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Structural Analysis of a Wind Turbine Blade Under Operational Loads

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Abstract. *With an increasing demand of energy and its associated costs, it is mandatory that different sources of energy are researched, providing the market with more efficient and economically feasible power options. An alternative to Hydroelectric power, dominant in Brazil and receiving more investments every day, Wind Power is still more expensive than other sources. Then, the need to study the design, model, and optimize it, arises. The purpose of this work is to present the development of a computational tool intended to aid the preliminary structural design of a Wind Turbine Blade, given the aerodynamic geometry (span, profile and chords). As an applied example, a 2MW turbine glass-fiber blade model and operational loads are automatically (batch driven) generated and analyzed concerning stress and deformation. Some iterations are made and a structural resistant and light weighted geometry is defined.*

Keywords: *finite element, wind turbine, composite material*

1. INTRODUCTION

According to Brasil (2010), Brazil is the most promising country in the world in terms of wind power generation due to its immense untapped potential. Also, the development of a wind power matrix is quite strategic, since in the Brazilian northeast region the winds are stronger during the dry season (June-December), when the production of hydroelectric power, responsible for 75% of the national energy production (Brasil, 2010), is lower.

Wind Power, although still more expensive than other sources, is perceived as a low environmental impact energy generation technology (Katherine Ortegon, 2013) because it is a non-polluting and a renewable energy source, i.e., it does not contribute to the greenhouse effect and do not generate toxic by-products, besides being continually replenished.

According to Larsen (2009), wind turbine blades are predicted to have a lifecycle of about 20-25 years, and would afterwards become garbage. There is an estimated 10 kg of rotor blade for each 1 kW installed. Due to the fact that the wind turbine industry is so young, has been limited practical experience on the recycling of turbine blades. Landfill and incineration are two common options, but there are already some companies in the U.S.A. recycling turbine blades and towers.

There have been many key scientific advances in order to lower the wind turbine and its installation costs, enabling better designs and greater efficiencies than were possible previously (Aaron Miller and Chen, 2013). One of them is the mathematical modelling of complete turbine structures, including the simplification necessary to extract robust design rules (Tavner, 2008). This work is about part of the mathematical modelling, the wind turbine blade aerodynamic geometry and its structure.

Motivated by the need to design an optimized Wind Power Blade and, at the same time, keeping the design and construction costs low, a set of softwares is currently being developed by a team based on ITA, Brazil. The results of two of the softwares are presented here. The first one, based on MATLAB®, reads the output of another software, the aerodynamic geometry definitions (aerodynamic profile, chords and twist along span) and uses it as inputs. Then, analytically, the software estimates and outputs both the operational loads and the structure dimensions based on stress and displacement. Then, the second software, based on Python, reads the first software's outputs and generates the Abaqus Finite Element Method (FEM) model, applies the boundary conditions and runs a static linear analysis.

At the results section, the differences between the Analytical and Numerical methods assumptions and results are compared and analyzed. The method applicability is validated, and further works are suggested.

2. ANALYSIS PROCEDURE

2.1 Model Geometry

The block diagram of the work sequence can be seen in Fig. 1.

As a practical example, a 2 MW turbine three-blade geometry was generated from a "practical blade design" MATLAB® software (Claudio T. Da Silva and Silva, 2011) based on the blade element momentum (BEM) theory (T. Burton and Bossanyi, 2001). The inputs are shown in Tab. 1. The resulting optimum blade span was then R=43.5 m, and its geometry parameters are shown in Fig. 2 and Fig. 3.

Concerning the structural design, the nomenclatures exhibited in Fig. 4 are used throughout this work.

