Fatigue Assessment Method for Composite Wind Turbine Blade

Chen Cheng, *Wang Tongguang* *

Jiangsu Key Laboratory of Hi-Tech Research for Wind Turbine Design, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, P. R. China

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Abstract: Fatigue strength assessment of a horizontal axis wind turbine (HAWT) composite blade is considered. Fatigue load cases are identified, and loads are calculated by the GH Bladed software which is specified at the IEC61400 international specification and GL (Germanisher Lloyd) regulations for the wind energy conversion system. Stress analysis is performed with a 3-D finite element method (FEM). Considering Saint-Venant′s principle, a uniform cross section FEM model is built at each critical zone. Stress transformation matrixes (STM) are set up by applied six unit load components on the FEM model separately. STM can be used to convert the external load into stresses in the linear elastic range. The main material of composite wind turbine blade is fiber reinforced plastics (FRP). In order to evaluate the degree of fatigue damage of FRP, the stresses of fiber direction are extracted and the well-known strength criterion-Puck theory is used. The total fatigue damage of each laminate on the critical point is counted by the rain-flow counting method and Miner′s damage law based on general S-N curves. Several sections of a 45.3 m blade of a 2 MW wind turbine are studied using the fatigue evaluation method. The performance of this method is compared with far more costly business software FOCUS. The results show that the fatigue damage of multi-axis FRP can be assessed conveniently by the FEM-STM method. And the proposed method gives a reliable and efficient method to analyze the fatigue damage of slender composite structure with variable cross-sections.

Key words: fatigue assessment; wind turbine blade; finite element method (FEM); stress transformation matrix

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0 Introduction

Thanks to the advantages of wind turbine electricity generator, such as pollution free, fast installation, commissioning capability and low operation and maintenance cost etc., the recent growth rate of wind energy capacity has been well documented and predicted to accelerate worldwide in the next years. Along with these advantages, the main disadvantage of the wind energy industry is the temporary nature of wind flow. Therefore, using reliable and efficient equipment is critical for getting as much as energy from wind during the limited period of time.

The blade is one of the most important components in a wind turbine which is designed according to aerodynamic science in order to capture the maximum energy from the wind flow[1]. Nowadays, almost all MW scale blade of horizontal axis is completely made of composite materials. Advanced fiber reinforced plastics (FRP) composite materials systems (carbon/epoxy and glass/epoxy) are extensively used in the design. These composite materials systems and laminates improve the stiffness/mass and strength/mass ratios and also provide good resistance to the static and fatigue loading[2].

The blade of wind turbine is expected to sustain its mission for about 20—30 years. Therefore, designers must carefully consider the fatigue life of the blades in their structural design and must test the full-size structure. The first

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* Corresponding author, E-mail address: tgwang@nuaa.edu.cn.

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barrier of full-size test is to determine the equivalent test loads by fatigue load spectrum which is calculated according to IEC61400 and GL2010. Freebury[3] revealed a simplified method that transforms fatigue load spectrum to equivalent-damage loads and their method was used to design and test the new blade. However, the full-size test needs much time and money. It is another barrier to overcome. So a fatigue assessment method is accepted if it could simulate the fatigue damage precisely using the powerful computing capacity of modern computer. Palmgren[4] and Miner[5] proposed the linear damage hypothesis: the stress cycle, which remained constant throughout a fatigue lifetime, was equal to N, and the fraction of that lifetime consumed in every cycle was constant and equal to $1/N$. For the particularity of the wind turbine blade, there still are some difficulties need to be considered. On the one hand, the long-term loads on the blade, including aerodynamic load, force of gravity, gyroscopic moment and inertia force, etc., are almost impossible to predict and are also changing among all cross sections. Applying all these time-series loadings of every section to one blade in simulation should be carefully considered. On the other hand, the fatigue damage criteria of composite material are important in fatigue analysis.

This study focuses on these aspects mentioned above and proposes a fatigue assessment procedure of composite wind turbine blade. Based on the hypothesis that the materials is in the range of linear elasticity during the working period, a stress transformation matrix (STM) is set up to convert the time-series fatigue loads into stress components. And according to the Puck's theory[6-7] the stresses of fiber direction are extracted. The total fatigue damage of each laminate on the critical point is counted by the rain-flow counting method and Miner's damage law based on general S-N curves. The proposed procedure has been written into a code in Matlab, called the FEM-STM method. The performance of this method is compared with that of a far more costly business software FOCUS. The fatigue damage of multi-axis FRP could be assessed conveniently by the FEM-STM method. This proposed method gives a reliable and efficient method to analyze the fatigue damage of slender composite structure with variable cross sections.

1 Load Analysis

1.1 Source of loads

It is necessary to understand the loads on the wind turbine blade before fatigue assessment. The most important sources of the load of a wind turbine are gravitational load, inertial load and aerodynamic load[8].

The earth's gravitational field causes a sinusoidal gravitational load on each blade. This load is easily recognized in the time series of the edge-wise bending moment. Since the wind turbine is expected to operate over 20 years, the stresses from gravity load are important in the fatigue analysis.

Inertial load occurs when the turbine is accelerated or decelerated, such as the start-up of the rotor and shut-down of the rotor. The component of the inertial load affects the flap-wise bending moment.

