

## Measurements and FEM validation of local deformations

**Margrethe Werk (Bladena), Peter Greaves (ORE Catapult)**

October 2026



## Executive summary

This whitepaper is the third paper in the series describing the full-scale torsional fatigue test campaign performed on an 88m wind turbine blade in collaboration between RES/Bladena and ORE Catapult. Whitepaper I presented the motivation, test objectives, and overall test setup introducing torsional loads. Whitepaper II presented the load introduction and measurement plan. This paper presents the measured structural response and compares it with the FEM simulations.

FEM models are a numerical tool which simulates the structural response of a blade under torsional load. However, before placing full trust in the FEM results, the results must be compared with physical measurements from blade tests. FEM models usually predict global blade response with a good accuracy, and they are generally good at predicting where local deformation patterns appear on the blade. The amplitude of the local response, however, usually comes with a higher level of uncertainty. Since it is exactly these local response amplitudes that are linked to structural failure modes, validation against measured data is required before the model can be used with confidence for local lifetime assessment.

The key technical message of this paper is that controlled torsional loading was applied to trigger local structural response; which is causing critical peeling stresses in bondlines and bending of sandwich panels which can lead to delamination.

During the static test, measurements were performed on the blade under the applied torsional loading, and the FEM analysis is validated against these measurements. Local deformations were measured, including out-of-plane panel deformation and cross-sectional shear distortion. The FEM results are in good agreement with the experimental results.

The outcome of the campaign is a validated FEM model. The validated model can be used to deliver a more reliable input for lifetime assessment using S–N curve-based fatigue evaluation or fracture mechanics approach.

## Introduction and scope

The full-scale torsional test campaign was designed as a validation platform for local deformations in the max chord and transition zone regions. It is part of the 7-step validation process for large blades introduced in whitepaper I, and the instrumentation and measurement plan were described in whitepaper II. This paper covers Step 6 (FEM model validation): what the measurements showed and how they compared with the FEM predictions. The results can be used as input to Step 7 (updated lifetime assessment).

This paper covers the static torsional test. The effect of structural mitigation solutions is not covered in this paper. This will be addressed in a future publication, including the Lattice Bar™ concept and a comparison of the blade response with and without the lattice bars installed.

The purpose of this paper is to document:

- How local deformations are triggered by applying a pure torsional load.
- The measured structural response obtained during the torsional test.
- Validation of the FEM model against test measurements.
- The reduction of uncertainty on how much local deformation is present.

The local blade responses of interest are the phenomena that drive structural failure modes in large blades:

- Cross-Sectional Shear Distortion (CSSD): CSSD contributes to critical loading of the shear webs and trailing edge bondlines.
- Out-Of-Plane (OOP) panel deformation: OOP panel deformation shows that the panels are being bent and is directly linked to the failure mode of composite panel bending leading to interlaminar stresses.

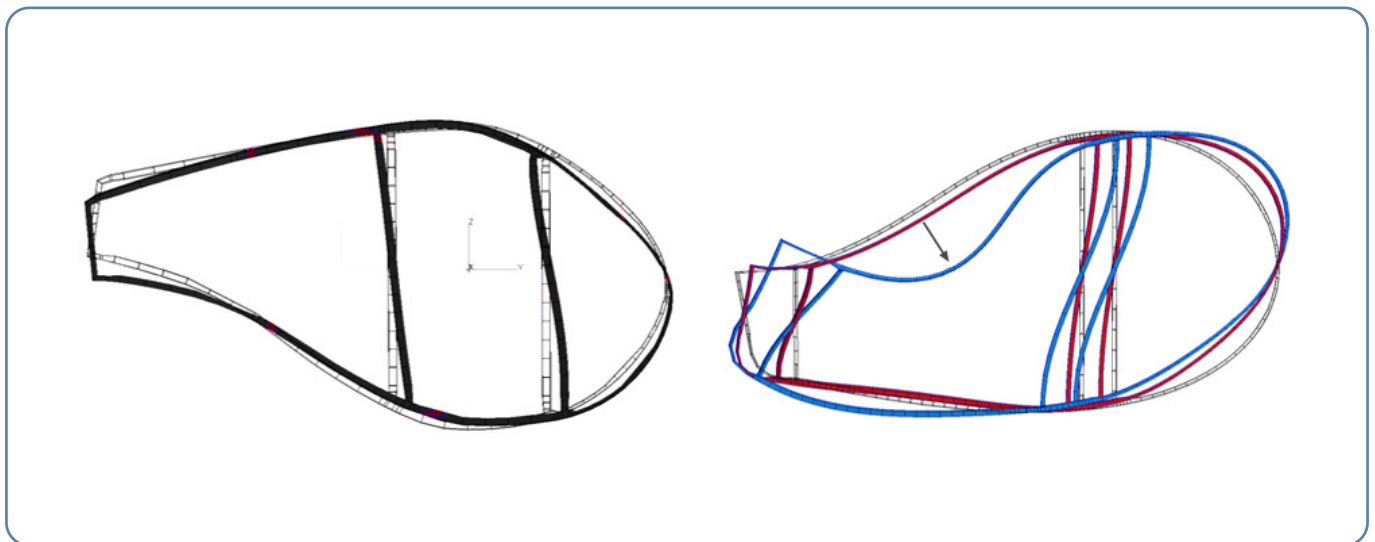


Figure 1: The local blade phenomena Cross-Sectional Shear Distortion (LEFT) and Out-Of-Plane panel deformation (RIGHT) shown on a 2D blade profile.

## Role of FEM validation in the test campaign

The FEM model is a central tool for interpreting the full-scale torsional test. The test provides measurements of the structural response under controlled loading, while the FEM model provides a numerical simulation of the blade behaviour under the same applied loading. During the campaign, measurements were taken on the blade, and the FEM analysis can be validated against these measurements.

The validation work considered both the local response Cross-Sectional Shear Distortion and Out-Of-Plane panel deformations. The measured quantities used for the validation are listed in Section 5.

The objective was to assess whether the FEM model represents the physical behaviour of the blade with sufficient accuracy to support local structural evaluation and lifetime assessment.

