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Network Study of Plant Leaf Topological Pattern and Mechanical Property and its Application[1]

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Abstract: In order to explore the compliance structure and adaptability of the vein pattern of plant leaf, five fresh and mature leaf samples, which represent the typical leaf network in nature, are collected, and the finite element model of the samples are established and simulated. The results show that the topological pattern of plant leaf is self-adaptive to the multi-load fields. When considering the change of wind loads, it is found that the main vein consistently remains unchanged, and the lateral vein changes slightly along different wind load direction. Inspired by the similar work environment and structure, the bionic methodology of wind turbine blade is developed in this paper. Firstly, the wind turbine blade structure is optimized by using SIMP method. The results indicate that material distribution of wind turbine blade is similar to the leaf vein, where, the spar cap of the blade is equivalent to the main vein of leaf, and the skins are correspond to the lateral vein of leaf. Secondly, considering the similar stress environment, such as random wind loads, rain, snow, and self-weight, the topology structure of wind turbine blade was decided by referring the natural structure. Finally, the bionic method is used to design the spar cap region of the blade. The results show that the best fatigue life appears in blades with the ply angle in the range between 45° and 65°. It is not only coincident with the side vein angle of most plant leaves, but efficiently improves the blade fatigue performance.
Keywords: Plant Leaf; Medial Axis; Self-Adaptability; Wind Turbine Blade; Bionic Design

1. INTRODUCTION

The natural plant leaf endures wind loads throughout the year or years, which brings up good compliance and wind resistance. The network of plant leaf is not only unique but also general characteristics in biology

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organization (Blum & Nagel, 1978). It was studied that the vein pattern of plant leaf not only plays a role in transmitting humoral, but also the major structural element that enables the plant leaf to stand the self-weight and the environmental stress. The work in this paper has made a confirmation that the organization structure has direct relation with the environmental stress.

Sarikaya et al. (Sarikaya et al., 1990) and Gordon et al. (Gordon & Jeronimidis, 1980) investigated the biologic composite material and performance, and concluded that the organisms optimized themselves in structure, shape and function through long-term evolutionary process. Steele (Steele, 2000) and Somerville et al. (Somerville et al., 2004) proved that the biology shape and structure had direct relation with the environmental stress by means of mechanics method. The work of Jones et al. (Jones & Platts, 1998) showed that the optimized structure of biological organization is similar to Michel's truss structure, and matched the principal stress path. Liu Wangyu et al. (LIU et al., 2007; LIU et al., 2009) utilized a group of samples made of copper fibres which imitated the vein distribution of leaf to explore the effect of vein angles on the mechanical performances when considering the angles change between random wind loads and main vein in vertical plane through experimental and numerical method.

Wind turbine blade is one of the most important components in the whole wind machine system. With the time being, big size wind turbine blade becomes the main stream (Simon & Geir, 2009). How to reduce the influence of random wind loads on wind turbine blade, prolong the blade life, broaden the running time, and increase the efficiency of capturing wind energy, has become the developing trend of wind turbine blade design.

Compliant structure design has been regarded as an efficient method to solve the problems mentioned above. Andrew et al. (Andrew & Richard, 1999) investigated the capability of a 50 kW wind turbine to automatically adjust the power output in gusts by feathering the blade. The result showed that the maximum twist rate obtained is up to 1.25 degree per meter based on a 0.136m per meter flapwise deflection rate, which were insufficient for power control by feathering. Lobitz et al. (Lobitz & Veers, 1998) made a study by combining theoretical derivation with beam element coupling theory and the result was proved by using combined experiment blade. Lobitz et al. (Lobitz et al., 2001) continued his study in 2001. This time, they made a detailed report to verify the bend-twist effect on energy production or load mitigation for 300KW blade, and found the coupling blade could capture extra energy between 5% and 10% depending on twist coupling parameters and inflow environments.

The authors noticed that there were some similarities between the wind turbine blade and plant leaf in performance requirement and environmental stress. For example, the plant leaf could self-adjust its position in the air to balance the wind load when it runs up against high wind or gusts. This behavior is quite similar to the bend-twist coupling response in designing compliant wind turbine blade. Whereas, how could wind turbine blade imitate the plant leaf, and how to evaluate the bionic result need systematic investigation. The initial study about the bionic methodology is carried out in this paper.

