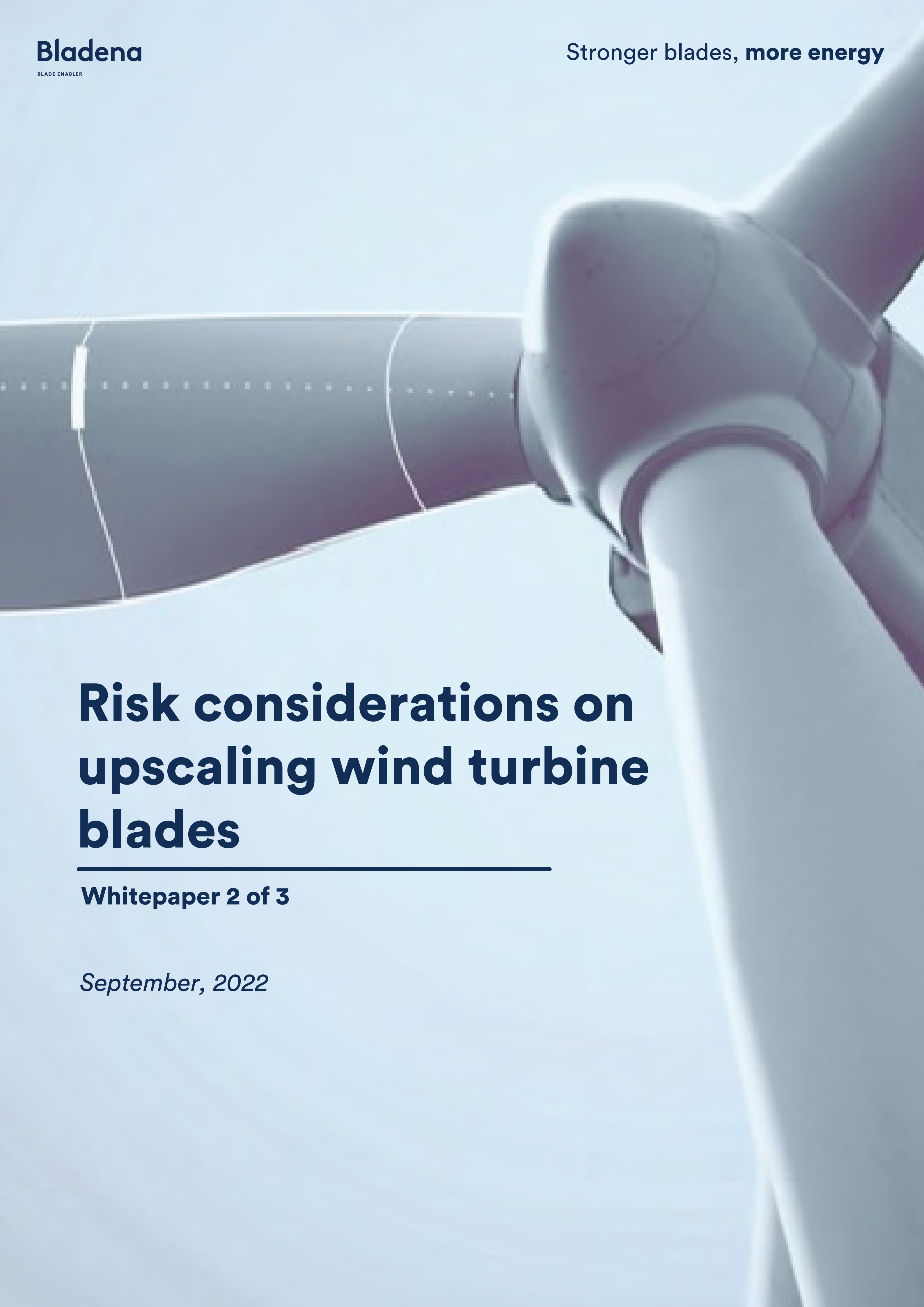
Stronger blades, **more energy**



Risk considerations on upscaling wind turbine blades

Whitepaper 2 of 3

September, 2022

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Introduction

Wind turbines scaling in size is a challenging task and has taken place over the last decades. The manufacturing of next-generation wind turbines is expected to follow the same trend indicating the need for larger wind turbine components e.g., blades that now exceed 100m. When it comes to blade scaling, it is not only a regular scale-up of existing smaller blade versions but there is also a need to consider the cubic law of mass growth and limit weight [1]. The upscale of a wind turbine blade is not a simple approach and the understanding of the behavior of the blade that changes as a function of the blade length is very important.

