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Finite Element Analysis of a Composite VAWT Blade

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A B S T R A C T

High values of centrifugal forces play a significant role in the design of straight blades of a vertical axis wind turbine. Centrifugal forces add up with aerodynamic forces and result into a high value of bending stresses and deflections in these blades. These forces can be reduced by reducing the weight of the blade which can be done by choosing a low density material. The blade made up of composite materials can have thin walls due to high strength to weight ratio of the materials. A straight Darrieus vertical axis wind turbine blade made up of Aluminium was designed in the previous research. The same blade is modeled with a composite material to optimize its design. It is discussed why Glass-Epoxy can be chosen as a suitable composite material to model a wind turbine blade. SOLID and SHELL element types are analyzed and layered SHELL elements are found as more useful to model the composite blade. Different stacking sequence and ply thickness of Glass-Epoxy is used and a right stacking sequence is found. The values of all forces acting on the blade are computed and compared with the Aluminium blade. The unidirectional strength is achieved by computing and optimizing the results of maximum deflection and maximum stresses at the location where maximum loads are applied. High strength to weight ratio is achieved by reducing the values of centrifugal forces, maximum deflections and maximum stresses in the composite blade.

1. Introduction

The wind turbines are categorized into two classes depending upon the axis of rotation of blades. They are classified as Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). The VAWT can accept air from any direction. There are various categories of vertical axis wind turbines. The H-Darrieus wind turbine is a special category of VAWTs that based on lift forces for its operation and has structure like letter 'H'. The long and straight blades of VAWT can fail due to high value of aspect ratio which causes a large value of bending moments and deflections (Kragten, 2004). The reduction in values of centrifugal forces is important for a safe blade design which in turn reduces the bending stresses and deflections viz. the primary task of this research. The similar efforts have been made in previous research for the optimization of blade design (Jureczko et al., 2005; Hansen Martin, 2002; Det Norske Veritas and Riso National Laboratory, 2002). A detailed finite element mesh of a 2.5 m long fiberglass composite wind turbine blade was generated to optimize the use of material. A program was written in a format for direct input in commercially available finite element software, STRAND6. The final blade shape was achieved by considering many stacking arrangements of the blade elements through blade element theory in order to reduce the tip deflection and maximum stress to minimum values for blade at operating design conditions (Bechly and Clausent, 1997). An actual collapse testing of a large composite wind turbine blade was done under ultimate flap-wise loading to study the structural response of the blade by correlating the experimental findings with the numerical results (Yang et al., 2013). Finite element method was used to perform the dynamic analysis of blade which was applied to the production of 20 KW composite wind turbine blade. For mechanical properties analysis, a computer program was developed to optimize the blade's actual shape and layer structure (Song et al., 2011). Modeling the blade precisely to describe the layer structure is a difficult problem and has great significance in mechanical analysis (Haichen, 2007). The 3D coordinates of blade sections was solved using MATLAB and solid model was generated using Pro/E to design and model the wind turbine blade (Tian, et al., 2009; Li et al., 2009). The finite element method was implemented to carry out the static strength analysis of the wind turbine blade by discretizing the blade skin using SHELL elements (Kongand Bang, 2005). Using composite

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laminate theory and finite element method, the theoretical calculations for stress in four different lay-up structure of a 1.2 MW wind turbine blade was verified under extreme load conditions. The optimal lay-up scheme $[0°/\pm 60°/90°]_S$ is proposed through numerical tests for safe blade design (Lanting, 2012).

In this research paper, the selection of suitable composite material for wind turbine blade and its properties are discussed. The centrifugal forces acting on the composite blade are compared with the values of these forces evaluated over an Aluminium blade. A commercially available software ANSYS is used for the numerical analysis. The selection of suitable layered element type used to model the composite materials is discussed. The right combination of layers of the selected composite material is determined in order to reduce the values of maximum stresses and maximum deflections, which achieves a high strength to weight ratio. In post processing, a path is taken at the location of application of maximum load on the blade and the values of deflections and stresses in each direction along that path are determined. These maximum values are compared with the uni-directional strength of the selected composite material to ensure the safe design.

2. Selection of suitable blade material

Dynamic stresses and diversified load conditions are more severe on straight bladed VAWT blades than many other mechanical applications. For delivering mechanical or electrical energy based on the operational parameters and surrounding conditions, a typical blade material of a straight bladed VAWT blade must have certain useful properties (Islam, 2008). The most important of these properties are adequately high yield strength for longer life, high material stiffness to maintain optimal aero-dynamic performance and low density for reduced amount of gravity and normal force component. The modern wind turbine materials are composites made up of fiberglass reinforcements. For turbine blade design, they are composed of E-glass with epoxy, polyester or vinyl ester and normally hand-layup fabrication techniques are used (Sutherland, 2000). The glass-epoxy composite material is recommended for the design of wind turbine blades due to its useful characteristics (National Research Council (NRC), 1991).