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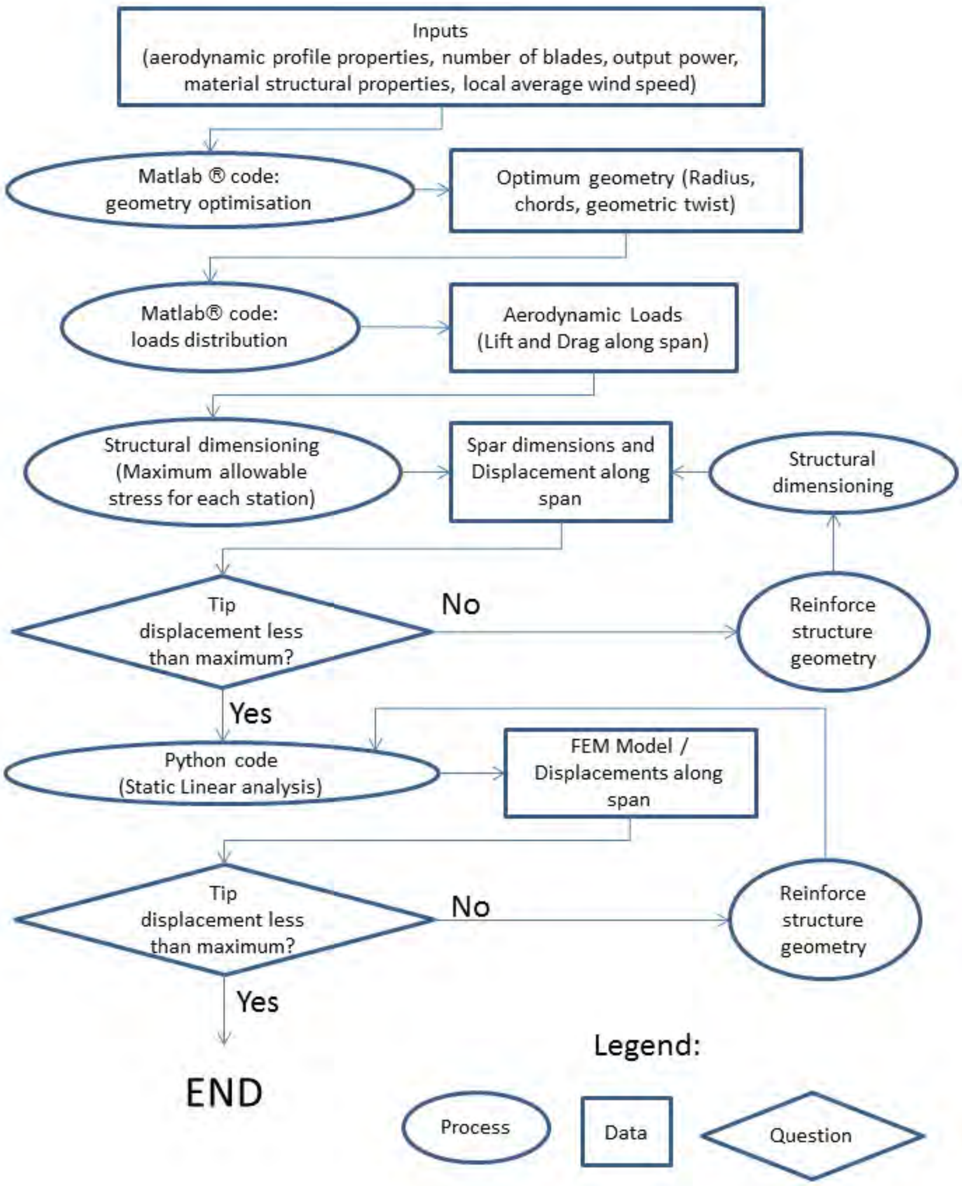

Figure 1. Block diagram

Table 1. Blade and environment inputs

Input name	Input value	Unit
Number of blades	3	-
Nominal Power	2.0	MW
Local predominant wind speed	10.0	m/s
Altitude	Sea Level	m
Tip speed ratio	8.0	-
Aerodynamic Profile	NACA 4412	-
Profile optimum lift coefficient	0.70	-
Profile optimum angle of attack	3.0	degrees

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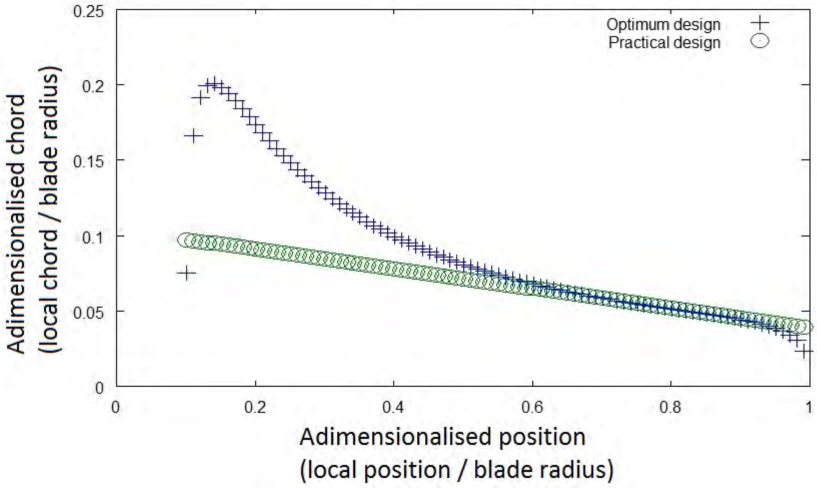

