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STRUCTURAL AND MODAL ANALYSIS OF WIND TURBINE BLADES

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Abstract - *Wind turbine blades are complex structures made of 3D surfaces resulting from the assembly of airfoil sections with various chord lengths, different twist angles etc. They are usually constructed from glass reinforced fibers, carbon reinforced fibers etc. and they should be light and rigid as possible. Throughout their operating life, wind turbine blades are subjected to huge wind forces. This paper aims to find the structural and modal analysis of a horizontal axis wind turbine blade and the effect of spars shape by defining the natural frequencies and vibration mode shapes of I shaped and Box shaped spars for the entire blade. The analysis is done using ANSYS Finite element analysis software. The results show that the resonance effect does not occur for the blade and also the proposed layup model offer sufficient resistance to the structure*

Key Words: Wind turbine blades, Spar, Materials, Resonance, Finite element analysis

1. INTRODUCTION

Wind power production has been under the main focus for the past decade in power production and also tremendous amount of research work is going on renewable energy, specifically on wind power extraction. Wind power provides an ecofriendly power generation and helps to meet the national energy demand when there is a diminishing trend in terms of non-renewable resources. Thus, the wind energy sector has grown rapidly in the past few years. This leads to an increase in the establishment of wind turbines [1-3].

There are mainly two types of wind turbines. Horizontal axis wind turbines (HAWT) and Vertical axis wind turbines (VAWT). In HAWT the axis of rotation of the blades are horizontal and in VAWT the axis of rotation of the blades are vertical. In this paper the analysis was carried out on HAWTs. For these wind turbines, the favorable wind speed ranges from 5m/s to 25m/s.

2. METHODOLOGY

2.1 Profile Selection

The most important step to design a wind turbine blade is to generate or select a profile of blade which is used for further design of the blade. SERI, NACA etc. are various international agencies which define various blade profiles according to the various configuration of blade to be designed.

In the airfoil profile, the forward point is called the leading edge and the rearward point is called the trailing edge. The straight line connecting the leading and trailing edges is called the chord line of the airfoil. The distance from the leading edge to the trailing edge measured along the chord line is chord (c). The locus of points midway between the lower surface and upper surface when measured normal to the chord line is called mean camber line. The camber is the maximum distance between the mean camber line and the chord line, measured normal to the chord line. The thickness (t) is the distance between the upper and lower surfaces also measured normal to the chord line. The shape of the airfoil at the leading edge is usually circular, with a leading-edge radius of 0.02c, where c is the chord length. The upper and lower surfaces are also known as suction and pressure surfaces respectively. The angle of attack (α) is the angle between the chord line and the relative wind direction [4].

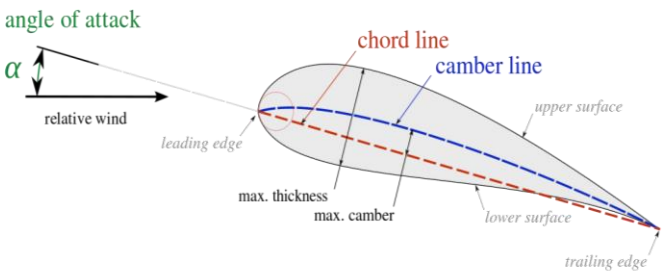

Fig -1: Airfoil Nomenclature

Table -1: Selection of airfoil

Blade Length (m)	Generator Size (kW)	Thickness Category	Airfoil Families
1-5	2-20	Thick	S822, S823
1-5	2-20	Thin	S801, S803, S804
5-10	20-150	Thin	S805, S806, S807, S808
10-20	150-400	Thin	S809, S810, S814, S815
20-25	400-1000	Thick	S816, S817, S818

Table -2: Properties of different airfoil

Airfoil	Re.No. x 10^6	t/c	$C_{L\,max}$	$C_{D\,min}$
S810	2.0	0.180	0.9	0.006

S809	2.0	0.210	1.0	0.007
S814	1.5	0.240	1.5	0.012
S815	1.2	0.260	1.1	0.014

In this analysis, blades of length 20m and power output of 240kW were taken. So, from **Table 1** S809, S810, S814, S815 airfoil families were selected [5,6]. From **Table 2** S810 airfoil profile has the lowest value for $C_{L\,max}$ (0.9). Since the $C_{L\,max}$ value is low, it allows the use of longer blade. Thus, the swept area increases and the power production also increases even at low wind speed. Thus, for the analysis S810 airfoil profile was selected. **Fig. 2.** shows the profile of S810 airfoil.