## Uncertainty of FEM results

Comparisons between experimental measurements and numerical FEM make it clear that FEM simulations come with uncertainty. The main sources of uncertainty can be divided into three groups:

- **Geometry:** The method of modelling the geometry may introduce uncertainty. Blade geometry has a significant effect on local blade response. OEMs will typically have access to blade geometry with less uncertainty than third parties.
- **Layup:** Assumptions and simplifications of the blade layup introduce uncertainty in the FEM blade model.
- **Loads:** Loads will always be a simplified representation of the real loads on the blade, and boundary condition and load application assumptions introduce uncertainty. In the present test campaign this uncertainty source was strongly reduced, because the applied torsional test loading was controlled, known, and repeatable.

In addition to these groups, modelling choices such as mesh density, element formulation, and the representation of connections, reinforcements, and structural details contribute to the model uncertainty. These sources may have limited influence on global blade response but can have significant influence on local bending strain, local bending deformation and peeling stresses in bondline.

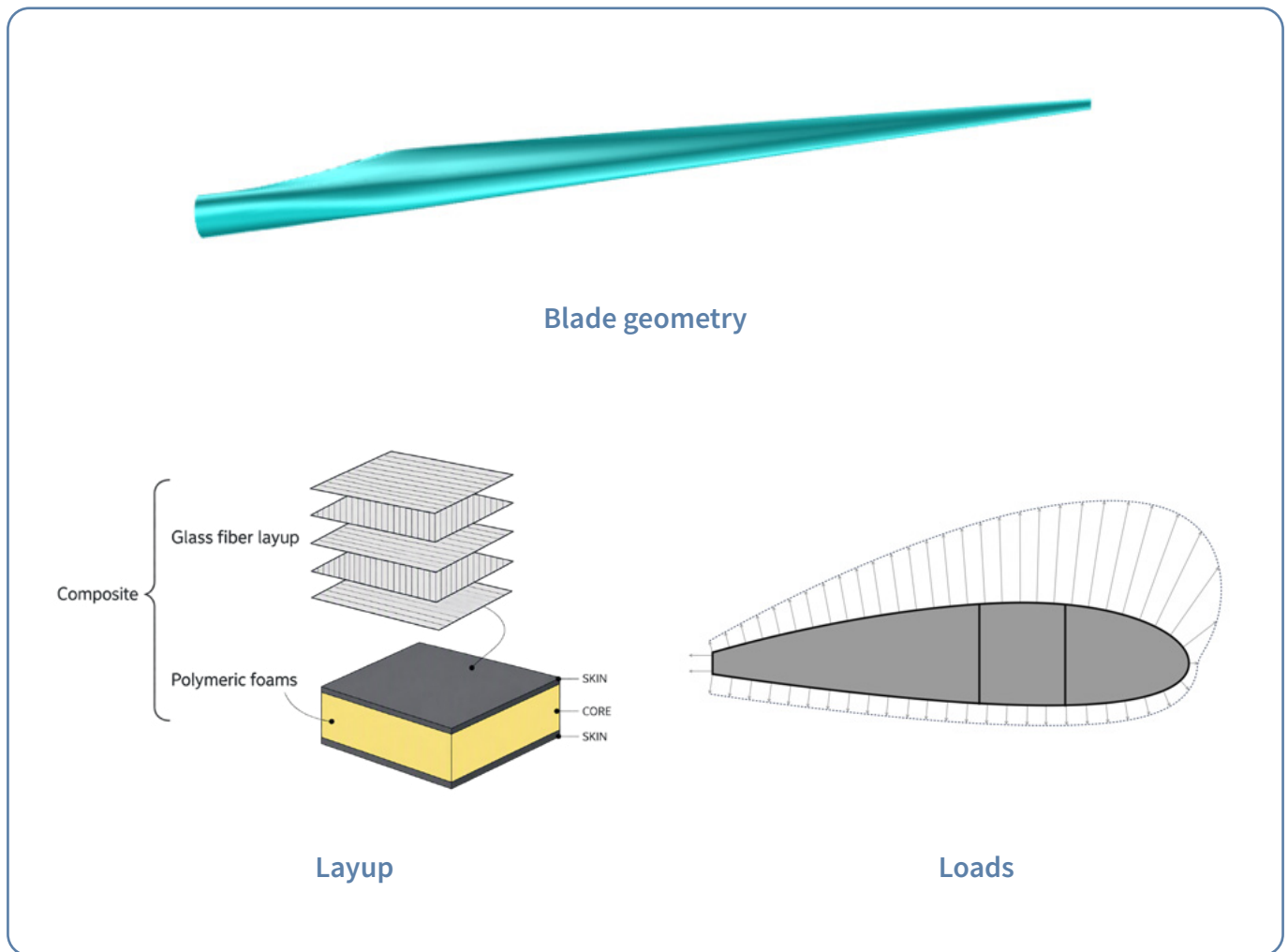


Figure 2: The main sources of uncertainty in FEM results divided into three groups: Geometry, Layup and Loads.

In general, global blade responses are easier to predict with FEM simulations, but the more local a blade response is, the higher the uncertainty is expected to be:

- **Global blade response** — model uncertainty is low: FEM models can represent global blade response (tip deflection, global longitudinal strains, and torsional twist) with a high degree of accuracy.
- **Region of local blade response** — model uncertainty is medium: FEM models are quite good at predicting where on the blade specific local response phenomena will occur.
- **Local blade response amplitude** — model uncertainty is high: The amplitude of the local response, which is directly linked to the associated failure mode, comes with a high level of uncertainty.