As a result of wind shear, the mean wind speed increases with the height above the ground. Wind shear gives a sinusoidal variation of the wind speed seen by a blade with a frequency corresponding to the rotation of the rotor. The turbulent fluctuations superimposed on the mean wind speed also produce a time variation in wind speed and thus in angle of attack.

In addition to the above main source of loads, tower shadow effect, cross wind and yaw rate also produce a time variation in the aerodynamic load. According to the actual wind turbine design, however, their effects are small and can be neglected.

1.2 Load calculation

The reference frame of load is shown in Fig. 1. Aerodynamic loads are calculated by GH bladed software based on momentum-blade ele-

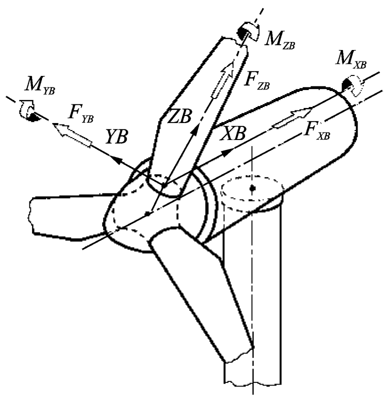


Fig. 1 Blade coordinate

ment theory which has been widely used in aerodynamics design. According to this theory, the normal force component and tangential force component of the blade in the blade coordinate[9] can be derived as

$$F_{YB}(r)=\frac{1}{2}\times\frac{B}{2\pi}\rho\int_{0}^{2\pi}\int_{r}^{R}C_{YB}(r)C(r)\Omega^{2}\,\mathrm{d}\theta\mathrm{d}r \quad (1)$$

$$F_{XB}(r)=\frac{1}{2}\times\frac{B}{2\pi}\rho\int_{0}^{2\pi}\int_{r}^{R}C_{XB}(r)C(r)\Omega^{2}\,\mathrm{d}\theta\mathrm{d}r \quad (2)$$

where ρ is the air density, B the quantity of blades, r the local radius, θ the azimuth angle of wind turbine, $C(r)$ the length of chord, $C_x(r)$, $C_y(r)$ the lift coefficient and resistance coefficient of local radius. And $C_x(r)$, $C_y(r)$ can be derived by the lift coefficient, resistance coefficient of airfoils and inflow angle ϕ as follows

$$C_{XB}=C_{\mathrm{L}}\sin\phi-C_{\mathrm{D}}\cos\phi \quad (3)$$

$$C_{YB}=C_{\mathrm{L}}\cos\phi-C_{\mathrm{D}}\sin\phi \quad (4)$$

The flap wise moment, edgewise moment and torque can be derived as follows

$$M_{XB}(r)=\int_{r}^{R}r\,\mathrm{d}F_{YB} \quad (5)$$

$$M_{YB}(r)=\int_{r}^{R}r\,\mathrm{d}F_{XB} \quad (6)$$

$$M_{ZB}(r)=-\left[\int_{r}^{R}(x_p-x_c)\,\mathrm{d}F_{YB}+\int_{r}^{R}(y_p-y_c)\,\mathrm{d}F_{XB}\right] \quad (7)$$

where P is the pressure center of airfoil and C the torsion center.

The gravitational load (Fig. 2) in the blade coordinate can be derived as

$$\begin{bmatrix}P_x\\P_y\\P_z\end{bmatrix}=\begin{bmatrix}0\\-\sin(\theta)\cdot mg\\-\cos(\theta)\cdot mg\end{bmatrix}\qquad \theta\in[0,2\pi] \quad (8)$$

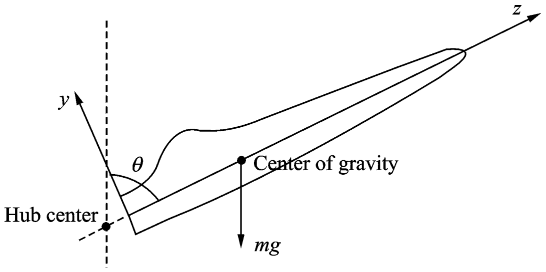
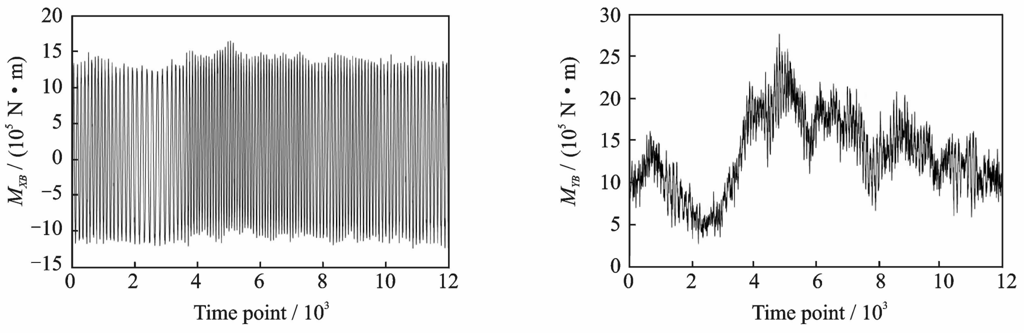