The consequence of going with larger blades will not have only an impact on cost, due to the increase of the mass, but also the risk of failure will be higher. With increased blade lengths, the loads that act at the blades have also increased, resulting in structural challenges which lead to additional risk and high operational expenses through unplanned maintenance and repair costs and loss of annual energy production (AEP).

Herein, the main objective is the effect of critical factors such as blade length, torsional loads, and localized phenomena on blade behavior, giving the reader an understanding of the impact of scaling and its consequences on modern blades in terms of risk.

Tensional peeling stresses on the aft shear web (fish-mouth region) are investigated (see, Figure 1) for a blade under operation, evaluating different phenomena that affect the magnitude of these stresses and subsequently reduce the expected lifetime of the blades. A cross section sketch is also presented in Figure 1 [1].

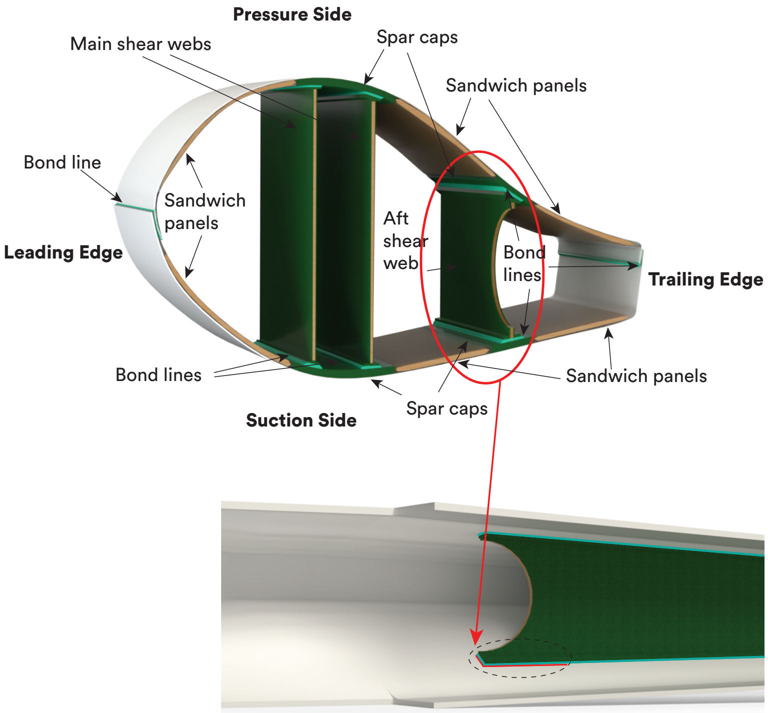


Figure 1 - 3D sketch of a cross section (top), aft shear web fish-mouth geometry, marking the peeling in the adhesive bondline (bottom).

Impact of blade length and torsional loads

Finite Element models were analyzed under several load cases in order to investigate peeling stresses in aft shear web. When a turbine operates, and the blades rotate, the incoming wind causes aerodynamic flapwise loads, deflects the blade towards the tower, while the gravitational forces add the majority to the edgewise loading. The combination of flapwise and edgewise loading creates a torsional load, which makes the blade twist, see Figure 2.

