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Under-testing of wind turbine blades above 60 meters length causes field structural issues

Bladena Whitepaper

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1. Introduction

As wind turbine blades continue to increase in size, unexpected blade related costs are increasing at an unprecedented rate. Blades are now experiencing damages more frequently than in the past. Inspection and repair of these damages at offshore conditions lead to high Operation and Maintenance (O&M) costs due to longer downtime periods, leading to increased Operational Expenses (OPEX) cost and potential Annual Energy Production (AEP) losses.

Some sectors of the wind energy industry are experiencing economic downtrends, partially due to blade issues. There is a clear imperative for a change in blade design and testing methods to achieve robust blade designs that can withstand wind and gravity loads without structural damages.

This whitepaper focuses on certification testing campaigns and why certified large blades are seeing increased failure rates. We have observed that critical areas of the blade are often undertested, a major contributing factor to these increased failures.

In this paper, Bladena presents its view on why blades face structural issues and how these issues can be avoided. Primarily, during the certification test campaign, blades are not tested under a combined loading scenario replicating operational load scenario. Especially, torsional loads which are critical and are not sufficiently included in full-scale blade tests.

In addition, sub-component bending tests of unsupported panels are usually not sufficiently addressed. while focus remains on the in-plane longitudinal strains in the blade. Bladena's opinion is that such strains are not of primary concern for blades in operation. Current design standards require full-scale tests, which results in overloading some blade parts compared to what is representative of the field conditions.

This paper focuses on these under-tested areas, since they are highly associated with common structural damages seen in field. Addressing this issue will potentially significantly reduce the current high blade failure rates.

2. Current testing campaign

This section presents a brief overview of the certification test campaign that all blades must undergo (at least in Europe) before being launched to the market.

The certification process for wind turbine blades is a fundamental element in the wind energy industry, aiming to guarantee that blades meet operation and safety requirements before operation.

The continuous rapid upscaling of blade size presents new challenges that the current certification should address. The increase in blade size significantly impacts structural integrity, influencing on critical variables such as the edgewise root bending moment, which scales with the power of 3.4 [1], [2] and the root torsional moment, which scales with the power of 4 [1], [2].

Despite these challenges, part of the certification process has not progressed sufficiently to address the increasing challenges. Current testing methods concentrate on ocus pure flapwise and pure edgewise loading in full-scale testing, underestimating the importance of aspects like peeling tests or combined loading tests. Recognizing this issue, DNV and other certification bodies are in the process of modernizing their standards. Mature manufacturers are aware of these limitations, and tend to perform additional testing and analysis. The table on Figure 1 presents an overview of common failure modes and current practices according to current standards.

Failure Mode	IEC 61400-5:2020	IEC 61400-23:2014	DNVGL-ST-0376:2015	Used in industry	Uncertainty of tools	Impact of torsional loads
Bondlines (Peeling test)	(2)	(1)	(3)	(YES)	MEDIUM	HIGH
Skin debonding from core (Test)	(2)	(1)	(3)	(NO)	MEDIUM	HIGH
Interlaminar failure (Bending test)	(2)	(1)	(2)	(NO)	LOW	HIGH
Global strain (failure criteria)	(5)	(5)	(5)	YES	LOW	LOW
Shear web disbonding	(2)	(1)	(3)	(YES)	MEDIUM	HIGH
Root failures	(5)	(5)	(5)	YES	LOW	NO

Figure 1 - Overview of failure modes. Status and Bladena recommendations (1 means there is no reference in the standard and 5 means it is required in standards). [3]

As commented, a significant oversight in the current certification procedures is the absence of combined loading tests that include the torsional load component. In real-life scenarios, blades experience these combined loads, which exert additional stresses on a blade, especially at known 'hotspots' areas. Such real-life stresses are not captured in standard tests, where the loading is not representative, leading to potential vulnerabilities in blade designs that might only be evident under operational conditions. This topic is addressed in more detail in section 3.

2.1. Over-testing of longitudinal in-plane strength

As highlighted in the previous section, both IEC and DNV standards heavily emphasize on in-plane stresses and strains during testing. While ensuring these stresses and strains do not exceed critical limits is crucial, however it is not currently the primary cause of structural issues in blades.

Composite materials in modern large wind turbine blades do not fail due to lack of in-plane strength, but rather due to out-of-plane panel deformations. By checking the material properties of glass fiber, it can be seen how the longitudinal in-plane strength varies from 16000με in compression to 22000με in tension (see Figure 3).