Fig. 2 Gravitational loading

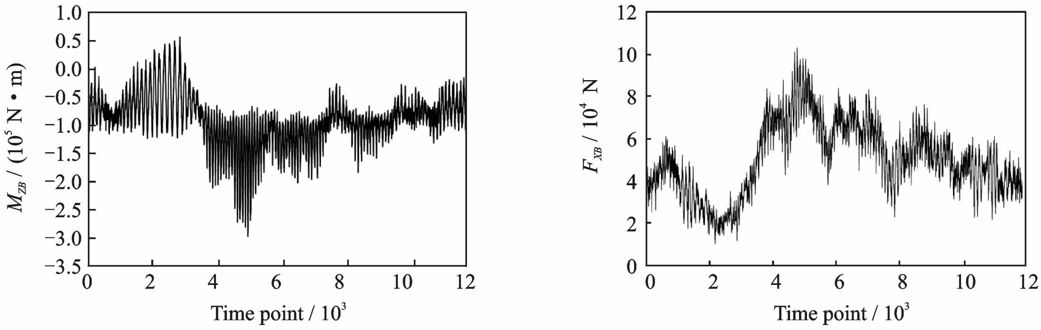
The inertial loading generated by blade rotation is considered as axial load which is not change with time. Fig. 3 shows the time-series fatigue loadings of one load case of a 2 MW wind turbine blade at the blade root section. The wind speed is 6 m/s and keeps for 10 min in this load case. Calculation performs every 0.05 s and six loading components are saved at each time, so every loading component contains 12 000 time points in total.

1.3 Loading cycle

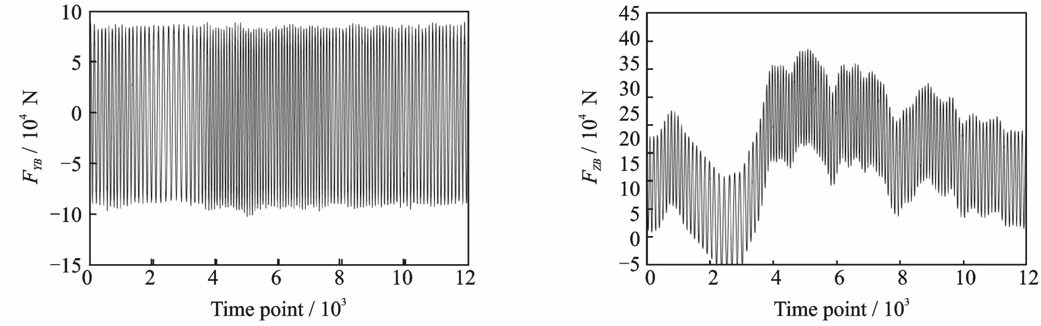
To calculate the blade fatigue damage cumulatively, the different wind speed and cycle number should be assumed. The Weilbull distribution is used to describe the wind speed distribution. The wind speed probability density function and



(a) Edge wise moment (b) Flap wise moment



(c) Torque (d) Flap wise force



(e) Edge wise force (f) Axial force

Fig. 3 Time-series fatigue loadings at blade root

cumulative distribution function can be described as

$$f(v) = \frac{K}{c}\left(\frac{v}{c}\right)^{K-1} \exp\left[-\left(\frac{v}{c}\right)^{K}\right] \tag{9}$$

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^{K}\right] \tag{10}$$

If the wind speed is divided into a number of intervals, the total hours of interval in a year is

$$T_i = 8\ 760F(v)\ \Big|_{v_i-\Delta}^{v_i+\Delta} \tag{11}$$

where Δ is the range of interval.

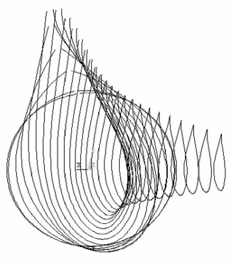
2 Structure Analysis

In order to assess the fatigue damage of blade, the stress of blade structure is necessary. FEM method is used and calculation is implemented in the ANSYS software. The stress analysis is performed with a 3-D finite element model at every blade section where the fatigue loadings is calculated. Taking the Saint-Venant′s principle into consideration, uniform cross section FEM models are built at each section. Based on the hypothesis that the materials is in the linear-elastic range during the working period, an STM is set up to convert the time-series fatigue loadings into stress components. According to the Puck′ theory, the stress component of fiber direction as the equivalent stress is used to calculate the fatigue damage of laminate composites.

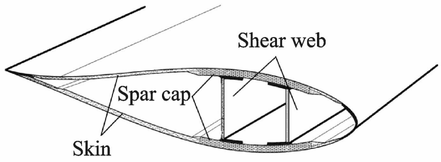
2.1 FEM model

The proposed method is suitable for slender structure of which the loading changes along the span-wise direction. The investigated blade consists of three main parts, called the spar cap, shear web and skin. Fig. 4(a) shows the section profiles of blade from the view of blade root, and Fig. 4(b) the internal structure of blade.