The comparative study of Aluminium and Glass-Epoxy shows that Aluminium has been extensively used as VAWT blade material but Glass-Epoxy has been used for HAWT blade only and its application on VAWT blades has not been utilized yet by manufacturers (Islam et al., 2008). However, Glass-Epoxy is considered as one of the prospective materials for the construction of straight bladed VAWT blades (CANMET Energy Technology Centre (CETC), 2001), because they are economically attractive and have a good combination of material properties e.g. high strength, moderate density and stiffness.

The straight bladed VAWT blades is designed with glass-epoxy, its properties are given in Table 1 (Gay et al., 2003)

Density of Glass-Epoxy with $V_f=60\%$ and $V_m=40\%$ is calculated as follows,

$$\rho_c = \rho_f V_f + \rho_m V_m = 2500(0.6) + 1200(0.4) = 1980\ \text{Kgm}^{-3}$$

where, ρ and V represents density and volume fraction, respectively. The subscripts f and m defines fibre and matrix, respectively.

Table 1
Material Properties of Carbon/Epoxy Plies with 60% Fiber Volume Fraction and Thickness=0.13 mm.

E_x	$E_y=E_z$	$\nu_{xy}=\nu_{xz}$	ν_{yz}	$G_{xy}=G_{xz}$	G_{yz}
45 GPa	12 GPa	0.3	0.2	4.5 GPa	5 GPa

Table 2
Comparison of Total Forces Acting on the Blade.

Wall Thickness (mm)	Cross Sec Area, A (10^{-3}) (m^2)	IChord (10^{-7}) (m^4)	Mass, m Aluminum (Kg)	Mass, m Glass-Epoxy (Kg)	Magnitude of total force (Centrifugal+ Normal Force) Ft (kN)	
					Glass-Epoxy	Aluminium
5	1.92	1.79	13.37	9.81	8.859	11.832
4	1.56	1.56	10.89	7.99	7.34	9.763
3	1.19	1.27	8.29	6.08	5.751	7.594
2	0.807	0.920	5.62	4.12	4.12	5.371
1	0.409	0.499	2.85	2.09	2.425	3.060

3. Evaluation of forces acting on the blade made up of glass-epoxy

The centrifugal forces have a large contribution to the magnitude of the overall forces acting on a VAWT blade (Eriksson et al., 2008; Kragten, 2004). It is desirable to use a material with lower value of density in order to reduce the centrifugal forces (Paul and Stephen, 2015). In previous research, a VAWT blade made up of a low density metal, Aluminium, was designed and these centrifugal forces were evaluated for difference values of blade wall thickness. The optimal range of wall thickness of the blade was selected as 3 mm to 4 mm. The complete design parameters of blade, evaluation of aerodynamic (lift) and centrifugal forces are presented in (Hameed and Afaq, 2013).

In the current research, these forces are evaluated again on the same blade using a composite, glass-epoxy, as blade material. Glass-Epoxy has lower density than Aluminium which causes a significant reduction in the centrifugal forces acting on the blade. The comparison of total forces (F_t=Aerodynamic+Centrifugal Forces) acting on both Aluminium and Glass-Epoxy blades is presented in Table 2. As the cross sectional area of the blade does not vary so this is the total normal force acing on the blade which is the sum of uniformly distributed forces along the blade span. The values of aerodynamic forces remain same in both cases since there is no change in the overall aerodynamic shape of the blades. Therefore, the reduction of total forces in case of Glass-Epoxy is only due to the reduction in centrifugal forces.

4. Selection of suitable element type in ANSYS

The layered element types, available in ANSYS, are considered to create the finite element model of the composite blade. The implementation and accuracy of the results produced by these finite element models are checked by solving a simple benchmark problem defined in ANSYS as Verification Manual 82 (VM82). VM82 defines a simply-supported square cross-ply laminated plate subjected to uniform pressure p_o. The stacking sequence [0°/90°/90°/0°] of the plies is symmetric about the middle plane. The value of center deflection δ (z-direction) of the plate due to pressure load p_o is unknown of the problem. The detailed