Figure 2. Blade Geometry - Adimensionalized chord along span

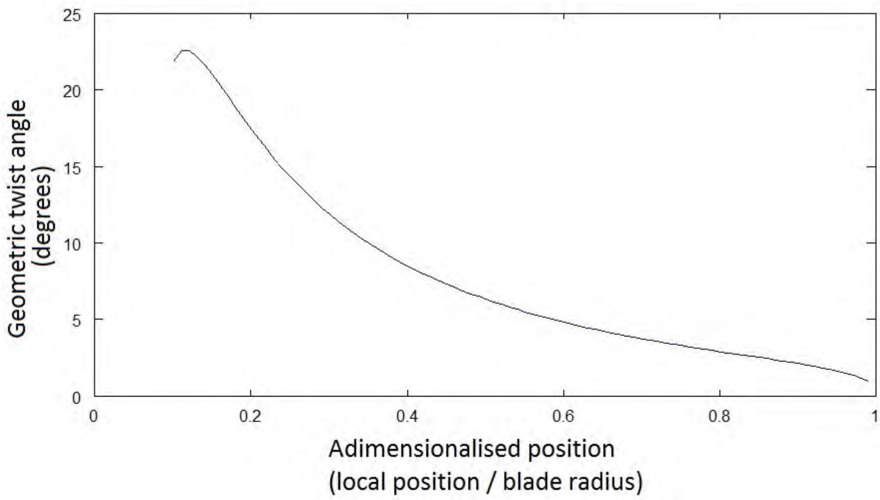

Figure 3. Blade Geometry - Twist along adimensionalized span

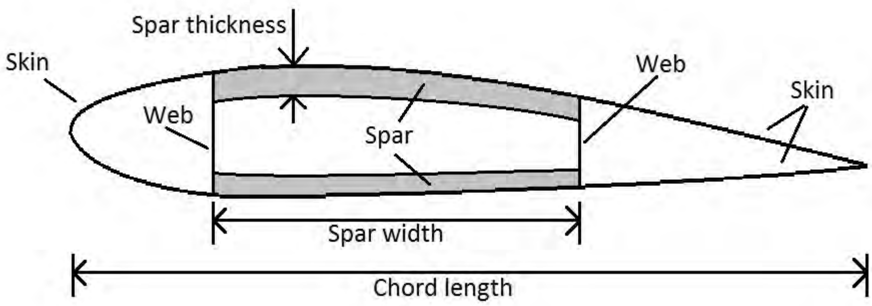

Figure 4. Structure nomenclature

2.2 Material Properties

As the most common material for wind turbines (A. Rashedi, 2012) is bi-directional glass fiber reinforced epoxy, it was selected for the blade skin and web, while a uni-directional glass fiber reinforced epoxy was selected for the spar.

In order to avoid fatigue damage, the fatigue stress for 10^7 cycles of 120 MPa (T. Burton and Bossanyi, 2001) was used in the design.

The glass fiber mechanical elastic properties listed in Tab. 2 (Mahmood M. Shokrieh, 2006) were considered for the FEM model.

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Table 2. Glass fiber epoxy reinforced mechanical properties

Material	E_1 [GPa]	E_2 [GPa]	Poisson	G_{12} [GPa]	Layup
Unidirectional Ply	43	9.77	0.32	3.31	$[0_n]$
Bi-axial	16.7	16.7	0.06	2.01	$[(0,90)_n]_S$

2.3 Determination of Aerodynamic Loads

Using the BEM method proposed by Glauert (1935) (Hansen, 2008), the aerodynamic force distribution was determined (Fig. 5) and, as the blade bending is the major concern of the design (Manwell J, 2002), the integrated bending moment for zero pitch was determined and is shown in Fig. 6.