Tri-axial, bi-axial fabrics and core materials (polyvinyl chloride (PVC) or B wood) are used in the skin structure commonly, and unidirectional, bi-axial fabrics and core materials are used in the spar structure usually. Bi-axial and tri-axial plies contain two and three same unidirectional fabrics, respectively, which are stitched together. The configuration of the bi-axial lamina is $[+45/-45]_{\mathrm{T}}$ and the configuration of the tri-axial laminate is $[0/+45/-45]_{\mathrm{T}}$. The bi-axial and tri-axial laminates and direction are shown in Fig. 5, where the solid line depicts the fiber of the com-

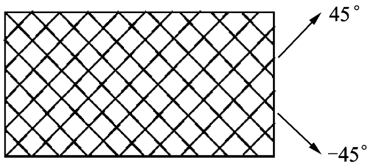


(a) Blade profile

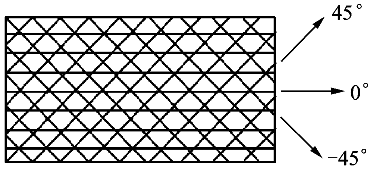


(b) Blade structure

Fig. 4 Blade profile and structure



(a) Bi-axial



(b) Tri-axial

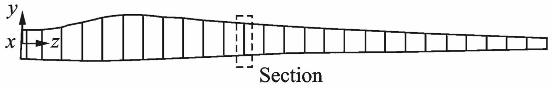
Fig. 5 Fiber direction of bi-axial and tri-axial laminate

posite.

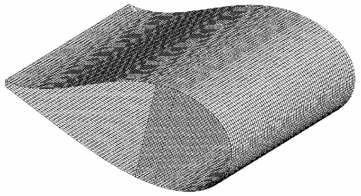
Wind turbine blade is the typical thin-walled structure. Under the plane stress hypothesis, the orthotropic materials has only four material parameters E_1, E_2, υ_{12}, G_{12}, and the constitutive equation is shown as follows

$$\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{Bmatrix}=\begin{bmatrix}\dfrac{1}{E_1} & -\dfrac{\upsilon_{12}}{E_2} & 0\\ -\dfrac{\upsilon_{21}}{E_2} & \dfrac{1}{E_2} & 0\\ 0 & 0 & \dfrac{1}{G_{12}}\end{bmatrix}\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{Bmatrix} \tag{12}$$

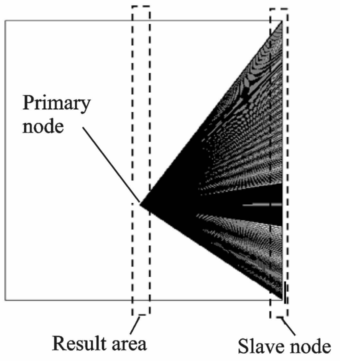
In order to obtain the structure stresses, uniform cross section FEM models are built at each critical section position. Fig. 6(a) shows the section profile of blade from top view, and Fig. 6(b) a FEM model of uniform cross section. Considering the Saint-Venant′s principle, the length of uniform cross section FEM model must be long enough. Multiple point constraint (MPC) is used to load the forces and moments onto the structure. Fig. 6(c) shows MPC method in the FEM model from top view.



(a) Blade profile



(b) Uniform cross section FEM model



(c) MPC constraint

Fig. 6 Uniform cross section FEM model

The primary node of MPC is located at the shear center of the cross section in the middle of the uniform cross section, and the slave nodes connect with the end of model. Displacement constraints are applied on the other end of the model. Through such processing, the force applied on the primary node won′t generate additional bending moment.

2.2 Stress transformation matrix

In order to convert the time-series fatigue loadings into stresses, an STM is set up based on the hypothesis that the materials is in the range of linear-elastic during the working period.

Under the condition of above assumption, the multi-force effect should satisfy the superposition principle. Firstly, a unit loading component ($M\times B=1$) is applied to the primary node of FEM model. Stresses of any node in the result area could be extracted in the layer coordinate (σ_1 means the direction of stress is parallel to the 0° fiber and the direction of stress is perpendicular to 0° fiber). Thus, the stress components of a node $[\sigma_1\ \sigma_2\ \sigma_3\ \tau_{12}\ \tau_{13}\ \tau_{23}]$ ($\sigma_3=\tau_{13}=\tau_{23}=0$ in the plane stress condition) come into being. Because of stress state of a point is a second-order symmetric tensor, under the plane stress hypothesis, the stress component of other direction can be derived as

$$\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{Bmatrix}^X=\begin{bmatrix}\cos^2\theta & \sin^2\theta & -2\sin\theta\cos\theta\\ \sin^2\theta & \cos^2\theta & 2\sin\theta\cos\theta\\ \sin\theta\cos\theta & -\sin\theta\cos\theta & \cos^2\theta-\sin^2\theta\end{bmatrix}\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{Bmatrix}^1 \tag{13}$$

where θ is the angle between the 1-coordinate system and x-coordinate system, as shown in Fig. 7, here, the solid line depicts the fiber of the composite.

