

COMPARISON OF MOBILE NONDESTRUCTIVE TESTING METHODS TO DETECT IMPACT DAMAGES IN FIBER REINFORCED PLASTICS

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Abstract. This paper evaluates and compares the application of current methods and the new method local acoustic resonance spectroscopy for nondestructive evaluation of damages in glass fiber reinforced plastics. Generic plates of a standardized material (Vetronit EGS 619), and segments of rotor blades of wind turbines were tested. The generic specimens, 2 mm and 6 mm in thickness, were damaged with various impact energies and a spherical impactor with a diameter of 16 mm, which generated impact damages ranging from barely visible to clearly visible. The impacts have been measured to account for damage diameter, form and area, indentation-depth and bulge height. In addition, blind holes of different depths have been drilled to assess the depth of penetration of the methods tested.

As observed in scientific literature, as well as in the current research, impact damages exhibit a peanut-shaped damage area, when impacted with minimum threshold energy. The current research tested several of the specimens using X-Ray computed tomography as a reference measurement. These results were compared to the data obtained by ultrasonic methods, local acoustic resonance spectroscopy and optical lock-in thermography. Finally, all methods have been applied to evaluate rotor blades of wind turbines. The results are discussed in respect to practical applications and accuracy.

1 Experimental Setup

1.1 Description of Impact Test Rig and Specimens

To ensure reproducibility, the studies were executed with a standardized material of woven glass fiber reinforced polymers (Vetronit EGS 619). This high pressure laminate consists of warps and wefts with a ratio of 17 to 8 in an epoxy matrix. Reference plates with blind holes with a diameter of three and five millimeters were generated. The purpose of the blind holes was to have a reference boundary layer in a defined depth to examine the penetration of different NDT methods.



Impact damages were generated by an impact tower which releases a weight onto the specimens. The shape of the chosen impactor was circular with a diameter of 16 mm. The impact energy was controlled by a position sensor placed next to the fall line, giving an analogue tension output which was digitalized using a sample frequency of approximately 2 kHz, and was analysed to determine the speed at the time the impactor hit the surface representing the impact energy. Low velocity damage mechanisms can be assumed as the velocity was below 5 m/s at all times.

1.2 Description of impact damage

The four modes of failure postulated by Richardson [1] were observed. Low impact energies left a round indentation in the specimens. This indentation was displayed by blurring of the material and is described by the first mode of failure as “matrix mode”. The specimens with 2 mm thickness start to develop peanut shaped damage characteristics at an impact energy of approximately 8 J (Figure 1). The name peanut shape refers to the form of the damage and was introduced by Liu [2] and other authors [3]. Peanut defects include both delamination and fiber breaks as seen in the computed tomography images. For the specimens with 6 mm thickness, this characteristic is not as pronounced as for the thinner specimens. Bigger deteriorations can be observed at approximately 80 J. The material described here is relatively resistant to delamination caused by impact, as opposed to the results presented by Chong [4]. Figure 1 illustrates the results for impacts on plates with a thickness of 2 and 6 mm.

