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The identification of structurally sensitive zones subject to failure in a wind turbine blade using nodal displacement based finite element sub-modeling

Owaisur Rahman Shah*, Mostapha Tarfaoui**

ENSTA Bretagne, MSN/LBMS/DFMS, 2 Rue François Verny, 29806, Brest, CEDEX 9, France

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ABSTRACT

The wind turbine blades are complex structures in terms of their geometry and the materials used. They need to be modeled, on the one hand as accurately and precisely as possible, while on the other hand the models should be light enough to be run in a reasonable amount of time using reasonable computational resources. Sub-modeling is a technique used to reduce the domain size of a finite element model to a more manageable size. One of the motivations behind sub-modeling is the capacity to develop highly refined and detailed models, without using increased computational resources, as the refined model domain is small and hence has a smaller number of elements. There are different methods of sub dividing the problem domain into smaller simpler domains, of which the transfer of nodal displacement form one parent model to its child will be used in this study. Furthermore the use of surface to solid sub-models is also discussed.

1. Introduction

The wind turbine blades are complex structures. They are modeled in finite elements to deal with their structural complexity. The finite element analysis is done for the validation of the structural design as well as the dynamic or modal response of the blades, as vibration at natural frequencies is an important part of blade design [1] [2].

The finite element analysis of wind turbine blades can be done with varying degrees of complexity. The blade can be modeled as a beam with varying degree of complex or simple beam elements [3–5]. Three dimensional shells can be used to simplify the problem field yet keeping the overall geometry of the blade. The shell elements as shown in Fig. 1 are given material properties based on classical composite plate theory to reduce the computational costs [6]. Shell elements are used to model structural elements in which two dimensions are much greater than the third one and when the change of the analyzed feature across this third direction can be neglected. It is reasonable for static analysis of panel/planar elements such as slabs or walls as well as thin-walled spatial elements such as shells. The advantages of the use of shell elements results mainly from time-saving due to reduced number of finite elements (and consequently the equations to solve).

Shell elements can be a huge time saver since they allow the modeling of thin features with relatively fewer elements as compared to solid elements. They are also easier to mesh and less prone to negative Jacobian errors which might occur when using extremely thin solid features.

Further more precise models are possible which include the thickness effects of the composite layups. But these models are usually for small portions of the blade instead of the complete structure owing to the complexity and computational costs. For this reason some analytical 3D models have also been developed [7].

The structural analysis of wind turbine blades although gives the overall behavior of the blade, but there is always a need to understand the limits at which the blade would fail [8]. And also how it would fail. For this purpose, linear fracture mechanics are applied to detailed models at the sensitive zones, which include the bonded joints where the blades are assembled [9] [10].

As the wind turbines experience reversed loads they undergo fatigue loading of up to 4 million cycles per year. This puts a lot of emphasis on the fatigue life determination of the blades. Cumulative damage modeling has thus been used to model the life of these

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* Corresponding author.
** Corresponding author.
E-mail addresses: owaisur_rahman.shah@ensta-bretagne.fr (O.R. Shah), mostapha.tarfaoui@ensta-bretagne.fr (M. Tarfaoui).

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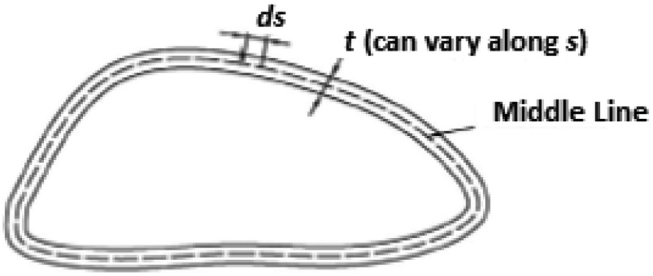

Fig. 1. 3D Shell with classical composite plate theory definition.

blades [11]. The application of cyclic loads may be based on measurements done in the field [12].

The modeling in terms of structure is augmented with the aerodynamic analysis. Aero-elastic behavior with coupled fluid structure interactions is used to calculate the loads applied on the blade during their service [13] [14].

The finite element models of wind turbine blades finally need to include all the structural properties and the boundary conditions applied as close as possible to the real cases. These parameters are applied in instantaneous state models or as probabilistic models, dealing with the load events taking place at some intervals of time [15].

