Monitoring System for Delamination Detection – Qualification of Structural Health Monitoring (SHM) Systems

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Abstract

Traditional vibration-based monitoring techniques provide general information about the investigated structure by identifying and analyzing specific resonance modes. Using low frequencies, they are limited to the identification of large defects, and in the precision of their localisation as well. The paper shows that vibration monitoring of essential structure parts can be significantly enhanced by using elastic waves in the kHz frequency range generated by piezo fibre composite-modules. The mentioned active modules can be embedded within a structure due to their low thickness and show a significantly different sensitivity in directions parallel or perpendicular to the fibre direction. Having a shorter wave length, these guided waves are more sensitive to smaller defects. Theoretical foundations for describing their propagation in various structures and the interaction with defects are reviewed. On the basis of this analysis, methodical concepts for active and passive monitoring systems have been developed which employ acoustic signature analysis and acoustic emission techniques. Implemented in an early-warning system, they can raise an alarm long before any critical damage occurs.

Acoustic monitoring techniques require technical solutions that eliminate noise as much as possible. To meet this requirement, sensor near evaluation of the signals can contribute substantially. A micro system for signal evaluation has been developed which is based on modular components complying with the Match-X platform technology. This solution contains components for analog preprocessing of acoustic signals, their digitization, algorithms for data reduction, and digital communication. The core component is a digital signal processor.

The acoustic monitoring concept using guided waves has been tested in combination with GFRP (glass fibre reinforced plastic) structures. Test specimens were damaged with mechanical impacts and were then tested. Application examples show how the monitoring system reveals delaminations.

Before a new technology like the above presented Monitoring System can be introduced using existing production processes several conditions have to be met.
For the reliability of any Structural Health Monitoring Concept with integrated systems appropriate quality management must be maintained in the production process of the fibrecomposite-structure to ensure the proper position, cable routing and function of the modules after curing of the fibre composite material. Necessary modifications in the process have to be economically justifiable.
The cable routing and the sensor of an embedded SHM-system must not have a negative influence on the structural integrity of the component to be monitored. The most important factor here is the possible generation of delaminations by the embedded modules or cables.
The reliability and durability of the sensor under cyclic loads is another critical factor which is investigated. A degradation of the sensor signal in connection with fatigue has to be accounted for when interpreting the signals. Otherwise the degraded signal could appear as a defect in the GFRP-structure.
By considering these aspects early in the development a safe and reliable Structural Health Monitoring System can be developed.

1. Introduction

Fibre Composite Materials allow to manufacture large and complex structures with minimum weight at relatively low costs. This is a typical material for e.g. aircraft, boats or rotorblades for wind energy plants. However when compared to metal the fatigue behaviour of composite material is more complex [1], [2].

In thunderstorms the impact of hail or thunderbolts can cause delaminations of the individual laminated layers of fibre composite material. This initial delamination slowly grows when alternating or fluctuating mechanical loads stress the structure. The delamination leads to a loss in stiffness. When a part of the structure is finally to weak to withstand the loads a sudden rupture of the fibres in the remaining cross section occurs. This can lead to a chain reaction destroying the whole structure, as shown in fig. 1. A rupture of a rotorblade of wind energy plants can endanger residents or other plants as far as 600 meters away.

It is therefore important to detect and monitor damages in high loaded safety components made of fibre composite materials to receive an early warning for a well timed shutdown of the facility respectively landing of the aircraft.

Fig. 1: Destruction of a wind energy plant after rupture of a rotorblade
source: (http://mitglied.lycos.de/nature2000/04032005.htm)

2. Structural Health Monitoring Concept based on acoustic detection

There are several structural health monitoring concepts for damage detection in fibre composite materials including fibre bragg sensors or modal analysis techniques. The first method provides information only when the damage is near the sensor. Traditional vibration-based monitoring techniques provide only global information about a structure under monitoring by identifying and analyzing specific resonance modes. Due to the low frequencies only large defects can be identified and moreover, cannot be precisely localized in general.