2. MECHANICAL PROPERTY AND BIONIC STUDY OF COMPLIANCE STRUCTURE OF PLANT LEAF

2.1 Sample preparation and measurement method

In order to explore the compliance structure and adaptability of the vein pattern of plant leaf, five fresh and mature leaf samples, which represent the typical leaf network in nature, are collected. Five samples, which are ficus altissima, pineapple, kemirinoten, madagascar palm, ficus viren, and royalplam are picked in the campus shown in Fig. 1. Royalpalm and madagascar palm are monocotyledons plants with parallel pulse, the others are dicotyledonous plants with network veins. Royalplam is one of the most wind resistant plant in offshore, whereas, ficus viren has poor ability in carrying high wind load. In addition to the different abilities in carrying loads, the five plants are also quite different in thickness, shape outline, leaf texture and vein distribution. Therefore, the samples chosen are representative.

Fig. 1 (a) Ficus altissima

Fig. 1 (b) Kemirinoten

Fig. 1 (c) Madagascar

Fig. 1 (d) Ficus viren

Fig. 1 (e) Royalplam

Fig. 1: Five fresh plant leaves

For each kind of plants, 15 fresh samples with similar shape and size are collected. Firstly, a digimatic calliper is used to measure the leaf thickness. As the actual thickness of plants leaf is different from the root to the tip, the thickness measured was processed into an average value along the leaf spanwise direction. Secondly, in order to prevent the water loss of leaf from influencing the density result, the leaves with the polythene bags on are placed in the refrigerator, and keep the refrigerator temperature around 4℃. Before experiment, the leaves are wiped dry and each leaf mass is measured by using electronic balance with the accuracy of 0.001g. Finally, the mechanical performances are measured on a universal material tester, shown in Table 1.

Table 1: The material property of the plant leaves

Property	Symbol	Ficus altissima	Pineapple	Kemirinoten	Ficus viren	Royalplam
Thickness	$T\ (mm)$	0.43±0.023	0.37±0.029	0.29±0.016	0.17±0.019	0.25±0.029
Density	$\rho\ (kg/m^3)$	55.87±7.63	63.05±19.44	40.23±5.11	703.9±37.4	0.25±0.029
Mesophyll modulu	$E_m\ (MPa)$	55.87±7.63	63.05±19.44	40.23±5.11	45.31±10.14	938±120.24
Leaf vein modulu	$E_v\ (MPa)$	229.7±55.13	199.9±35.85	157.6±28.70	99.8±33.82	4833±913.93
Possion ratio[13]	ν	0.33	0.33	0.33	0.33	0.33

2.2 Numerical simulation and topology optimization of the samples

LH65 WENZEL trilinear coordinates measuring instrument is used to measure the plant leaf data. In this study, only the coordinate data of the main vein and lateral vein in the setup system are measured, meanwhile the minor veins are ignored, considering that it plays an insignificant role in the mechanical performances. In order to build the leaf mechanical model, the practical leaf structure is simplified. In practice, the cross section and thickness of the veins becomes smaller from the root (or the medial axis) to the tip (or the leaf rim). In this paper, the cross-section is hypothesized as round shape, and the outer diameter changes from the maximum to the minimum with linear function, whilst, the thickness keeps the same. The geometry model of leaves is built with the tool of ANSYS APDL, which are shown in Fig. 2. Then, the model is imported to the commercial software Hypermesh to make the topology optimization. The target function is the minimum weighted compliance, and the constraint equation is volume fraction, which is set to be 0.3. In addition, the leaves are assumed to withstand loads from different directions, such as wind loads, rain and gravity. The topological optimum results are showed in Fig. 3.

