THE WIND BLADE RESEARCH HUB

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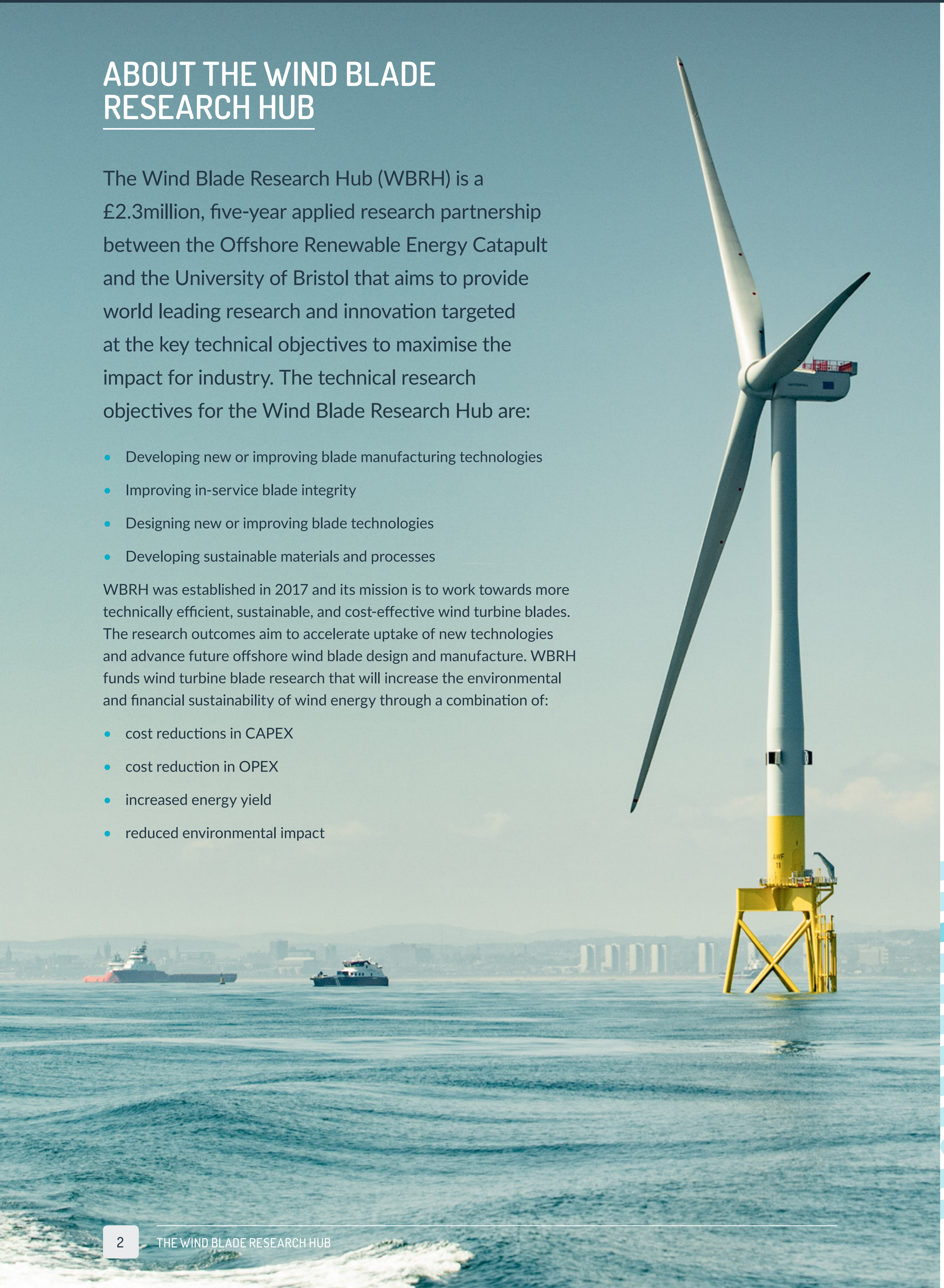


ABOUT THE WIND BLADE RESEARCH HUB

The Wind Blade Research Hub (WBRH) is a £2.3million, five-year applied research partnership between the Offshore Renewable Energy Catapult and the University of Bristol that aims to provide world leading research and innovation targeted at the key technical objectives to maximise the impact for industry. The technical research objectives for the Wind Blade Research Hub are:

- Developing new or improving blade manufacturing technologies
- Improving in-service blade integrity
- Designing new or improving blade technologies
- Developing sustainable materials and processes

