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ANALYSIS OF THE MECHANICAL BEHAVIOR OF A COMPOSITE BLADE USED IN HYDROKINETIC TURBINES

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Abstract. *Projections related to the world global demand for electricity foresee a very high growth in consumption in the coming decades. It has been shown that consumption will increase by 93 % by 2040, compared to the one in 2010. Currently, more than 60 % of the energy consumed comes from fossil fuels, which are limited resources and highly harmful to the environment, as well as to human beings. In this context, the use of hydrokinetic turbines operating with the flow of the rivers is an excellent choice, as they have better predictability, relatively to wind turbines, and higher power density. The main objective of this work is the design and stress analysis of a composite blade to be used in a horizontal axis hydrokinetic turbine, which can generate up to 500 kW of electricity, exploring Tucurui's river flow, in Pará state. This turbine has a rotor with three blades and nominal diameter of about 10 meters. Two types blades, subjected to the same load, were analyzed: (i) the first one manufactured with carbon/epoxy unidirectional reinforced prepreg laminas type AS4/3501-6; and (ii) the second made with 6061-T6 aluminum alloy. The blades have the same external geometry, and are composed by two skins, one cylindrical spar and stringers. Results were obtained using ANSYS, reputed finite element analysis (FEA) software, to carry out the stress analysis of 4.5 m long composite and metallic blades. Masters nodes and restrained equations were used to apply the hydrodynamic loading. The maximum failure index established for the composite and metallic blades were respectively 0.5, according to Tsai-Wu failure theory, and 0.5 according to von Mises yield criterion. The masses obtained for the composite and metallic blades were 221.87 kg and 709.16 kg, respectively. The maximum deflection at the blade tip were 5.65 cm for the composite blade and 2.45 cm to the metallic blade. Thus, the results obtained so far, for blades of equivalent strength, indicate that the carbon/epoxy blades can be significantly lighter but aluminum ones more rigid.*

Keywords: *Hydrokinetic turbine blade, composite structures, finite element method, structural analysis*

1. INTRODUCTION

After a huge success in the aerospace industry, due to the fact that are strong, light, free from oxidation and easy to be manufactures in complex shapes, composite structures are now been adopted in the fabrication of components for renewable energy devices (Levy Neto and Pardini, 2006). In comparison with fossil fuels, which are presently not far from exhaustion and are harmful to human beings and the environment, renewable energy supplies are of steadily increasing importance in all countries. In Brazil, as the global crisis aggravates, initiatives towards the development of clean and renewable sources of energy are starting to take place again. In particular, water current or hydrokinetic submerged river turbines are now being considerate to be explored commercially by Eletronorte. Unlike conventional hydro and tidal barrage installations, water current turbines can generate electricity from natural flowing rivers or streams, with almost zero environmental impact, over a much wider range of sites than those available for conventional tidal power generation. These turbines generate power from the kinetic energy of a flowing stream of water, without the use of a dam or barrage. Water current turbines can be installed in any flow with a velocity greater than 1.5 m/s. Systems can be installed in isolated or grid connected configurations, stand alone or as a supplement to existing generators, floating or fixed to the bottom of a water course. Since many remote communities are situated near moving waters these turbines represent a promising source of clean power. This work is mainly concerned with the development of a three-bladed rotor, horizontal axis, 10 m diameter, 500kW river current hydrokinetic turbine, planned to be installed downstream to Tucuruí Dam, in the state of Para, to generate electricity.

Hydrokinetic turbines are a class of “zero-head” hydropower and typically operate in flow regimes where the stream direction is more predictable than for wind turbines and hence yaw mechanisms can be simplified or eliminated. Hydrokinetic turbines operate on many of the same principles as wind turbines and share similar design philosophies. Meanwhile, wind turbines have grown in size over the past decades, using larger rotors and taller towers to take advantage of the faster winds aloft and to maximize the use of plant infrastructure. In contrast, hydrokinetic turbines are limited in size by the dimensions of the channel they can be placed in. Passively controlled fixed-speed stall-regulated hydrokinetic turbines are unlikely to attain an annual energy production as high as actively controlled variable-speed variable-pitch turbines, which are common in the wind industry. However, fixed-speed stall-regulated water current rotors have the potential to be more reliable and less costly due to the absence of extra control mechanisms and fewer moving parts. Moreover, in environments that have less variability in flow conditions, such as rivers in comparison to tidal straits, the added complexity and cost of a variable-speed rotor and variable-pitch blades may not be economically justifiable.

