

Paper II of III

Load introduction, measurement and instrumentation strategy for full-scale torsional blade testing

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Executive summary

This whitepaper presents the load introduction, measurement and instrumentation strategy to be used during the full-scale torsional fatigue test campaign on an 88m wind turbine blade at the Offshore Renewable Energy Catapult (ORE Catapult).

The campaign applies controlled torsional loading to the blade under safe, repeatable and well-defined test conditions. The loading is not intended to replicate the complete complexity of realistic in-service blade loading. Instead, it is a controlled torsional fatigue campaign, planned for approximately 1 million cycles, designed to activate and measure selected local structural response mechanisms that are difficult to assess from conventional blade testing alone.

The purpose of the measurement campaign is not only to monitor the test, but also to understand how the blade responds structurally under controlled torsional loading. The instrumentation has therefore been selected to capture both global blade behaviour and local structural response.

The key measured responses include applied loading, blade rotation, displacement, local strain, local deformation, cross-sectional response, out-of-plane panel deformation and response changes before and after possible structural mitigation.

The measurements are also essential for Finite Element Method (FEM) validation. They will provide the experimental basis for comparing numerical predictions with the actual blade response, particularly for local response quantities such as cross-sectional shear distortion, out-of-plane panel deformation, bondline-relevant strain and trailing edge deformation.

ORE Catapult's optical BODEM (Blade Optical Deformation Measurement) system forms an important part of the local deformation measurement strategy. It is expected to provide additional insight into the deformation of selected blade cross-sections during torsional loading and to support the interpretation of cross-sectional response together with string-pot and strain-gauge measurements. The BODEM measurements will also provide an additional comparison point for FEM validation, particularly where cross-sectional shape change and local deformation patterns are of interest.

This whitepaper does not present measurement data; it describes the instrumentation installed for the test campaign and the purpose of each measurement system. The measurement data acquired with this instrumentation will provide the basis for whitepaper III, where the measured response will be compared with FEM predictions. Whitepaper III will use the measurement data to assess FEM uncertainty and validate the FEM model. If needed the FEM model can be calibrated to measured local responses and give input to support updated lifetime assessment.

Load introduction

The torsional fatigue test setup is designed to apply a controlled and repeatable torsional load to the blade in a manner that activates the local response mechanisms being investigated. The test method is not intended to reproduce the full complexity of all operational blade loads simultaneously; rather, it is intended to reproduce the relevant torsion-dominated structural response with sufficient fidelity to assess the areas of greatest structural concern (the maximum chord region and the transition zone).

The blade is mounted at the root using a test hub that simulates the connection between the blade root and the pitch bearing. This arrangement provides a representative root boundary condition and ensures that the blade load path at the root is consistent with the way the blade is supported in service. The root connection and test hub interface will be documented as part of the test boundary condition.

Torsional load is introduced into the blade at a single spanwise location (35m from the blade root, see whitepaper I: Full-scale torsional load testing with ORE Catapult: test concept and setup). The load is introduced at one primary location meaning the position of the load application is a critical part of the test design. The load application point was selected so that the applied torsional moment activates the area of greatest concern for the blade, while avoiding unintended local damage at the load introduction point itself. The selection of this position was informed by the structural objective of the test, simulated FEM response, known or suspected damage-sensitive regions, and practical constraints associated with blade geometry, access, and maximum load.

The blade has been instrumented to verify the applied loading and to measure both global and local structural response during the test. Instrumentation should include load measurement, displacement and control signals, global blade displacement or rotation, local strain gauges, string potentiometers, BODEM measurements and visual monitoring. These systems provide the evidence required to confirm that the intended torsional loading mode is being achieved and to interpret the measured blade response.

The test control system will operate the load application safely and within the defined test specification. The control system monitors load, displacement, command signal, phase relationship, applied load, blade reaction and relevant interlock channels. The system automatically stops the test if the measured load application moves outside defined limits, if the blade response changes unexpectedly, or if any monitored safety parameter indicates a possible loss of control, change in load path, fixture issue, sensor fault or structural response outside the agreed operating envelope.

