Applying step heating thermography to wind turbine rotor blades as a non-destructive testing method

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Abstract

Structural flaws in wind turbine rotor blades cause serious accidents with personal injuries and damage to property. Hence economic and legislative demands for regular inspections need to be met by wind park operators.
Several methods for non-destructive testing exist, but are not applicable due to the large dimensions of wind power plants. As a consequence, those inspections are usually carried out manually by industrial climbers. Contact free on-site testing methods provide a promising outlook for minimizing the required maintenance efforts.
The kEFIR research project examines in how far active thermography is an appropriate technique to analyse the inner structural features of rotor blades. The particular focus of this paper lies on the sun as a heat source for step heating thermography.

1. Introduction

Modern wind turbine rotor blades have large dimensions. Rotor diameters in excess of 150 m are not rare [1]. Because of the large sizes, the forces acting on these blades are enormous. Additionally, the harsh environmental circumstances the blades are exposed to can lead to material fatigue. Over time, small defects are likely to grow in size and eventually cause the destruction of the whole plant. Damage in the rotor blade structure cannot always be detected with the available tools.
Some testing methods and tools exist to detect damage inside a rotor blade, but are not practicable in field. These includes acoustic emission [2], ultrasonic [2] and a combination of ultrasound and thermography [3].
In the previously published paper by Fey et al [4] the possibilities of active thermography without the need of a technical heating equipment is presented. Based on the basic setup presented there, this study focuses on comparing the effects of excitation by the sun with those of excitation by IR lamps.

2. Experimental Setup

Two testing setups were used for generating the heat step needed for the method described in Fey et al [4]. The first setup was built in the laboratory, using IR lamps to simulate the sun. The second setup transfers the general method to the outside world, using the sun as a heat source, as described in [9]. In both setups, the method was not applied to a whole rotor blade, but to a smaller test specimen cut from a

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decommissioned rotor blade. A second specimen was only tested in the laboratory setup so far, but provided different types of anomalies to look at.
In both cases the regular test procedure is to heat up one side with infrared radiation as homogenous as possible for 30 minutes and then end the irradiation, leading to a reversal of the heat flow and a cooling down of the specimen.
Step heating active thermography of glass fibre parts was done before, as for example shown in [9]. While outside experiments with rotor blades or test specimen are also documented, as for example in [10], those do not use active step heating using the sun.

3. Damage Types

Since wind turbine rotor blades are a composition of materials with widely different properties, damage can occur in diverse forms and be caused by multiple reasons. Some research groups [2, 6, 7] have taken on the objective of categorising those damage types. A summary of these groups' work is presented in Ciang et al [5]. Through talks with plant engineers and operators as well as through the investigation of different rotor blades, additional damage types were defined within this project.
The first of these newly defined damage types is the absence of material in places where it is intended to be. One example of this is the application of too little adhesive during manufacturing. This obviously weakens the joint between the two half shells.
The second newly defined form of damage is foreign material in the rotor blade. Apart from the possibility of excessive glue application, the manufacturing process is not a closed procedure, so it is possible for objects, such as tools, to unintentionally get enclosed inside the blade.

Table 1. Damage types

Type	Specifications	Source
1	Debonding in the adhesive layer joining skin and main spar flanges	**[5]**
2	Adhesive joint failure at the up- and downwind skins along leading and/or trailing edges	**[5]**
3	Debonding at the interface between face and core in sandwich panels in skins and main spar web	**[5]**
4	Internal damage formation and growth in laminates in skin and/or main spar flanges.	**[5]**
5	Splitting and fracture of separate fibres in laminates of the skin and main spar	**[5]**
6	Buckling of the skin due to damage formation and growth in the bond between skin and main spar under compressive load	**[5]**
7	Formation and growth of cracks in the gel-coat; debonding of the gel-coat from the skin	**[5]**
8	Absence of material	new
9	Foreign material inside the rotor blade	new

The separation of types 1 to 4 (Table 1), all of which are either failures of the adhesive joint or delaminations, makes sense from a systemic point of view, because their effects on the robustness of the blade as well as their origins differ a lot. On the other hand, in the context of infrared imaging, the damage types are very similar. In all cases, there is a separation of different layers of material, effectively insulating the inner parts. The material composition and thickness above of the faults will differ, though, due to different locations in the blade.