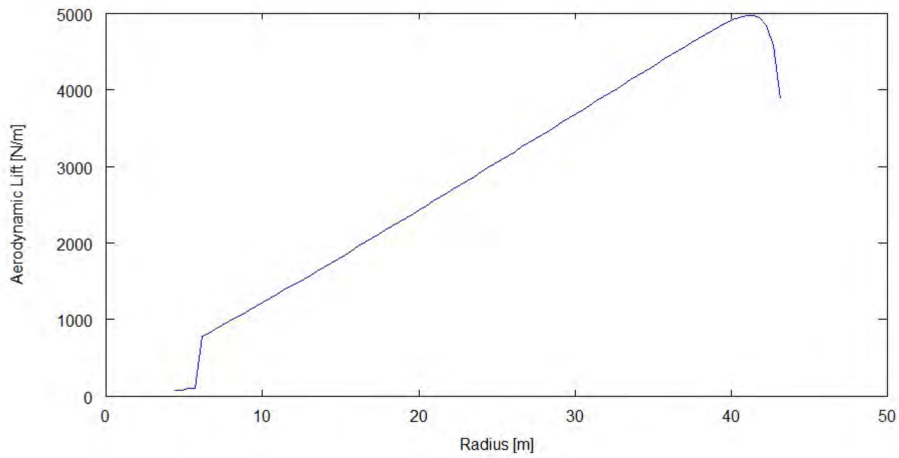

Figure 5. Blade Aerodynamic Loads - Lift along span

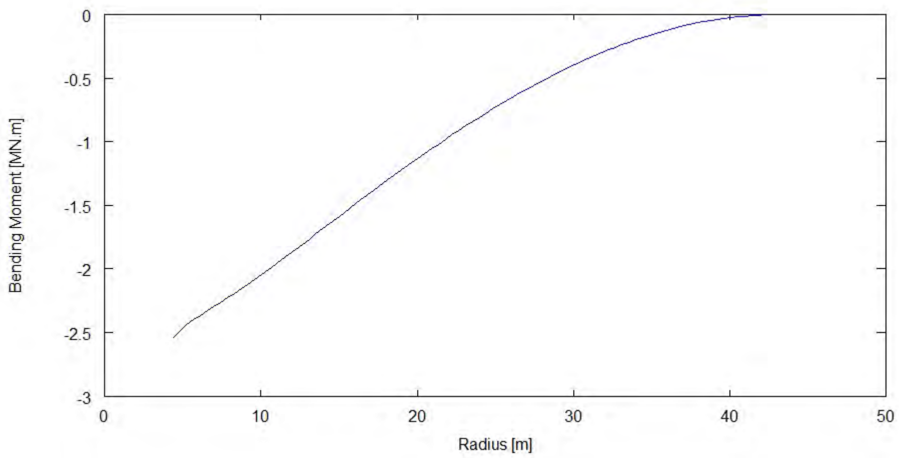

Figure 6. Blade Aerodynamic Loads - Integrated bending moment along span

2.4 Analytical pre-dimensioning assumptions

The following assumptions were made when pre-dimensioning the structure:

- Aerodynamic loads were considered, and they act upon the elastic line. No torsions were taken into account.

- Inertial loads, although relevant, are conservative, i.e., they act upon alleviating the aerodynamic loads, and were therefore not considered.

- Gyroscopic loads were disregarded, since they act in a transient basis, and only operation loads were being taken into account.

- The spar contribution to the section inertia was over estimated. The spar cross-section can be seen at Fig. 7 both as it would be constructed (a) and as it was considered (b). A more rigid solution was then expected.

- The skin and the web structural contribution were not considered.