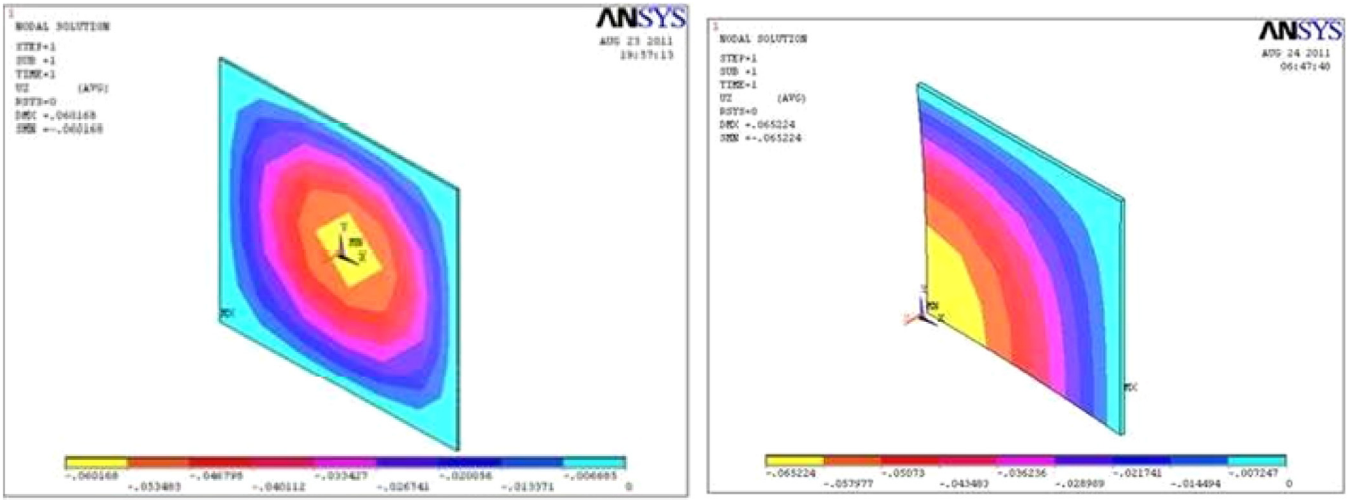

Fig. 1. VM82 Solution-SOLID46 Elements (left) $\delta_z=0.0602$, SOLID186 Elements (right) $\delta_z=0.0652$.

Table 3
Comparison of Results with Different Layered Element Types, Exact Solution = 0.0683 m - (VM82).

Results with SOLID46	% Error	Results with SOLID186	% Error	Results with SHELL99	% Error
0.0602 m	11.86%	0.0652 m	4.54%	0.0681 m	0.29

definition of the problem VM82 can be found in ANSYS help topics. The exact solution of this problem is already available as $\delta_z=0.0683$ m, (Reddy, 2008).

Initially, the SOLID element types, Soild46 and SOLID186, are used to model this problem. The value of δ_z obtained for each element type is shown in Fig. 1. The percentage error in both cases is evaluated by comparing the results with exact solution, presented in Table 3. The percentage error is lesser in case of SOLID186 so it is concluded that it provides more accurate results than SOLID46.

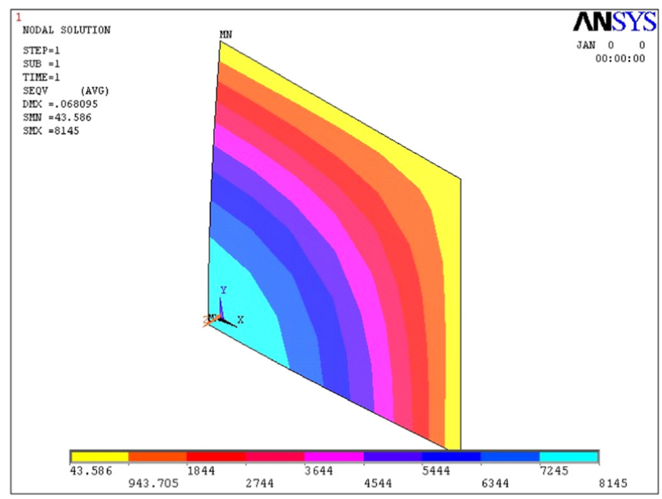

Fig. 2. VM82 Solution with SHELL99 Elements, $\delta_z=0.0681$.

4.1. Meshing Issues with SOLID Elements

When a layered element type is used, it is important to consider that how layers are defined within the element. The element type SOLID186 defines each layer in xy-plane and thickness of each layer is defined along z-direction. If we consider the cross-section of the blade (airfoil), this z direction should be along the thickness of the airfoil geometry.

Meshing blade geometry with a layered elements is not a straightforward task. Creating a three dimensional (3D) model of blade and meshing it directly with SOLID elements creates meshing errors. The errors occur due to very small angles in the cross-section of the blade and SOLID elements cannot fit in that geometry.

Therefore, first the cross-section of the blade is modeled and meshed with PLANER42 element type which is a two dimensional (2D) element type defined in xy-plane. In case of Aluminium blade, this 2D mesh was extruded in z-direction with non-layered SOLID45 element type to create the three dimensional (3D) meshed blade. But extrusion of same 2D mesh with layered SOLID186 does not create layers with their thickness along z-direction. In order to create the thickness of the layers in the desired direction, the 2D mesh cross-section should be either in xz-plane or yz-plane. This is not possible since PLANER42 creates meshes only in xy-plane. Therefore, the use of layered SOLID element types to mesh the composite blade is not a feasible choice due to geometric constraints.

