Initiation mechanism of transverse cracks in wind turbine blade trailing edge

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Abstract:

Transverse crack often occurs in the trailing edge region of the blade when it is subjected to excessive fatigue load in edgewise. In this paper a refined model was established through local mesh refinement methods in order to investigate the initiation mechanism of crack and its extension in blade trailing edge. The material stress around the crack in trailing edge region under different thicknesses is calculated based on the fracture mechanics theory. Then the coupons test is conducted to verify the simulation results. The factors affecting the fatigue robustness of blade trailing edge are concluded by investigating the results of finite element analysis and coupons test. In final, a practical design scheme to prevent crack initiation is given for the manufacture of wind turbine blade.

Keywords:

Fatigue crack initiation; Fracture mechanism; Composite laminates; Bonded joints; Finite element method

1 Introduction

Wind energy is expected to become one of the alternative energy to replace fossil energy in the process of reducing global warming. With the expansion of blade markets resent year, blade manufacturer adopt the method of reducing blade weight to cut down the costs. The design department introduces better geometrical form for blade based on GFRP (Glass Fiber Reinforced Plastic) through material and structure optimization. So, standards for testing blade performance are also being added to identify the robustness of the new lightweight blade [1-3].

In general, the design life of a wind turbine is 20-25 years. During its work condition, the blade is regularly subjected to a combined load, resulting in a large fatigue load or even blade failure [4]. So, accurate structural design and strength tests [5-10] of the blade are reasonably required in order to ensure the robust performance of the blade in its life. In recent studies, Chen [11] conducts the fatigue test of the blade through full-scale tests method, and he reports the development rule of materials performance and fatigue life of the blade under cycle load. Castro [12] studies the stress response of GFF (Glass Fiber Fabric) with cracks under cycle load and notes that the GFF with defects under a lower load levels would not produce more cracks, but extends the existing cracks; the GFF with defects under a higher load levels would produce more cracks around the existing cracks. More conclusions of the blade fatigue test are reported in the work of Robert [13].

Based on previous research, blade manufacturer noticed that the transverse crack defects (see Fig. 1(a)) are often generated in the blade trailing edge after a large number of fatigue tests. Similarly, the blade operating on the wind turbine tower is often damaged by cracks before reaching its design life (Fig. 1(b)). The blade trailing edge is a shell structure bonded by adhesive. In the middle and leading segment of the blade shell, there are only 2-6 multiaxial GFF layers, which is a little weak. Due to the poor capacity of fatigue performance of bonding structure, it is damage easily when loaded by fatigue force. Then stress concentration would be caused in the adhesive of trailing edge, making the trailing edge strength decrease and cracks easily.

Fig. 1(a) Defective blade in fatigue test Fig. 1(b) Defective blade in wind turbine tower

Fig. 1 Cracks defect in the blade

In the failure mechanism research of blade trailing edge, Chen [14] conducts a subcomponent test and points out that the trailing edge collapsed with adhesive joint and sandwich when subjected to the ultimate edgewise load. Bender [15] studies the strength of adhesive joint and finds that the adhesive joint structure with defects has a significant reduction comparing with intact subcomponent in performance. Therefore, transverse cracks have some influence on the structural strength of the trailing edge. Eder [16] conducts a test for adhesive joint strength and finds that the effect of different bonding structures on the adhesive joint performance of the adhesive joint is different. Further research on the effect of defects on subcomponent structure can be found in the reports of Ji [17] and Fernandez [18].

The failure mode of trailing edge is complex and multitudinous. In the only article mentioning the blade transverse cracks, Ataya [19] has notes the forms and locations of transverse cracks in blades without giving a failure mechanism.

The focus of this paper is placed on the crack defects in the blade trailing edge based on the research of Ref [19]. For that, a refined FE (Finite Element) model of the trailing edge is established. Then the influence of different bonding parameters on the extension of defects and the development rule of crack under fatigue load are determined. According to the test standard of blade material [20, 21], the specimens with defects are made for coupons test. The fatigue load is applied to the specimens, and then the test results are collected to verify the simulation results obtained in section 3. Finally, the initiation mechanism of transverse cracks in the blade trailing edge under fatigue load is concluded thoughtfully.