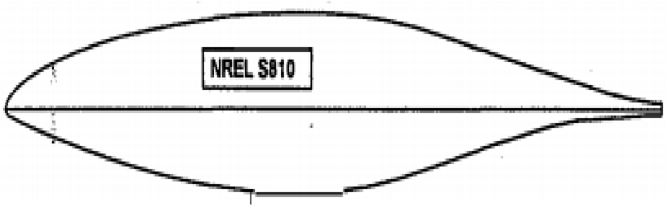

Fig -2: S810 airfoil profile

2.2 Structural Loads

After the selection of profile next step is to define the structural loads acting on blade and it is decided by the operating conditions of the blade. The wind turbine blades are mainly subjected to flap wise loading and edge wise loading. Flap wise loading is due to wind pressure and edge wise loading is due to torsional and gravitational loads.

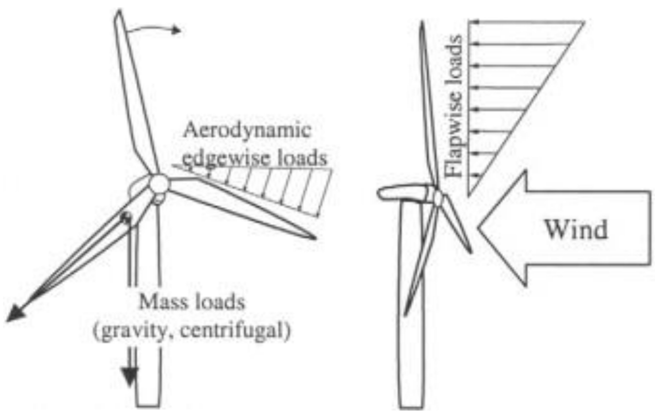

Fig -3: Edge wise and Flap wise loading

2.3 Spars

Spar is main load bearing structure of a wind turbine blade. It is used for reducing deflection of cap and web. It is chief structure to endure the force and bending moment in a blade, its size has a significant impact on the blade mass and the stiffness of blade. In this analysis two different shapes of spars are considered namely, I shaped and Box shaped spar.

Fig -4: I shaped spar

Fig -5: Box shaped spar

The entire structure of a blade undergoes considerable effort over its operation duration. The rigidity of the blade is therefore essential to resist bending. Generally, two strips of reinforcement material are often used to allow local reinforcement. However, to ensure the shear strength, these two strips must be structurally joined by a construction called spars. There are several ways to design those spars (either in the form of a beam connected by one or two longitudinal members or in the form of support structures of the load) [7,8]. The structural rigidity of the spar is essential because it prevents the blade from hitting the tower during rotation but they also had to be lightweight [9].