For crucial parts of a structure, vibration monitoring can be efficiently supplemented by using elastic waves in the kHz frequency regime. These ultrasonic waves have a shorter range but are more sensitive to smaller defects and thus, can serve as an early-warning system raising an alarm long before critical damage occurs. If the wavelengths are of at least the same size or larger than typical dimensions of the structure, the waves are called "guided waves". In this case geometrical dispersion cannot be neglected in general [3].

If using elastic waves for structural health monitoring purposes two different approaches are possible, a passive and an active approach. In a passive SHM system only sensors are needed and "natural" sources like impact, ambient vibrations or acoustic emission (AE) caused by crack generation and growth are detected (Fig. 2). The AE events can be localized and characterized and can also be used for imaging purposes using acoustic emission tomography [4].

In an active SHM system the transducers are acting as both, sensors and actuators (fig. 3). By using pulse-echo or acoustic signature techniques, scattered waves from inside the structure or changes in acoustic signature response can be detected and used as damage indicator. A set of transducers spans a so-called "synthetic aperture". By temporally delayed excitation and detection by individual actuators and sensors, elastodynamic wave fields can be focused to specific control volumes of the structure serving as basis for powerful SHM imaging techniques.

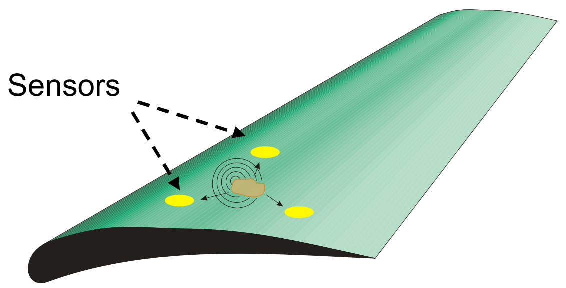


Fig. 2: Passive SHM approach: The sensors are used for detection of acoustic emission events caused by impacts or crack generation and growth. Also ambient vibrations can be monitored in principle.

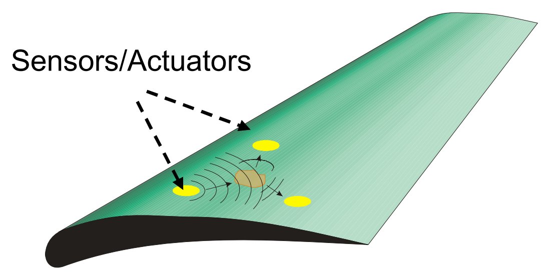


Fig. 3: Active SHM approach: The transducers are used as both, actuators and sensors in pulse-echo or transmission mode. Changes in acoustic signature response due to defect generation and growth serve as damage indicator during lifetime of the structure.

The simplest case of guided waves can be found in plate-like structures where so-called plate waves or Lamb waves can propagate. In general symmetric and antisymmetric wave modes are being distinguished (fig. 4 left). The dispersion diagram of a 1.5 mm thick aluminum plate showing phase velocity as a function of frequency reveals that various symmetric and antisymmetric wave modes are present and that they are dispersive in general (fig. 4 right). In most cases, SHM techniques are working in the low-frequency regime below 500 kHz and thus, only the 0th order Lamb waves are of interest for monitoring applications.

In addition to the Lamb waves also horizontally polarized shear waves (SH waves) can be used. In contrast to the Lamb waves the 0th order SH wave is non-dispersive. Numerical and experimental investigations show that each wave mode mentioned above shows different sensitivity to specific kinds of damage. For example the antisymmetric mode turns out to be well-suited for detection of delaminations.