4. Description of Test Specimens

The Ruhr West University of Applied Sciences has two pieces of one rotor blade. One is a part cut from the outer third of a decommissioned rotor blade, designated HRW 00, that was already used in [4] and [8]. The other is the recently acquired tip cut from the same rotor blade, designated HRW 01. All structural features existing in the other sample piece HRW 00 are also present in the wingtip, but at a smaller scale. The very end of the Blade is not made of glass fibre, but consists of a metal tip attached to the rest of the tip. Therefore, the structures of spar caps are joined by a perpendicular wall in the middle of the specimen. The structure between this wall and the metal tip is still unknown and will have to be examined with an endoscope.
Both specimens show some, but not all types of anomalies mentioned in 3. During previous studies, some artificial anomalies were added along the existing non-artificial damage to test specific methods.

4.1 Rotor Blade Specimen HRW 00

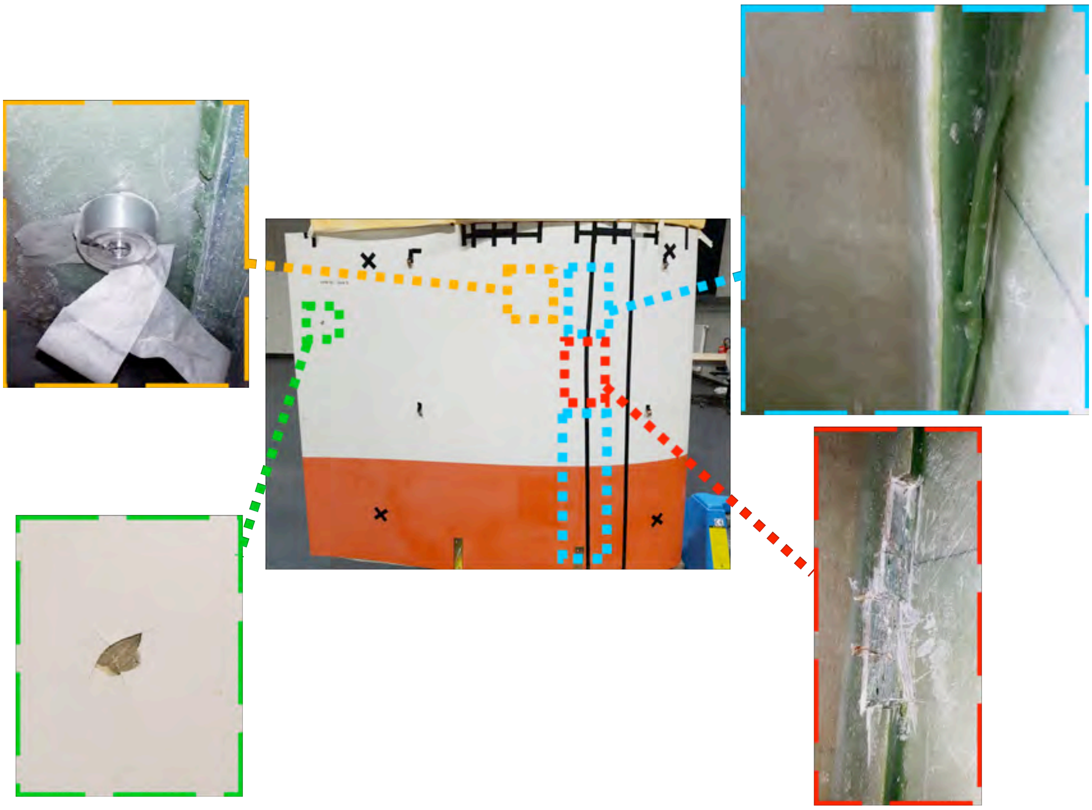

Figure 1. Anomalies of rotor blade specimen HRW 00: Green: Chip in the gel coat; Blue: Unbonded adhesive joint; Orange: Aluminium cylinder; Red: Removed material

