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Full-scale torsional load testing with ORE Catapult: test concept and setup

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The test does not replicate the full complexity of in-service loading and should not be read as a complete validation of blade lifetime. It is a controlled, targeted campaign designed to generate structural evidence on specific phenomena and within that scope, the results will be of high fidelity and direct engineering relevance.

Executive summary

As wind turbine blades continue to increase in size, torsional loading has become an increasingly important driver of local structural response and long-term blade durability. Conventional full-scale blade tests are typically focused on flapwise and edgewise bending, while torsional loading is often not directly targeted or controlled. However, operational experience and advanced numerical simulations show that torsion can contribute significantly to local deformation phenomena such as cross-sectional shear distortion, out-of-plane panel bending, and bondline-relevant strain response.

This paper presents the engineering basis and expected outcomes from a full-scale torsional fatigue test campaign will be conducted in collaboration between RES/Bladena and Offshore Renewable Energy Catapult. The campaign will be performed on an 88 m wind turbine blade using a bespoke test setup to apply controlled torsional loading under safe and repeatable test conditions.

The applied loading should not be interpreted as a complete replication of realistic in-service blade loading. Real blade operation includes complex combinations of aerodynamic, gravitational, inertial, environmental, flapwise, edgewise, and torsional loads. The present test is instead a controlled and simplified torsional fatigue campaign, designed to activate selected local structural response mechanisms under repeatable conditions.

The fatigue campaign is planned for approximately 1 million cycles. This will provide a significant repeated loading exposure for studying the targeted torsion-induced local structural responses, while maintaining the test as a controlled and non-destructive campaign. The purpose is not to reproduce the complete lifetime load history of the blade, but to observe whether the targeted local structural responses are activated, measurable, repeatable, and suitable for FEM (Finite Element Method, a computer simulation technique for predicting how a structure responds to load) validation and calibration. With these goals in mind, ORE Catapult has developed a methodology for calculating time series of measurements of cross-sectional deformation from the blade finite element model which can be used in a manner analogous to strain in a conventional fatigue test to calculate an equivalent accelerated test load.

The main objective is to apply controlled torsional loading to the blade, trigger local structural responses, measure these responses, and use the measurements to validate and calibrate the finite element model. The key local responses of interest include cross-sectional shear distortion, out-of-plane panel bending, local deformation of the trailing edge region, and strain response in damage-sensitive areas such as bondlines, panels, and shear-web-related structures.

A central motivation for the campaign is the uncertainty associated with FEM prediction of local blade response. While FEM models can provide valuable insight into global blade behaviour, the prediction of local effects such as cross-sectional shear distortion, out-of-plane panel bending, bondline strain, and trailing edge deformation is more uncertain. These local responses are sensitive to modelling assumptions, boundary conditions, material properties, stiffness distribution, adhesive representation, shell modelling, mesh density, and local geometric details.

Therefore, full-scale measurements are required to validate and calibrate the FEM model before the model is used for local lifetime assessment. The measured full-scale response will be compared with FEM predictions from both Bladena/RES and ORE Catapult. Where deviations are observed, the FEM model can be updated or calibrated. Once calibrated, the FEM model can be used with higher confidence to extract local stress and strain levels for lifetime assessment using S–N curve-based fatigue evaluation (a standard method relating stress level to number of cycles to failure) or fracture mechanics approaches.

The campaign therefore acts as a bridge between numerical modelling, full-scale measurements, and lifetime assessment. Its value will lie not only in the physical test result, but in the improved confidence it will provide in model-based prediction of local structural risk in large wind turbine blades.

Introduction and motivation

The rapid scaling of wind turbine blades beyond 60–80 m has fundamentally changed the structural behaviour that governs blade reliability. As blade length increases, the blade becomes more flexible and more sensitive to coupled deformation modes. In addition to global flapwise and edgewise bending, large blades can experience torsion-driven local deformation modes that may not be fully represented in conventional certification-driven full-scale tests.