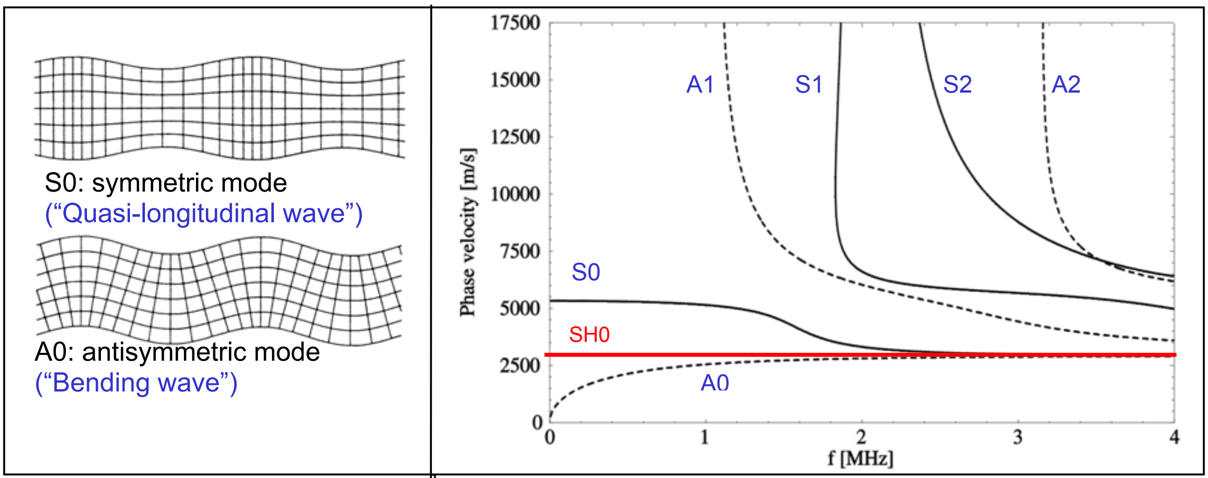


Fig. 4: Modes of vibration for 0th order Lamb waves (left). Dispersion diagram on the right: Phase velocity as a function of frequency (for a 1.5 mm thick aluminum plate) showing various symmetric and antisymmetric wave modes. The 0th order SH wave (horizontally polarized shear wave) is non-dispersive.

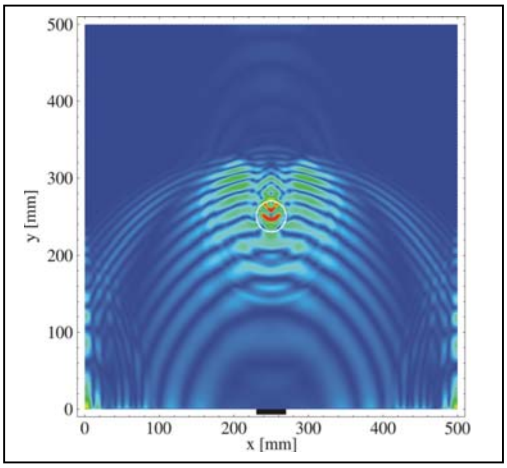


Fig. 5: Interaction of A0 mode with a circular delamination in a 3 mm thick GFRP plate

In fig. 5 the interaction of Lamb waves with internal defects obtained by numerical simulation using the elastodynamic finite integration technique (EFIT, [5]) is shown in an anisotropic 3 mm thick GFRP plate. In this case an incident A0 mode is scattered by a circular delamination in the GFRP plate.
In fig. 6 wave front snapshots at the surface of aircraft structures obtained by time resolved Laser vibrometer detection of the elastic wave field interaction of an A0 mode with two impact damages in a Carbon fibre reinforced plastics (CFRP) plate are shown. The numerical and experimental investigations serve as a basis for the design and optimization of the SHM system for specific structures with individual material properties and geometries.