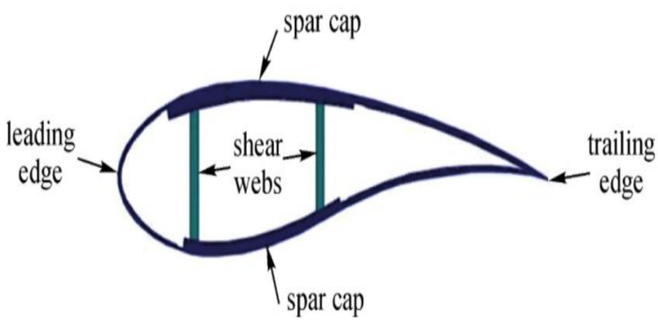

Fig -6: Spars geometry

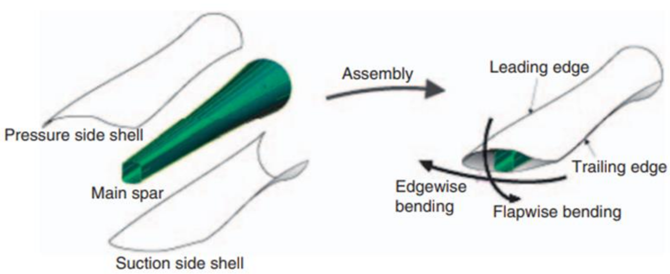

Fig -7: Structure of wind turbine blade

2.4 Material Selection

A wind turbine blade material should be light and have high strength and load carrying capacity [10]. Here two different materials namely Carbon fibers and Glass fibers are used.

Carbon fibers are fibers of diameter about 5 to 10 µm and composed mostly of carbon atoms. They have several advantages including high stiffness, high tensile strength, light weight etc. But they are expensive. Its structure consists of sheets of carbon atoms arranged in a regular hexagonal pattern.

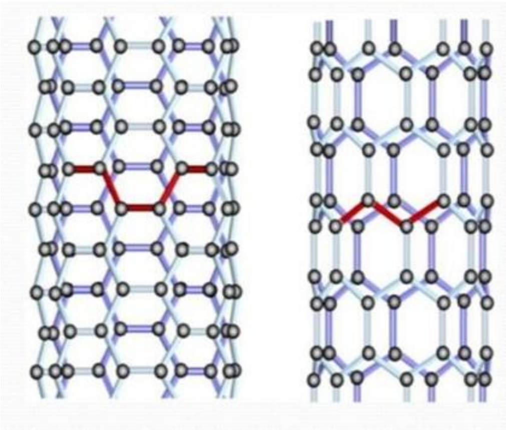

Fig -8: Structure of carbon fibers

Glass fibers are fibers of diameter about 5 to 24 µm and is made from extremely fine fibers of glass. It has high strength, low density, good electrical properties etc. also it is less expensive. Common glass fibers are silica based. It forms SiO_4 groups with tetrahedral structure with silicon atom at the center and four oxygen atoms at the corners.

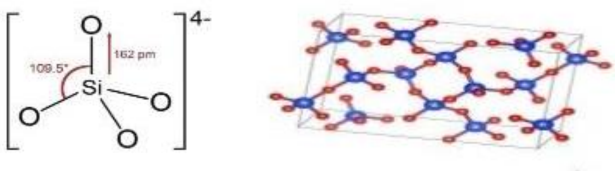

Fig -9: Structure of glass fibers

Table -3: Properties of Carbon and Glass fibers

Parameters	Carbon fibers	Glass fibers
Fiber diameter	5-10 µm	5-24 µm
Tensile modulus	294 GPa	78.5 GPa
Tensile strength	5880 MPa	1956 MPa
Density	1.8 g/cm³	2.55 g/cm³
Failure strain	2%	2.5%

Fig. 10 represent the stratification model for the shear webs, which consists of a sandwich material, with six plies of carbon/glass fibre oriented [- 45/45]3 and a total thickness of 2 mm of the skin and 50 mm of foam. **Fig. 11** represent the layup parameters of spars cap, giving by nine plies of carbon/glass fibre oriented [-45/0/45]3 with a total thickness of 8.7 mm [11].

