Structural Optimization of a Composite Wind Turbine Blade (CWTB) for Material and Blade Weight

Prof. Dr. Ramadan A. Almadane[1,*], Prof. Dr. Mustafa. E. Jarnaz[2] , Mrs Eman Alijaly Daman[3],
[1] Libyan Academy for Postgraduate Studies Tripoli - Libya [2] College of Engineering Technology-Jounzur Libya
[*]ramadanalmadani@ymail.com, [2]mustafajarnaz@yahoo.com, [3] eman_daman@yahoo.com

Abstract

In order to reduce electrical energy production costs, the size of commercial wind turbines has grown considerably during the past decade. Currently, the largest wind turbine installed gives more power. However, as the size of the wind turbine rotor increases, the structural performance, durability and dynamic stability requirements tend to become more and more challenging to meet. The two main structural performance requirements for wind turbines are sufficient flapwise bending strength to withstand highly rare extreme static and dynamic loading conditions (e.g. 50-year return-period gust or a short-term extreme operating gust), sufficient flapwise bending stiffness to ensure that a minimal clearance is maintained between blade tip and the turbine tower at all times during wind turbine operation. To satisfy the above two extreme operating conditions, several methods have been proposed to evaluate the extreme structural performances of horizontal axis wind turbine (HAWT) blades. One of these method materials basis and weight of wind turbine blade so in this paper two different blade materials were modeled with ANSYS software and the stress ratio and tip deflection under extreme gust loads and the normal wind load are evaluated. The results were compared and presented for different blade materials.

Index Terms—wind , blade, composite, stress, deflection

INTRODUCTION

THE blade design process starts with a “best guess” compromise between aerodynamic and structural efficiency. The choice of materials and manufacturing process will also have an influence on how thin (hence aerodynamically ideal) the blade can be built, and at what cost. Therefore, the structural engineering process has a critical role in bringing all the disciplines of design and manufacture together and producing the optimum solution in terms of performance and cost. The lift force on the blade, which drives the turbine round, is distributed along the blade approximately in proportion to the local radius, i.e. there is more lift force close to the tip than there is near the hub. [1]

The lift force tends to make the blade bend. It can be noted at a section of the blade at some point along its length, all the lift forces outboard of that point will have a cumulative effect on the tendency to bend, with those furthest away having the greatest effect as they have the greatest leverage. The effect is called bending moment. The bending moment is greatest at the root of the blade: at this point there is more blade outboard (contributing to bending moment) than at any other point along the blade. At the tip the bending moment drops to zero as shown in Fig.1 [1].

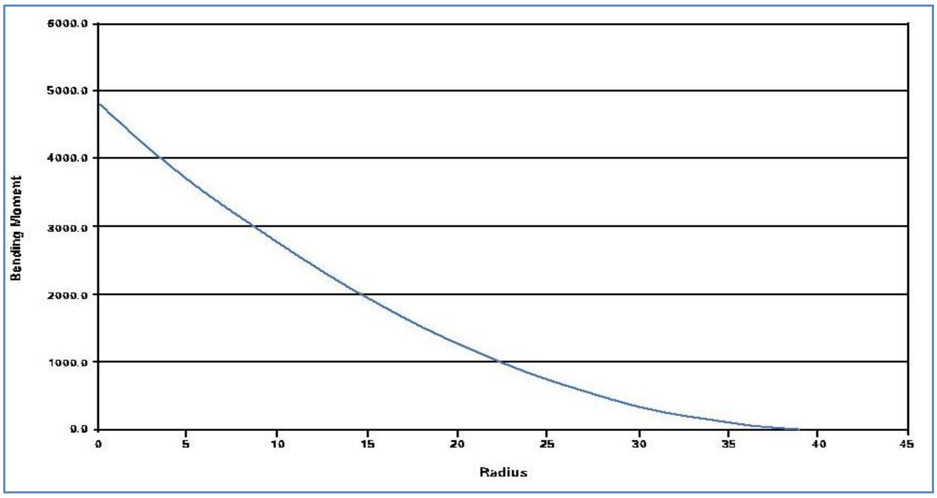


Fig.1 Bending moment against radius in a large turbine blade[1]

