

FATIGUE TESTING OF WIND TURBINE BLADES WITH COMPUTATIONAL VERIFICATION

R.S. Court¹, S. Ridley¹, H. Jones¹, P.A. Bonnet², A.G. Dutton²

¹ NaREC, Eddie Ferguson House, Ridley Street, Blyth. NE24 3AG.
richard.court@narec.co.uk

² Energy Research Unit, Rutherford Appleton Laboratory, Science & Technology Facilities Council, Chilton, Didcott. OX11 0QX. (STFC-RAL).
geoff.dutton@rl.ac.uk

SUMMARY

A novel procedure for conducting wind turbine blade fatigue testing is presented. It features simultaneous loading in two orthogonal directions – flap and edge-wise – and uses the blade natural frequencies to force cyclic fatigue loads. This experimental scheme is modelled and studied with a finite element approach, using a full 3D blade model.

Keywords: Fatigue testing, wind turbine blades, finite element modelling

WIND TURBINE BLADE TESTING

Background

Fatigue testing of wind turbine blades provides extremely valuable data for both blade manufacturers and turbine end-users, in terms of design validation and certification for in-service requirements [1]. However, existing tests tend to use only one loading direction at a time – flap and edge testing done separately – which is a gross simplification of the fatigue experienced by blades in service. Fatigue testing of blades can be achieved using either forced actuation or resonance methods. Various different practical means for introducing the loads into the blade have been devised, including the use of hydraulic actuators for forced actuation and the use of rotating eccentric masses to induce resonant loading. A second method for inducing resonance using sliding masses mounted on the blade, powered by hydraulics, was pioneered by NREL (National Renewable Energy Laboratory) in the USA [2], and has been developed further by NaREC in the UK [3]. NaREC's development work in hydraulically powered resonant methods has led to a test method that now allows both flap and edge loading of blades to be achieved simultaneously. This is a valuable contribution to the wind industry's desire to reduce testing costs, whilst improving the rigour of the testing methods.

Test Method – Dual Axis Fatigue

The general arrangement of a blade fatigue test at NaREC is shown in Figure 1. The blade is bolted to the reinforced concrete test-stand, typically with the pressure (windward) face orientated facing up, and the leading-trailing edge chord line, a blade

major axis, running approximately horizontally. It should be noted that this arrangement is not a fixed standard, and that alternative orientations are equally possible.



Figure 1: General arrangement of blade on test-rig.

The key part of the test set-up for achieving dual axis testing using a resonant system is to keep the dynamic moving mass that induces the resonance close to the neutral axes of the blade, thereby reducing overturning moments on the saddle supports. This is particularly important in the flap testing direction where blade deflections can be large, and moments can rise to high levels, requiring additional support structure and ensuing weight penalty. NaREC's solution for the moving mass system was to develop the Compact Resonant Mass (CRM), as shown in Figure 2.

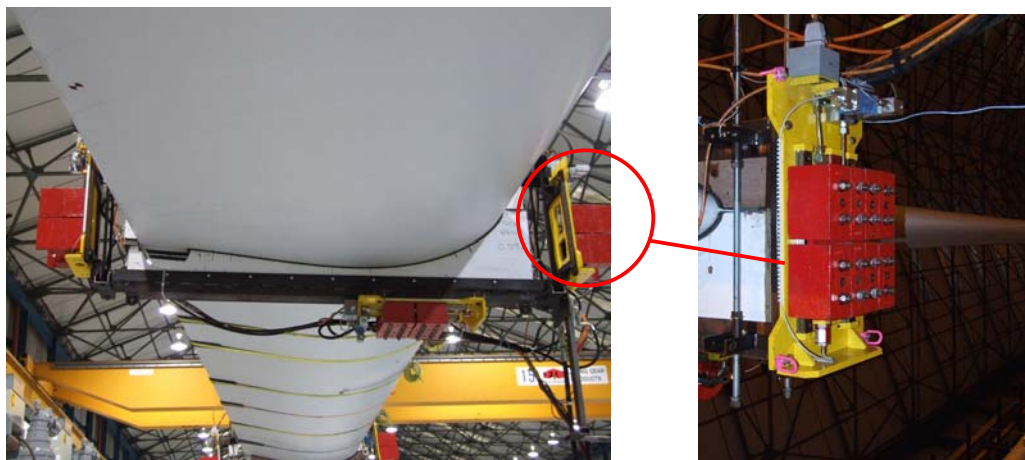


Figure 2: Compact Resonant Mass (CRM) units on a loading saddle fitted to a blade.