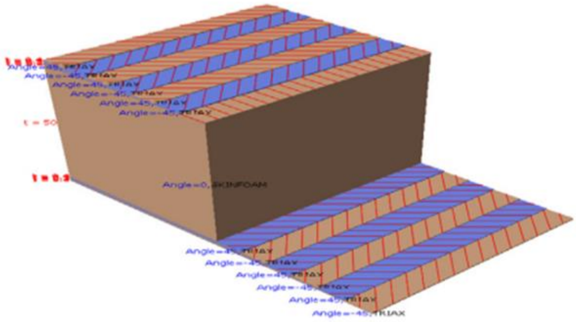

Fig -10: Stratification model for the shear webs

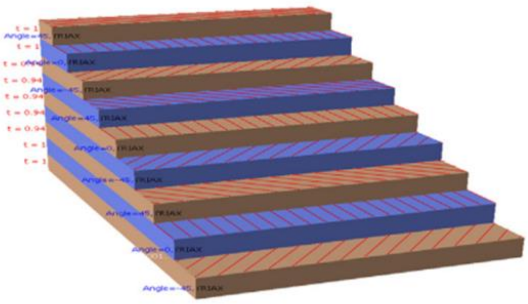

Fig -11: Layup parameters of spars cap

3. CALCULATION OF WIND POWER

Wind turbines work by converting the kinetic energy in the wind first into rotational kinetic energy in the turbine and then electrical energy that can be supplied. The energy available for conversion mainly depends on the wind speed and the swept area of the turbine. Thus, wind power can be calculated by using the following formula:

$$P = \frac{1}{2} \rho A V^3$$

where ρ is the density of air, A is the circular area covered by the blade and it is called as swept area (πR^2), V is the speed of the wind.

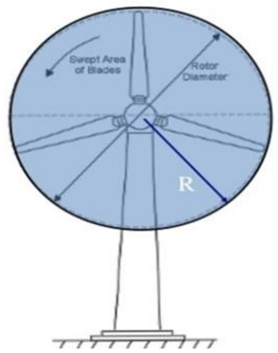

Fig -12: Swept area of wind turbine

Table 4 shows all the properties used in design of the blade and boundary conditions used in ANSYS for the purpose of analysis. Whole three-dimensional model of aerofoil has been constructed in ANSYS and linear quasi statics analysis has been done in ANSYS software. At the trailing edge of aerofoil (at X=0) all degree of freedom has been locked and at leading edge of aerofoil (at X=L) load of 10KN is applied. After that results are observed for particular duration of time [10].

Table -4: Parameters used for the design of wind turbine blade

Properties	Quantitative approach used
Wind speed	5-10 m/s
Length of blades	20 m
Power output	240 kW
Profile used	S810
Angle of attack	15°
Material used	Carbon fiber, Glass fiber
Spar used	I shaped spar, Box shaped spar
Coefficient of lift	0.9
Lift force	10 kN
Drag force	Negligible
Boundary conditions	All DOF are arrested at the trailing edge (at X=0). 10kN load is applied at the leading edge (at X=L).

4. RESULTS AND DISCUSSION

4.1 Structural Analysis

S810 profile is designed with I shaped and Box shaped spar using ANSYS. The stresses exerted in both the cross sections of the wind turbine blade using I shaped spar and conventional box shaped spar is compared with each other as the input parameters and boundary conditions of both the cross section is kept the same.

Chart 1 represents the Von-mises stress induce in both the profiles with respect to time even though the loads applied is quasi static. It is evident from the graph that stresses induced in Box shaped spar is more than the stresses induced in I shaped spar.

