# Learning from the lab to drive better blade performance

Comprehensive system and component testing of wind turbine blades provides crucial insights into their performance and durability. By identifying potential issues early, these tests help optimize operation and maintenance strategies, enhance reliability and minimize downtime.

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The wind industry has made tremendous progress in increasing turbine size. For more than 15 years, the Fraunhofer Institute for Wind Energy Systems (IWES) has been an integral part of this journey, supporting wind turbine manufacturers in validating components across the entire system, from foundations to blades, pitch bearings to drivetrains, and more recently, even electrolyzers. While verification and validation remain central to Fraunhofer IWES's activities, the operation and maintenance of wind turbines have increasingly become a focus of our research efforts.

### Root cause analysis for component failure

Advances in material technology, manufacturing methods and design and validation processes have enabled the wind industry to install and operate increasingly larger turbines with high reliability. As a result, wind turbine components have grown in size, and the potential impact of damage has increased accordingly.

Although catastrophic failures are rare, minor defects requiring maintenance or component replacement occur more frequently and can cause operational disruptions and financial losses. Regardless of severity, identifying the root cause of any damage is the essential first step toward implementing effective corrective measures. In many cases, independent expertise is required and researchers at Fraunhofer IWES are frequently called upon to support this process.

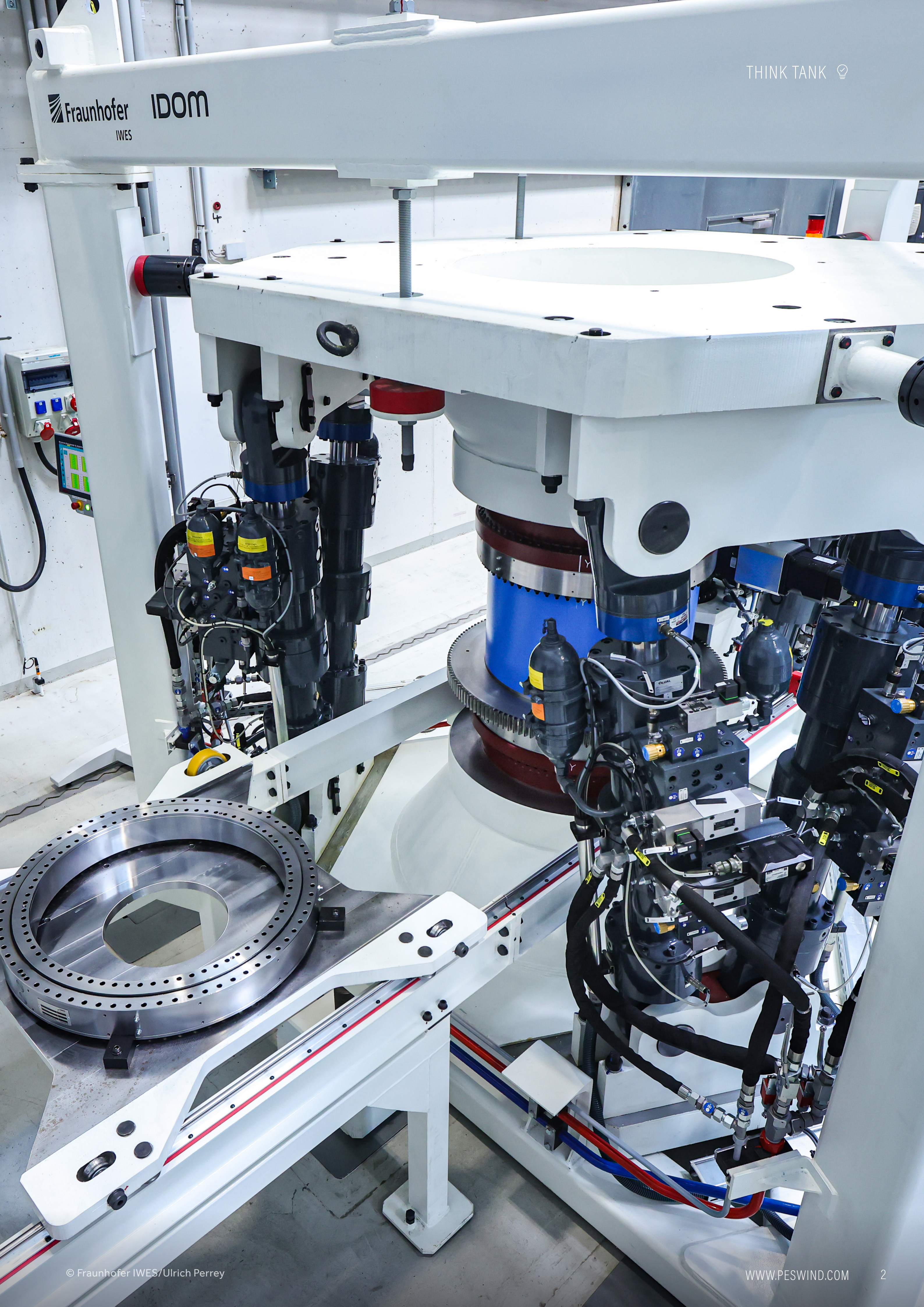
