Journal of Engineering and Applied Sciences 14 (8): 2745-2751, 2019
ISSN: 1816-949X

Finite Element Analysis and Safety Evaluation on a Multi-MW Class Wind Turbine

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Abstract: The wind turbine blade is the system that changes kinetic energy of the wind into the mechanical energy, it is categorized into the main component, since, it can have an impact on power performance of wind power generation system, energy conversion efficiency and load and dynamic stability. Therefore, it requires the integrated design of aerodynamic-structure and the structural integrity has to be validated through design evaluation by international standard or certification agency in order to achieve optimum design of blade. In this study, the detailed explanation on evaluation category and criteria required for certification of blade design as well as the result of structural integrity of which compatible to multi-MW blades are presented. The calculation results of the ultimate strength by finite element analysis, the energy release rate was reviewed and it was confirmed that the wind turbine blade meets the structural integrity in the part of strength.

Key words: Multi-WM class, turbine blade, composite, structural analysis, energy release rate, NASTRAN

INTRODUCTION

Recently, wind power generation has recently become a hotbed of renewable energy and mainly developed in Europe and its demand is increasing worldwide. As the volume of wind power generation grows, studies on the large-scale MW-class wind power generation systems are becoming more active. The blade is the main component of designing of wind power generation system. It is the latest trend that the size and weight of blades are getting bigger which resulted in many limitations on large scale of design projects. Therefore, it requires the use of composite materials which have great aspects of light weight, high strength, corrosion and environment resistance. For that reason, studies on composite material blades is keeping its momentum. Among the related studies, Wang *et al*. (2016) is introducing state-of-the-art aeroelastic modeling of wind turbine blades and conducted comprehensive review on the model which can facilitate in analysis of aerodynamic, structure and cross-sections. Schwerdt *et al*. (2007) combined aerodynamics with multi-structural simulations to present an integrated methodology for analyzing turbine blades used in operation. Peeters *et al*. (2018) constructed a collection of parametric blocks to create a wind turbine blade model consisting of shell elements, solid elements, or combinations.

The lightweight blade technology of advanced Foreign companies that dominate the composite material blade market is divided into polyester (LM glass fiber), Epoxy iifusion (Allothe) according to the application method. In particular, many studies have been done on the application of wind power generation blades due to the superior properties of prefrag composite materials with 35% of the world's wind power generation blades being produced by Vestas and Gamesa increasing in demand.

Once the integrated design of the aerodynamic-structure for wind power generation is completed, the structural integrity will be evaluated in accordance with the guide lines of international standard (IEC 61400-1, 2005) or local certification agency.

A structural integrity evaluation based on design criteria is a pre-requisite for validation of draft of design in each step of design process. For integrated design process, it requires review process for majority of design draft to get the final design which meets the lightening and structural integrity. At this time, it is not possible to conduct finite element analysis and test evaluation for all items for design evaluation (Kim *et al*., 2013). The blade with low safety of margin against tip-tower deflection evaluation item cannot satisfy the structural integrity of other items. As such, in order to effectively design blades, it is required to evaluate tip-deformation based on the beam theory and then, determine suitability. For blade design evaluation, it is required to have history of factored or fatigue load applying on the specific cross-section of blade and this can be achieved from the result of system integrated load analysis. Structural integrity evaluation consists of tip-tower intersection, ultimate limit state and fatigue limit state and stability section and each evaluation result should meet the evaluation criteria.

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In this study, it was conducted that the static strength analysis on multi-MW blades and confirmed its structural integrity and calculated the energy release rate for calculation of fatigue life using virtual crack closure technique.

MATERIALS AND METHODS

Multi-MW turbine blade configuration: In this chapter, the DTU 10 MW turbine blade selected as a subject of study. The DTU 10 MW turbine blade is the model developed by aerodynamic and structural optimization to reduce enlargement and cost of wind power turbine in Denmark, many researchers are selecting as study model (Bergami *et al*., 2014) and it is shown in Table 1. The turbine blade consists of laminated composite materials of skin, spar and core as shown in Fig. 1. The finite element modeling built due to the fact that it takes much time and capacity to build three-dimensional turbine blade with solid element. In order for two-dimensional analysis on cross-section of implemented turbine blade, each section where the width or configuration is largely changed classified as in Fig. 1.

