Numerical Assessment of the Structural Performance of a Segmented Wind Turbine Blade

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Abstract. Segmented wind turbine blade (SWTB) development remains a major challenge for constructors so as to reduce blade transport and manufacturing costs. The blade structural properties must be examined in the design stage to enhance their mechanical behavior and fatigue life. This paper presents a numerical investigation of a SWTB prototype. Teeth inserted in holes at the interfaces of segments, were designed to avoid relative displacements between the segments assembled along a spar. Modal and fatigue analysis were established using ANSYS Workbench software to evaluate the structural performance of the investigated wind turbine blade (WTB). This work covers the impact of the assembly force and the rotation velocity effect on the blade fatigue life. Previous findings of an experimental study, of the SWTB at rest, were considered to validate the blade finite element model. To assess the used spar location, along the blade segments, the edgewise and flapwise deflections of the blade under assembly force effects were analysed. This study reveals the significant impact of the exerted assembly force on the SWTB fatigue life versus the rotation velocity effects. Interestingly, the obtained results indicate that a segments assembly force must be respected in the blade assembling to ensure the optimum service life.

Keywords: Fatigue analysis · Modal analysis · Segmented wind turbine blade · Finite element modeling

1 Introduction

In recent years, the concerns about the global warming consequences, caused essentially by the excessive fossil energy production, has made renewable energy development more and more indispensable for a sustainable future. In this context, wind energy is treated as one of the most profitable clean energy sources. Actually, power generation efficiency and cost represent the primary factors which govern wind turbine development. Thus, maintenance and manufacturing cost reduction remains a primary need. Undoubtedly, the wind turbine blades are the most crucial parts, in terms of performance and cost, of the wind power system. For this reason, many works have analysed the rotor blades fatigue and vibration, aiming to extend their service life. Shokrieh and Rafiee (2006) studied

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the fatigue phenomena of a 23 m wind turbine blade (WTB) manufactured by the Vestas Company to predict its lifetime. By adopting a stochastic approach, the service life of the selected blade has been predicted to be limited to 18.66 years. Jensen et al. (2006) tested to failure, a composite WTB, under flapwise loading. The structure displacements were registered throughout the loading history. The experimental measurements and the numerical simulation results were processed to determine the location of the initial failure.

Recently, because of the intricacy of manufacturing and transport processes of the long WTBs, the blade fragmentation was proposed to solve such issues (Abdulaziz et al. 2018). Yangui et al. (2020) developed a numerical model of a SWTB using shell elements. To update the used material properties in the numerical model from the natural frequencies identified experimentally, an iterative technique was followed based on the substructuring technique. Dutton et al. (2001) tested a segmented form of a 13.4 m blade with a connecting tube to investigate the durability of the advanced fragmentation method. Static load tests, in the edgewise and flapwise directions were performed and repeated after a five million cycle fatigue test in the flapwise direction. The blade inspection shows that no damage was occurring in the segment interfaces and connections. Static and fatigue analysis of a SWBT were performed by Bhat et al. (2015) to evaluate its structural performance. The determined numerical results, of the non-segmented and the segmented blade, indicate that the effect of the fragmentation on the entire structural performance is minimal. Nevertheless, the outcomes of the load applied to assemble the segments were neglected. Yangui et al. (2019) performed an experimental analysis to inspect the effects of the assembly force adjusted by a nut on the WTB dynamical behavior. The determined experimental results, using the Eigen-system Realization Algorithm (ERA) modal identification method, showed the notable influence of the assembly force change on the blade eigenfrequencies versus the effects resulting from the blade rotation. Nevertheless, the impacts of the applied force on the blade shape and lifetime were not addressed.

In the present paper, an attempt to address this issue has been made by investigating the displacements and the fatigue life of a SWTB taking into account the mounting force of the segments. Based on previous experimental modal identification, the blade numerical model developed using Ansys Workbench software was validated. Static and fatigue analysis were performed to assess the effects resulting from the assembly force and the rotation velocity on the SWTB structural performance.

2 Blade Finite Element Modeling

A SWTB model, consisting of 5 segments assembled along a spar, was designed as seen in Fig. 1.

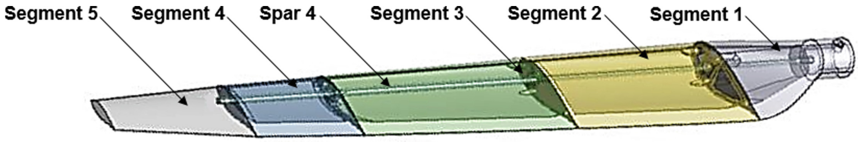

Fig. 1. Segmented blade CAD model

The full length of the designed blade is 500 mm and the segment skin thickness is about 3 mm. Regarding to the assembly, a spar with a length of 420 mm and a diameter of 4 mm was used. The material properties of the SWTB components are presented in the following Table 1.