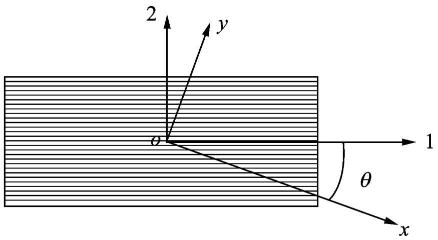


Fig. 7 Transformation of coordinates

Applying the other five loading components ($M_YB=1$, $M_ZB=1$, $F_XB=1$, $F_YB=1$, $F_ZB=1$) separately on the primary node of FEM model in the same routine, the corresponding stress components could be extracted.

In order to facilitate the following description, the stress component which is obtained from $M_XB=1$ could be represented symbolically by $[\sigma_{11}, \sigma_{21}, \sigma_{31}, \sigma_{41}, \sigma_{61}]^{\mathrm{T}}$. Analogously, the other stress components can be represented symbolically in the same way. Thus, the stress transformation matrix of the ith node can be built using the above stress components.

$$\boldsymbol{STM}(i)=\begin{bmatrix}\sigma_{11} & \sigma_{12} & \sigma_{13} & \sigma_{14} & \sigma_{15} & \sigma_{16}\\ \sigma_{21} & \sigma_{22} & \sigma_{23} & \sigma_{24} & \sigma_{25} & \sigma_{26}\\ \sigma_{31} & \sigma_{32} & \sigma_{33} & \sigma_{34} & \sigma_{35} & \sigma_{36}\\ \sigma_{41} & \sigma_{42} & \sigma_{43} & \sigma_{44} & \sigma_{45} & \sigma_{46}\\ \sigma_{51} & \sigma_{52} & \sigma_{53} & \sigma_{54} & \sigma_{55} & \sigma_{56}\\ \sigma_{61} & \sigma_{62} & \sigma_{63} & \sigma_{64} & \sigma_{65} & \sigma_{66}\end{bmatrix} \tag{14}$$

When time-series fatigue loads are applied to a cross section of this blade, the time-series stress result of every node on the section can be obtained by STM.

$$\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \tau_{12}\\ \tau_{13}\\ \tau_{23}\end{Bmatrix}=\boldsymbol{STM}(i)\cdot\begin{Bmatrix}M_{XB}\\ M_{YB}\\ M_{ZB}\\ F_{XB}\\ F_{YB}\\ F_{ZB}\end{Bmatrix} \tag{15}$$

2.3 Fatigue analysis

After getting the time-series stress components, fatigue damage is estimated by using the S-N linear damage equation and Goodman diagrams. Goodman diagram shows the relationship between the mean and the range component resistances R and actions S and it can be constructed in Fig. 8. The number of tolerable load cycles N can be determined as follows[9]

$$N=\left[\frac{R_{k,t}+|R_{k,c}|-\left|2\times 2.205\cdot S_{k,M}-R_{k,t}+|R_{k,c}|\right|}{2\times 1.6335\times S_{k,A}}\right]^m \tag{16}$$

where N is the permissible load cycle number, $S_{k,M}$ the mean value of the characteristic actions, $S_{k,A}$ the amplitude of the characteristic actions,

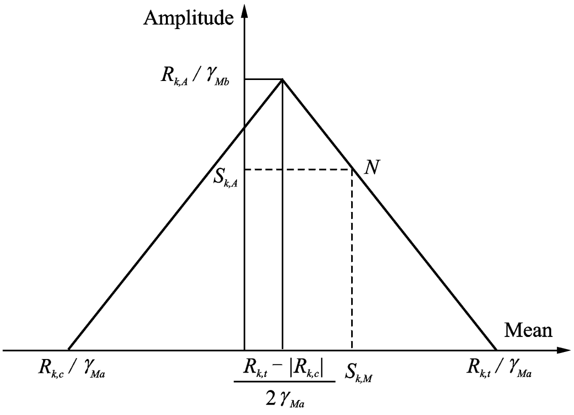


Fig. 8 Goodman diagram[9]

$R_{k,t}$ the characteristic short-term structural member resistance for tension, $R_{k,c}$ the characteristic short-term structural member resistance for compression, m the slope parameter of the S-N curve ($m=10$ for glass fiber reinforced plastics (GFRP) and laminates with epoxy resin matrix).

According to the Puck's theory[7], the stress component of fiber direction is used to calculate the fatigue damage of laminate composites. The mean value and amplitude value of time-series stress component is calculated by the rain-flow counting method. The fatigue damage D is defined as the sum of the quotients of existing load cycle number to permissible load cycle number N_i.

$$D=\sum_i \frac{n_i}{N_i} \tag{17}$$

To sum up, the proposed fatigue assessment method could be described by the flow chart shown in Fig. 9.

