International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 7 Issue 06, June-2018

Finite Element Analysis and Design Optimization of Ocean Current Composite Turbine Blade

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Abstract - **Marine energy is a promising method of generating electricity from ocean tides in the very near future. The blades that are present in the turbine used for electricity production suffers from problems like vibration and buckling .Vibration characteristics of an ocean current turbine blade can be analyzed using Finite Element Analysis. The design of composite structures such as an ocean current turbine blade is a challenging problem due to the importance for pushing the material utilization to the specific limit in order to obtain cost effective and light structures. As a consequence of the minimum material design versus more efficiency strategy, the structures are becoming thin-walled, concludes that buckling problems may be addressed, and in this research work the aim is to obtain static, modal and buckling analysis of ocean current turbine blades.**

Keywords* – *CFRP, FEA, GFRP, Modal Analysis, Prestress, S2 Glass, Static Analysis

I. INTRODUCTION

Oceans cover more than 71% of earth surface. They offer largest and renewable energy resource that is capable of producing large amounts of sustainable power. The cleanest and most abundant source of renewable energy is that of oceans. The two most significant and sustainable energy forms of renewable energy are through ocean thermal conservation (OTEC) and kinetic energy conservation (KEC). OTEC uses the thermal gradient produced as a result of heat absorbed by the sun at /near the surface and the much cooler water far beneath the surface to produce energy. KEC is associated with the waves, current, and tides, producing energy using a turbine or wave buoy. As the price of fossil fuel increases alternative forms of energy become more and more attractive.

To date, lack of robust and alternative concepts, challenging environmental conditions, high installation and maintenance costs, and limited financial investment have prohibited widespread commercialization of free flow turbines for tidal, ocean current and river applications. The challenging hydrodynamic conditions require considerable emphasis on operational, structural, and mechanical fatigue aspects of turbine design. Blade and structural failures have been caused by inadequate design and/or manufacturing defects that cannot withstand the harsh and under water conditions. Unsteady flow due turbulence, wave activity, and depth variations cause unsteady blade loading, resulting in fatigue. Fatigue occurs as a result of vibration of turbine blade. Thus reduction in vibration reduces fatigue. Designing reliable components requires both in-depth vibration and stress analysis.

A vibration analysis determines the natural frequencies and mode shapes of turbine blade. The mode shapes and natural frequencies are important parameters in the design of an ocean current turbine blade for dynamic loading conditions. Modal analysis can also be performed on a pre-stressed spinning turbine blade. Buckling analysis are of the blade with the pre stressed and free vibration mode should also be considered in this analysis. For that the first four buckling modes of the blade is analyzed. The purpose is to find if the modal with specific material is safe from buckling effect.

II. MATERIALS CHOSEN

A composite material (also called a composition material or shortened to composite, which is the common name) is a material made from two or more constituent materials with significantly different physical or chemical properties that, when combined, produce a material with characteristics different from the individual components. The individual components remain separate and distinct within the finished structure, differentiating composites from mixtures and solid solutions.

Composite materials are ideal for application of structures in the ocean environment with their high strength to weight ratio, excellent corrosion resistance, and ability to tailor a design compatible with loads.

The materials chosen for the analysis of turbine blade are:

- Carbon Fiber Reinforced Polymer
- Glass Fiber Reinforced Polymer
- S2 Glass

III. CARBON FIBER REINFORCED POLYMER

Carbon fiber reinforced polymer, carbon fiber reinforced plastic or carbon fiber reinforced thermoplastic (CFRP, CRP, CFRTP or often simply carbon fiber, carbon composite or even carbon), is an extremely strong and light fiber-reinforced plastic which contains carbon fibers. They can be expensive to produce but are commonly used wherever high strength-to-weight ratio and rigidity are required, such as aerospace, automotive, civil engineering, sports goods and an increasing number of other consumer and technical applications. CFRPs are composite materials. In this case the composite consists of two parts: a matrix and reinforcement. In CFRP the reinforcement is carbon fiber, which provides the strength. The matrix is usually a polymer resin, such as epoxy, to bind the reinforcements together. Because CFRP consists of two distinct elements, the material properties depend on these two elements.