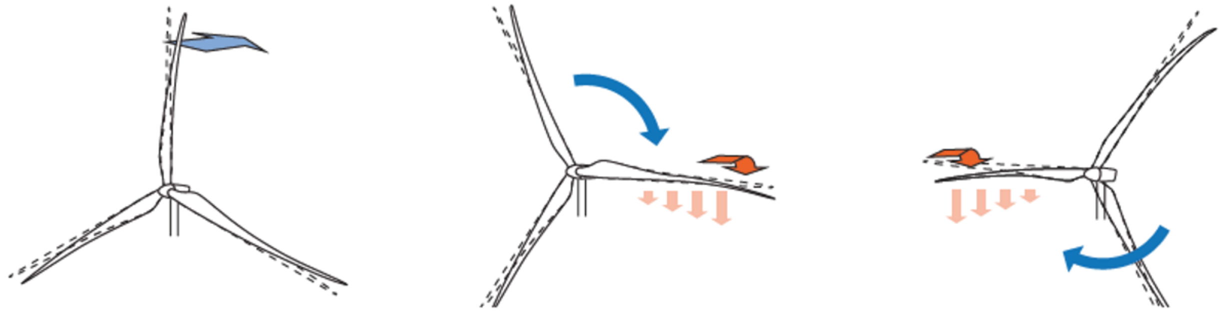
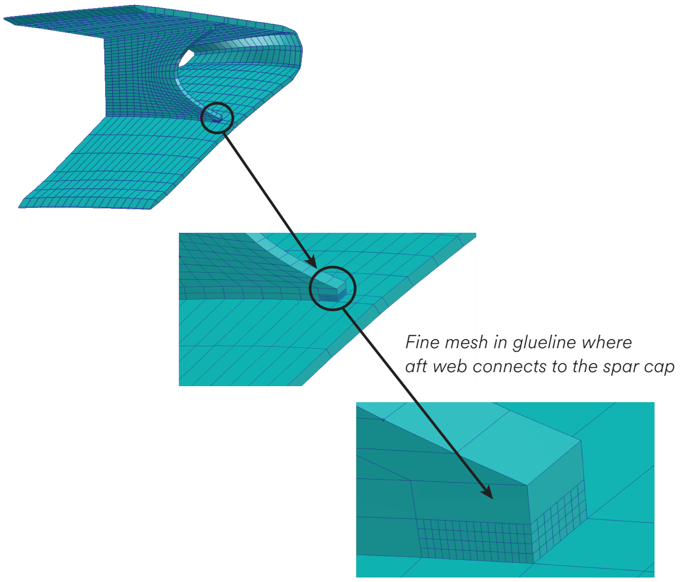


Figure 2 - On the left, flapwise load marked with blue arrow and deflection. In the middle and on the right, illustration of gravitational forces (light orange arrows), which in combination with aerodynamic flapwise loads generates an additional torsional load component (dark orange arrow) – edgewise deflection is TTL (left) and LTT (right).

Depending on the azimuth position of the blade, the gravitational load alternates the edgewise loads from leading edge to trailing edge, which makes this area of the blade highly loaded in a fatigue perspective.

In Figure 3, the aft shear web with a fish-mouth and a fine mesh at the beginning of the bondline, where the aft shear web is connected to the spar cap, is illustrated.



Fine mesh in glueline where aft web connects to the spar cap

Figure 3 - Aft shear web with a fish-mouth and a fine mesh at the beginning of the bondline.

Peeling stresses are appearing in the adhesive bondlines and in the connection of the shear web to the spar caps, causing debonding issues when the magnitude of the stresses is high. The aft shear web on a blade and the fish-mouth geometry are illustrated in Figure 4.

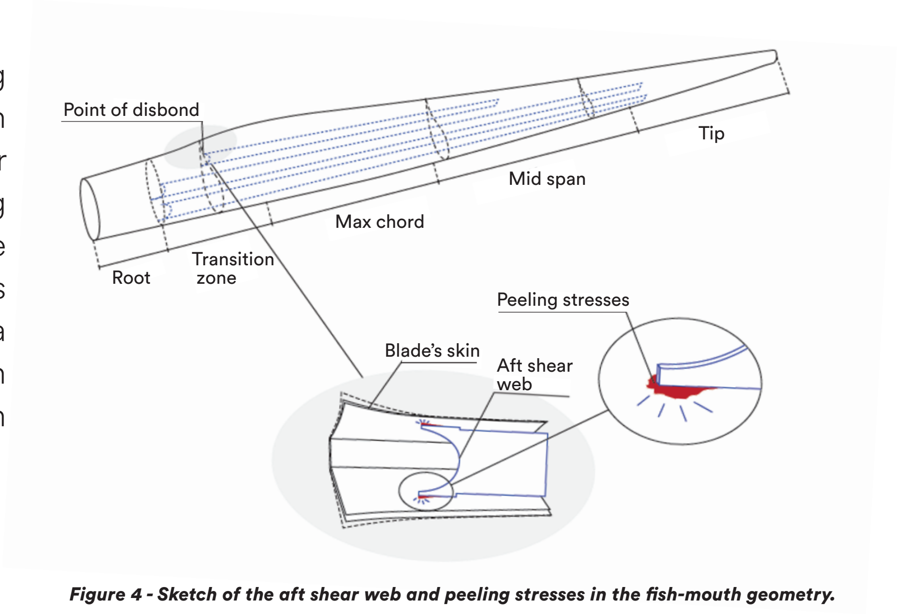


Figure 4 - Sketch of the aft shear web and peeling stresses in the fish-mouth geometry.