The CRM system consists of a moving mass, coloured red in Figure 2, mounted on a carriage that slides on tracks. The carriage and tracks are mounted on a frame, shown yellow in Figure 2, which is fixed to a loading saddle profiled to fit the chosen blade section. The carriage is moved using a hydraulic cylinder, with displacement measured

using a non-contacting ultrasonic transducer. An MTS system is used to control the CRM. For a dual-axis test, at least four CRM units (two sets) are required, mounted in orthogonal orientations, as shown in Figure 2.

Testing in dual-axis resonance requires the two separate first resonant frequencies to be determined for the flap and edge orientations of the blade. This requires some initial tests in single-mode operation, where the size, frequency and amplitude of the moving masses are tuned to provide resonance in the single axis direction. Single axis tests are usually controlled to achieve a specific strain range or bending moment at a particular location on the blade. Once the CRMs have been tuned for single-axis operation, it is possible to operate both the flap and edge CRM units at the resonant frequency for each direction, thereby testing both the flap and edge directions simultaneously.

Although strain gauges are usually used to monitor and control strain ranges (bending moments) in a single-axis test, the fact that the resonant frequencies for flap and edge directions do not usually have a convenient ratio, means that strain gauge data can initially appear non-intuitive as to what is occurring during the test. For this reason NaREC developed a real-time digital video monitoring system that captures the motion of the tip of the blade, giving instantaneous feed-back on the motions that the blade is undergoing in the test. A digital video camera, operating at a frame rate of 20Hz, captures the image of a target attached to the tip of the blade, see Figure 3. The field of view of the camera has been calibrated to equate each pixel to a known distance, so that in each frame the location of the target can be converted into x and y coordinates. These coordinates are recorded as part of the test data, and can be displayed as a real-time plot showing the progress of the blade through the dual-axis test, Figure 4.



Figure 3: Target (black dot on white background) attached to tip of blade and digital camera used for tip-tracking of blade during dual-axis fatigue test.

Strain gauge data for the test was collected from gauges mounted around the circumference of the blade, at a distance of 2 metres from the root. Sixty gauges were used, positioned at 6° spacings around the circumference. The blade root diameter was nominally 2000mm.

Test Results – Dual Axis Fatigue

The results from the tracking the displacement of the tip of the blade during a dual-axis test are shown in Figure 4, as plots of x and y values for 50 and 200 cycles of testing.

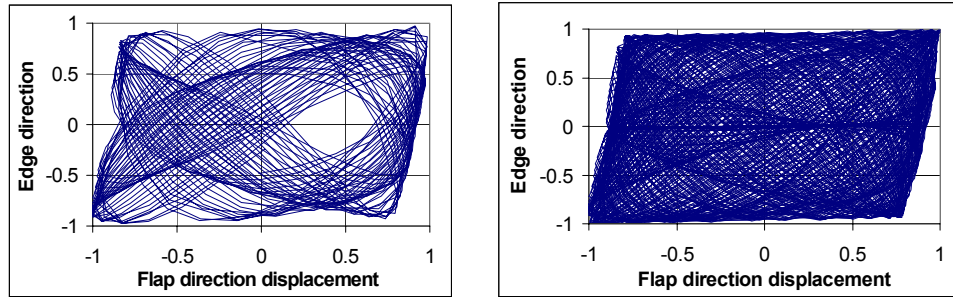


Figure 4: tip plots of 50 and 200 cycles of data, showing movement of blade tip during a dual-axis test. (Data normalised for confidentiality)