Torsional loading can activate local deformation phenomena such as cross-sectional shear distortion, out-of-plane panel bending, local trailing edge deformation, and bondline-relevant strain response. These responses are particularly important in large blades because they may contribute to fatigue damage in damage-sensitive regions such as trailing edges, shear webs, adhesive bondlines, and shell panels. Although the torsional moment is typically orders of magnitude smaller than the flapwise and edgewise bending moments, it plays an outsize role in driving local deformation of the blade cross-section, as shown in Figure 1. For the blade currently under test, including the torsional load in addition to the bending moments increases measures of equivalent sectional deformation by around 10%, which is very significant for the lifetime of the blade.

Traditional full-scale blade tests have historically focused on flapwise and edgewise bending. These tests remain essential for blade certification and global structural validation. However, they may not sufficiently activate all local deformation mechanisms that occur under coupled operational loading. As a result, there can be a gap between the structural response validated during conventional testing and the response experienced by blades in service.

The full-scale torsional test campaign presented in this paper is designed to address part of this gap. It provides a controlled full-scale test environment where torsional loading can be applied to the blade and the resulting global and local responses can be measured. These measurements can then be used to validate and calibrate FEM predictions of torsion-induced local structural behaviour.

The test deliberately isolates torsional loading from the blade's other operating loads, so that the local structural response it drives can be measured and compared directly with numerical predictions.

The central technical motivation is therefore not only to demonstrate that torsional loading can be applied at full scale, but to use the test as a validation and calibration platform for local structural response.