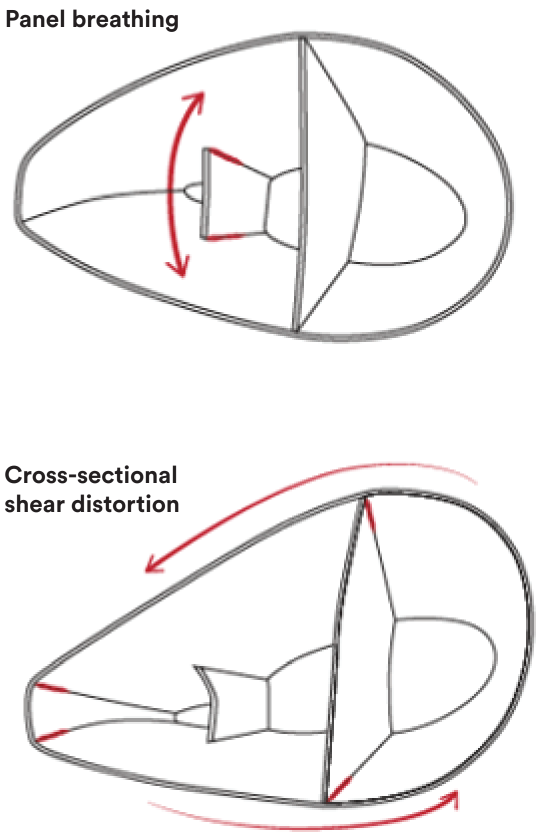


Figure 5 - Panel breathing and cross-sectional shear distortion.

Two different in terms of size blades were simulated in FEM with the analysis concluding that the size of the blade is a key parameter for peeling stresses in this area, Figure 6. Higher peeling stresses are observed when the blade increases in size.

Three regions have been defined in the whole study (A, B, and C) as it can be seen in both Figure 6 and Table 1. The reason is that localized phenomena (breathing and cross-sectional shear distortion) are analyzed below in Chapter 2, therefore, membrane stresses [1] which are related to the breathing of the panels, as well as bending stresses which are related to CSSD are needed.

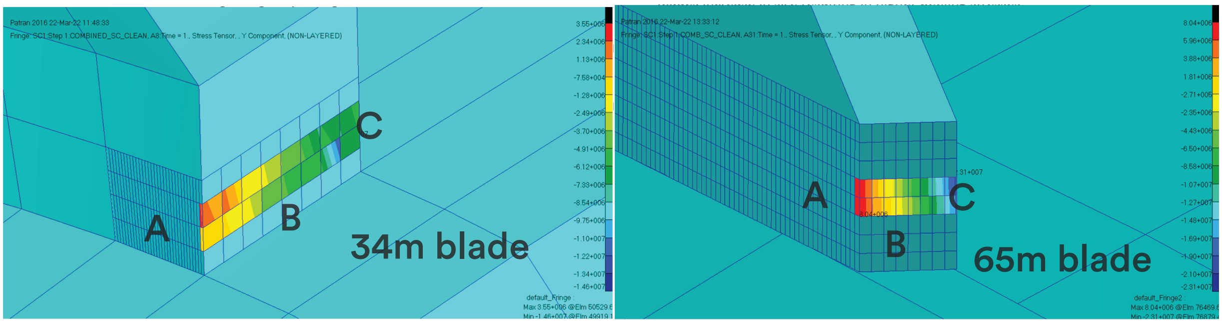


Figure 6 - Peeling stresses in the bondlines of the aft shear web of two different blade sizes (34m vs 65m blade).

On Figure 6 stress field variation for the two blades is post-processed. In Table 1 both membrane and bending stresses are being compared.