The most notable difference in a water current turbine is that the density of water is about 850 times greater than air so the energy in a given flow stream is much greater for a hydrokinetic turbine than for a wind turbine. However, average flow velocities for a tidal or river flow tend to be an order of magnitude lower than flow velocities at a good wind site. The net impact is that the Reynolds numbers tend to be in the same range for both wind turbines and hydrokinetic turbines, which allows for much of the same experimental airfoil/hydrofoil data to be used in the design process. Additionally, hydrokinetic turbines can be analyzed and designed using the same incompressible flow techniques used for wind turbines.

This work is mainly concerned with the development and stress analysis of hollow (shell type) composite (carbon/epoxy) and metallic blades for a passively controlled stall-regulated, horizontal axis, three blades hydrokinetic turbine. Its nominal diameter is 10 m and the aim of this study is to present the preliminary design, as well as the structural analysis of the blades. Initially, considering the hydrodynamic loads at 30 rpm, a static stress analysis of a 4.50 m long blades, as showed in Fig. 1 (with the upper shell removed to show the cylindrical spar and stringers in the inner volume); fully clamped at its root, manufactured either with unidirectional carbon/epoxy laminae or Al-Mg-Si alloy (AA 6061-T6), was carried out. The distance from the center of the turbine axis to the tip of the blade is 5.00 m. In Figure 1, the variable x represents the radial direction of the blade.

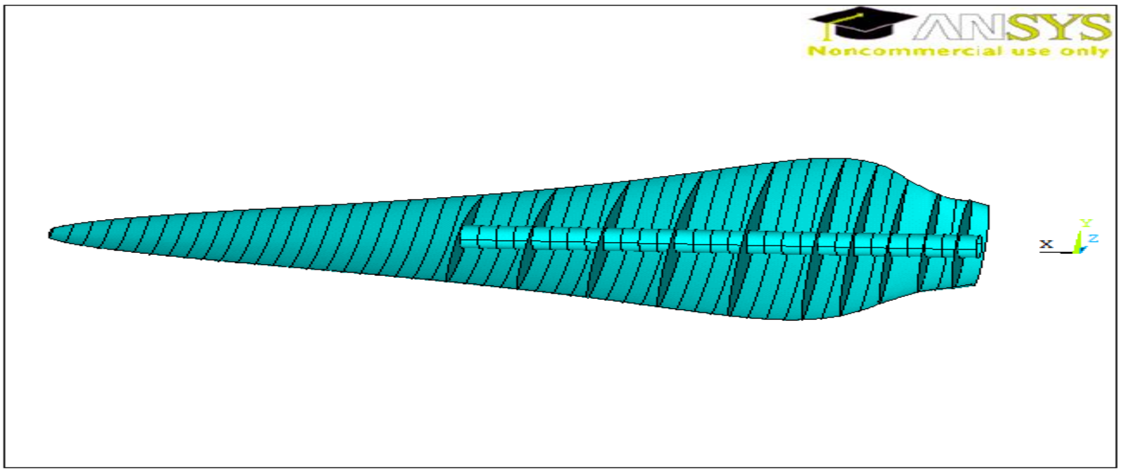

Figure 1. Internal geometry of the 4.5 m long blade under development (the right end is fully clamped).

2. MATERIALS AND METHODS

2.1. Hydrodynamic loads and numerical model

The simulated blades were developed from 50 hydrodynamic profiles obtained using a methodology based on the theory known as BEM (blade element momentum). As a result, from the application of this theory, the obtained profiles (NACA 65_3-618), which generated and defined the external geometry of the blade, have continuous variable chord and angles of attack, according to Fig. 1. The turbine works immersed into the water and the river flow, perpendicular to the rotor plane, interact with the blades making them rotate. Thus, in order to calculate the stresses acting on them, taking as reference the vertical plane in which the blades rotate (i.e. the rotor plane), as shown in Figs. 2 and 3, the applied distributed loads on each blade were specified as normal (represented by vector F_n in Fig. 3) and tangential (see vector F_t in Fig. 3) to the rotor plane. These loads, measured in kN per meter (kN/m), are continuously distributed along the radius ($r \equiv x$) of the blade, from the clamped base (which is connected to a hub, in the axis of the turbine, by means of an approximate 0.34 meters long transition segment, at the right end of Fig. 1) towards the free end tip.