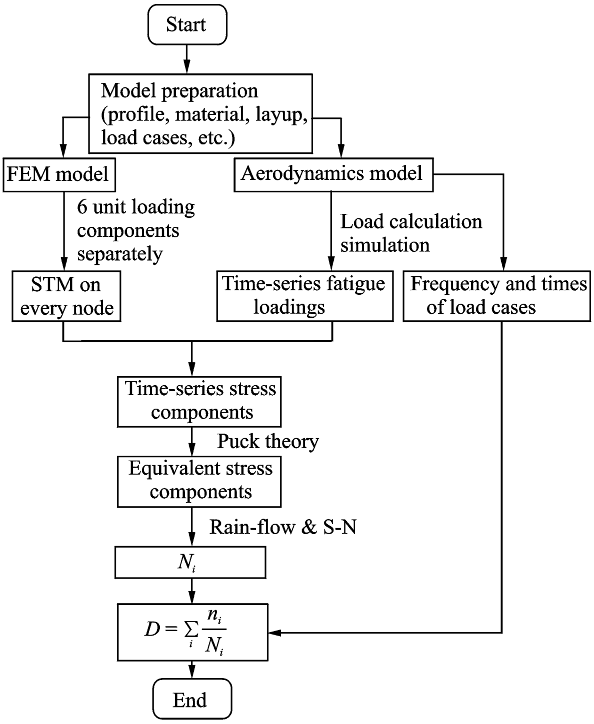


Fig. 9 Flow chart of fatigue assessment

3 Calculation Examples

According to the fatigue assessment method mentioned above, the fatigue damage of root section of a 2 MW-45. 3 m variable speed variable pitch wind turbine GFRP blade is estimated. Fatigue load cases are identified and loads are calculated by the GH bladed software, The wind speed is 6 m/s and keeps for 10 min and yaw angle is 0° in this load case. This load case will happen 70 931 times in 20 years. The time-series fatigue loadings of blade root section are shown in Fig. 3.

The pitch circle diameter of the blade root is 2. 2 m. The layup of the root contains 2-layer bi-axial as inner skin, 35-layer tri-axial as root reinforcement, and 2-layer bi-axial as outer skin. The material properties are shown in Table 1.

The FEM model of root section and its boundary conditions are shown in Fig. 10.

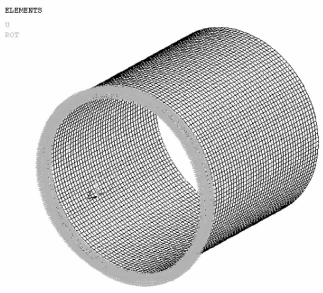
The stress transformation matrix of the first tri-axial layer on node No. 1290 is obtained by the aforementioned method as follows.

Table 1 FRP material properties

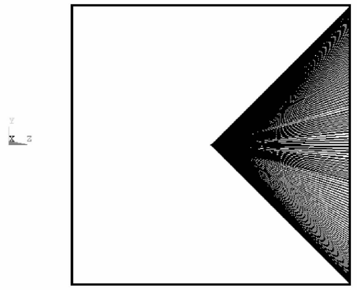
Composite	Configuration	E_1/MPa	E_2/MPa	v_{12}	G_{12}	Thickness/mm	$R_{k,t}$/MPa	$R_{k,c}$/MPa
Uni-directional	$[0]_T$	39 750	6 300	0. 282	6 200	0. 87	770	565
Bi-axial	$[+45/-45]_T$	11 400	11 400	0. 490	12 800	0. 514	—	—
Tri-axial	$[0/+45/-45]_T$	29 250	11 000	0. 300	6 200	0. 862	680	545

$$\boldsymbol{STM}(1\,290)=$$

$$\begin{bmatrix} -6.90\mathrm{E}-5 & -4.80\mathrm{E}-5 & 6.96\mathrm{E}-10 & 3.75\mathrm{E}-5 & -5.70\mathrm{E}-5 & 1.39\mathrm{E}-5 \\ -6.7\mathrm{E}-11 & -4.5\mathrm{E}-11 & 6.64\mathrm{E}-16 & 3.59\mathrm{E}-11 & -5.5\mathrm{E}-11 & 4.04\mathrm{E}-8 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 2.68\mathrm{E}-13 & -3.9\mathrm{E}-13 & 1.58\mathrm{E}-9 & 2.48\mathrm{E}-6 & 1.67\mathrm{E}-6 & -1.4\mathrm{E}-13 \\ 3.07\mathrm{E}-13 & -4.5\mathrm{E}-13 & 1.24\mathrm{E}-13 & -4.6\mathrm{E}-12 & 9.58\mathrm{E}-13 & 9.05\mathrm{E}-13 \\ -1.9\mathrm{E}-16 & -1.1\mathrm{E}-16 & 1.11\mathrm{E}-13 & -5.4\mathrm{E}-9 & 7.56\mathrm{E}-9 & 7.33\mathrm{E}-17 \end{bmatrix}$$



(a) FEM model



(b) MPC constraint

Fig. 10 FEM model of blade root section and MPC constraint

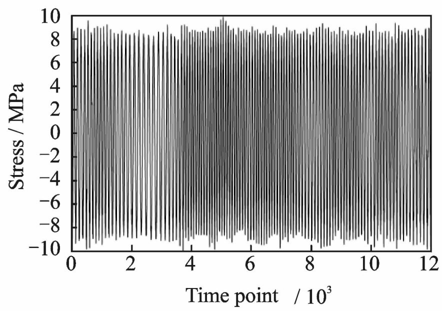


Fig. 11 Time-series stress component of the first triaxial on node No. 1290

For GFRP and laminates with the epoxy resin matrix, the slope parameter of the S-N curve is $m=10$. After getting the time-series stress component (see Fig. 11), the fatigue damage of this layer at the position of node No. 1290 is calculated by the rain-flow counting method and S-N curve. Under this load case, the total damage of this layer at the position of node No. 1290 in 20 years is $D=1.730\ 56\times10^{-10}$.

