MODULES FOR AN EFFICIENT AND HOLISTIC APPLICATION OF NDT METHODS FOR FIBER REINFORCED POLYMERS

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Abstract
Fiber reinforced polymeric materials are used for lightweight constructions during several decades. GFRP or CFRP, for example, are an integral part of cars, airplanes, or rotor blades of wind turbines even up to a high percentage of the total range of used materials. While in the early years the optimization of the design and processing techniques and the reduction of production costs were governing the design process, today issues of life-cycle costs, recycling, maintenance and quality control becomes more and more significant as well. Non-destructive testing (NDT) methods play usually and increasing role in all parts of the life cycle of a product including the design, manufacturing, lifetime and recycling. NDT techniques can be included into the quality management system, used for inspections and for structural health monitoring (SHM) applications. NDT data can even be used for a better control and operation of structures. However, this requires an early integration of NDT in the design phase, a definition of defects (type, size, and location) that are critical (*Effect of Defect*) and the determination of the *Probability of Detection* (PoD) of such defects. A combination of testing methods for quality control and inspection is beneficial including for example ultrasound, infrared-thermography, eddy-current, CT scanning, microwaves, vibration testing, and acoustic emission analysis.
Very rarely, all the above-mentioned points – that can be considered as modules – are considered in the initial design phase of a structure what is leading to a loss of performance and can be cost-inefficient. Techniques and processes to include efficiently NDT and SHM methods into the life cycle of a product are in its infancies but this is of particular interest for fiber-reinforced polymers. It will be demonstrated how this process can be optimized in a holistic way giving examples from applications in different fields including automotive and aeronautic.

1. Introduction

In general, non-destructive testing techniques can be subdivided according to the field of application into methods applied during the design and development of new structures, the quality control during manufacturing and the inspection and structural health monitoring during the lifetime of a structure. The recent development of advanced lightweight constructions and the use of fiber-reinforced materials require modified and adjusted testing procedures. After some examples for NDT applications in the following section it will be shown how these techniques can be applied in a more holistic way.

2. Overview of applications for NDT techniques

For decades, material testing was performed mainly in the frame of empirical destructive techniques and procedures using tensile, pullout or bending tests. In most cases, samples or prototype structures were tested in a quasi-static or in a dynamic way while the failure was observed. This quite simple procedure has disadvantages since many samples have to be destroyed to perform a significant number

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of tests with variations of one or several material parameters. Another drawback was that the samples were usually broken or useless for further evaluations.
With the availability of computers, these procedures were altered by using numerical simulations (based for example on finite element modeling, FEM) in addition to classical destructive material tests. This allowed for the first time a more detailed analysis of fracture processes and the materials behavior under load. Almost at the same time, non-destructive testing techniques were developed to form a powerful triple of destructive, non-destructive and simulation techniques. Numerical simulations alone are very much depending on the set boundary conditions and NDT techniques can fill this gap by providing data about material properties determining start parameters.

2.1. NDT applications in prototype design

A thoughtful combination of this triple of techniques (destructive testing, FEM and NDT) is particularly essential for the development of new fiber-reinforced composites, e.g. out of glass (GFRP) or carbon fibers (CFRP). These materials have a beneficial relation between weight and strength and many other advantages but they are opaque and complex with a high heterogeneity and anisotropy of material properties. This complexity is challenging for the application of NDT techniques (and numerical simulations), in particular, if they are applied to reveal hidden defects under the surface. However, modern NDT techniques are on a level today [Busse 2000] to be applied in a very efficient way in the fields of material design and prototype testing. These techniques are the same as they are described in the third section of this paper. However, the application of NDT techniques at prototypes in the design phase could be easier since some of the constraints in relation to time and environment are easier to be influenced as it is the case for the production or service phase.

2.2. Testing methods for quality control during manufacturing

The manufacturing process plays a significant role in regard to the lifetime of a structure. Some defects being identified later and that are leading to failure are based on inappropriate production processes. Since this process is still complex concerning GFRP and CFRP several problems can occur in case of fiber-placement errors leading to undulations, dry laminates, increased porosity, or contaminated laminate layers causing debonding. Less critical are the manufacturing processes regarding mechanically induced defects by impacts or other loads leading to delaminations, fiber breaks, or matrix fissures – these defect types can occur more often later during the service phase.