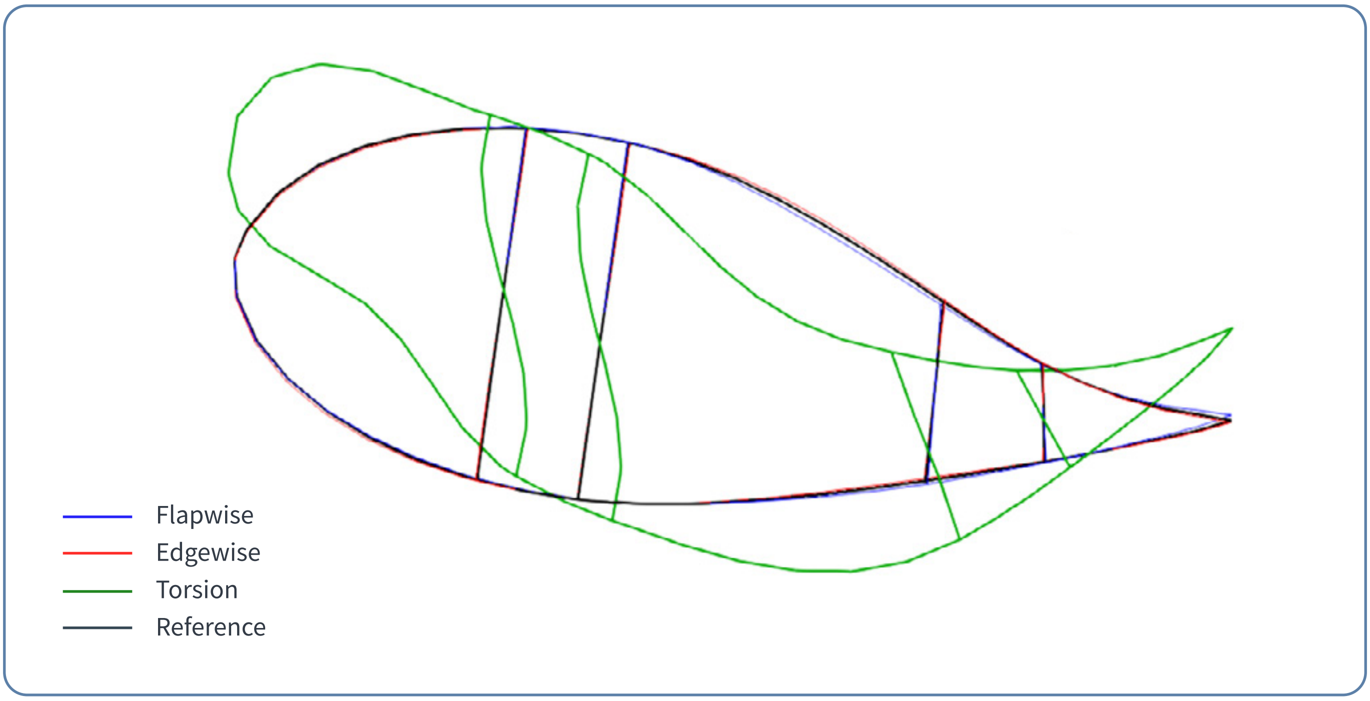


Figure 1 - Local deformation for 1 MNm of applied moment (response scaled 30 x)

Standards and industry context

Current international blade testing standards provide limited explicit guidance on full-scale torsional fatigue testing. Torsion is present in real blade operation through aerodynamic loading, gravitational effects, coupled deformation, and load eccentricities, but it is typically not directly targeted or controlled in standard full-scale blade test configurations.

For large blades, this limitation becomes increasingly relevant. Local deformation modes caused or amplified by torsion can influence fatigue-sensitive structural details. If these local effects are not validated experimentally, the confidence in model-based lifetime predictions may be reduced, particularly for blade regions where local stress or strain is strongly influenced by cross-sectional deformation.

The full-scale torsional test described in this paper should therefore be understood as a complementary validation activity. It is not intended to replace conventional certification testing. Instead, it provides additional engineering evidence that supports a more complete understanding of blade behaviour under torsion-driven loading conditions.

This is illustrated in Table 1 – alone, no test will properly cover all of the failure modes seen in service because of the inherent simplifications to loading that are required to test such large structures at full scale. However, a combination of testing methods can address many more of the failure modes seen in the field than a conventional certification test programme, which only considers flapwise and edgewise fatigue loading. Using a damage-based approach it is possible to combine the tests together so that any damage already accrued in previous phases of the test programme is considered.

The campaign also supports wider industry discussions on how full-scale testing, numerical modelling, measurement technologies, and lifetime assessment can be connected more directly. For future large blades, this connection is essential if structural risks are to be evaluated before damage becomes critical.

Failure mode	Flapwise fatigue	Edgewise fatigue	Bi-axial fatigue	Torsion fatigue
In-plane strain (spar caps)	representative	poor representation	representative	poor representation
In-plane strain (LE/TE)	poor representation	representative	partially representative	poor representation
In-plane strain (panels)	poor representation	poor representation	representative	poor representation
Bondline peel	poor representation	partially representative	partially representative	representative
Delamination (panel bending)	poor representation	partially representative	partially representative	representative

Colour coding

representative — partially representative — poor representation

Table 1 - Comparison of failure modes triggered by different fatigue test types

Test concept and philosophy

The guiding principle behind the test campaign is to reproduce controlled torsional loading at full scale while maintaining safe and repeatable boundary conditions. The test is not designed to drive the blade to failure. Instead, it is a non-destructive, targeted campaign designed to activate and measure specific structural phenomena that are relevant for blade reliability.

The fatigue campaign is planned for approximately 1 million cycles. This cycle count provides a meaningful repeated loading exposure under controlled torsional loading. However, it should not be interpreted as a complete blade lifetime simulation. The cycle count will be used to study whether the targeted local structural responses remain stable, evolve, or change under repeated torsional loading.

The campaign has two connected objectives:

- To induce and measure local structural response under sustained torsional loading. The key phenomena of interest are cross-sectional shear distortion, out-of-plane panel bending, local deformation of the trailing edge region, and strain response in bondline- and panel-sensitive areas.
- To use these measured responses to validate and calibrate the FEM model. The test allows numerical predictions to be compared with the physical behaviour of the blade under controlled loading. This is particularly important for local response validation, since global blade response alone does not guarantee that the FEM model correctly predicts the local stress and strain fields used for fatigue assessment.