The fatigue campaign will apply approximately 1 million torsional load cycles at the specified load range. The applied load range, cycle count, frequency, control limits, stop criteria and inspection intervals have been defined before the start of fatigue testing. Static checks are completed before and during the campaign to confirm that the load introduction system, instrumentation and blade response remain stable. Any observed change in load transfer, measured blade response or local structural condition will be recorded and assessed before testing continues.

A concise record of the as-built load introduction arrangement will be maintained, including the test hub configuration, blade root boundary condition, phasing arrangement, load control parameters, instrumentation channels and stop criteria. This record is essential for interpreting the measured response and for ensuring that the FEM comparison reflects the actual test configuration rather than only the nominal design intent.

Purpose of the measurement campaign

The measurement campaign is designed to capture how the 88m blade responds under controlled torsional static and fatigue loading at full scale.

The purpose of the test is to:

- verify the applied loading and test boundary conditions;
- measure global blade response under torsional loading;
- capture local structural response in damage-sensitive regions (hotspots);
- detect torsion-induced deformation modes such as cross-sectional shear distortion and out-of-plane panel deformation;
- measure local strain response in the pressure side and suction side panels;
- support interpretation of the blade response during static and fatigue loading;
- compare measured response before and after possible structural mitigation;
- provide experimental data for FEM validation and calibration;
- improve understanding of how torsional loading contributes to local damage mechanisms in large wind turbine blades.

The instrumentation strategy is focused on the transition zone and maximum chord region, as these areas are expected to show significant local deformation under torsional loading. These regions are also the most critical because localised deformation is highest and most difficult to simulate with sufficient accuracy.

The test campaign therefore aims to generate a dataset that is useful at two levels;

1. At the test level, the measurements support monitoring, interpretation and comparison of structural response during the fatigue campaign.
2. At the numerical level, the measurements provide direct validation points for FEM predictions and support calibration of uncertain local response quantities.

Test context and measurement philosophy

The full-scale torsional blade test creates a controlled test environment where torsion-dominated response mechanisms can be investigated more directly than in conventional flapwise or edgewise blade testing.

Traditional full-scale blade tests are usually designed to demonstrate that a blade can withstand flapwise and edgewise loads. They typically focus on global response parameters such as applied load, flapwise deflection, edgewise deflection and overall structural integrity. However, local deformation mechanisms may not be fully captured when the instrumentation is mainly focused on global blade behaviour.

For this test campaign, the measurement strategy is designed to capture both:

Global blade response

This includes applied load, rotation, blade torsional twist, overall displacement and general test behaviour.

Local structural response

This includes back-to-back strain in the trailing edge panels, and local structural response from string potentiometers to capture cross-sectional shear distortion (CSSD) and out-of-plane panel bending, which affects the bondlines.

This combined approach allows the test to be used not only as a structural demonstration, but also as a validation campaign for numerical models and local structural design assumptions.

The measurement systems are therefore selected so that the physical test can be interpreted at different levels:

- test input level, using load measurement;
- global blade response level, using displacement and rotation measurements;
- local deformation level, using string potentiometers and BODEM;
- local strain level, using strain gauges;
- visual and qualitative level, using CCTV and inspection monitoring;
- numerical validation level, using direct comparison with FEM outputs.

Structural response mechanisms of interest

Global torsional response

The global torsional response describes the overall twist and rotational behaviour of the blade under the applied torsional loading. It provides the primary confirmation that the test is generating a torsion-dominated structural response, rather than an unintended response driven by flapwise displacement, edgewise displacement, fixture movement or local load introduction effects.

This is important because the global response establishes the baseline structural state of the blade during the test. Before local measurements such as strain, cross-sectional shear distortion or panel bending can be interpreted with confidence, the test team must confirm that the blade is responding globally in the intended manner. If the global torsional response is not well understood, it becomes difficult to determine whether local measurements represent genuine blade behaviour or are influenced by unintended load paths, control effects, instrumentation issues or changes in the test setup.