All damage documented in specimen HRW 00 so far is marked in Fig. 1. A non-artificial damage is a chip in the gel-coat, marked in green. Beside this chip, a gap in the adhesive layer between the front spar cap and the shear web, marked in blue, was identified as a second non-artificial anomaly. The unbonded area starts a few centimetres below the outer cutting edge of the specimen. While it can be expected to show thermal behaviour similar to a failure of the adhesive joint (Table 1, type 1), it is a case of absent material (Table 1, type 8).
Two artificial anomalies were added during earlier experiments, a glued in aluminium cylinder, marked in orange, and an area of removed glue at the joint of the front spar cap and shear web, marked in red. Their exact specifications are described in Fey et al [4].

4.2 Rotor Blade Specimen HRW 01

A non-artificial adhesive joint failure is located at the trailing edge of this specimen (Fig. 2). This large failure of the adhesive joint is accompanied by additional damage, such as local delaminations, cracks and chips of the gel-coat, which are not individually addressed.

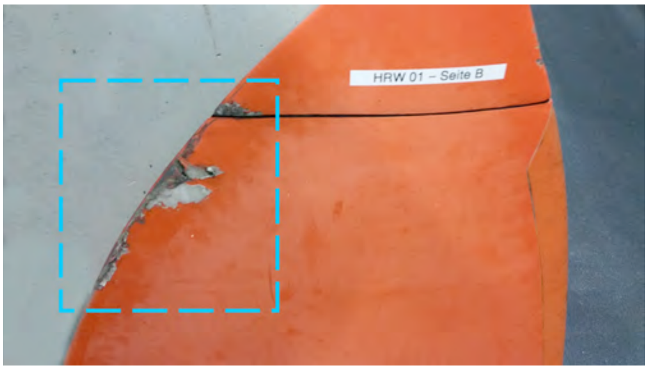

Figure 2. HRW 01. Blue: Failure of the trailing edge joint

Figure 3. HRW 01. Blue: Foreign objects; Orange: Excess glue

A look at the inside of the specimen reveals the rough processing of the adhesive joint in the wingtip. This is due to technical difficulties during the manufacturing process and can to some degree be expected in every rotor blade. A few centimetres above the

cutting edge of the wingtip, some foreign objects were attached to the blade's inner side during earlier experiments:
Three pieces of glue from the adhesive joint of the rotor blade that were found in the specimen were glued to the inside of the shell. Further out, two metal rings of different diameter were also glued in, with an additional drop of glue left between them. A metal bracket was screwed in, positioned so only its tip is in contact with the inner surface of the shell. Both areas are marked in Fig. 3.

While some anomalies are indicators of damage or structural weaknesses, others can be intended to be a part of the blade. An example for that is the water outlet shown in Fig. 4. This water outlet is situated a few centimetres from the metal end of the tip.

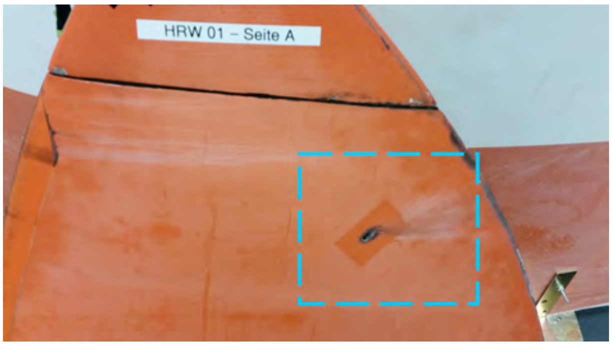

Figure 4. HRW 01. Water outlet

5. Results

To achieve comparable results, the same specimen HRW 00 was recorded in outside experiments using the sun as well as laboratory experiments using IR lamps for excitation. This particular specimen is riddled with anomalies, so a number of different kinds could be imaged with both excitation sources.
Additionally, laboratory experiments were conducted with a second piece of the same rotor blade, HRW 01.