4.2. Selection of SHELL99 Element Type

SHELL elements usually have a smaller element formulation time which reduces the complexities in meshing. SHELL99 element type can be used for layered applications of a structural shell model. SHELL99 does not need the solid model of blade, it only needs the shell model and defines layers theoretically in the background as a set of real constants. The benchmark problem VM82 defined earlier for SOLID elements is solved again using SHELL99 element type. The results are shown in Fig. 2, the deflection in z-direction $\delta_z=0.0681$ which is very close to the exact solution with error less than 1%, as calculated in Table 3. Therefore, SHELL99 element type is chosen because it is more accurate than SOLID elements and there are no geometric restrictions in meshing the shell model of the blade.

The blade model is shown in Fig. 3, it is a shell model with unit wall thickness. The shell model is generated because in SHELL99 element type, the thickness of the blade wall is defined in its real constants. The model apparently looks like shell but it has a certain wall thickness which is defined in SHELL99 element definition. The blade model is meshed with SHELL99 element type, with

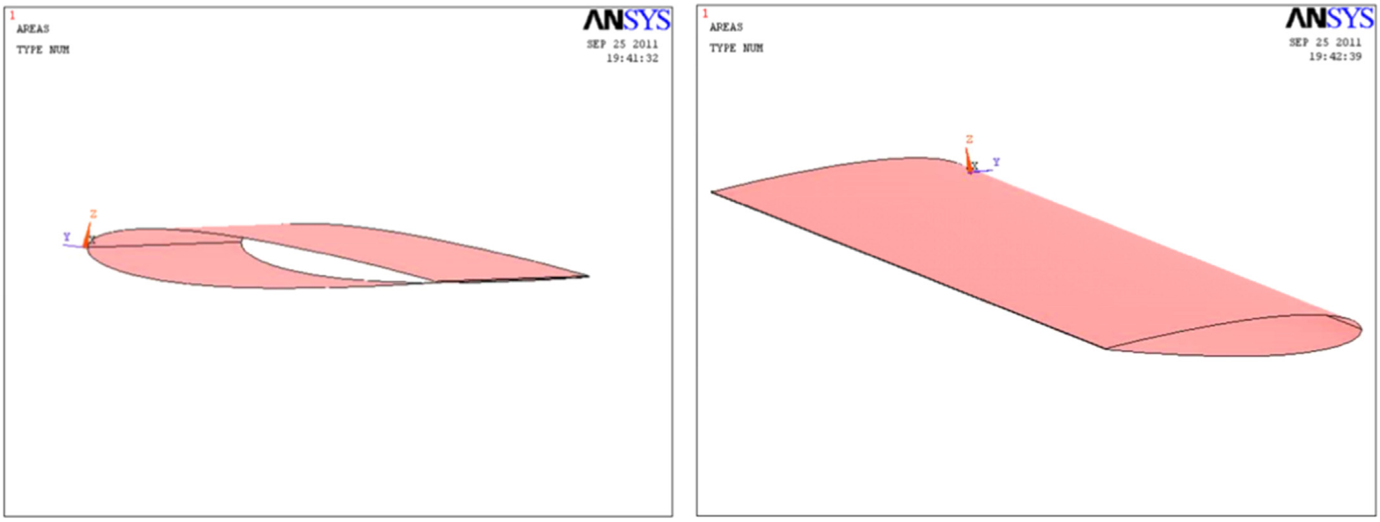

Fig. 3. Blade Geometry for SHELL99 Element Type.