Table 1. Material properties of the blade components.

Parameters	Material	Density (kg/m^3)	Poisson's ratio	Elastic modulus (GPa)
Blade segments	PC-ABS	1070	0.3879	2.25
Spar	Steel	7850	0.3	210

Using ANSYS Workbench finite element software, solid elements with three degrees of freedom per node and a free mesh were adopted to model the blade structure. Considering the blade segment's complex shape, the tetrahedral finite element was used. For the spar, the mesh was simplified by adopting the quadratic element as shown in Fig. 2.

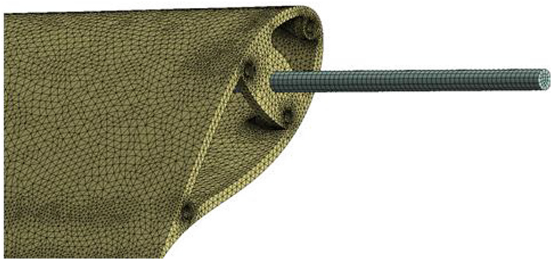

Fig. 2. Segmented blade mesh

To simulate the contact between the different parts of the blade, a frictional contact was defined between the segments and the spar and at the interfaces of segments. The contact between the tip and the root segments of the blade and the spar was bonded.

To validate the established numerical model, modal analysis was carried out without applying the assembly force. The assembled blade structure was clamped at its root. To optimise the mesh size, a convergence study was conducted for various mesh sizes. Accordingly, 979306 nodes and 613326 elements were generated. The natural frequencies, obtained numerically and those reached experimentally by Yangui et al. (2019), are given in Table 2.

Table 2. Segmented blade natural frequencies.

	Present work	Yangui et al. (2019)	Error %
1st natural frequency	17.9	17.4	2.87
2nd natural frequency	23.5	24.8	5.24
3rd natural frequency	80.9	85.7	5.60

An acceptable agreement is found, between the simulated and experimental findings, where the maximum error is about 5.6%. Thus, the introduced numerical model can be reliably employed to evaluate the fragmented blade structural performance.

3 Structural Performance Assessment

The WTB efficiency depends essentially on the blade shape. Thus, the segments mounting force and the spar location must be primarily treated during the blade design to avoid structural distortion. Figure 3 shows the blade tip edgewise and flapwise displacements for different assembly loads. In this section, only the static assembly load of the blade segments was exerted.

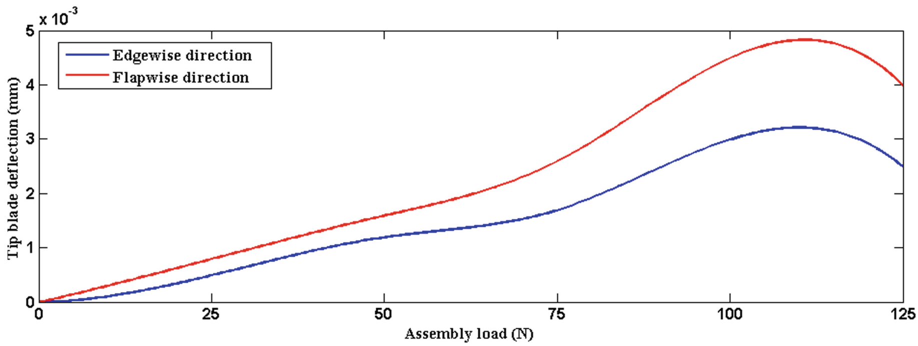

Fig. 3. Edgewise and flapwise displacements as a function of the assembly load.

The displacement amplitudes proved the negligible influence of the assembly force on the blade shape, where, up to a significant assembly effort of 125 N, the maximum deflection does not exceed 0.005 mm. Therefore, the spar location along the blade is well designed.

To assess the impact of the assembly force on the lifetime of the WTB structure, fatigue analysis was performed using Ansys Workbench fatigue module. Stress life type analysis was adopted based on Stress-Cycle (S-N) curves of the segments and spar materials. A bending load, in the flapwise direction, equal to 5 N was applied on the third blade segment as illustrated in Fig. 4. Based on the results obtained from the static load analysis, the fatigue analysis was performed where the zero-based constant amplitude loading type was assumed.

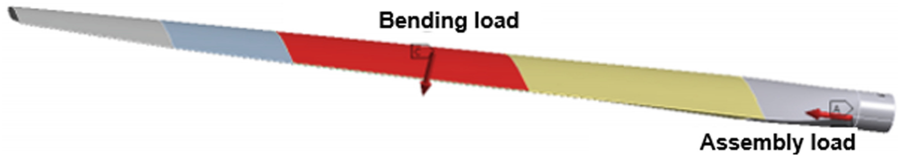

Fig. 4. Blade bending and assembly loads.