Turbine blade FE modelling: In this chapter, modelling for structural analysis on multi-MW wind power blade is carried out.

Composite rotor blade configuration: The wind power blade meets the structural integrity based on the association of e-Glass and thermoset resin material, these materials mainly applied, since, they are economically advantageous.

The main material that resist for bending and shear load should be reinforcement material, matrix material and e-Glass, epoxy or composition of polyester resin applied. The core material for remaining blade cross-section configuration and local buckling resistance is mainly base or PVC material (8).

Table 1: 10-MW reference wind turbine

10 MW wind turbine	Values
Rated power	10 MW
Num. blades	3
Rotor diam	178.3 m
Blade length	86.35 m
Hub height	119.0 m
Rated wind speed	11.4 m/sec
Rated rot. speed	9.6 rpm

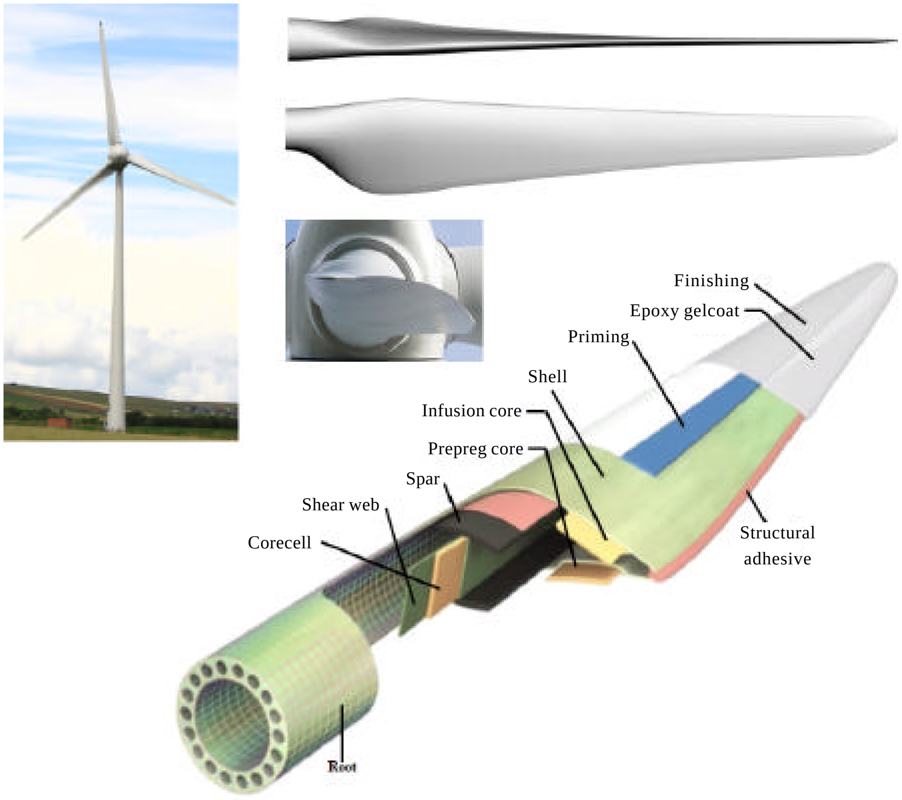

Fig. 1: Wind-turbine blade configuration

Table 2: Material properties of wind turbine

Variables	UD (Glass)	Glass-epoxy	Carbon-epoxy
E11 (MPa)	43100	39000	142000
E22 (MPa)	13200	8600	10300
E33 (MPa)	13200	8600	10300
ν_{12}	0.24	0.28	0.27
ν_{23}	0.45	0.47	0.46
ν_{13}	0.24	0.28	0.27
G_{12} (MPa)	3620	3800	7200
G_{23} (MPa)	4550	2930	3520
G_{13} (MPa)	3620	3800	7200
ρ (kg/m^3)	1939	2100	1580