A further objective is to evaluate whether the test setup is sensitive enough to detect the structural effect of mitigation measures, such as the Lattice Bar™ reinforcement concept. By comparing the blade response before and after the installation of structural mitigation, the campaign can provide evidence of whether response reductions are measurable at full scale and whether these reductions are captured by the FEM model.

The test campaign will therefore provide a structured basis for linking:

- Controlled torsional loading.
- Approximately 1 million cycles of repeated torsional fatigue exposure.
- Full-scale measurement.
- Local structural response.
- FEM validation and calibration.
- Improved lifetime assessment.

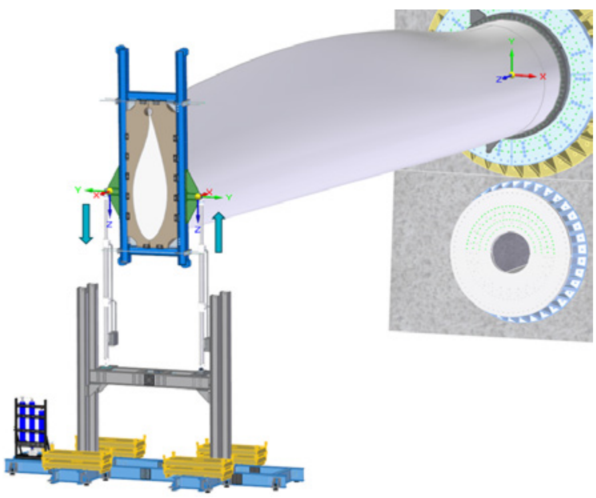


Figure 2 - Schematic overview of torsional load introduction method (blade shown truncated for clarity)

Seven-step validation process for large blades

The full-scale torsional test campaign forms part of a wider validation process intended to improve the reliability of lifetime assessment for large wind turbine blades. This process combines aeroelastic load analysis, FEM modelling, sub-component testing, full-scale measurements, and model calibration. The seven-step validation process is shown in Figure 3.

