# SIZE EFFECT ON WIND TURBINE BLADE'S DESIGN DRIVERS

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## Abstract:

The aim of this paper is to find out the design drivers and critical issues for very large scale wind turbine blades. A classical up-scaling law and a finite element model are used to perform the assessment.

Structural responses such as stresses and displacements due to aerodynamic and inertial loadings are analyzed for 5, 10, 15 and 20 MW blades. Based on the results of simulation, challenges for design of very large blades and some design guidelines will be proposed.

**Keywords:** wind turbine blades, up-scaling law, finite element analysis, structural response

## 1 Introduction

Wind turbines are growing in size and as the result design drivers of components may change. Aerodynamic forces governed the design for the past and present commercial blades, but as the blade continues to become larger the inertial forces seem to act as the design driver and affect the structural behavior.

This paper studies the structural behavior of very large scale blades. Two different approaches for modeling have been used.

The first model is an analytical up-scaling model to obtain the first estimates of forces and stresses. The second model is a 5 MW Finite Element (FE) model as a base point and three more sizes that are 10, 15 and 20 MW. Structural responses such as stresses and displacements due to aerodynamic and inertial loadings are analyzed.

Based on the results, the issue which acts as the design driver or the most dominant case for each specific size is analyzed and a comparison is made between different sizes. Some of the objectives of this study are: an insight into the design driver for very large scale blades, highlighting challenges for design of larger blades and offering some design guidelines as the size increases.

This work is part of a PhD project which is running at Delft University of Technology and the final result should be the conceptual and preliminary design of a large scale offshore wind turbine (up to 20 MW) in which the current concepts should be reinvestigated carefully for larger sizes.

Based on this investigation the modifications to current concepts, knowledge and tools should be done to pave the road to achieving large scale turbines.

## 2 Modeling the blade

Two different models are used for this study. A simple up-scaling model which uses analytical functions to obtain first estimates of forces, moments and stresses on the blade and a FE model coupled with the blade element momentum theory to get aerodynamic loads on the blade and do the stress analysis.

### 2.1 Up-scaling law

A simple way to get some general insight into a given design is to find the relation between a numbers of important parameters that govern the design.

As the blade's length changes some other important parameters such as forces, torque and stresses also change and by studying these changes the way that the blade behaves can be analyzed with a low accuracy.

The fundamental relationships between the blade's length and the parameters mentioned above can be formulated by using up-scaling laws [1]. These scaling relations start with three distinct assumptions:

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- Blade material remains the same
- The tip speed ratio remains constant
- All other geometrical parameters vary linearly with the blade's length

Based on these assumptions the relation between blade length and other important parameters is given in table 1.

| Parameter | Proportionality |
| --- | --- |
| Blade length | R |
| Average wind speed at hub height | $R^{\alpha *}$ |
| Blade thickness | R |
| Blade chord | R |
| Blade sectional area | $R^{2}$ |
| Blade flap wise force (due to aerodynamic loads) | $R^{2\alpha+2}$ |
| Blade lead-lag force due to gravity | R |
| Blade torsional moment | $R^{3+2\alpha}$ |
| Blade flap wise stress | $R^{2\alpha}$ |
| Blade lead-lag stress | R |
| Blade axial stress | R |
| Blade torsional stress | $R^{2\alpha}$ |
| Tip deflection | R |
| Blade weight | $R^{3}$ |

* $\alpha$ = power law exponent

Table 1: Scaling relations

It should be emphasized that scaling relations can only be used when the design concepts do not change. If this condition is met then the effect of size on the general behavior of the blade can be predicted with a low accuracy.

## 2.1 FE Modeling

The FE method has been used comprehensively for the structural analysis of wind turbine blade's design during the past decades. It is a very useful method which captures all the necessary details and allows the designer to determine structural responses for a variety of load cases.

FE models of wind turbine blades normally use layered shell elements. These elements provide an efficient means of modeling structures composed of laminate composite materials which is used in the wind turbine industry. The orthogonal stiffness properties of the elements are calculated by the use of laminate theory [2].

In this study two different types of 3D shell elements are used; a nonlinear laminated shell element for modeling the sandwich parts and a linear laminated shell element for modeling the rest [3].

The types of loading that are applied in the model include:

- An externally applied force due to the wind which is known as aerodynamic load
- Inertial forces

Aerodynamic loads are obtained using the Blade Element Momentum (BEM) theory. Lift and drag forces generated in steady wind conditions are analyzed as normal and tangential forces on the blade sections. These forces are applied as boundary loads on some specific nodes on the FE model and along the blade.

Providing rotational velocity and gravitational acceleration by the user, inertial forces are applied automatically by ANSYS that is used in this simulation and are combined with the mass matrices to form a body force load vector term. However, inertia loads are effective only if the model has some mass. To do so, density specification is used in this research.