The normal and tangential distributed loads, calculated using the blade element momentum theory, as well as the resultant of these distributed forces, are fully described and can be find in the work of Ferreira (2014). The resultant forces acting on each blade are W_1 = 62,86 kN (6408 Kgf) for the composite carbon/epoxy blades, and W_2 = 62,86 kN (6408 Kgf) for the aluminum 6061-T6 blades, respectively. In Fig. 3, the vectors F_L and F_D represent the lift and drag forces, respectively, acting on the blade. From the: (i) geometry; (ii) boundary conditions (fully clamped on the right end of Fig. 1); (iii) distributed aerodynamic loads; (iv) the self-weight (in four different positions, two vertical, at the top and the bottom, and two horizontal, left and right); and (v) centrifuge forces due to the rotation of the rotor, a finite element model of the blades, using the program ANSYS, was created in order to simulate the static mechanical behavior of the blades, as described in Ferreira (2014).

Figure 2. From and back views of the 3 blades floating turbine

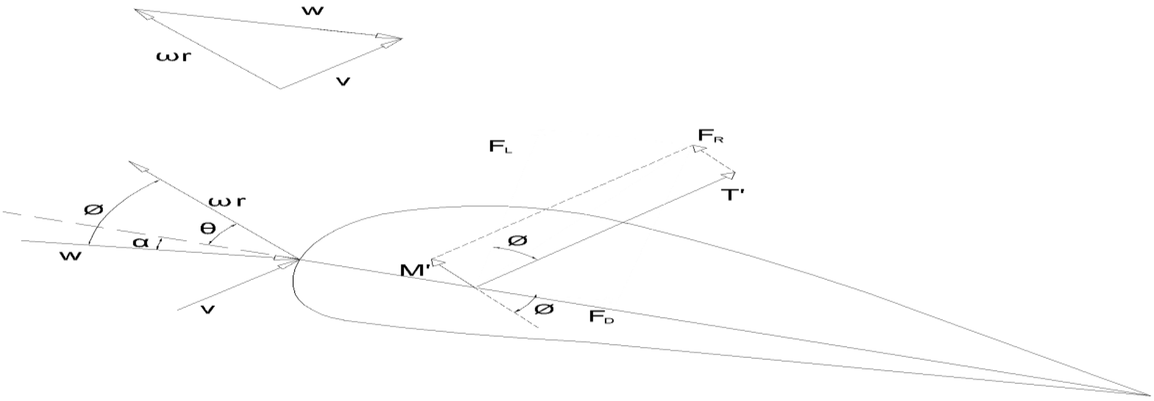

Figure 3. Representation of the aerodynamic loads relatively to the rotor plane

2.2. Mechanical properties of materials

Elastic properties and mechanical strengths from carbon/epoxy unidirectional reinforced prepreg laminas type AS4/3501-6 are presented in Tabs. 1 and 2, respectively. Table 3 shows the mechanical properties of aged aluminum 6061-T6.

Table 1. Elastic properties of carbon/epoxy unidirectional prepreg laminae type AS4/3501-6 (Assef, 2009)

E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	G_{12} (GPa)	G_{23} (GPa)	G_{13} (GPa)	ν_{12}	ν_{23}	ν_{13}
143	10	10	6	3	5	0.3	0.52	0.3

Table 2. Mechanical strengths of carbon/epoxy unidirectional prepreg laminae type AS4/3501-6 (Assef, 2009)

F_{1t} (MPa)	F_{1c} (MPa)	F_{2t} (MPa)	F_{2c} (MPa)	F_{3t} (MPa)	F_{3c} (MPa)	F_4 (MPa)	F_5 (MPa)	F_6 (MPa)	c_4	c_5	c_6
2172	-1558	54	-186	59	-186	87	94	124	-1	-1	-1

Table 3.Mechanical Properties of aged aluminum 6061-T6 (Callister Jr., 2007)

Properties	AA6061-T6 (aged)
Yield stress (σ_y), MPa	276
Ultimate stress (σ_u), MPa	310
Fatigue limit (σ_f), MPa	96.5
Rupture strain, %	17
Elasticity Modulus (E), GPa	68.9
Poisson's ratio (ν)	0.33
Density (ρ), g/cm^3	2.7

3. MAIN RESULTS

The orientations of the composite laminae of each part of the blade (upper and lower shell, cylindrical spar and stringers) were obtained searching for the best performance (i.e. the one with the lowest failure index, according to Tsai Wu Theory) among 86 different symmetric laminates, as described in Ferreira (2014). The laminates found were: [0,30,-30,0]s to the cylindrical spar, [90,0,0,0]s to the stringers and [0,30,-30,90]s to the shells (upper and lower). The total thickness for each component of the composite blade was 1.2 cm for the cylindrical spar, 1.6 cm for the stringers and 0.6 cm for the shells. The failure indexes, according to Tsai-Wu criterion, for the cylindrical spar, stringers and shells are presented in Figs. 4 to 6, respectively.

