

STATIC ANALYSIS OF A COMPOSITE WIND TURBINE BLADE USING FINITE ELEMENT MODEL

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Keywords: Composite Materials, Finite Element Analysis, Static Analysis, Wind Turbine Blade

Abstract: This study is presented here that the stress characteristics of an existing 5-meter composite wind turbine blade for 30 kW wind turbine designed for METUWIND is known by using finite element method. Modal and static analysis is performed in order to obtain static and dynamic behavior of the blade. To perform analysis, the geometric three-dimensional model of the blade is obtained by using two-dimensional drawings of the blade. After geometric modeling of the blade, the materials that are used in blade structure are applied to Ansys ACP. Then, the blade structure model is adapted a finite element solver, Ansys Workbench. Finally, loading conditions are applied along the blade and the results are obtained. The results of this study indicate that the internal flange is the main force-supporting part, while other parts of the blade are mainly keeping the blade stable.

1. INTRODUCTION

The long-term reliability of wind turbines is very important for sustainable and economically viable wind energy utilization. Therefore, wind turbine designs must be optimized to minimize costs and maximize lifetime. To do these requires performance and durability characteristics of wind turbine materials, components and structures must be understood extensively. The most critical component of a wind turbine is the composite rotor blade. A rotor blade failure can have a significant impact on turbine downtime and safety. To avoid a blade failure, knowing the strength of the rotor blades is essential. Hence, validation of blade resistance must be checked by structural testing and/or analysis [1]. For instance, a full-scale 34-meter composite wind turbine blade was tested to failure under flap-wise loading and simulated in finite element calculations [2]. Furthermore, to evaluate a proposed medium scale composite wind turbine blade, structural analysis was performed by using the finite element method [3]. However, the

structural testing methods such as full-scale testing of the blade are expensive and troublesome due to constructing a test set-up. The structural analysis of a blade is necessary before testing of the final design. Structural analysis is usually conducted to determine stress distribution, deflections, modal analysis and fatigue behavior. Additionally, to investigate natural frequency of a wind turbine blade it is essential to consider the dynamic characteristics of the turbine like rotational speed, wind speed [4]. The most acceptable and common analysis method for the structural validation of a wind turbine blade is finite element modeling.

The objective of this paper is to develop a finite element model to analyze an existing 5-meter wind turbine blade to check the strength of the blade subjected to static and dynamic loading. The existing blade was designed as part of a project between METUWIND – Center of the Wind Energy and Core Team of the University of PATRAS according to IEC 61400-2 [5]. The blade was designed for a wind turbine that has 30 kW nominal power capacity at 10 m/s wind speed. According to the wind turbine characteristics, the blade optimized aerodynamic and geometric design was finalized by blade manufacturer.

The existing blade consists of five main parts: Suction Side, Pressure Side, internal flange, “hat shaped” chassis, and flange; see Figure 1. Total length of the blade is 5 meters. Two shear webs part of a “hat shaped” chassis and the internal flange are placed in the blade, starting at 0.5 m away from the root and extending up to 4.0 m.

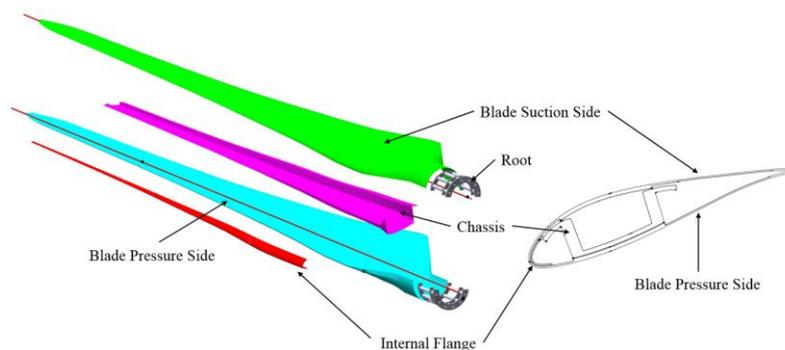


Figure 1. Blade assembly [6].

2. FINITE ELEMENT MODEL

2.1. Geometric Modeling

The two-dimensional blade drawings which include the blade aerodynamic design details such as cord length and twist angle along the blade were provided by the blade manufacturer. By

using these given two-dimensional blade drawings, the three-dimensional geometric modeling of the blade is performed in NX 10.0 environment [7]. The geometric modeling of the blade and some blade sections are given in Figure 2.