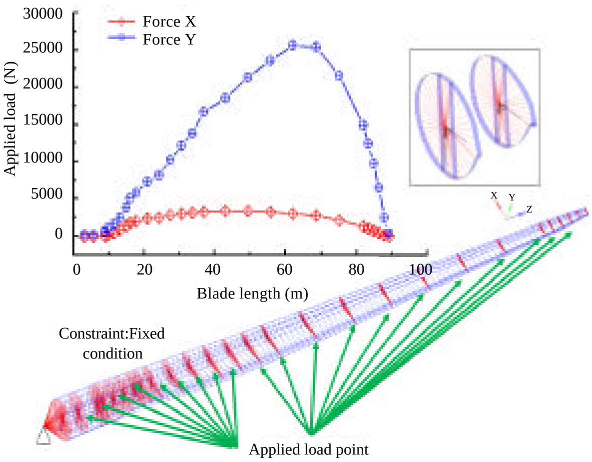

Fig. 2: Applied load of wind turbine blade and constraint

The applied material properties for structural design and analysis of blade in this study are shown in Table 2. In general, the blade has a structure in which the roots of blade become thick and its end become thinner to reduce the effect of the moment caused by wind.

Applied load and constraint: Through the static analysis of turbine blades, it is possible to confirm the position where crack can be created at the state of displacement or stress. It is not easy to apply the load directly on the three-dimensional configuration to conduct the static analysis. As shown in Fig. 2, the static analysis can be implemented by dividing load to the cross-section from the center point once the center of gravity founded on each cross-section of configuration.

Partial margin of safety: Since, the composite material mostly constitutes blades has a wide variation of material property based on the manufacturing process, the partial safety coefficient on material will be applied selectively during design evaluation.

As for the evaluation criteria for tip deformation of blades, 70% of maximum allowable distance set at the design process applied and the reciprocal of safety factor, IRF (Inverse Reserve Factor) concept is applied for laminates, buckling safety and evaluation of ultimate strength of core material. The guidelines of international standard and most of wind power certification agencies recommend higher partial safety factor on the evaluation of fiber failure than other categories. This is because the fiber failure can cause severe continuous structural damage by rapidly losing the load support capability of blade structures.

Table 3: Acceptance criteria and partial safety factor

Evalution items	Criteria for structural safety	Safety factor (load)	Safety factor (Material)
Laminate failure	Inverse reserve Factor<1	FF:1.35/1.1 IFF:1	FF:2.205 FF:1.764
Tip displacement	Tip disp.<Tower clearance ×0.7	1	1
Buckling analysis	Linear:load factor>1	1.35/1.1	Skin:2.045 Core:1.865
	Non-linear: load factor>1	1.35/1.1	Skin:1.636 Core:1.492
Core failure analysis	Inverse reserve factor<1	1.35/1.1	1.492

As for the evaluation of buckling safety, the value of partial safety factor for skin material is applied conservatively compared to the core material, this is because the mechanical properties of each material on the actual structure can be lower than the mechanical properties of material by sample test under the influence of penetration of air bubbles and other substances, deterioration by environment, deterioration of resin during the manufacturing process of fiber reinforced composite material. The partial safety margin applied on wind power blade is same as in Table 3.

RESULTS AND DISCUSSION

Structural analysis results for wind turbine blade: In this chapter, the laminated composite material modeling was built by lay-up base that can relatively accurately copy. The finite element analysis was implemented using hypermesh. For efficient finite element and laminate modeling, it is required to have process of dividing surface based on the drawing once the three-dimensional modeling of blade configuration completed. The surface of blades is divided into approximately 26 EA of cross-section based on laminated drawing. The ultimate load applied on the blades by distributing the load from 11 m/sec to each cross-section and static analysis conducted using Nastran. The fully restrained condition was applied on root area of blades as a boundary condition.

Results of checking maximum deflection: By finite element analysis, the analysis of maximum deformation of blade tip was conducted with four kinds of conditions which are Mx, maz, Mx, min, My, max and My, min. The analysis result is shown in Fig. 3.

The evaluation criteria of maximum deformation of tip is within 70% of maximum allowance distance of tip-tower (8.3 m). As a result of analysis, the tip deformed toward flap wise direction and in edge wise it was within 1 m. It was confirmed that the safety margin is sufficient compared to the judgment criteria.

Results of checking laminate strength: The guidelines of IEC International Standards and most of certification agencies define that the Fiber Failure (FF) and Inter Fiber Failure (IFF) should be evaluated under extreme load condition. Currently, various composite material failure evaluation criteria exist but most of wind turbine agencies recommend the criteria that Puck and Schurmann (1998) presented for separate failure evaluation.