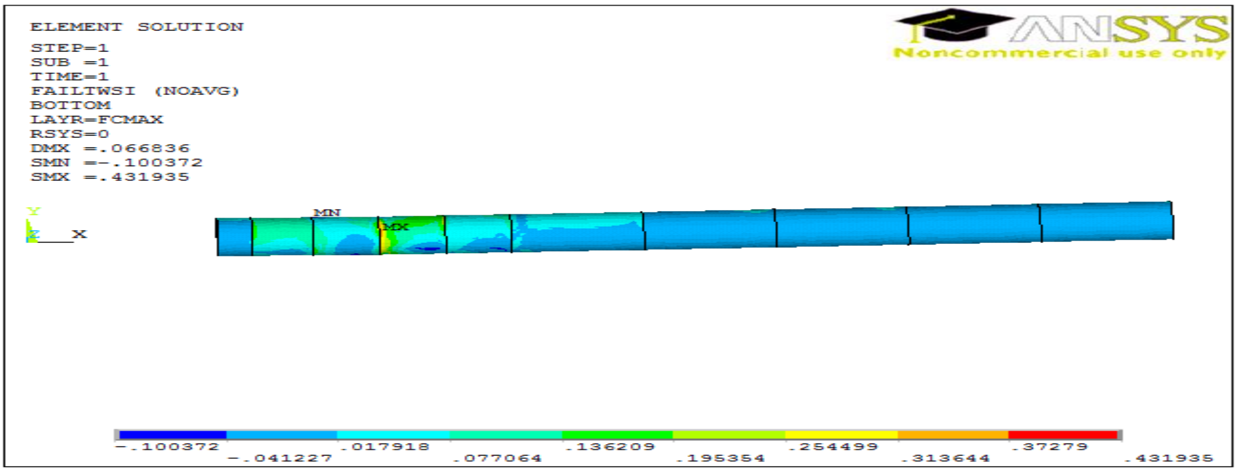

Figure 4. Failure indexes according to Tsai-Wu for the cylindrical spar

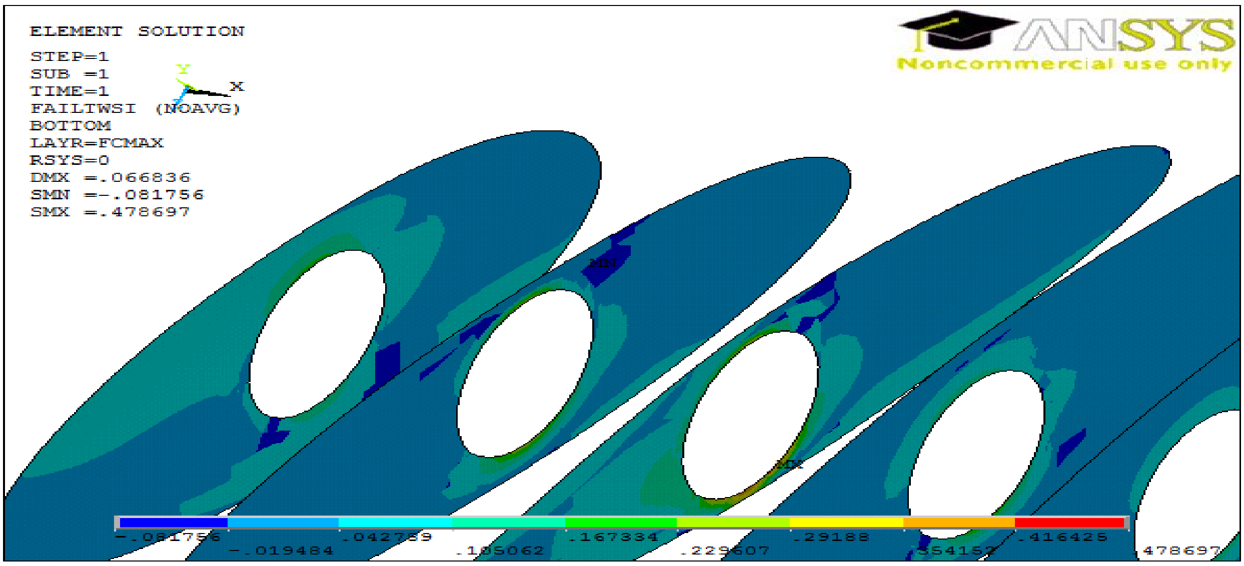

Figure 5. Failure indexes according to Tsai-Wu for the stringers

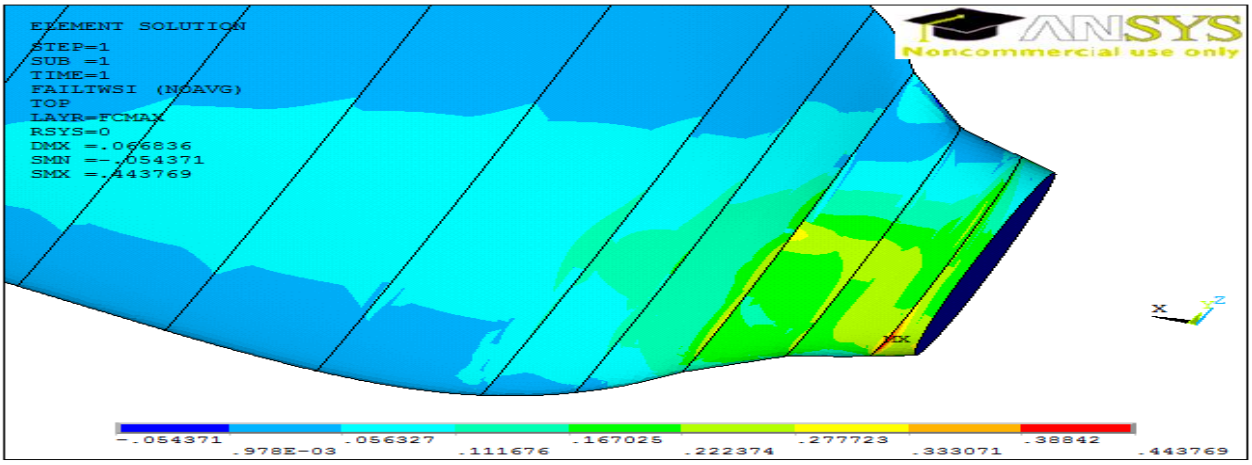

Figure 6. Failure indexes according to Tsai-Wu for the shells

The maximum failure index according to Tsai-Wu theory, found in each component of the blade, was less than 0.5 (0.43 to the cylindrical spar, 0.48 to the stringers and 0.44 to the shells). The maximum vertical deflection (y direction) of the composite blade was 5.6 cm at the free end tip (see Fig. 7).