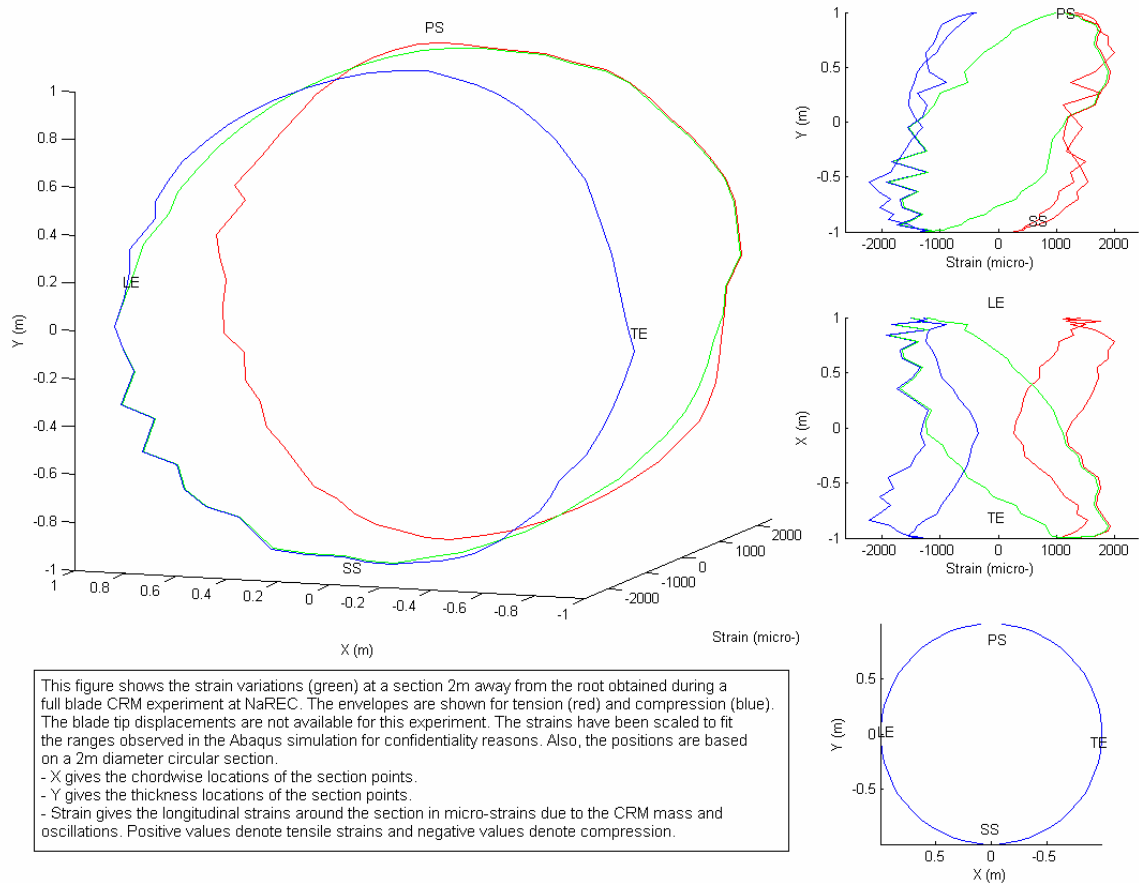


Figure 5: Strain gauge data from dual-axis testing. Green lines show instantaneous values of strain. Blue and red lines show extreme values recorded for each strain gauge. (N.B. Experimental results have been scaled to protect confidential blade data.)

Strain gauge data from the dual axis testing is shown in Figure 5. The main plot uses a 3-D graph to plot strain gauge location as x and y co-ordinates around the blade root, with recorded strain values shown on the third axis. The green lines are an instantaneous record of strain values at a set time, whilst the red (tension) and blue (compression) lines show the maximum recorded values at each strain gauge location. The smaller plots show 2-D projections of the 3-D graph, viewed from each combination of two axis. The experimental strain data has been scaled to protect the confidential nature of the strain information, whilst still allowing comparison to be made with data from the FE model.