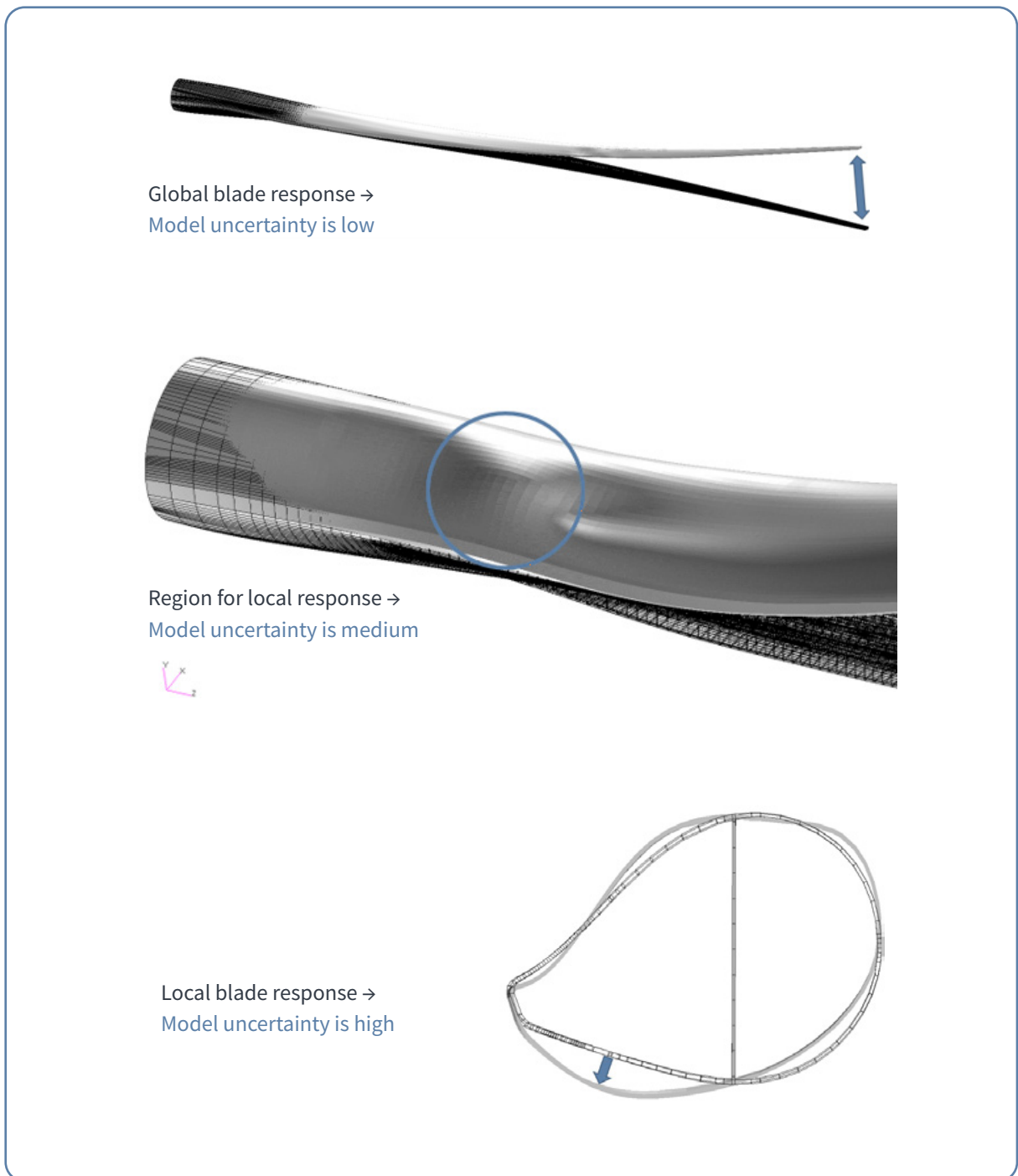


Figure 3: Global blade responses such as tip deflection, global strains and bending moments are relatively easy to predict. Amplitudes of local blade responses are much harder to predict to a high degree of accuracy.

Global response drives local response — and this is equally true for torsion. A FEM model that represents the global properties and global stiffness of the blade correctly is therefore the foundation for predicting the local response.

The level of uncertainty also depends on the blade region. The max chord region is typically more predictable in FEM simulations: the profiles are well-defined and the load paths are relatively straightforward. The transition zone introduces greater complexity and uncertainty, as it often contains double-curved geometries that are difficult to capture accurately in a FEM model.

## Applied loads

The results presented in this whitepaper are for a one-direction static torsional test load. The load was applied through the load introduction system described in whitepaper I and whitepaper II, introducing a controlled torsional moment into the blade under known and repeatable conditions.

The load achieved in the static commissioning test was sufficient for the scope of the first phase of the test campaign: it triggered measurable local deformations in both the max chord region and the transition zone, and thereby provided the basis for the FEM validation presented in this paper, see Figure 4.

