Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 13 (10): 1895-1900, 2013
ISSN 1812-5654 / DOI: 10.3923/jas.2013.1895.1900

Mechanical Analysis of Fatigue Damages on Offshore Wind Turbine Blades

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Abstract: Aiming at the structural characteristics and main damage types, a fatigue damage model of blade was proposed based on theory of damage mechanics. Combining with Talerja vector damage model, a fatigue damage vector model of the interface and the single plate matrix and plane tense-strain constitutive relation was deduced on basis of fatigue damage of single plate. The analysis results of this model show that the single plate cracks first in 90° matrix, then 45° matrix and delamination appears at the 90/45° interface, finally fiber fracture occurs. Delamination is the dominate damage mode in high-circle fatigue. The results correspond well with experimental observation which proves the feasibility of this model. The evolution rule of fatigue damage was proposed to further explicate the fatigue damage mechanism of blades.

Keywords: Offshore wind turbine, blade, damage mechanics, fatigue

INTRODUCTION

With the worldwide rise of offshore wind farms and their increasingly large design scale, the analysis of the reliability of large scale wind turbines becomes more and more important. The blade of wind turbine is one critical part of wind-electricity system and covers about 20% construction cost of the whole system. The property, strength and rigidity of the blade are critical for the reliability of wind turbines (Xu and Zhang, 2009). The damage to the structure of wind turbines is inestimable once the blades broke down. In order to ensure the entire performance of offshore wind turbines, study of the damage mechanism of wind turbines under fatigue loads is significant for the structure-strength analysis and reliability design.

At present, at home and abroad, study of the fatigue damage of offshore wind turbine blades mainly concentrates on recognition and forecast of the damage (Li *et al*., 2012; Fu and Wang, 2011) while the mechanism is relatively less studied. In this study, a mechanic model for the fatigue damage of offshore wind turbines has been established by applying Talerja vector damage theory on basis of analyzing main types of damages to offshore wind turbine blades. On basis of this model, the fatigue damage mechanism was discussed which provides a theoretical principle for recognition and monitoring of fatigue damage of offshore wind turbine blades.

ANALYSIS OF FACTORS THAT DAMAGE BLADES OF OFFSHORE WIND TURBINE

Environmental factors: After about two years' service, pocked surface of blades form due to sand pumping grinding. Combination of electrostatic dust and salt dog gives rise to black strips on blade surface. Edges of blades are corroded by salt fog which leads to weathering phenomenon. One more year later, blades will change into bright black strips and blocks in heavy salt fog affected areas. Edges of blades are corroded by salt fog and lose solid adhesion ability. While many potential cracks exist at tips of blades. After about four years, due to high temperature and high humidity of salt fog, the protective film of blade ridge begins to age. Solid adhesion ability of blade tips decreases to minimum and the surface complex material of blades are saturated by salt fog. Tips and edges of blades can be cracked, torn and damaged by these surrounding factors.

Structural factors: Requirements for blades of wind turbines are higher at sea than at land. More and more sandwich structures are applied to design of offshore wind turbine blades which enhances solidity, fatigue property and anti-corrosion performance. The typical sandwich structure is shown in Fig. 1. Main damage types of this structure are listed in Table 1 (Ciang *et al*., 2008; Sundaresan *et al*., 2002; Sorensen *et al*., 2002) and shown in Fig. 2 (Ciang *et al*., 2008; Sorensen *et al*., 2004).

The function of the skin is to mainly supply aerodynamic contour and bear partly bending loads and most shear loads. The sandwich structure of the skin includes gel coat, glass fiber mat reinforced layer and the strength layer. The gel coat supplies a smooth aerodynamic surface which enhances the aerodynamic performance of blades. The glass fiber mat layer acts as a buffer layer between the gel coat and the strength layer. The strength layer acts as the load-bearing layer which is strengthened by bi-directional glass fiber fabric to