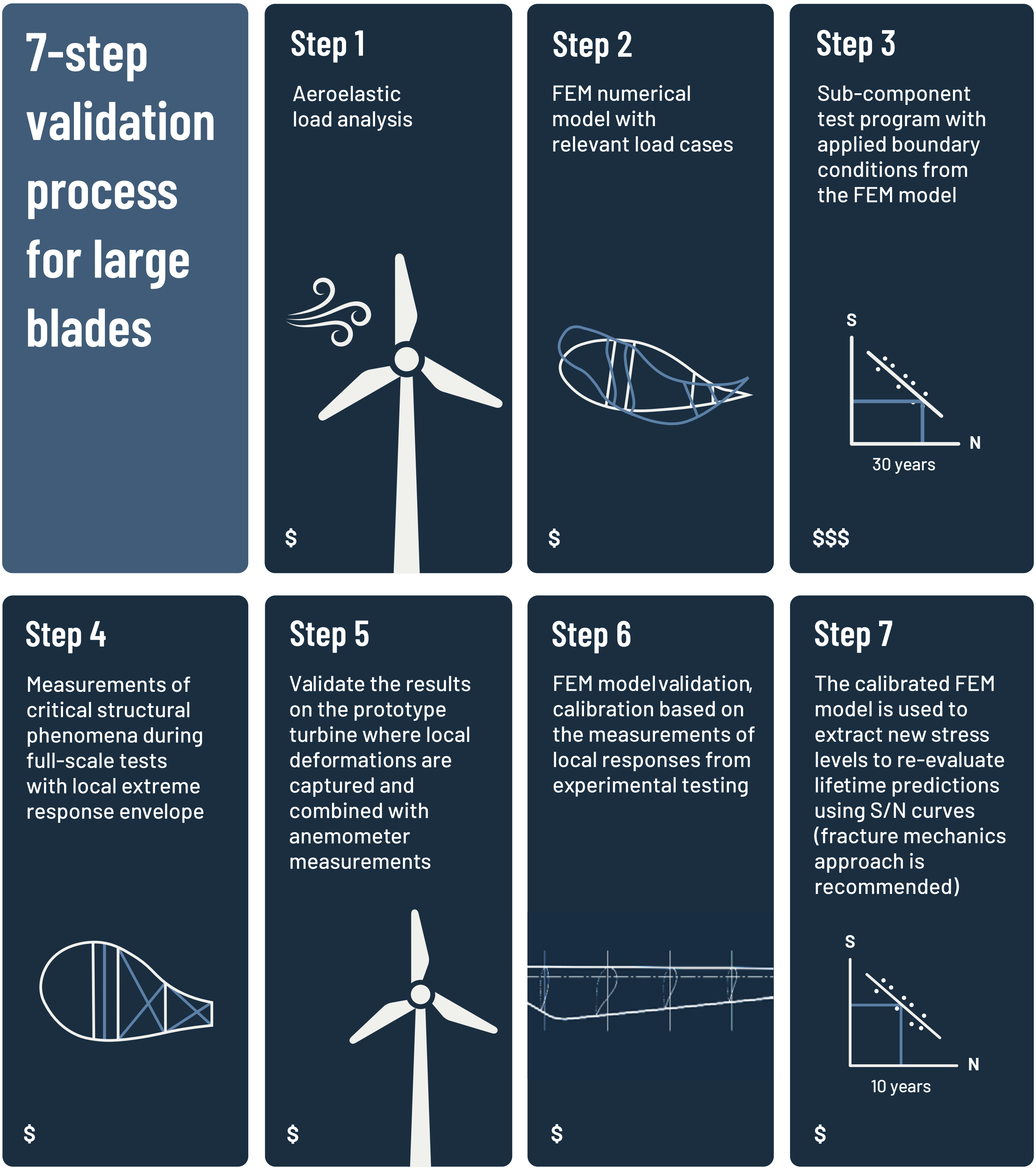


Figure 3 - Seven stage validation process for large blades

Seven-step validation process for large blades

Step 1 – Aeroelastic load analysis

The process begins with aeroelastic load analysis to define the relevant operational load cases acting on the blade. These load cases provide the global boundary conditions and loading envelope for subsequent structural assessment. The purpose of this step is to ensure that the loading used in the structural analysis is representative of the blade's operational environment. The output from this step is a set of relevant load cases that can be applied to the FEM model.

Step 2 – FEM model with relevant load cases

A numerical FEM model of the blade is developed and loaded with the relevant load cases identified from the aeroelastic analysis. The purpose is to identify critical structural responses, damage-sensitive regions, and expected deformation modes. For the torsional test campaign, the FEM model is used to predict where torsion-induced local responses are expected. These include local panel deformation, cross-sectional shear distortion, trailing edge response, and bondline-relevant strain.

Step 3 – Sub-component test programme with applied FEM boundary conditions

Sub-component testing is used to reproduce selected local boundary conditions from the FEM model. This allows specific structural details to be tested under controlled laboratory conditions. Examples include bondline details, trailing edge regions, reinforcement concepts, local panel behaviour, or other structural details where fatigue or local instability may be relevant. Sub-component testing helps verify whether the local structural response predicted by FEM is physically realistic at a smaller scale.

Step 4 – Full-scale measurements of critical structural phenomena

During the full-scale torsional test, the blade is instrumented to measure critical structural responses under controlled torsional loading. The objective is to capture local extreme response envelopes and verify whether the phenomena predicted by the FEM model are physically triggered in the full-scale blade. This step is particularly important because some local deformation modes may only become fully representative at full scale due to blade size, geometry, structural coupling, and boundary conditions.

Step 5 – Validation of measured response on the prototype turbine

The measured responses from the prototype turbine will be used to confirm whether the relevant local deformation modes are captured. This includes global deformation measurements, local strain measurements, displacement measurements, and advanced local deformation measurements. ORE Catapult's Blade Optical Deformation Measurement (BODEM) system is expected to contribute to this step by providing additional insight into local cross-sectional deformation. Other installed measurement systems also support this validation step by capturing blade twist, displacement, strain, and local response at selected critical regions.