5.1 Visible Features of Specimen HRW 00

The first visible feature is the aluminium cylinder glued to the inside of the back spar cap (Fig. 5, marked in blue). It is clearly visible in both the laboratory and the outside test, even though it is mounted behind the 20mm thick layer of glass fibre composite. Its diameter in the infrared image appears smaller than its physical diameter due to lateral heat diffusion, but equally so for both setups.
Also clearly visible are the large unbonded areas of the front spar adhesive joint (multiple areas marked in red). Their visibility differs slightly in the outside tests, with better results for the orange painted areas of the wing surface. Again, the depictions of the glue joints are slightly smaller than the actual structures due to diffusion, but the form and appearance (straight edges for the well-made back spar, marked in light blue, wavy edges on the faulty front spar) is well preserved.
The sawed-out part of the glue joint is visible as well, with the same side effects as the original areas of missing glue.

Two warmer areas of unknown origin are visible in both test setups (marked in yellow). While it can be assumed that they might be areas of overlapping fibre mat pieces, only destructive testing will provide conclusive evidence. As further non-destructive testing of the specimen is planned, this was postponed.
Only visible in the outside test is the transition from the orange painted surface area to the white area (marked in purple). A dependency on the spectrum of the excitation light source can be suspected, but must be clarified by further specific tests.

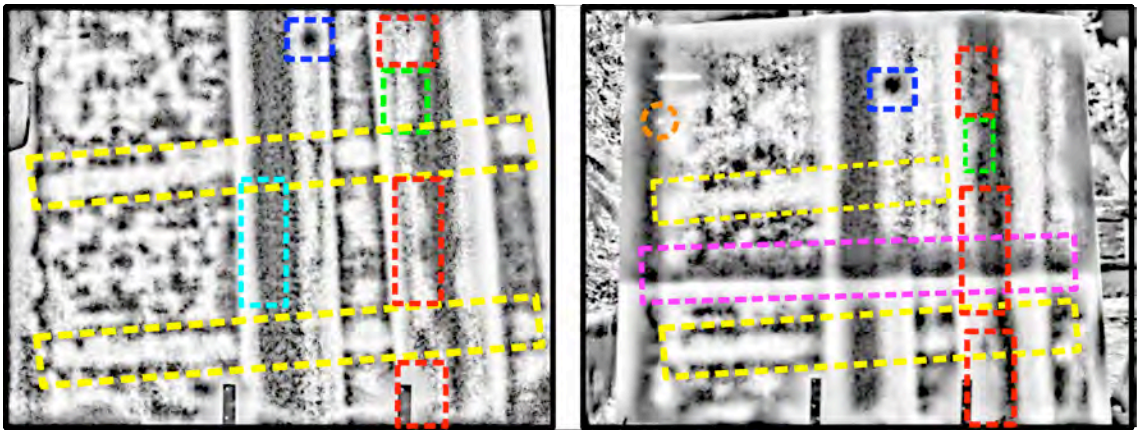

Figure 5. Visible features of specimen HRW 00 in the laboratory setup (left) and in an outside test (right). Blue: Aluminium cylinder; Red: Unbonded glue joint; Light blue: Intact glue joint; Green: Sawed-out material; Yellow: Unknown subsurface structure; Purple: Edge of the orange safety marking; Orange circle: Gel-coat chip. Image processing was applied.