Wind turbine blades are usually made in polymer matrix composites, often glued together to integrate the entire blade. The following materials are used in constructing the blade in this simulation:

- Biax glass/epoxy in the spar web
- UD glass/epoxy in the spar flange
- PMI foam in the spar web for constructing sandwich composites
- PVC foam in skin, except leading and trailing edges for constructing sandwich composites

The geometry of the blade consists of a rectangular beam box extended from the root to the tip to carry most of the structural loads, and the skin to generate the aerodynamic forces that results into extracting power from the wind.

The geometry of 10, 15 and 20 MW blades is found by applying the up-scaling law and linearly scaling all blade dimensions of the 5 MW reference design with respect to the blade length which means that the blades for 10, 15 and 20 MW turbines are not really designed and/or optimized.

After meshing the model and in order to apply the boundary condition on the blade, all degrees of freedom (except the rotational degree of freedom) should be locked at the root part of the model.

This FE model was solved with ANSYS FE package for 4 different MW sizes of the blade that are 5, 10, 15 and 20, see Figure 1.

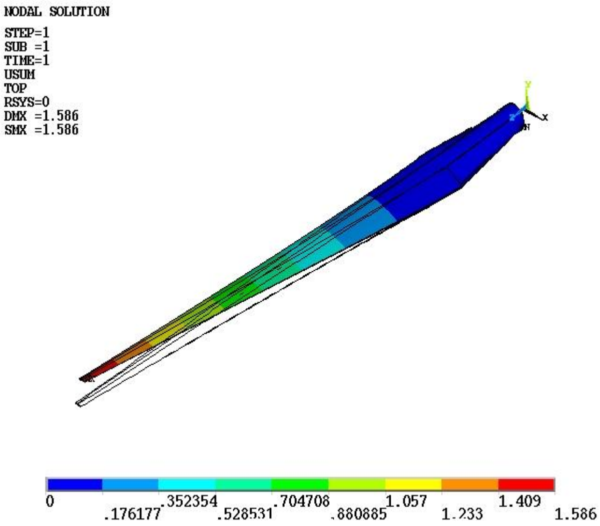


Figure 1: Deformation plot of the blade, colors indicate the total displacements of the blade

The results of the stresses and displacements are given and interpreted in next section.

# 3 Interpretation the results and discussion

Based on the results obtained with FE simulation and the model provided by the up-scaling law the following results are presented and interpreted.

- **Tip deflection**

Based on the up-scaling model, tip deflection increases linearly with size, R. The equation of the curve fitted to the result of FE simulation in Figure 2 shows:

$$y = 0.0398x^{1.0846} \quad (1)$$

Taking into account that the coefficient of 0.0398 in the above formula is a dependent parameter of the design variables and can change from design to design, we focus only on the exponent part of the formula.

According to FE simulation results, tip deflection increases with an exponent of 1.0846 with R, comparing with the exponent of 1 from the up-scaling model, which shows good agreement between the two models. However, having tip deflections in the order of 5 to 8 meter might be a problem for larger scale upwind turbines.

Pre-coning the blades, tilting the rotor and using downwind concept are design solutions which might help. Using a new internal architecture for the blade can decrease this high tip deflection as well.

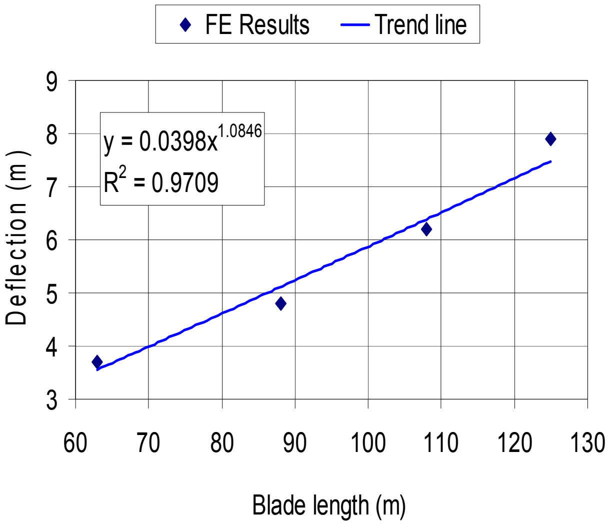


Figure 2: Tip deflection

- **Flap-wise stress**

Aerodynamic load is the main source of flap wise stress and normally the maximum flap wise stress occurs during a 50 year gust while the turbine is in operation [4]. However, a steady wind is accurate enough for the purpose of this research. The flap-wise stress is presented in Figure 3.