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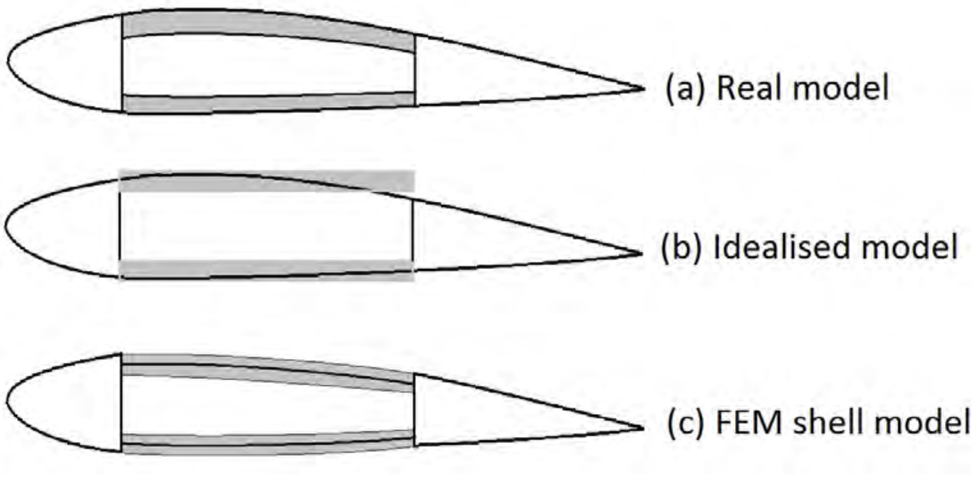

Figure 7. Structural cross-section (grey): a- The spar as it is; b- The spar as considered in the analytical method; c- The spar as in FEM model (shell element).

2.5 Analytic Pre-dimensioning

For the pre-dimensioning, an analytic solution was used. The stress at a given section was calculated with Eq. (1), so a stress-optimized structure has inertias along the span that results in the maximum allowable stress. The minimum inertia was then isolated to Eq. (2), and the section inertia could be approximated (Hansen, 2008) by Eq. (3) (variables defined as in Fig. 8).

$$\sigma = \frac{M.b_1}{I_{yy}} \quad (1)$$

$$I_{min} = \frac{M.b_1}{\sigma_{max}} \quad (2)$$

$$I = \frac{2}{3}a(b_1^3 - b_2^3) \quad (3)$$

Considering b_1 as half of the maximum profile thickness (12% times local chord for the NACA 4412), b_2 was then isolated from Eq. (3) to Eq. (4) and the necessary spar thickness for each station was calculated. In other words, each section was dimensioned in a way that the stress acting upon the spar would equal the defined limit stress.

$$b_2 = (b_1^3 - \frac{3}{2}I)^{\frac{1}{3}} \quad (4)$$

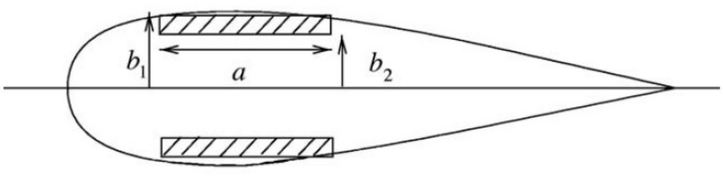

Figure 8. Simplified Section Inertia Estimation.

A variable spar thickness along the blade span was allowed, and its width was fixed as 50% of the local chord. The displacement was computed using the Beam Theory (Hansen, 2008) implemented on the same MATLAB® code.

The rotor plane must be tilted from 5 ^{o} to 6 ^{o} (T. Burton and Bossanyi, 2001) in order to increase the gap between the blade and the supporting structure, preventing one from hitting another. Then, considering a blade of 43.5 m, but disconsidering the pylon length, there is a maximum estimated gap of 4.54 m when the structure is unloaded.

The result of dimensioning the structure based only on the material stress was a very flexible blade with approximately 10.0 m of tip displacement when subjected to operating loads. Therefore, the spar thickness was increased in steps of 0.010 m until the tip displacement was less than 3.0 m. This resulted in spar thickness of 0.030 m, being considered constant along the span, making the construction simpler.

2.6 FEM Model

Once the pre-dimensionalization process was finished, the final geometry and loads were exported to a Python script designed to generate a finite element shell model (Fig. 9) at Abaqus software. The blade structural cross section can also be seen in Fig. 7c.