Global torsional response is also an important indicator of test stability during fatigue cycling. Changes in measured twist, displacement, phase behaviour or actuator response may indicate a change in blade stiffness, fixture behaviour, saddle interaction, hydraulic control performance or developing structural damage. For this reason, global response measurements provide both an interpretation function and a safety-monitoring function throughout the test campaign.

The global response is also one of the main comparison points for FEM validation. Measured twist applied load and displacement response will provide an initial check on whether the numerical model captures the overall torsional stiffness and dynamic behaviour of the blade. This comparison creates the context for later local comparisons, including strain, cross-sectional shear distortion and out-of-plane panel deformation.

The global response is mainly supported by:

- load measurement;
- displacement sensors;
- global rotation measurements;
- actuator force, displacement and phase monitoring;
- FEM comparison of twist, displacement and load response.

Cross-sectional shear distortion

Cross-sectional shear distortion is a local deformation mode where the blade cross-section changes shape under torsional loading. Instead of the blade behaving as a perfectly rigid cross-section, the section can distort due to the flexibility of the shells, shear webs, trailing edge region and bondlines.

This response is important because excessive cross-sectional distortion can increase local deformation and strain around:

- shear web bondlines;
- pressure-side panels;
- local structural transitions.

String-pot measurements and optical BODEM measurements are especially relevant for this response.

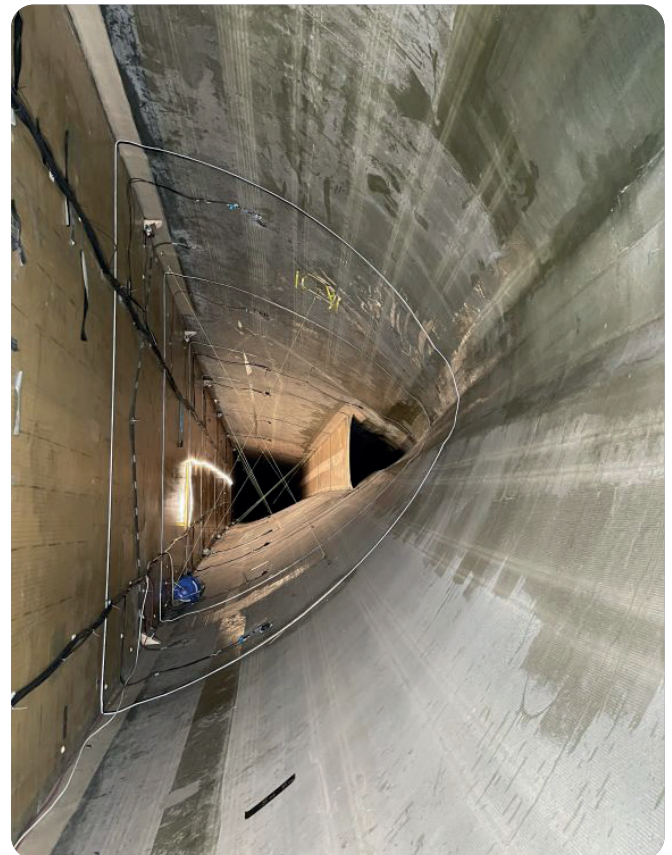


Figure 1 - Internal view of the blade box section showing the diagonal string-potentiometer arrangement used to capture cross-sectional shear distortion.



Figure 2 - String-potentiometer instrumentation is installed inside the blade box section at a measurement station.

Out-of-plane panel deformation

Out-of-plane panel deformation refers to local bending of blade panels, particularly the curved pressure-side panel, under torsion-induced cross-sectional shear distortion. This deformation can create local bending strains and peeling-type loading in nearby bondline regions.

This response is important because it can contribute to local damage initiation and growth in areas such as:

- web-to-shell bondlines;
- trailing edge bondlines;
- panel regions between webs;
- transition and maximum chord regions.