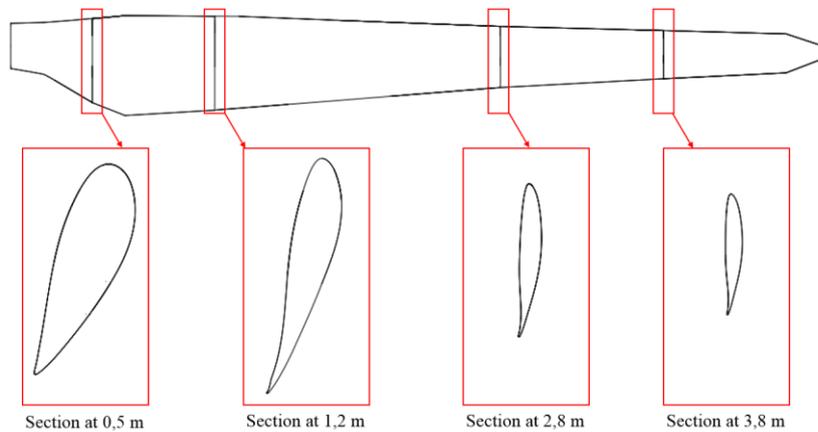


Figure 2. Geometric modeling of the blade.

2.2. Material Modeling

Materials in blade structure are composed of gel coat, steel and composite laminates. In the existing blade, gel coat, chopped strand mat (CSM 300), steel, polymeric foam (Divinycell H45) and two fiberglass composite materials are used. These glass/epoxy composites are: unidirectional laminate and tri-axial laminate. The unidirectional laminate is called METYX L600E10C-0 of 623 g/m² with parallel continuous fibers. The second glass fabric, METYX XL800E10F-[0/45/-45] of 835 g/m², is a tri-axial architecture with fibers in the 0, +45° and -45° directions in a ratio of 2:1:1. These layers have the same properties but different thicknesses.

The laminate materials of the blade are named as follows:

- i. Unidirectional laminate with a thickness of 0.716 mm
- ii. Tri-axial laminate [0/45/-45] with a thickness of $h_{0TRI}=0.483$ mm, $h_{+45TRI}=0.238$ mm and $h_{-45TRI}=0.238$ mm.
- iii. Steel with a thickness of 5.3 mm
- iv. Gel Coat with a thickness of 0.9 mm
- v. CSM 300 with a thickness of 0.358 mm
- vi. The polymeric foam, Divinycell H45 of DiAB group, with thickness varying from 5 mm to 10 mm.

Table 1 lists the experimental material properties of the blade materials [8].

Table 1: Experimental mechanical properties of the UD ply

Material Property		Unidirectional Laminate	Steel	Gel Coat	CSM 300	Divinycell H45
Density, ρ	$[kg/mm^3]$	1896	7850	1200	1896	200
Thickness, h	$[mm]$	0.716	5.3	0.9	0.358	5 or 10
E_1	$[GPa]$	12.17	210	1.95	4.47	0.269×10^{-3}
E_2	$[GPa]$	4.47				
ν_{12}		0.14	0.3	0.17	0.14	0.2
G_{12}	$[GPa]$	1.38				7.35×10^{-3}
X_T	$[MPa]$	191.73	581.8	35.29	16.86	1.4
X_C	$[MPa]$	101.16				0.6
Y_T	$[MPa]$	16.86				1.4
Y_C	$[MPa]$	50.41				0.6
S	$[MPa]$	11.29				0.56

The lamination plan of the pressure and suction sides of the blade can be described below:

- The outer surface of the blade is covered with transparent Gel Coat and a layer of chopped strand mat, 300 g/m^2 CSM 300.
- The root part of the blade is composed of unidirectional laminate, tri-axial laminates and steel.
- The lay-up sequence for the pressure and suction side differs only in the area from 1.25 m to 2.0 m where an additional unidirectional glass fabric was placed in the suction side of the blade.
- The Divinycell H45 foam used in the trailing edge is of 10 mm thickness in the area from 0.7 m to 2.0 m and 5 mm thickness from 2.0 m to 3.0 m.

The composite layups of the blade were defined in ANSYS Composite PrepPost (ACP) [9]. Due to different lamination plan for different blade section, the thickness of the blade varies along the blade. The composite layer thickness changes can be clearly seen from Figure 3. The dark blue areas are the thinnest regions while light blue areas (“hat shaped” chassis area) are thicker regions. The thickest region is the orange region (area from 0 m to 0.2 m) as expected.