Property	Value	Unit
Density	1750	kg/m^3
Orthotropic Elasticity		
Young’s Modulus X direction	77300	MPa
Young’s modulus Y direction	4600	MPa
Young’s modulus Z direction	4600	MPa
Poisson’s Ratio XY	0.220	
Poisson’s Ratio YZ	0.3	
Poisson’s Ratio XZ	0.22	
Shear Modulus XY	3270	MPa
Shear Modulus YZ	1860	MPa
Shear Modulus XZ	3270	MPa
Field variables		
Temperature	Yes	
Shear Angle	No	
Degradation Factor	No	
Tensile Yield Strength	846	MPa

Table 1. Material properties of CFRP

IV. GLASS FIBER REINFORCED POLYMER

First developed in the mid 1930's, Glass Fiber Reinforced Polymer (GFRP) has become a staple in the building industry. Originally used merely for the construction of parts, in 1967, the architectural advantages were discovered with the attempted destruction of Disneyland's "House of the Future."

Today, Stromberg Architectural provides a variety of products in GFRP to fit your building needs and aesthetic vision. Stromberg’s in-house design and drafting teams work closely with the client to capture idea on paper. Once all the drawings have been approved, our sculptors carve a model to specifications. A mould is then made of fiberglass, steel, wood or rubber depending on the detail. Into this mould a carefully designed mix of polyester or epoxy resin is sprayed, along with alkali resistant glass fibers. Virtually any shape or form can be molded. GFRP can be used for both interior and exterior fixtures in a variety of shapes, styles, and textures; in new buildings or restorative projects.

Property	Value	Unit
Density	1000	kg/m^3
Orthotropic Elasticity		
Young’s Modulus X direction	28900	MPa
Young’s modulus Y direction	4000	MPa
Young’s modulus Z direction	4000	MPa
Poisson’s Ratio XY	0.26	
Poisson’s Ratio YZ	0.3	
Poisson’s Ratio XZ	0.26	
Shear Modulus XY	1520	MPa
Shear Modulus YZ	1520	MPa
Shear Modulus XZ	2650	MPa
Field Variables		
Temperature	Yes	
Shear Angle	No	
Degradation Factor	No	
Tensile Yield Strength	464	MPa

Table 2. Material properties of GFRP

V. S2 GLASS

Glass fiber (or glass fiber) is a material consisting of numerous extremely fine fibers of glass. mass manufacture of glass fiber was only made possible with the invention of finer machine tooling. Glass fiber has roughly comparable mechanical properties to other fibers such as polymers and carbon fiber. Although not as strong or as rigid as carbon fiber, it is much cheaper and significantly less brittle when used in composites. Glass fibers are therefore used as a reinforcing agent for many polymer products; to form a very strong and relatively lightweight fiber-reinforced polymer (FRP) composite material called glass-reinforced plastic (GRP), also popularly known as "fiberglass". This material contains little or no air or gas, is denser, and is a much poorer thermal insulator than is glass wool. Glass fiber is formed when thin strands of silica-based or other formulation glass are extruded into many fibers with small diameters suitable for textile processing.

Property	Values	Unit
Density	1.58	kg/m^3
Orthotropic Elasticity		
Young’s modulus X direction	143000	MPa
Young’s modulus Y direction	10000	MPa
Young’s modulus Z direction	10000	MPa
Poisson’s Ratio XY	0.3	
Poisson’s Ratio YZ	0.52	
Poisson’s Ration XZ	0.3	
Shear Modulus XY	6000	MPa
Shear Modulus YZ	3000	MPa
Shear Modulus XZ	5000	MPa
Field Variables		
Temperature	Yes	
Shear Angle	No	
Degradation Factor	No	

Table 3. Material properties of S2 Glass

VI. BLADE GEOMETRY

The NACA 4 series has a more round leading edge and a thicker trailing edge than most other foils used in the marine energy industry. This allows it to distribute in-plane loads more accurately and uniformly; loads of traveling ocean debris is distributed uniformly without inserting load-impact on blades in NACA 4 series blade models. The thicker trailing edge is also comparatively easier to fabricate and makes the use of a trailing edge web possible.