The response is measured using diagonal displacement sensors and back-to-back strain gauges placed at selected spanwise positions.

The strain gauge measurements are especially important for FEM validation, because they allow comparison between measured strain and virtual strain gauge outputs extracted from the FEM model.

Measurement systems and their purpose

The main measurement systems used in the campaign are summarised below.

Measurement system	Main purpose	Main structural response supported
Load measurement / load cells	Verify applied load and test input	Load control, boundary condition verification, FEM load comparison
String potentiometers / displacement sensors	Measure local diagonal displacement and cross-sectional shear distortion	Cross-sectional shear distortion, panel bending, local deformation
Strain gauges	Measure local bending strain using two strain gauges placed back to back, and longitudinal strain using a single strain gauge	Local strain, bending strain, bondline-relevant response, FEM strain validation
BODEM system	Measure local deformation of selected blade cross-sections	Cross-sectional shear distortion, FEM deformation comparison
Inclinometers and Qualisys tracking	Measure global blade rotation, tilt and rigid-body displacement/position tracking; also measure local opening angle between spar and web	Global torsional response, blade twist and displacement verification, torsional shear and adhesive degradation at spar-web bondlines, FEM comparison of global twist and displacement
CCTV / visual monitoring	Observe blade behavior and monitor local regions during testing	Test monitoring, damage observation, qualitative correlation

The measurement scope is shared between the two project partners according to global and local blade response:

Global measurement

Global measurement covers the overall response of the blade under the applied torsional loading, including applied load, blade twist, global rotation and overall displacement.

- applied load measurement and load control;
- global rotation response;
- overall blade displacement and torsional twist;
- verification of the applied torsional loading mode and test boundary conditions.

Local measurement

Local measurement covers the local structural response of the blade, including local strain, cross-sectional shear distortion and out-of-plane panel deformation.

- local strain response from strain gauges;
- cross-sectional shear distortion from string potentiometers;
- out-of-plane panel deformation at selected spanwise stations.

ORE Catapult BODEM system

ORE Catapult's BODEM (Blade Optical Deformation Measurement) system is included in the measurement strategy to provide additional insight into the local deformation of selected blade cross-sections during torsional loading. The system has been in development since 2016, see Reference 7.

While the string-pot measurements provide relative displacement between selected anchor points and the strain gauges provide local laminate strain response, BODEM is expected to add a broader view of the cross-sectional shear distortion pattern.

This makes it particularly useful for interpreting local cross-sectional behaviour, including deformation modes such as shear distortion and panel movement.

The BODEM measurements are positioned in the same overall test philosophy as the other instrumentation: they support understanding of the blade response under controlled torsional loading and provide an experimental basis for comparison with FEM predictions.

Measurement principle

The BODEM system measures local deformation of selected cross-sections of the blade during loading. The system is intended to capture how the cross-sectional shape changes as the blade is subjected to controlled torsional excitation.

The BODEM system works by placing reflective marker strips around the perimeter of the inside of the blade cross-section in the trailing and leading edge cavities. These marker strips are placed in a manner that ensures inboard marker strips do not obscure the marker strips placed further down the blade – this placing can be simulated by rendering a CAD image of the inside of the blade with appropriate focal length settings for the camera simulated in the rendering, as shown in Figure 3. These markers are then illuminated by highly directional LED lights and the image is recorded by a dedicated machine vision camera system in the leading and main trailing edge cavity.

By processing these images with a dedicated image processing algorithm, it is possible to extract the markers and compare them to a reference state by removing the global rotation and translation. The difference between the two is the local deformation, and this can be better visualised by scaling the vector between a point's deformed and reference position. This process is shown visually in Figure 4.

The positions of the markers have been collocated with stringpots measuring cross-section deformation to validate the system.

