Characterization of the Mechanical Influence of Comparative Vacuum Measurement (CVM) Sensors in the Context of Structural Health Monitoring (SHM) Systems

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ABSTRACT

Due to the rising number of fiber-reinforced plastic (FRP) parts in industry, nondestructive testing (NDT) as well as structural health monitoring (SHM) is becoming increasingly important to detect damage and to guarantee structural safety. Both methods have in common that the same damage types have to be detected. In the first case the damage evaluation is performed during maintenance whereas in the second case the status of a structure is monitored during service. Therefore this paper describes typical defect types and gives an overview of the main NDT and SHM methods, before a new SHM method is addressed and described in detail. The comparative vacuum measurement (CVM) method can be used to localize and detect defects in complex structures in service as well as during maintenance. The main advantages of this method are the low sensor costs as well as the applicability to complex geometries and structures together with a simple data evaluation. The main drawback is the mechanical treatment of the substrate. Patterns of small holes have to be drilled into the structure and may have an effect on its mechanical properties. Therefore tensile tests with a typical hole pattern are performed and the local strain distribution around the holes is investigated using a stereo correlation measurement system. The obtained experimental results should build a base for the application of such SHM networks on larger structures.

INTRODUCTION

In the past years, the number of FRP applications for high performance structures was strongly increasing in nearly all kinds of industry. Due to their good weight specific properties, FRP and in special carbon fiber reinforced plastic (CFRP) is

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heavily used in aerospace as well as in the automotive industry. The heterogeneity of the material results in different damage mechanisms compared to metallic structures. In most cases damage occurs in the structure and is not optically visible. Therefore NDT techniques as well as SHM methods have to be used in order to locate occurring defects.

COMPARISON OF SHM AND NDT METHODS

Before comparing the different methods, typical damage types of FRP structures have to be addressed.

Typical defect types

In general three different kinds of damage can be observed in FRP structures. Damage can occur within the matrix (e.g., delamination), at the interface between matrix and fiber (e.g., fiber-matrix debonding or fiber pullout) or the fiber itself can break (e.g. fiber cracks). In most cases these damage types occur in combination with each other. In order to perform a parametric study to characterize the defect sensitivity of a SHM or NDT system, defects of different kinds and size have to be inserted in specimens systematically (see for example [1]).

Delaminations are thought to be one of the most critical damage types due to the high influence on the compression and shear properties of a fiber laminate [2]. That is the reason why this special damage type should be addressed in detail in this paper.

In order to create delamination areas of different sizes, inclusions of foils can be inserted into fiber laminates that have similar properties compared to real delaminations [3]. The advantage of this method is that all kinds of different defect geometries can be created reaching from circular areas of different diameters up to rectangular delaminations of different sizes or any user defined shape. Another approach that is often used is damage caused by external impact loads [3]. Different damage areas can easily be achieved by varying the impact energy. Compared to the previously described method, the two main drawbacks are that the shape of the damaged area is fixed and that other damage types occur in combination with delamination.

NDT Methods

Although there are large numbers of different NDT methods available on the market, only some techniques are used in most cases for the characterization of structures in aerospace or automotive industry. Apart from ultrasonic measurements different thermal techniques are commonly used to detect defects in FRP structures after fabrication or during maintenance.

These methods are completed by high precision three dimensional techniques that are commonly used to determine damage in detail at selected specimen (in general small geometries) and to define references for ultrasonic and thermal measurement systems (e.g., Computer Tomography - CT).

Acoustic Methods

In the aerospace industry, water coupled impulse-echo ultrasonics is commonly used to qualify CFRP structures. The principle of this measurement technique is described in [4]. Delaminations can be detected very well as shown in **Figure 1**, in which a delaminated area after impact can be observed. Due to the combination of punctual measurements, a high contrast between damaged and undamaged areas can be achieved, strongly depending on the chosen investigation grid. The measurement time is correlated directly with the grid size. That is the reason why a tradeoff has to be made for the investigation of large parts.

