Active Thermographic Structural Feature Inspection of Wind-Turbine Rotor

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Abstract: Checking wind turbines for damage is a common problem for operators of wind parks, as regular inspections are legally required in many countries and prevention is economically viable. While some of the common forms of damage are easily visible on the surface, structural problems can remain invisible for years before they eventually result in catastrophic failure of a rotor blade. Common forms of testing fibre composite parts like ultrasonic testing or X-ray tests are impractical due to the large dimensions of wind turbine components and their limited accessibility for any short-range methods.

Active thermographic inspection of wind turbines is a promising approach to testing for structural flaws beneath the surface of rotor blades. As part of an ongoing research project, a setup for testing the general viability of this method was built and used to compare different thermographic cameras. A sample cut from a discarded rotor blade was modified to emulate structural damage.

The results are promising for the development of a cost effective on-site testing system.

Keywords: Non-destructive testing; Composite materials; Condition monitoring; Infrared imaging

1 Introduction

1.1 Motivation

The forces acting on wind turbines are usually high. Modern wind turbines can have rotor diameters in excess of 150 meters [7]. Harsh environmental circumstances can cause damage to the structure, which can not always be detected with the tools available.

Although several testing methods and tools to detect damage inside a rotor blade exist for the production state, those are not practicable for plants already in operation. In practice the most common form of inspection is a visual, haptic and acoustic examination of the blade by industrial climbers. This method is time intensive, unrewarding, inaccurate and dangerous to perform. Therefore damage is often not found and as a result preventable accidents occur. Realistic a detailed statistic about accidents regarding wind farms are not available because accidents do not have to be reported to anyone if they occur on private property. A private collection of accident reports is provided by the Caithness Windfarm Information Forum [1], which is a community of wind energy critics.

The active thermographic method introduced in this paper should provide an alternative without the negative points from the other methods and show a way to realize a more reliable, less time intensive, rewarding, accurate and safe option for detecting damage inside a wind turbine rotor blade.

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1.2 Rotor Blade Topology

The used sample piece was cut from a decommissioned, damaged set of rotor blades from an old unit of unknown type. The rotor diameter was determined to be roughly 30m.

In general, the rotor blades of a wind turbine are comparable to large airplane wings made of fiber composite material [2]. Ignoring the root and tip areas, much of the blades is built as a hollow tube strengthened by one or more spars running along the length.

The cross section of the used sample piece (Fig. 1) is representative along most of the rotor blade it was cut from. It uses two separate spars. Each of those is made of two high density fiber composite spar caps joined by shear webs consisting of fiber composite and wood. The outer shell consists of three relevant layers. The first and third layer are fiber-mat based. The mid layer is composed of wood and the spar caps. As an oddity of this specific sample, the spar caps have rather irregular cross sections and are matched to the wooden cores with some kind of light grey filler material.

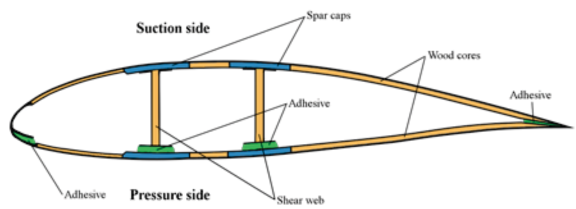

Figure 1. Schematic cross section of the sample piece

The whole rotor blade is built from two half-shells, which are laminated in open molds during production and glued together while still in their molds. The resulting seams are a natural weakness of any composite wing structure, as they are unreachable during the bonding process and hard to test afterward.

In the case of the used sample piece, the leading edge seam is on the pressure side of the blade, while the trailing edge seam is approximately symmetrical. The shear webs are build into the suction side shell. The joint at the pressure side, a thick seam of adhesive, is between the spar cap and the shear web.

1.3 Active Thermographic Inspection

Thermographic inspection in general shows the temperatures at the surface of a structure. While that information is enough to detect problems in some common cases like the inspection of electrical installations or building insulation, the rotor blades of wind turbines do not, in general, heat up on their own. The resulting thermal image of their surface is more or less featureless in normal operating conditions.

To make internal structures visible on the surface, heat flow has to be stimulated from some external heat source. This approach of active thermography has been used in different areas [5], expanding to less heat-conductive materials [4], and looks promising for the inspection of rotor blades. A number of heat sources are easily available outside, like the change of air temperature over time, the sun [3] or heat from aerodynamic friction [6].