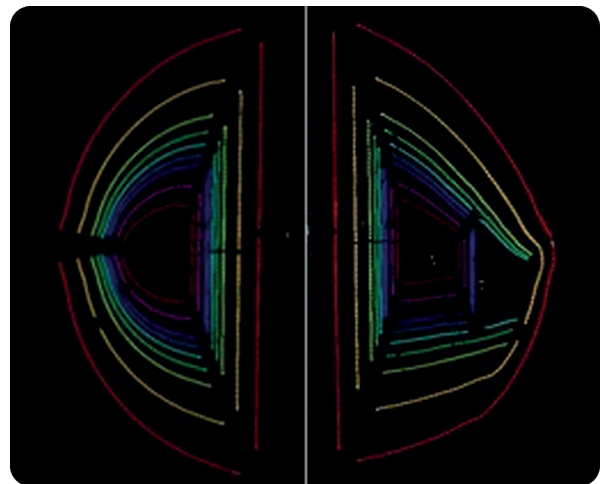
The principle of the BODEM system is visualised below on a blade from a previous test. Results for the 88m blade will be shared in whitepaper III.



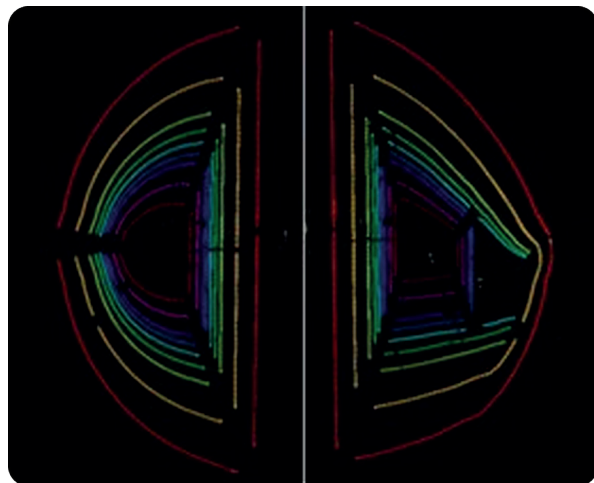
Figure 3 - CAD rendering of LE cavity to plan BODEM reflective marker positioning



1. Illuminate markers and acquire image in reference state



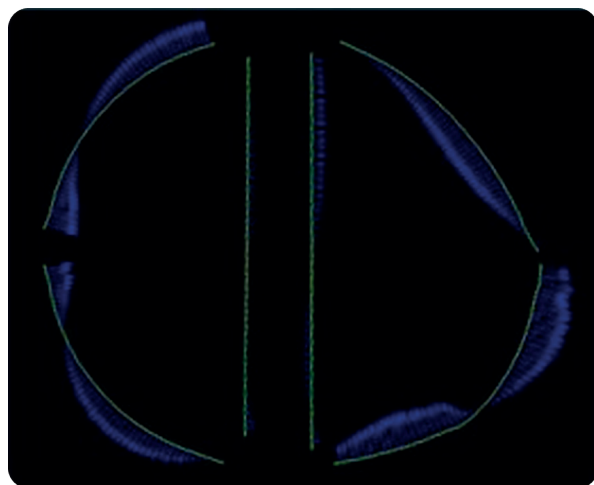
2. Isolate markers in reference image



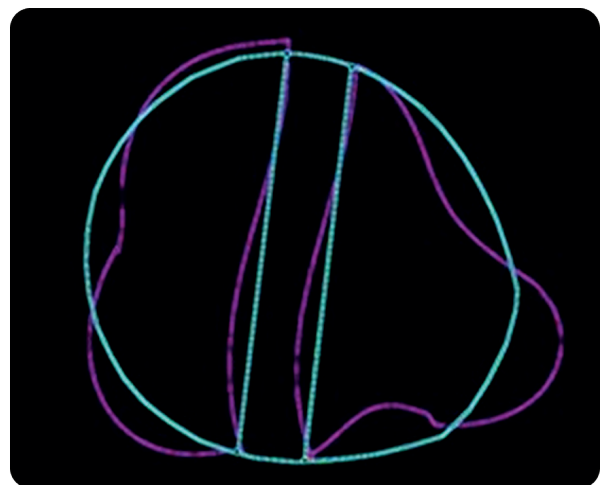
3. Isolate markers in each frame



4. Illuminate markers and acquire footage as blade deforms



5. Remove global translation and rotation to map each section to reference state for each frame, then display scaled deformation



6. Compare to finite element model

Figure 4 – The principle of the BODEM method are shown on a blade as an example. Results for the 88m blade will be shared in the next whitepaper, which will be presenting results.