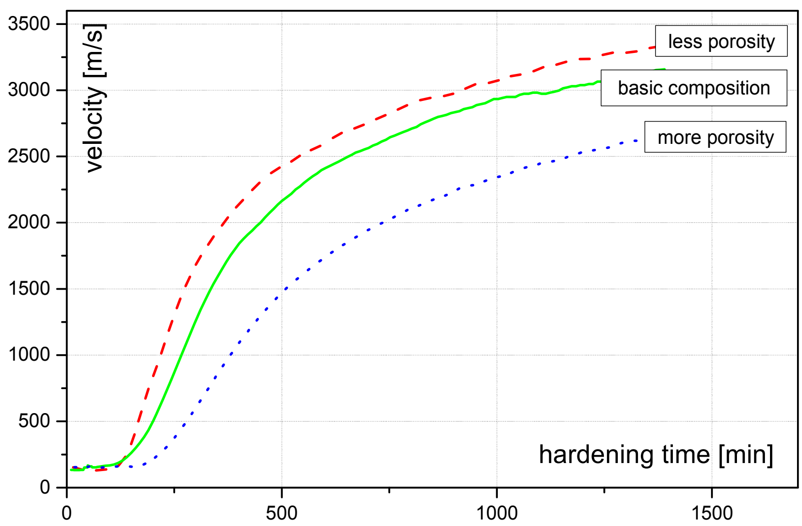

Figure 1. Example of the hardening process of a laminate during manufacturing and the changing ultrasound velocity over time – a mix with higher density or lower content of porosity, respectively, is reaching final velocity values earlier

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A conventional discrimination process during production separating well-manufactured components from defective parts involved in the past visual inspections, but non-destructive testing methods become more and more important. They can also help to reduce waste. Internally sound parts that would be sorted out by visual inspections alone can be accepted after NDT. Besides an inspection of individual semi-finished parts and components, NDT techniques can be applied also under complex production conditions, i.e. at an assembly belt in mass production. This application is known as “in-line NDT”.
Additional value of NDT is given, if an optimization of the manufacturing process is added to defect detection. The improvement of production in a timely manner is essential for fiber-reinforced composites and can be addresses by optimizing the hardening process of the laminates’ matrix of molded components. Fig. 1 represent an example of such an application using ultrasound. The hardening of a laminate and the optimal time for demolding is determined via the analysis of ultrasound velocities that are derived from propagated ultrasound signals and their changing travel-times as a function of the hardening time. This function is usually non-linear and depend on many parameters, where the relation of ultrasound velocity and porosity is only one. In other applications, the evolution of the elastic modulus can be controlled by ultrasound measurements.

2.3. Birth certificate for components

For later inspections, a precise knowledge of the used material components and their properties is valuable. What is required is a determination of the initial state of the material. With this knowledge – and the according data from NDT measurements –, it is much easier to detect defects. One just have to scan for deviations from the initial state. Otherwise, if such data do not exist, a complete non-destructive assessment of the component and a characterization of defect types have to be done. This could be a time-consuming process. Reference measurements can establish a cost-efficient way of quality control. This is true in particular, if a repetitive inspection of the component during its lifetime have to be scheduled anyway. The implementation of reference measurements right after manufacturing along with data recordings is suggested. Such an electronic data file can be considered as a “birth certificate” of a structure. The type of the data should follow the requirements of later inspections following the rules of EoD and PoD as described in the following sections.

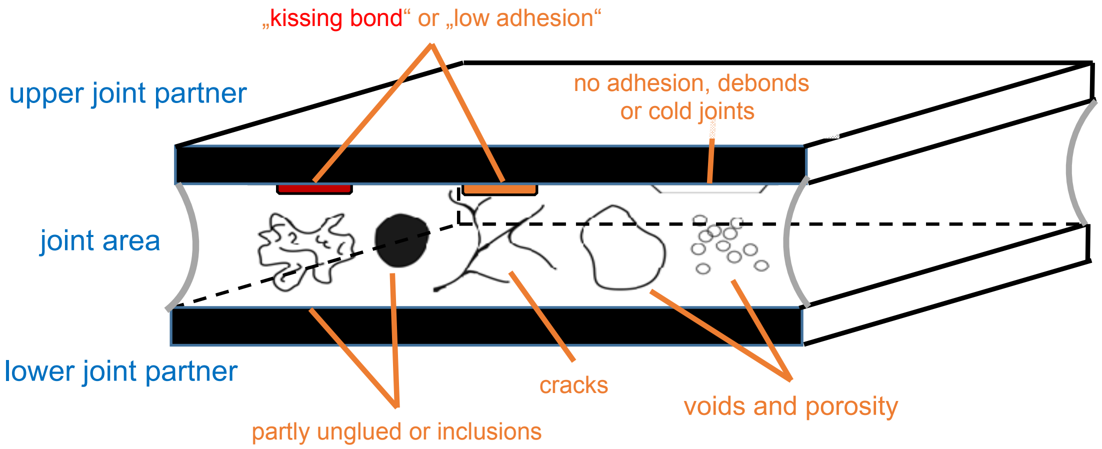

Figure 2. Defect types of glued joints – own drawing inspired by Adams & Cawley [1988]