As well as the transition of orange and white paint, the small chip in the gel-coat (marked in orange), could only be detected outside with this type of setup. Therefore, a new experiment with different setup parameters was performed. In this new setup, just one IR-Lamp was used to apply a short, intense heat pulse to a small area. The thin layer of debonded material reacts very quickly and intensely to applied heat. In addition, it rapidly cools when the heat flow is turned off. Pictures taken immediately after the short heating period expose those areas with high contrast. With a short heating period and little time for lateral heat diffusion, the image is very sharp but only shows structures close to the surface. Those same conditions also expose a rhombic pattern that can be attributed to the weaving of the outermost glass fibre mat layer. Fig. 6 shows a close up of the chip and surrounding area.

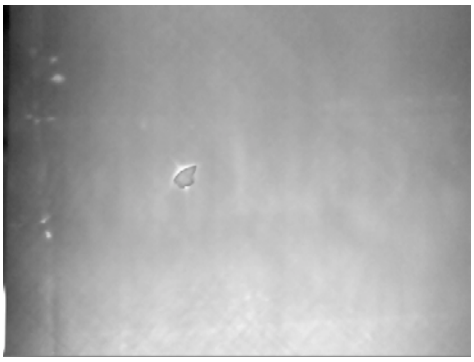

Figure 6. HRW 00. Effects of a short heat pulse

5.2 Visible Features of Specimen HRW 01

Specimen HRW 01 was only tested in the lab, as bad weather prohibited outside tests so far.

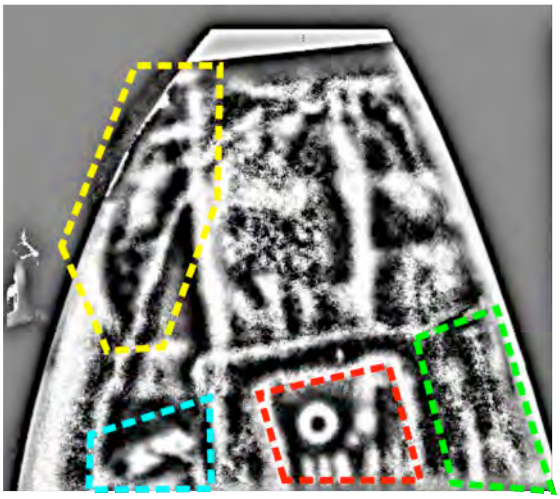

Figure 7. Visible features of HRW 01. Red: Foreign objects; Green: Excess glue; Light blue: Thicker material at the edge of the core material; Yellow: Adhesive joint failure at trailing edge. Image processing was applied.

Clearly visible in direct observation as well as the thermal images, is the failed glue joint at the trailing edge (Fig. 7, marked in yellow). The failure is visible as a dark area and clearly structured. This structure could be confirmed with a thin metal probe: Part of the failure (the lower part in Fig. 7) can be probed to the inside, while other areas (the middle part in Fig. 7) are blocked after a short distance.

Interestingly, the green marked area of the adhesive joint and excess glue is indistinguishable from other, not obviously structured areas.

In contrast to this, the picture allows a clean view on every single object attached to the inside of the specimen (area marked in red), even the thin drop of glue.

The intense anomaly between the back spar and the trailing edge (marked in blue) appears to be a thicker area of fibre mats and glue at the transition from the core material to a thinner, fibre reinforces plastic only shell at the outer tip. As with the unknown anomalies in HRW 00, this will have to be examined destructively after non-destructive testing has been finished.