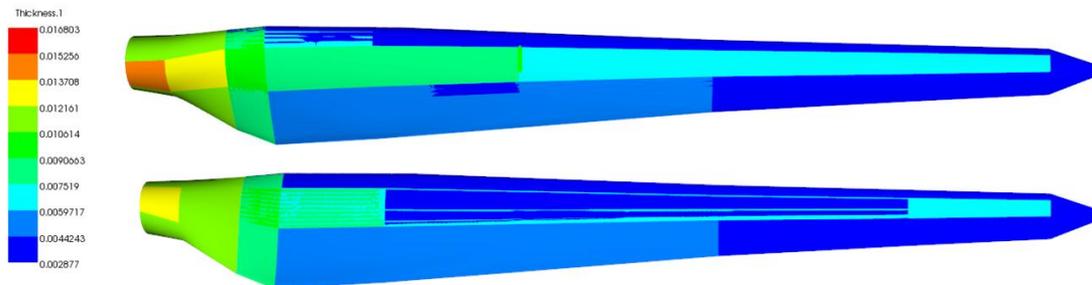


Figure 3. The composite layer thickness for different blade section.

After material modeling of the blade was finished in Ansys ACP, the blade was meshed entirely with 20013 layered shell elements and 42975 nodes in ANSYS Workbench [10]. The fine mesh density was chosen on the blade training edges because of investigating more detailed stress distribution on these areas.

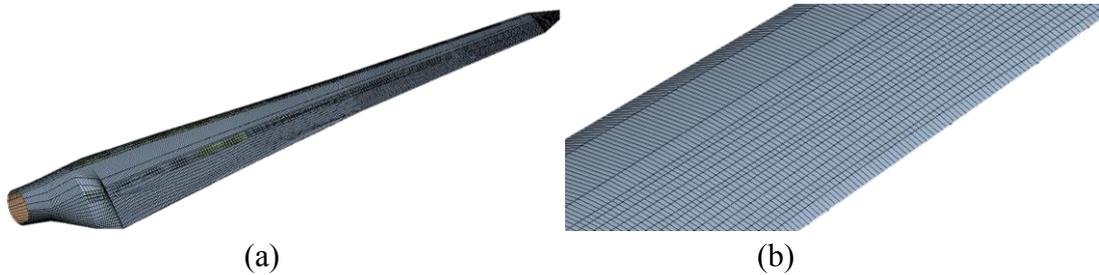


Figure 4. (a) The mesh all around the blade (b) The mesh around the tip of the blade.

3.RESULTS

The result for the modal analysis is presented in Section 3.1 and static analysis is in Section 3.2.

3.1. Modal Analysis

Modal analysis proves to determine dynamic characteristics of wind turbine blades. To estimate the mode shapes and natural frequencies of the existing blade, a modal analysis was performed in ANSYS Workbench. In the modal analysis, the blade was fixed at the root by fixing all degree of freedom. Table 2 presents the results of the modal analysis that calculated the natural frequencies for bending modes in the edgewise and flapwise directions. The mode shapes of the blade in both directions can be seen in Figure 5.

Table 2: Results of modal analysis.

Mode Shapes		Natural Frequencies [Hz]
1 st Mode Shape	1 st Flapwise Bending	6,1
2 nd Mode Shape	2 nd Flapwise Bending	10,9
3 rd Mode Shape	3 rd Flapwise Bending	17,2
4 th Mode Shape	4 th Flapwise Bending & 1 st Edgewise Bending Coupling	29,2
5 th Mode Shape	5 th Flapwise Bending & 2 nd Edgewise Bending Coupling	38,0
6 th Mode Shape	3 rd Flapwise Bending & 1 st Torsion Coupling	42,0