3. NDT for inspection of components

Imperfections and defects in materials can also occur after production during the service life of components – for example due to impacts. The compression after impact (CAI) can cause delaminations between individual layers of a laminate or between two joint partners. Many more defect types are known and NDT techniques are required to detect them. How challenging the inspection is will be addressed in another example, where fiber-reinforced polymers are laminated and

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individual parts are glued together. The interface between the two laminated partners and the joint area are critical parts and can be defective. Some of the defect types are represented in Fig. 2. The drawings depict defect types that have different reasons and can influence the performance of a structure. A low adhesion interface can for instance be induced by a contamination of the two jointed partners with oil or grease [Heckner et al. 2015]. Not only the defect type but also its size and position inside the specimen play an important role as addressed later. Such defect types are not only relevant for monolithic laminates but also for other constructions like sandwiches or honeycombs [Schürmann 2007]. All these lightweight constructions have benefits over the traditional rivet joint techniques because of lower weight and the avoidance of fiber breaks during riveting. However, investigations of glued joints (for either defects or determining the thickness of the glue) are challenging.

3.1 NDT and SHM techniques and inter-relation to other disciplines

There is a whole basket full of non-destructive testing techniques being applied in mechanical engineering. Their classification is useful to establish an efficient quality control concept but this is a difficult task. The methods can be subdivided into the used physical measuring principle (waves, fields, particles, other effects) or according to their field of application. It does not help significantly to restrict this task to applications in the field of fiber-reinforced composites. Tab. 1 is demonstrating the related issues and how a classification can work. It organizes the methods on one hand according to their application in relation to the product's life stage in regard to the introduction (section 1) into design, manufacturing and lifetime (inspection and monitoring) of a product.

Table 1. Classification of NDT and SHM techniques.

1.	**Design of new materials and test of prototypes**	
2.	**Quality control during manufacturing**	
3.	**Inspection during lifetime (selection of some methods)**	
	Visual inspection techniques	
	Radiographic techniques	
		Computer tomography
		Laminography
	Acoustic techniques	
		Ultrasound
		Tapping test and local acoustic resonance spectroscopy
		Vibration and modal analysis
	Electro-magnetic waves	
		Infrared thermography
		Shearography
		Micro waves and terahertz
	Electric and magnetic fields	
		Eddy current techniques
4.	**Structural Health Monitoring**	
	Acoustic emission techniques	
	Vibration and modal analysis	

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On the other hand, some classification criteria are used in the table based on the physical principle (acoustic, electro-magnetic etc.). The techniques are also sub-divided into inspections and monitoring, where the first describes a single or repetitive measurement in longer intervals and the latter a measurement in relatively short periods. As can been seen for vibration and modal analysis some techniques (or many) can be used in shorter (monitoring) or longer (inspection) intervals, i.e. for both categories. This illuminates why Tab. 1 is certainly incomplete giving only an idea about a classification scheme for non-destructive testing techniques. More classification criteria are certainly available, discriminating between detection and localization techniques, methods being used to find a certain defect type or using a certain sensing or coupling technique. Considering coupling techniques, contact and non-contact techniques can be subdivided. Measuring setups using ultrasound with sensors in contact to the specimen are for example named “immersion impulse echo”, “dry-coupled transmission”, “water-coupled phased array”, or “full-matrix capture” [Grager et al. 2016]. In comparison to coupled techniques, non-contact methods have a significant advantage since they are usually faster and applicable along with robot controlled testing procedures what is beneficial for in-line manufacturing and quality control. While some of the techniques mentioned in Tab. 1 are anyway contact free (like thermography, shearography, microwaves and terahertz [Schlamp 2013] or eddy-current), other techniques are nowadays being developed towards contact-free options, as it is the case for “air-coupled ultrasound” [Hillger et al. 2004, Guruschkin 2015]. Fig. 3 gives an example of the application of optical lockin thermography at an aeronautical structure (tail plane fin) as a non-contact application.

Figure 3. Optical lockin thermography at an empennage (© Werner Bachmeier, TU München)

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There is a close relation between NDT techniques, developed for different disciplines. Two examples are given here. For obvious reasons are non-destructive diagnosis techniques preferential to inspect the human body. NDT applications for medical and engineering purposes have been very often stimulating each other. However, the nomenclature was different – and is still. Some examples are given in Tab. 2, where the terms used in health care sector originating from Latin.