FINITE ELEMENT MODELING

Methods – Finite Element Modeling

In this work, the finite element (FE) modeling has been conducted using the parametric wind turbine blade modeling tool [4] developed at Rutherford Appleton Laboratory (RAL) and running within the Abaqus software package. A generic FE blade model, developed as part of the studies undertaken by the Supergen Wind consortium, has been used in the modeling, since construction and materials data details of the exact blade tested are commercially confidential. In the model the blade position is defined relative to the rest of an operating rotor and to the tower. To represent the typical dual-axis compact resonant mass (CRM) testing position in this coordinate system, the blade azimuth is set to 90° and the set angle (pitch) is set in the vicinity of 90° . This ensures that the suction side of the blade is facing the ground, so that the gravity acts in the same direction as a typical operational flap load (i.e. compression in the suction side and tension in the pressure side). The exact set angle value depends on the twist at the station where the saddle and the CRMs are placed, in order to ensure that the oscillations of the CRM sets are initially horizontal and vertical. The general arrangement used in the computation is shown on Figure 6.

The simulation of the dual-axis fatigue test is conducted by taking into account the full system dynamics. The mass and damping properties of the blade and CRMs assembly are included so that the gravity and inertial loads are reproduced in this analysis. In the full analysis sequence, gravity is first applied to the blade in position equipped with the CRM testing apparatus. A natural frequency extraction then follows. Finally, a dynamic analysis is conducted with sinusoidal loads input in the flap and edge directions. It should be noted that the deformed state obtained at the end of the gravity step is always taken as the base state at the start of the dynamic step calculations.

In this problem, the loading apparatus is assumed to be perfectly rigid. The mass of the system is represented by 5 discrete point-masses. The mass of the loading frame is concentrated in a point typically inside the aerofoil section (the ActuatorFrame-BladeTie point, see Figure 6). The CRMs are represented by 4 point-masses located outside the aerofoil. These 5 masses are fixed in position relative to the mesh nodes defining the local section aerofoil (pink nodes in Figure 6). The inertial loads imposed by the accelerations of the CRMs in the actual test are introduced in the model by concentrated loads at the ActuatorFrame-BladeTie point. Constant frequency sinusoidal inputs are specified, with the frequencies typically set to the natural frequencies of the

1st flap and edge modes found in the frequency analysis. These loads are transmitted to the aerofoil nodes according to the local relative stiffness distribution in this part of the blade.