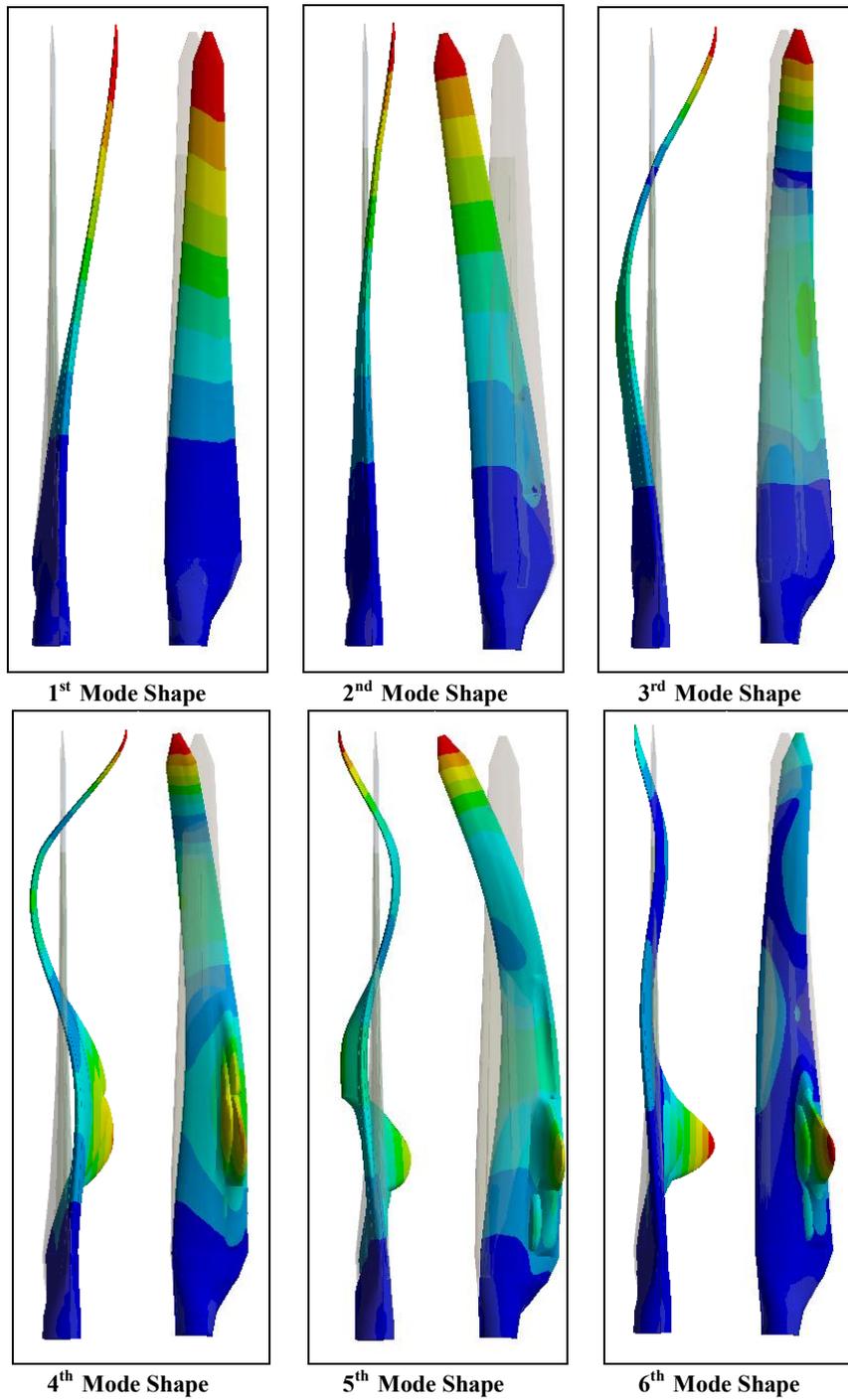


Figure 5. Mode shape of the blade.

3.2. Static Analysis

To investigate the blade behavior under static loading, loading is applied to the blade in both edgewise and flapwise directions. In these directions, loads were selected according to blade design conditions. These design loads were obtained from the worst case scenario of the wind turbine operating conditions. The extreme force distributions on the blade are presented in Figure 6. These forces were placed at 21 stations along the blade. The edgewise and flapwise analysis results are presented in the following sections.