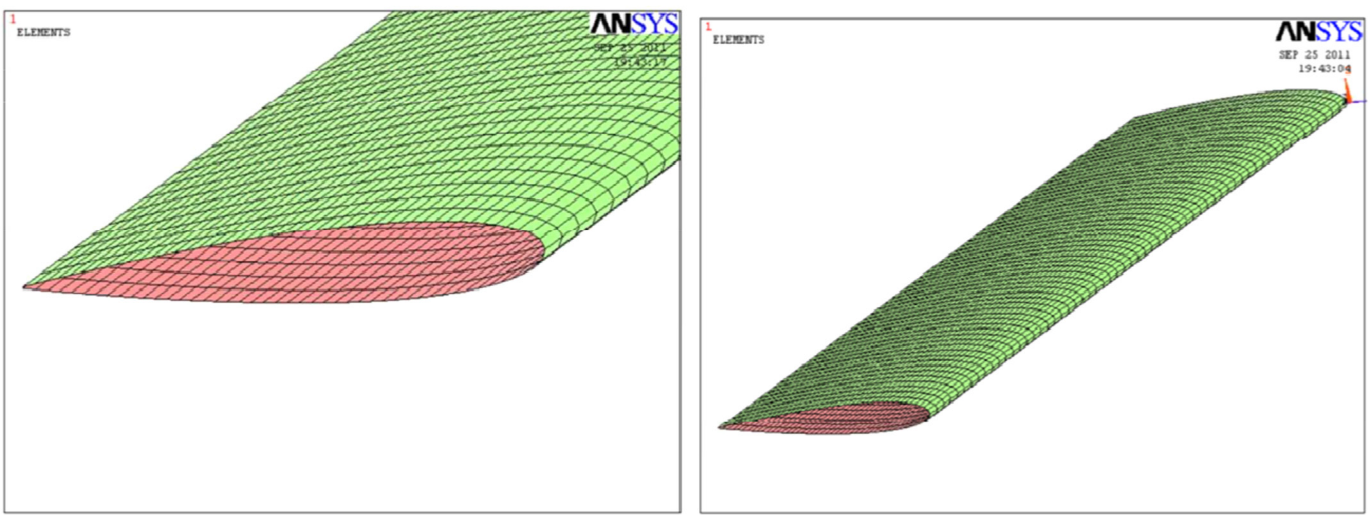

Fig. 4. Blade Geometry Meshed with SHELL99 Element Type.

the division of blade length in 60 and cross-section in 50 equal parts for structured meshing, as presented in Fig. 4.

A convergence study is performed on maximum values of bending stresses and deflections. It is noted that as we increase the number of nodes the difference between the values starts to reduce, as shown in Fig. 5. For the number of nodes equal to 10246, the mesh shown in Fig. 4, the difference from the previous value is less than 10^{-3}, which is taken as convergence criteria.

5. Analysis of the glass-epoxy blade design

The design of the Aluminium blade with wall thickness 4 mm is further improved by modeling it with Glass-Epoxy. The weight of the blade has already been reduced by replacing the Aluminium with Glass-Epoxy. The aim of further analysis is to reduce the values of bending stresses and deflections as much as possible so that a high strength to weight ratio can be achieved for Glass-Epoxy blade.

5.1. *Generation of Finite Element Model*

The geometry of blade with wall thickness of 4 mm is meshed with SHELL99 elements and the material properties of Glass-Epoxy are applied, defined earlier in Table 1. The blade displacements are constraints in all degrees of freedom at 0.56 m from each end and the value of load is taken from Table 2 for 4 mm blade viz. 7341.17 N. These steps are explained in detail for the previous case of Aluminium blade in (Hameed and Afaq, 2013).

5.2. *Suitable Combination of Glass-Epoxy Layers*

Different stacking sequences are tried while analyzing the blade with Glass-Epoxy and the results for Aluminium and Glass-Epoxy blades are compared in Table 4.

It is observed that maximum stresses in all the combinations have been reduced but the maximum deflections have increased. This is due to the lesser number of layers (plies) in the direction along which the load is applied i.e. 90° direction. This directional strength will increase (and deflections will reduce) by bring more layers from 0° orientation towards 90° orientation but at the same time the bending stresses will increase. Our aim is to achieve both

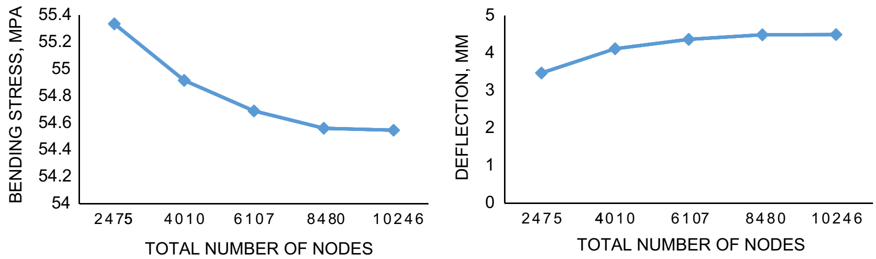

Fig. 5. Convergence of Results by Improving the Mesh Quality.

Table 4
Different Combination of Layers of Glass/Epoxy and Comparison of Results (Maximum stress in Aluminium is 74.9 MPa and maximum deflection is 4.86 mm).

Stacking Sequences	Thickness of each Layer (m)	Max. Stress (MPa)	Max. Deflection (mm)
[0°/90°]	0.002	45.9	7.5
[90°/0°/90°]	0.0013	68.1	6.06
[0°/90°/90°/0°]	0.001	27.9	6.86
[0°/90°/0°/90°/0°]	0.0008	27.5	7.4
[90°/0°/90°/90°/ 0°/90°]	0.00067	75.6	6.6
[90°/0°/90°]	90°: – 0.00175 0°: – 0.0005	61.1	5.46
$[90°/0°/90°]_S$	90°: – 0.000925 0°: – 0.00015	60	5.34
Recommended Combination of Layers			
$[45°/90°/0°/\text{-}45°]_S$	0.0005	39.4	5.78
$[45°/90°/0°/\text{-}45°]_S$	45°: 0.00013 90°: 0.00156 0°: 0.00026 – 45°: 0.00013 – 45°: 0.00013 0°: 0.00026 90°: 0.00143 45°: 0.00013	54.6	4.493

Table 5
Glass-Epoxy Plies Thickness with their Orientation.