Figure 5 represents the SWTB lifetime change as a function of the applied assembly load.

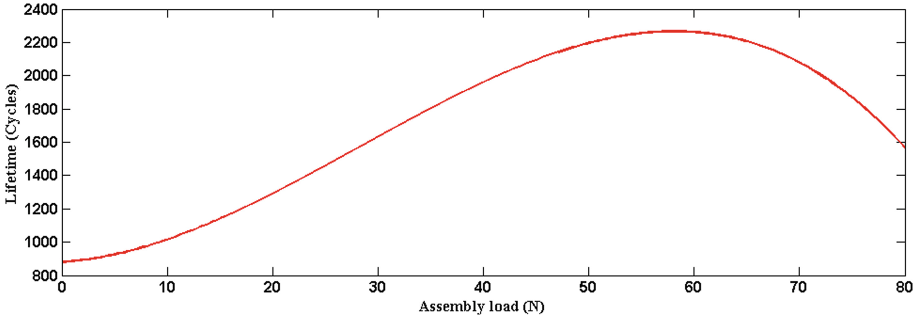

Fig. 5. Segments assembly load impact on the blade fatigue life.

It is observed that the lifetime of the blade is significantly dependent on the assembly load. The maximum fatigue life of the blades, equal to 2273 cycles, is obtained by applying an assembly load equal to 59 N. For an assembly load higher than 60 N, the blade cycles of fatigue life start to decrease.

To analyse the rotation velocity results on the blade fatigue life, a constant assembly load equal to 59 N was applied. The rotational velocity direction was performed as seen in Fig. 6.

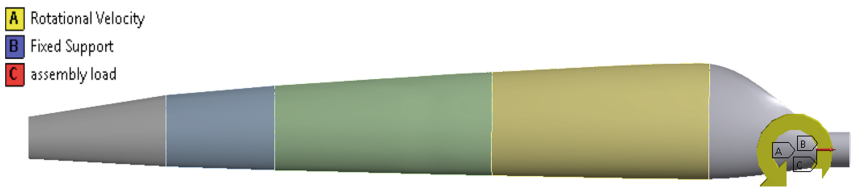

Fig. 6. Rotating blade model

Based on a static analysis, the blade fatigue life investigation was performed assuming a ratio loading type with a tolerance of 10%. Thus, the alternating load, provoked by the blade spinning velocity, was limited to 10% of the static load amplitude. The prediction of the rotating blade fatigue life is presented in Fig. 7.

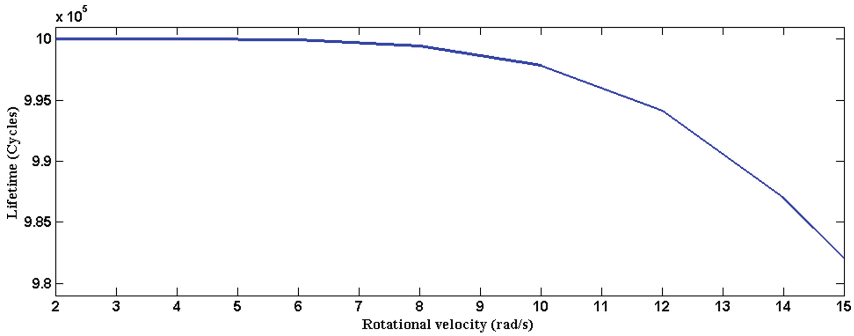

Fig. 7. Rotation velocity effects on the blade fatigue life.

Clearly, the increase of the WTB rotation velocity from 2 rad/s to 15 rad/s engenders a negligible loss of the blade fatigue life. Thus, the spar is well localized along blade segments in a way that it did not generate an important bending force component in the centrifugal load produced by the blade rotation.

4 Conclusion

In the present study, numerical analysis were performed to evaluate the structural performance of a SWTB. The numerical model of the blade was validated by reference to experimental analysis. The blade deflections, at rest, under the assembly load were determined the prove the satisfactorily location of the spar along the blade segments. Static and fatigue analysis were also performed to inspect the impacts of the segments assembly force and the rotation velocity on the blade fatigue life. Findings show that an assembly load must be respected during the WTB mounting to ensure the maximum service life, and thus, the sustainability of the wind turbine system. Again, the designed spar location was perfectly assessed by the negligible effects of the rotation velocity on the blade lifetime. In this work, only the flapwise bending fatigue was treated. Therefore, this research can be extended through the development of a dual-axis, edgewise and flapwise, fatigue testing.

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