Fig. 6. This rule is consistent with the definition of notch type (Fig. 5). The damage of the scratch notch is shallow while that of the V notch is sharp, which leads to significant difference in notch depth. The damage size showed obvious dispersion, especially in the damage depth.

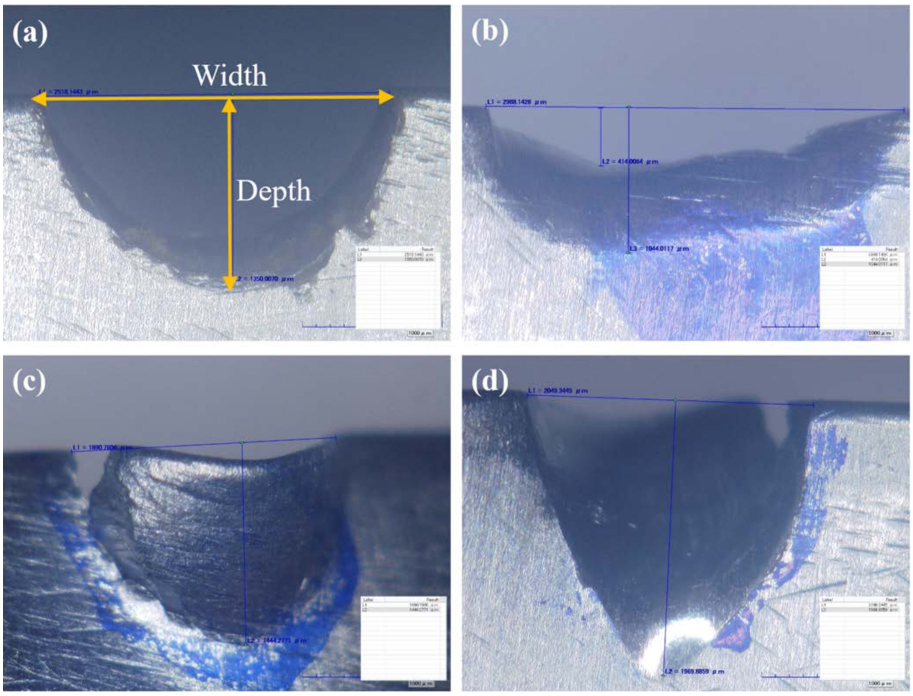

Figure 5 Notch types and the definition of damage sizes. a) Semicircular notch; b) Scratch notch; c) Tearing notch; d) V notch.

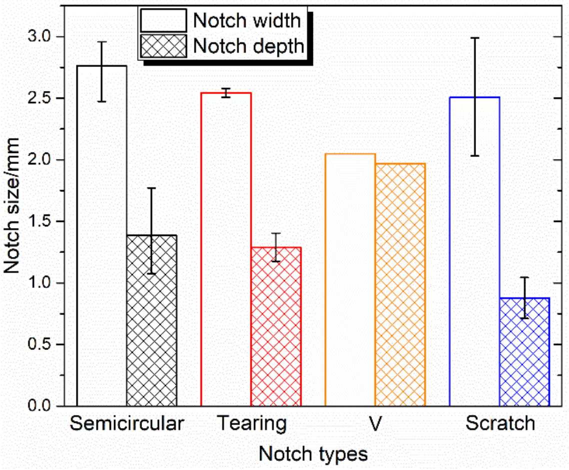

Figure 6 Distribution of notch size with respect to notch type.

3.2 HCF strength

The test results for the HCF strength of compressor blades at a life of 10^7 cycles are shown in Fig. 7. It can be seen from the figure that there is a certain relationship between the fatigue strength and the notch size. It is shown in Fig. 7b that, on the whole, the fatigue strength of FOD compressor blades decrease with the increase of the notch depth. The distribution of fatigue strength with the notch width is disordered, as shown in Fig 7a. It is more obvious that the fatigue strength of FOD compressor blades varies with different notch types. It can be seen from Fig. 7c that the fatigue strength of the scratch notch is the highest, that of the semicircle notch is lower than the scratch notch, and that of the tearing notch and the V notch is the lowest. Therefore, it is necessary to classify the types of FOD notches, so as to carry out targeted fatigue strength prediction method study.