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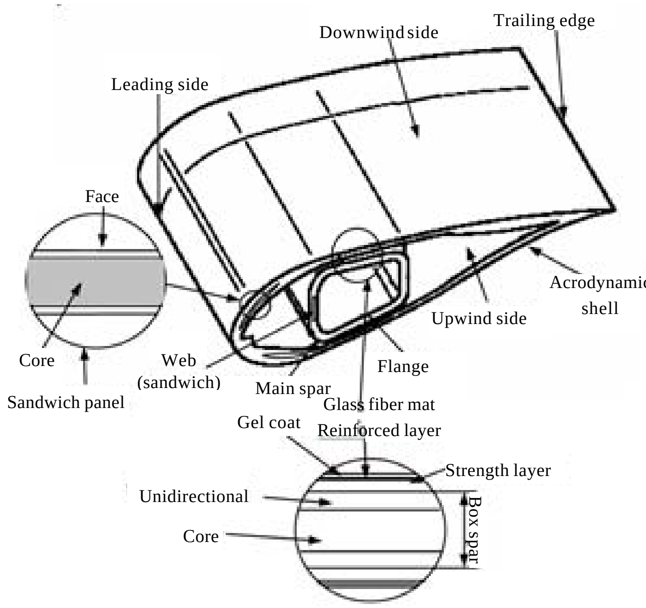

Fig. 1: Structure of blade

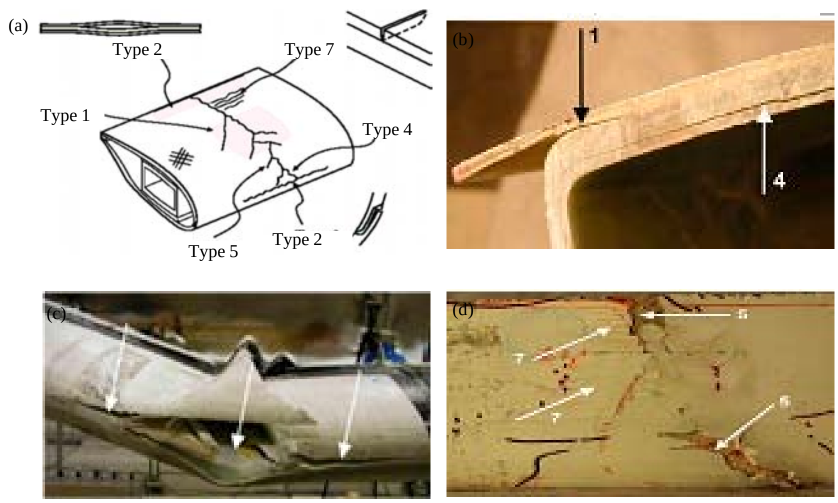

Fig. 2(a-d): Damage type of wind turbine blades (Ciang *et al*., 2008; Sorensen *et al*., 2004), A sketch illustrating some of the common damage types found on a wind turbine blade, (b) Damage type 1 (main spar flange/adhesive layer debonding) and type 4 (delamination by buckling load), (c) Damage type 2 (adhesive joint failure between skins) at the leading edge and (d) Damage type 5 (laminate failure in compression) and type 7 (gel-coat cracking) at the bottom of the leading edge

improve the shearing strength of the skin. A sandwich structure is applied to the trailing edge of the skin, whose inner surface is also strengthened by bi-directional glass fiber fabric in order to improve buckling instability of the rear vierendeel structure.

The main spar is the main load-carrying structure which bears most bending loads of blades. It is a box spar glued to both the upper and lower skins. The cross section of a blade is divided into three rooms by the box spar which occupies the middle room consisted of 70% single directional glass fiber fabric and 30% bi-directional glass fiber fabric spread alternatively to enhance the integrity of the layers. A sandwich structure is applied to the spar web in order to strengthen the rigidity of the spar web and the rigidity of the blade in chord wise.

Table 1: Typical damage of wind turbine blades (Ciang *et al*., 2008; Sorensen *et al*., 2004)

Type	Description
1	Damage formation and growth in the adhesive layer joining skin and main spar flanges(skin/adhesive debonding and/or main spar/adhesive layer debonding)
2	Damage formation and growth in the adhesive layer joining the up-and downwind skins along leading and/or trailing edges (adhesive joint failure etween skins)
3	Damage formation and growth at the interface between face and core in sandwich panels in skins and main spar web (sandwich panel face/core debonding)
4	Internal damage formation and growth in laminates in skin and/or main spar flanges, under a tensile or compression load (delamination driven by a tensional or a buckling load)
5	Splitting and fracture of separate fibres in laminates of the skin and main spar(fibre failure in tension; laminate failure in compression)
6	Buckling of the skin due to damage formation and growth in the bond between skin and main spar under compressive load (skin/adhesive debonding induced by buckling, a specific type 1 case)
7	Formation and growth of cracks in the gel-coat; debonding of the gel-coat from the skin(gel-coat cracking and gel-coat/skin debonding)

As shown in Fig. 2 and Table 1, the main damage types of offshore wind turbine blades include matrix cracking, firber fracture, interfacial debonding and delamination.