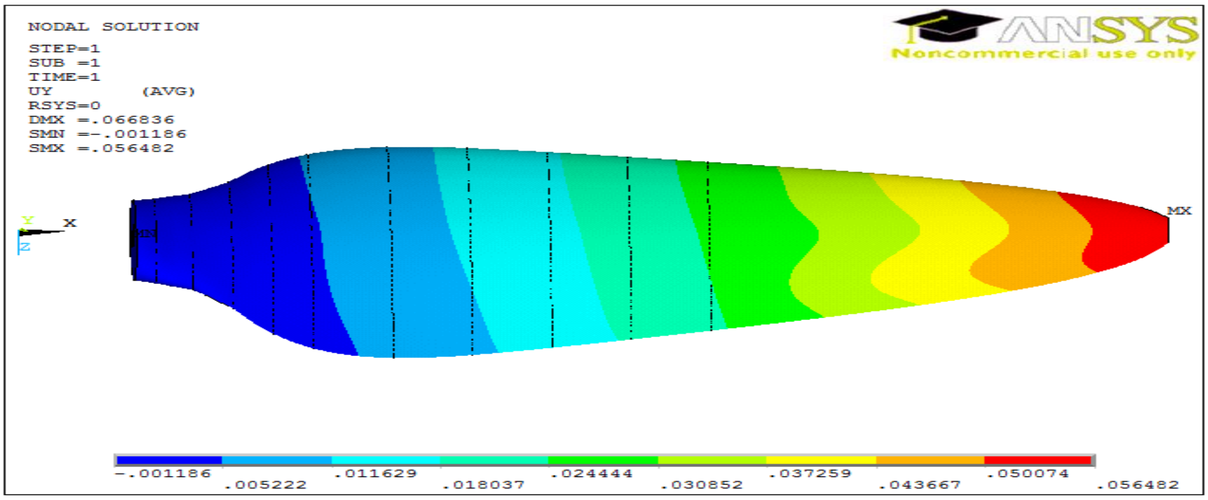

Figure 7. Vertical deflections (y direction) distributions for the composite blade

The Von Mises stresses of the metallic blade for the cylindrical spar, stringers and shells are presented in Figs. 8 to 10, respectively. The maximum failure index related to the yield of the metallic material did not exceed the value of 0.5 in any part of the blade. The maximum vertical deflection (y direction) of the metallic was 2.5 cm at the free end tip (see Fig. 11).