WBRH was established in 2017 and its mission is to work towards more technically efficient, sustainable, and cost-effective wind turbine blades. The research outcomes aim to accelerate uptake of new technologies and advance future offshore wind blade design and manufacture. WBRH funds wind turbine blade research that will increase the environmental and financial sustainability of wind energy through a combination of:

- cost reductions in CAPEX
- cost reduction in OPEX
- increased energy yield
- reduced environmental impact

The collaboration builds a stronger, complementary offering of academic research, innovation and testing to the offshore renewables sector. As a strategic overarching investment rather than sponsorship of individual PhD projects on a case-by-case basis, the research hub enables a coherent research programme with a greater contribution from senior academics. It provides the researchers a broader peer group, access to leveraged funding and more insight into potential applications and developing products and services.

WBRH supports 7 doctorial students (PhD/EngD) in post and 5 years of post-doctoral research including academic and industrial supervision, facilities access, and oversight. The hub has enabled the appointment of Dr Terence Macquart, Lecturer in Aeroelastics at the University of Bristol, with a focus on research on Servo-aeroelastic tailoring of wind turbines. The hub provides a framework that encourages collaboration beyond the hub partnership with Industry and other Universities.

This hub ties in with ORE Catapult's Blades Knowledge Area (KA), a key strategic area which develops products and services to address current challenges for wind turbine blades. These include reducing blade manufacturing and ownership costs and increasing energy yield. Special emphasis is placed on services which can reduce blade failure risk at the design stage, through dedicated high-fidelity models and better validation methods in blade testing.

ORE Catapult complements the University facilities by offering the researchers access to Blades KA related assets including:

- The 7 MW Levenmouth demonstration offshore wind turbine: Located at Levenmouth in Fife (Scotland), the turbine is the world's most advanced open access offshore wind turbine dedicated to research and product validation. It is a platform for testing innovative blade technologies and operational settings, but also provides open access to its design information which allows a wider research scope for a number of disciplines and components.
- The Blade Test facilities (BTF): The 50m blade test facility (BTF1) and the 100m facility (BTF2) can accommodate a range of blades to meet offshore wind market blade length requirements. The facilities deliver static and fatigue structural tests for the certification of wind turbine blades and support the development of novel testing methods for more representative and economic testing.
- The National Offshore Anemometry Hub (NOAH): Installed three nautical miles off Blyth, Northumberland, this meteorological mast provides wind resource and environmental data to validate turbine and associated component and sub-system demonstrations.

ORE Catapult is part of the hub governance structure ensuring research is directed towards industry needs. Our research staff provide expert supervision to the researchers with a particular focus on validation and testing, which is complemented by our test data and knowhow.