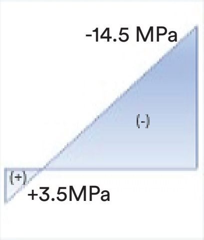
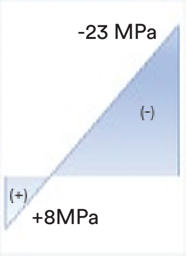
Combined loading (Flapwise + LTT)				
	Region B	Region A	Region C	Graph presentation of the stresses
	Membrane Stresses [MPa]	Bending Stresses (incl. membrane) [MPa]	Bending Stresses (incl. membrane) [MPa]	
34m blade	-5.5	3.5	-14.5	
65m blade	-7.5	8.0	-23.0	
Change %	*35*	***125***	*60*	

Table 1 - Membrane and Bending Stresses for the two blade cases.

It can be seen from Table 1, both membrane and bending stresses are increased when the blade length is bigger. In regions B and C, compressional stresses slightly rose while in region A there is significant growth in bending tensional stresses.

Apart from the size of the blade, another parameter that plays an important role in peeling stresses magnitude in the aft shear web is the torsional load component. The 65m blade was analyzed with and without the torsional load component, the only parameter that is varying in this case. By changing the flapwise load application point, from the shear center to the aerodynamic center [1], a torsional load component is introduced. In Figure 7, peeling stresses in the bondlines of the aft shear web of a 65m blade are presented.

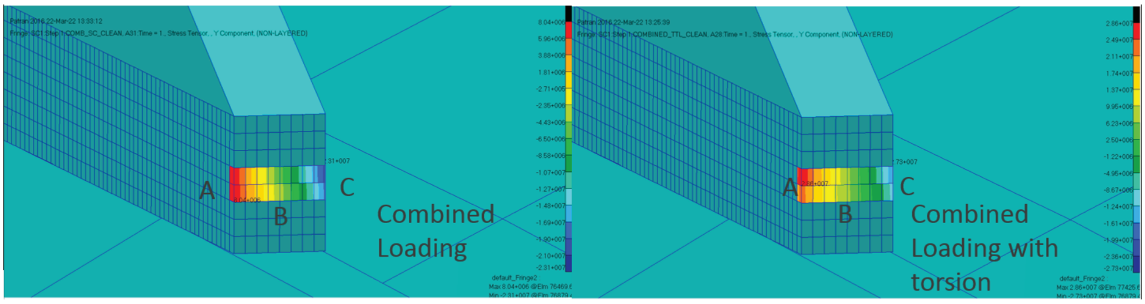


Figure 7 - Peeling stresses in the bondlines of the aft shear web of a 65m blade for two different load cases (with and without torsional loads).

In Figure 7 stress field variation for the two load cases in a generic 65m blade is post-processed. In Table 2, the results are tabulated.

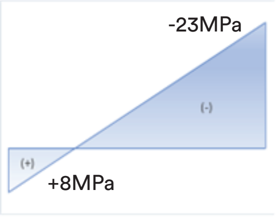
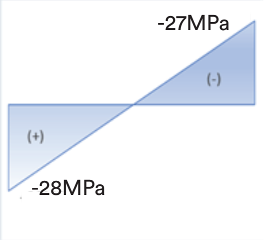
65m blade				
	Region B	Region A	Region C	Graph presentation of the stresses
	Membrane Stresses [MPa]	Bending Stresses (incl. membrane) [MPa]	Bending Stresses (incl. membrane) [MPa]	
Combined loading	-7.5	8.0	-23.0	
Combined loading + Torsion	0.7	28.0	-27.0	
Change %	-110	*250*	18	

Table 2 - Membrane and Bending Stresses for two combined load cases (with and without torsional loads).

It can be seen from Table 2, that bending tensional stresses in region A significantly grow when torsional loads are introduced to the load case. In region C there is a small increase of compressional stresses when torsional loads are included while in region B compressional stresses are turning to tensional.

Impact of localized phenomena

The topic of this chapter is to evaluate the impact of root transition zone breathing phenomenon on tensional peeling stresses of aft shear web. In addition, cross-sectional shear distortion for a generic 65m blade is investigated.

Root Transition Zone Breathing

It is known that composite materials have a relatively low strength when they are deformed out-of-plane. In this case, FEM is utilized to post-process the localized deformations and understand what the localized out-of-plane deformations are, as a result of global blade deformations.