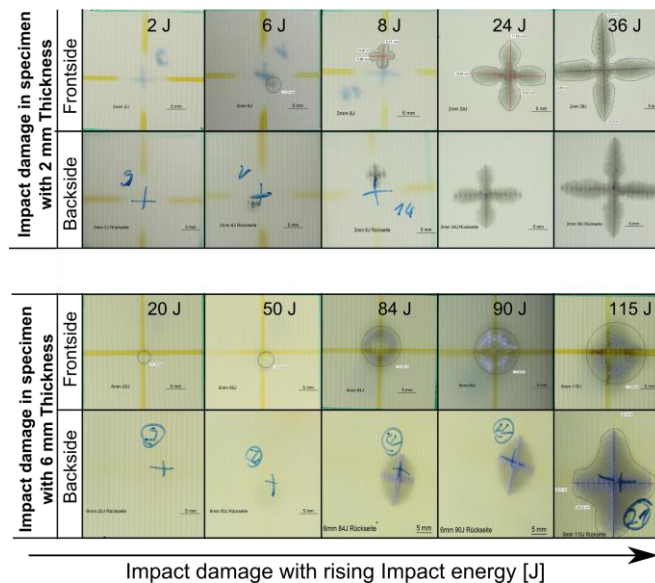


Figure 1: Photos of impacts in specimens of 2 and 6 mm thickness

1.3 Local Acoustic Resonance Spectroscopy (LARS)

The LARS was executed using a miniature impact hammer with a sensitivity of 22.7 mV/N. In order to record the acoustic signals, a half inch free-field microphone with a frequency response of 3.15 Hz to 20 kHz of ± 2.0 dB was used. The analogue-to-digital converter RME ADI 2 transformed the signals of the microphone and the signals of the force sensor with a sampling rate of 90 kHz to be further processed. The data was analysed with a self-written MATLAB code determining the full width at half maximum and characteristics of the acoustic spectrum. Jüngert [5-7] introduced the LARS technique and examined applications on wind turbine rotor blades. The LARS technique is a further development of the well-known “tap testing” to a technique suitable for automation and

unmanned inspection. A portable test hammer apparatus to make traditional “tap testing” more reliable has already been invented and patented by Bruce Pfund [8]. The LARS technique is suitable and was tested in this article in particular to detect delamination with a larger extension on widespread areas.

1.4 Ultrasound (UT)

Ultrasound inspections were done using a mobile ultrasound echo device with a single test probe and phased array techniques. Probes with center frequencies ranging from 2.5 MHz to 5 MHz were used. Ultrasound testing has been utilized in various applications in civil and mechanical engineering, medicine and other areas [9]. The method was developed over more than 60 years, and optimized test systems are available. Current research investigates air coupling [10, 11], phased array [12, 13] and automated applications.

1.5 Optical Lock-in Thermography (OLT)

OLT techniques were applied using a standard microbolometer based uncooled infrared camera together with the lock-in system developed by the company Edevis and 2 kW spotlights. Thermography typically provides good results for shallow depths or on thermoconductive materials such as carbon fiber reinforced polymers.

2 Results

2.1 Evaluation of Impact Damages Using Local Acoustic Resonance Spectroscopy

During inspection, signal differences caused by the three different thicknesses of the specimens were perceived. The thinner plates generated a lower and bumper sound when excited with the hammer, while the thicker plates generated a sharper and higher tone. The technical characteristics of the sound of the hammer excitation were also different on the three thicknesses. Jüngert [5, 6] uses the shift of the acoustic spectrum to display different characteristics of the specimen. Additionally to the sound, the LARS analyses the force excitation of the hammer. The thinner plates yield a bigger full width at half maximum of the force excitation and, consequently, a lower maximum force, whereas the thicker plates yield a smaller full width at half maximum and a higher maximum force. The mean value of the normalized force excitation of five measures on 2 mm thick specimen yielded 79.2 μs , on 6 mm thick specimen 62.5 μs and on 11 mm thick specimen 43.73 μs . In this study, there were five hammer taps on flawed spots and five hammer taps on intact spots. As illustrated in Figure 2, the results show that there is a difference in the full width at half maximum of the force excitations. The results are illustrated in a color scheme: Blue tones stand for a small full width at half maximum value, a sharp and narrow force excitation signal and therefore for an intact spot. Red and yellow tones stand for a high full width at half maximum value and therefore for flawed spots.