So it is intuitive that the blade must be thickest, i.e. strongest, at the root and can taper in thickness towards the tip where the bending moment is less. As it happens, that suits the aerodynamics too: the blade needs a thinner section at the tip where drag is most critical and the local chord (width) of the blade is small. Also for turbines that rely on stall for power regulation in strong winds, a thin section stalls more easily so is beneficial at the tip. Closer to the root the chord is wider, but to avoid making it very wide (hence expensive) the blade needs to be thicker to generate enough lift given the lower wind speed close to the hub (thicker aero foils can generate a greater maximum lift before they stall). Unfortunately the thickness needed to make the blade stiff and strong enough is greater than that required for aerodynamic efficiency, so a compromise must be found between structural weight (= cost) and loss of aerodynamic efficiency.[2]

2. Governing Principle of Wind Turbine Blade

The principle behind the operation of the wind turbine for generating power from the forces of nature is a revolutionary one. The blades harness the energy from the wind by rotation depending on the wind force applied and the direction of the wind. The wind turbine blade geometry plays vital role in power generation process.

The most important part in designing a wind turbine is the blade and the choice of airfoils used at various sections of the blade. The lift generated from these airfoils causes the rotation of the blade and performance of the blade is highly depended of airfoils performance. For this research, SERI-8 wind turbine blade was selected. The SERI-8 was originally designed by the Solar Energy Research Institute (SERI), now called the National Renewable Energy laboratory, (NREL) in 1984. The SERI-8 blade is **7.9 m** long and has a set of airfoils S806A, S806A, S807, S808 airfoils which were designed for medium size turbines rated at 20-100 kW. The airfoils closer to the tip of the blade generate higher lift due to the speed variation in the relative wind. The purpose of the airfoils at the root of blade is mainly structural, contributing to the aerodynamics performance of the blade but at a lower level. Thus the root of the blade is bigger and stronger than its tip.

The SERI-8 blade is shown in Fig.2. The SERI-8 blade is 7.9 m long and was divided into 13 equal sections. The twist axis is located at 30% of chord and the blade geometry. The SERI-8 has two ribs at 60 inch and 252 inch locations from the root, which were not considered in the present research. The geometry data of SERI-8 was found in Ong and Tsai [6]. The baseline design of SERI-8 blade was designed in CATIA v14.5 [9]based on the data provided and imported into the ANSYS design modeler as shown in Fig.2.

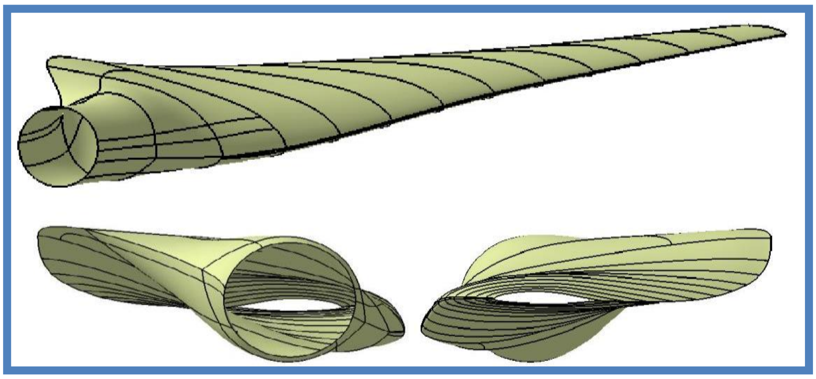


Fig.2. CATIA model of SERI-8 blade[6]

3. Composite Material

Majority of wind turbine blades is made of fiberglass material and reinforced with polyester or epoxy resin. The materials used for SERI-8 blade design were same as that of Ong and Tsai [6]. This design consists of TRIAX and MAT as skin materials and C260 glass/epoxy as the major structural material (Table 1.).