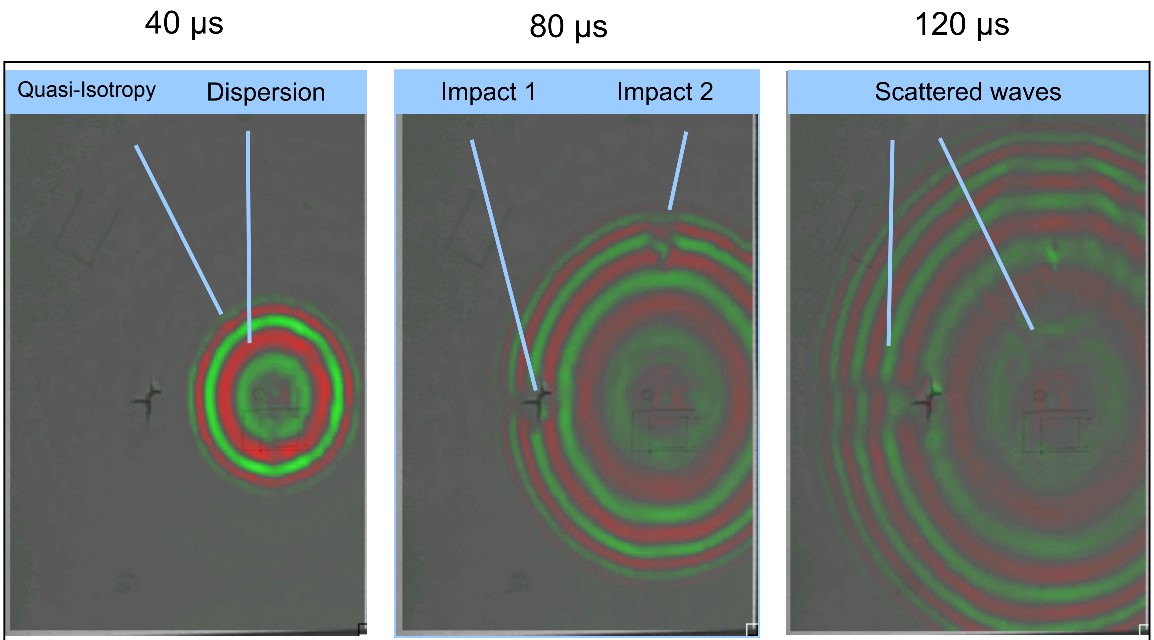


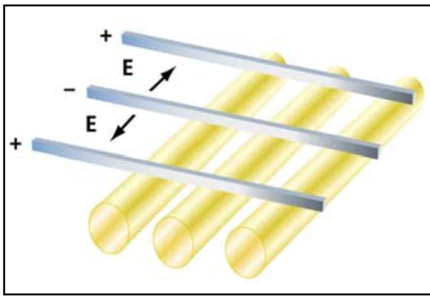
Fig. 6: Laser detected wave front snapshots of wave propagation and scattering of an A0 mode in a CFRP plate with two impact damages. The A0 wave is dispersive and shows significant interaction with the damage zones.

3. PZT fibre transducers

For the SHM-system piezo fibre transducers made of lead zirconate titanate (PZT) are used due to their low thickness. Fig. 7 shows the layout of a PZT fibre transducer with corresponding electrode structure. It can be used for both, excitation and detection of elastic waves.

The directional characteristic of the PZT fibre transducer depends on its size, the material properties of the structure and the signal frequencies used for monitoring. Therefore, optimised transducers for specific kinds of structures can be designed and applied. Moreover, by using enhanced electrode configurations a wave-mode specific excitation and detection of guided waves is possible.

The PZT ceramic is prepared by a special sol-gel process. Gelous PZT-precursors are spun to thin fibres with a diameter of around 30 µm. The endless green fibre is cut into 30 cm long threads to be sintered at 1100 °C in a special gas atmosphere. The sintered piezoceramic fibre threads are embedded in a polymer matrix and electrically connected with silver electrodes in an interdigital design (fig. 7). After polarization in an electrical field of 3 kV/mm these thin and flexible transducers (fig. 8) are ready for use.



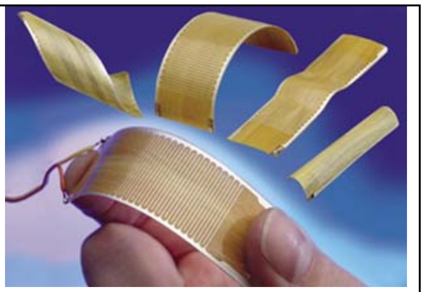


Fig. 7: Interdigital electrode on piezoelectric fibres

Fig. 8: Piezoelectric fibre composites - moldable to different geometries

Tests on fibre sensors laminated into a glass fibre reinforced plate show a high sensitivity to impact events depending on the orientation of the fibres respectively. For ultrasonic applications the piezoelectric transducers can be manufactured in a special design for frequencies up to more than 10 MHz. Fig. 9 shows a transducer resonance in the impedance spectrum of a piezoelectric fibre composite. The properties of the transducers are listed in fig. 10. The transducers are developed and produced at Fraunhofer ISC.