## Case study 1: Bond line failure

A recurring issue observed in many blade types across manufacturers and platforms is the occurrence of bond line cracks, which can originate from a variety of root causes. The first step in any root cause analysis is to review the available documentation, including inspection reports, drone footage, design data and manufacturing records. A site visit and physical examination of the damaged blade often provide crucial insights that help formulate a failure hypothesis.

In many cases, physical specimens taken from the blade can further substantiate the analysis. If significant void defects in the bond lines are suspected, a computed tomography (CT) scan can confirm or refute this assumption. If the available data suggest partially insufficient curing of the bond line, Dynamic Mechanical Analysis (DMA) can provide clarity. When necessary, Fraunhofer IWES experts can also review and witness the production process to identify potential issues in the bonding procedure.

Alternatively, the bond line may be defect-free and fully cured, with damage instead resulting from excessive loads exceeding the design specifications. While full-scale blade tests conducted according to IEC 61400-23 can capture bond line damage and reveal potential design weaknesses, they are limited in their ability to replicate certain specific load conditions. To address this gap, Fraunhofer IWES has developed sub-component tests for various scenarios, such as the trailing edge test, to better assess these conditions.

BEAT1.1 for scaled pitch bearings

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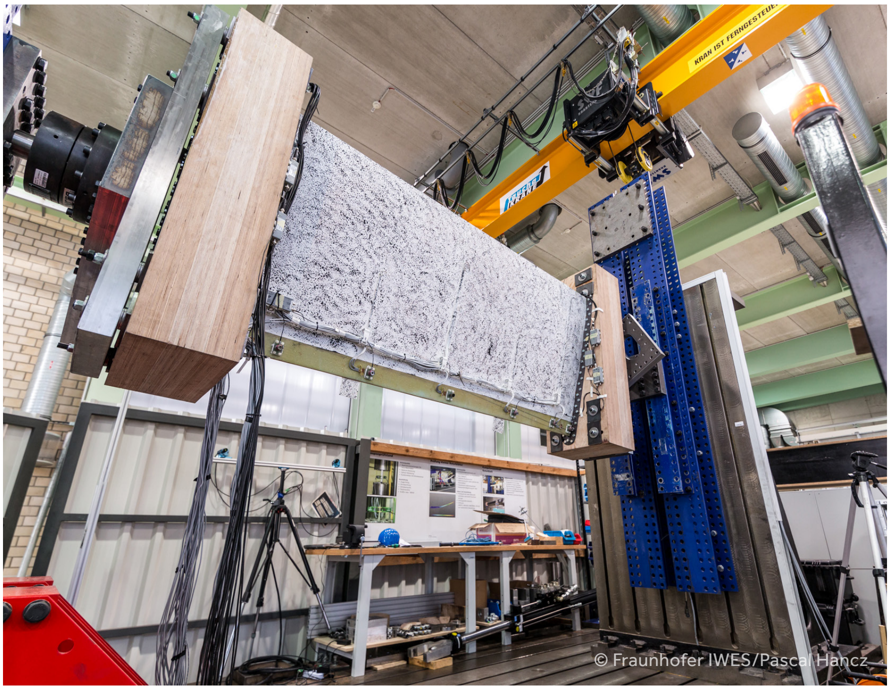



An example of subcomponent testing: trailing edge test

The test involves mounting a section cut from a wind turbine blade onto a modular test rig anchored to a strong floor. Load introduction is achieved using steel reinforcements, into which the specimen is bonded with a conventional epoxy-based bonding paste. Static and dynamic loads are applied through a single actuator connected to a large lever arm.