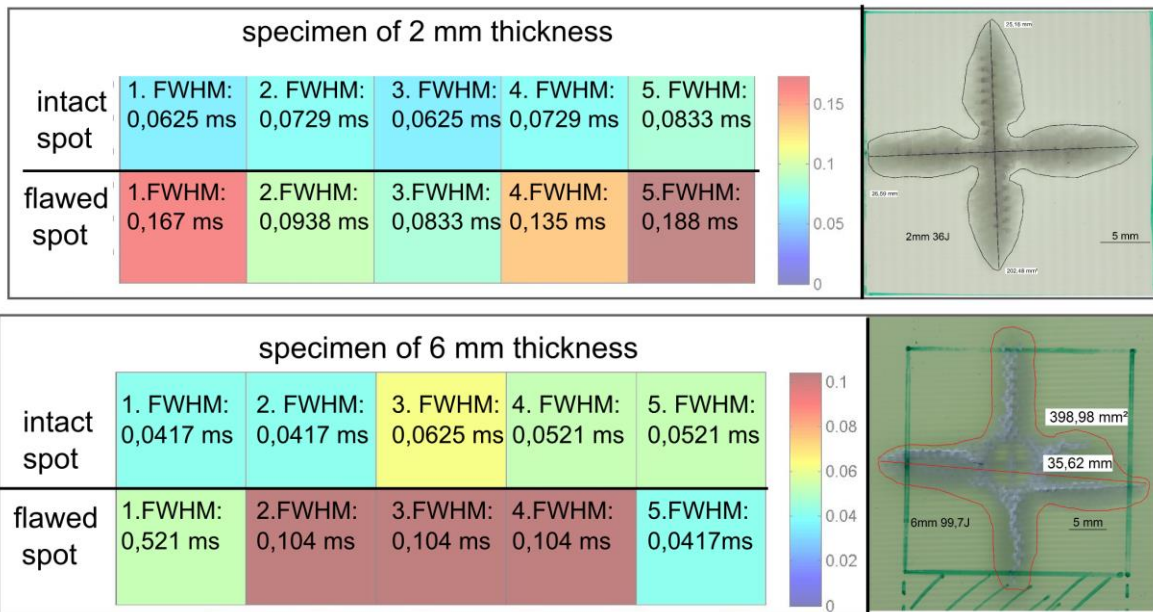


Figure 2: Comparison of five taps on the specimen with 2 mm and 6 mm thickness on intact structure (top) and five taps on a defect structure (bottom) shows the bigger value of the full width at half maximum of the force excitation signal on the defect structure

Figure 3 shows the grid for a measurement on specimen 2 mmM damaged with 8 impacts with an impact energy $E_I = 2-14$ J. Every measuring point with reference to Figure 3 was tapped with the hammer. The software acknowledged the position of the grid displayed in Figure 3 generating a color coded image. As illustrated in Figure 4, the results of the full width at half maximum in show that the LARS is capable of detecting damages in specimens of 2 mm thickness if they were impacted with an impact energy of at least $E_I = 6$ J. However, the taps were executed directly on the impacts, which is an optimistic constraint for tests under real conditions. The color plotted measurements depicted in Figure 4 indicate that the full width at half maximum of the force excitation does not grow with a growing spatial scope of the damage. Moreover, although identical measurements were executed, the impacts caused during the second measurement could not be as clearly detected as those caused during the first measurement.