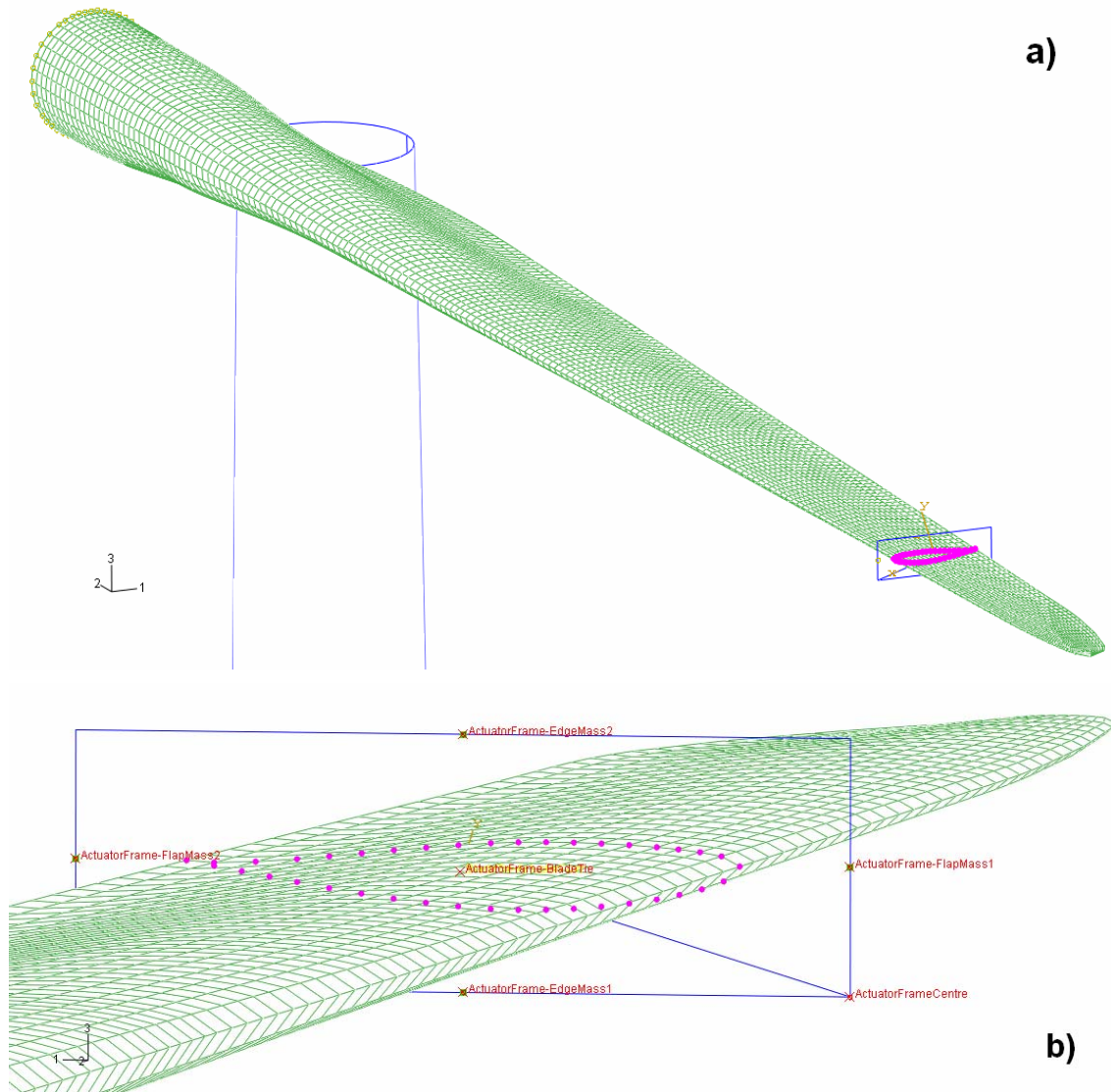


Figure 6: Arrangement of blade and CRM in the FE computational test. a) Overall view.
b) Close-up on loading section.

Since the structure is excited at its natural frequencies, damping must be introduced into the model to avoid an exponentially increasing response. Viscous material damping expressed in the Rayleigh form is available in Abaqus. No type of material damping is likely to be suitable to model aerodynamic damping accurately. However, the amount of material damping specified in the model could be tuned by matching the experimental blade tip displacement time histories obtained from given CRM displacement histories.

A choice of numerical procedures and options is offered to conduct the dynamic analysis. Most importantly, the solver can be implicit or explicit (and subspace-based) and the analysis may or may not take into account non-linear effects (here only geometrical). These choices greatly affect the solving time, and impact on the permissible time-step used during the numerical integration, but the respective solutions all give very similar results. Therefore, the explicit linear solution is used for most computations as it is less computationally expensive (with a slightly coarse mesh, the time factor is about 60 when solving on the E-Science SCARF computing cluster, i.e. simulating 1s takes 1min). Alternatively, the dynamic study could have also been restricted to the specification and analysis of the 4 corner points of the flap/edge displacement loading range. This possibility has not been investigated since the running time of the sub-spaced scheme was manageable.

Results – Finite Element Modeling

The results from the FE model showing the displacement of the blade tip in time during a dual-axis test are shown in Figure 7. The deflections are shown in metres of displacement, positive and negative, from the position of the blade tip at rest.

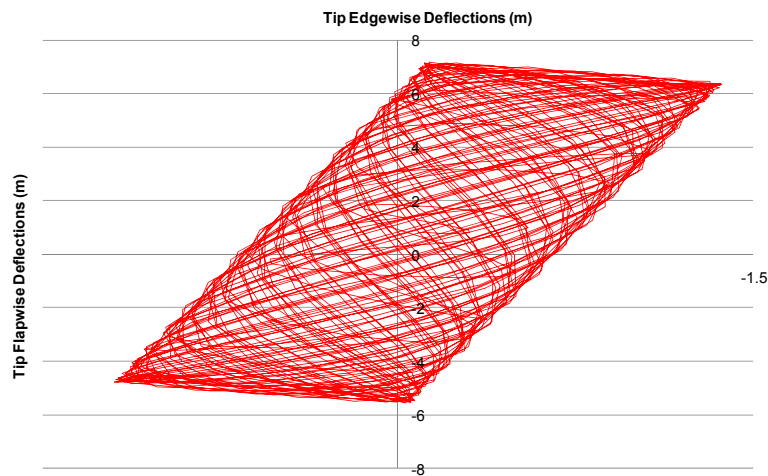


Figure 7: Blade tip displacement, flapwise and edgewise, from the FE computation.