BLADE PARAMETERS	VALUES
Rotor diameter(m)	6.75
Blade length(m)	3
Number of blades	3
Swept area(m^2)	35.3
Design flow speed(m/s)	1.7
Design RPM	25
Maximum flow speed(m/s)	2.5
Maximum RPM	36.5

Table 4. Rotor blade characteristics

Blade Element Theory

Blade Element Theory (BET) was used to design an ocean current turbine blade. This method assumes the blade is composed of hydro dynamically independent, narrow strips, or elements. Each differential blade element of chord and width located at a radius from the rotor axis is considered as a hydrofoil section. BET is an iterative method which can be used to find an efficient hydrodynamic shape of a blade and the corresponding forces that act on it. Eight blade elements, or sections, of width 0.3 m were used for designing the proposed rotor blades. Figure contains an illustration of the loads that act on a local blade section.

VII. FINITE ELEMENT METHOD

Finite element analysis is a numerical method of solving problems of engineering and mathematics and mathematical physics. It is also called as finite element analysis (FEA).

All models were generated using the bottom-up solid modeling method in ANSYS Classic. The skin and web material properties were entered as orthotropic and the stacking sequence was defined using the section data command. The skin and webs were meshed using SOLSH190, a linear layered 3-D, 8-node, 3 degree of freedom (DOF) per node element. The isotropic core material was meshed with SOLID186, a 3-D 20-node, 3 DOF per node quadratic element. By meshing in the order of linear to quadratic all midside nodes are eliminated resulting in proper element connectivity. The EORIENT command was used to ensure that the skin and web elements were properly aligned.

Vibration analysis of each design was conducted. A linear static structural analysis and an Eigen value buckling analysis was also conducted for each of the designs.

A failure analysis was also carried out using Tsai-Wu and Maximum Stress criterions. The flap wise pressure distribution was applied and the root was fixed in degrees of freedom.

Natural frequencies and mode shapes of any structure can be extracted from ANSYS. It is also capable of performing modal analysis on a pre-stressed structure to include stiffening and thermal effects from static loads. ANSYS modal cyclic such as plasticity and contact (gap) elements are ignored symmetry obtains natural frequency and mode shapes of a cyclically symmetric structure by modeling just one of its sectors. ANSYS modal analysis is a linear analysis. Any non-linearity, even if they were defined.

In this paper we investigate model for modal analysis to predict the natural frequencies and mode shapes of the entire structure of blade. Model was generated using the Pro/Engineer software package by using NACA 48 series, and then the models were imported to the ANSYS workbench v14.0 using .iges extension. The skin and web material properties were entered as orthotropic and the stacking sequence was defined using the section data command.

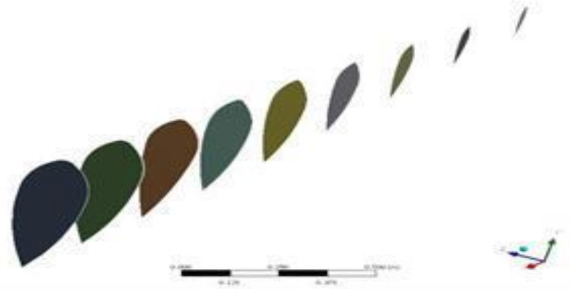


Figure 1. Section wise distribution of blade

VIII. MESHING

Generating a good mesh is the most important part of CFD problem, to reduce overall mesh size confine small cells to area where they are needed that is where high gradients are expected. The smaller the meshes are the finer is the result obtained. Meshing is the program of discretion of the model into finer elements which later form up the complete model.