In contrast to a full-scale blade test, which can take several months to more than a year to complete, these sub-component tests can be carried out within a significantly shorter time frame. Moreover, the loading conditions can be adjusted to replicate specific load combinations suspected of causing damage in the field.

### Repair methods

Once the root cause of a component has been identified, adequate repair methods need to be implemented. Repair methods should be durable, reliable, efficient and repeatable.

## Case study 2: CureMonitor

Structural repairs of wind turbine blades usually require on-site curing of fibre reinforced polymers. Ambient temperature, wind speed and humidity significantly influence the curing behavior. This is generally taken into account through process windows in which a specific resin is to be used. However, as long as the desired degree of cure is reached, repair could still work.

Researchers at Fraunhofer IWES have developed a handheld device designed to monitor the curing process in real time. Using an integrated thermometer, the device records the temperature history, while an underlying curing kinetics material model, calibrated through extensive laboratory trials, calculates the final degree of cure. Once curing is complete, the CureMonitor automatically sends an email notification. This enables adaptive curing times while ensuring process consistency and full traceability through automated documentation.

## Case study 3: Up tower repair of spar caps

Carbon Fibre Reinforced Polymers (CFRP) offer higher specific strength and stiffness compared to glass fibre reinforced polymers, making them the material of choice for spar caps in longer, highly loaded wind turbine blades. Pultruded pre-manufactured planks are commonly used for this purpose, as the pultrusion process enables high production rates and near defect-free material quality.

Repairing damages in spar caps made from pultruded planks is particularly challenging. Currently, such repairs require the blade to be taken down from the turbine. The CaReUp research project, funded by the German Federal Ministry for Economic Affairs and Energy, aims to make it possible to repair pultruded CFRP spar caps directly on the turbine (up tower), thereby minimizing system downtime.

This approach involves addressing several key aspects. First, the stability and structural integrity of the rotor blade at the repair site must be ensured. To achieve this, a large clamp has been developed to secure the blade and relieve structural loads from the spar cap. The repair itself involves bonding pre-cured pultruded inserts into the scarfed repair area on site. Numerous boundary conditions must be considered to guarantee both the feasibility of the process and the full restoration of load-bearing capacity, durability and lightning protection.