Figure 2 - In-plane compression test demonstrates the over capacity of in-plane strength, shown on Figure 3.

	UD Glass	Triaxial glass	Biaxial glass
Allowable tensile strain	22000με	23000με	17000με
Allowable compressive strain	16000με	16000 με	14500με

Figure 3 - Allowable tensile and compressive strain for glass fiber. This information comes from an experimental test conducted by GL for a SSP34m blade [4].

Comparing these experimental longitudinal in-plane strain values with operation or certification test values, leads to the conclusion stated by Povl Brøndsted in the book titled Advances in Wind Turbine Blade Design and Materials [5]: "blades are probably over-dimensioned since they do not appear to be approaching the limits of the materials". Additionally, research performed at Risø (today DTU wind) shows that in-plane strength capacity is much higher than any blade ever will see in operation [4].

FEM simulations made by Bladena [1] corresponds with the quote above, showing that under non-extreme combined loading scenario including torsional loads, the longitudinal strain values are around ±3000με, see Figure 4.

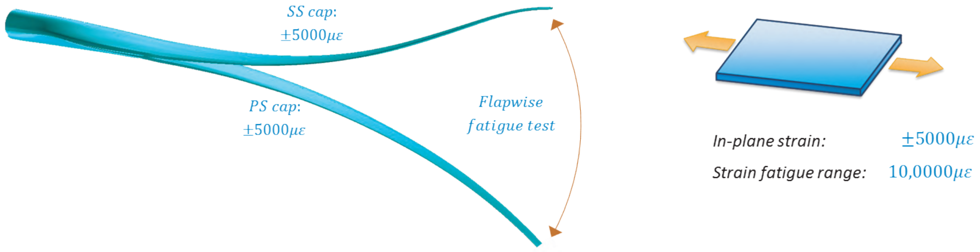

Figure 4 - Longitudinal strain values for a blade exposed to a combined loading scenario considering torsional loads replicating operational conditions.

Despite this large margin between field longitudinal in-plane strains and the material limit for glass fiber, expensive, and time consuming fatigue flapwise tests that strains in the longitudinal direction are still conducted [6]. The results from these full-scale tests show that longitudinal strain measurements peak around 5000με, see Figure 5. This represents approximately 60% increase over operational strains yet is significantly below what the material can withstand.

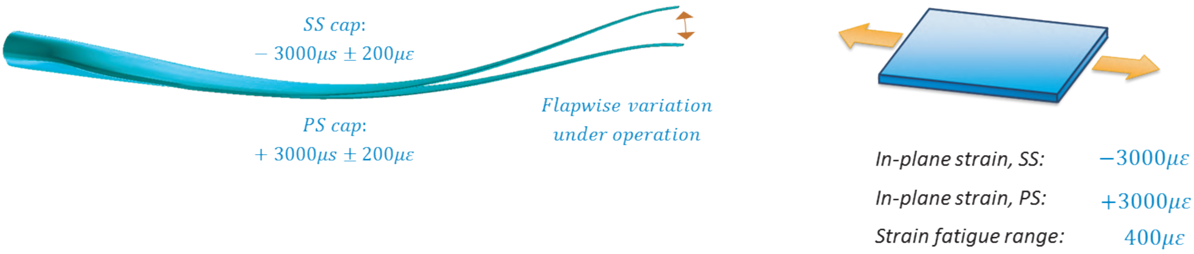

Figure 5 - Longitudinal strain values for a blade exposed to flapwise fatigue test as part of a certification test campaign.

Furthermore, Figure 3 illustrates that the fatigue range is around 10000με as the blade during the test moves towards the pressure side and then back towards the suction side. In operational conditions, aerodynamic forces tilt the blade towards the suction side, generating an oscillation range of around 400με under "regular" operational conditions.

To sum up, in-plane longitudinal strength for large current blades should not be the main focus for a certification testing campaign. High strain levels seen today may not be necessary even if flapwise fatigue tests are desired.

3. Under-tested blade components

Current standards from certification bodies, such as DNV and IEC cover a large variety of topics from a very detailed and technical perspective, providing relevant considerations and requirements for specific topics. However, as mentioned in the introduction, many large blades have structural issues and require improvements.

One of the identified key factors is the under-testing in both sub-component panel bending tests and large-scale tests with torsional loads

3.1. Today's lack of a sub-component panel bending test

Section 2.1. highlights that a lack of in-plane strength is not the root cause of the field damages observed in current large wind turbine blades. Moreover, as explained in section 4, a detailed study of the most critical failure modes from a structural perspective show that the focus should be on out-of-plane panel deformations.