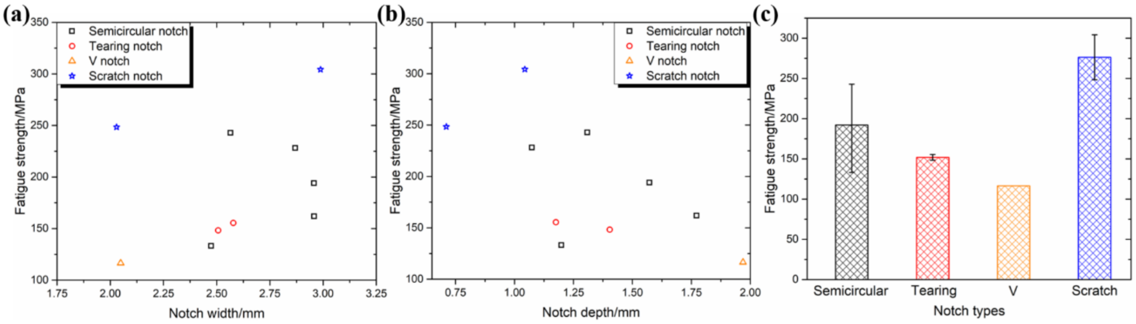

Figure 7 Relationships between HCF strength and FOD sizes. a) HCF strength versus notch width; b) HCF strength versus notch depth; c) The average HCF strength for different notch types.

4. Fatigue strength prediction

4.1 The average stress model

In the early stage of fatigue research on notched components, the stress concentration factor (K_t) is often used to describe the effect of notches on the fatigue performance of notched components. Subsequently, the fatigue notch factor (K_f) was introduced to characterize the difference of fatigue properties between notched and intact components more accurately. The fatigue notch factor is defined as the ratio of the intact specimen fatigue strength to the notched specimen fatigue strength under the same conditions and number of cycles, as described in the following equation.

$$K_{\mathrm{f}} = \frac{\sigma_{\mathrm{intact}}}{\sigma_{\mathrm{notched}}} \tag{3}$$

where σ_{intact}=575 MPa, obtained by bending vibration fatigue test of 1Cr15Ni4Mo3N stainless steel standard fatigue specimen at 10^7 cycles.

In this work, the Peterson formula (Eq. 4) and Neuber formula (Eq. 5) of the average stress model were both used to predict the fatigue strength of FOD compressor blades.

$$K_\mathrm{f} = 1 + \frac{K_\mathrm{t} - 1}{1 + \alpha_\mathrm{P} / \rho} \tag{4}$$

$$K_\mathrm{f} = 1 + \frac{K_\mathrm{t} - 1}{1 + \sqrt{\alpha_\mathrm{N} / \rho}} \tag{5}$$

where ρ is the radius of the notch root (the radius of the incident steel ball is selected to approximately express it in this work) and α_P, α_N are the material constants under the influence of tensile stress, which can be taken from the α-σ_b curve (Fig. 8, [30]). Given that the tensile strength of 1Cr15Ni4Mo3N stainless steel is 1234 MPa, α_P can be seen to be 0.147, α_N can be seen to be 0.02.