The results from analysing the FE model to provide strains at the 2metre root distance circumference are shown in Figure 8. The main plot uses a 3-D graph to plot strain gauge location as x and y co-ordinates around the blade root, with calculated strain values shown on the third axis. The green lines are calculated strain values at a set time, whilst the red (tension) and blue (compression) lines show the maximum calculated values at each strain gauge location. The smaller plots show 2-D projections of the 3-D graph, viewed from each combination of two axis.

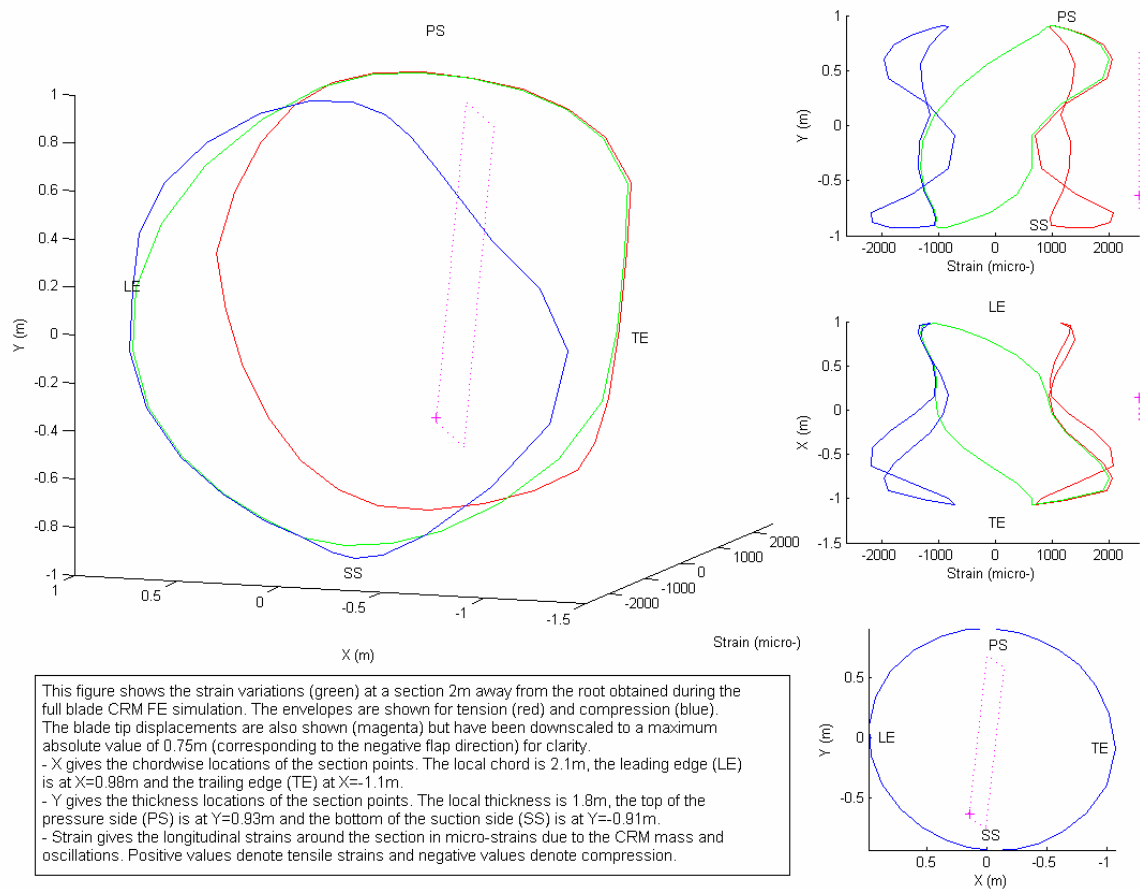


Figure 8: Strain gauge data from FE model. Green lines show instantaneous values of strain. Blue and red lines show extreme values recorded for each strain gauge.