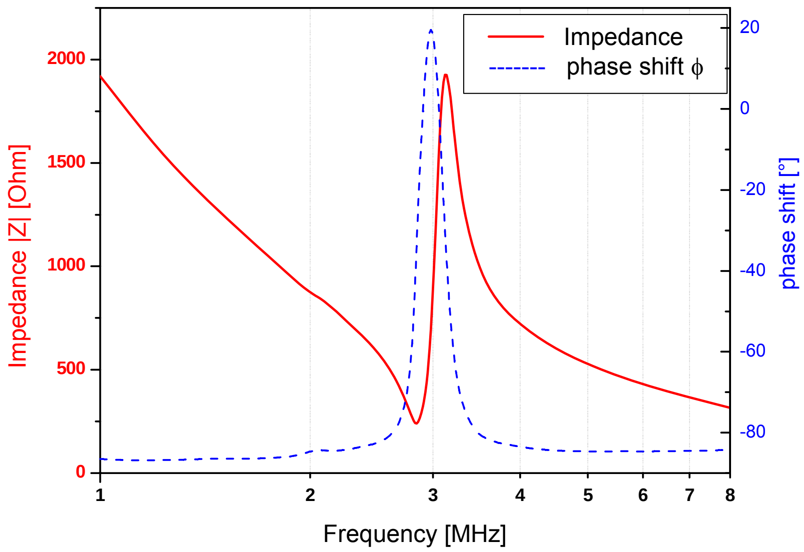


Fig. 9: Resonance of a ultrasonic transducer

Size	in 1-2 design 60mm / 25mm / 0.6 mm
Fibre content	20 ... 50 %
Matrix polymer	2 K epoxy for aircraft application
Temperature range	-40 ... 80 °C
Frequency range	0.1 ... 10 MHz
Sensitivity	1 ppm (0.001‰)
Capacity C	200 pF (@ 1kHz)
Loss tangent tan δ	0.012 (@ 1 kHz)
Impedante Z	2 MΩ (@ 1 kHz)
Permittivity ε_r	1200 (@ 1kHz)
Critical field E_C	1.2 kV/mm
Coupling coefficient k_{eff}	0.25
Piezoelectric modulus	200 pC/N
Young's modulus	8 GPa

Fig. 10: Typical properties of piezoelectric fibre transducers

4. Integration of transducers in the structure

As the material allows the integration of thin transducers in the structure an ideal acoustic coupling can be achieved. The embedded monitoring device is directly bonded to the fibres. By avoiding thick adhesive films and using the top and bottom side of the monitoring device a higher acoustic performance can be achieved. Embedding sensors offers several unique advantages compared to applied devices. Both concepts are compared in fig. 11.

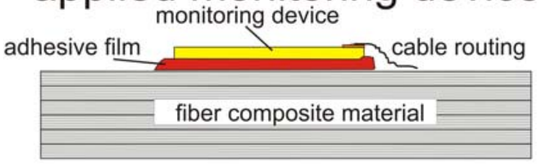
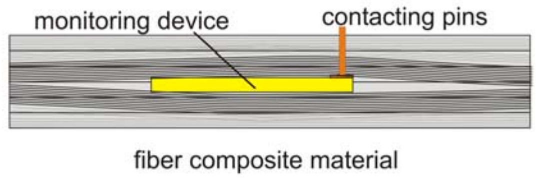
applied monitoring device	integrated monitoring device
 	
+ easy to apply in accessible areas + no influence on the structural durability of the fibre composite material	+ better bonding of the embedded element to the structure (top and bottom side are used) + lower costs in mass production possible + monitoring device can be integrated everywhere in the structure + better protection from environmental effects + better protection from forces of acceleration + no influence on aerodynamic shapes - influence of the embedded device on the structural durability of the fibre composite material must be taken into consideration.