Table 2. Related concepts between techniques used in engineering and health care.

Engineering	Health care
construction or component history (record)	anamnesis
inspection	diagnosis technique
maintenance	prophylaxis
repair	rehabilitation
examination	autopsy

There are also close relations between NDT applications in engineering and geophysics. Geophysics is the science to probe the earth – mainly non-destructively. Earthquakes have always been a hazard to humankind and observation techniques for this hazard were highly required. This led to developments in seismology. Furthermore, there was a demand for geophysical prospection techniques since water, oil, gas and other resourced were increasingly needed. This is the reason why probing techniques as reflection and refraction seismic were developed that were the basis for modern NDT techniques in mechanical engineering. Some of these techniques that have relations are named in Tab. 3.

Table 3. Examples for related probing techniques in geophysics and engineering.

Geophysics	Engineering
seismology	acoustic emission analysis
seismic	ultrasound
common depth point migration	full-matrix capture ultrasound
ground penetrating RADAR	micro wave techniques
earth's oscillation analysis	modal analysis

3.2 NDT techniques – academic and non-academic personal qualification

The development of NDT techniques was focused in the last century on testing metals due to the importance of this material. Nowadays, there are many applications in this field and a relatively long tradition and experience exist including standards for testing procedures, certificated measuring instruments, and personal qualification procedures. The training is mainly organized in non-academic certifying level courses with level I, II and III, where the last level is the highest degree. This training is application oriented and commercially driven, while the development of new NDT techniques and NDT research is mainly a task of academic institutions. Lectures on NDT at universities [Grosse 2016] are admittedly rare and usually not comprehensive.

With the introduction of fiber-reinforced composites, the need for modified standards and certification procedures is obvious since the existing techniques and instruments became inadequate for many applications. Experienced experts are required to apply these adjusted techniques to GFRP, CFRP and other fiber-reinforced materials. The complexity of such composites is caused on the one hand by the different failure processes of fiber-reinforced materials (as it was described in the introduction to section 3). On the other hand are heterogeneities and anisotropy effects challenging for the detection of defects. New level-based non-academic training courses are required and at the time being in preparation.

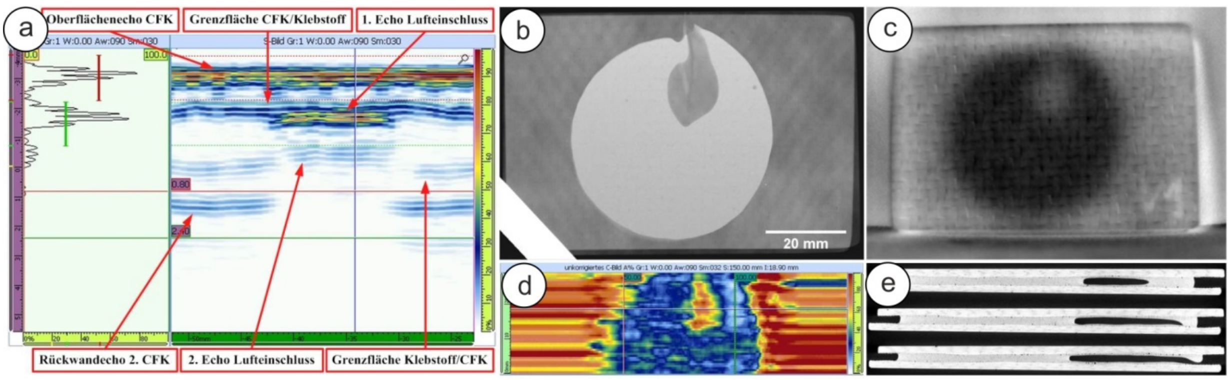

Figure 4. CFRP sample investigated with ultrasound A- and B-scan (a) and C-scan technique (d) as well as with radiographic CT scanning (top view: b and cross section: e) and optical lockin thermography (c) [Grager 2013; Prade 2013]

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3.3 Combination of NDT techniques and combinations with numerical simulations