However, the maximum tensile stress and compressive stress were calculated and compared to the allowable value for conservative analysis. Fiber fracture occurs when the fibre-directional stress and fibre-directional strain of composite material are exceeded by allowable value of material and two modes for tensile and compressive loads occur. The results of strength analysis of turbine blades are shown in Fig. 4 and 5. The turbine blades under extreme load conditions can be assessed by ensuring the safety margin that is sufficient under extreme load condition.

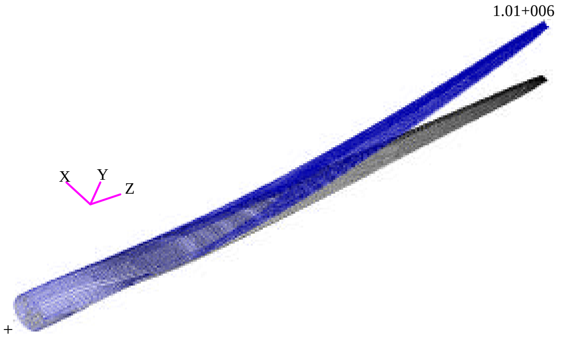

Fig. 3: Displacement result of wind turbine blade

In accordance with Table 4, the maximum stress derived from allowable value and analysis for evaluation of static strength of turbine blade and free margin were calculated.

Tensile and compression stress determined to be structural integrity. As the design progresses, more detailed load will be applied and it is expected that the structural weight will be reduced. Compression stress on the end part has relatively low level of free margin. The effectiveness of calculated stress will be demonstrated through static structural experiment of turbine blade.

Calculation of energy release rate for turbine blades: Through static analysis of turbine blade, the stress is larger on the margin where the different components

Table 4: Structural results and margin of safety

Location r/R	Failure index	Max. stress	Margin of safety
0.456	0.88	860 MPa	1.56
0.95	0.25	143 MPa	3.00