Fig. 11: Comparison of applied and embedded monitoring devices

5. Electronics

The integration of the monitoring system into a modular development platform is based on so-called Match-X micro-systems technology [6]. Fig. 12 shows a single sensor/actuator node system stack with a CAN bus. Alternatively, wireless data transmission modules are available. This system is in further development at Fraunhofer IZFP.

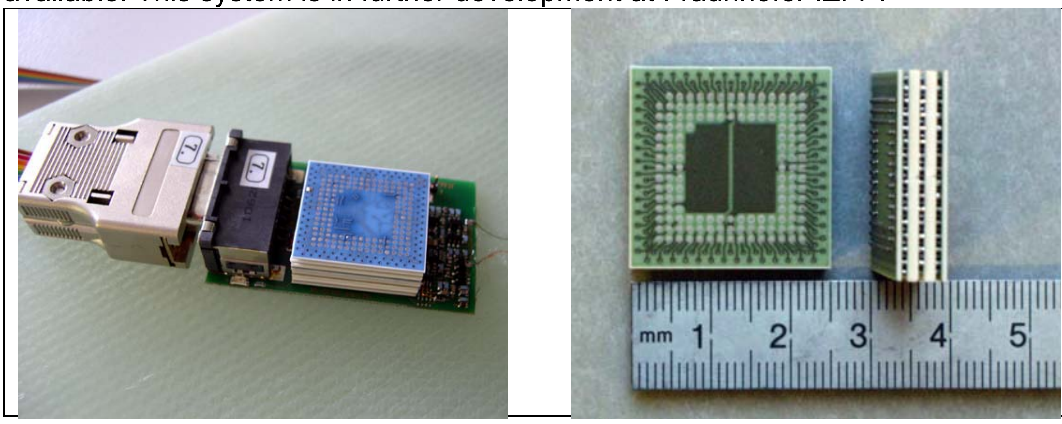


Fig. 12: Sensor/actuator node based on Match-X technology as used for SHM applications.

6. Examples of application

Fig. 13 shows the instrumentation of a 3.5 mm thick GFRP plate with four Match-X sensor nodes for passive impact detection. Data transmission is performed via CAN bus.

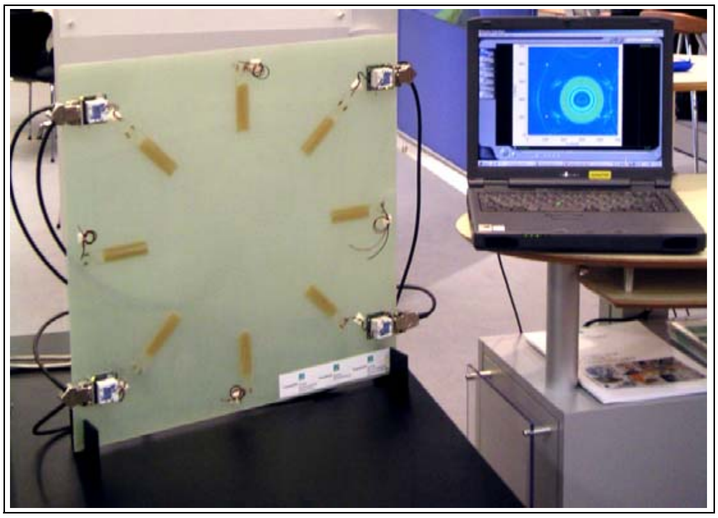


Fig. 13: Instrumentation of a composite plate with four sensor/ actuator nodes

Fig. 14 shows an aircraft sandwich-wing with embedded PZT fibre transducers. The SHM system can detect impacts, fibre cracks and delamination in this and similar structures. The typical production process for such structures needs only minor changes to ensure reliable electric contacting of the transducers after curing the fibre composite material.

Fig. 14: Embedded PZT fibre transducers for Structural Health Monitoring of an aircraft wing.

7. Qualification of SHM-systems

Before a new SHM-system can be introduced its reliability must be proven [7], [8]:

- The reliability of the monitoring device concerning a possible signal degradation by fatigue and the interaction with the observed structure during service must be proven. A possible signal degradation of the transducer signal by fatigue has to be taken into account for the correct interpretation of the signals. Otherwise the degraded signal of a faultless structure could be mixed up with a signal of a defect structure. In this project the lifetime of piezoelectric fibre composites has been proven for more than 10^8 cycles at 1‰ strain. At the moment the effects of embedded monitoring devices on the structural durability of fibre composite structures are investigated at Fraunhofer LBF.