The total damage of the first layer and the last layer of root reinforcement is computed and compared with the result of FOCUS software under the same condition. They are shown in the radar chart in Fig. 12. The circumferential coordinate represents the position of the profile, and the radial coordinate is $\log_{10}(D)$. Since FOCUS gives multilayer equivalent results comprehensively, the results of FOCUS are between the result of the first layer and the last layer in the FEM-STM method which can calculate the result of each layer accurately.

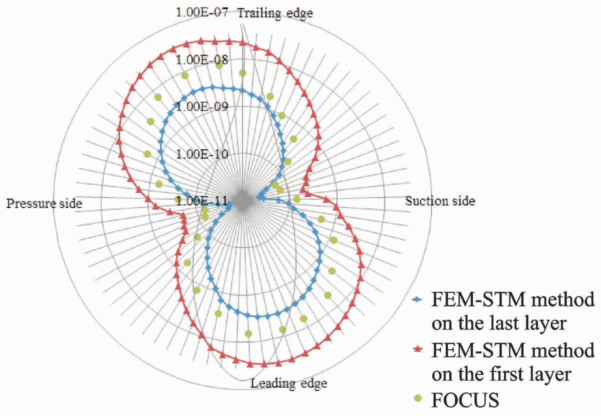
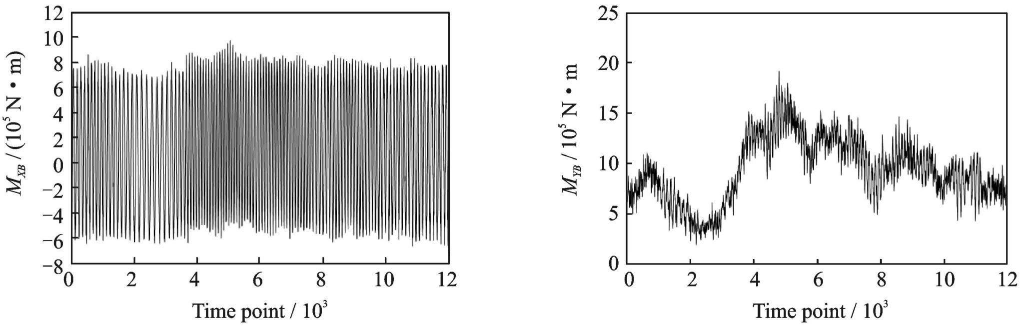


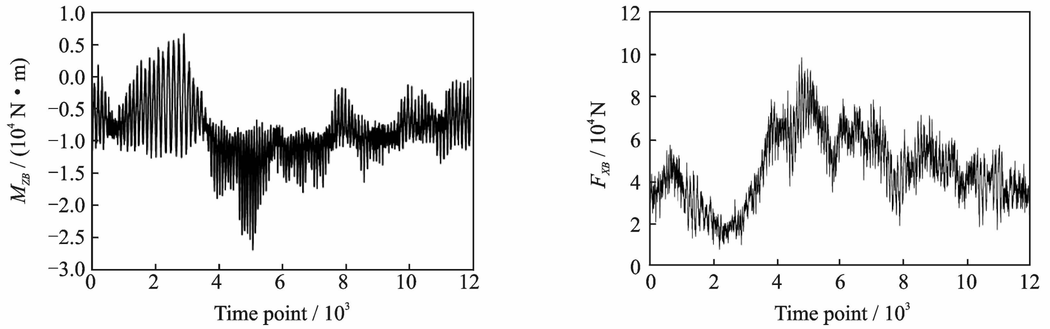
Fig. 12 Fatigue damage of blade root in radar chart

As another calculation example, the fatigue damage of a section which is 8.438 m away from root is estimated.

The fatigue loadings are shown in Fig. 13. The layup of 8.438 m section is shown in Fig. 14 in detail.