The before mentioned complexity requires very often the application of more than one NDT technique at the same component. This reduces the uncertainty of measurements increasing also the redundancy. In addition, the precision and efficiency can eventually be increased. Some defect types can be detected with a certain technique only. If a component can contain more than one defect type the probability to detect all of them is dramatically increased using different NDT techniques. Fig. 4 shows an example for applications of different techniques at a glued laminate out of CFRP with a debonded area [Grager 2013] using ultrasound (a and d), computed tomography (b and e) and lockin thermography (c). Since all three techniques are based on different physical principles, they “see” different properties of the material and the defect. The combination of NDT techniques gives a much more detailed picture about the inner properties and the shape of the defect as one alone [Kiefel et al. 2014; Goldammer et al. 2016; Sause et al. 2016].
There is another combination being powerful as well. Numerical simulations were established as finite element modelling (FEM) in the middle of the last century. The load response of a structure was simulated to improve the materials behavior and to support the design of structures. If the model is appropriate, the occurrence of defects (e.g. cracks) and the failure of structures can be predicted. This is usually compared to empirical structural tests (static, dynamic, fatigue), what is still time-consuming and laborious. A more efficient way is to involve data from NDT to set properly the boundary conditions for the simulations and to reduce the number of destructive tests needed to evaluate a new construction. Numerical simulations can in return increase the significance of a single experimental result and decrease uncertainties of several experience due to material and data scattering.

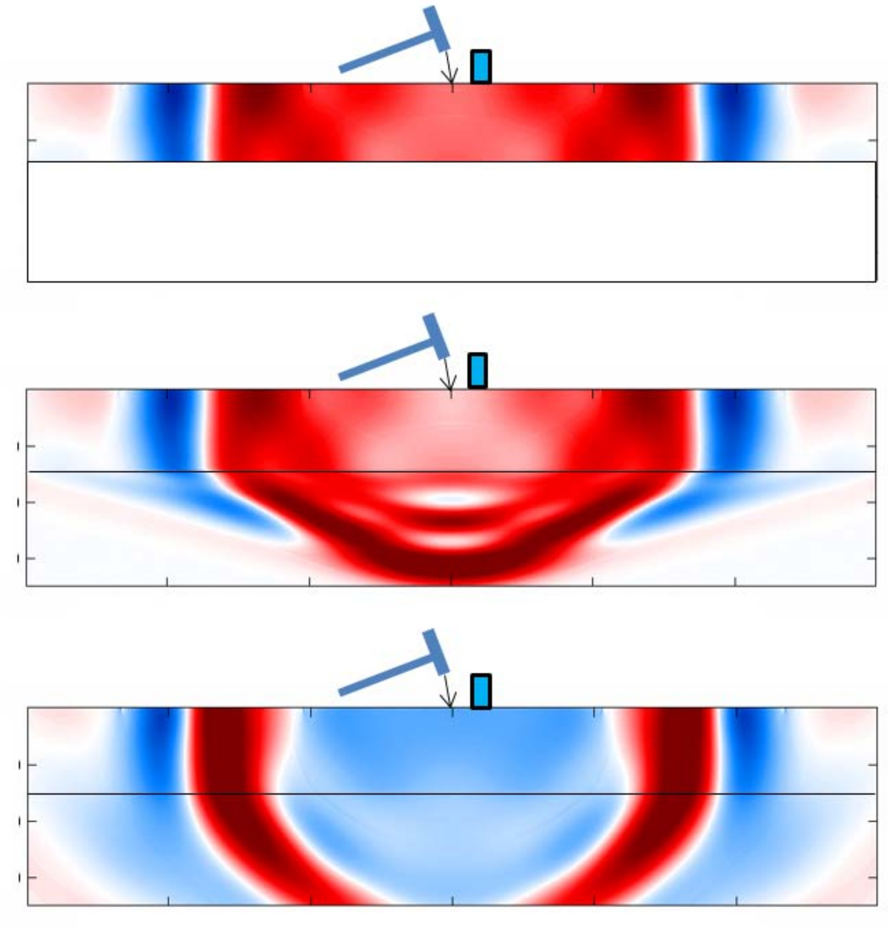

Figure 5. Numerical simulation of a tapping test according to Jüngert et al. [2013], Andreisek et al [2016] and Mueller et al [2016] at a laminate out of two layers with no bond (top), bad adhesion (middle) and good bond (lower graph)

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A different way to involve numerical simulations with NDT is the simulation of the interaction between the NDT signals and the components, recording changes of the waves or fields propagating through the material. Fig. 5 gives an example. It shows the simulation of a tapping test to evaluate the quality of the bond between two layers. The waves are excited by an impact (hammer) at the surface producing waves that are propagating through the specimen. These waves are completely reflected at an interface in case of a bad bond (upper graph), transmitted through the interface into the second layer, if the bond is good (lower graph), and only partly transmitted or reflected in case of low adhesion (mid graph).