Layer Number	Equal thickness Orientation (degree angle)	Thickness (mm)
1	45	0.5
2	90	0.5
3	0	0.5
4	– 45	0.5
5	– 45	0.5
6	0	0.5
7	90	0.5
8	45	0.5
Layer Number	**Variable thickness Orientation (degree angle)**	**Thickness (mm)**
1	45	0.13
2	90	1.56
3	0	0.26
4	– 45	0.13
5	– 45	0.13
6	0	0.26
7	90	1.43
8	45	0.13

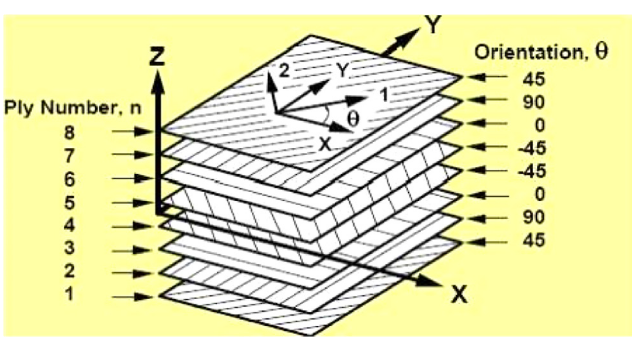

Fig. 6. Recommended Orientation of Glass-Epoxy Layers for Wind Turbine. Blades (Walczyk, 2010).

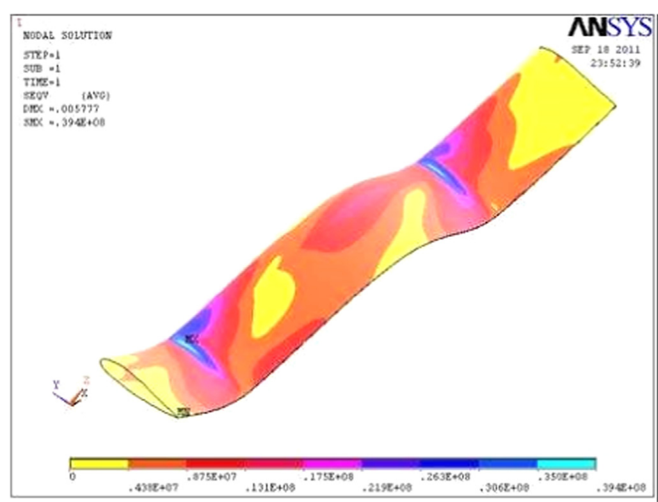

Fig. 7. Deformed shaped of VAWT blade with Recommended Combination of Layers (Equal Thickness).

the values for Glass-Epoxy blade lower than the Aluminium blade. Therefore, a suitable stacking sequence has to be chosen to achieve the best results for both deflections and stresses.

In literature, the wind turbine manufacturers have proposed some useful combinations for Glass-Epoxy layers based upon experimental data. A combination of Glass-Epoxy layers [45°/90°/0°/– 45°/– 45°/0°/90°/45°] is applied to the current blade model, shown in Fig. 6 and recommended by (Walczyk, 2010). The combination of layers in this orientation is first applied with same and then varying thickness of each layer. The value of each layer thickness with its orientation is shown in Table 5 for both cases.

The results for both cases are shown in Figs. 7 and 8 and compared with Aluminium in Table 4. It can be seen from the results that we have finally achieved a combination of layers which has reduced the values of both maximum stresses and maximum deflections when compared with Aluminium. The orientation of Glass-Epoxy layers $[45°/90°/0°/-45°]_S$ with varying thickness of each layer (as shown in Table 5) is chosen for the best design of straight blade of a VAWT.

The percentage of each ply orientation in the laminate is shown in Table 6. Total sum of all the ply thicknesses is 4 mm which is the total wall thickness of the blade. The ply/layer thickness of Glass/Epoxy is 0.13 mm (Gay et al., 2003). Therefore, it can be concluded that the deflection has also reduced because there are 74% of the total layers facing the load in 90 direction. At the same time, there are layers in 0 and 45 orientations which are mandatory to avoid the delamination in composites.