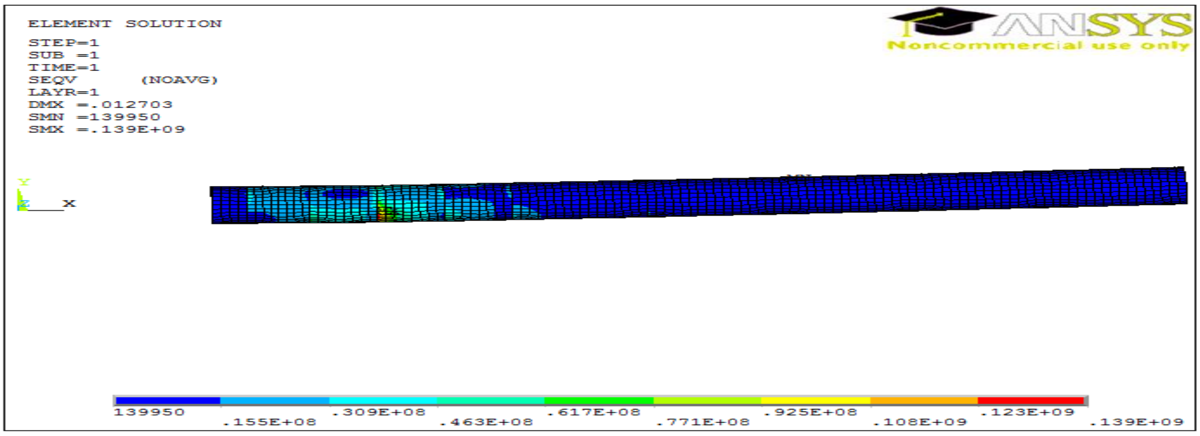

Figure 8. Von Mises stresses for the cylindrical spar

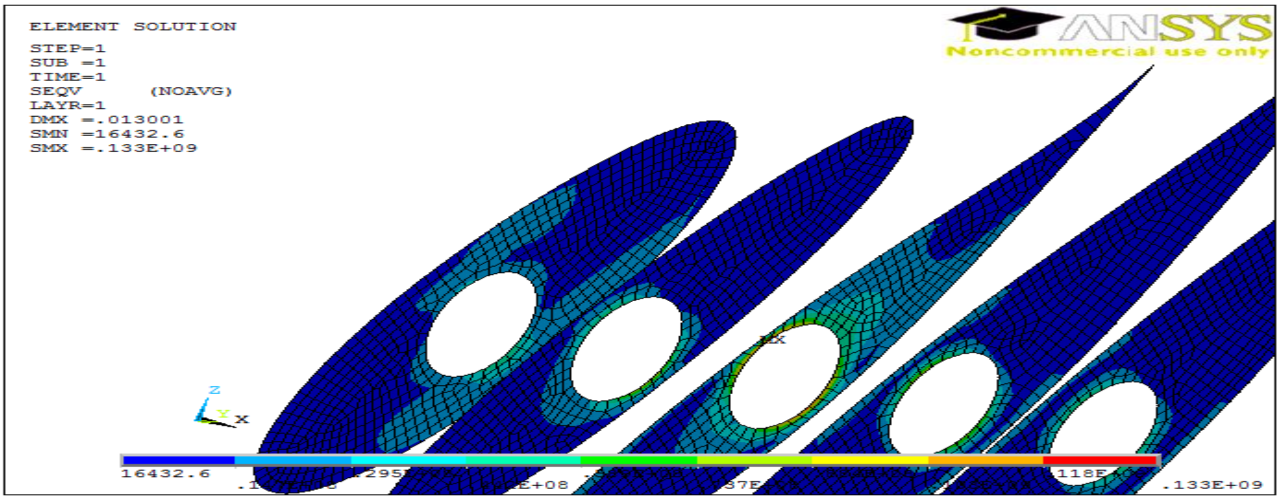

Figure 9. Von Mises stresses for the stringers

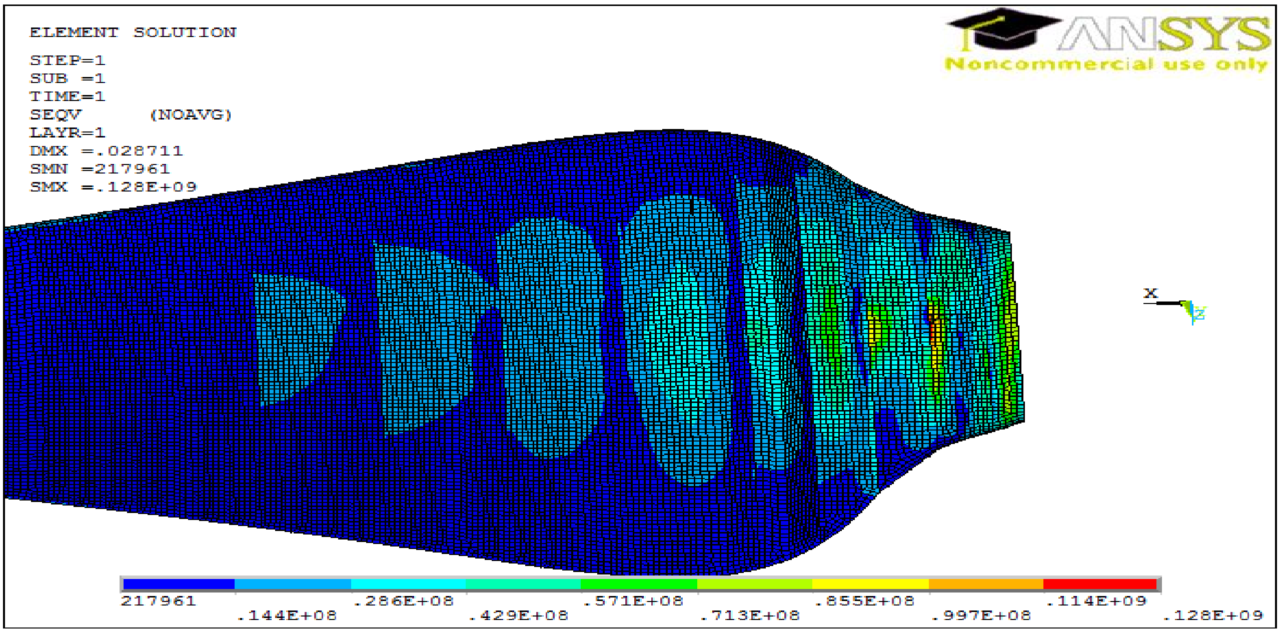

Figure 10. Von Mises stresses for the shells

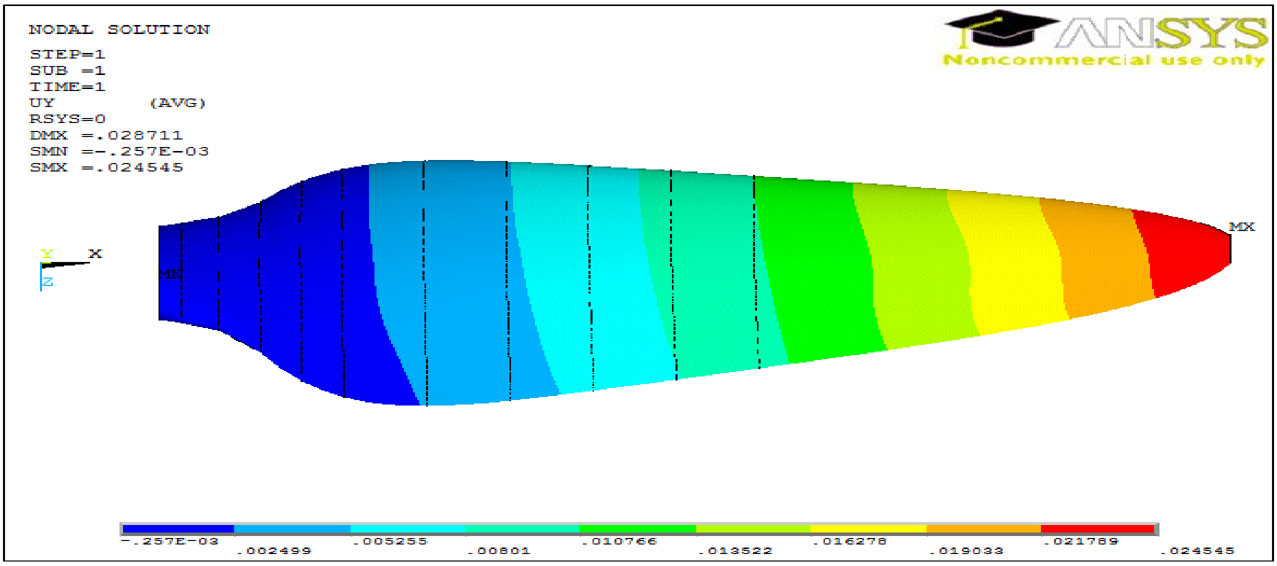

Figure 11. Vertical deflections (y direction) distributions for the metallic blade

In relation to the total thickness for each component of the metallic blade, the used values were 3.0 cm to the cylindrical spar, 1.9 cm to the stringers and 1.3 cm to the shells.

4. ANALYSIS AND DISCUSSION OF THE RESULTS

A synthesis of the results, after searching from 86 different stacking sequences of composite laminates, including the failures indexes of each component (spar, stringer and covering shells), obtained from static stress analysis, via the finite element program Ansys, of the composite and metallic blade are presented in Tabs. 4 and 5, respectively.

Table 4.Synthesis of the components of the composite blade

Component	Laminate	Thickness (cm)	Failure index according to Tsai-Wu (Fracture)
Cylindrical spar	[0,30,-30,0]s	1.2	0.43
Stringers	[90,0,0,0]s	1.6	0.48
Shells	[0,30,-30,90]s	0.6	0.44

Table 4.Synthesis of the components of the metallic blade

Component	Thickness (cm)	Failure index according to Von Mises (Yielding)
Cylindrical spar	3.0	0.50
Stringers	1.9	0.48