Data scattering can be handled better using simulations along with measurements. Besides, a time-consuming setup of (non-destructive) tests can be reduced. In most cases, it is possible to optimize the setup in a way that the best sensor (sensing frequency, aperture, sensitivity etc.) and the optimal setup (sensor position, proper NDT technique etc.) can be determined for a certain type of defect prior to measurements. In a consequence, it helps to interpret the NDT data and to decide if a technique is able to "see" a defect or not under certain circumstances [Zelenyak et al. 2016]. Considering, that a non-destructive evaluation of a component does not indicate any defect, one can wonder about the value of the result. Does this mean that the component is free of defects or is the applied NDT technique just unable to detect the defect? Simulations can help to decide about this question. As a side effect, it help to increase the cost-efficiency of NDT.

3.4 Relevance of a defect

When it comes to establish a quality control or inspection system in a company, this decision is very often based on the already available measuring techniques, NDT devices and sensors. With this equipment, measurements are then performed and the NDT data are evaluated concerning features in the data that possibly are defects. However, such a procedure can be inefficient. Some defects can be overlooked leading to a lack of quality of the inspection. It is much more efficient to evaluate first the relevance of a certain defect type. One should consider an imperfection in a material as a feature rather than a defect before such a classification was done.

To setup NDT and SHM techniques in the most efficient way the following questions need to be answered prior to any measurement:

Type:	Which feature (see for example section Fig. 2) can possibly occur?
Position:	In which part of the component or structure is the feature expected?
Size:	Which sizes of the feature are to be expected?

Most important is the answer to the fourth and last question: Which feature is relevant, and in which position and size? Only a feature being relevant should be named *defect*. In the literature, this is known as the "Effect of Defect" (EoD) principle [Oster 2012a and 2012b] that is considering the function of the component and the structure and the relevance of an imperfection during the lifetime and under operational loads. Under quasi-static conditions, the porosity of a component can be harmless but under dynamic fatigue be critical leading to early failures. This could be similar for most other defect types (or features resp.).

3.5 Probability of detection

An efficient selection of the most suitable NDT technique (or combinations) can be done only after the specification of relevant defect types and sizes. Material variations and differences in the setup can be handled as statistical quantities. Therefore, the certainty to detect a defect can usually be described using probability functions. This principle is usually called "Probability of Detection" (PoD) [Berens 1989; Kanzler et al. 2012]. The PoD give indications about the detectability of a certain defect type and size and at a certain location inside a component [Setz 2015; Grosse et al. 2016]. The PoD relies on not only the defect type, selected measuring method and the equipment but also on the type and geometry of the component, the way the measurement is conducted and so on. The PoD concept was developed in the early 70ies at NASA in the United States [Ginzel 2006]. To determine practically a PoD numerous and statistically relevant measurements have to be performed at (similar) components with the same or similar defects under the same (or similar) conditions. To shortcut this time-

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consuming procedure PoD values (curves) can be determined at generic components. Generic components can be reference specimen with artificially included artifacts (defects) as it is displayed in Fig. 6.

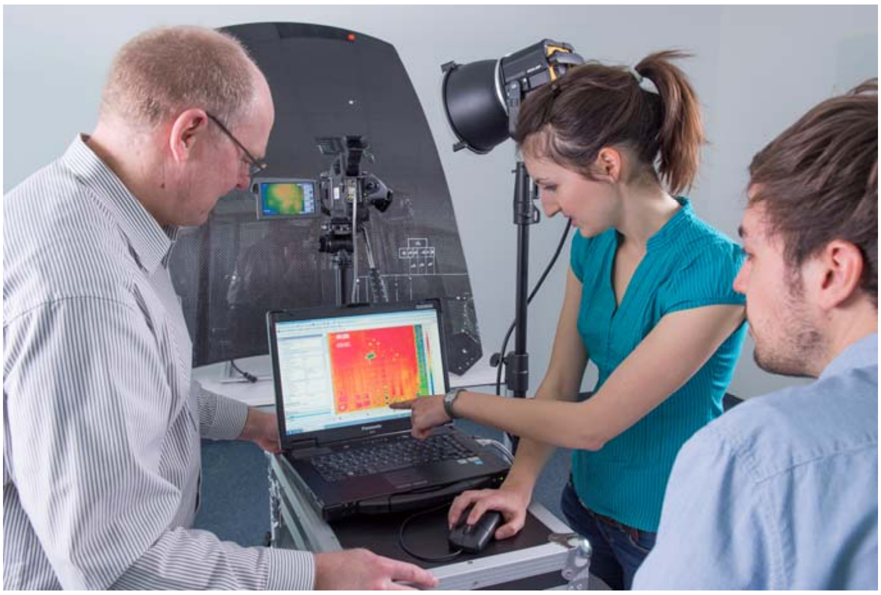

Figure 6. Measurements to determine the PoD for thermography using a reference plate with artifacts (pin holes of different size and depth and laminated defects inside) (© W. Bachmeier, TU München)

4. Structural Health Monitoring

As described in section 3.1 structural health monitoring techniques are a special repetitive application of NDT measurements, i.e. repetitive in relatively short intervals. In practice, some of the techniques mentioned in Tab. 1 are more suitable for monitoring than others; among them are vibration and acoustic emission techniques. Applications depend on the type of the deterioration, its extension and evolution. Acoustic emission techniques are powerful as a precursor method to detect the early beginning of cracks and to warn prior to failure [Sause 2013; Radlmaier et al. 2012].