One of the localized deformations is the so-called breathing. Breathing is the relative deformation between the panels at the middle point from the spar cap to the trailing edge, see Figure 8.

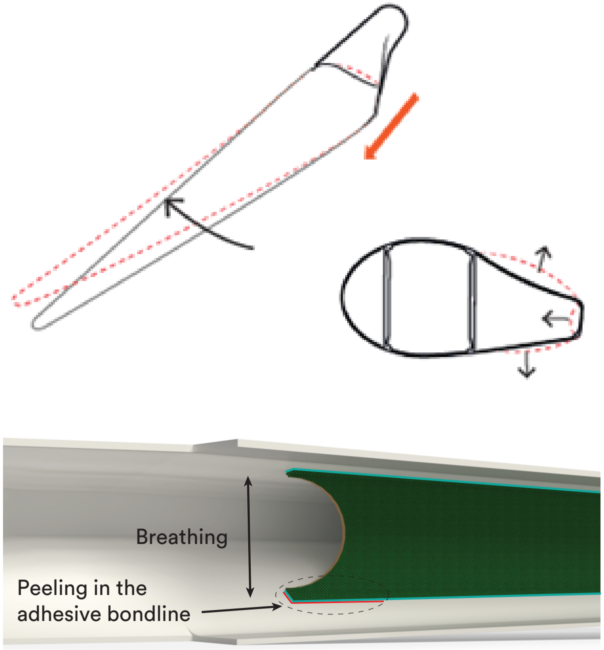


Figure 8 - Breathing effect on a blade.

In Figure 9 peeling stresses in the bondlines of the aft shear web of a 65m blade are presented. Regarding the load case, combined loads including the torsional load component are applied on the 65m blade.

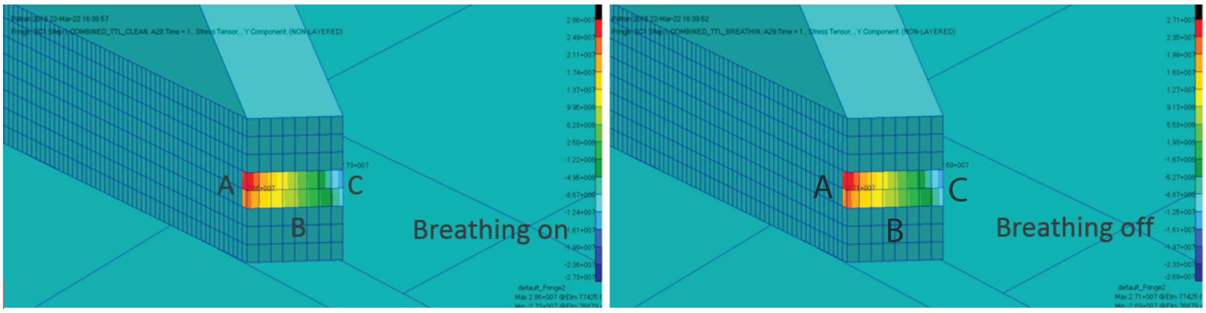


Figure 9 - Peeling stresses in the bondlines of the aft shear web of a 65m blade with and without Root Transition Zone breathing.

In Figure 9 stress field variation for the two cases in a generic 65m blade is post-processed. In Table 3 both membrane and bending stresses for the cases with and without breathing are being compared.

65m blade (with and without RTZ breathing)			
	Region B	Region A	Region C
	Membrane Stresses [MPa]	Bending Stresses (incl. membrane) [MPa]	Bending Stresses (incl. membrane) [MPa]
Breathing on	0.7	28.0	-27.0
Breathing off	0.1	27.1	-26.9
Change %	-85	-5	-2

Table 3 - Membrane and Bending Stresses for a 65m blade (with and without RTZ breathing).

It can be seen from Table 3, that bending tensional stresses in region A insignificantly decrease when RTZ breathing is eliminated. In region C there is a small increase of compressional stresses when RTZ breathing is excluded while in region B there is a significant reduction of membrane tensional stresses.

Cross-Sectional Shear Distortion

Another aspect that shall be considered when torsion (aka twisting) is addressed is the Cross-Sectional Shear Distortion parameter, see Figure 10.