Therefore, bending tests are considered essential to guarantee the reliability of a blade before it is certified to be launched in the market.

The DNV ST-0376 standard, especially in Annex E [7], addresses bending in both static and fatigue full-scale tests – an approach that Bladena commends. However, several aspects need to be commented:

1.) The loads on a wind turbine are higher in the root-transition zone and the max chord area. Any damage developing in these parts of the blade pose severe risk to the structural integrity of the blade. This highlights the suitability of a sub-component panel bending test for the mentioned areas.

2.) Measurements during a full-scale test should aim to capture the out-of-plane deformation of the panels. Both field experience and previous studies [8] conclude that common field damages, such as transverse cracks and potentially trailing edge opening, are a consequence of the stress generated during the out-of-plane bending of the panels. As a result, deformation sensors that capture this phenomenon should be a strict requirement.

3.2. Lack of a large-scale test with torsional loads

Another concern regarding large blades is the torsional loads generated during operation. The combination of edgewise and flapwise loads generates a high torsional component which significantly contributes to increasing out-of-plane panel deformations, leading to higher interlaminar stresses.

This topic has been studied in detail by Bladena and its project partners in a journal paper released in September 2023, titled Torsional Effects on Wind Turbine Blades and Impact on Field Damages. See Ref [1] and [2]. An illustration of an operational combined loading scenario is presented in Figure 6.

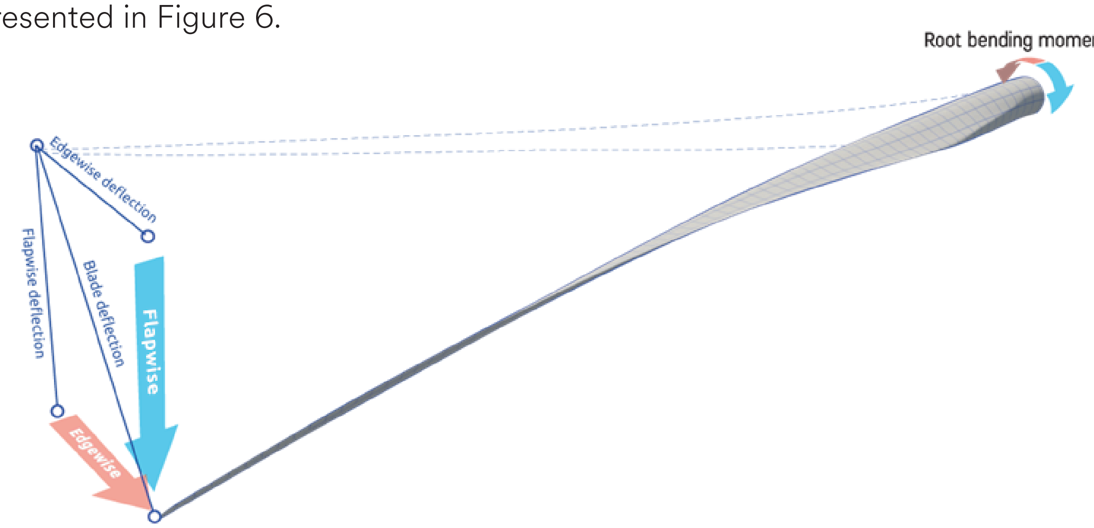

Figure 6 - Flapwise and edgewise load components and tip deflection generate Root Torsional Moments (RTM). The arrows are representative, the forces act along the whole blade. More details can be found in Ref [5] and [6].

The tip deflection shown in figure 5 is a consequence of the combination of flapwise loads due to incoming wind and edgewise loads from gravity and rotating blade dynamics. These movements cause forces to act not exactly at the blade's shear center, thereby creating an arm that generates a Root Torsional Moment (RTM).

A direct consequence is that the bending of the panels increases. Also, shear distortion of the cross section becomes concerning in this scenario, causing peeling, which can lead to further damages that risk the structural integrity of the whole blade. The relationship between the undertesting and the development of field damages, is explained in more detail in next section.

Finally, the relevance of torsional loads is recognized by both IEC Standards [6] (Section 9. Test loading and test load evaluation, section 10.1.6.3. Induced torsion loading, or even section 7.2. Test Program) and by the DNV-ST-0376 [7] in section 2.1.5. Design loads. Despite this, torsional loads are not compulsory to be applied. In Bladena's opinion, this is the major shortcoming that must be addressed.