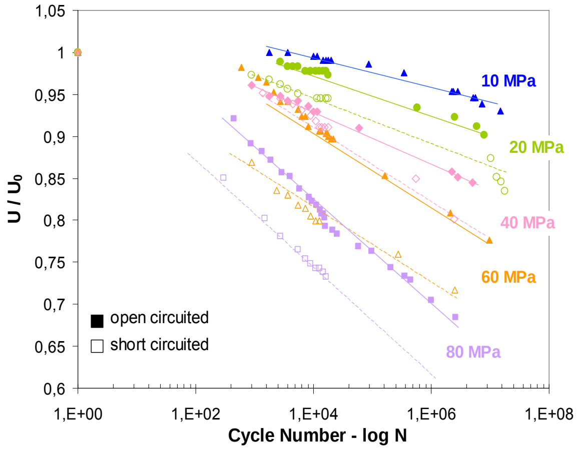


Fig. 15: Change in signal output of PZT-material due to fatigue [9].

- The reliable response of the SHM-system to the critical failure must be proven in a preliminary test. For this purpose the indicated signal of the new system has to be matched with alternative monitoring systems to calibrate the new system. An example is given in the following figures.

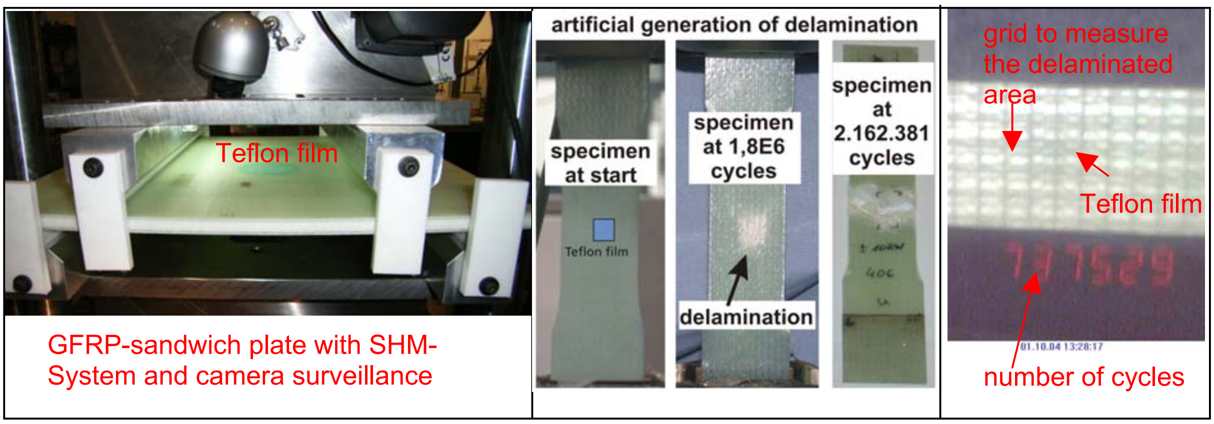


Fig. 16: On the left a recently designed test rig for a composite sandwich-plate of 500 mm x 500 mm is shown. In the middle of the plate a Teflon film generates an artificial delamination as shown in the pictures in the middle. An optical surveillance system as shown on the right is used to compare the data (position and size of number of cycles of the SHM-System in the laboratory test.

8. Summary

In this paper a short review of typical failures in safety components of fibre composite material is given. It is shown how waves propagate in shell- and plate-like structures and how they interact with defects. This interaction is the key of the Monitoring System and can be studied by using numerical simulation techniques and Laser vibrometric detection. The transducers, the advantages of their integration in the structure and the electronics are reviewed in detail. Finally a suitable qualifying concept for SHM-Systems is demonstrated.

The SHM-concept of the three involved Fraunhofer Institutes based on acoustic detection by guided waves is an appropriate option to increase the safety of critical components.

9. References

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