### Optimized operation

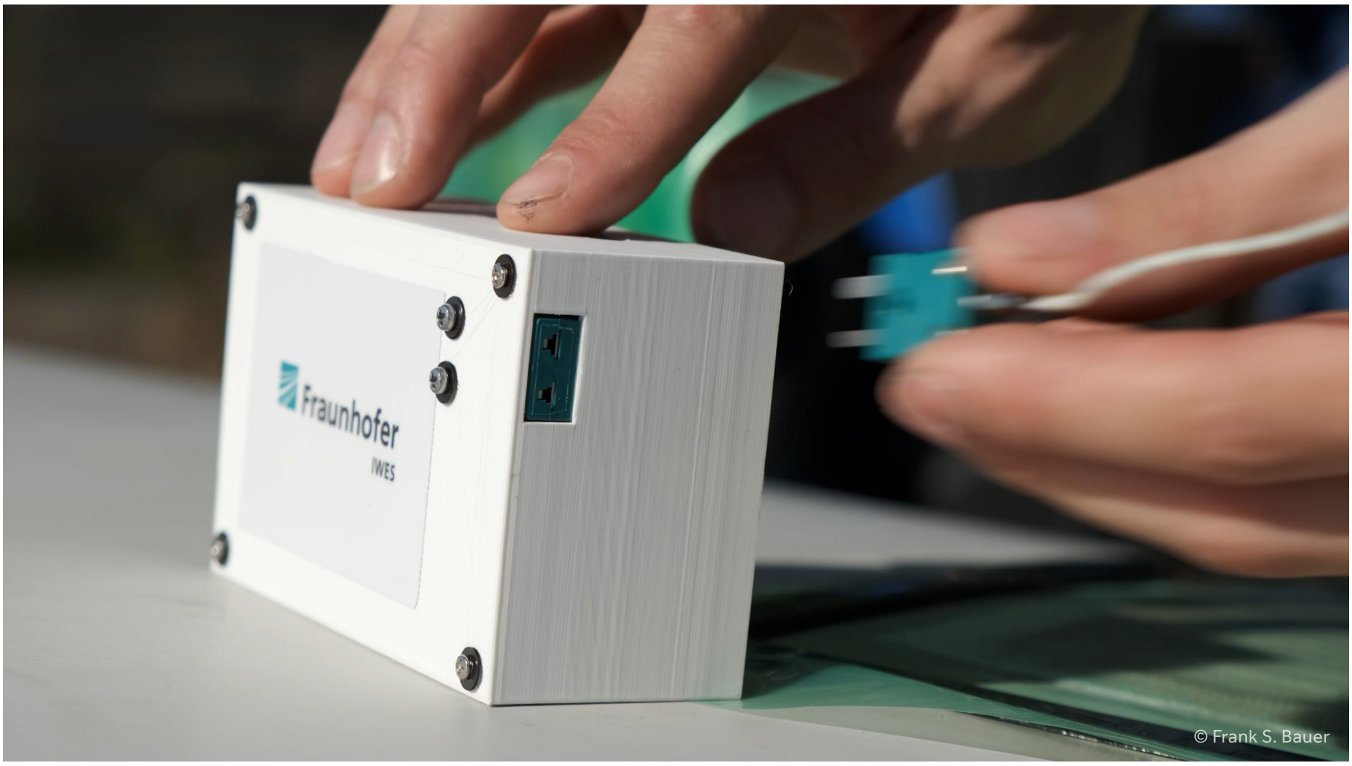
Most of the time, wind turbines operate without damage and disruption. Still, lab trials are valuable drivers for optimization of wind turbine operation.

## Case study 4: Pitch bearing lubricants and condition monitoring

The Fraunhofer IWES Large Bearing Laboratory (LBL) in Hamburg was established


Bi-axial blade test in one of Fraunhofer IWES´ test benches

## Validation and verification have long been, and will continue to be, essential components of wind turbine development.




The CureMonitor device sends a message once the resin is fully cured

in 2019 and is equipped with multiple test benches for Highly Accelerated Lifetime Testing (HALT) of pitch bearings, with the BEAT 6.1 (Bearing Endurance and Acceptance Test) at the core of the facility. The highly versatile BEAT 6.1 can test pitch bearings up to six meters in diameter and employs sophisticated adapters to emulate the surrounding stiffness, along with a hexapod load application system to apply both static and dynamic loads in six degrees of freedom. In-house methods for modeling, adapter design and test program development ensure realistic test conditions to validate the robustness of pitch bearing designs against various failure modes.

Building on the experience gained from over 500 tested bearings in both full-scale campaigns and small-scale fundamental research, the LBL team has developed advanced testing and scaling approaches that support the optimization of pitch bearing operation and maintenance.

Selecting the appropriate lubricant for a pitch bearing is critical for ensuring reliable operation under harsh and demanding conditions. High loads, oscillating movements, site-specific environmental factors and turbine control strategies all influence the risk of premature wear.

LBL integrates all these parameters to design test programs that determine the optimal lubrication strategy for each application, ensuring dependable performance. In-house scaling methods, applied using test rigs such as the BEAT 1.1, allow this challenge to be addressed in a cost-efficient manner with rapid lead times, while still providing results that can be reliably transferred to real-world operation.

The insights gained from extensive testing of both full-scale and scaled pitch bearings at the LBL have led to the creation of a comprehensive database of sensor signals, as well as advanced models and modeling methods that capture the complex behavior of pitch bearings.

Ongoing test activities support the development of in-house monitoring solutions and can also be used to evaluate and validate existing technologies. These efforts enable the reliable detection of early signs of damage and support predictive maintenance strategies to ensure long-term bearing performance.

### Summary

Validation and verification have long been, and will continue to be, essential components of wind turbine development. Fraunhofer IWES is well prepared and equipped to support the ongoing advancement of wind turbines through comprehensive validation testing.

As the number of turbines in operation continues to grow, issues related to operation, maintenance, and repair are becoming increasingly important. Many of these questions can also be addressed effectively through laboratory testing.

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