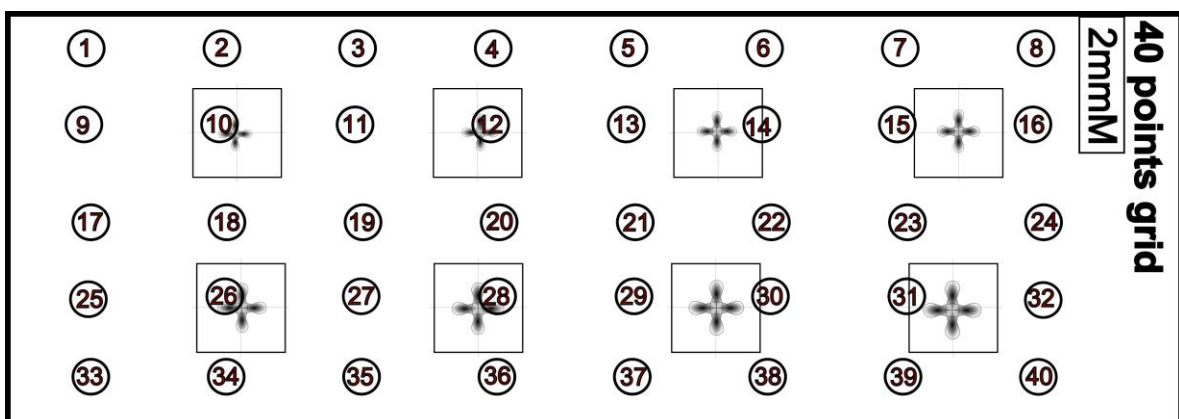


Figure 3: Grid of measurements on 2 mmM specimen

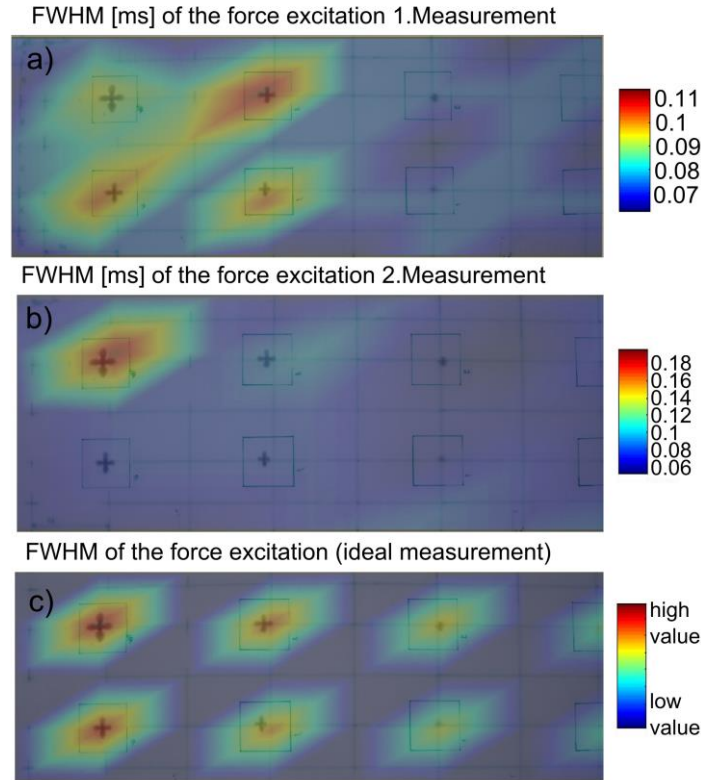


Figure 4: Color plotted measurements of the fullwidth at half maximum with the local acoustic resonance spectroscopy: a) first measurement. b) second measurement. c) artificially created ideal image of the measurement

2.2 Evaluation of Impact Damages Using Ultrasound

Ultrasound tests with water as coupling medium were conducted on reference plates with blind holes of different depths. These tests showed that the proper detection of boundary layers in glass fiber reinforced plastics is possible, considering material used and the constraints. Boundary layers that lie deeper in the material are partially hidden, and as a result the measurement of the remaining wall thickness becomes difficult. In the impacted specimen, the damage did not show extensive delamination. As a result the characteristics of the damage did not show a clear boundary layer, making detection with ultrasound testing difficult. However, the presence of damage is still visible in the signal. In the 2 mm specimen, impacts with an impact energy of at least 5 J could be detected. The weakening of the echo in the rear panel as observed in several instants, indicates the existence of damage. Impacts with an impact energy of at least 50 J were visible in 6 mm specimens with Ultrasound testing. Testing with an Olympus Omniscan MX2 phased array ultrasound device showed the capability of phased array devices to detect impact damage greater than 60 J. On the cutaways of the real rotor blades, the testing with the single probe ultrasound did not provide usable results. However, with the phased array test probe, impact damage for $E_1 > 60$ J was revealed.