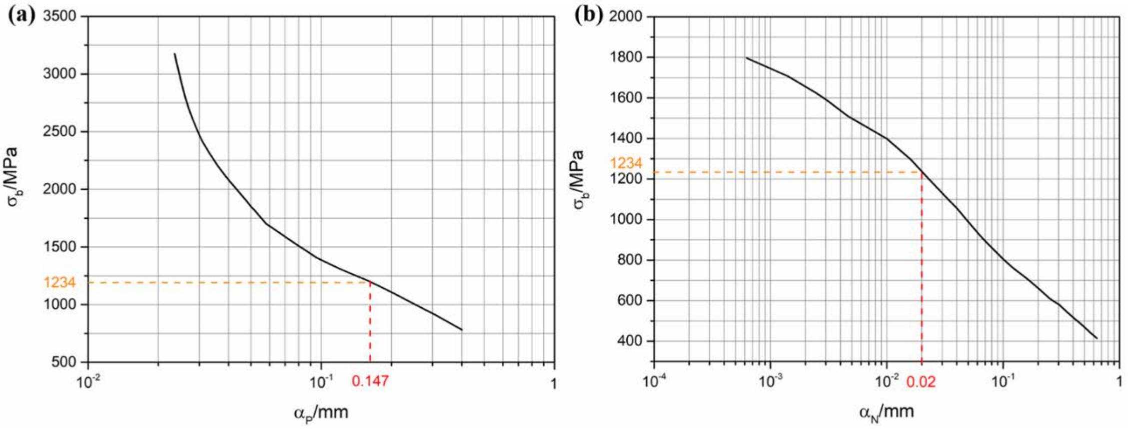

Figure 8 α-σ_b curve. a) Peterson formula; b) Neuber formula.

The theoretical stress concentration factor K_t of the plate edge notch can be calculated by using a half-model of an elliptical hole in an infinite plate. In engineering application, the approximate equation (Eq. 6) derived from the above method is common used.

$$K_\mathrm{t} = 1 + 2\sqrt{\frac{d}{\rho}} \tag{6}$$

where *d* is the depth of the notch.

The error distributions of the fatigue strengths of FOD compressor blades predicted by the Peterson formula and Neuber formula are shown in Fig. 9. The error here is defined as the ratio of the difference between the predicted value and the test value to the test value, as shown in the following equation.

$$\mathrm{error} = \frac{\sigma_\mathrm{prediction} - \sigma_\mathrm{test}}{\sigma_\mathrm{test}} \tag{6}$$

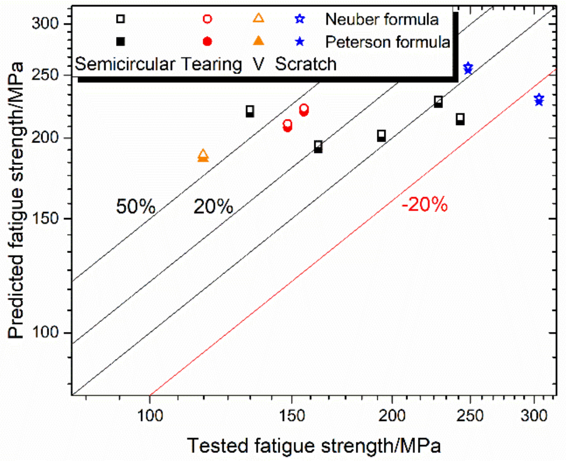

Figure 9 Prediction error distribution of fatigue strength according to the Peterson formula and Neuber formula for different notch types.

It can be seen from the figure that the predicted value of Peterson formula is lower than that of Neuber formula, and the difference is within 2%. It can be concluded that the two methods have similar prediction results on fatigue strength of notched compressor blades. The number of test samples with predicted value greater than the test value accounts for the majority. It is obvious that the prediction on bending fatigue strength of compressor blade by these two formulas is dangerous in engineering. The prediction error of V notch is the largest, which is more than 50%. The fatigue strength prediction errors of the other three types of notches are mostly within 50%, but also show obvious difference with the notch types. The prediction error of tearing notch is around 40%, of scratch notch is over -20%, and of semicircular notch mostly in the range of ±20%. Considering the obvious difference of fatigue strength prediction error on notch type, the average stress model is modified for different notch types in the following work.

4.2 The modified average stress model based on notch types

The notch type of FOD compressor blade is distinguished according to its shape, which has the greatest influence on the stress concentration factor. The Peterson formula and the Neuber formula both use the approximate equation of theoretical stress concentration factor derived from the half-model of an elliptical hole in an infinite plate. When the equation is applied to the damage notch caused by high velocity impact of the steel ball on the leading edge of the blade, there must be a great error. The high velocity impact process will cause micro cracks, adiabatic shear bands and other micro damage characteristics to the notch, so the stress concentration factor calculated by the approximate equation is often lower than the actual value. As a result, the predicted value of the fatigue notch factor is also lower than the actual value, and the predicted value of the fatigue strength of notched compressor blade is higher than the actual value. This is dangerous in engineering use.