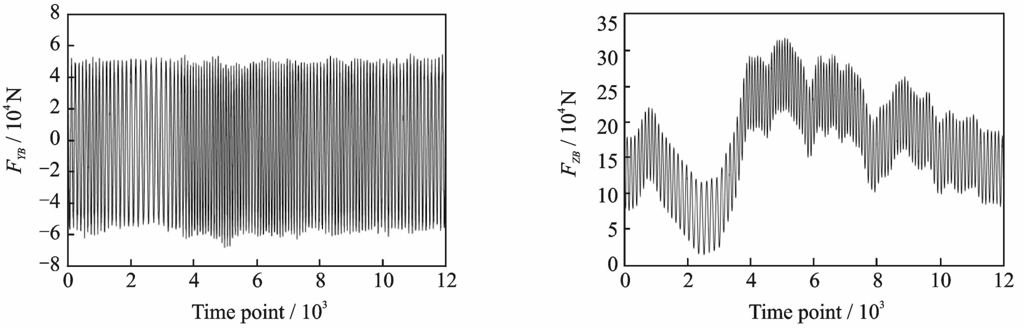


(a) Edge wise moment (b) Flap wise moment



(c) Torque

(d) Flap wise force



(e) Edge wise force

(f) Axial force

Fig. 13 Fatigue damage in radar chart

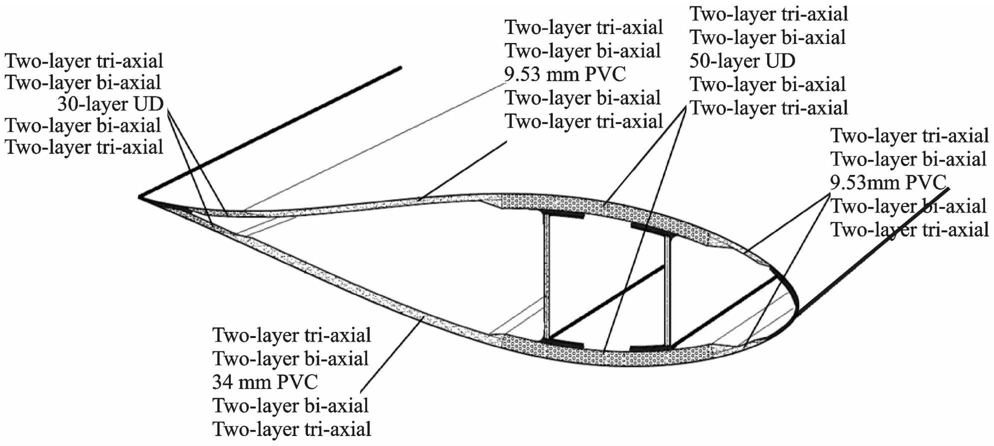


Fig. 14 Layup of 8.438 m section

The total damage of the first layer and the last layer of tri-axial is computed and compared with that of FOCUS under the same condition. They are shown in the radar chart in Fig. 15. From the simulation results, it is obvious that the damage of suction side is more serious than the damage of pressure side. The flap wise moment (M_YB) keeps positive in this load case. The suction side is working in the state of compressive and the pressure side is working in the state of tension. Nevertheless, the compression performance of the tri-axial laminate is weaker than the

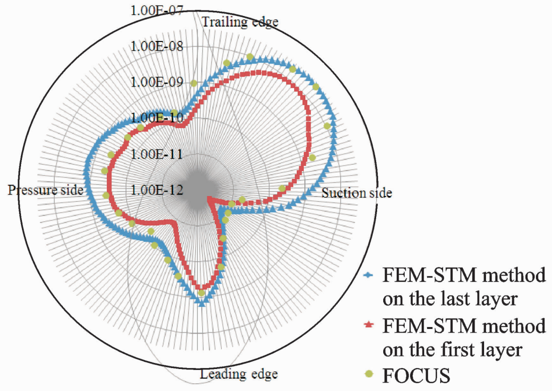


Fig. 15 Fatigue damage of 8.438 m section

tensile performance. This result is strongly in line with the theorized expectation. Because of trailing edge reinforcement layers, the tri-axial laminates of trailing edge have less damage than that of leading edge. Furthermore, the result also shows that the FEM-STM method has a consistent result with FOCUS.

4 Conclusions

Fatigue damage assessment is important in the wind turbine blade design. A practical engineering fatigue assessment method is proposed in this study. Different from other assessment methods, this method focuses on dealing with difficulty that the loadings along span-wise direction are changing constantly, and calculating the fatigue damage of laminates with multilayer of orthotropic materials. Obtaining STM is the key step in the method. The time-series stresses can be converted by STM from time-series fatigue loadings. Fatigue damage can be calculated by rain-flow counting method and S-N curve. Two calculation examples of a 2 MW-45. 3 m variable speed variable pitch wind turbine GFRP blade are estimated. Based on the comparison of the calculation examples, the accuracy of the proposed fatigue assessment method is verified. And the proposed method has better adaptability and the result can be obtained one layer by one layer. The proposed method gives a reliable and efficient method to analyze the fatigue damage of slender composite structure with variable cross-sections.

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Mr. **Chen Cheng** is a Ph. D. student of Nanjing University of Aeronautics and Astronautics (NUAA). His research interests lie in aerodynamics.

Dr. **Wang Tongguang** is the Director of Jiangsu Key Laboratory for Wind Turbine Design at NUAA. He was designated as the Chief Scientist of the "973 Program"by the Ministry of Science and Technology, China in 2007, and successfully completed the project "Fundamental Study of Large Scale Wind Turbine Aerodynamics". As the Chief Scientist again, he is now in charge of another project of the "973 Program"—"Key Mechanical Issues and Design of Large Scale Wind Turbines". Prof. Wang graduated from NUAA with B. S. degree and M. S. degree in 1983 and 1988, respectively, and he received his Ph. D. degree from the University of Glasgow in 1999 and has been a postdoctoral fellow at the University of Glasgow from October 1999 to August 2001. During this period, he was invited to join in the Wind Turbine Unsteady Aerodynamics Experiment — Blind Comparison, organized by the National Renewable Energy Laboratory (NREL) of USA. His paper "An examination of key aerodynamic modeling issues raised by the NREL Blind Comparison" was awarded The Best Paper Prize by ASME/AIAA in 2002.

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