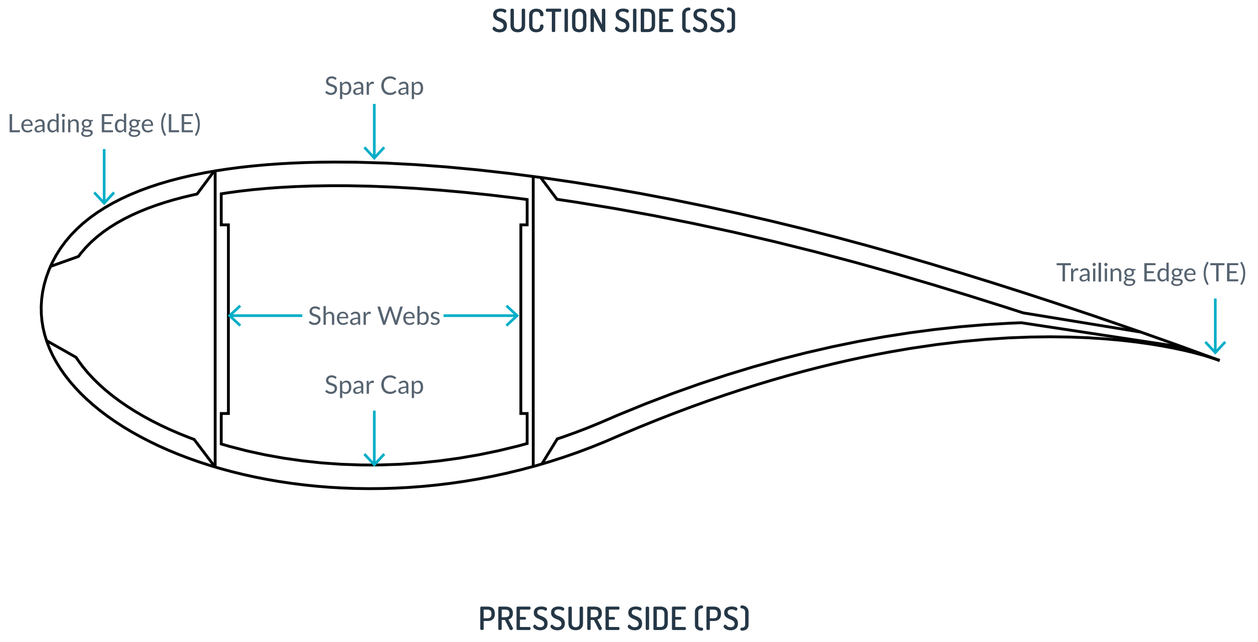
WIND TURBINE BLADE EXPLAINER

The blades are some of the most critical components of the turbine – not only are they key to improving energy production, but catastrophic failure of a blade can lead to failure of other parts of the turbine structure and so it is to be avoided at all costs.

The primary function of a wind turbine blade is to capture the energy in the wind and transfer the energy to the rotor to generate electricity. In doing so, creates a bending moment on the root bearing and a torque on the main shaft. A blade is a large cantilever beam, which is primarily loaded in two ways. Flapwise, or out-of-plane, bending loads arise from aerodynamic forces and edgewise, or in-plane, bending arises from blade self-weight. These loads are determined using aero-elastic codes – sector specific software which simulates turbine behaviour for a huge variety of load cases. The software must be highly computationally efficient as many thousands of complex load case simulations are required by the design standards to ensure safety.

The blade structure is designed to resist these loads whilst having a form which is as close as possible to the optimal aerodynamic shape. The suction side and pressure side shells are large aerodynamic panels designed to "catch the wind" and transfer the loads to the spar caps. The shells are comprised of a lightweight core material sandwiched between triaxial glass fibre reinforced plastic (GFRP).

They are typically moulded in two "blade shell" tools using vacuum assisted resin transfer moulding, and adhesively bonded to each other along their leading and trailing edge, and to the spar caps in the middle. The skins have low thickness; they therefore need to be stabilised using a lightweight core (typically made from balsa wood or PVC foam) to prevent buckling.



CROSS SECTION SHOWING TERMINOLOGY AND PARTS OF A WIND TURBINE BLADE

The spar caps are the key structural components which transfer the load along the blade. Spare caps are generally made of uniaxial material (often carbon fibre reinforced plastic (CFRP) instead of GFRP as it is has a higher specific strength) placed at the thickest part of the section to maximise their contribution to the bending stiffness. The shear webs transfer the forces between the spar caps and are typically made of biaxial GFRP with a core material (again made from balsa wood or PVC foam). Composite materials are used because of their high specific strength and stiffness, good fatigue properties and the ability to tailor properties by altering the ratio of fibre directions.

The entire exterior of the blade is coated to protect the composite structure from the environmental conditions of UV degradation and moisture ingress and provide an aerodynamic surface. This general coating is typically a gelcoat applied in mould but can also be a filler and topcoat. Additionally, on the leading edge close to the tip a rain erosion resistant material is applied.

This structure is typically modelled by applying the loads determined with aero-elastic codes to a finite element model of the blade. These models usually use shell finite elements – this makes for easier modelling of the blade but does not capture through-thickness stresses, for which a solid model is required. If the designer uses an increased level of fidelity for these analyses then design standards allow them to use reduced material safety factors, which allows the blade to be lighter weight and therefore reduces material costs.

THEME 1 – AEROELASTICITY

The Wind Blade Research Hub has four main themes, the first of which is aero-elasticity. If you've ever stuck your hand out of a moving car's window and noticed how the force on your arm changes with the angle of your hand then you have experienced this phenomenon.

Wind turbine blades are no different – the force on the blades varies greatly with the angle of attack of the blade (the angle it makes with the incoming flow), which effects how much the blade bends and twists. This in turn changes the angle of the blade to the incoming flow, which means that the elastic nature of the blades and the aerodynamics are strongly coupled. Understanding this relationship is key – it affects how heavily loaded the blades are (and therefore how much material is required to withstand these loads), the aerodynamic efficiency (and therefore the amount of power the turbine will produce) and the stability of the blades (resonance can occur, leading to runaway vibrations which could damage the whole turbine). The WBRH has supported three projects in this area.