In view of the above reasons, the approximate calculation equation of theoretical stress concentration factor is modified based on the characteristics of different notch types. Considering the micro damage of the FOD notch, the actual stress concentration factor of other three notch types should be larger than the theoretical value, except the scratch notch. The tearing notch and the V notch are sharper so that the actual stress concentration factor should be much larger than the theoretical value. Therefore, the constant term in the theoretical stress concentration factor equation is modified according to the order of the V notch being the largest, the tearing notch being the second, the semicircular notch being the third and the scratch notch being the smallest. The modified calculation equations of stress concentration factor are listed in Table 2. According to the modified calculation equations, the fatigue strength of FOD compressor blades are predicted using both the Peterson formula and the Neuber formula, and the error analyses are shown in Figure 10.

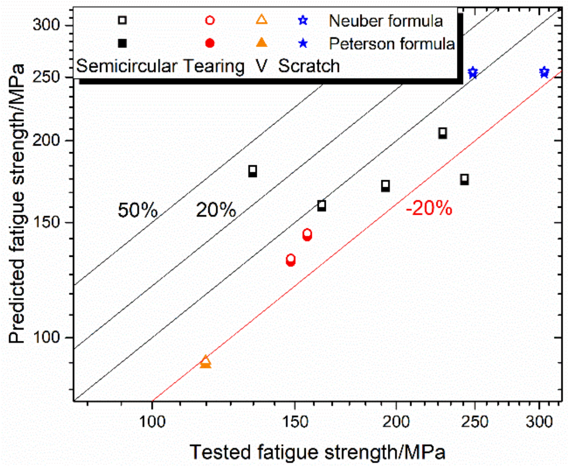

Figure 10 Prediction error distribution of fatigue strength according to the modified Peterson formula and Neuber formula for different notch types.

Table 2 Approximate calculation equation of stress concentration factor based on damage type modification

Notch types	Equation
Scratch notch	$K_t = 1 + 2\sqrt{\frac{d}{\rho}}$
Semicircular notch	$K_t = 1.5 + 2\sqrt{\frac{d}{\rho}}$
Tearing notch	$K_t = 2.5 + 2\sqrt{\frac{d}{\rho}}$
V notch	$K_t = 3 + 2\sqrt{\frac{d}{\rho}}$

It can be seen from the analyses of the above figure that the fatigue strength prediction accuracy of FOD compressor blades using the modified stress concentration factor equation has been greatly improved. The prediction errors of all notched samples are less than 50%, and most of them lie in the range of -20% to 20%. The fatigue strength predicted value of all blades are lower than the test value except for two samples, which is safe in engineering application. This makes the modified average stress model have certain engineering application value.

5. Conclusions

HCF test studies of FOD 1Cr15Ni4Mo3N stainless steel compressor blades of a turbine-shaft engine and the fatigue strength prediction method modification researches allow us to draw the following conclusions:

(1) The damage size showed obvious dispersion, especially in the damage depth. According to the difference in the morphology of the notch, it is divided into four types, namely the semicircular notch, the tearing notch, the V notch and the scratch notch.

(2) HCF test results showed a certain relationship between the fatigue strength and the notch size. The greater the notch depth, the lower the fatigue strength. The notch type has a more obvious influence on the fatigue strength of the damaged blades. The fatigue strength of the scratch notch is the largest, of the semicircle notch is lower, and of the tearing notch and the V notch are the lowest.

(3) The prediction difference between the two formulas is very small. The prediction errors are within the range of -20% to 50%. This is dangerous in engineering applications. The approximate equation of theoretical stress concentration factor was modified according to notch types, improving the

prediction accuracy to the error range of -20% to 0.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgements

The authors thank the anonymous reviewers for their critical and constructive review of the manuscript. This work was supported by the National Major Science and Technology Project of China [grant number J2019-IV-0014-0082]; the National Natural Science Foundation of China [grant numbers 51875574] and the National defense Basic research program [No. JCKY2019802B001].

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