2.3 Results of Optical Lock-in Thermography

The specimens of glass fiber reinforced plastics used in this study offered an easy insight into the material by putting them against strong light. However, internal damage characteristics on coated specimens could not be analysed by this simple visual testing. For this, optical thermography was used. On opaque, and more thermoconductive carbon fiber reinforced plastics, the OLT also reveals non visible damages. The penetration depth of the

OLT depends on the lock-in frequency; the lower the lock-in frequency, the deeper the position of the displayed plane. On the other hand, a lower lock-in frequency prolongs the test. With four periods of measurement and a lock-in frequency of 0.001 Hz, generating one image takes more than one hour for one measuring process. The penetration depth with the settings in this study is roundabout three millimeters at a lock-in frequency of 0.001 Hz. Testing a segment of a real rotor blade showed that the optical lock-in thermography is capable of showing hidden defects. Figure 5 shows a surface-near separation of the layers, which is not visible. By comparing the lock-in frequencies, Figure 5 also shows that the flaw increases in depth towards the left-hand side.

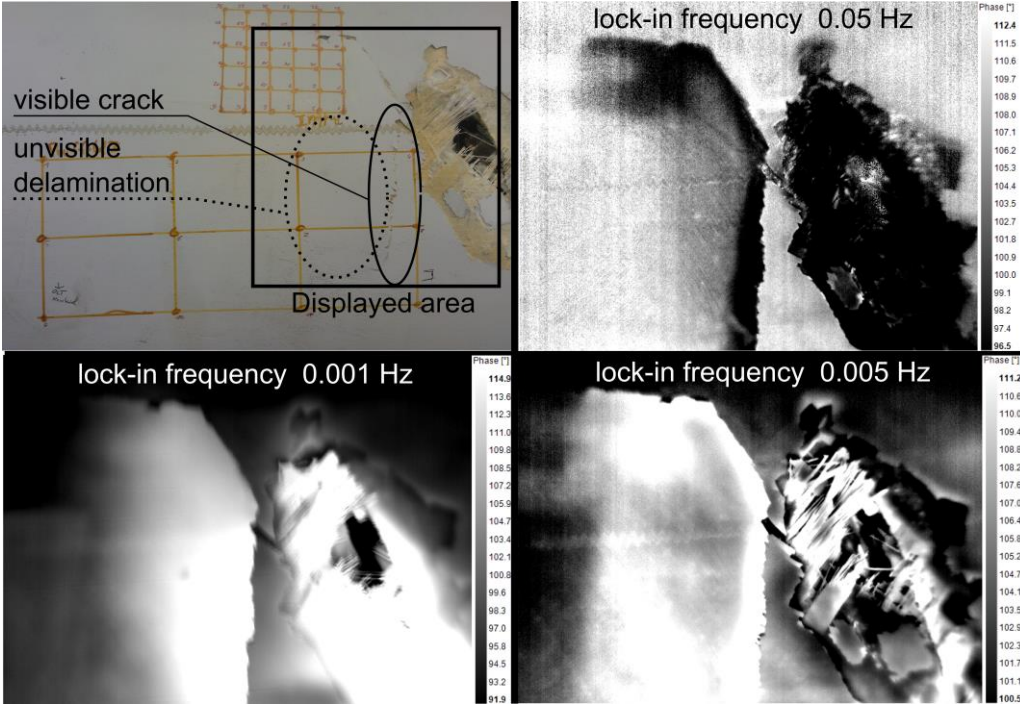


Figure 5: Phase images with different lock-in frequencies and a photo of the damaged specimen. A delamination is visible with OLT. This delamination is not visible in the photo of the specimen on the upper photo on the left. (Dotted line)

2.4 Results of the Computed Tomography

The computed tomography (CT) gives a good insight into the inner structure of a material and is also a common method for developing and comparing other techniques of non-destructive testing. In this research project, the computed tomography was executed by a phoenix nanotom m with a resolution of roundabout 15 μm. Figure 6 shows the rising defect of the cutaway view for the 2 mm specimen. Figure 7 shows three tomographies from the center of the impact showing the higher resistance of thicker specimen against impacts. The initiation of the damage occurs from the rear panel for thinner laminates and from the front side for thicker laminates as described in [3]. This can be seen in Figure 7. In the upper layers, failure of the material occurs by shear stress induced rifts, whereas in the lower laminates failure occurs through tensile strain.