2 Blade trailing edge descriptions

2.1 Materials

The typical wind turbine blade is a shell structure (see Fig. 2), and its shape has the aerodynamic performance. It is usually made of two half-shells of PS (Pressure Side) and SS (Suction Side). Adhesive joints are designed at the leading edge and trailing edge of the blade, and the two half-shells are bonded together by bonding paste. The spar cap placed in the middle of shells, and the shear web fixed in the middle of spar cap constitutes the box-beam structure. The blade is subjected to the flapwise load caused by wind pressure and edgewise load caused by gravitational. And the box-beam is the major part to carry flapwise load which is generated by 70% gravitational force and 30% aerodynamic load. A UD (Unidirectional) tape structure is placed in the trailing edge region of two shells. UD tape is the minor part to carry the edgewise load.

Multilayer triaxial GFF is set on the shell of the blade root region to carry the load accumulated from the global blade. Another part of the shell is a sandwich structure composed of 2-3 layers of multi-axial GFF and balsa wood so that the global structure of the blade has appropriate stiffness to resist deformation.

At present, the shell of PS and SS are manufactured separately, and adhesive joint is designed at the leading edge and trailing edges. The two shells are bonded together by bonding paste. The type of bonding structure is usually in the form of socket, bonding lip and direct bonding (see Fig. 3), and its type is selected according to the size of trailing edge.

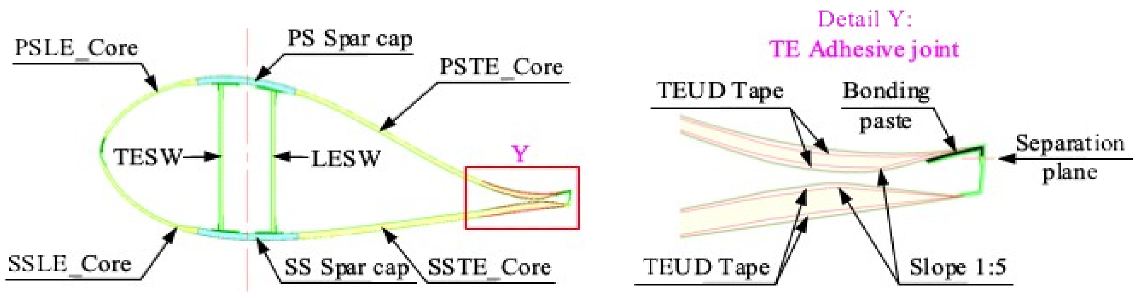
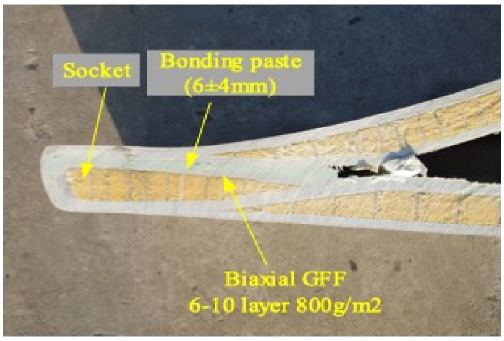


Fig. 2(a) Section structure of wind turbine blade   Fig. 2(b) Details of blade trailing edge

Fig. 2 The structure of blade trailing edge: (LE: leading edge, SW: shear web, TE: trailing edge)



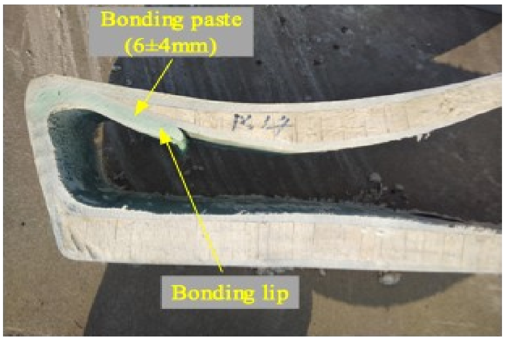


Fig. 3(a) Socket at blade trailing edge   Fig. 3(b) Bonding lip at blade trailing edge