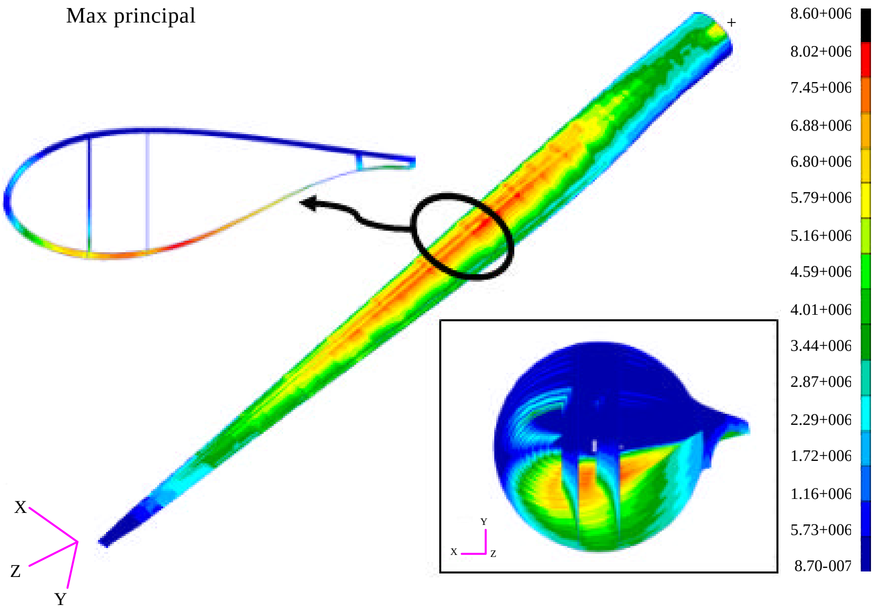

Fig. 4: Tensile stress result of turbine blade

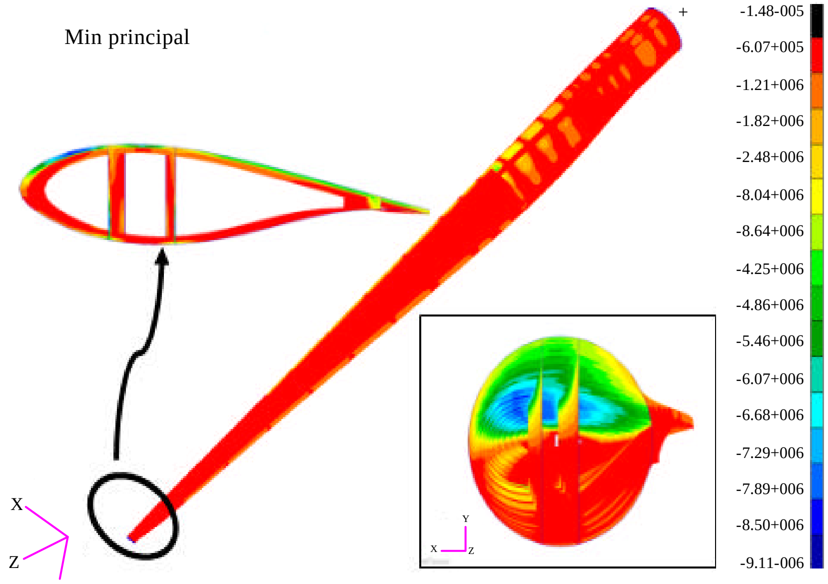

Fig. 5: Compression result of wind turbine blade

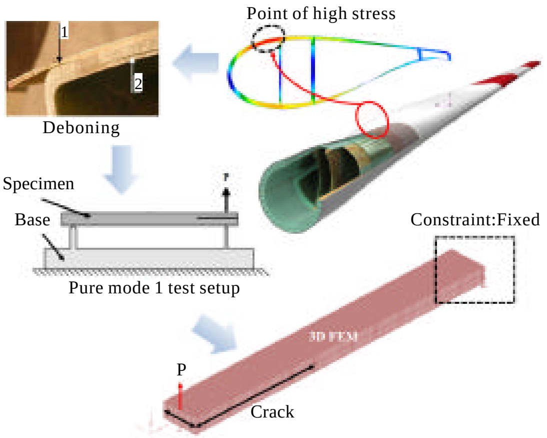

Fig. 6: Crack model for calculating energy release rate for turbine blade

combined than other position and during manufacturing phase, it causes relatively more defects than single high stress and manufacturing defects increase the potential of failure and cause various problems like durability. Crack issues, especially, it happens during manufacturing process, require various judgment and approaches. As shown at the top of Fig. 6, the crack can be regarded as the result of de-bonding created between laminates of composite materials.

We would like to do a comprarative analysis on the result of energy release ratio derived from dimensional recovery analysis with the result of experiment of Noorman (2014). As shown in Fig. 7, the experiment condition was built and the three-dimensional crack growth model constructed same as the experiment condition. The configuration of crack growth beam and its material information are lited in Table 5 geometry and material property of the crack growth beam has 32.9 mm of initial crack and the load applied from the end edge toward Z-direction. As for the three-dimensional configuration, 8 nodal points of solid element facilitated and finite element model created accordingly. Noorma achieved the relation between test sample and three-dimension by relation of displacement and load and achieved the result same as in Fig. 7. The result was similar to the results of three-dimension and test sample, energy release ratio calculated from the load having same displacement. Figure 8 shows the stress analysis results of the experimental model of Noorman (2014).

Table 5: Geometry information of specimen

Geometry information	Values
Length (mm)	102
Width (mm)	25.4
Thickness (mm)	3.12

The maximum stresses are calculated in Node 21 as shown in Fig. 8 and the load and stress values can be used to calculate the energy release rate G_I. The results of the three-dimensional analysis, compared to the experimental values (Noorman, 2014), produced a relative error of 0.0103%.

The energy release ratio calculated from crack area using load and displacement on the achieved nodal point.