As the size of the structure to be modeled in finite element methods increases the model needs to be simplified to keep the computational costs lower. Hence to model all the geometrical and material details of such a structure in detail would require too many computational resources. The approach hence used in this study is to model the blade as a surface model, to define the material as in the real structure. A static bending test is done on the full scale blade to validate the proposed design. The results from these static tests are then used to validate the sub-modeling regime formulated in this study in terms of strains measured at the blade surface using strain gauges.

2. Experiments

Two types of experiments were carried out in order to validate the sub-modeling approach. The first type of experiments was performed on the coupon level to characterize the material and interlaminar/bonded interface properties. To this aim single lap joints where then tested and compared to modeled results to validate the modeling strategy used. In the other type of tests full scale tests were carried out on the complete blade structure in static bending to determine the stiffness of the structure as well as the strains at the skin of the blade.

The composite materials have been tested under tensile tests to determine their elastic and damage properties. The material properties thus determined through monotone tests are given as in Tables 1–6.

Table 1
Details of the Unidirectional (UD) mat used for composite manufacture.

Construction	Areal weight (g/m^2)	Tolerance (±%)	Material	Linear density (tex)
0°	1152	5	E – Glass	2400
90°	49	5	E – Glass	68
Stitching	12	5	PES 110 dtex	
Total areal weight	1213	5	Binder	Warp-Tricot

Table 2
Details of the 45° Biax mat used for composite manufacture.

Construction	Areal weight (g/m^2)	Tolerance (±%)	Material	Linear density (tex)
+45°	451	5	E – Glass	600
−45°	451	5	E – Glass	600
Stitching	12	5	PES 76 dtex	
Total areal weight	912	5	Binder	Warp

Table 3
Details of the NORPOL PF adhesive.

Properties	Unit	Value	Test method
Physical data in liquid state at 23 °C			
Viscosity Brookfield HBT sp B/5 rpm	poises	1350–1500	2460-001
Density	g/cm^3	1.12–1.15	2100-001
Gel time, 2% NORPOL N°24	minutes	55–65	2160-006
Exothermic peak with 2% NORPOL N° 24	°C	90–120	2340-002
Storage stability from date of manufacture	months	4	
Non reinforced casting properties			
Tensile strength	MPa	35–40	ISO 527-1/2-93
Tensile elongation at break	%	2.5–3.5	ISO 527-1/2-93
Flash point	°C	70	ISO 75-1/2-93
Linear shrinkage	%	1.8	ASTMD2566-69

Table 4
Mechanical properties of composite in longitudinal direction.

Specimen	E_L (GPa)	E_{Lavg}	ν_{LT}	$\nu_{LT\ avg}$	X (MPa)	X_{avg} (MPa)
UD_0°_01	55.02	48.11	0.31	0.28	990.65	965.50
UD_0°_02	46.24		0.25		934.80	
UD_0°_03	47.24		0.27		956.55	
UD_0°_04	43.98		0.29		980.00	
IMA Dresden		45.78	–			1021.3

Table 5
Mechanical properties of composite in transverse direction.

Specimen	E_T (GPa)	E_{Tavg}	ν_{TL}	$\nu_{LT\ avg}$	Y (MPa)	Y_{avg} (MPa)
UD_90°_01	10.66	11.21	0.086	0.096	32.50	33.50
UD_90°_02	10.4		0.094		34.60	
UD_90°_03	11.04		0.095		37.20	
UD_90°_04	11.21		0.098		31.40	
UD_90°_05	12.76		0.107		31.80	
IMA Dresden		10.21	–			40.9

Table 6
Mechanical properties of composite in shearing direction.

Specimen	G_{LT} (GPa)	G_{LTavg}	S (MPa)	S_{avg} (MPa)
UD_45°_01	4.36	4.42	45.68	48.69
UD_45°_02	8.52		50.55	
UD_45°_03	4.53		48.37	
UD_45°_04	4.52		49.35	
UD_45°_05	4.29		49.50	
IMA Dresden		4.21	–	35.30

a) Caracterization of interlaminar strength

The interlaminar strength of the composite material has been determined using the Double Cantilever Beam DCB, for Mode I