Step 6 – FEM model validation and calibration

The FEM model will be compared against the measured full-scale responses. Where the measured and predicted responses differ, the FEM model can be updated or calibrated to improve the representation of the actual blade behaviour. This step is especially important for local response validation. A FEM model may show acceptable agreement at global level while still under- or over-predicting local strain or deformation in critical regions. Therefore, the calibration must consider both global and local response quantities.

Step 7 – Updated lifetime assessment

The calibrated FEM model will be used to extract improved local stress and strain levels. These values can then be used for updated lifetime assessment, either through S–N curve-based fatigue evaluation or, where appropriate, fracture mechanics-based methods. This step is the final link between test evidence and practical engineering decision-making. A calibrated model improves confidence in lifetime predictions and can support decisions related to inspection, maintenance, retrofit, or operational risk management.

Role of controlled torsional loading in FEM validation and calibration

A key purpose of the test campaign is to use controlled torsional loading as a practical method for activating local deformation modes that are difficult to validate through conventional bending tests alone.

Flapwise and edgewise bending tests are important for global blade validation. However, they do not necessarily reproduce the same local deformation mechanisms that occur under coupled operational loading. Torsional loading can generate local responses such as cross-sectional shear distortion, out-of-plane panel bending, and local deformation of the trailing edge and bondline regions.

These local responses are important because they can influence:

- Local fatigue damage.
- Adhesive bondline performance.
- Panel stability.
- Trailing edge separation risk.
- Structural reliability of large blades.
- The effectiveness of mitigation concepts.

The FEM model may predict these phenomena, but confidence in such predictions depends on experimental validation. The full-scale torsional test therefore provides a direct opportunity to compare predicted FEM response with measured response from the physical blade.

The validation and calibration process includes:

1. Comparing global blade response, such as twist, rotation, and displacement, with FEM predictions.
2. Comparing local strain and deformation measurements with FEM local response fields.
3. Identifying whether the FEM model captures the correct deformation and relative response levels.
4. Calibrating the FEM model where necessary to improve correlation with measured data.
5. Using the calibrated FEM model to extract more reliable local stress and strain values for lifetime assessment.

The main technical message is therefore that the test is not only a demonstration of torsional loading. It is a validation and calibration platform for local structural response. This is essential for improving confidence in model-based lifetime predictions for large blades.

FEM uncertainty and need for calibration

The FEM model is an essential tool for understanding blade structural behaviour, but it also contains uncertainty. This uncertainty becomes particularly important when the model is used to predict local response rather than only global blade behaviour.

Global quantities such as overall blade deflection, twist, or root reaction may show reasonable agreement between model and test, while local quantities such as bondline strain, out-of-plane panel bending, trailing edge deformation, or cross-sectional shear distortion may still deviate significantly. This is because local response is highly sensitive to modelling choices and structural details.

Key sources of FEM uncertainty include:

- Load representation and boundary conditions.
- Local stiffness distribution.
- Composite layup assumptions.
- Adhesive and bondline modelling.
- Shell element idealisation.
- Local geometry and thickness variations.
- Material property assumptions.
- Mesh density and element formulation.
- Representation of connections, reinforcements, and structural details.
- Simplification of local structural details.
- Uncertainty in boundary conditions applied during test modelling.

For this reason, the full-scale torsional test will be used as a calibration platform. The measured response will provide experimental evidence that can be compared directly with FEM predictions. Where deviations are observed, the model can be adjusted to improve correlation with the measured blade behaviour.

The calibration process is especially important because the calibrated FEM model will later be used to extract local stress and strain levels for fatigue and lifetime assessment. Without calibration, the uncertainty in local FEM response may lead to either non-conservative or overly conservative lifetime predictions.

The purpose of the campaign is therefore not only to demonstrate torsional loading at full scale, but to reduce uncertainty in the FEM-based prediction of local structural response.

Full-scale test setup at ORE Catapult

The full-scale test campaign is currently being conducted at the ORE Catapult 100 m blade test facility using an 88-m wind turbine blade representative of modern offshore designs, as shown in Figure 4. The facility provides the necessary infrastructure to support controlled load introduction, precise instrumentation, and safe execution of torsional fatigue loading scenarios.