Table 1. SERI-8 composite materials properties [6]

Materials			
	TRIAX	C260	MAT
Density (lb/in^3)	0.085513	0.062757	0.010339
Mass Density (lb/in^3 /g /12)	0.000221	0.000163	2.68E-05
E1 (psi)	3930000	6140000	1100000
E2 (psi)	1640000	1410000	1100000
G (psi)	940000	940000	940000
Poisson's Ratio	0.3	0.3	0.3
Limit Stress Dir 1 Tension (psi)	88200	103000	19000
Limit Stress Dir 1 Compression (psi)	53100	49800	20000
Limit Stress Dir 2 Tension (psi)	13600	2300	19000
Limit Stress Dir 2 Compression (psi)	15000	2300	20000
Limit Shear Stress (psi)	15000	3600	13000
Limit Interlaminate Stress (psi)	15000	3600	13000
Thickness (in)	0.015	0.005	0.005

The reference fiber direction for the composite material is considered along the span direction. All sections have same number of MAT skin material layers. The ANSYS ACP composite prepost [8] was used as a preprocessor for composite layups modeling as well as for post processing to check the failure criteria. The numbers of layers of C260 material for individual sections were tagged as a parameter which would be the input as the structural design variable for the optimization process.

4. Multidisciplinary Design Optimization

In this paper, the cost calculation for one blade based on Ong and Tsai [5] was done. The labor cost, material cost and total cost were calculated. Assumptions were made as per Ong and Tsai's paper [5]. Furthermore, the tooling cost was not considered in this analysis. The total labor hour for each lay-up is taken as 9.1 hours [5]. The total cost for single blade can be calculated as follows:

Material cost = Material mass (lb) × Material cost ($/lb) **(1)**

Labor cost = Total labor hours (hr) × Labor rate ($/hr) **(2)**

Total cost = Material cost + Labor cost **(3)**

The total cost of the blade was calculated by defining new output parameter in ANSYS workbench [9] and mentioned as a design objective to be minimized in the optimization process.

It is not possible to formulate the problem of optimum design of wind turbine blades as a single-criteria optimization task because this process requires many criteria to be taken into account. In many cases, these criteria are mutually incomparable, uncountable and sometimes even contradictory, which precludes their simultaneous optimization. The following criteria have taken into account in the process of optimal wind turbine design,

- Minimize weight of the blade
- Minimize blade total cost
- Minimize blade vibration and keep modal frequency at acceptable level
- Maximize power output
- Accomplishment of appropriate strength requirements

The mass and material cost of a blade is correlated and depends on the blade structural stiffness. If the blade design robustness is at optimal level then both the criteria can be satisfied. The optimal blade thickness for different blade section helps to satisfy these criteria. Minimization of vibration is a better way to obtain optimal design of blade structure and at the same time it contributes to keep the cost low and provide high stiffness. Hence, to minimize vibration, the natural frequency of the blade should be separated from the harmonic vibration associated with rotor resonance. Therefore, mode separation constraint was setup to examine the first three natural frequencies and is separated from each other by more than ±5% of its natural frequency.

Furthermore, to meet the strength requirements of the structure, optimization of maximum displacements of the blade at the tip would have to be carried out with a limiting constraint and permissible stress should not be exceeded. To maximize a torque and hence power, blade pitch angle and shape should be optimized. Henceforth, optimal pitch angle need to be obtained to maximize the power generated.