Data acquisition and processing

The BODEM data should be synchronised with the other measurement systems so that the local cross-sectional response can be related to applied load, displacement, strain and rotation.

The processing should define how the raw measurement data are converted into engineering outputs that can be used for interpretation. This may include reference correction, filtering, coordinate transformation and extraction of deformation quantities.

The BODEM processing requires that the reference condition used for comparison is available. Typically, the reference is based on the unloaded state.

Output parameters

The BODEM output parameters are selected so that they support interpretation of local cross-sectional shear distortion and comparison with FEM.

Relevant output quantities may include:

- local displacement of selected points;
- relative deformation between defined locations;
- change in cross-sectional shape;
- local rotation or angular change;
- deformation changes before and after fatigue cycling;
- deformation changes before and after possible structural mitigation.

The final output parameters should be defined so that they can be compared with equivalent quantities extracted from the FEM model.

Link to FEM validation and calibration

The measurement campaign is directly linked to FEM validation and calibration.

The measured global response (applied load, twist, rotation and displacement), local deformation (string-pot displacement, cross-sectional shear distortion, out-of-plane panel deformation and BODEM outputs) and local strain can be compared against the corresponding FEM predictions. The comparison methodology and results are presented in whitepaper III.

Summary

The load introduction, measurement and instrumentation strategy for the full-scale torsional blade test has been developed to capture both global and local blade response under controlled torsional fatigue loading.

The instrumentation includes load measurement, string potentiometers, strain gauges, BODEM, inclinometers and Qualisys tracking, CCTV and inspection monitoring. Together, these systems allow the test team to measure blade twist, displacement, local strain, local rotation, cross-sectional shear distortion and, out-of-plane panel deformation.

The strategy is particularly focused on the transition and maximum chord regions, where local torsion-induced deformation mechanisms are expected to be most relevant. The measurements will support both test interpretation and FEM validation.

A full-scale test of an 88m blade is a rare and costly opportunity, and its value depends on two conditions. First, the applied loading and boundary conditions must be representative of the torsion-dominated response being investigated; if the load introduction, root fixation or control approach do not activate the intended structural mechanisms, the measured response cannot be attributed to genuine blade behaviour and the comparison with FEM loses its meaning. Second, the data captured from the test must be maximised. Every measurement channel installed, every synchronised system and every documented as-built detail increase the number of independent response quantities available for interpretation and calibration and reduces the risk that an important local mechanism goes unobserved. A blade test that is representative but poorly instrumented, or well instrumented but unrepresentative, delivers only a fraction of the insight that the same investment could otherwise provide. The strategy described in this whitepaper is therefore designed to secure both conditions at the same time.

The outcome of this measurement campaign will be a high-value experimental dataset that can be used to understand local blade behaviour, validate numerical models, calibrate uncertain response quantities and support improved lifetime assessment of large wind turbine blades under torsional loading.

This whitepaper does not present measurement data. It describes the instrumentation installed for the test campaign and the purpose of each measurement system. The measurement data acquired during the campaign using this instrumentation, once processed, will provide the technical basis for whitepaper III.

Whitepaper III will focus on the comparison between measured response and FEM simulations. It will use the measurement data to:

- validate the FEM model;
- assess model uncertainty;
- identify where the FEM model agrees with test data;
- identify where local response is over-predicted or under-predicted;
- improve confidence in future blade test interpretation.

As a next step the measurement data can be used to:

- calibrate local response where required;
- support updated lifetime assessment;

Whitepaper II therefore acts as the bridge between the physical test campaign and the numerical interpretation work presented in whitepaper III.

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