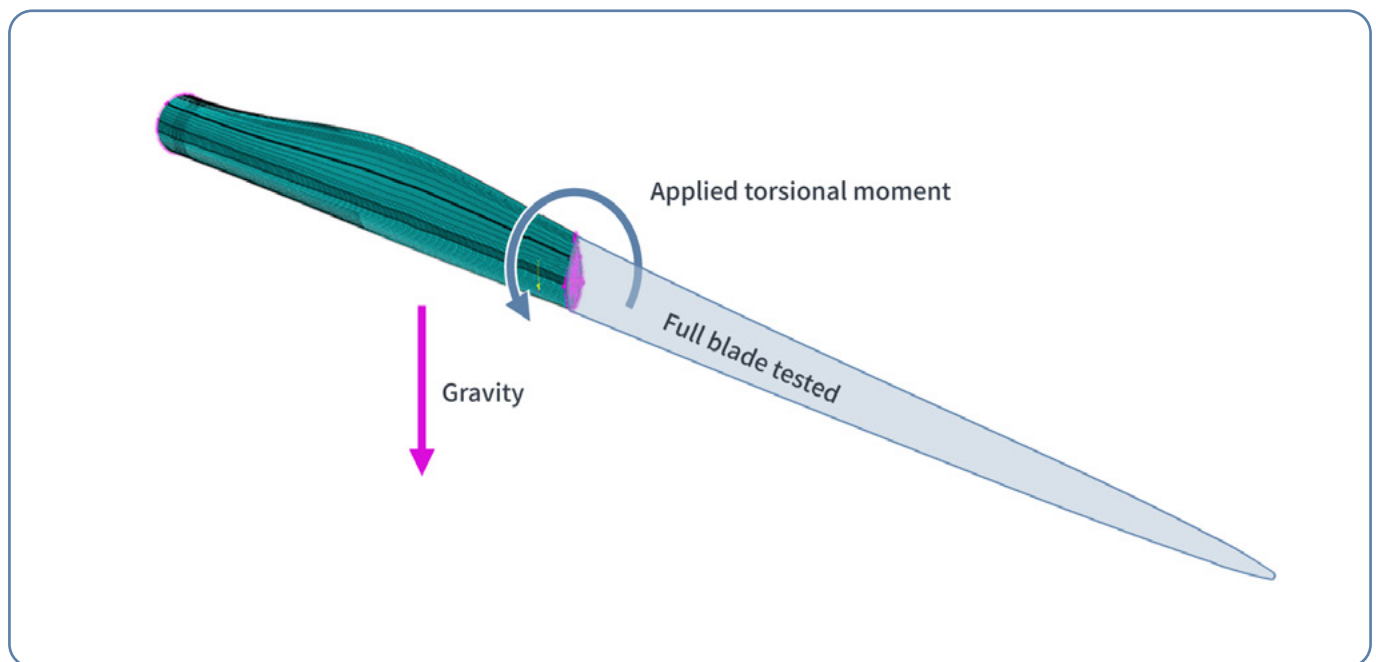


Figure 4: The applied one-direction static torsional test load as applied on the blade at 35m from the root. The full 88m blade was tested.

Because the applied loading was controlled and known, the load uncertainty in the FEM comparison is significantly reduced: the FEM model was loaded with the same static torsional load case as applied in the static test, so the measured and predicted responses are directly comparable. The applied load is a controlled, targeted load case rather than a representation of the full complexity of in-service loading; within that scope, it generates specific structural evidence for specific phenomena at high fidelity and with direct engineering relevance.

## Measured results

The measurement campaign provided the experimental basis for the FEM validation. The instrumentation strategy and measurement plan were described in whitepaper II; The following types of measured results were used:

- Applied torsional load.
- Global blade displacement and global blade twist.
- Global strain in panels.
- Local bending strain.
- Local deformation response, including Cross-Sectional Shear Distortion and Out-Of-Plane panel deformation in max chord and transition zone. Local deformations were measured with string potentiometers.

This paper presents the measured results for local deformations and how they were used in the FEM comparison.

The measured results were used to evaluate whether the FEM model predicted both the magnitude and the deformation mode correctly.

## Comparison of measured and simulated response

The measured full-scale response was compared with the FEM results. In this paper only local deformation results are presented. The FEM results are compared against measurements at the instrumented critical regions for four quantities: Out-Of-Plane pressure side panel deformation in the max chord region, Cross-Sectional Shear Distortion (CSSD) in the max chord region, out-of-plane pressure side panel deformation in the transition zone, and out-of-plane suction side panel deformation in the transition zone.

The comparison is presented as plots in which the measured response and the FEM results are shown together along the blade. A summary of results then compares the measured and FEM values at each measurement station along the blade, including the percentage deviation of the FEM amplitude from the measured amplitude (Table 2).

Four local deformation quantities are compared: Out-Of-Plane pressure side panel deformation and Cross-Sectional Shear Distortion (CSSD) in the max chord region, and Out-Of-Plane pressure side and suction side panel deformation in the transition zone. Each quantity is shown in a separate plot with the measured response and the FEM result along the blade, and the values at each measurement station are summarised in Table 2 at the end of this section.

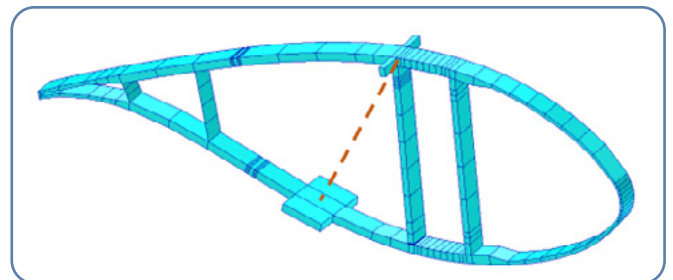


Figure 5: Blade cross section in the max chord region, showing the measurement position for Out-Of-Plane pressure side panel deformation.