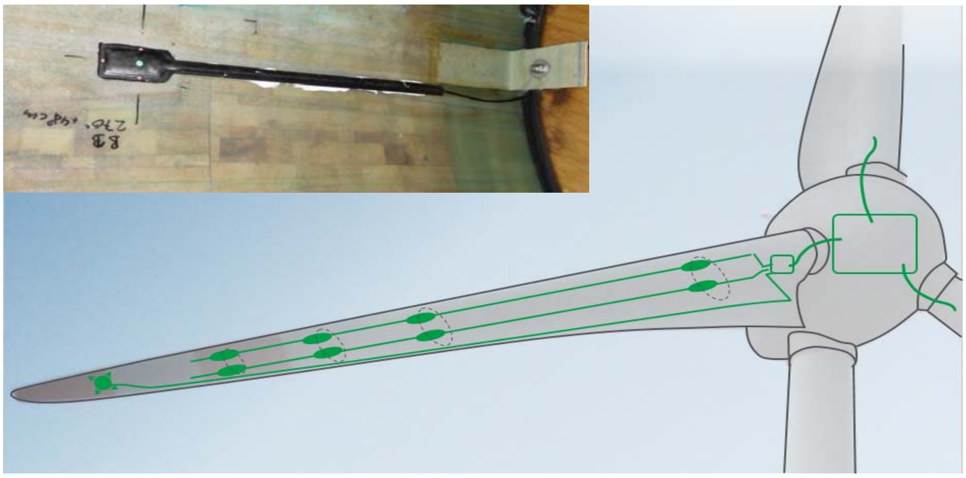

Figure 7. Fiber optical sensing system (green lines above and black in the insert) inside of a rotor blades to optimize the performance of wind turbines as developed by www.fos4x.de in Munich

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A conventional application for SHM techniques for example in automotive or aeronautic is the detection of defects in warning systems. Such an application could be cost-intense and might be applicable to structures of high value or with a strong need for security only. Monitoring systems can be applied also to less expensive structures, if the data are usable for other purposes too: the control of systems. Monitoring devices (sensors) can be used in adaptive constructions improving the performance and durability. In wind turbines for example, SHM for defect detection is not a big seller. However, if the data are in addition used to increase the availability of the turbine (ice detection), to detect imbalances and to decrease the costs of electricity or maintenance by optimizing the yaw and pitch angle such a monitoring system can amortize the expenditures after a few months. Such a technique is provided by fiber optical systems attached to the rotor blades of such wind turbines as illustrated in Fig. 7 (by courtesy of the company fos4x).

5. Summary - Selection and classification of NDT and SHM techniques

One can consider the selection of proper NDT and SHM techniques, their combination and the application of methods like numerical simulations, PoD and EoD as modules that can be chosen to perform a measuring task in the best way. In the frame of holistic NDT a clear concept is required to decide on the different modules. The flow chart given in Fig. 8 is suggesting such a concept. If the selection of the most suitable NDT or SHM technique (or their combination) is considered (Fig. 8, center), this has to be based on a clear definition of the requirements (Fig. 8, upper left). It is certainly helpful to determine the defect type, size and location under consideration as well as the required *Probability of Detection* (PoD). Only defects that have an effect on the structural integrity or that lead to a loss of required properties (*Effect of Defect*, EoD) are desired for detection. The combination of testing techniques with simulations (Fig. 8, bottom left) is another way to increase the efficiency. Finite element techniques are often applied to simulate the reaction of a component to a static or dynamic load. However, numerical models need the input from measurements to define the boundary conditions for the simulation and to validate the approach chosen. NDT can give valuable input and need in return simulations as well to reduce the complexity of measurements at heterogeneous structures such as CFRP. Simulations are not restricted to study the effect of loads but can be applied also to the non-destructive testing process itself (Fig. 5).