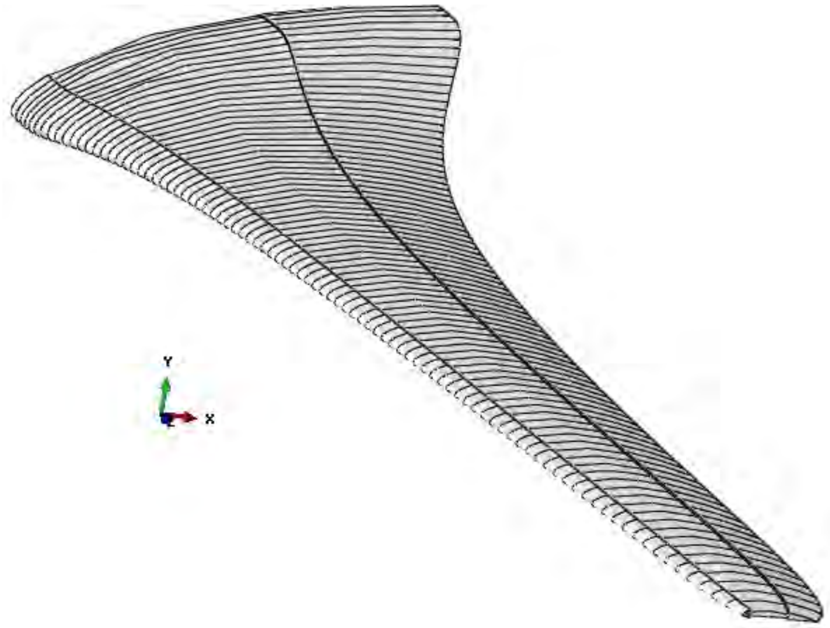

Figure 9. Blade Model

The mesh was also automatically generated by the Python script using the 'sweep' technique with a seed part of size 0.10m. Part of the model mesh (blade root) is shown in Fig. 10.

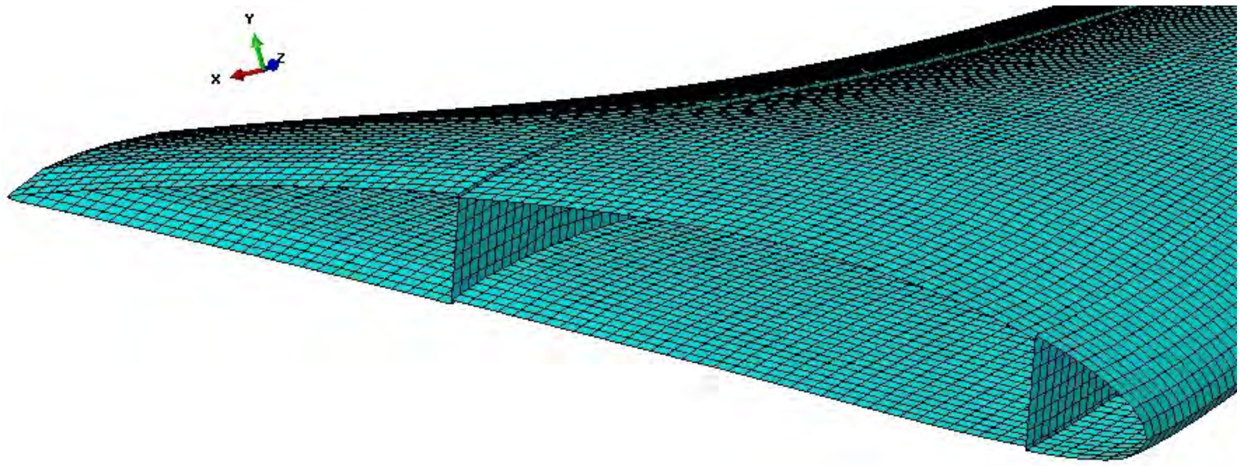

Figure 10. Blade Model Mesh

The geometry was generated with 0.030 m of constant spar thickness (from the analytic pre-dimensioning) and, as well as Neil Buckney and Weaver (2012), a web and skin thickness of 0.002 m was used.

The blade was fixed at the root and the estimated aerodynamic forces were applied as concentrated forces distributed along the span divided in 90 stations. The torsion moments were disconsidered, and the forces were applied at 10% of the local chord for convenience.

The mesh was generated with 60520 shell elements (Abaqus' S4R - Standard Linear Quad with Reduced Integration) and 59976 nodes, and a linear static analysis was processed.

2.7 Convergence

A convergence analysis can be made by analyzing the number of elements and the solution convergence. From tab. 3 it was concluded that the number of elements was appropriate.