Hexagonal meshing

Industries consider hexagonal mesh for structural analysis. Hexagonal meshing provides computational efficiency where less nodes and elements are required to achieve high solution accuracy. Assuming the geometry is amenable; a hexagonal mesh can save orders of magnitude of CPU time, and require significantly less RAM and disk space over the tetrahedron mesh, often with better accuracy. Also, a mesh where all elements contain three mostly parallel faces is easy to check, since the exterior faces provide enough detail to fully comprehend the entire mesh geometry.

IX. STATIC ANALYSIS

Static analysis is significant for calculation of ultimate strength of the blade and also to trace the critical zone for vibration analysis. A static structural analysis determines the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effects. Steady loading and response conditions are assumed; that is, the loads and the structure's response are assumed to vary slowly with respect to time

In static analysis, we are analyzing two cases;

- Without pre stress
- With prestress

The types of loading that can be applied in a static analysis include externally applied forces and pressures, steady state inertial forces (such as gravity or rotational velocity), imposed (non-zero) displacements, temperatures (for thermal strain).

X. MODAL ANALYSIS

Natural frequency is that frequency at which an object vibrates when excited by any force. At this frequency, the structure offers the least resistance to a force and if left uncontrolled, failure can occur. Mode shape is deflection of structure at a given natural frequency.

Vibration analysis conducted to discover the natural frequencies and mode shapes of the turbine blades while they are operating. Vibration modal analysis using the finite element theory is referred to as Dynamic finite element analysis of the blade. The most convenient process is to conduct a modal analysis with pre-stress i.e. from prior static analysis, and increase the value of density of the blade material to explanation for added-mass. Damping is not involved in this method.

Modal analysis is used to identify natural frequencies, especially low-order frequencies and vibration modes of wind turbine blades. From the modal we can learn in which frequency range the blade will be more sensitive to vibrate. Blades should be designed to avoid the resonance region with the tower and other components in order to prevent some destruction of related components. Modal analysis was carried out to check whether the mechanical properties of the blade meet certain safety requirements.

General Process

The general process flow for modal analysis comprises of five steps:

- Build the FE model
- Apply the loads
- Obtain the solution
- Expand the modes
- Review the results