## Max chord: Out-Of-Plane pressure side panel deformation

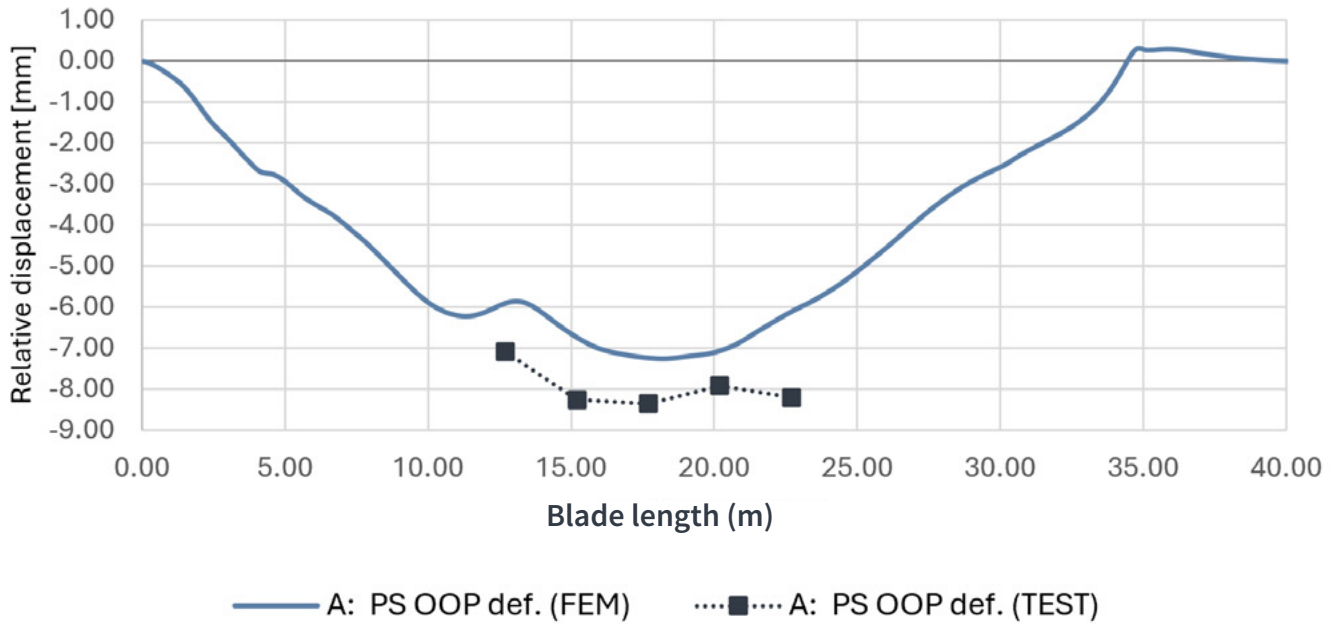


Figure 6: Out-Of-Plane pressure side panel deformation in the max chord region — measurement and FEM in one plot, based on string potentiometer measurements.

The FEM results from the max chord OOP pressure side panel deformation are in good alignment with measurement results with FEM results being 11% to 25% less than the measurements. This means the FEM model is stiffer than the actual blade, and that the FEM results underpredict the local deformation the blade actually experiences. This is as expected based on similar FEM validation projects with other blade test subjects where a general trend shows FEM models to be stiffer than the blades. This enforces the importance of measurements of local deformations on actual blades.

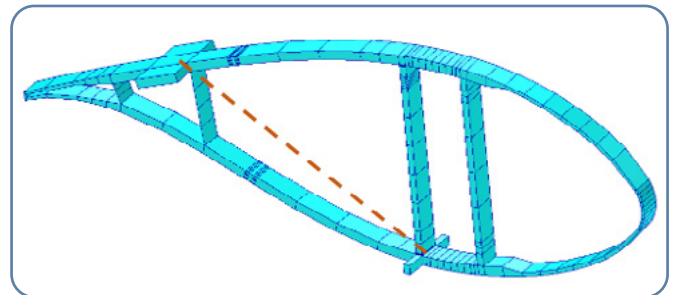


Figure 7: Blade cross section in the max chord region, showing the measurement positions for Cross-Sectional Shear Distortion (CSSD).

## Max chord: Cross-Sectional Shear Distortion

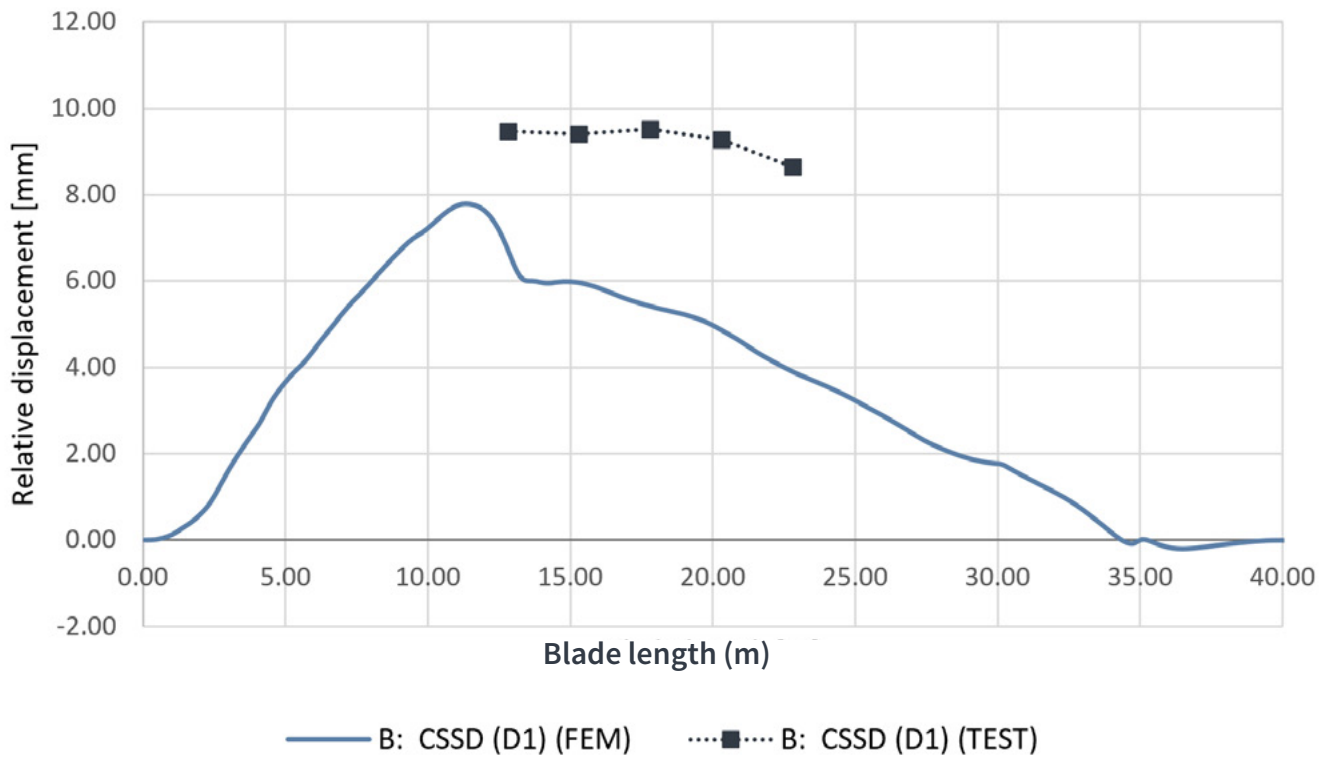


Figure 8: Cross-Sectional Shear Distortion (CSSD) in the max chord region — measurement and FEM in one plot, based on string potentiometer measurements.

For the Cross-Sectional Shear Distortion measurements in the max chord region the alignment is also relatively good. The deviation of FEM results from measurements are 29% to 55%, which sounds like a lot, but with the stiffnesses of two corners affecting the results it is to be expected that the FEM model will be stiffer than the measurements. If input from FEM should be used for lifetime estimation, the FEM model corner modelling can be softened and calibrated to match measurement results. Again the FEM model over-predicts the actual stiffness of the blade and therefore under-predicts the local deformation.