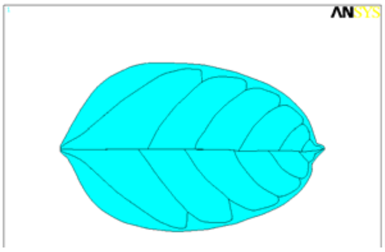


Fig. 2 (a) Ficus altissima

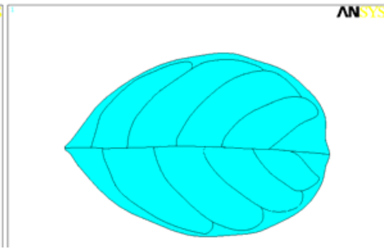


Fig. 2 (b) Kemirinoten

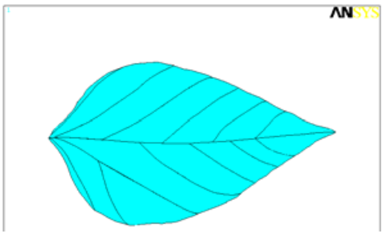


Fig. 2 (c) Madagascar palm

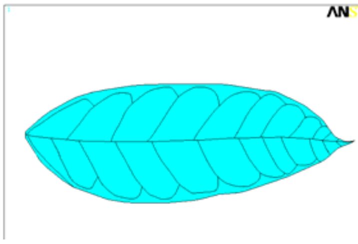


Fig. 2 (d) Ficus viren

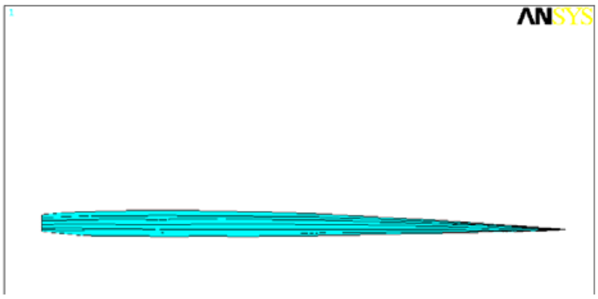


Fig. 2 (e) Royalplam

Fig. 2: The geometry model of five plant leaves

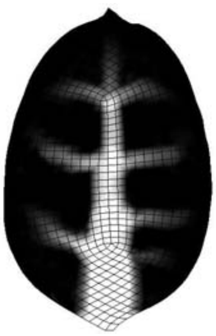


Fig. 3 (a) Ficus altissima

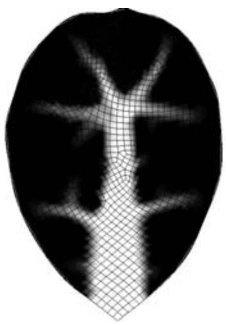


Fig. 3 (b) Kemirinoten

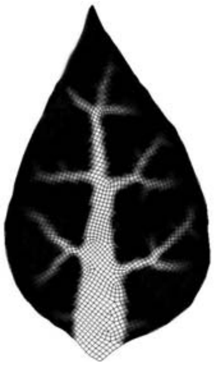


Fig. 3 (c) Madagascar palm

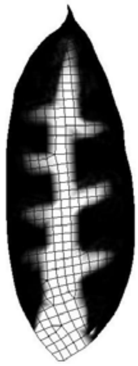


Fig. 3 (d) Ficus viren

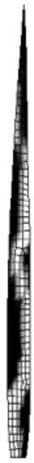


Fig. 3 (e) Royalplam

Fig. 3: Topological structure of five plant leaves

The results show that the topological structure of plant leaf is similar to the natural vein network in the multi-load fields. The main vein consistently remains unchanged, the lateral vein changes slightly along different load direction, which shows that the vein network of leaf has robust adaptability. The analysis shows that the plant leaf helps to keep the internal strain energy at a small value, and the environmental stress is one of the inducing factors for vein growth. It deserves to notice that the vein network of the plant leaf not only lends itself the physiological functions but also adapts to the complex environmental stress by evolving itself into a steady network pattern.

3 BLADE OPTIMIZATION FOR WIND TURBINE

The baseline blade is originally developed by institute of renewable energy research of Shan Tou University for 1.5 MW wind turbine, which is illustrated in Fig. 4. The length of the blade is 34m, and the airfoils are derived from Wortmann FX77/79Mod airfoil series, where the first airfoil profile position begins at 8.15m from root part, whose detailed profile parameters and design operating case have been thoroughly documented in Ref (HAN, 2008). In order to prevent big deformation of blade tip from influencing the accuracy of calculation, the tip part is magnified slightly.