MECHANICAL ANALYSIS OF DAMAGE MECHANISM ON OFFSHORE WIND TURBINE BLADE

The offshore wind turbine blade has a thin shell structure composed of layers of glass fiber reinforced plastic or carbon fibers glued to matrix (resin fibers). The number of layers in the shell is large up to 30 and at least 10. But the single layer only has four types, among which the matrix material and the fiber type are the same. The difference exists only in fibers' formation or direction (Fu and Wang, 2011). The common layer in the shell is composed of ±45° fiber fundamental complex pressed layers and layer-plates (along longitudinal direction of blades). The master pressed layer and the reinforced pressed layer are both 0° single directional fibers. Seen from the types and directions of single layer fibers, the difference between layers is small. That is the interactions between layers are weak. Thus the damage of the whole blade originates mainly from the damage of a single layer. While the material of a single layer appears isotropic at transverse scale and its damage happens mainly at the matrix and the interface where fibers are glued to the matrix.

Mechanical analysis of fatigue damage to the single plate matrix: The resin matrix of single plates presents mainly transverse mechanical properties. The fiber reinforcement mainly affects the longitudinal mechanical properties of complex materials. When imposing transverse pressed loading, cracks appear in matrix leading to damage of blades. In addition, due to corrosion of salt fog caused by the pumping grinding of sandstorm, crazes appear in the inner part of materials which makes the physics properties of materials deviate into the anisotropic viscoelastic law. The strain-softening phenomenon will appear in the stress-strain curve when the stress gets to the threshold. Coordinate system is set as follows: direction parallel to fiber is axis 1, direction normal to fiber is axis 2, outer direction normal to the layer axis 3. The damage mode of matrix a = 1. According to Talerja vector damage model(Talerja, 1987a; Talerja, 1989), the damage vector is:

$$D^{(1)} = D^{(1)}n^{(1)} \tag{1}$$

$$[D^{(1)}]^2 = \frac{Kt_c^2}{ts\cos\theta} \tag{2}$$

In Eq. 1, $D^{(1)}$ is the a=1 damage vector with respect to the crack plane, $n^{(1)}$ the a=1 orientation unit vector normal to the crack plane. In Eq. 2, K is a constant, t_c the thickness of the damaged layer, s the average spacing of cracks in the longitudinal direction of the matrix, θ the angle between the crack plane and the direction normal to the fiber.

Combing Eq. 1 and 2, components of damage vector $D^{(1)}$ can be obtained:

$$\begin{aligned} D_1^{(1)} &= t_c\sqrt{\frac{K\cos\theta}{ts}} \\ D_2^{(1)} &= t_c\sin\theta\sqrt{\frac{K\cos\theta}{ts}} \\ D_3^{(1)} &= 0 \end{aligned} \tag{3}$$

Seen from Eq. 3, matrix damage cracks can be divided into two types in accordance with directions. One is parallel to the fiber direction, the other is normal to the fiber direction. For the first type, the matrix crack parallel to the fiber originates from the large shearing stress normal to the fiber which is caused by the variation of layer-up angle and the inhomogeneous in-plane rigidity between adjacent layers when loads are imposed on the complex material layer-up plates of wind turbines. The second type of matrix crack originates from the in-plane shearing stress normal to the fiber and the inter-layer shearing stress. When transverse alternative load is imposed on the complex material layer-up plate, the maximum tensile stress will be produced parallel to the fiber while the maximum normal stress will be produced normal to the fiber which makes the crack open parallel to the fiber and propagate in the direction normal to the fiber and leads to the departure of fibers from the matrix when reaching the threshold.

Mechanical analysis of the fatigue damage on the interface: The interfacial damage is also an important form of damages to the complex material layer-up plates of wind turbines. According to the Talerja vector damage model, with the same coordinate system setup in section 2.1, set the interfacial damage mode a = 2, then the damage vector is:

$$D^{(2)} = D^{(2)}n^{(2)} \tag{4}$$

$$[D^{(2)}]^2 = \eta q a^3 \tag{5}$$

In Eq. 4, $D^{(2)}$ is the a = 2 damage vector with respect to the crack plane, $n^{(2)}$ the a = 2 orientation unit vector normal to the crack plane. In Eq. 5, ç is the density of cracks(number of cracks in unit volume), q a constant, a the average value of diameters of circular cracks.