Fig. 3 Bonding structure of blade trailing edge

2.2 Numerical theory

The cumulative fatigue damage caused by cycle load leads to the failure of the material and results in the crack defects shown in Fig. 1. The generation of cracks experienced three stages: crack initiation, stable crack extension and fracture. The global fatigue life of the blade can be divided into two parts: crack initiation life and crack growth life.

$$N_{\text{tatal}} = N_{\text{initiation}} + N_{\text{propagation}} \quad (1)$$

The adhesive used in the bonding paste is a brittle material, and it has a poor fatigue performance. The fatigue load causes the crack in bonding paste, and then the crack gradually extends to the complete fracture. There is a notch effect between the bonding paste and laminate at crack region. Notch effect raises the local stress of laminate and accelerates the process of fatigue failure, and finally notch effect produces transverse cracks at the blade trailing edge. In this paper, the coefficient of elastic stress concentration K_t is used to describe the crack defects.

$$K_{\text{t}} = \frac{\sigma}{S} \quad \left(\sigma < \sigma_{\text{ys}}\right) \quad (2)$$

Where, σ is the maximum stress at crack region. S is the nominal stress at crack region.

Evaluation of blade life needs the fatigue load value [19, 21]. The fatigue load of the blade trailing edge can be gained by combining the simulation software "Bladed" and FEM (Finite Element Method). The maximum fatigue life of related materials under different stress amplitudes and average values can be calculated according to the Goodman formula represented by Eq. (3).

$$N_i = \left(\frac{R_{k,A} - \left| \gamma_{m,\text{short term}} \cdot S_{k,M} - \left(\frac{R_{k,t} - \left| R_{k,c} \right|}{2} \right) \right|}{\gamma_{m,\text{fatigue}} \cdot S_{k,A}} \right)^m \quad (3)$$

According to the corresponding cycle number provided by Eq. (3), the Miner linear fatigue damage cumulative rule expressed by Eq. (4) can be used to evaluate the fatigue life of tested blade.

$$D = \sum_i \frac{n_i}{N_i} \leq 1 \quad (4)$$

2.3 FE model of trailing edge

The FEM can reduce the expenses of blade design and optimization. So a refined model of the blade was established in order to investigate the initiation mechanism of the transverse crack under different bonding scales in blade trailing edge.

The classic wind turbine blade is a shell structure. Using shell elements for blade modeling can accurately calculate the global stress distribution and deformation of the blade. However, the blade trailing edge has a complex bonding structure. The shell element modeling method simplifies the structure details of the adhesive joint, which is hard to gain accurate local stress of blade trailing edge. Besides, the solid element modeling method needs a large number solid element which needs a complicated calculation. The blade layer structure is complex, so it is hard to build a refined model using the shell or solid elements. In order to solve this problem, hybrid shell-solid elements are used to model the trailing edge. The blade of LZ40.3 is selected as the analysis subject. The shell element model for blade and the solid element model for blade trailing edge are created. Firstly, the whole model is calculated, and the displacement data of shell element nodes is collected. Then the displacement data is sets as the boundary conditions and maps to the subcomponent composed of solid elements, as shown in Fig. 4.