A dedicated load introduction system was developed by ORE Catapult to apply torsional loads along the blade span while limiting unintended bending effects. The test setup is designed to apply torsional demand in a repeatable manner, allowing measured blade response to be compared with FEM predictions.

The test setup has three main objectives:

- **Apply controlled torsional loading** - The loading system is designed to introduce torsional demand into the blade in a controlled and repeatable way. This enables a direct comparison between the applied test load and the corresponding FEM load case. The loading is simplified compared with real in-service conditions. This simplification is intentional, because the test is designed to isolate selected torsion-induced response mechanisms and make them measurable under controlled conditions.
- **Measure global and local response** - The blade is instrumented to capture both global blade motion and local response at critical structural regions. This includes twist, displacement, strain, local deformation, and cross-sectional response.
- **Validate and calibrate the FEM model** - The measured response will be compared with the FEM model. Where the measured and predicted responses differ, the FEM model can be updated or calibrated to improve the representation of local structural behaviour.

A key part of the test philosophy is that local response is the main validation target. Global blade response alone is not sufficient to validate the structural risk at damage-sensitive regions. Therefore, the instrumentation strategy focuses on capturing local phenomena such as cross-sectional shear distortion, out-of-plane panel bending, and bondline-relevant strain response.

The test setup and loading regime were determined using a combination of aero-elastic simulations and finite element modelling.

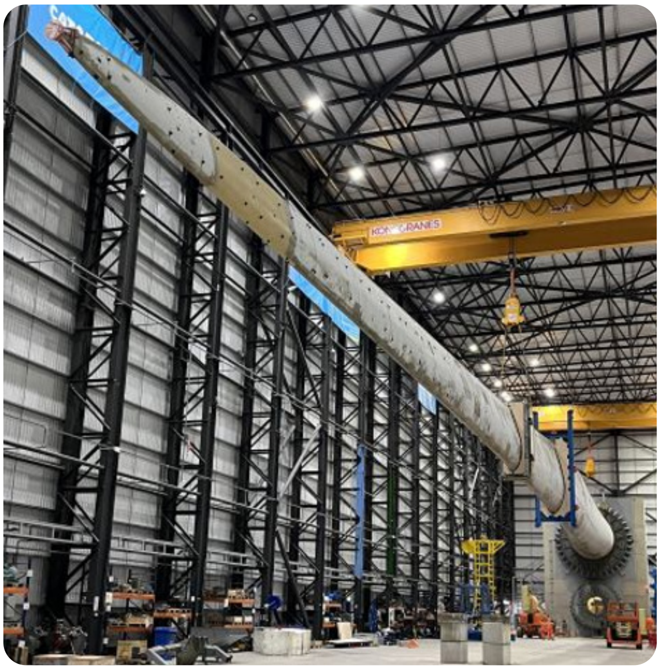


Figure 4 - Full-scale blade installed at ORE Catapult with torsional load introduction system

As the cross-sectional deformation is triggered by both bending and torsional loads, the torsional moment must be higher than the damage equivalent load (DEL) for torsion which can be directly obtained from the aeroelastic simulations if only torsion is applied.

The aeroelastic simulations of the blade revealed that the torsional DEL was fairly constant from the root to around 20 m, after which it steadily reduces towards the tip. However, placing the saddle at 20 m would mean a large part of the blade where cross-sectional deformation occurs is untested or influenced by local effects caused by the saddle, so the load introduction point was moved out to 35 m to balance the structural integrity of the blade with triggering the local responses, which are the objective of the test.

The finite element model was then used to assess a load level which would trigger a level of cross-sectional deformation equivalent to the service life after 1 million cycles. Virtual sensors representing string potentiometers were placed in the model to measure cross-sectional deformation and panel breathing. Machine learning was used to develop a surrogate model which could predict the measurements provided by these sensors from loading from the aeroelastic model. Any measurement from the FEM model could have been taken in this way, but the process was aiming to use measurements which could be replicated in practice during testing.