2 Experimental Setup

To get a more systematic approach on finding the right conditions for imaging of deeper structures in a rotor blade, a laboratory setup was built. It allows to test different thermal cameras under variable and reproducible thermal conditions.

2.1 Camera Comparison

Different IR-cameras exist on the market, which are potentially suitable for active thermographic inspection of wind turbine rotor blades. At first basic information was gathered and is shown in table (Tab. 1) The theory that Mid-wavelength infrared (MWIR) and Long-wavelength infrared (LWIR) differ in the aspect of detecting structural damage inside a rotor blade was postulated. To verify this theory LWIR and MWIR cameras were compared, but because of the poor availability of MWIR cameras, only the A6700sc was included in the study.

Table 1. Thermographic Cameras; Data From The Respective Data-Sheets

Name	*Picture resolution*	*NETD*	*Dimensions L*W*H mm*
FLIR T1030sc	1024x768	20mK	167x205x188
FLIR A655sc	640x480	30mK	216x73x75
FLIR T365	320x240	50mK	106x201x125
FLIR A6700sc	640x512	20mK	216x102x109
Optris Pi 450	382x288	40mK	46x56x90
Gobi 640 Gige	640x480	50mK	49x49x79
Varioscan 3021	360x240	30mK	not specified

2.2 Specimen

The size of wind turbine components does not allow testing a full blade in a laboratory test. Therefore, the specimen piece shown in Fig. 2 was used. It shows little damage on the outside. At one position a slit-off with nearly 2cm in diameter exist but the GFRP layers beneath are not affected. The inside surface of the blade shows no obvious anomalies.

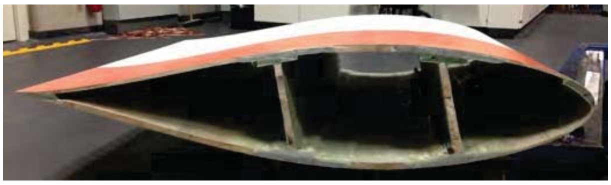

Figure 2. Cross section of the sample, the pressure side is up. The spar caps

In order to create damage and anomalies that are invisible from the outside but can hopefully be detected in a thermographic image, a 20cm long and 3cm wide part was cut off the adhesive joint between the shear web and the spar cap. Such a lack of material can realistically happen within the manufacturing process of the blade and weakens the connection of the spar. The area in which the damage was created was marked on the outside with adhesive tape and plastic marks.

On the other hand adhesive that was added in excess can form big chunks of lose material that break out and crash against the hull while the rotors are spinning. To proof the visibility of displaced material chunks a block of aluminum was glued on the inside of the blade. To reseal the volume of the blade, the cut surfaces were sealed with insulating foam. This should restore the insulation between the outside and the air volume inside the blade.

2.3 Heating method

In order to generate a thermal image of the internal structure on the surface, heat flow either into or out of the sample must be induced. After an initial literature research, step heating active thermography [8] was chosen as the most promising method.

Figure 3. Overview of the experimental setup

To create a step in the heat energy insertion the specimen was first heated up with a heat source and then the heat source was turned off (Fig. 3). On a full size rotor blade that is installed onto a wind turbine the preferred way to heat up the material is the radiation of the sun. Therefore, the setup is constructed to simulate this heating method. The sun emits infrared radiation, which heats up the rotor blade directly. The infrared radiation is also emitted by IR-Lamps. The distance between the lamps and the rotor blades surface can be freely chosen.

The pressure side features the spar joints and is generally more interesting. The specific distance was chosen to obtain sensibly short heating times. On-site heating times will depend on the available solar irradiation.

The cooling phase is very easy to implement in the laboratory where full control over the heat source is given. When using the sun outdoors, the only option suitable conditions can be archived is by rotating the blade's side of interest away from the sun. To simulate such behavior in the test the heating source was not disabled, but turned around to face the suction side.

3 Results

During the experiments, heating times as well as the observation period during the cooling process were varied. Different cameras were used for direct comparison. Because the cameras needed to be borrowed from the manufacturer not every one of them was available at the same time. That resulted in images, which are taken from the same perspective but not at the same time.