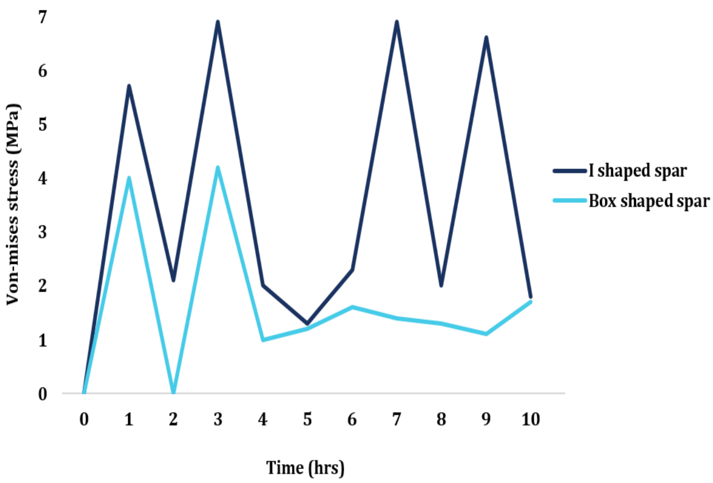

Chart -1: Comparison of I shaped and Box shaped spars

Chart 2 represents the comparison between the Von-mises stress acting on the Carbon Fiber and Glass Fiber. It is evident from the graph that stresses induced in Glass Fiber is more than the stresses induced in Carbon Fiber.

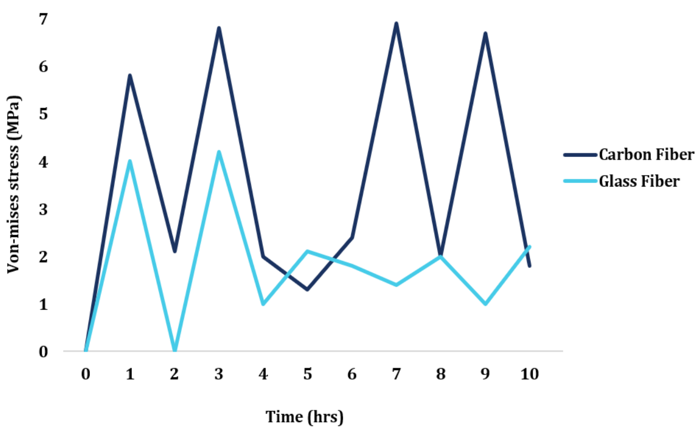

Chart -2: Comparison of Carbon and Glass Fibers

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4.2 Modal Analysis

Table -5: Frequency and Displacement of I shaped and Box shaped spars for the first three modes

Spar Shape	Frequency & Displacement	1st Mode	2nd Mode	3rd Mode
	F (Hz) U (mm)	0.313 1.016	0.471 1.173	0.631 1.077
	F (Hz) U (mm)	0.348 1.012	0.548 1.038	0.971 1.028

Fig. 13(a)to **Fig. 14(c)** shows the displacements of I shaped and Box shaped spars for the first three modes of frequency with a scale (x4600) in order to be seen in the visualizations. Moreover, **Chart 3** & **Chart 4** are graphs showing the variation of the displacement with spars length for the first three modes. From the graphs it is clear that displacement of Box shaped spar is less than I shaped spar.