NOVEL AEROELASTIC TAILORING METHODS VIA MULTI-DISCIPLINARY OPTIMISATION

Offshore wind is moving toward larger turbine rotors that generate greater power. Sizing, and hence cost, of many turbine components is defined by aerodynamic loads from the rotor. It is desirable to reduce the cost of components as much as possible, whilst increasing overall turbine size and power generating capacity. Therefore, reducing aerodynamic loads without severely impacting energy production is one way of minimising the levelised cost of energy (LCoE).

Aeroelastic tailoring allows wind turbine (WT) blades to passively alleviate loads, in addition to the active load alleviation incorporated in most modern WT controllers (such as individual pitch control). Passive load alleviation is most often achieved by building in structural bend-twist coupling into the blade structure. Such load alleviation has the potential to reduce extreme and fatigue loading on the blades, as well as other turbine components such as the drivetrain, tower, and foundations. Alternatively, it opens up the potential to increase the size of the rotor without the associated increase in loads, thus improving energy capture.

The breakthroughs in this work are twofold; firstly, couplings from multiple sources will be considered for reducing LCoE and secondly, the variables related to coupling have been included in the whole turbine optimisation problem. The outcome is a tool called ATOM (Aeroelastic Tailoring Optimisation Methods) which can do preliminary aero-structural rotor-turbine design considering aeroelastic tailored blades. The aero-structural design problem is large and requires much computing power, therefore, many techniques for improving computational efficiency have been included in this work. The impacts of this research for industry will be that global turbine concepts (i.e. 3 vs 2 blades, downwind vs upwind, specific site conditions etc) will be able to go through a fully optimised preliminary design phase using fewer employee resource and considering the aero-structural design trade-off.

TORSIONAL TESTING OF WIND TURBINE BLADES

As wind turbine blades have become longer and more compliant, the ability to predict blade twisting has become more important. The structural twisting, or torsion, of blades has a significant impact on loading, power production and aero-elastic stability. It is, therefore, critical that the torsional response of blades is well understood and captured within the numerical analysis tools used for wind turbine design (such as aero-elastic codes). Currently there are no requirements under the IEC design standards to verify the torsional stiffness of blades. Furthermore, there are numerous well documented issues concerning the numerical prediction and manufacturing impact on the torsional characteristics of blades. Currently, blade manufacturers have limited opportunities to validate their models and as a result may restrict their innovation to address the uncertainty in the torsional response of a blade.

This work has both a simulation and experimental elements. Accurate solid finite element models of the blade and test fixtures used to perform the torsional test on a 40m blade have been developed. These will be used to understand how boundary conditions, result measurement and different methods of applying loads influence the torsional response of the blade. The optimal test method developed in the simulation phase will then be used to determine the test program for a 40m blade which will be performed at ORE Catapult's facilities in Blyth.

The goal of this research is to help the industry move towards a standardised method for performing torsional tests which minimises any uncertainties related to test methodology. The test methodology de-risks the technology in a laboratory environment before the technology is deployed offshore.

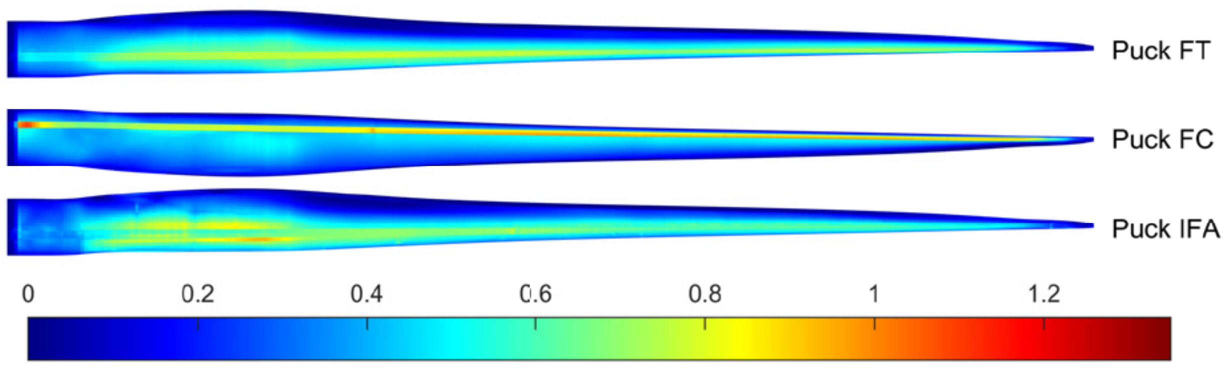
NON-LINEAR AEROELASTIC STABILITY ANALYSIS OF WIND TURBINE ROTORS USING NUMERICAL CONTINUATION

The aim of this project is to investigate aeroelastic stability issues and the dynamic behaviour of large, slender, modern wind turbines, caused by the combination of low structural damping, aerodynamic stall, geometric non-linearity, and complex aero-servo-elastic couplings.