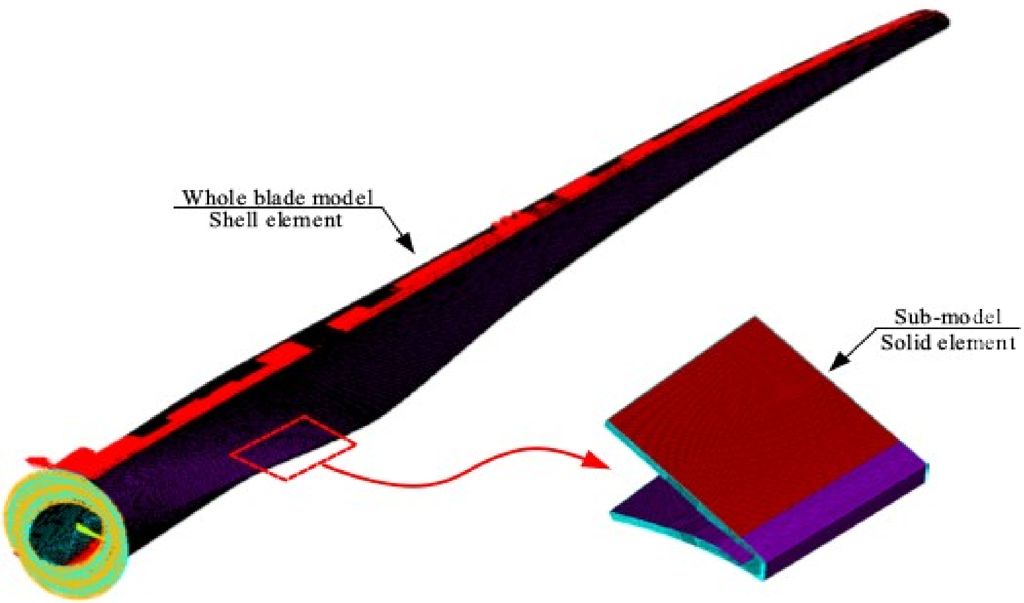


Fig. 4 The refined FE model of blade

According to the different thicknesses of the bonding paste mentioned in Section 2.1, the finite element model (see Fig. 5) is established.

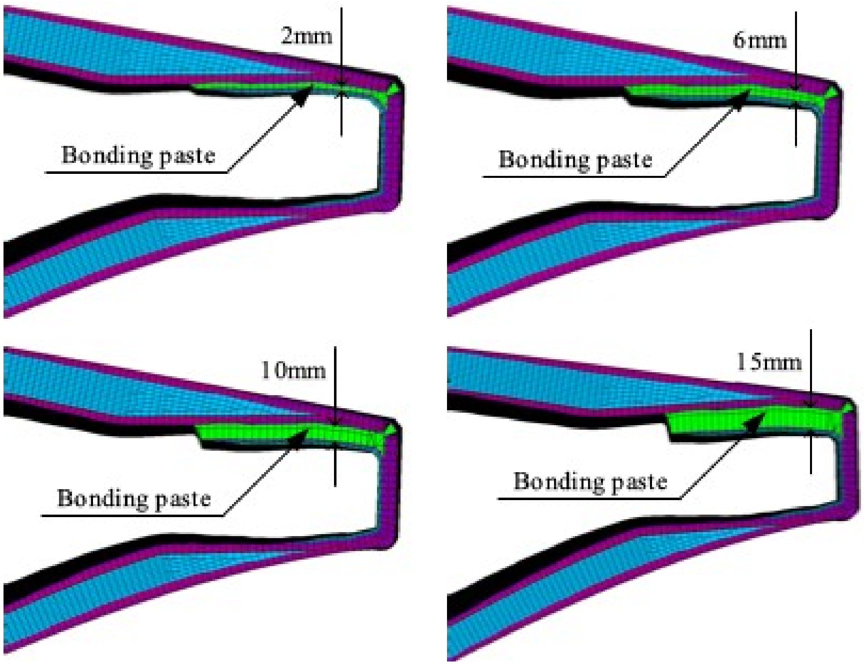


Fig. 5 Solid element model with different bonding paste thickness

3 Simulation results

By establishing the trailing edge model with different bonding thicknesses, the local stress distribution of the adhesive joint with a crack at the trailing edge is simulated, respectively. Finally, a reasonable explanation is given. It can be seen from Fig. 6 that: the laminate crack causes stress redistribution in crack region of the blade trailing edge; and different bonding parameters lead to different stress distribution. The stress concentration factors of adhesive joint models with different thickness are obtained by extracting the element stress in crack region, see Tab. 1. The stress concentration factor is cited in the fatigue analysis of the blade trailing edge. Then the fatigue strength of the GFF material is calculated referring to the Markov matrix of the blade. In final, the influence of eigenvalue λ on the fatigue results of the trailing edge is collected under different stress concentration factors.