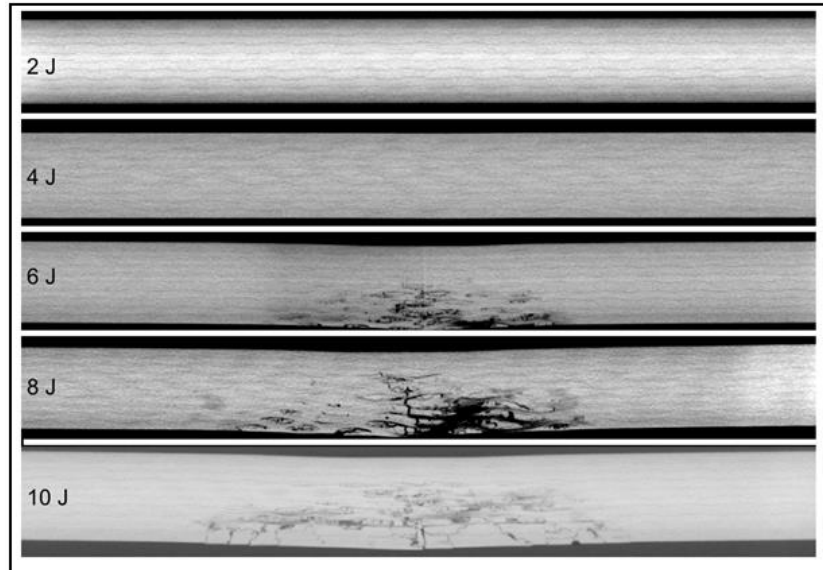


Figure 6: Cutaway view of impact damages in 2 mm specimen. The picture shows rising impact energies from the top to the bottom.

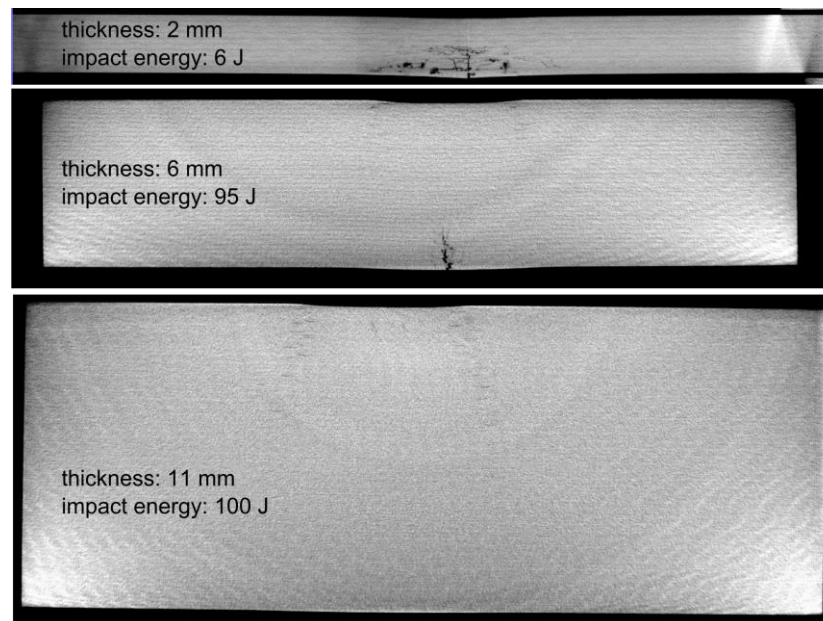


Figure 7: Comparison of different damage characteristics in different thicknesses. In a very thin specimen the damage initiation is at the rear side of the specimen, whereas at very thick specimen the damage starts from the front side

3 Valuation of the Methods of Nondestructive Evaluation

3.1 Local Acoustic Resonance Spectroscopy

The coin tapping method is already being applied in professional practice. Hammers with different peaks belong to the basic equipment for surveyors. Experience combined with a sharpened ear give the worker an insight into a material. The information is based on the tactile response of the material, such as for the commercially available Mitsui Woodpecker, as well as the audible tapping sound. The LARS analyses not only the force excitation, but also the sound of the tapping. However, the LARS has a low technological readiness level. There are no established systems, therefore the hardware has to be put together, and the software has to be developed. Impact damages in this study were difficult to detect, if they were not hit exactly by the hammer. Damages can only be detected, by hitting the center of the impacted spot. An advantage of the LARS is the good handiness of the system: the

hammer fits on a worker’s belt. Evolutions of future applications should maintain this handiness as it enables testing of widespread areas with little effort. In comparison to thermography and ultrasound testing, LARS is not vulnerable against the high damping of sonic waves and requires no high thermoconductivity as opposed to OLT.