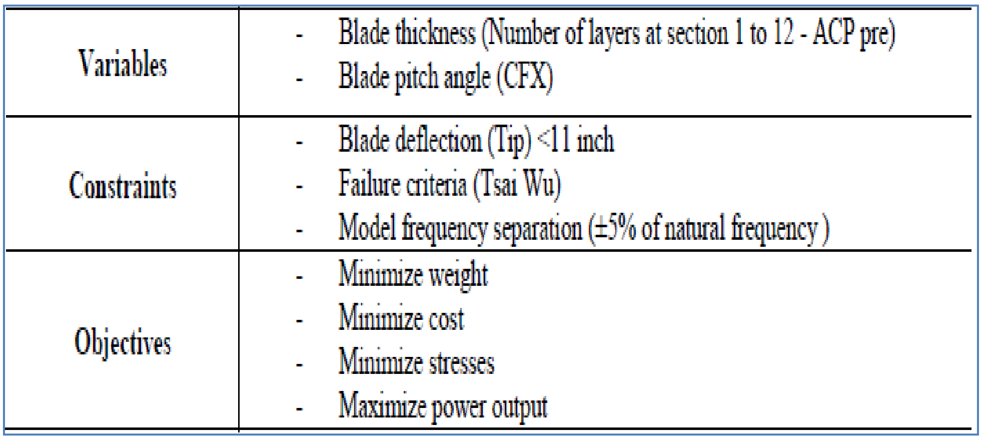
As explained earlier, the main objective of the present work was to develop a multidisciplinary design optimization procedure for SERI-8 blade. The blade needs to be optimized for optimal aerodynamic performance and structural robustness. The key objectives were to minimize mass and cost of the blade and maximize power output. The reference SERI-8 blade was aerodynamically optimized based on BEM theory with modified twist angle. The blade pitch angle was given as an input variable parameter to guarantee a good aerodynamic performance. The numbers of layups at different sections were tagged as a structural design variable.[6]

The constraints in wind turbine blade design are as follows:

- Displacement of the blade cannot exceed the set value (global stability must be ensured),
- Maximum stresses generated in the blade cannot exceed permissible stresses (appropriate strength requirements for the structure)
- Separation of natural frequencies of the blade from harmonic vibrations associated with rotor rotation.

The design constraints, variables and objectives for this case study are summarized in Table 2.

Table. 2. Variables, constraints and objective for the MDO process



Variables	- Blade thickness (Number of layers at section 1 to 12 - ACP pre) - Blade pitch angle (CFX)
Constraints	- Blade deflection (Tip) <11 inch - Failure criteria (Tsai Wu) - Model frequency separation (±5% of natural frequency)
Objectives	- Minimize weight - Minimize cost - Minimize stresses - Maximize power output

ANSYS Workbench 14.5 [9] and design explorer module was used to carry out the multidisciplinary design optimization problem. Design exploration describes the relationship between the design variables and the performance of the blade by using Design of Experiments (DOE), combined with response surfaces and identifies the relationship between the performance of the blade and the input design variables. Once the response surface has been introduced, the optimization study needs to be defined, Central Composite Design-G optimality method was used and desired objectives and constraints were set within the specified domains.

RESULTS

The two comparable materials fiber glass reinforced Epoxy and carbon fiber reinforced epoxy were used in modeling for composite turbine blade with the help of ANSYS finite element software. The stress contour plots and deflection results were obtained as shown in Figs(4,5,6,7).

It was noted that the deflection of carbon fiber-epoxy blade it reduces to 0.78 mm compared to the deflection of fiber glass-epoxy blade which is 5.0 mm this is clearly shown also in the case of stress analysis, which means we can obtain stiff and strong composite wind turbine blade using carbon fiber-epoxy but cost should be considered as well;