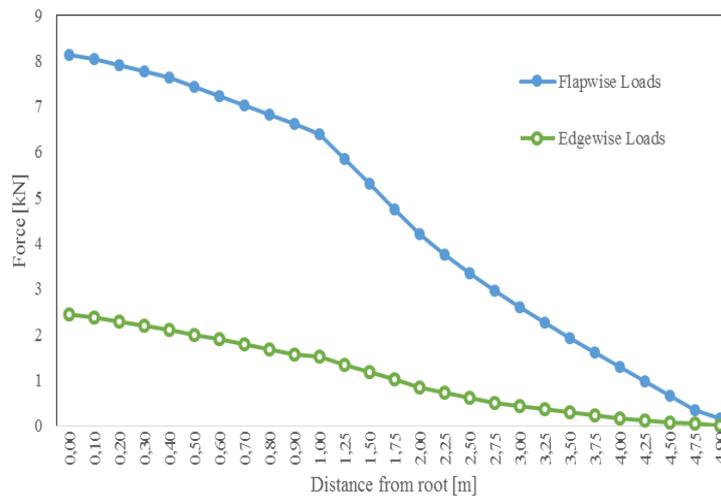


Figure 6. Force distribution over blade radial position

3.2.1. Edgewise Analysis

Blade mass and gravity causes bending moment in the edgewise direction of the blade. In the edgewise analysis, the blade was fixed at the root by fixing all degree of freedom. The weight due to standard earth gravity was added to the extreme design loads given in Figure 6 at the stations along the blade. The deformed geometry and the stress distribution are given in Figure 7 and Figure 8, respectively.

The total deformation occurs at the tip of the blade as expected and has a value of 83 mm in the edgewise direction.

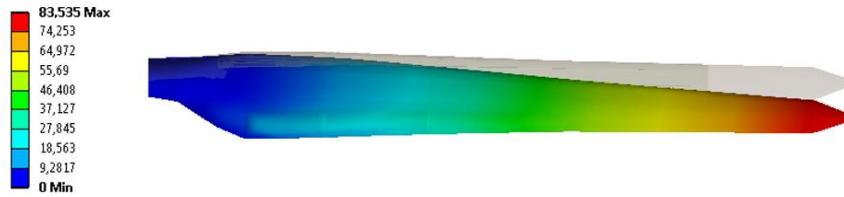


Figure 7. Total deformation under loading in the edgewise direction.

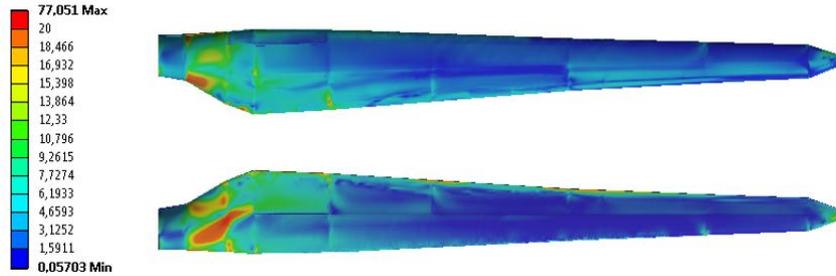


Figure 8. Stress distribution under loading in the edgewise direction in the suction and pressure sides.

The maximum equivalent stress is approximately 77 MPa at 4.0 m from the root. The detailed stress distribution in the blade cross-section at 4.0 m from the root is given in Figure 9. The stress in the pressure and suction sides reaches the maximum value of 26 MPa at the leading edge. In the chassis, the stress is the maximum at the corner of the shear webs and the spar cap near the leading edge. Finally, absolute maximum stress of 77 MPa occurs in the internal flange at the suction side.

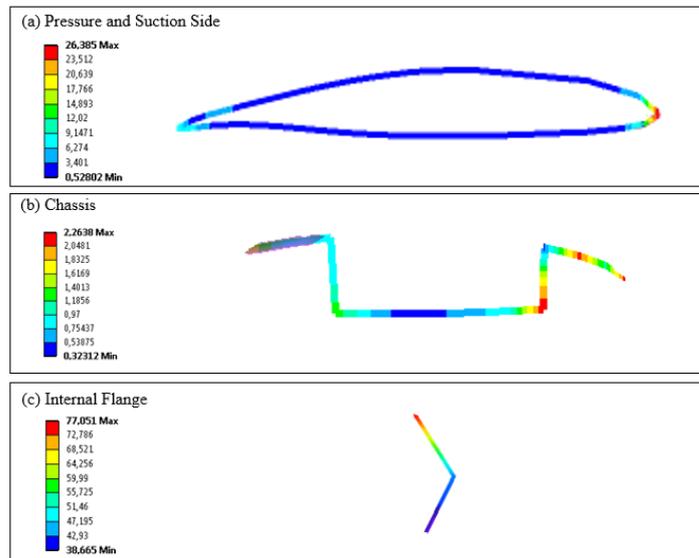


Figure 9. The stress distribution at the blade section at 4.0 m from the root in the a) pressure and suction side, b) chassis, c) internal flange.

3.2.2. Flapwise Analysis

The most significant bending moments in the blade occur in the flapwise direction. Therefore, the blade must have high rigidity in that direction. To evaluate the rigidity, the blade was constructed at the root end surface by fixing all six degree of freedom and flapwise loads are given in Figure 6 were applied along the blade. The deformed geometry and the stress distribution are given Figure 10 and Figure 11, respectively.