5.3. *Unidirectional strength test*

Composite materials are orthotropic materials having different properties in different directions. At this stage, it is also important

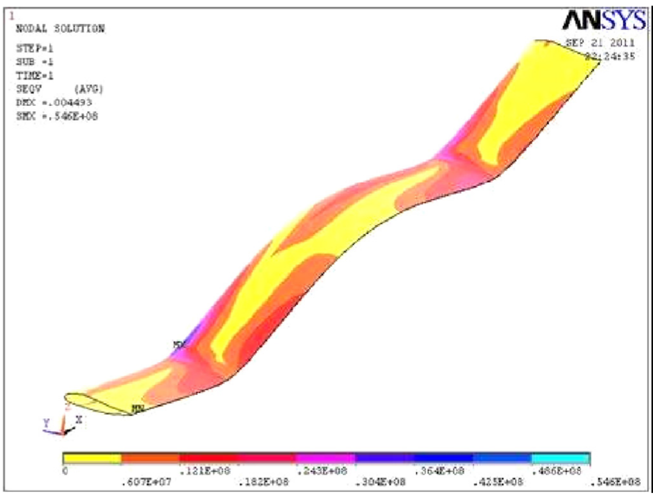

Fig. 8. Deformed shaped of VAWT blade with Recommended Combination of Layers (Variable Thickness).

Table 6
Percentage of Each Layer Orientation in the whole Laminate.

Layer Orientation	Percentage of Layer in the Laminate	No. of Plies (Ply thickness 0.13 mm)
−45°	6.50%	2
0°	13%	4
90°	74%	23
45°	6.50%	2

to check that maximum value of stresses in each direction does exceed the unidirectional strength of Glass-Epoxy. The maximum values of stresses are required at quarter chord location where the maximum loads on the blade are applied. A path is considered by selecting all the nodes along quarter chord location as shown in Fig. 9.

The variation in the value of von Mises stress (or equivalent tensile stress) along the path is plotted as graph in Fig. 10 as SEQV. It can be seen in the graph that there are maximum values of stresses appearing at the locations from where the blade is constraint in all degrees of freedom. The variations in the values of stresses in x and y directions along the path are also plotted as SX and SY respectively. The maximum values of SX and SY along the path are 14.97 MPa and 11.95 MPa respectively. These maximum values are compared with the unidirectional strength of Glass-Epoxy along each direction in Table 7. These are the values calculated at the critical loading conditions for a low wind speed of 8 m/s as chosen in (Hameed and Afaq, 2013). The comparison shows that the maximum values of stresses, obtained for this blade design, are lesser than the maximum allowable unidirectional stresses for Glass-Epoxy in Table 7. The values of deflections in each direction and the sum of deflections along the path are plotted in Fig. 11. It shows that deflection is minimum at the locations where blade is constraints and maximum deflections are at free ends. All the loads were applied normal to the chord and along the span (z-direction). This is the reason of high deflections along z-direction (UZ) which is almost equal to the total blade displacements (USUM). The maximum deflection is each direction is presented in Table 7. The maximum displacement (4.492 mm) is within acceptable range, that is, less than the maximum

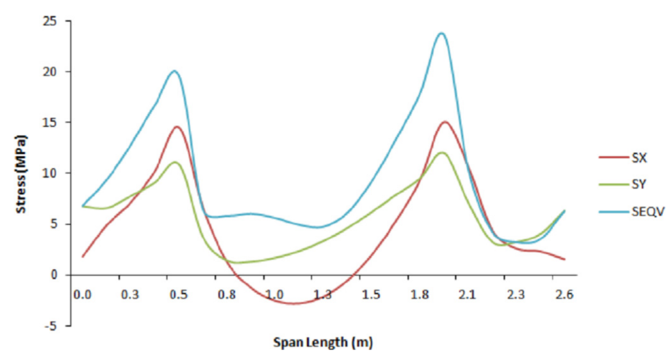

Fig. 10. Unidirectional Stresses and Von Mises Stress Along a Selected path.