COMPARISON AND DISCUSSION OF EXPERIMENTAL AND MODELING RESULTS

Tip displacement results

The comparison of results shown in Figures 4 (experimental) and 7 (FE modelling) show that the model broadly re-creates the pattern of tip displacements seen experimentally in dual-axis testing. The tip-tracking data reveals that there is coupling between the flap and edge modes of a wind turbine blade. The use of CRMs and dual-axis testing means that the blade can be simultaneously loaded in flap and edge directions, unlike in single-axis tests.

However, the exact details of the experimental dual-axis test were not able to be re-created in the FE model due to blade confidentiality, which meant that only approximate representations of blade structure and materials could be used in the FE model. It should also be noted that dual-axis experimental tests are very sensitive to the exact resonant frequency of the system, which means that the tip displacement traced by the blade will vary, dependent on the ratio of flap and edge natural frequencies. Re-creating a detailed

replica in a FE model would require more detail than it is sensible to try and obtain and then use. Hence, on this tip displacement aspect, it is sufficient for the FE modeling of tip displacement to indicate broad trends, rather than provide accurate predictions.

Strain results

The results from monitoring experimental strains and calculating strains using FE can be compared using Figures 5 and 8, which present snapshots of the strain state in a blade. At the instances shown in Figures 5 and 8 the blade pressure side and trailing edge are under tension simultaneously, as indicated by the green lines. The maximum strains in both experiment and modeling are seen in locations where combinations of loads take place, which would not be seen in a single-axis test. These maximum strain locations are not on the major axis of the blade, as would be indicated by the maximum strain values occurring at X and Y values of 1m or -1m (based on the 2m diameter blade root). Instead the maximum strain values are at locations around the +/- 0.6m to 0.7m value for X or Y – which places these strain maxima on what could be described as the minor axis of the blade, or axis at angles of 45°-225° and 135°-315°, rather than the 0°-180° and 90°-270° of the major axis.

The interesting observation is the similarity in strain distributions and ratios between the experimental and modeling results – this in spite of the fact that the detailed lay-up and material properties were unavailable to the model due to confidentiality. Strain maxima are seen on the minor axis of the blade, as described in the paragraph above. It should be noted though that the exact computational strain profile is very sensitive to the local composite lay up that is modeled, making it difficult for precise comparisons to be made between experimental and modeled strain values.

The fact that strain maxima in dual-axis testing and modeling are seen not on the major flap and edge test axis, but on the minor axis, indicates that single axis testing will not test the blade with the combination of loadings that undoubtedly occur whilst blades are operating. These combined operational loads will place strain maxima onto the blade minor axis, suggesting that a test method that helps achieve this type of loading, as with this dual-axis method, will be beneficial.

CONCLUSIONS

The coupling of flap and edge modes for wind turbine blades means that two loading directions are associated. This dependence has the result that strain patterns will arise from operational loads, that are not thoroughly investigated by single axis testing. A dual-axis testing method, as presented in this work, will be more representative of these combined loads.

The structural analysis FE model developed by RAL was used in a dynamic analysis of an experimental fatigue test, and was found to give broad agreement with experimental results.

From the work undertaken as part of this project, it is apparent that the generic blade FE model developed by ERU can be used to assist the development of the dual-axis test method, and can also be used to understand better the combined loading that blades experience whilst in-service.

ACKNOWLEDGEMENTS

The finite element modelling developed by the ERU at RAL was supported by the EPSRC through the Supergen V Wind consortium. The Blade Test Facility at NaREC was developed with assistance from the One North East Regional Development Agency.

References

1. Technical Specification. IEC TS 61400-23 Wind turbine generator systems – Part 23: Full-scale structural testing of rotor blades.
2. “Evaluation of the NEW B-REX Fatigue Testing System for Multi-Megawatt Wind Turbine Blades,” D. White, W Musial, S Engberg, 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, USA. Jan 10-13, 2005.
3. “Blade Testing – NaREC’s Innovations in Full Scale Dual Axis Fatigue Testing”, R S Court, A Waggott, P Hope, I Williamson. EWEC08, Brussels, Mar 31 – Apr 3, 2008.
4. “Parametric Modelling Of Large Wind Turbine Blades”, P A Bonnet, G Dutton. Proceedings of the Abaqus UK Regional User Meeting, November 2007.