XI. RESULTS AND CONCLUSION

- CAD Model

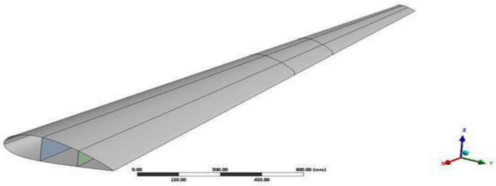


Figure 2. CAD Model

- Mesh plot

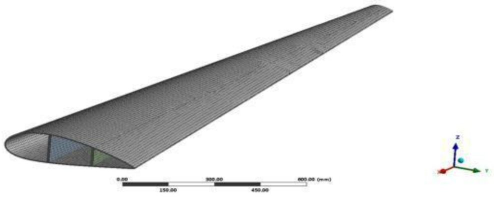


Figure 3. Mesh plot

- CFRP

a) Without pre stress analysis

- Boundary conditions

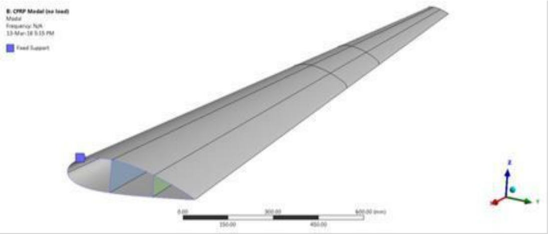


Figure 4. Boundary condition of the blade

- Mode shapes obtained in modal analysis without prestress
- Mode shape 1

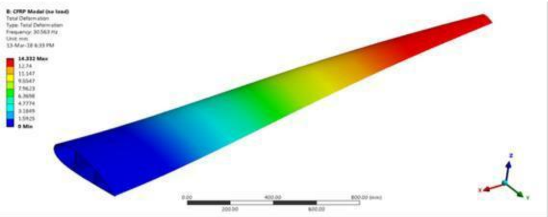


Figure 5. Mode shape 1 without prestress

- Mode shape 2

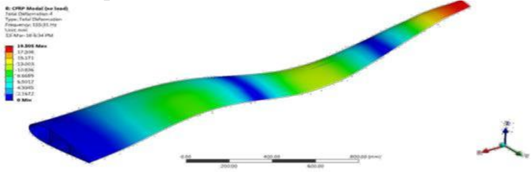


Figure 6. Mode shape 2 without prestress

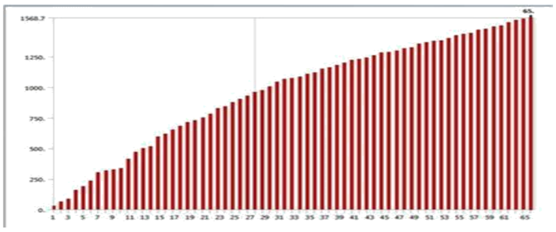


Figure 7. Graph for frequency vs. mode shape

b) With prestress modal analysis

- Boundary condition

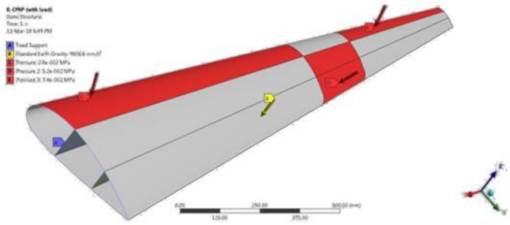


Figure 8. Boundary condition

- Deformation plot

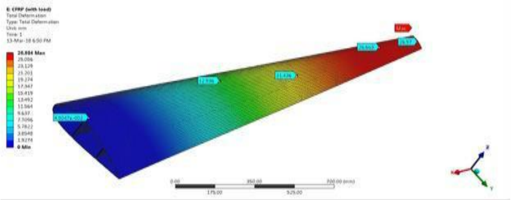


Figure 9. Deformation plot

- Stress plots

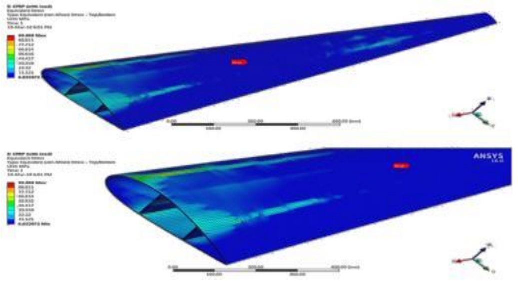
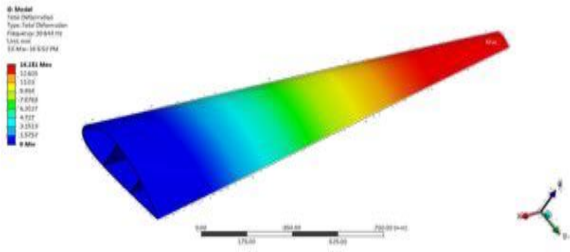


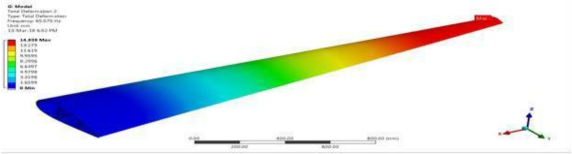
Figure 10. Stress plots

c) Modal analysis results (with stress)

- Mode shape1



- Mode shape 2



- Mode shape 3

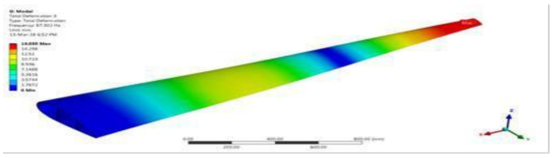
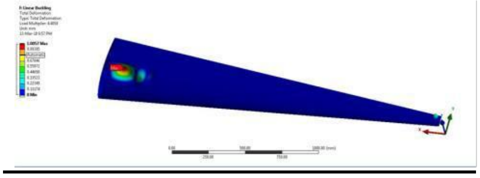