In the wind energy industry, almost no attention to the cross-sectional shear distortion deformation has been taken. Thin-walled structures without internal reinforcement will tend to distort their profile in the transverse direction when loaded [2]. This mechanism is even more prominent when the cross-section is non-symmetric, both in geometry and layup, since the cross-section will also try to twist, see Figure 10.

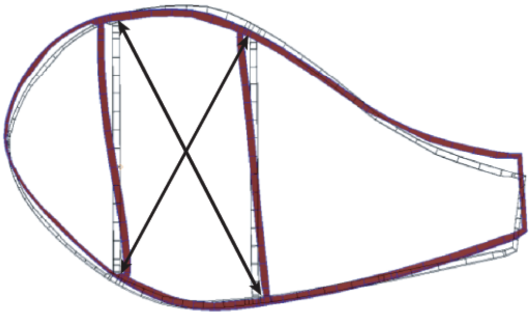


Figure 10 - Cross-Sectional Shear Distortion (CSSD) as a parameter of twisting shall be measured at the diagonal between the shear webs.

CSSD was evaluated for a generic 65m blade through the peeling stresses on the aft shear web. In Figure 11 peeling stresses in the bondlines of the aft shear web of a 65m blade are presented. Regarding the load case, combined loads including the torsional load component are applied on the 65m blade.

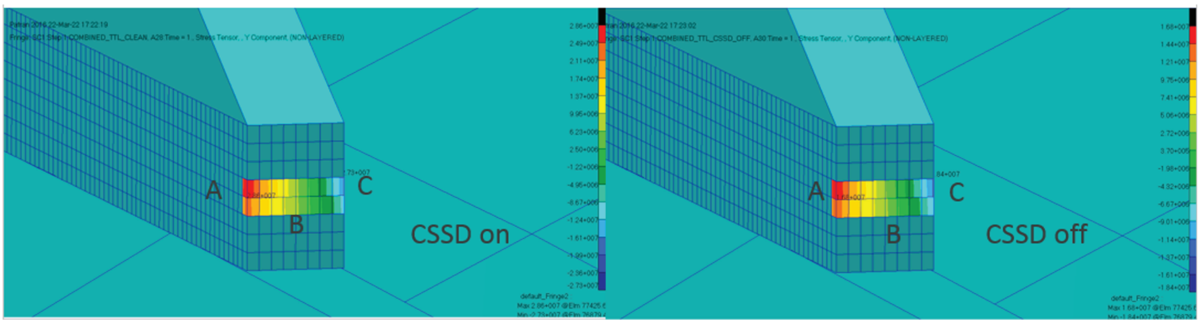


Figure 11 - Peeling stresses in the bondlines of the aft shear web of a 65m blade with and without CSSD.

In Figure 11 stress field variation for the two cases in a generic 65m blade is post-processed. In Table 4 both membrane and bending stresses for the cases with and without breathing are being compared.

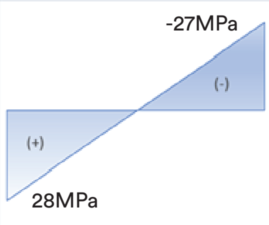
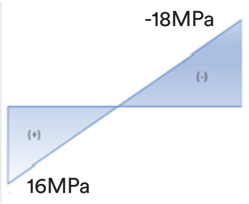
65m blade (with and without CSSD)				
	Region B	Region A	Region C	Graph presentation of the stresses
	Membrane Stresses [MPa]	Bending Stresses (incl. membrane) [MPa]	Bending Stresses (incl. membrane) [MPa]	
CSSD on	0.7	28.0	-27.0	
CSSD off	-0.8	16.0	-18.0	
Change %	*-223*	-40	*-35*	

Table 4 - Membrane and Bending Stresses for a 65m blade (with and without CSSD).

It can be seen from Table 4, bending tensional stresses in region A are significantly decreased when CSSD is eliminated. In region C there is also an important reduction of compressional stresses when CSSD is excluded while in region B tensional stresses are turning to compressional.

Risk considerations and mitigations

From the study done and presented above, it can be seen that there is a correlation between peeling stresses and blade characteristics (length), as well as phenomena such as breathing and CSSD.