This process also made it possible to isolate the effect of torsion. Depending on the sensor location, torsion was found to increase the equivalent deformation by between 5% and 20% compared to bending moments alone.

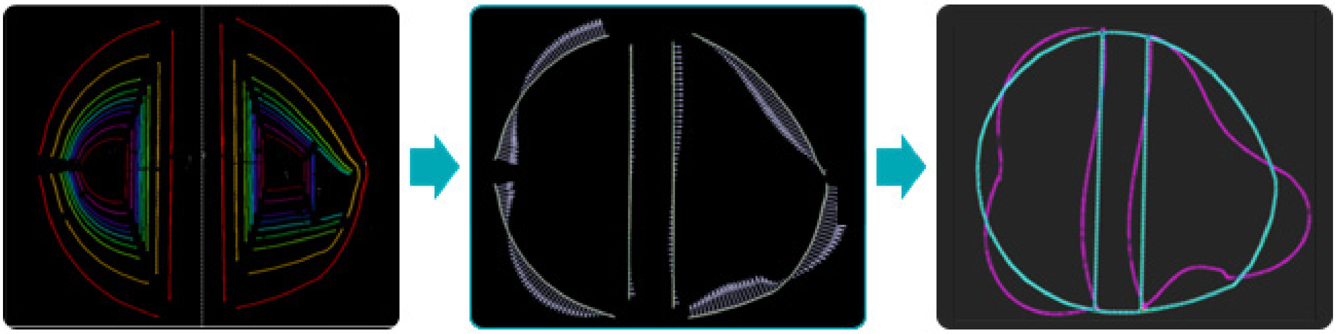
The blade is oriented with the trailing edge pointing upwards, and is loaded by two cylinders connected to the pressure side and suction side of the loading fixture located at 35 m from the root. The cylinders apply equal and opposite forces to induce a pure moment about the blade pitch axis.

Test instrumentation differs substantially from a conventional certification test, with a much greater focus on characterising local cross-section deformation. Figure5 shows an internal view of the blade trailing edge cavity, with several of the sensors outlined below clearly visible.

- Axial strain gauges – minimal quantity to validate strain response in finite element model
- Rosette strain gauges – measure shear strain
- Back-to-back transverse strain gauges (internal and external) - characterise panel bending
- Internal inclinometers - characterise global torsional response and validate other torsion measurements
- Accelerometers - ensure safe test shutdown in the event of a failure/ characterise modal response to establish a safe operating frequency
- Qualisys system - measure global displacements
- String potentiometers – Measure cross-sectional deformation and validate BODEM system
- Blade Optical Deformation Measurement (BODEM) system – provide more detail on cross-sectional deformation for cross-sections where it is installed
- Displacement and load feedback in hydraulic actuators – understand applied load, control test accurately

Figure 5 - internal view of the blade trailing edge cavity showing instrumentation

The BODEM system works by using reflective tape placed around the perimeter of the blade cross-section at defined intervals. The markers are illuminated by a light source which is colinear with a machine vision camera. During testing, a reference image is acquired with the blade in an unloaded state – images are then acquired as the test progresses. The tape is isolated by a custom image processing algorithm, and a Procrustes fit (a technique for aligning shapes to isolate local differences) is used to remove global deformation. Deformation can be estimated if the distance from the camera is known. Results can then be compared to the finite element model as shown in Figure 6.



Isolate markers in each frame | **Visualise individual section** | **Compare to finite element model**

Figure 6 - BODEM system

Outlook and next steps

The full-scale torsional test presented in this paper represents an important step towards more representative blade validation. The test is currently in the commissioning phase, which will involve applying controlled displacements to the blade to characterise its stiffness. Fatigue testing will begin in the coming weeks, with continual analysis of the data coming from the test.

Future work will extend testing to additional load cases, refine measurement techniques, and further integrate experimental data with numerical models.

The insights gained also contribute to ongoing industry discussions on the evolution of blade testing standards and best practice for large blades.

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