Figure 11.Mode shape with pre stress

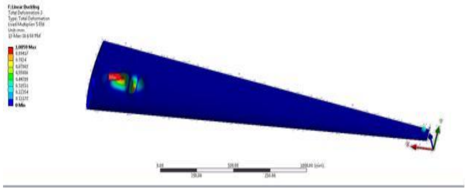
- Eigen value buckling analysis with stress

The linear buckling problem of structure is formulated as an Eigen value problem $([K]+\lambda_i[S])\{\Psi\}_i=\{0\}$,where $[K]$, $[S]$, $\{\Psi\}_i$ and $\{0\}_i$ is stiffness matrix, stress stiffness matrix, i_{th} Eigen value (used to multiply the loads generated by matrix [S], also called load factor commonly) and ^{i}th eigenvector of displacements, respectively

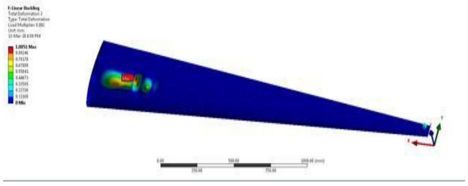
- Mode shape1



- Mode shape 2



- Mode shape 3



- Mode shape4

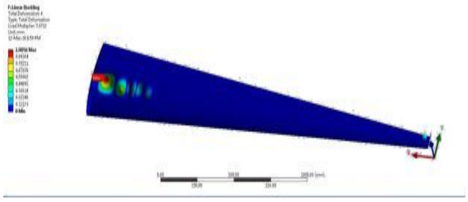
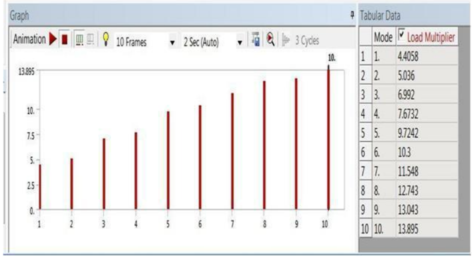


Figure 12. Mode shapes (Eigen value buckling)

- Buckling load factor (load multiplier)



	Mode	☑ Load Multiplier
1	1.	4.4058
2	2.	5.036
3	3.	6.992
4	4.	7.6732
5	5.	9.7242
6	6.	10.3
7	7.	11.548
8	8.	12.743
9	9.	13.043
10	10.	13.895

Figure 13. Mode vs. Load multiplier

Similarly the mode shapes of GFRP and S2 Glass are obtained and the properties of these three materials are analyzed.

XII. OBSERVATIONS

After analyzing the three different cases:

i. With prestress modal analysis,
ii. With prestress buckling analysis,
iii. Without prestress modal analysis,

the results obtained are as follows:

- With prestress

Static analysis	CFRP	GFRP	S2 GLASS
Deformations	26.984mm	47.653mm	13.855mm
Loading	99.909MPa	85.077MPa	95.235MPa

(i) Modal analysis results (Frequency in Hz)

CFRP	GFRP	S2Glass
30.644	30.696	45.083
65.575	63.603	95.453
87.302	87.753	128.69
157.73	159.07	232.86
190.45	184.17	277.17
234.41	235.46	345.81
302.80	291.92	455.93
318.21	321.59	460.11
328.40	326.28	477.72
339.05	330.23	493.61
415.22	412.12	611.64
472.68	430.73	674.22
502.99	488.72	733.04
516.88	509.37	760.16
596.18	548.71	853.41

619.35	581.55	914.78
652.48	623.25	982.2
682.70	635.62	995.31
728.25	671.99	1060.6
751.87	712.53	1089.0
780.91	775.21	1170.6
829.74	788.06	1200.0
877.04	826.92	1278.1
905.79	848.47	1315.4
931.58	853.79	1341.0
975.38	913.07	1419.1
1005.1	932.13	1454.8
1044.5	959.22	1509.9
1075.7	999.74	1549.5
1085.8	1003.4	1571.4
1108.7	1021.3	1597.5
1120.5	1040.6	1620.0
1152.6	1045.5	1673.1
1162.1	1064.4	1677.5