There are other factors influencing the selection of NDT techniques as named in Fig. 8 (upper right). The efficiency of non-destructive inspections is – concerning an in-line manufacturing process – based on the clock cycle as well as on the investment for equipment (devices, sensors) and personal (training, qualification). The required PoD needs to be crosschecked with the effective PoD considering the chosen techniques and defect types. This can lead to a classification of NDT techniques for a certain application. Thus, CT scanning would be (in most cases) a “gold standard” to detect defects, but for a certain in-line application, it could be too slow and too expansive. A combination of techniques (NDT and simulation) can further optimize the procedure. A fast but rough NDT method can for instance be used to separate problematic components that later on are examined in more detail with a slower but more precise technique. Such a procedure can be called *NDT escalation strategy*.

The proper selection of NDT and other related techniques enables for a more efficient application of measurements. They can help to optimize the manufacturing process, reduce waste and increase the life span of the structure. A reduction of the total costs can finally be the result (Fig. 8, mid left).

For a full holistic NDT, the integration of these procedures into the whole production process is important (Fig. 8, lower right). This integration can be labeled “*Design to NDT*” what includes also the required level of automation as well as standardization and certification. An early integration of the above considerations is required, since a certain material composition, geometry, or surface property can result later on in impeded or impossible NDT applications. Today, such problems are not always avoided from the beginning. In regard to an increased life span of products and improved sustainability, quality and inspection procedures should be configured and scheduled at the earliest possible time using all available manufacturing techniques like rapid prototyping or computer-aided manufacturing.

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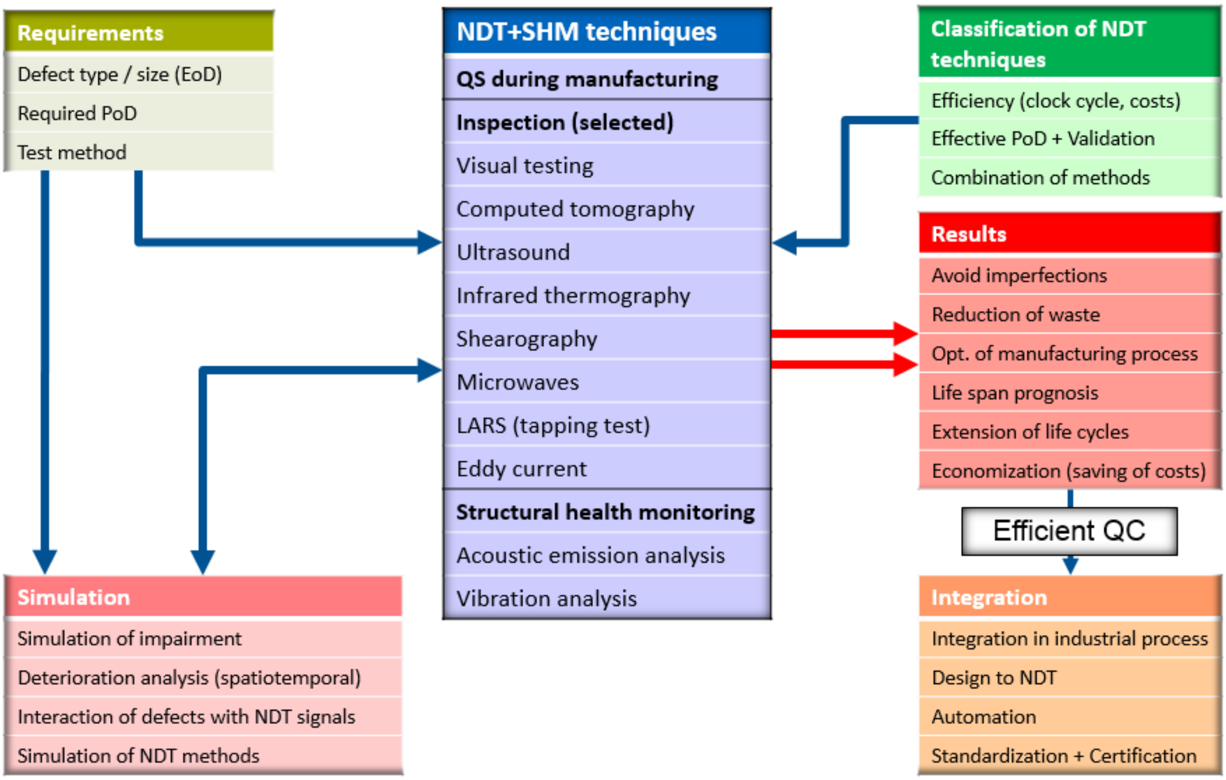

Figure 8. Holistic concept for an efficient selection of NDT and SHM techniques in the context of quality control [Grosse et al. 2016]

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