Best results were archived with longer up-heating periods between 60 and 120 minutes. Fig. 4 to Fig. 7 show a whole course of up-heating and cooling.

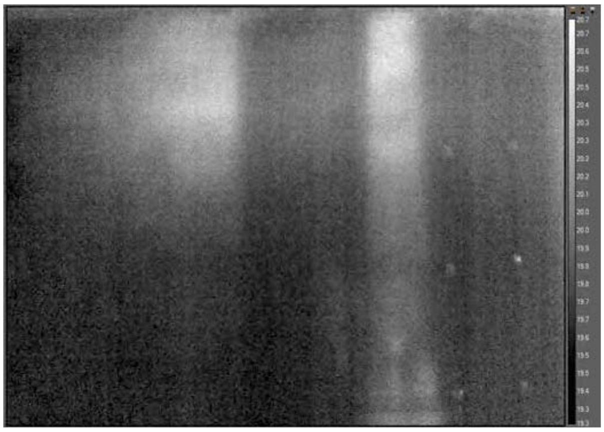

Figure 4. The blade front before heat source was activated

As can be seen in Fig. 4, some structural features of the rotor blade already become visible from the slow heating up of the room. If the blade is exposed to an infrared radiator, the contrast increases and additional features are unveiled. In Fig. 5, taken after 10 minutes, the wooden cores can be identified along with some horizontal lines, which most likely are overlapping fiber-mats.

Figure 5. Heating up the blade

At the beginning of the cooling process, the temperature is almost homogeneously distributed over the whole surface (Fig. 6). Afterward the image shows cool areas that are located where the wooden plates are and hot areas that appear where only fiber composite is located.

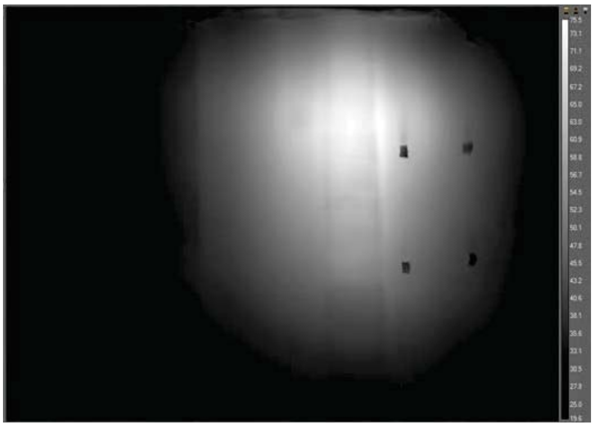

Figure 6. Begin of cooling process

At the end of the observation period, after about 1 hour of cooling, the initially cooler areas show little contrast while the hot areas have split up into regions, which adapted their temperature differently. Those areas correspond to the structural density of the rotor blade. At the location of the aluminum block, the surface temperature clearly differs from the surrounding area (Fig. 7 ROI 1). The effects of the damaged adhesive joint are less dominant but an anomaly can be seen exactly at its position (Fig. 7 ROI 2).

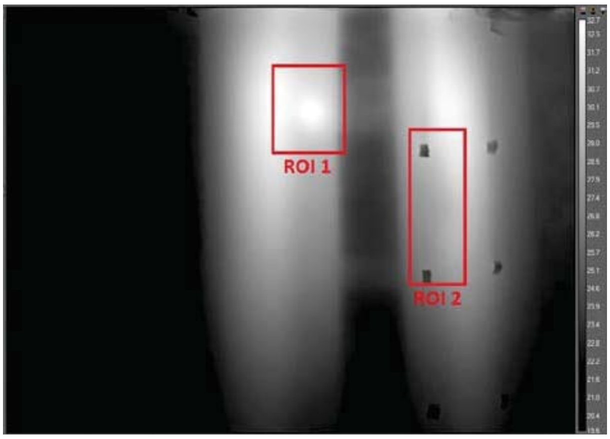

Figure 7. End of the cooling process

Variation of the heating interval has shown that the final results depend on the parameters chosen for heating up the blade. Due to the low thermal conductivity of the materials in the rotor blade, the inner parts of the structure take a long time to heat up. Short heating periods do not completely heat-up the inner parts with a high heat capacity. During the cooling phase, heat from the outer parts is conducted into those still cold structures. Consequently, the temperature contrast is decreased or even inverted compared to longer heating periods. This effect is shown in Fig. 8.