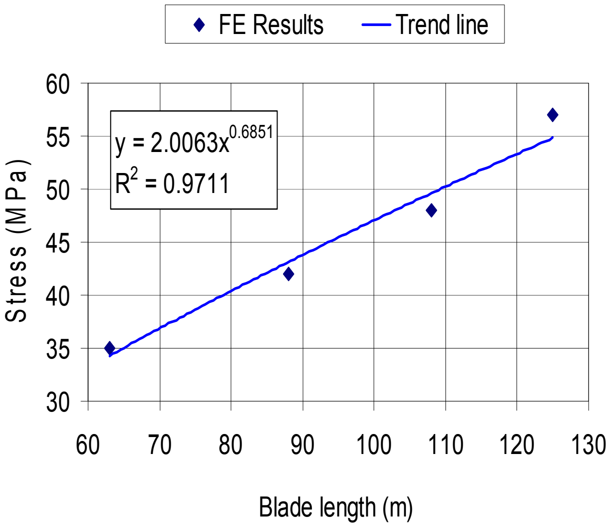


Figure 3: Flap-wise stress

The up-scaling model shows that the blade's flap wise stress increases with $R^{2\alpha}$ and assuming a power law exponent of 0.15, it becomes an exponent of 0.3.

The equation of the curve fitted to the result of FE simulation in Figure 3 shows:

$$y = 2.0063x^{0.6851} \quad (2)$$

It means that flap wise stress increases with an exponent of 0.6851 with R for the case of FE simulation.

- **Lead-lag stress**

The up-scaling model shows a linear increase of lead-lag stress with size, R, which is only due to the weight of the blade.

The equation of the curve fitted to the result of FE simulation in Figure 4 shows:

$$y = 6E\text{-}05x^{2.3043} \quad (3)$$

This has an exponent of 2.3043.

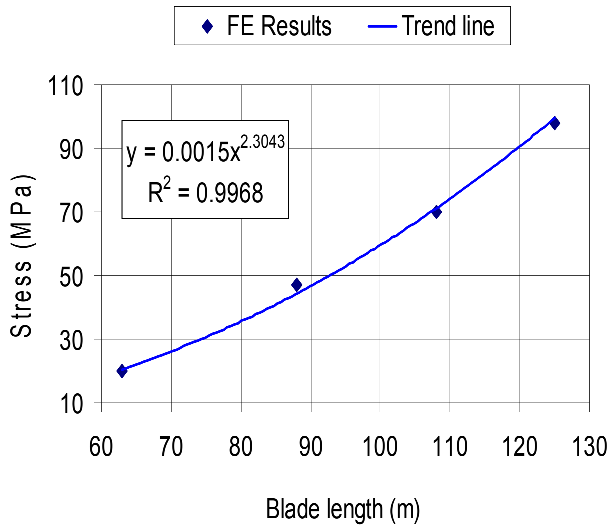


Figure 4: Lead-lag stress

A reason for this discrepancy might be the inertia load applied on the blade due to its rotation which is not included in the up-scaling model.

The summation of the loads caused by rotation and gravity force are responsible for the lead-lag stress.

However it should be mentioned that the bend-twist coupling of the composite blade makes the situation difficult to keep a track of the changes of the stresses. This discrepancy was also seen in the flap-wise direction.

To discover the origin of these discrepancies, comparison of a FE model which has isotropic material properties with the case of non-isotropic model and using a non rotating blade might be useful.

- **Axial Stress**

The up-scaling model shows a linear increase of axial stress with size, R, which is only due to the weight of the blade, and it does not include the effect of rotation through the centrifugal force on the blade.

The equation of the curve fitted to the result of FE simulation in Figure 5 shows:

$$y = 0.002x^{1.7602} \quad (4)$$

This curve has an exponent of 1.7602 and includes the effect of centrifugal forces due to the rotational velocity of the blade.

Part of the discrepancies between these two models is the presence of centrifugal force on the FE model and it should be mentioned that the results of the FE simulation is more reliable for the rotating case.

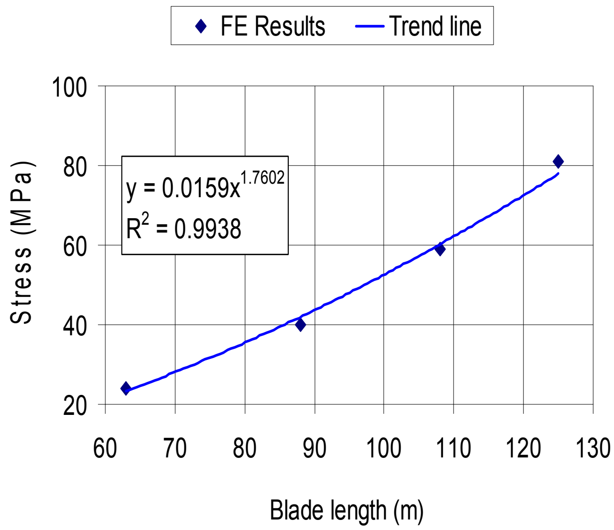


Figure 5: Axial stress

- **Torsional stress**

In the up-scaling model torsional stress increases with R $^{2\alpha}$ to the size and assuming a power law exponent of 0.15, it becomes an exponent of 0.3.