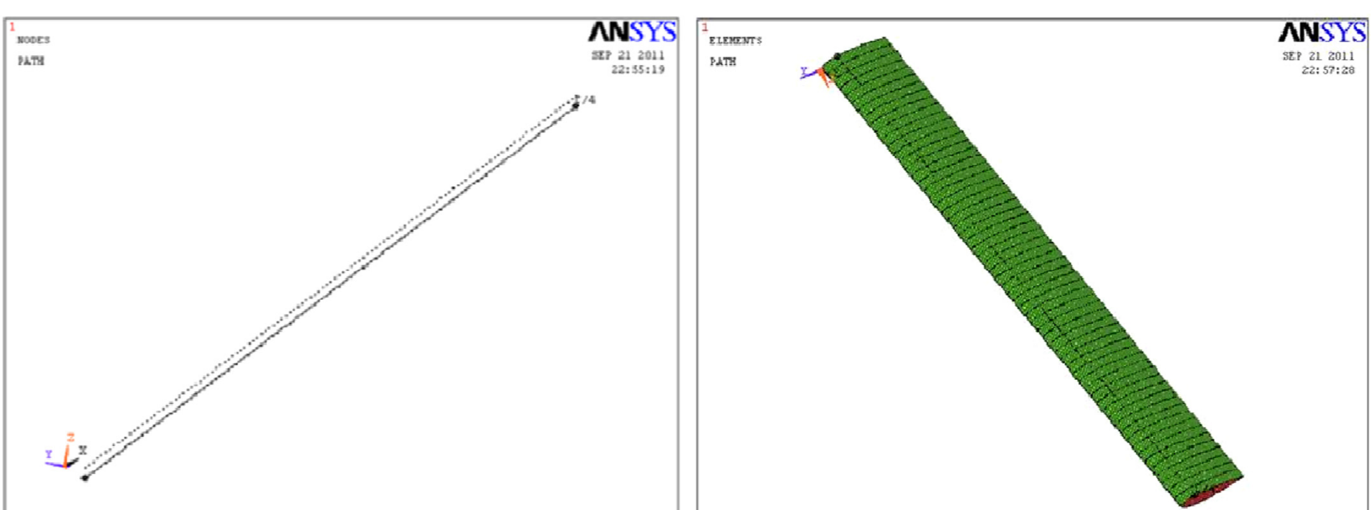

Fig. 9. Path Plot at Quarter Chord along Span of VAWT Blade.

Table 7
Evaluation of Maximum & Minimum Values on the Selected Path at Critical Loading for Low Wind Speed of 8 m/s.

Deflections	Maximum Deflections (mm)	Minimum Deflections (mm)	Stresses	Maximum Stresses °max (MPa)	Minimum Stresses °min (MPa)	Unidirectional Strength of Glass-Epoxy (MPa)
UX	0.117	−0.1166	SX	15	−2.774	1250
UY	0.00128	−0.00941	SY	11.96	1.273	35
UZ	4.492	0.16244	SZ	0.0118	0.00126	–
USUM	4.492	0.16420	SEQV	23.554	3.236	–

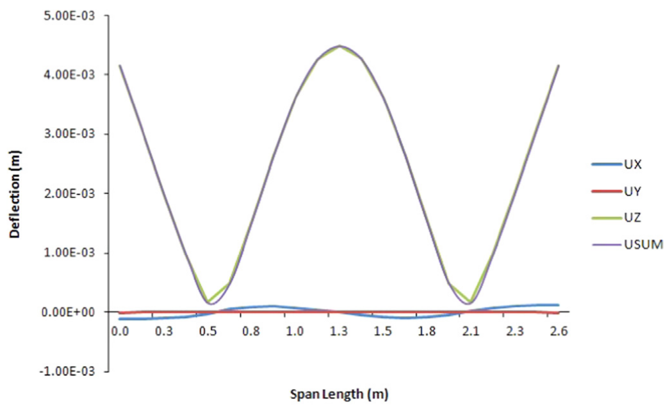

Fig. 11. Deflections Along a Selected path.

displacement in Aluminium blade (4.86 mm). Therefore, this blade design is a safe design.

6. Discussion of results

1. In order to achieve high strength to weight ratio for the VAWT blade, it is modeled with Glass/Epoxy and different combination of layers/plies orientations are analyzed. The suitable combination of layers is found as, $[45/90/0/-45]_S$ with an optimized number of layers in each direction and with variable thicknesses.
2. Keeping more number of layers in 90 directions, reduces the value of maximum stresses and deflections because applied load is normal to the chord and blade span length. Therefore, more layers in 90 direction supports the load.
3. The maximum values of stresses and deflections are evaluated at location where the maximum loads are applied and compared to the unidirectional strength of Glass/Epoxy.
4. The complete model of the composite VAWT blade with a suitable stacking sequence have maximum stresses 54.6 MPa and maximum deflections 4.493 mm which are lesser than these values (74.9 MPa & 4.86 mm) for the same blade of 4 mm wall thickness made up of Aluminium.

7. Conclusions

It has been seen that the centrifugal forces play an important role in the design of H-Darrieus vertical axis wind turbine blades. Bending stresses and deflections are not only a function of aerodynamics forces but also very dominantly controlled by centrifugal forces. In order to model the composite materials in any finite element software, the layered SHELL elements should preferably be used instead of layered SOLID elements. SHELL elements are more compatible with complex geometries which have sharp edges, produce equally good results and require less computational time as compared to SOLID elements.

The effect of centrifugal forces acting on the blade can be further reduced by using the Glass-Epoxy instead of Aluminium. This is because Glass/Epoxy has a lower value of density as compared to Aluminium and a high strength to weight ratio. A suitable combination of layers needed to be found in order to reduce both the maximum deflections and maximum stresses when compared with the Aluminium blade. In case of Darrieus straight bladed VAWT, keeping more layers in 90° orientation, reduces the maximum deflection but increases the maximum stress. These maximum values can be reduced by choosing a suitable number of layers in 90° orientation.

Therefore, the best VAWT blade design can be achieved by choosing a material which has low density and high strength. Composite materials, with a right orientation of plies, are best choice to achieve these features. These features help to achieve a high strength to weight ratio which in turn reduces the overall weight of the blade and centrifugal forces acting on it.

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