Figure 8. Heating over shorter time

On the other hand, very short heating intervals of less than 1 minute expose structural features right below the surface in fine detail. Fig. 9 and Fig. 10 show this effect. Being taken after an up-heating period of 10-20 seconds, both pictures clearly show structure of the fiber-mats right below the gel coat. On both pictures, the mats are clearly visible in form lines with a course of 45° angle. These are not detectable on the surface by the naked eye. There is also a big horizontal line in both pictures. This big line is probably an area of two overlapping fiber-mats. However, more research needs to be done to clearly classify such structures in the outer layers of the blade and how they can be used for early damage recognition.

The pictures were taken with the Flir A655sc (LWIR) and the Flir A6700sc (MWIR). They show the same region of the blade but were not recorded simultaneously, as the two cameras were not available at the same time. Images from other tests also show comparable results between the two spectral ranges. The thermal sensitivity of the cameras is also of little relevance to the results of this method. The critical areas on the surface were several hundred mK in difference and sometimes far greater than 1 K. Compared to the thermal sensitivity the pixel resolution of the camera is the more important factor, because the higher resolution allows a better detection of small failures in the large blades. Even with significantly worse thermal sensitivity, the same structures can be detected if the picture resolution is high enough.

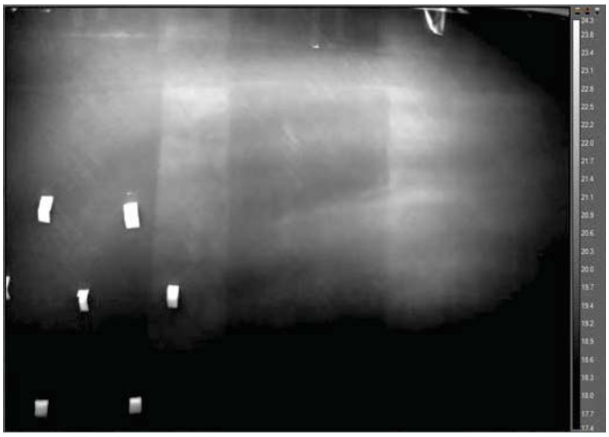

Figure 9. Very short heating, A655sc

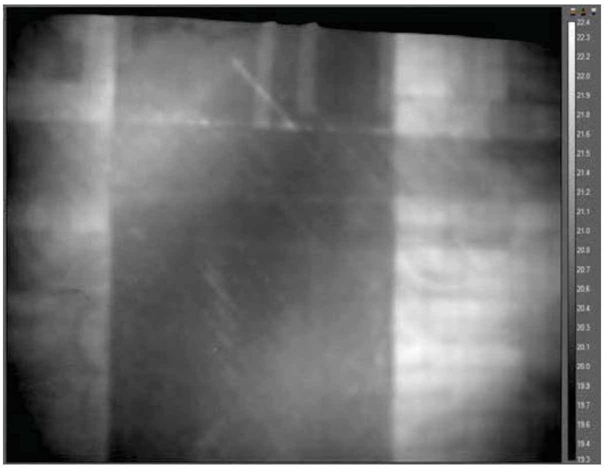

Figure 10. Very short heating, A6700sc

Another interesting part of the blade that can be investigated with very short heating times is at the trailing edge. These joints can be seen with less effort as the joints in the middle because the blade is far less thick in these areas.

Figure 11. Glue under the surface

4 Conclusion

The study shows that active thermography is a promising approach to achieving a practicable and reliable way of detecting damage inside a wind turbine rotor blade. The laboratory setup suggests that same results can be achieved on-site by using the sun as the only heating source, which is to prove in further tests. The theory that Mid-wavelength infrared and Long-wavelength infrared differ in the aspect of detecting structural damage inside a rotor blade was disproved. In addition, the difference in thermal sensitivity between the tested cameras was proven irrelevant.

It was also confirmed that there is an increasing blur depending on how deep the structure lies under the surface and the details are just visible for a short amount of time and just right below the surface. This knowledge can be used to design individual test scenarios for each rotor blade type, depending on the structure elements to be investigated.

Future work is aimed at refining the existing methods and validating them in the field.

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