3.2 Ultrasound Testing

Ultrasound testing has been developed in the last 50 years. In contrary to the local acoustic resonance system, ultrasound testing gives information on the depth of the flaw. Outlines of the flaw can easily and precisely be drawn on the surface. A disadvantage of ultrasound testing is the coupling of the method. Consequently the method is not suitable for widespread areas.

3.3 Optical Lock-in Thermography

The OLT does not require coupling and produces an easy to interpret image. Moreover thermographical images can be taken from afar, using the right lenses. This gives the method a great flexibility and potential for various applications. However, excitation requires a lot of hardware with high power supply and cannot be applied from afar. Passive thermography uses natural thermal gradient to bring forth internal structures, and could be a solution to avoid elaborate and costly excitation.

3.4 Computed Tomography

Computed tomography delivers by far the best insight of the damage, but is also the most sophisticated and expensive method. Computed tomography in this work showed that effect of defect is more severe on thinner specimen.

4 Discussions

The results from the experiments in this study uncover the weaknesses and strengths of the methods of nondestructive evaluation used. The strengths of each method should be combined to develop efficient holistic processes. Table 1 summarizes the examined methods.

Table 1: Evaluation of the used methods of non-destructive testing

		Practicability	Technological Readiness Level	Depth of information	Possible field of work
Technique	LARS	++	--	-	Quick first evaluation of structural integrity on bigger components
	UT	0	++	+	If more information of e defined spot is needed
	OLT	+	+	+	Gives an easy to interpret overview

In reality, each field of nondestructive testing in automotive, aeronautical and civil engineering has its own constraints. In an ongoing research project in which this study is involved, the nondestructive testing of wind turbine rotor blades is discussed. This can be separated into two main areas: one is the testing of the rotor blades after manufacturing, and the other is the testing of mounted rotor blades. Flaws in manufacturing are the main reason for severe and expensive accidents in service [14]. For this reason, the quality of wind

turbine rotor blades is important, making it essential to check all rotor blades after manufacturing. Flaws in newly manufactured rotor blades include debonding between the half shells and between the half shells and the stringer, and wrinkles/waviness in the fabric in the laminate.

On mounted rotor blades, the constraints for nondestructive testing are different. The main challenges are the high altitude and difficult access of rotor blades in turbines. Currently, the inspector checking the condition of the rotor blade is rappelled down from the top. This method is inherently risky and offers little room for automation. Passive thermography offers great insight into the structure of rotor blades for wind turbines [15, 16]. Additionally, the application of drones is becoming more and more varied. With this in mind, the inspection of rotor blades of wind turbines with thermography drones would be suitable. The sight check could be captured by a drone's video capabilities and then assessed by a technical expert. However, this idea is not entirely new, there are patents on the idea of detecting flaws from the air with thermography [15], as well as the use of drones for this task [17, 18].

5 Conclusions

In effort to add to this body of research, this study found that in order for an impact hammer to detect damage, it needs to make contact in precisely the same spot of an impact damage. Additionally, this research found that the greatest advantage of LARS is its usability. Consequently, the method is recommended for big structures and for the detection of widespread flaws.

Ultrasonic testing gives information on the depth of the flaw and provides an image of the defect that can be sketched on the surface which provides information on size and shape. However, coupling makes the method more tedious. Therefore, ultrasonic testing is recommended after a method used for widespread areas has encircled the area of the damage, or if the area of required testing is known.