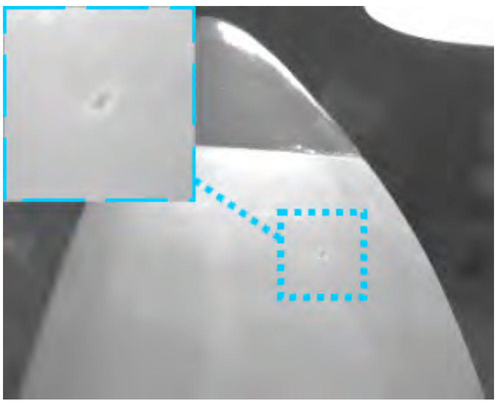

Figure 8. HRW 01. Water outlet

Like explained in 4.2, not every irregular structure in the rotor blade, necessarily has to be damage. Some of those structures are just architectural features of the wind turbine. This includes the water outlet shown in Fig. 8

6. Conclusion

Step heating thermography using the sun as heat source seems to be an applicable method for analysing the condition of wind turbine rotor blades. Inner structural features such as spar elements, artificial and non-artificial anomalies became visible during the phase of down cooling. The findings largely correspond to those from earlier laboratory set-ups.

One major difference though, is that surface features, such as orange visibility markings and chipping of the gel-coat stay visible during the phase of down-cooling in the outside experiment. This effect could not be reproduced in the laboratory experiments. As these features are recognisable in the visible light spectrum, further research on the possible cause of this difference was postponed.

At this point in time, there is one set of features that could not be shown using only the sun. In the laboratory setup, strong, short heating pulses showed the structure of the gel coat in very fine detail. As this structure was imprinted by the fibre mats, it allows a look at what the outermost fibre layer looked like during production. With the slow movement of wind turbines (or even moving the specimen by hand to turn it around), lateral heat diffusion has long erased the visible effects of those structures by the time the camera looks at them.

Ongoing research is directed at proving the viability of this method for varying environmental conditions. Making damage visible when the rotor blade is exposed to differing sun intensities at different wind speeds is one of the next steps in the development of a robust basic tool set for a cost-efficient specialist-operated on-site testing system for wind turbine rotor blades. A classification of possible procedural errors and their occurrence in the thermal response is part of a larger project, which is intended to eventually create a data driven automated damage detection.

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References and footnotes

[1] Wind Turbines - senvion.com. [Online]. Available: https://www.senvion.com/global/en/wind-energy-solutions/windturbines/. [Accessed: 08-May-2017].

[2] B F Sørensen et al 2002, "Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades - a Preproject" Ris-R-1336(EN) Ris National Laboratory, Roskilde, Denmark

[3] G. Walle et al, "Defect indications in sono-thermography in relation to defect location and structure", 2004 Quantitative InfraRed Thermography

[4] J. Fey et al, “Active Thermographic Structural Feature Inspection of Wind-Turbine Rotor” (2017) In: Far East Non-destructive testing conference, June 22-24, 2017, Xi’an, China

[5] C. C. Ciang, J.-R. Lee, and H.-J. Bang, “Structural health monitoring for a wind turbine system: a review of damage detection methods,” Measurement Science and Technology, vol. 19, no. 12, p. 122001, Dec. 2008.

[6] Sørensen, “Improved design of large wind turbine blade of fibre composites based on studies of scale effects (Phase 1) - Summary Report.” Sep-2004.

[7] M. J. Sundaresan, “Structural Health Monitoring Static Test of a Wind Turbine Blade.” National Renewable Energy Laboratory, Aug-1999.

[8] Schwahlen et al, “Increasing Economic Viability and Safety Through Structural Health Monitoring of Wind Turbines”, submitted to: 5th Annual IEEE Conference on Technologies for Sustainability, November 12-14, 2017

[9] T. Worzewski et al, “Thermographic inspection of a wind turbine rotor blade segment utilizing natural conditions as excitation source, Part I: Solar excitation for detecting deep structures in GFRP”, Infrared Physics & Technology 76 (2016), 756-766

[10] T. Worzewski, R. Krankenhagen, M. Doroshtnasir, “Thermographic inspection of wind turbine rotor blade segment utilizing natural conditions as excitation source, part II: The effect of climatic conditions on thermographic inspections – A long term outdoor experiment“, Infrared Physics & Technology 76 (2016), 767-776