Figure 10. Total deformation under loading in flapwise direction.

The total deformation is almost 1.0 m at the tip of the blade.

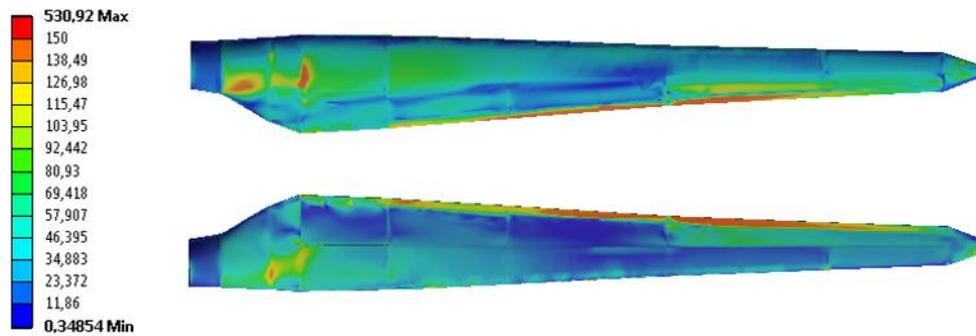


Figure 11. Stress distribution under loading in the flapwise direction in the suction and pressure sides.

The maximum equivalent stress is approximately 530 MPa at 4.0 m from the root. The detailed stress distribution in the blade cross-section at 4.0 m from the root is given in Figure 12. The stress in the pressure and suction sides reaches the maximum value of 78 MPa at the leading edge. In the chassis, the stress is the maximum at the corner of the shear webs and the spar cap near the leading edge. Finally, absolute maximum stress of 530 MPa occurs in the internal flange at the suction side.

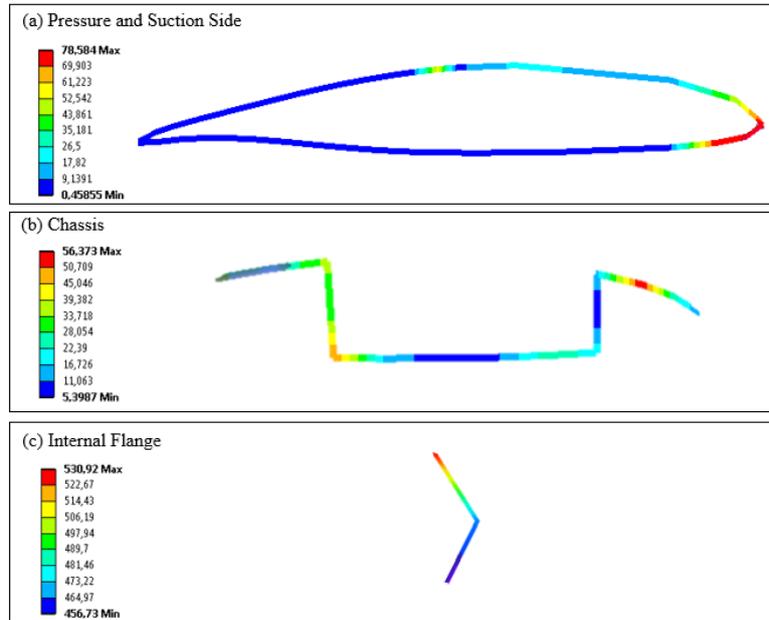


Figure 12. The stress distribuion at the blade section at 4.0 m from the root in the a) pressure and suction side, b)chassis, c) internal flange.

4. CONCLUSIONS

Within the scope of this article, an existing 5-meter long wind turbine blade was modeled and analyzed with finite element program using Ansys Workbench environment. Static and modal analyzes were performed to investigate edgewise and flapwise loading behaviors. The loads were selected according to blade design conditions.

The lowest frequency from the modal analysis was found to be 6.1 Hz for first mode. The primary modes are found to be dominantly of either in the flapwise or edgewise direction. The edgewise and flapwise coordinates are coupled in the mode shapes, and the coupling is not negligible.

Both edgewise and flapwise static analysis shows that the whole stress level at the internal flange is higher than that of chassis, pressure and suction sides of the blade. It indicates that the internal flange is the main force-supporting part, while other parts of the blade are mainly keeping the blade stable.

In the light of the points having been put forward so far, it can be concluded that main function of the chassis is not to support bending loads, but to resistance shear deformation, and to enhance the structural stability of the blade.

5. REFERENCES

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