The usual way of addressing this issue is to use a time-stepping algorithm (as implemented in an aero-elastic code) to increase the rotor speed until an instability develops, which is computationally intensive and does not give much information about what is driving instabilities.

There is therefore a requirement for low to mid-level fidelity tools which can accurately predict the onset of flutter in the early stages of the design process. In this work, numerical continuation and bifurcation analysis is used to predict the onset of instability, eliminating the need for the time-stepping process. This method can give useful information about what is causing instabilities and can also predict types of instability which could not be found using conventional stability analysis methods. These subcritical bifurcations could occur if, for example, a sudden gust of wind moved the blade into an excitation mode which would have been stable at the current wind speed.

To date the project has compared the nonlinear beam shapes (NBS) model against the corotational beam model implemented in ATOM, checked the stability for parked blades and implemented an aerodynamic model suitable for wind turbines.



Pictured: Contour plot of the Puck failure criterion for a redesign of the blade for the IEA 15MW reference turbine. A value of 1 indicates that the material has failed, so this preliminary design shows good material utilisation without major failures. Compared to the original design this blade is 4% longer, reduces blade mass by 11%, increases AEP by 1.5% and reduces LCoE by 2.3%

THEME 2 – LEADING EDGE EROSION

The second theme of the WBRH is minimising leading edge erosion. This issue is usually cited as the biggest problem relating to wind turbine blades from an operations and maintenance perspective – it occurs when raindrops and other particulates impact the leading edge of the blades, which travel at around 100m/s (220 mph).

It affects the bottom line for wind farm operators in two ways – by reducing the aerodynamic efficiency of the blade profile and by driving up maintenance costs and downtime. It can affect onshore turbines too, but it is a particular problem for offshore turbines which tend to have higher tip speeds because there is not as constraint around aerodynamic noise (longer blades and increasing the rotational speed decreases the torque required to achieve a given power rating, which decreases the cost of drivetrain components). Maintenance is also much more challenging offshore.

LIFETIME PREDICTION OF LEADING EDGE PROTECTION SYSTEMS

Leading edge protection (LEP) coating systems which have good rain erosion test (RET) results in the laboratory do not always correlate with good performance in the field, so an improved methodology is required to translate between coating tests and coating lifetimes in different operational environments because they are affected by rain conditions. A Joint Industry Project named COBRA has published recommendations for designing rain erosion protection systems.

This research aims to expand on the COBRA methods, by furthering the understanding of damage mechanisms to improve current lifetime prediction models. This will then be used to understand the relationship between the rain erosion test (RET) and the offshore environment, to ensure testing is representative. The COBRA methodology was scrutinised for different RET conditions and materials but was not validated for all LEP systems. The methodology uses outdated testing and LEP systems to develop its key equations and is unrepresentative of current approaches. The north sea offshore environment has been characterised using measurements from ORE Catapult's NOAH platform, which have shown that precipitation occurs in discrete periods often with a long time period between events. Dynamic mechanical thermal analysis studies have shown that a viscoelastic material recovers in 20 minutes. Current rain erosion testing does not allow this recovery, causing more brittle failures and results which are unrepresentative of the offshore environment.

The research aims to develop an improved correlation methodology, which provides the representative RET and lifetime prediction capability required by the wind industry. This will enable a suitable qualification method which helps to inform the design of new materials, ultimately helping to reduce the loss in energy production and operation and maintenance costs.

MEASUREMENT AND UNDERSTANDING OF VISCOELASTIC WIND BLADE EROSION COATINGS

This project aims to develop measurement techniques to quantify and develop the understanding of the viscoelastic response of coatings in both accelerated RETs and real wind turbine environments. Examples of this include studying the effect of high strain-rates, temperature, and recovery on material properties. Current rain erosion lifetime prediction models work generally well with homogeneous materials which undergo brittle failure. However, state-of-the-art models are incapable of accurately predicting the effect of rain erosion on the lifetime of highly viscoelastic materials which are currently being developed at industrial levels. This is due to a lack of understanding of the failure mechanisms and an inability to measure key material properties using standard methods. This work is part of a collaboration between ORE-Catapult, University of Bristol, University of Strathclyde, and two commercial coatings manufacturers; under the BLEER project which aims to further the understanding of damage mechanisms and improve current lifetime prediction models.