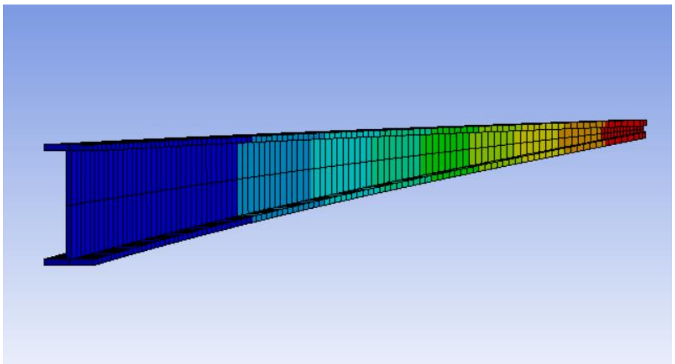

Fig -13(a): Displacement of I shaped spar at mode 1

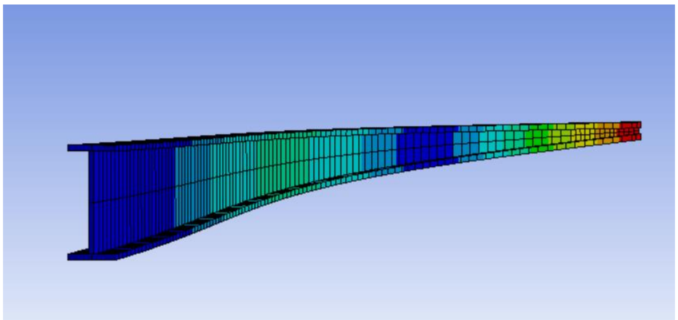

Fig -13(b): Displacement of I shaped spar at mode 2

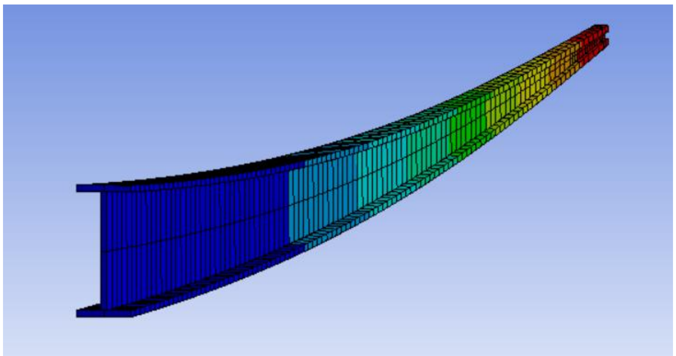

Fig -13(c): Displacement of I shaped spar at mode 3

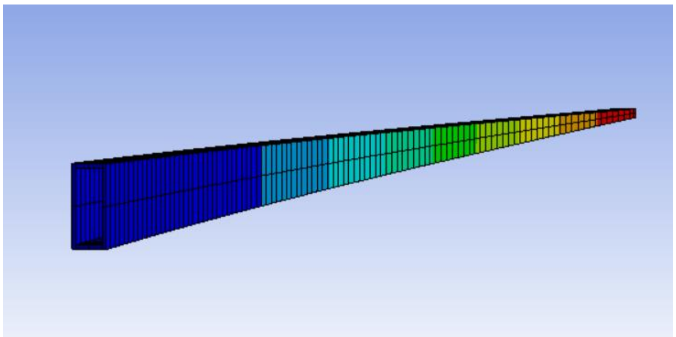

Fig -14(a): Displacement of Box shaped spar at mode 1

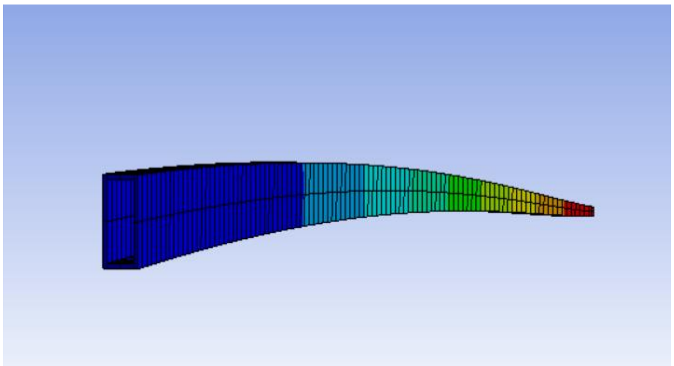

Fig -14(b): Displacement of Box shaped spar at mode 2

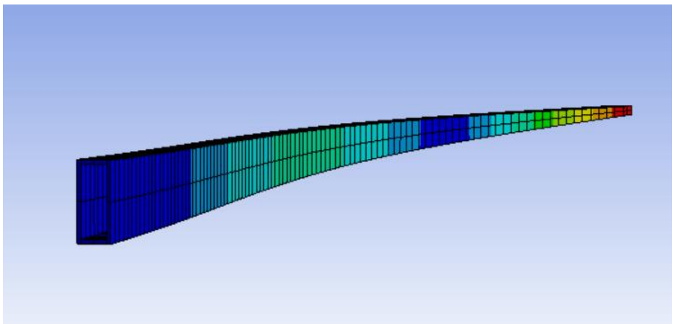

Fig -14(c): Displacement of Box shaped spar at mode 3

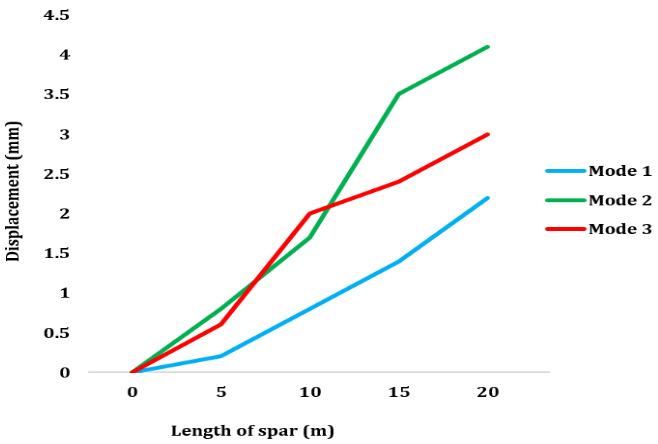

Chart -3: Displacement vs Length for I shaped spar

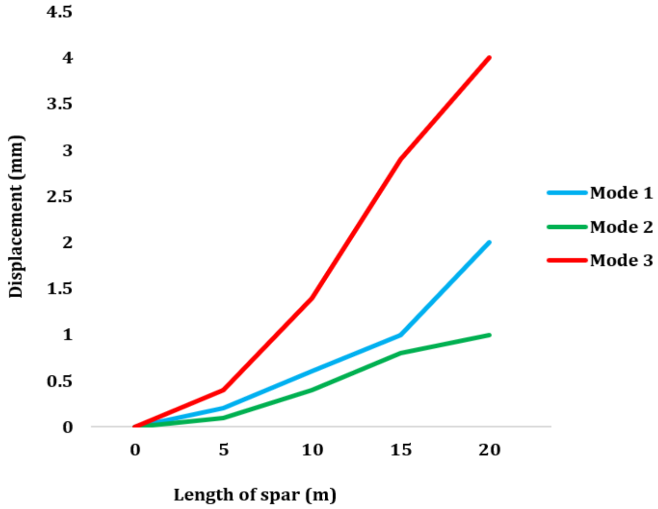

Chart -4: Displacement vs Length for Box shaped spar

According to Germanischer Lloyd Wind Energy GmbH regulations for certification and standards for wind turbines, to avoid the phenomenon of resonance, we have to check the condition giving by equation:

$$F_R / F_n \leq 0.95 \quad \text{or} \quad F_R / F_n \geq 1.05$$

where F_R is the maximum rotating frequency of the rotor (F_R = 0.267 Hz) and F_n is the n^{th} natural frequency of the tower [11]. **Table 6** shows the ratio of F_R / F_n for both I shaped and Box shaped spars for the first three modes. From the table it is clear that both spars satisfied the above equation and Box shape spar possess the least value than I shaped spar.

Table -6: Computational results of the resonance effect for the two spars

	Spar Shape	1st Mode	2nd Mode	3rd Mode
	I shaped spar	0.830	0.552	0.412
F_R / F_n	Box shaped spar	0.748	0.474	0.268

5. CONCLUSION

From the structural analysis it was found that I section can withstand more high loads as compared to Box shaped spar and therefore it can be concluded that it is better to use, I section on the action of wind turbine acting on high loads. But I section also requires more material than box spar and also the design and construction of box shaped spar is comparatively easy. Also, it can be concluded that the use of Carbon Fibre can be very effective even more than Glass Fibre. But Carbon Fibre is more costly than Glass Fibre, so it must be used when the wind turbine is designed with the consideration that it has to withstand a large amount of load.

From the modal analysis it was found that for the first three modes resonance will not occur for both I shaped and Box shaped spars and the value of F_R / F_n was less for Box shaped spar compared to I shaped spar.

So, while considering both the structural and modal analysis it can be concluded that, in the regions where lower wind speed is experienced it is better to establish wind turbine with Box shaped spar and Glass Fiber as the material. Whereas in regions where higher wind speed is experienced it is better to establish wind turbine with, I shaped spar and Carbon Fiber as the material.

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