4. Field damages associated to under-testing

The table below shows the common structural damages detected in field on modern large wind turbine blades. A short description of each damage is presented in this section. All of them have a common factor: they are highly influenced by torsional loads and out-of-plane deformation.
(https://www.bladena.com/uploads/8/7/3/7/87379536/table_of_failure_modes.pdf)

Addressing the undertest scenario covered in this whitepaper could potentially allow the detection of these failure modes during the certification test campaigns, preventing unexpected and highly costly OPEX.

Blade region	Hot spot	Failure mode	Observed damages	Root cause	Possible measurements for validation
Transition zone	Aft shear web bondline at fishmouth	Debonding of the aft shear web from the glass fibres in the blade cap/panels. Over time this can lead to a disconnection of the load carrying shear web and the cap comprimising the flapwise stiffness of the blade.	**Very frequent**	A combination of breathing between TZ panels and CSSD of the TZ cross section.	Measuments of breathing between the unsupported panels approx 0.5 to 1m from the fishmouth towards the root. Measurements of breathing between the panels on both sides of the fishmouth/start of aft web. Measurements of CSSD in the diagonals between main shear web and aft web and between aft web and FB.
Transition zone	Trailing edge panels, both PS and SS.	Skin debonding from the sandwich core. Transverse cracks or interlaminar stresses in monolytic layup.	**Frequent**	Out-of-plane bending of the large un-supported panels causing interlaminar stresses followed by skin debonding and cracks or interlaminar stresses between glass layup. Bending pattern: 3D waves. Note: Composite fibres fail in bending, not not due to in-plane loads.	Strain gauges on either side of the sandwich panel to measure strains on both sides. From this measurements bending strain can be calculated. Posiwires from shear web bondline to mid panel (diagonal, out-of-plane deformation can be calculated with trigonometri) Obstacle: To find the best spot on intact panels to measure bending.
Transition zone	Flatback Trailing edge	Delamination between the layers. Skin-debonding if the flatback is a sandwich construction.	**Occasional**	Bending of the flatback causing interlaminar stresses and delamination.	Measurements of relative displacement between the mid-flatback and the bondline of the nearest shear web. Measurement can be taken from FB to SS shear web bondline or PS shear web bondline. Obstacle: Measurement should not be taken to mid-nearest shear web in case the also bends.
Transition zone	Adhesive connection in the flatback pressure side corner	Peeling in the bondline/Adhesive connection	**Occasional**	CSSD of the TE box introduced fatigue peeling stress in the bondline.	Measurements of CSSD in the diagonals between aft shear web and and FB (for corners, two diagonals).
Max chord	Max chord pressure side panels	Skin debonding from the sandwich core. Transverse cracks.	**Very frequent**	Out-of-plane bending of the large un-supported panels causing interlaminar stresses followed by skin debonding and cracks. Bending pattern: 2D waves. Note: Composite sandwich panels fail in bending, not in-plane loads.	Strain gauges on either side of the pressure side sandwich panel to measure strains on both sides. From this measurements bending strain can be calculated. Posiwires from shear web bondline to mid PS panel (diagonal, out-of-plane deformation can be calculated with trigonometri). Note: Most MC transverse cracks are found in the pressure side panel. This is beacause curved panels will experince more out-of-plane bending when subjected to loading.
Max chord	Max chord trailing edge bondline	Peeling in the TE bondline developing into peeling cracks and interface failure between the adhesive and blade glass fibre. Over time this will develop into an open trailing edge.	**Frequent**	Breathing between the large un-supported max chord trailing edge panels introduces peeling stresses in the trailing edge bondline.	Measurements of breathing (relative displacement) between the SS panel and the PS panel.
Max chord	Max chord region bondlines between shear webs and spar caps	Peeling in the shear web bondline(s) developing into peeling cracks and interface failure between the adhesive and blade glass fibre. Over time this can lead to a disconnection of the load carrying shear webs and the caps comprimising the flapwise stiffness of the blade.	**Occasional**	Breathing between the large un-supported max chord trailing edge panels and CSSD of the blade introduces peeling stresses in the shear web bondlines.	Measurements of CSSD in the diagonals between two main shear web or in the TE box (or a blade specific constallation). Measurements of breathing (relative displacement) between the SS panel and the PS panel.