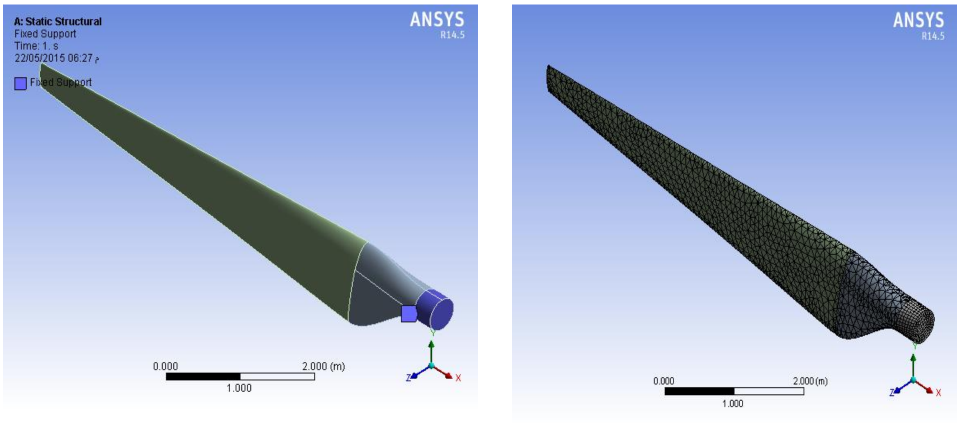


Fig.3. F.E. Model of Composite Turbine Blade

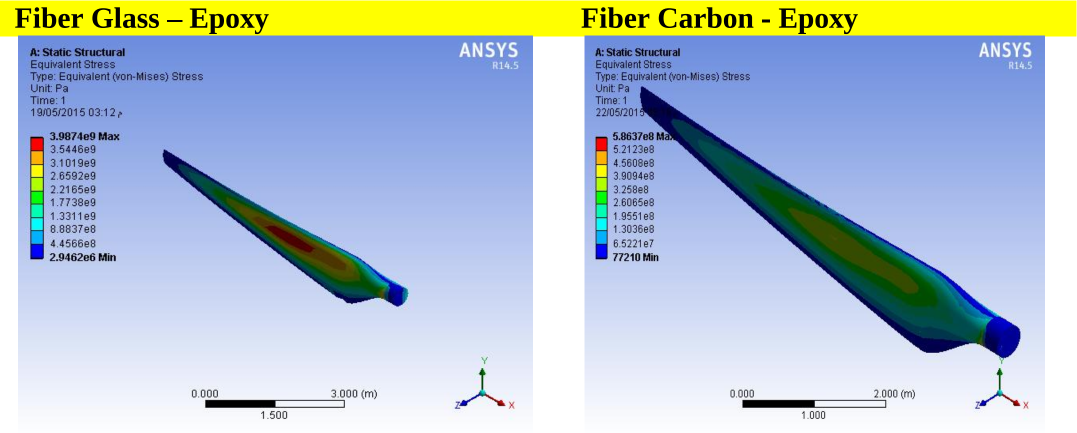

Fiber Glass – Epoxy **Fiber Carbon - Epoxy**

Fig.4. Equivalent Stress of Composite Turbine Blade

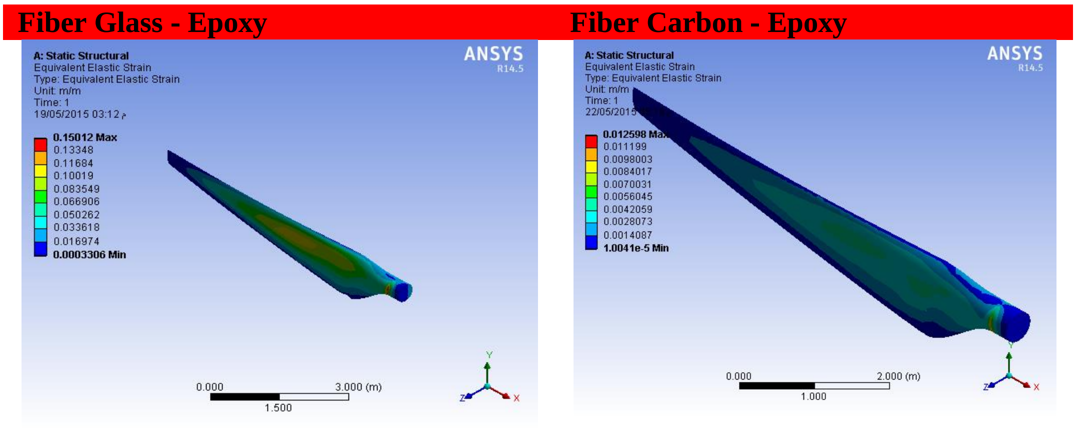
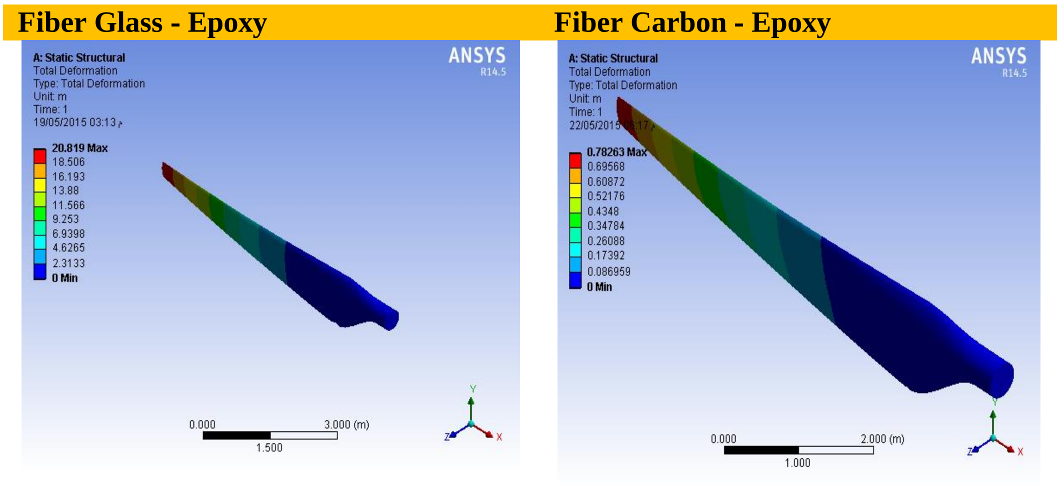