Combing Eq. 4 and 5, components of damage vector $D^{(2)}$ can be obtained.

$$\begin{aligned} &D_1^{(2)} = 0 \\ &D_2^{(2)} = 0 \\ &D_3^{(2)} = \sqrt{\eta q a^3} \end{aligned} \tag{6}$$

Seen from Eq. 6, the interfacial damage is the result of the propagation of matrix cracks to the interface. After the generation of a damage crack in some layer of matrix in the blade, this matrix crack will further propagate propelled by the in-plane normal stress and the inter-layer shearing stress. The layer-up interfacial constrains lead to the increase of the in-plane normal stress and inter-layer shearing stress which further causes the propagation of the matrix crack. Repeatedly in this way, a delamination damage will appear when reaching the threshold.

Seen from the common results of both Eq. 3 and 6, the single plate cracks first in 90° matrix, then 45°matrix and delamination appears at the 90/45° interface, finally fiber fracture occurs. Delamination is the dominate damage mode in high-circle fatigue which corresponds well with experimental observation results.

Constitutive relation of stress-strain about fatigue damage: Local coordinate is set as follows: the direction parallel to fiber is axis1, the direction normal to fiber axis2, outer direction normal to the layer axis 3. For the single plate of the wind turbine blades, made of macroscopic isotropic complex material with damage cracks as defects, the Talreja two order symmetric tensor was used to describe the damage, based on a determining method of n vector polynomial with integral base vectors proposed by Pipkin and Rivlin. For the complex material layer-up plate, it's a planar strain (planar stress) problem and its fixed base vectors are:

$$\begin{aligned} &\varepsilon_{11}, \varepsilon_{22}, \varepsilon_{23}^2, \varepsilon_{12}\varepsilon_{21}, \varepsilon_{12}\varepsilon_{23}\varepsilon_{31} \\ &D_1^{(1)}, D_2^{(1)}\varepsilon_{21}, D_2^{(1)}\varepsilon_{23}\varepsilon_{31}, D_2^{(1)}D_2^{(2)}, D_2^{(1)}\varepsilon_{23}D_3^{(2)} \end{aligned} \tag{7}$$

As for the single damage vector D, on small strain condition, the elastic potential energy of transverse isotropic material is:

$$\begin{aligned} W &= W^0 + W^1 \\ W &= W(\boldsymbol{\varepsilon}, D^{(a)}) \end{aligned} \tag{8}$$

According to the strain Eq. 9:

$$\sigma = \frac{\partial W}{\partial \varepsilon} \tag{9}$$

And apply Voigt signs, thus the stress can be expressed:

$$\sigma_p = (C_{pq}^0 + C_{pq}^1)\varepsilon_q \tag{10}$$

In Eq. 10, the coefficient matrix $[C_{pq}^0]$ is the coefficient symmetric matrix of undamaged material and $[C_{pq}^1]$ is the coefficient matrix of damaged material.

For the problem of the matrix cracking normal to the fiber direction in the single layer plate of wind turbine blades, the damage vector $D = D_p(0, 1, 0)$, the effects of this type of cracks on the rigidity in the axis 2-axis 3 plane can be neglected due to the fact that these cracks are parallel to the plane of axis 2 and axis 3. As for the problem of the matrix cracking parallel to the fiber direction, the damage vector $D = D_p(0, 1, 0)$, the effects of this type of cracks on the rigidity in the axis 1-axis 3 plane can be neglected due to the fact that these cracks are parallel to the plane of axis 1 and axis 3. Set $\boldsymbol{\sigma}_3 = 0$, then the planar stress-strain constitutive relation applying for the matrix cracking damage in single-layer plate is:

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_6 \end{Bmatrix} = [C_{pq}^0 + C_{pq}^1] \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_6 \end{Bmatrix} \tag{11}$$

where the undamaged rigidity matrix $[C_{pq}^1]$ is:

$$\begin{aligned} &C_{11}^0 = 2A_1 \\ &C_{12}^0 = C_{21}^0 = C_{13}^0 = C_{31}^0 = A_2 \\ &C_{22}^0 = 2(B_1 + C_1) = C_{33}^0 \\ &C_{23}^0 = C_{32}^0 = 2B_1 \\ &C_{44}^0 = 2C_1 \end{aligned}$$

$$C_{55}^{0} = C_{66}^{0} = G_1$$

The left coefficient equal to zero.