This project aims to develop measurement techniques to quantify and develop the understanding of the viscoelastic response of coatings in both accelerated RETs and real wind turbine environments. Examples of this include studying the effect of high strain-rates, temperature, and recovery on material properties - current rain erosion lifetime prediction models work generally well with homogeneous materials which undergo brittle failure but are incapable of accurately predicting the lifetime of highly viscoelastic materials which are currently being developed at industrial levels. This is due to a lack of understanding of the failure mechanisms and an inability to measure key material properties using standard methods.

The work aims to inform commercial coating manufacturers and interested members of the academic community of properties that influence the performance of materials used in current wind turbine leading edge protection solutions. A suite of techniques will be developed into an overarching methodology to characterise current commercial products and compare their viscoelastic characteristics. This will allow for rapid, relevant, and cost-effective laboratory test methods for early erosion performance screening, reducing overall development time for new leading edge protection materials.

Pictured: Rain erosion test rig

THEME 3 – DETAILED STRUCTURAL MODELLING

The third theme of the WBRH is detailed structural modelling. Wind turbine blades are typically modelled at three levels of fidelity, all of which have their strengths and weaknesses.

The lowest fidelity method used is beam models, which break the 3D problem down into a 2D cross section and a 1D length direction. These models are highly computationally efficient (which is why they are used in aero-elastic simulations), but they cannot predict the stresses in parts of the blade where it cannot be considered as a prismatic structure (like the transition from the circular root to an aerofoil shape). However, these types of models can give accurate predictions of the torsional response of the blade.

Shell models treat the blade as a 3D structure, so they can capture effects arising from rapid changes in cross-section, but their prediction of torsional properties is poor, and they cannot predict through-thickness stresses which are key for several blade failure modes. They have an acceptable computational cost when analysing the blade in one piece.

Finally, the highest fidelity models use solid elements. These elements give good predictions of torsional properties, can capture through thickness stresses, and represent the true blade geometry rather than an abstraction. However, with conventional finite element types solid elements are restrictive because they cannot have a large difference between the length of their sides in each direction. As the blade is very thin in the thickness direction, this means models inevitably end up using very small elements and therefore the computational burden is high.