Fiber Glass - Epoxy **Fiber Carbon - Epoxy**

Fig.5. Equivalent Strain of Composite Turbine Blade


Fiber Glass - Epoxy

Fiber Carbon - Epoxy

Fig. 6. Deformation of Composite Turbine Blade

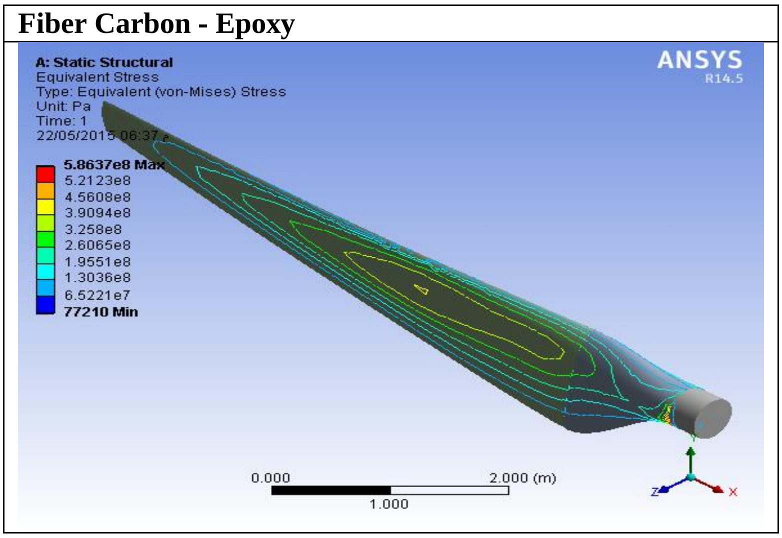

Fiber Carbon - Epoxy

Fig. 7. Iso stress of Composite Turbine Blade

CONCLUSION

The aerodynamic performance of the optimized wind turbine design is improved by about 4% compared to the baseline design. In addition the following were observed in the optimized design: mass reduction of 23.67%, cost reduction of 27.25%, reduction of maximum deformation and maximum stress reduction just by using different material for wind blade this reduction is clearly shown in case using fiber glass and fiber carbon as presented in Figs(4,5,6).

This process presented here can be applied to the design of wind turbine blades to obtain a structurally optimized blade design with optimal blade thickness distribution and maximum deflection using two different composite materials, but in meanwhile consider cost effectiveness of both materials.

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