When the blade doubles in size, there is a 125% increase in the peeling stress magnitude (aft shear web, fish-mouth region). By comparing a 65m blade with and without torsional loads, the peeling stresses increase is much higher, reaching 250% when torsional loads are included in the study. Therefore, by connecting this information with the S-N curves, the expected lifetime decreases significantly. The aforementioned reduced lifetime is visually presented on the graph in Figure 12.

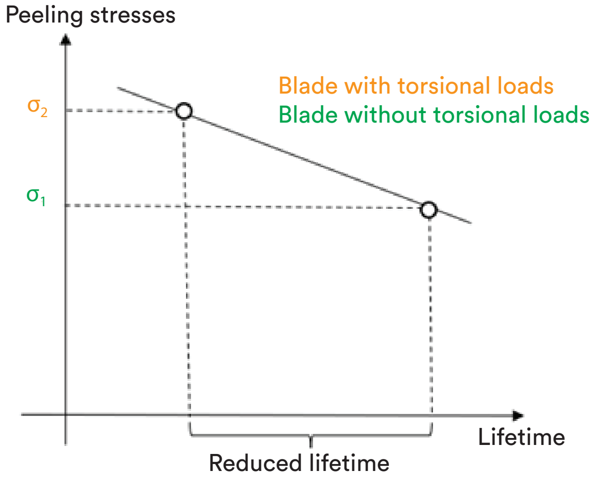


Figure 12 - Sketch presenting the reduced lifetime of a blade when torsional loads are included in the study.

Blades that may last less than expected are an alert that increases the risk in the field, especially if someone considers that torsional loads are not even captured properly during testing of the blade.

Since larger blades are required in the industry that is capable of harvesting more energy, and torsional loads exist in the realistic loading of the blades under operation, it is the localized phenomena and especially CSSD that could be eliminated contributing to a risk decrease. As proved in the study (regarding a 65m blade), the CSSD could potentially decrease 40% of the peeling stresses observed in the aft shear web, fish-mouth region.

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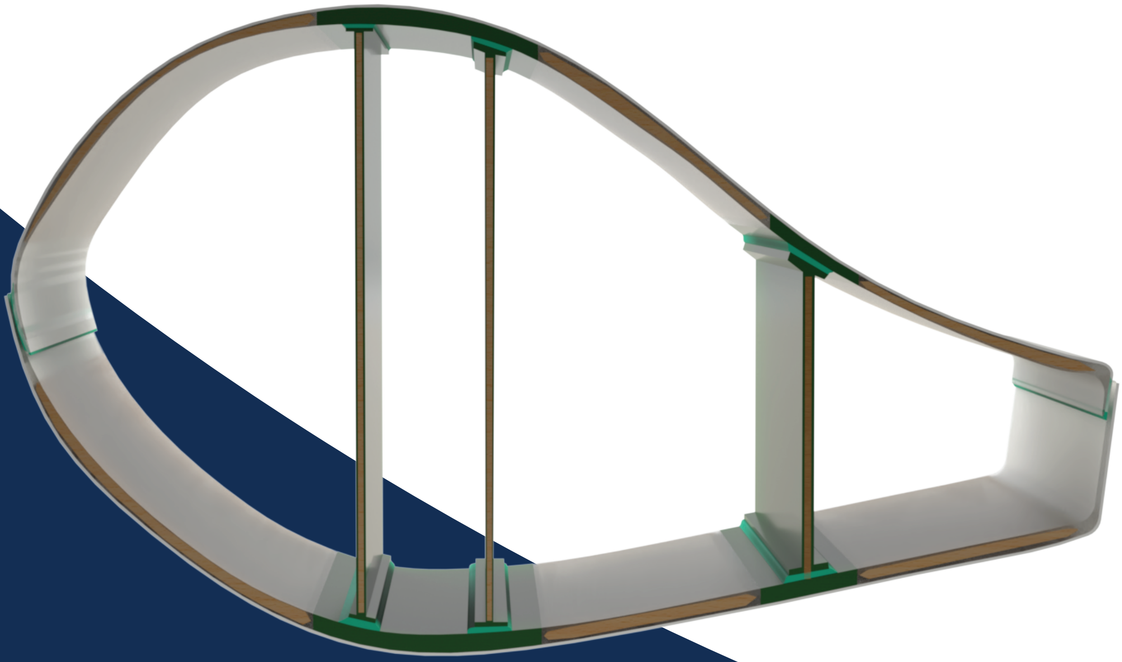

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