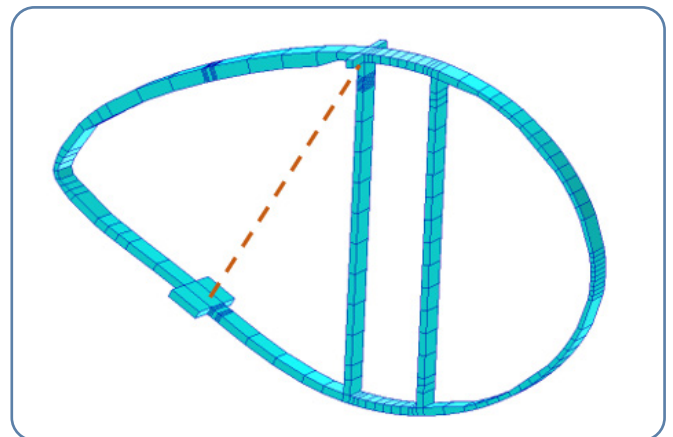


Figure 9: Blade cross section in the transition zone, showing the measurement position and direction for Out-Of-Plane pressure side panel deformation.

## Transition zone: Out-Of-Plane pressure side panel deformation

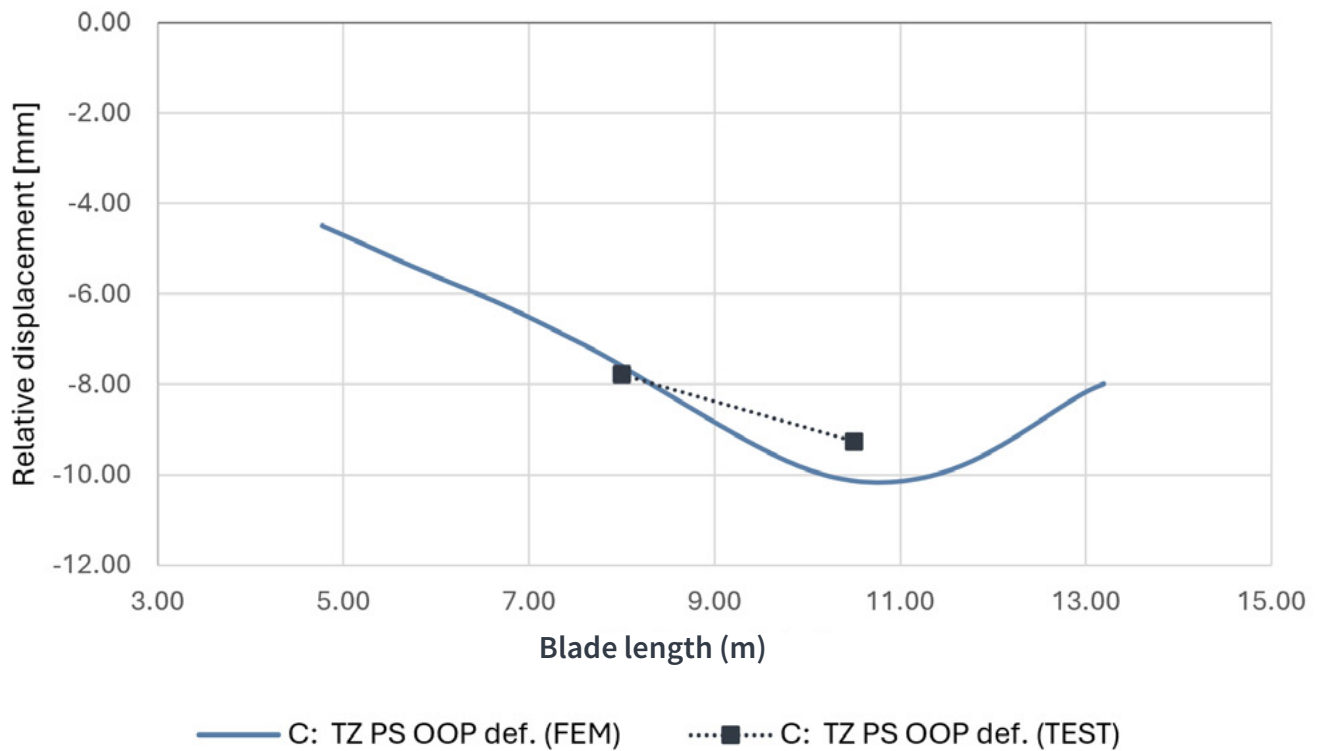


Figure 10: Out-Of-Plane pressure side panel deformation in the transition zone — measurement and FEM in one plot, based on string potentiometer measurements.

In the transition zone, the FEM results for the OOP PS panel closely match the measurements at both measurement stations, deviating by less than 10%. This is better than expected, as the transition zone is known for its complex geometry and layup.

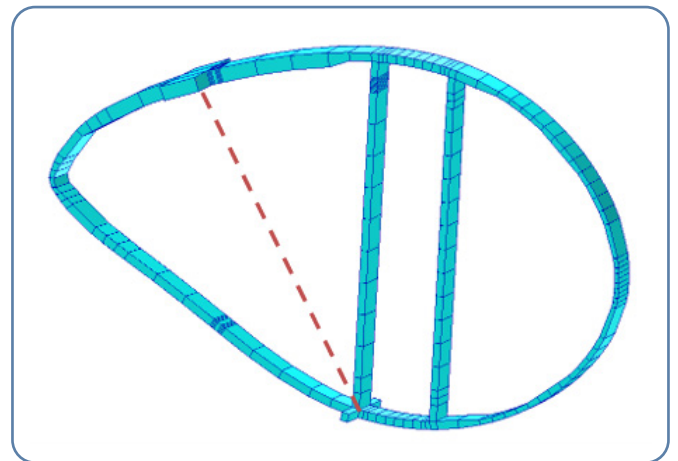


Figure 11: Blade cross section in the transition zone, showing the measurement position and direction for Out-Of-Plane suction side panel deformation.