Tab. 1 Stress data of blade adhesive joint

Bonding paste thickness /mm	Bonding paste stress /MPa	Shell stress/MPa		Stress concentration factors Kt	$\lambda_{Max\ effort}$
		No crack	With crack		
2	3.93	26.99	27.20	1.01	0.926
6	4.15	26.58	27.32	1.03	0.952
10	4.24	26.30	27.43	1.04	0.965
15	4.28	25.79	27.73	1.08	1.018

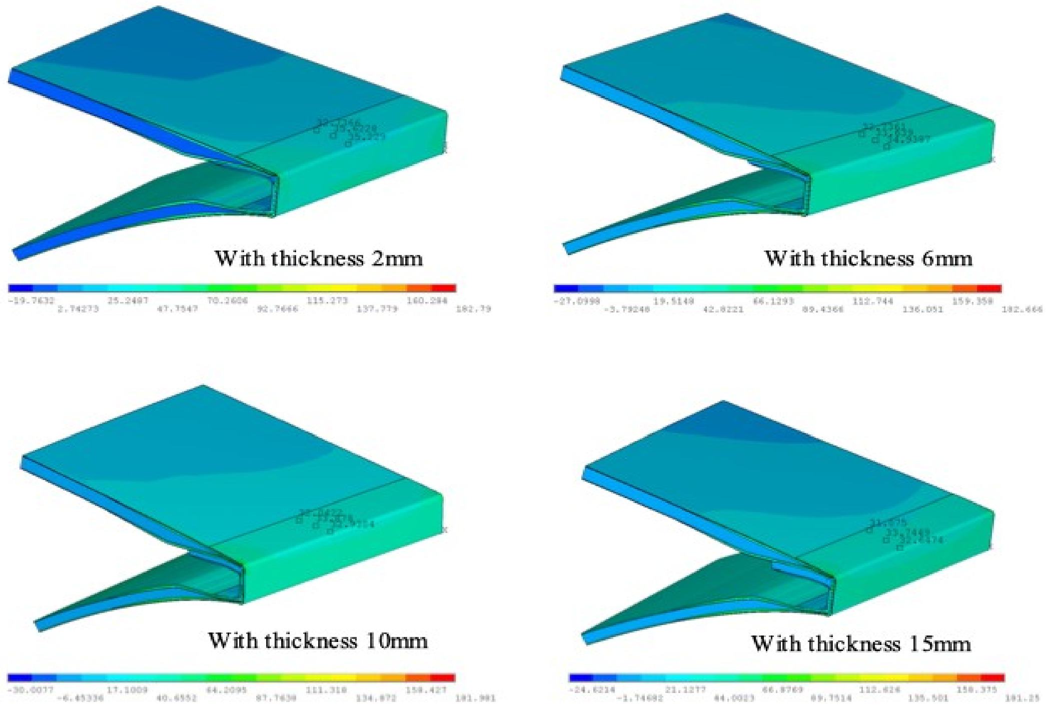


Fig. 6 Simulation results of adhesive joint with different bonding paste thickness

Kt represents the level of stress concentration of the crack regions. It can be seen from Tab. 1 that the stress concentration factor Kt and λ have a noticeable increase with the adding of adhesive thickness. It indicates that the stress contribution factor of bonding paste in global structure performance increases with adhesive thickness. The bonding paste absorbs a larger fatigue load when has a thicker adhesive. Simultaneously, laminate with cracks will release more stress and transfer to the surrounding laminate so that the adhesive joint can obtain a higher stress concentration factor, which makes the shell more prone to fatigue cracks.

The FE results show that when the bonding paste thickness adds, the fracture will cause a more serious local stress concentration, which makes the trailing edge shell has a higher probability of fatigue failure and transverse cracks. And the actual production shows that when the bonding paste is too thick in production, it is easy to produce internal stress and cavity defects in the curing process, which makes the bonding paste has a poor performance and fatigue strength. Therefore, better control of bonding paste thickness in its production is conducive to improve the strength of trailing edge.