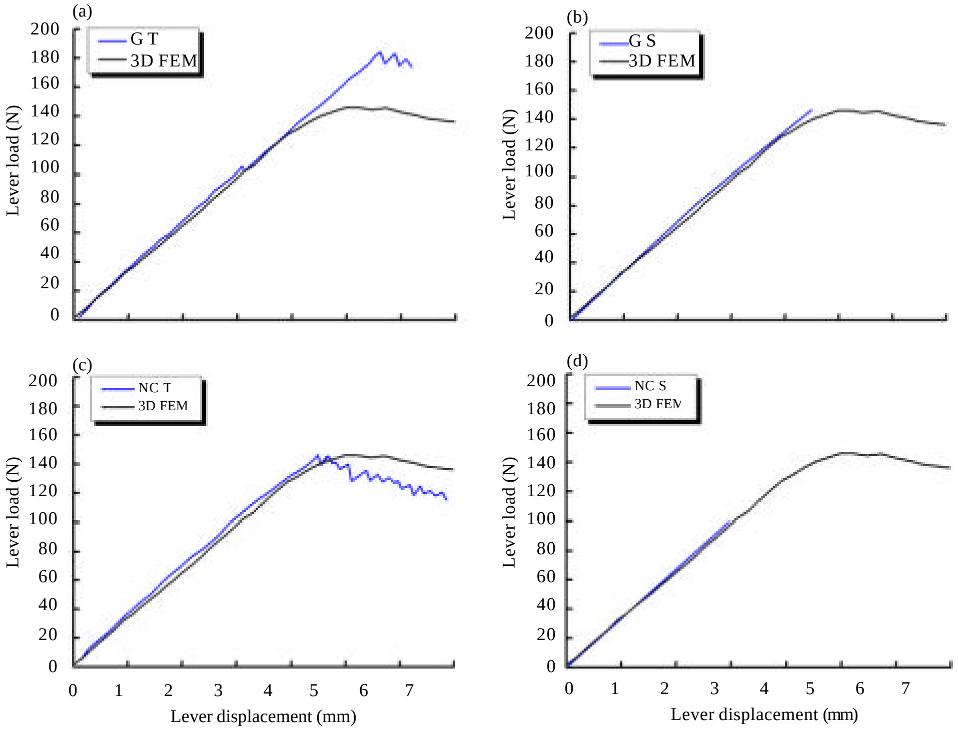

Fig. 7: a-d) Load and displacement: 3D FEM and specimen (Integration point location scheme: Gaussian/Newton-cotes; Stiffness matrix: Secant/Tangent)

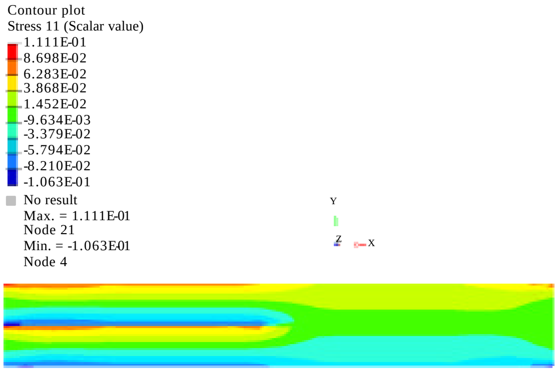

Fig. 8: Stress contour result for crack model for calculating energy release rate for turbine blade

The comparing the results of 3-D Model and test is shown in Table 6. As comparison result of experimental value, the result of three-dimensional analysis model achieved same value. When calculating the energy release ratio of three different directions, the margin of safety can be calculated using Eq. 1. In addition, the energy release ratio can be facilitated on calculation of fatigue life:

$$K^2 = \left[\left(\frac{G_1}{G_{IC}}\right)+\left(\frac{G_2}{G_{IIC}}\right)+\left(\frac{G_3}{G_{IIIC}}\right)\right] = 1 \qquad (1)$$

Margin of safety = K-1

Table 6: Energy release rate

Variables	Specimen	3D FEM
G_1 (kJ/m^2)	0.9690	0.9689
Error rate	-	0.0103%
Computation time	-	362 sec

CONCLUSION

In this study, the structure integrity evaluation compliance with technical criteria of international certification agencies was conducted to perform structural analysis of multi-MW wind power blades. As for structural integrity evaluation, the strength and tip-deformation analysis conducted by using ultimate load and energy release ratio calculated. The energy release ratio can be facilitated for structural integrity evaluation. Afterwards, core crack and buckling stability analysis will be conducted. And as for the design of lightening, the optimization of laminates on the cap of spar required and at the same time, the material of form core should be reinforced on the area of blade root where relatively high local stress occurs. It is required to achieve lightening design at a level that does not exceed the allowable tip-deformation limit.

One of aspects that can have biggest impact on bending stiffness of blades is the cap of spar which accounts for 20% of blade weight. As such, it is the most important to optimize of laminate structure of cap of spar in terms of lightening design.

Therefore, the optimization of laminates on the cap of spar required and at the same time, the material of form core should be reinforced on the area of blade root where relatively high local stress occurs.

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