That is:

$$[C_{pq}^{0}] = \begin{bmatrix} 2A_1 & A_2 & 0 \\ & 2(B_1 + C_1) & 0 \\ & & G_1 \end{bmatrix} \quad (12)$$

For the crack damage normal to the fiber, the elastic rigidity matrix of the planar stress constitutive relation equation:

$$[C_{pq}^{1}] = \begin{bmatrix} 2A_3D_N^2 & A_7D_N^2 & 0 \\ & 2(B_2 + C_2)D_N^2 & 0 \\ & & \frac{1}{2}G_2D_N^2 \end{bmatrix} \quad (13)$$

For the crack damage parallel to the fiber, the elastic rigidity matrix of the planar stress constitutive relation equation:

$$[C_{pq}^{1}] = \begin{bmatrix} 2A_5D_P^2 & (A_6 + A_8)D_P^2 & 0 \\ & 2(B_4 + B_5 + C_3)D_P^2 & 0 \\ & & \frac{1}{2}(G_3 + F_1)D_P^2 \end{bmatrix}$$

Seen from Eq. 12 and 13, the two matrixes have an identical form which implies that the elastic behavior of the material still has macroscopic isotropic properties. That is, cracks normal to fibers have no effects on material properties. While the coefficient matrix in Eq. 14 has the same form with the coefficient matrix of orthogonal materials which implies that the elastic behavior of the material has no more transverse isotropic properties, that is, cracks parallel to fibers' direction will change macroscopic isotropic properties of materials into orthogonal anisotropic properties.

MECHANICAL ANALYSIS OF DAMAGE EVOLUTION RULE OF OFFSHORE WIND TURBINE BLADES

The layer-up manner of off-shore wind turbine blades is generally 1-2 layers of short-cut mat, 1-2 layers of 90°single directional cloth, 1 layer of ±45° bi-axis cloth and the left are all 0° single directional cloth. The 0° single directional layer has strong constrains on the non-zero degree directional layer which can decrease the property differences of different layers and strengthen the non-zero degree directional layers (Talerja, 1987b). Thus, it's feasible to use the damage rule of single layer plate to forecast the fatigue damage of the whole blade. So set the damage variable of single layer plate as:

$$D = (A - \tilde{A})/A \quad (15)$$

In Eq. 15, A is the initial undamaged area and $\tilde{A}$ is the reduced effective load-carrying area.

In high-circle fatigue, the main damage mode is delamination. Thus the effective elastic modulus caused by delaminaton damage is:

$$E = E_0 + (E^* - E_0)(A - \tilde{A})/A \quad (16)$$

In Eq. 16, E_0 is the elastic modulus of the undamaged layer-up plates and E^* is the elastic modulus of the layer-up plates with total delamination.

After total delamination, the elastic modulus of offshore wind turbine blade plates with total delamination can be obtained according to the layer-up theory:

$$E^*/E_0 = 0.65 \quad (17)$$

Combining Eq. 15-17, the evolution rule of damage can be obtained:

$$dD/dN = \frac{-2.857}{E_0} dE/dN \quad (18)$$

In Eq. 18, N is the load circle number.

CONCLUSION

- According to the structure of offshore wind turbine blades and the layer-up characteristics of the shell, it can be drawn that: the damage of the whole blade shell is mainly caused by the damage of single-layer complex material. While the materials in single-layer plate present isotropic properties and the main damages happen in the matrix and at interfaces where fibers are glued to the matrix. It's feasible to use the damage rule of single layer plate to forecast the fatigue damage of the whole blade
- Seen from the fatigue damage vector model of the matrix and the interfaces in the single-layer plate, the matrix damages are mainly due to the matrix cracks parallel to the fiber direction caused by the shearing stress normal to the fiber direction. The departure of fibers from the matrix originates from the in-plane shearing stress normal to the fiber and the inter-layer shearing stress while the interfacial damage is the result of the propagation of the matrix crack to the

interfaces. And the single plate cracks first in 90° matrix, then 45° matrix and delamination appears at the 90/45° interface, finally fiber fracture occurs. Delamination is the dominate damage mode in high-circle fatigue which corresponds well with experimental observation results

- Seen from the planar stress-strain constitutive relation of the fatigue damage of single-layer plate, cracks normal to fibers have no effects on material properties. While cracks parallel to fibers' direction will change transverse isotropic properties of materials into orthogonal anisotropic properties.

ACKNOWLEDGMENT

This study was supported by universities in jiangsu province natural science research project funding (10KJB480003). This work was also supported by Jiangsu photon manufacturing science and technology key laboratory open fund project (GZ201103).

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