4 Test

4.1 Preparation of specimens

The specimens (see Fig. 7) made of GFF and adhesive are prepared in the laboratory in order to further investigate the failure mechanism of the transverse crack on trailing edge and verify the results of FE simulation. Then the coupons test is conducted to simulate the bonding structure of blade trailing edge.

More detailed about composite performance of specimens and the process of crack extension are collected in this fatigue test.

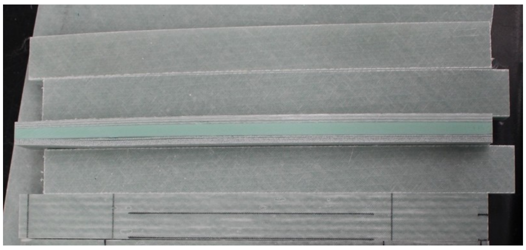


Fig. 7 Laminate specimens of fatigue test

4.2 Test results

The stress sensor is set on the press machine to collect the compressive strength of tested specimens. Firstly, the static test is conducted to obtain the ultimate strength of the specimens. Then the load data under different load cycles is preliminarily estimated to determine the load spectrum of fatigue test. After that, the fatigue test is carried out. According to the stress and failure process of the specimens, the failure mechanism is deduced.

The specimen is fixed on the press machine with a special clamp applying pressure along the fiber direction to the specimen until it fails, as shown in Fig. 8. The ultimate strength values of the specimens measured by test are 121/114/120/140/133 MPa in Fig. 9, with an average of 123.6 MPa.

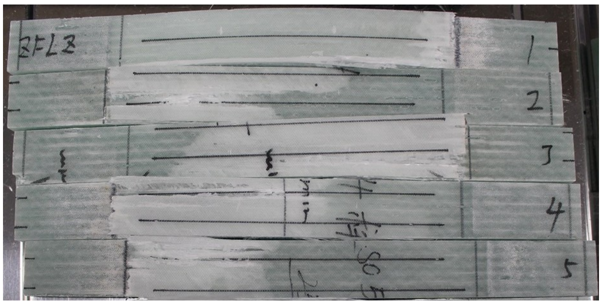


Fig. 8 Fracture behavior of the specimens in static test

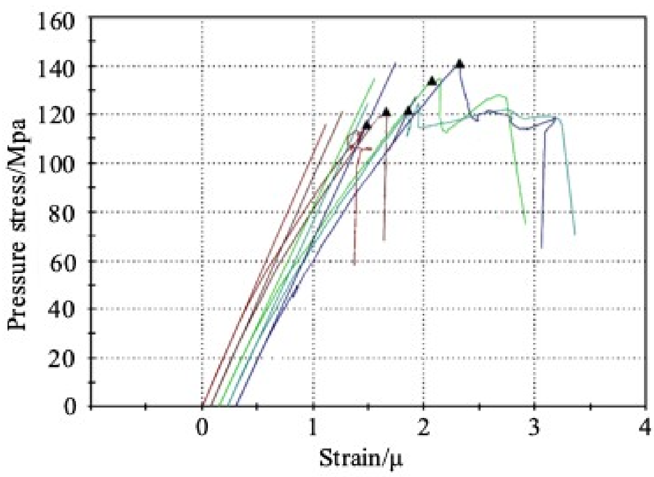


Fig. 9 Stress data of the specimens in static test

In fatigue test, the maximum value in load spectrum is set as 40/50/60/80/100 MPa, then the S-N data of the specimens is collected. The failure modes include laminate damage and adhesive crack in Fig. 10. The specimens have more serious damage when subjected to the larger cyclic load, as shown in Fig. 11. Macroscopic observation of the test process shows that the initial cracks are always generated in adhesive. Adhesive cracks induce the final transverse cracks of laminates.