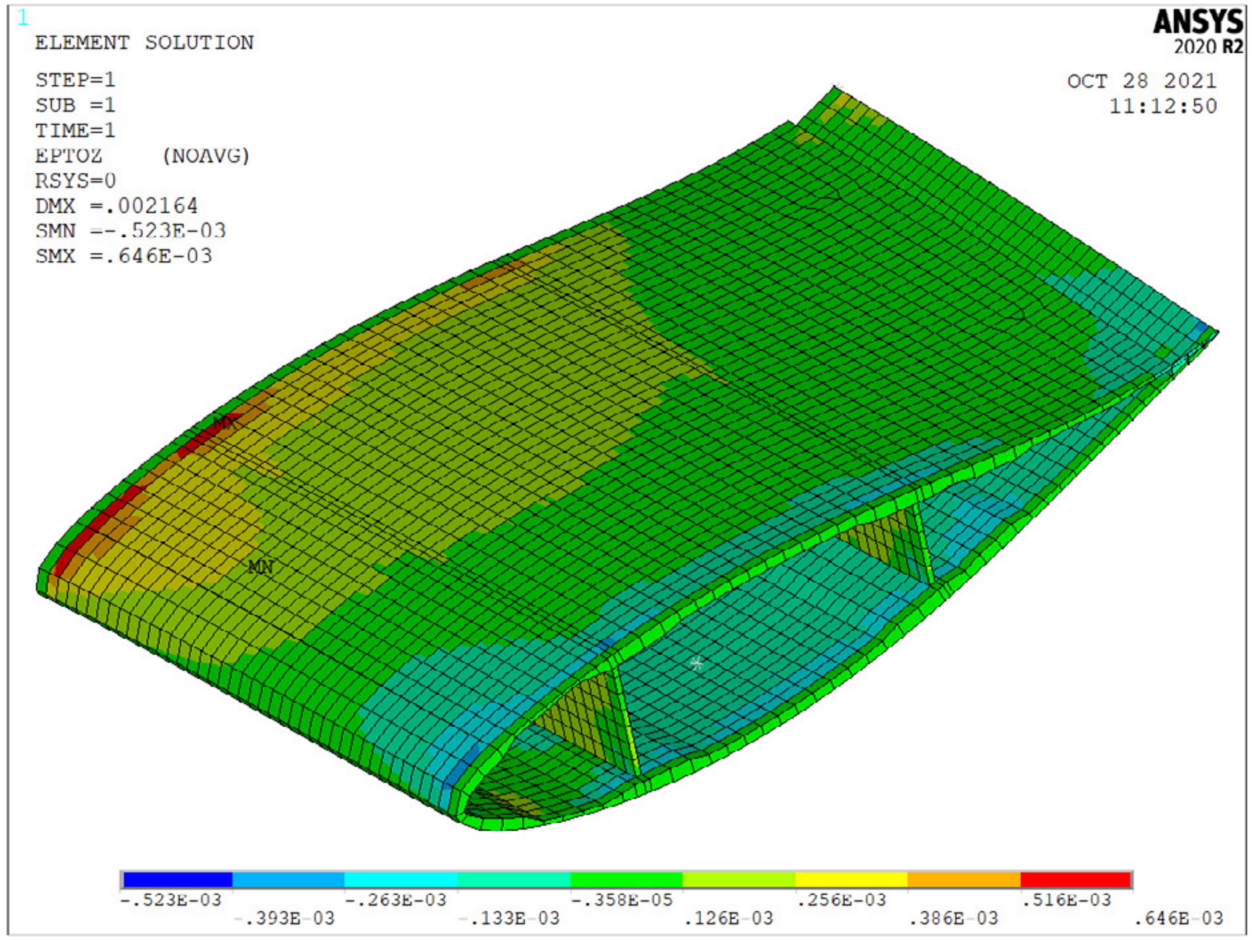
VARIABLE KINEMATICS CONTINUUM FINITE ELEMENT FOR MODELLING WIND TURBINE BLADES

Accurate estimation of stress distributions in wind turbine blade structures is essential for predicting failure initiation and propagation. Recovering local features, such as through-thickness transverse stresses or displacement field gradients close to singularities are addressed at later stages of the design process by treating the structure as a three-dimensional (3D) continuum. This is challenging, as this could require modelling hundreds of composite layers.

There is a need to develop an efficient mathematical method that can capture salient displacement and stress features in structures for incorporation into early-stage design iterations.

The University of Bristol have developed a variable kinematics modelling approach that builds upon the hierarchical Serendipity Lagrange finite elements, eliminating the issue around element aspect ratios described above which restricts the use of solid modelling techniques. This approach can predict accurate 3D stress fields with reduced computational effort, including local features such as geometric, kinematic, or constitutive boundaries. The model can analyse multi-layered composite structures either by adapting global approximation theories based on Equivalent Single-Layer (ESL) approaches or by employing discrete-layer approximation theories based on Layer-Wise (LW) approaches and can switch between these approaches depending on the desired level of accuracy. The global response (i.e. nonlinear deflection) of the structure can be captured by an ESL model, while the root, where transverse stresses are significant and can cause delamination failure, could be modelled using the LW approach.

As part of the WBRH this methodology has been extended towards an adaptive multi-scale model for turbine blades, with the end goal of eliminating the need to perform a separate global/local analysis. In the first iteration, the global response of the entire structure is predicted by employing the ESL model. In subsequent iterations, based on the modelling error, hot spots are identified and the kinematic fields in these regions will be varied following an adaptive strategy, either by increasing the expansion order or by mesh discretisation until all plies in that region are explicitly modelled. Thus, different level of responses can be obtained. The method will eventually be integrated into the ATOM code described in theme 1.



Pictured: Section from solid model of a 83.5m blade

THEME 4 – ADDITIVE MANUFACTURING

The final theme of the WBRH is additive manufacturing. The overall way in which wind turbine blades are manufactured has changed little in almost 30 years, despite the huge growth in the size of the blades.

Vacuum infusion resin transfer moulding is an effective means of making blades, but it has several downsides – it is challenging to automate, is wasteful in terms of consumables and requires huge and very expensive moulds for the blades. Additive manufacture offers the possibility of removing some of these issues and allowing the creation of site-specific blades.