Shells	1.3	0.46

The mass of the composite blade is 221.87 kg, while the metallic blade is 709.16 kg, i.e. the composite blade is lighter by a factor of 3.2 times. The composite blade is 3.2 times lighter and the failure indexes of both, the composite and metallic blades are nearly the same. The difference is that the failure mechanism of the composite blades is controlled by fracture (carbon/epoxy is brittle), whereas for the aluminum blade it is controlled by yielding. The maximum displacements in the y axis (i.e. vertical) to the composite blade and the metallic blade are respectively: 5.65 cm (1.2 % of the total length of the blade) and 2.45 cm (0.5% if the total length of the blade is considered as reference), which represents a composite blade deflection greater by a factor of 2.3 times.

As presented by Ferreira (2014), the failure index according to Tsai-Wu varies significantly with the orientation of the laminae. Therefore, a selection method to choose the best laminate searching from many different stacking sequences, should always be used to obtain the most favorable laminate.

5. CONCLUSIONS

Both kinds of blades were subjected to the same loads, their failures indexes are very close to each other and the composite blades are lighter. Thus, as far as the mechanical strength over weight is concerned, the composite blades are more efficient than the metallic ones. The carbon/epoxy blade, with mechanical strength close to the blade made with aluminum alloy 6061-T6 and the same external geometry, is lighter by a factor of 3.2 times. With the additional advantage that the composite blades do not corrode if immersed in a river or ocean current.

The metallic blade had better absolute bending stiffness compared to the composite blade (composite blade deflectected 5.65 cm in the y direction, while the metallic blade deflected only 2.45 cm in the same axis). However, as the deflection of the composite blade was greater by a factor of 2.3 times, the composite blade is lighter by a factor of 3.2 times. Therefore, the bending stiffness by weight of the composite blade is more favorable.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Asseff, N.S., 2009. “Design and finite element analysis of an ocean current turbine blade”. Ph.D. thesis, Florida Atlantic University, Dania Beach.

Callister Jr., W.D., 2007. “Ciência e Engenharia dos Materiais - uma introdução”, LTC, Rio de Janeiro.

Ferreira, G. V., 2014. “Análise do Comportamento Mecânico de uma Pá Compósita Usada em Turbinas Hidrocinéticas”. Master’s Thesis, University of Brasilia, Brasília, Distrito Federal.

Levy Neto, F., Pardini, L. C., 2006, "Compósitos Estruturais: Ciência e Tecnologia". Editora Edgard Blücher, São Paulo.

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