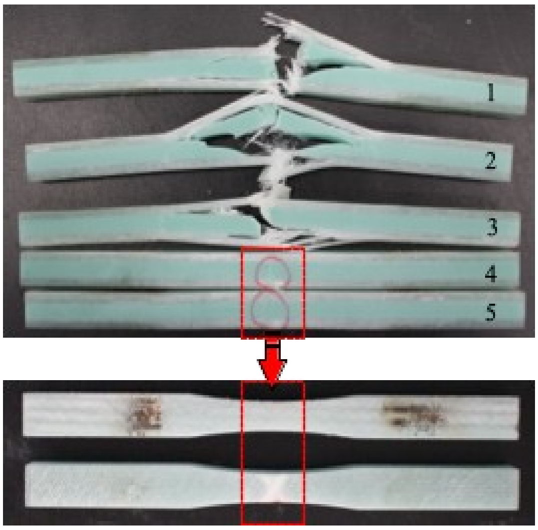


Fig. 10 Fracture behavior of the specimens in fatigue test

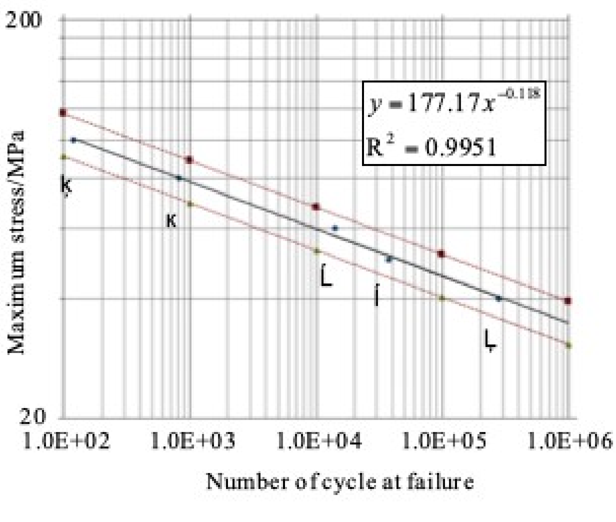


Fig. 11 S-N data of tested specimens

4.3 Failure mechanism

The trailing edge is a vulnerable part of the blade. Due to its high stiffness and low strength material performance, the adhesive has no ability to resist the stress transmitted by the trailing edge structure. So when the blade is subjected to low cycle fatigue load, the adhesive crack will be caused. The stress concentration occurs around the crack region under fatigue load. In the crack extension process, the laminate on both sides of the crack is also damaged due to adhesive structure defect. The crack in laminate extends laterally, which reduces the global structural performance of the blade.

5 Conclusions

The FE analysis and the coupons test are conducted in order to investigate the initiation mechanism of transverse crack at the blade trailing edge. Based on the simulation and test results, some conclusions can be drawn:

- From the simulation and test results, it can be seen that the fatigue strength of the adhesive is weedier than that of GFF. Damage of adhesive is the major cause that makes the transverse appear at adhesive joint. In actual production, when the adhesive thickness is too thick, cavity defects will be introduced in the production of blade. It is easy to produce high internal stress and initial micro-cracks during the solidification process of adhesive, which will further reduce the fatigue strength of adhesive.
- In blade service life, cracks may occur in bonding paste. If the bonding paste is too thick, it will cause a larger stress concentration of the materials in the adhesive crack area, and the fatigue strength of the adhesive joint will be weakened. Then the transverse crack of the trailing edge will quickly extend, which will lead to the failure of the trailing edge.

There are two methods to avoid the transverse crack in trailing edge: 1. Redesign the bonding paste of the trailing edge and reasonably determine the adhesive thickness in the blade production. 2. Adding GFF crack control layer in the laminate, which can reduces the stress concentration and improves the fatigue strength of the trailing edge. In the latest blade design, anti-cracking layer is added to the shell at trailing edge. After blade fatigue test, there is no transverse crack on the trailing edge.

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Author Contribution Statement

Conceptualization, J.W. and X.H.; methodology, X.H.; software, J.Z.; validation, J.W., L.Z. and X.H.; formal analysis, L.Z.; investigation, X.H.; resources, L.Z.; data curation, C.Y.; writing—original draft preparation, J.W.; writing—review and editing, Z.L.; visualization, J.Z.; supervision, C.Y.; project administration, X.H.; funding acquisition, L.Z.

The article has been approved by all listed authors before submission. The authors declare that they have no conflict of interest.

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