TOPOLOGICAL OPTIMIZATION OF ADDITIVELY MANUFACTURED WIND BLADES WITH A GRADED LATTICE CORE

Additively manufactured internal structures for wind blades could remove the requirement for expensive female moulds, but as the male mould would now be part of the blade structure, it must be designed for minimum weight while still providing the required structural properties. For a given domain, topology optimisation generates the optimal material distribution. This material distribution is often described by a field of varying density where higher density material is placed along load paths and lower density or void regions are generated to reduce weight where material is not needed. To aid in the manufacture of the topology optimisation solutions, cellular architectures made up of repeated unit cells can match the density distributions and therefore provide the required structural properties and a male mould for the layered composites (which must still be applied because current materials available for additive manufacture cannot compete with the specific strength and stiffness of continuous fibre reinforced composites).

The project will focus on developing a rational design basis for the inclusion of additive manufacturing in the production of wind blades. Its aim is to develop new topology optimisation design paradigms and tools – graded unit cell architectures (lattices) and layered composite components will be topologically optimised in combination, to achieve the desired improvement in structural performance within a design for additive manufacture framework.

LIST OF RESEARCH PROJECTS

Project: Aeroelastic tailoring including tool development, and Novel wind turbine designs for future reduction in costs of energy.
Researcher: Terence Macquart

Project: Condition Monitoring of Wind Turbine Blades.
Researcher: Kyungil Kong
Supervision team: Ian Hamerton, Paul Weaver, and Kirsten Dyer

Project: Variable Kinematics Continuum Finite Element for Modelling Wind Turbine Blades.
Researchers: Mayank Patni and Sander van den Broek
Supervision team: Alberto Pirrera and Peter Greaves

Project: The development of an improved rain erosion lifetime prediction Model to predict in-service coating erosion behaviour.
Researcher: Robbie Herring
Supervision team: Carwyn Ward, and Kirsten Dyer

Project: Wind blade aeroelastic tailoring: benchmarking of structural design options.
Researcher: Sam Scott
Supervision team: Terence Macquart, Alberto Pirrera Paul Weaver, and Peter Greaves

Project: Structural Testing Methods for Next Generation Wind Turbine Blades.
Researcher: David Langston
Supervision team: Ole Thomsen, Terence Macquart, and Peter Greaves

Project: Measurement and Understanding of Viscoelastic Wind Blade Erosion Coatings.
Researcher: Imad Ouachan
Supervision team: Carwyn Ward, Ian Hamerton, and Kirsten Dyer

Project: Topological Optimisation of Additively Manufactured Wind Blades with a Graded Lattice Core.
Researcher: Alex Moss
Supervision team: Alberto Pirrera, Terence Macquart, Mark Forrest, and Peter Greaves

Project: Non-linear aeroelastic stability analysis of wind turbine rotors using numerical continuation.
Researcher: James Ascham
Supervision team: Mark Lowenberg, Terence Macquart, and Peter Greaves

CATAPULT
Offshore Renewable Energy

CONTACT US

info@ore.catapult.org.uk
ore.catapult.org.uk

ENGAGE WITH US

GLASGOW

ORE Catapult
Inovo
121 George Street
Glasgow
G1 1RD

+44 (0)333 004 1400

BLYTH

National Renewable
Energy Centre
Offshore House
Albert Street, Blyth
Northumberland
NE24 1LZ

+44 (0)1670 359555

LEVENMOUTH

Fife Renewables Innovation
Centre (FRIC)
Ajax Way
Leven
KY8 3RS

+44 (0)1670 357649

GRIMSBY

O&M Centre of Excellence
ORE Catapult, Port Office
Cleethorpe Road
Grimsby
DN31 3LL

+44 (0)333 004 1400

ABERDEEN

Subsea UK
30 Abercrombie Court
Prospect Road, Westhill
Aberdeenshire
AB32 6FE

07436 389067

CORNWALL

Hayle Marine Renewables
Business Park
North Quay
Hayle, Cornwall
TR27 4DD

+44 (0)1872 322 119

PEMBROKESHIRE

Marine Energy Engineering
Centre of Excellence (MEECE)
Bridge Innovation Centre
Pembrokeshire Science
& Technology Park
Pembroke Dock, Wales
SA72 6UN

+44 (0)333 004 1400

CHINA

11th Floor
Lan Se Zhi Gu No. 15
Ke Ji Avenue
Hi-Tech Zone
Yantai City
Shandong Province
China

+44 (0)333 004 1400

LOWESTOFT

OrbisEnergy
Wilde Street
Lowestoft
Suffolk
NR32 1XH

01502 563368