Figure 6 - Table of failure modes focusing on the blades' undertested areas, full screen version is available under the following link: https://www.bladena.com/uploads/8/7/3/7/87379536/table_of_failure_modes.pdf

5. Summary

Some large blades are experiencing early and costly field damages at a higher frequency than in the past. This whitepaper has connected this fact with the current certification testing campaign, identifying key factors that if addressed, could have a positive impact on reducing the current high blade failure rate.

In Bladena's view, there are three main aspects to highlight:

1.) Overtest of longitudinal in-plane strength: Composite materials in modern large wind turbine blades do not fail due to lack of in-plane strength. By checking the material properties of glass fiber, there is a large margin between field longitudinal in-plane strains and the material limits.

2.) Lack of sub-component panel bending test: The most critical failure modes from a structural perspective point out the importance of out-of-plane panel deformations. A sub-component panel bending test should be performed, together with out-of-plane strain measurements.

3.) Lack of a large-scale test with torsional loads: the combined loading scenario with both flapwise and edgewise loads including torsional loads is the closest representation of operational field loads. Individual flapwise and edgewise loads are not sufficient for this purpose. Torsional loads have a high impact on certain field structural issues [1].

There is a direct connection between the three main aspects above and the most common structural damages in large blades presented in section 4, consequently, these aspects should be considered.

DNV has significantly increased the recognition of operational conditions including torsional loads in the new standards which that is currently on development. In some cases, requirements regarding static torsion test will be set as an obligation and torsional loads, for instance, now shall be encompassed in the extreme load envelope. DNV is also now requiring peeling tests for bondlines, which is another positive step due to related field damages (see Figure 6). In addition, some mature manufacturers are recently implementing additional bending panel tests as they are aware of the connection between out-of-plane deformation and some of the common field damages.

A positive shift in the industry mindset seems to be in place. However, further effort and improvements are still needed to overcome the industry issue with the increasing and increasing Operational Expenses (OPEX) costs and with the associated potential Annual Energy Production (AEP) losses.

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- *Potential operational consequences of undertested (and overtested) blade parts*
- *Importance of sub-component testing with representative bending loads*

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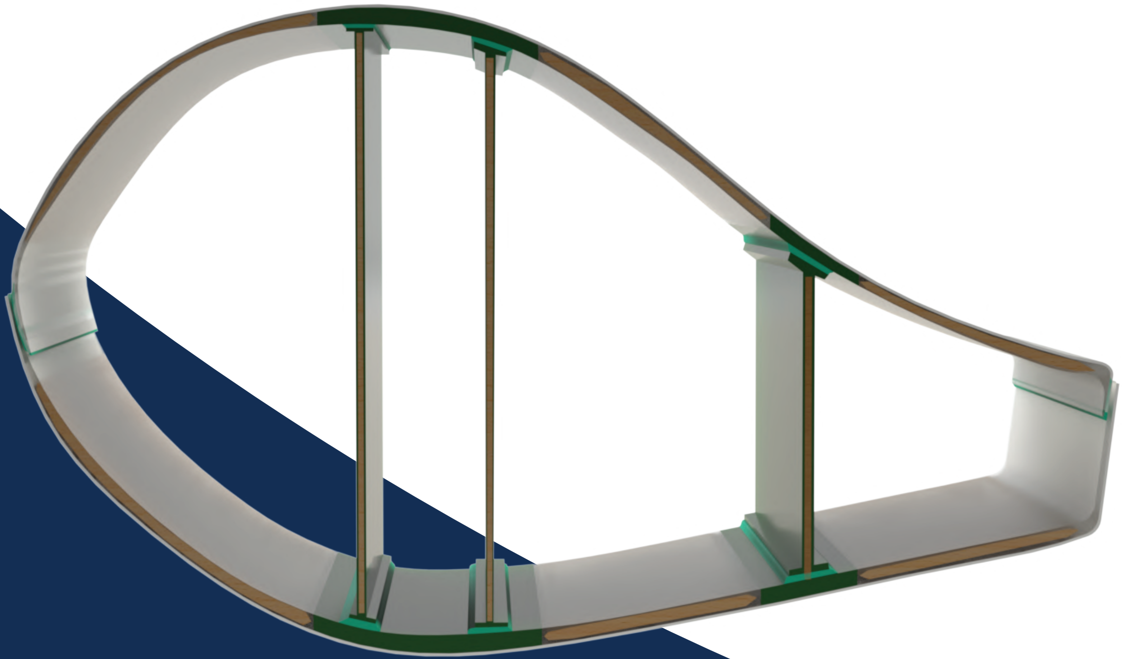

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