The equation of the curve fitted to the result of FE simulation in Figure 5 shows:

$$y = 0.5137x^{0.8985} \quad (5)$$

It has an exponent of 0.8985.

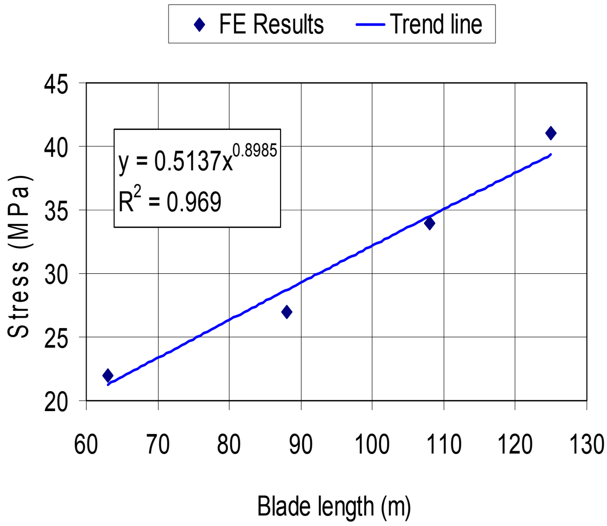


Figure 6: Torsional stress

The result of FE simulation and the up-scaling model show a difference in the prediction that is distinguishable.

A reason for this might be the blade bend-twist coupling. On the other hand, part of the strain energy which is required for bending the blade causes torsion in the blade as well and vice versa.

# 4 Conclusion

The aim of this paper was to find the changes of design drivers of large scale wind turbine blades as the size increases.

Two different models were used for this purpose. An up-scaling model that used some analytical functions to obtain first estimates of the loads on the blade and get some initial insights, and a FE model of a linearly scaled blade coupled with the blade element momentum theory to derive loads and do the stress analysis.

The results of these two different models were compared and discussed in previous section and it was shown that the up-scaling model underestimates the stresses and displacement and can not be used in any real design process. Therefore, the results of FE simulation are used to do the conclusion.

Two main sources of loads were distinguished in the FE model. One is the aerodynamic load and the other is inertial load.

According to the results of FE simulation which is plotted in Figure 7, as the size of the blade increases the significance of different contributions of the above mentioned loads to the stresses change.

It can be seen that for the given 5 MW reference blade, flap wise stress is the dominant stress which governs the design from a stress analysis point of view.

As the size of blade increases, lead-lag and axial stresses take over and become more important. Roughly at 82 meter blade length, which is called a transition point, the lead-lag stress is the dominant stress case and governs the design. This size represents a wind turbine with an 8.5 MW power in this study.

However, it should be emphasized that the location of the transition point depends on the design parameters and different design settings have a different transition point. That is, this phenomenon might happen at a size which represents a turbine of 7 MW power or 10 MW power.

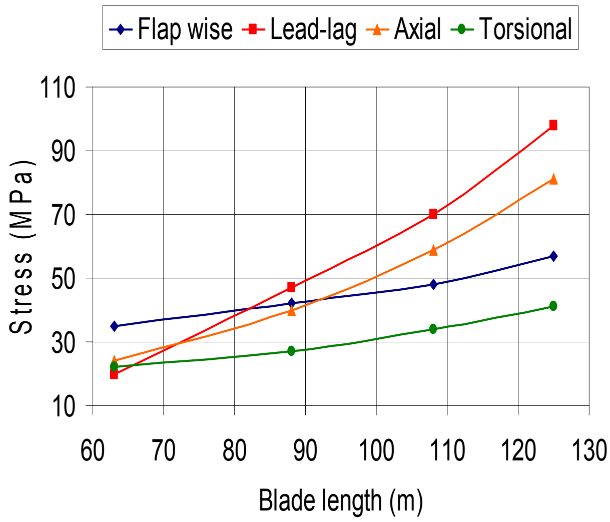


Figure 7: Change of stresses with size

From the size of 82 m up to 125 m, lead-lag and axial stresses which are mainly due to inertial loadings increase with a larger slope and are more severe than other stresses and govern the design.

Based on the preliminary results of the simulations done in this paper, designers of the future wind turbine composite blades should focus on the inertial loads as a dominant source of forces applied on the blade and dynamic cases (rapid acceleration and/or deceleration such as emergency stop) should be taken into account carefully, since they can significantly influence the inertial based stresses.

In order to be able to continue with the up-scaling, redesign of the blade geometry for inboard sections and using light-weight materials are also necessary.

## 5 Acknowledgements

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