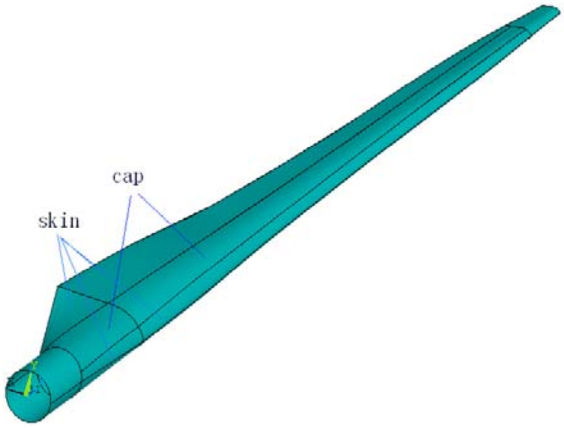


Fig. 4: 1.5MW blade model

We select the blade segment from 12 to 20m along the blade spanwise direction, and suppose this part is made of homogeneous material. The finite element model of the blade is established in HyperMesh, where, PSOLID elements and Solid Isotropic Material with Penalization (SIMP) method are used for structure topology optimization. The target function is the minimum weighted compliance, and the constraint equation is the volume fraction, which is set to be 0.3. Topological optimization results are shown in Fig. 5 with the load of critical wind of 50 m/s and gravity. As shown is Fig.5, the blade topological structure suggests a rough impression of the blade material distribution, which are, the cap, web and skin. If the blade topology pattern compares with the plant leaf, much more clear impression could be achieved, shown as Fig. 6. The blade spar cap and webs correspond to the main vein, and the blade skin corresponds to the lateral vein, which would change with the wind load direction.

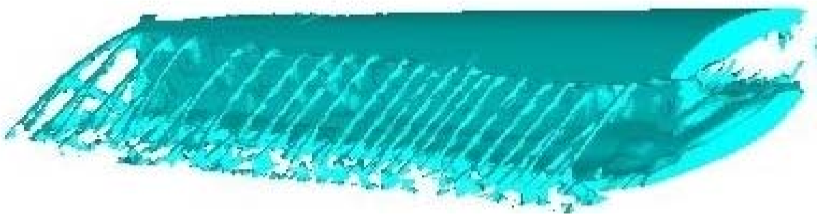
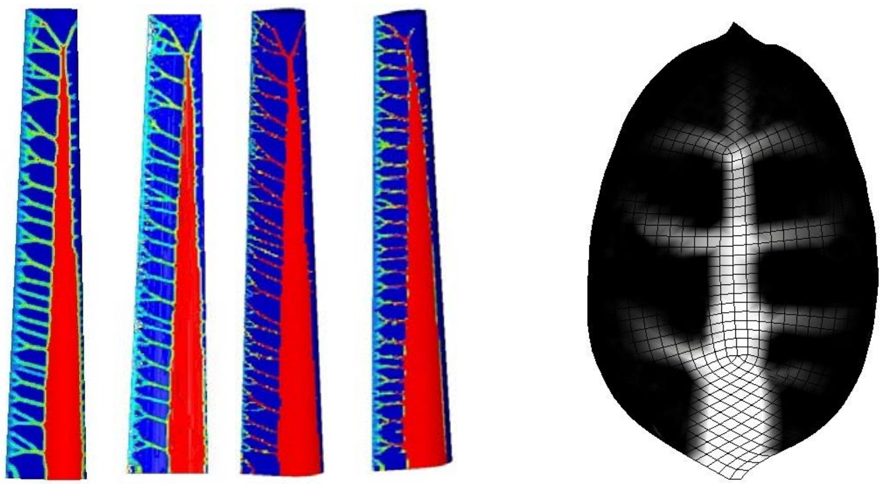


Fig. 5: Blade topology optimization result



30° 45° 60° 90°

Fig. 6 (a) Blade topology result

Fig. 6 (b) Plant leaf topology result

Fig. 6: The blade and plant leaf topology pattern under multi-load cases

Wind turbine blade and plant leaf are similar in the configuration and stress environment and so on (LIU et al., 2009). On the one hand, the shape of blade is similar to the plant leaf; on the other hand, both of the leaf and the wind turbine blade are working in the same stress environment suffering the random wind loads and rain and so on. As the vein network of plant leaf exists everywhere for every kind of plants leaves, the bionic design methodology can be developed for wind turbine blade design.

4. BIONIC DESIGN OF WIND TURBINE BLADE

Majority of wind turbine blades are made of FRP composite material, sometimes, mixed with carbon fiber. Wind turbine blades are the key component of wind power system. Blade structure determines the performances of wind machine, that is, blade strength, stiffness and fatigue performances mostly decide the reliability of wind machine. Therefore, blade design and manufacturing technology are regarded as the key technology of wind power generation system.

The structural design of wind turbine blade involves the proper selection of some important parameters, such as the material type, the blade shell thickness, the fibers orientation and ratio in blade skin, spar caps and stiffen webs. Many literatures discussed the influence of some parameters on the blade performances (Lobitz & Veers, 1998; Lobitz et al., 2001; LI, 2008; LIU et al., 2010). With the blade size increasing, the kind of adaptive blade achieved through twist-flap coupled design is becoming the developing trend. Although some individual performances of the adaptive blade, such as stress and strain, can be improved through twist-flap coupled design, the blade comprehensive performances, such as the fatigue and reliability performances, have not been discussed yet.