Table 6: Modal analysis results (frequency)

(ii)Eigen value buckling analysis results

CFRP	GFRP	S2 GLASS
30.563	30.731	45.084
65.567	63.712	95.454
86.317	87.891	128.70
155.31	159.39	232.88
190.37	184.39	277.17
229.66	235.96	345.84
302.33	292.22	455.93
313.79	322.7	460.09
327.01	326.83	477.70

Table 7: Eigen value buckling

(iii)Without prestress modal analysis results

(Frequency in Hz)

CFRP	GFRP	S2 GLASS
30.563	30.731	45.084
65.567	63.712	95.454
86.317	87.891	128.7
155.31	159.39	232.88
190.37	184.39	277.17
229.66	235.96	345.84
302.33	292.22	455.93
313.79	322.7	460.09
327.01	326.83	477.70
338.66	331.05	493.60
407.24	413.28	611.73
471.15	431.35	674.08
501.92	489.24	733.04
509.31	512.38	760.49
589.23	548.80	853.19
614.4	614.02	918.12
680.36	633.85	994.78
691.82	664.24	1005.0
703.49	673.29	1028.7
718.74	680.25	1061.1
749.01	721.05	1094.1
778.63	775.42	1170.6
811.13	793.51	1199.5
822.7	825.49	1218.3
874.25	836.40	1278.1
885.26	851.25	1317.4
913.78	861.51	1340.9
948.41	894.67	1382.2
950.31	911.72	1418.6
994.63	941.59	1454.4
1024.0	970.37	1510.7
1048.1	991.09	1535.7
1072.9	1007.5	1551.1
1083.8	1015.0	1570.7
1093.3	1025.8	1591.4
1120.4	1044.4	1623.3
1134.6	1060.0	1675.4
1151.2	1084.0	1681.7
1173.2	1104.2	1712.3
1203.4	1125.0	1744.3
1214.8	1148.7	1777.3
1225.6	1156.7	1828.6
1249.2	1181.9	1838.0
1266.6	1191.0	1845.6
1271.8	1205.8	1849.3
1279.2	1214.2	1868.9
1282.5	1234.6	1884.0
1291.6	1238.9	1897.6
1306.7	1260.4	1919.7

Table 8: Modal analysis results

XIII. CONCLUSION

From static analysis, we can conclude that deformation sand stress for CFRP, GFRP, S2 Glassrespectivelyare26.984mm, 47.653mm, 13.855 mm and 99.909 MPa, 85.077 MPa and 95.235 MPa. Thus from above values we can conclude that S2 Glass fiber is better than the other two: CFRP and GFRP.

One of the major challenges faced by tidal turbine blade designers is due to the density of water. Comparing similarly rated wind and tidal turbines, the issue becomes apparent: a 1 MW wind turbine would require a diameter of approximately 55m, while a similarly rated tidal turbine's diameter would be on the order of 22m. These results in considerably higher loading on a much smaller structure, and means the tidal turbine blade will require increased stiffness and strength.

XIV. FUTURE SCOPE

The concept of this turbine blade has three possible field developments for river, ocean current and tidal applications. A three dimensional hydrodynamics analysis can better understand the effects of tip deflection on power production. By conducting fatigue analysis on the design the following can be identified and can be evaluated:

- Lift and drag forces at maximum current, with velocity shear.
- Inertia loading due to acceleration/deceleration (statistical)
- Gravitational loading due to the positively or negatively buoyant blade sections
- Static pressure differential fluctuations.
- Wave loading (statistical)
- Eddy effects.

Delaminating analysis can be performed in ANSYS with either interface elements, or contact elements. This feature is available for use in a nonlinear static analysis or in a nonlinear full transient analysis.

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