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Table 3. Convergence of the FEM Model Solution

Number of Elements	Tip displacement
15486	5.1831m
60520	5.1836m
80705	5.1836m

3. RESULTS

The tip displacement calculated with the analytical method was 2.50 m, while the FEM model resulted in 5.18 m (Fig. 11).

As the tip displacement calculated with FEM model was greater than 4.53 m, the structure was not acceptable according to the maximum defined. The FEM model tip displacement, once greater than the 4.54m value estimated for 6 degrees tilted rotor planes and is, then, not acceptable.

One more iteration was made with the FEM model but, this time, with 0.060m of constant spar thickness. It resulted in a tip displacement of 3.21m and is then, acceptable. No more iterations were performed.

The resulting displacement of each method (analytical, FEM with t=0.030m and t=0.060m) can be seen in Fig. 11.

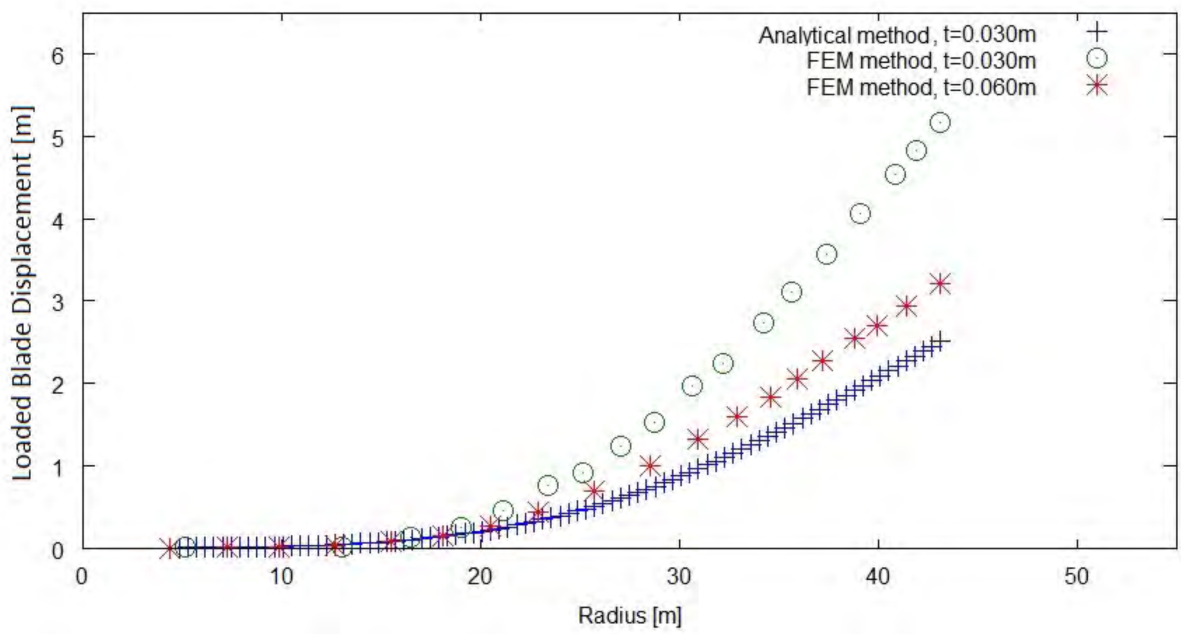

Figure 11. Methods Results Comparison

4. CONCLUSION

From the first analytic analysis we conclude that the structure is not dimensioned by the material stress, but by the tip displacement.

The analytical method is more rigid. Albeit far from reality, it serves as a good starting point for designs made from scratch. It is also useful to know that this analytical method results in displacements about 50% of the FEM model. Multiplying the analytical method spar thickness by two is enough to provide a more precise FEM model.

The difference from both methods is attributed to the approximated inertia calculation Eq. (3). This over-estimated variable is caused by the considered grey area outside the aerodynamic profile in Fig. 7b.

Further local structure reinforcement and other FEM analysis as local buckling and natural frequencies should be done in order to ensure the structure stability when under operational loads. Ultimate loads as extreme gusts and systems/structure failure should be taken into account in a more complete design.

Also, a more precise study concerning the blade torsion must be done, although some improvements must be implemented in the Python automatic model generator to apply both the aerodynamic forces and torsion moments at 25% of the aerodynamic chord.

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