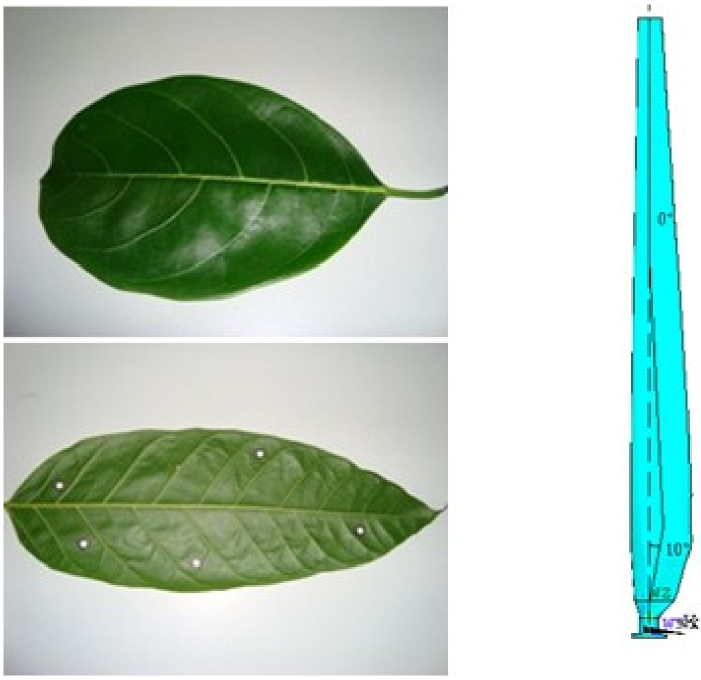


Fig. 7: The similarity between plant leaves and wind turbine blade

It is of indubitability that the most adaptive structure in the world comes from natural design. The authors were highly inspired by the similar cantilever structure between plant leaf and wind turbine blades, shown in Fig.7, as well as the similar stress environment. Therefore, it could be expected that wind turbine blade imitating the plant leaf structure could have the excellent adaptive performance. The main work of this paper mainly focuses on the fiber orientation design imitating the plant leaf skeleton. As it is known that different plant leaves have different morphological structure and side vein angles, in order to explore which leaf skeleton pattern are more suitable for the requirement of wind turbine blades, different plying angles changed in the range of [0,90] are chosen to make the fatigue calculation. Referring literature (LIU et al., 2009), the particular angle 20° is specially considered. The bionic angles, calculated from the medial axis of the blade, shown as Fig. 7, are [10°/0°]. In this paper, the stiffen spar is chosen as the design region. The FRP material parameters are listed in Table 2.

Table 2: Mechanical properties of involved materials of the blade

Material Parameters	Units	Values
E_x	Gpa	42.6
E_y	Gpa	9.5
E_z	Gpa	9.5
G_{xy}	Gpa	5.857
G_{yz}	Gpa	5.857
G_{xz}	Gpa	5.98
μ_{xy}	/	0.3
μ_{yz}	/	0.3
μ_{xz}	/	0.3
ρ	kg/m^3	1600

5. FATIGUE PERFORMANCE FOR BIONIC WIND TURBINE BLADE

5.1 The fatigue theory of FRP

Being different from common metal material, FRP material has no obvious fatigue limit stress. In this case, the stress sustaining 108 cycles were thought to be the fatigue stress and it is estimated to be a straight line for $S - \lg N$ fatigue curve of FRP.

$$a\sigma_i + \lg N_i = b \tag{1}$$

In Eq. (1), $b = \sigma_b / B$, σ_b is the material static strength, $a = 1/B$, σ_b / B is estimated to be constant 10, σ_i and N_i are the stress and cycle number when material is destroyed. For the reason that the S-N curve of FRP material was got under the required cycling character $r = \sigma_{\min} / \sigma_{\max} = -1$, different conditional fatigue stress can be calculated in accordance with the amended Goodman curve in the required cycling fatigue life.

$$\sigma_a = \sigma_{-1}(1 - \sigma_m / \sigma_b) \tag{2}$$

In Eq. (2), σ_a is the stress amplitude, σ_m is the average stress, σ_{-1} is the conditional fatigue limit.