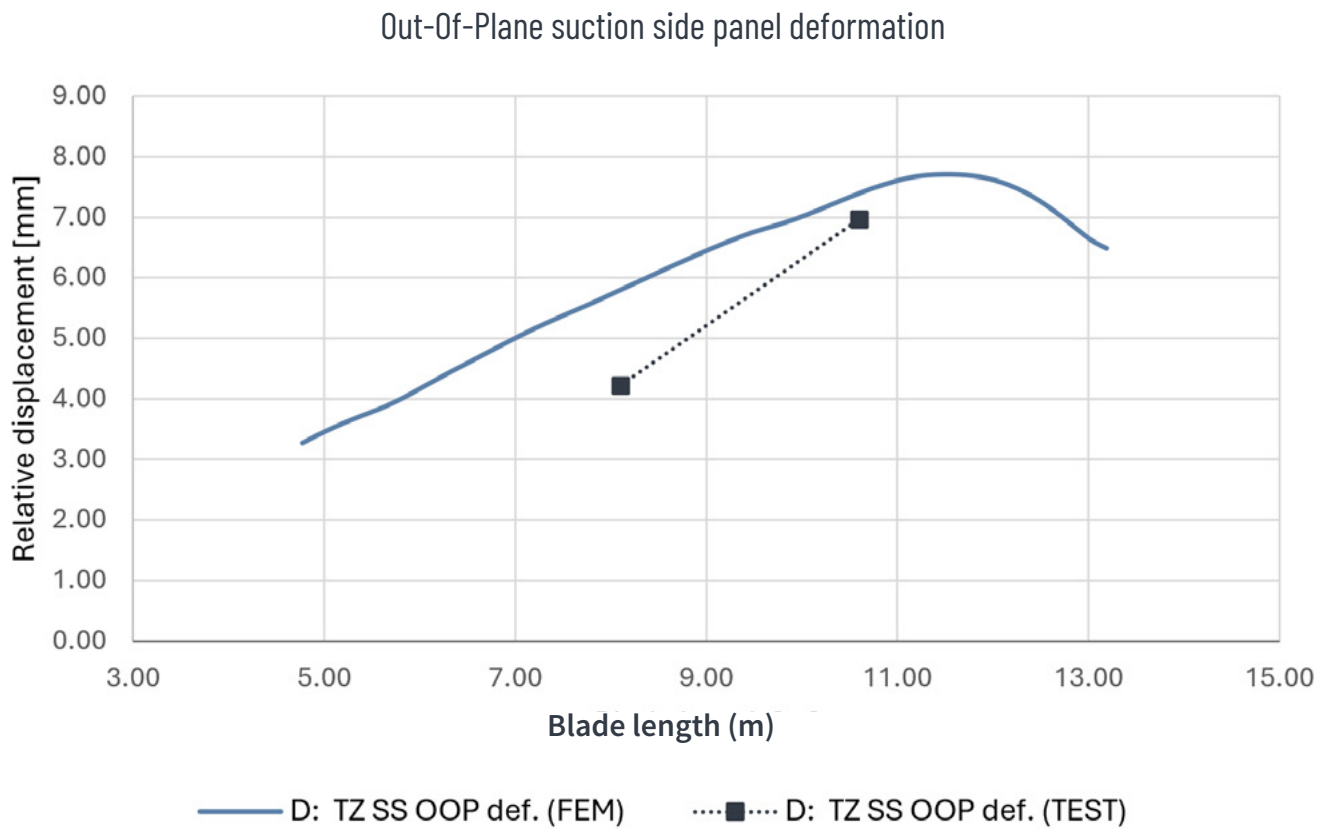


Figure 12: Out-Of-Plane suction side panel deformation in the transition zone — measurement and FEM in one plot, based on string potentiometer measurements.

**The OOP SS panel in the transition zone is in reasonable alignment with measurements, with FEM results deviating 6% to 37% from the measured values.**

| Quantity                                   | Blade length [m] | Test [mm] | FEM [mm] | Deviation [%] |
|--------------------------------------------|------------------|-----------|----------|---------------|
| Max chord – OOP PS panel deformation       | 12.7             | -7.1      | -5.9     | -17%          |
|                                            | 15.2             | -8.3      | -6.8     | -18%          |
|                                            | 17.7             | -8.4      | -7.3     | -13%          |
|                                            | 20.2             | -7.9      | -7.1     | -11%          |
|                                            | 22.7             | -8.2      | -6.1     | -25%          |
| Max chord – CSSD                           | 12.8             | 9.5       | 6.7      | -29%          |
|                                            | 15.3             | 9.4       | 6.0      | -37%          |
|                                            | 17.8             | 9.5       | 5.4      | -43%          |
|                                            | 20.3             | 9.3       | 4.9      | -48%          |
|                                            | 22.8             | 8.6       | 3.9      | -55%          |
| Transition zone – OOP PS panel deformation | 8.0              | 7.6       | -7.8     | -2%           |
|                                            | 10.5             | -10.1     | -9.3     | 9%            |
| Transition zone – OOP SS panel deformation | 8.1              | 5.8       | 4.2      | 27%           |
|                                            | 10.6             | 7.4       | 7.0      | 6%            |

Table 1: Summary of local deformation results from string potentiometer measurements — measured value and FEM results. The last column shows the FEM results deviation from test at each measurement station.

Table 1 shows the alignment between measurements and FEM results. The last column shows how much in percentage the FEM results deviate from the measured values for local deformations in the max chord and transition zone. In general, the FEM model are 10% to 50% percent stiffer than the tested 88m blade.

The stiffness offset matters directly for lifetime evaluation. When the FEM model is stiffer than the tested blade, the local deformations the blade actually experiences are larger than those predicted by the simulation. A lifetime assessment based on FEM deformations alone will therefore rest on a deformation level that is too low, and the damage accumulation at the local details will be underestimated. Full-scale measurements of local deformations are what make this offset visible and quantifiable, so that the model can be calibrated — or a correction applied — before the deformation fields are used as input for lifetime assessment. Without measured local deformations, the magnitude of this offset remains an unquantified uncertainty in the assessment.