OLT demonstrated its potential in nondestructive testing. Advantages of this method include that impacts were clearly visible, and the penetration depths can be easily adjusted by different lock-in frequencies. Its handiness, simple interpretation and the variation of methods of active thermography as well as passive thermography make thermographical testing attractive. Moreover, thermographical systems offer great potential for automatized applications.

Cost pressure in the wind energy industry is a stumbling block for the development of new automated holistic approaches for testing of rotor-blades of wind turbines. However, thorough testing of newly manufactured rotor blades pays off in the life cycle of the component.

Impact damages could be detected by all mobile methods of nondestructive evaluation starting from the approximate impact energy that produces the peanut shaped haziness in the specimen. From that energy on, CT uncovers characteristics like fiber breakage and air pockets in the material.

References

- [1] Richardson, M., Wishheart, M.: Review of low velocity impact properties of composite materials. *Compos. A* 27, 1123–1131 (1994).
- [2] Liu, D.: Impact-induced delamination—a view of bending stiffness mismatching. *J. Compos. Mater.* (1988). doi:10.1177/002199838802200706.
- [3] Abrate, S.: *Impact on Composite Structure*. Cambridge University Press, Cambridge (2005).
- [4] Choong, W.H., Yeo, K.B., Fadzlita, M.T.: Impact damage behaviour of woven glass fibre reinforced polymer composite. *J. Appl. Sci.* (2011). doi:10.3923/jas.2011.2440.2443.
- [5] Jüngert, A.: *Untersuchung von GFK Bauteilen mit akustischen Verfahren am Beispiel der Rotorblätter von Windenergieanlagen*. Dissertation, Universität Stuttgart (2010).
- [6] Jüngert, A.: Local acoustic resonance spectroscopy (LARS) for glass fiber-reinforced polymer application. *J. Nondestruct. Eval.* doi:10.10/1007/s10921-013-0199-3 (2013).
- [7] Jüngert, A., et al.: Zerstörungsfreie robotergestützte Untersuchung von Rotorblätter von Windenergieanlagen mit Ultraschall und Thermographie. *ZFP Ztg.* 115, 43–49 (2009).
- [8] Pfund, B.: Portable test hammer apparatus. US Patent 5,686,652, Appl. No.: 08/707,851 (1997).
- [9] Krautkrämer, J., Krautkrämer, H.: *Werkstoffprüfung mit Ultraschall*. Springer, Köln (1966).
- [10] Lin, S.: Study on the high power air coupled ultrasonic compound transducer. *Ultrasonics* (2006). doi:10.1016/j.ultras.2006.05.120.
- [11] Revel, G., Pandarese, G., Cavuto, A.: The development of a shocktube based characterization technique for air-coupled ultrasonic probes. *Ultrasonic* 54(6), 1545–1552 (2014).
- [12] Gaun, X. et al.: Post processing of phased array ultrasonic inspection data with parallel computing for nondestructive evaluation. *J. Nondestruct. Eval.* (2014). doi:10.1007/s10921-013-0219-3.
- [13] Huang, J., Que, P.W., Jin, J.H.: Aparametric study of beam steering for ultrasonic linear phased array transducer. *Russ. J. Nondestruct. Test.* 40(4), 46–53 (2004).
- [14] Balk, S.: *Status und Trends in der Entwicklung von Material und Fertigungskonzepten für Rotorblätter von Windkraftanlagen*. IABG mbH, München (2011).
- [15] Zell, H.: *Verfahren zur Überprüfung des baulichen Zustands von Windkraftanlagen*. EP 2 631 476 A2, Mühlheim an der Ruhr (2013).
- [16] Zell, H., Carl, V.: *Wind Turbine Inspection New Methods of Remote Nondestructive Inspection of Rotorblades*. Wilhelmshaven (2012).
- [17] Wobben, A.: Method for monitoring wind power plants, US Patent 6,785,637, Appl. No.: 10/089,774 (2001).
- [18] Fernandes, R.A.: Monitoring system for power lines and right of way using remotely piloted drone. US Patent 4,818,990, Appl. No.:95,152 (1989).