The theory of accumulative fatigue damage is the baseline method to estimate the fatigue life beginning from micro crack to macro crack of the part. When the micro crack grows, the effective running time of workpiece would decrease rapidly. In the following simulation, the typical fatigue S-N curve of glass fibers is input to the commercial software ANSYS, shown as Fig. 8.

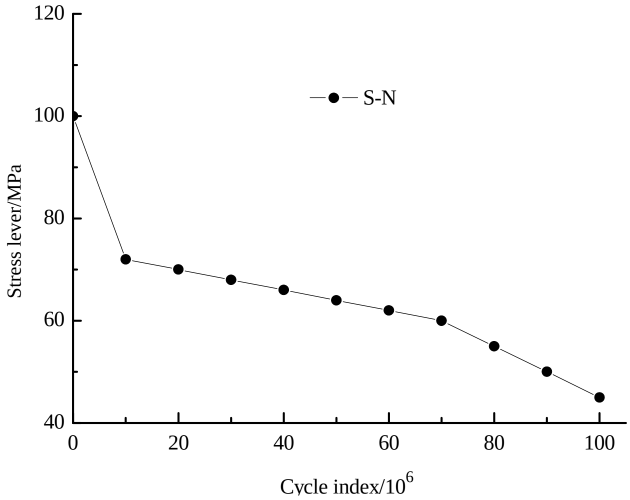


Fig. 8: The fatigue S-N curve

As one of the most important theory, the accumulative damage theory gave a good explanation to the cumulated damage mechanism and degree for material or structure when fatigue happens. Defined as that every fatigue stress factor is dependent and the fatigue damage could be accumulated, the linear fatigue cumulative damage theory is widely used, in which Miner cumulative damage theory is the most famous one. It defines that the workpiece fracture happens under the cycling stress when the damage reaches a critical value and the damage degree is increasing with the stress cycling number, that is,

$$\sum_{i}^{k} \frac{n_i}{N_i} = 1 \tag{3}$$

Where, n_i is the cycle number at the stress level σ_i , and N_i is the cycling number at damage.

5.2 The blade fatigue calculation for different ply stacking

The calculated result shows that the fatigue life for 45° and 65° ply is basically proportional to the off-axis fiber volume ratio, whereas , it is contrary for 7.5°, 15° and 20° ply shown as Fig. 9. The best fatigue life appears in blades with the ply angle in the range between 45° and 65°. It must be emphasized that this result is coincident with the side vein angle of most plant leaves.

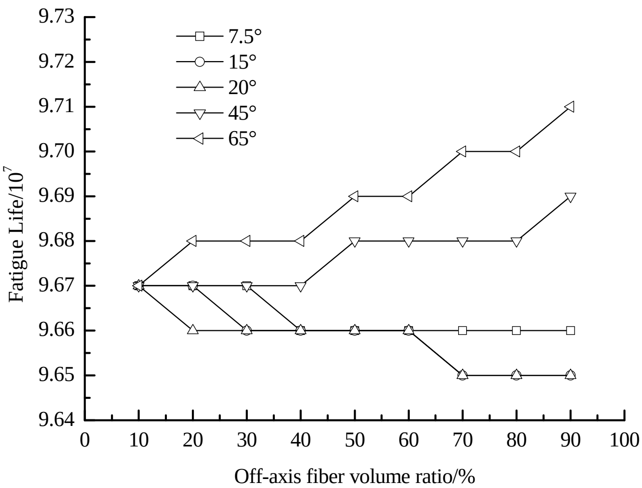


Fig. 9: Fatigue life of wind turbine blade

CONCLUSION

1. The vein network of plant leaf plays the main role in carrying random environmental loads. Although the environmental stress changes greatly with time, the vein network changes slightly. It can be concluded that the vein network of plant leaf has been evolved into a steady pattern to adapt to the change of environmental stress.

2. The topology result of 1.5MW wind turbine blade suggests the similarity between blade and plant leaf. The result can be explained from the similar structure and work environment between blade and plant leaf. Based on the analysis, bionic design method for wind turbine blade was put forward.

3. The bionic method based on the vein network of plant leaf is used to arrange the ply angles of fibres in the spar cap region of the blade. The results indicate that the best fatigue life appears in blades with the ply angle in the range between 45° and 65°. It is not only coincident with the side vein angle of most plant leaves, but efficiently improves the blade fatigue performance.

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