## Updated lifetime assessment

The validated FEM model can be used to extract improved local deformations and strain levels at the damage-sensitive regions. These values can then be used for updated lifetime assessment, closing Step 7 of the validation process, described in whitepaper I.

No sub-component testing programme is part of this campaign, and no S–N curves have been established. The value of the validation lies in the principle: the validated local response fields can be used as realistic input for lifetime assessment of the damage-sensitive details — for example composite panels in relation to out-of-plane panel deformation, or bondlines in relation to CSSD. The main use cases are:

- Using validated FEM results as realistic input (boundary conditions) for the assessment of structural details — for example panels in relation to out-of-plane panel deformation, or bondlines in relation to CSSD.
- Using validated FEM results to adjust lifetime estimation based on existing S–N curves, where a more realistic input (deformation) results in a more reliable lifetime estimation. As an example, the movements of trailing edge panels away from each other is a deformation which a validated FEM model can provide, the deformation then assures the right peeling stresses are presented in sub-component testing.
- Using the validated FEM model to predict local blade responses under loads not covered by the test loading — for example operational loads, extreme loading, or any other load case not easily applied in a test facility.
- Where appropriate, applying fracture mechanics-based methods using the validated local response fields.

The validated model thereby supports evaluation of critical local strain regions, bondline response, and panel bending response. It provides an improved basis for risk-based inspection, maintenance, retrofit, and operational decisions.

It is emphasised that the FEM model cannot be directly validated for peeling stresses in bondlines, as these cannot be measured experimentally at full scale. The validated deformation fields instead provide boundary conditions from which bondline-critical loading can be assessed.

The FEM model has been compared against full-scale measured response under controlled torsional loading. This improves confidence in the model when it is used for local assessment of torsion-sensitive blade regions.

## Summary and conclusions

In this paper results from a static torsional test load and measured the resulting local structural response has been compared. The key findings are:

- Torsional loading alone was sufficient to trigger local deformations in the max chord region and in the transition zone. Both cross-sectional shear distortion and out-of-plane panel deformation were measurable and present to a significant degree.
- The FEM model predicted correctly where the local deformations occur.
- The FEM model also gave a good prediction of the general magnitude level of the local deformations, but the amplitudes deviated systematically from the measurements: 11% to 25% for out-of-plane pressure side panel deformation in the max chord region, 29% to 55% for CSSD in the max chord region, 2% to 9% for out-of-plane pressure side panel deformation in the transition zone, and 6% to 27% for out-of-plane suction side panel deformation in the transition zone (Table 1).
- The FEM model proved to be too stiff relative to the tested blade — in general 10% to 50% stiffer. Since the blade deforms more than the simulation predicts, FEM deformations used directly as input would give non-conservative lifetime assessment. The stiffness offset must be calibrated out, or a correction applied, before the deformation fields are used for lifetime evaluation.
- The validated model, with documented agreement per phenomenon and evaluation parameter, provides a more reliable basis for lifetime assessment at the damage-sensitive regions.

The full-scale torsional test provided a valuable bridge between numerical prediction and physical blade behaviour. The measured results allowed the project team to identify where the FEM model was reliable and where further investigation may be needed. The validated model provides an improved basis for evaluating local structural response and lifetime assessment and supports a more risk-based approach to inspection, monitoring, maintenance, and retrofit decisions.

Further fatigue testing is planned as the next phase of the campaign.

## References

- [1] Bladerna and ORE Catapult. [Whitepaper I](#) – Full-scale torsional load testing with ORE Catapult: test concept and setup, CORTIR III project, 2026.
- [2] Bladerna and ORE Catapult. [Whitepaper II](#) – Load introduction, measurement and instrumentation strategy for full-scale torsional blade testing, CORTIR III project, 2026.
- [3] Waldbjørn, J. P., Buliga, A., Berggreen, C. and Jensen, F. M. Multi-axial large-scale testing of a 34 m wind turbine blade section to evaluate out-of-plane deformations of double-curved trailing edge sandwich panels within the transition zone. *Wind Engineering*, 45(6), 1395–1411, 2021. doi:10.1177/0309524X20978408
- [4] Waldbjørn, J. P., Buliga, A., Berggreen, C. and Jensen, F. M. Intermediate-scale fatigue testing and structural health monitoring of a retrofitted shear-web in the root-end section of a wind turbine blade. *Wind Energy*, 2025. doi:10.1002/we.70055
- [5] Jensen, F. M., Arconada, J., Werk, M., Berggreen, C., Sørensen, J. D., Zhong, G. and Haans, W. Torsional effects on wind turbine blades and impact on field damages. *IOP Conference Series: Materials Science and Engineering*, 1293, 012005, 2023. Presented at the 43rd Risø International Symposium on Materials Science, DTU Risø.
- [6] Find M. Jensen, John D. Sørensen, Malcolm McGugan, Johnny Plauborg, Christian Berggreen, Andrei Buliga, Lars Damkilde, Torben J. Larsen, Lars J. Nissen, Søren H. Petersen, Rune Kirt, Pedro Muñoz de Felipe. Torsional Stiffening of Wind Turbine Blades – Mitigating leading edge damages EUDP project 64013-0115 – Final report. September 2016
- [7] Fedorov, V., Dimitrov, N. K., Berggreen, C., Krenk, S., Branner, K., & Berring, P. (2010). Investigation of Structural Behavior due to Bend-Twist Couplings in Wind Turbine Blades.

## Acknowledgements

The authors acknowledge the close collaboration between Bladerna and ORE Catapult in the planning and execution of the full-scale torsional test campaign, as well as the contributions from project partners and funding bodies supporting this work.

Get in touch to learn more about our solutions and their application to your blades.



[bladena-sales@res-group.com](mailto:bladena-sales@res-group.com)



[info@ore.catapult.org.uk](mailto:info@ore.catapult.org.uk)



[bladena.com](http://bladena.com)



[ore.catapult.org.uk](http://ore.catapult.org.uk)

# Bladena

A RES company

**CATAPULT**  
Offshore Renewable Energy