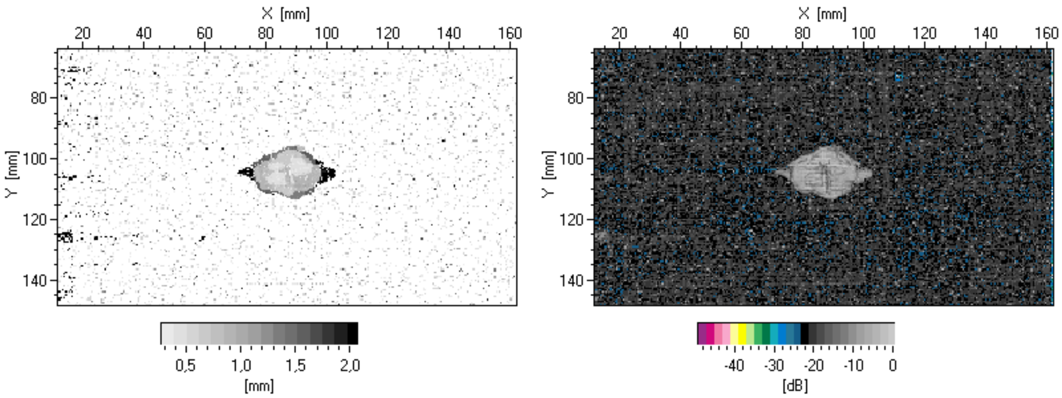

Figure 1. Ultrasonic C-scans of a 10 J impact damage of a 2 mm thick [0°/90°] CFRP specimen: damage depth (left) and attenuation of the backwall echo (right).

Due to the different acoustic properties of fibers and resin, also resin concentrations can be detected. Furthermore, porosity is often characterized using ultrasonic measurement after fabrication. The attenuation of the backwall echo can be correlated with the local porosity of a structure if the material and geometrical parameters are known. Due to the fact that this kind of measurement is only a relative measurement, reference CT measurements or cross-sections are required to define absolute values.

Thermal Methods

In industry, different kinds of thermal NDT methods are used. Apart from heat flow thermography, which is a low cost method with low defect sensitivity (see for example [5] or [6]), phase sensitive methods are used to identify defects in CFRP structures. In most cases, a modulated thermal excitation is used, which provokes a time dependent thermal flux in the specimen that interacts with defects. The thermal amplitude of the time dependent surface temperature together with the possible time or phase shift of the measured signal compared to the excitation is used for damage characterization.

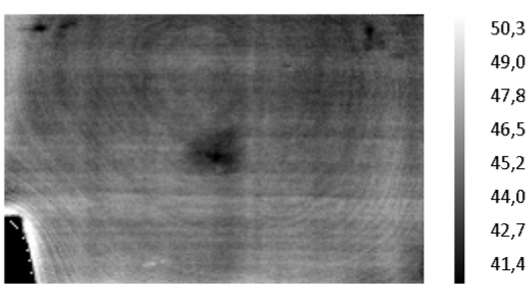

Figure 2. Thermal phase image of a 10 J impact damage of a 2 mm thick [0°/90°] CFRP specimen: Excitation frequency: 0,10 Hz.

Figure 2 shows the results of a thermal investigation of the same specimen as described above in the ultrasonic section. The used thermographic system is called Sequential Phase-modulated Thermography (SPT) [1] and is based on the Lock-In method. The results show a similar defect area compared to ultrasonic investigation.

Due to the fact, that the thermal measurement is a 2-D measurement, big structures can be characterized effectively by using a thermal sensor with high resolution. The defect sensitivity of this system is comparable to impulse-echo ultrasonics.

SHM Methods

In order to reduce maintenance costs and to increase structural safety of FRP structures, the number of SHM systems in use is increasing. In general a combination of multiple sensors is used in order to characterize the damage state of large structures (e.g., CFRP panels, etc.). In many cases, piezoelectric sensors or Fiber Bragg Grating (FBG) sensors are used to build these networks. A recent developed alternative method is the comparative vacuum measurement (CVM), which should be focused in this paper.

Acousto-Ultrasonic (AU) sensor network

In most cases, piezo stacks are used to generate acoustic waves that propagate in thin structures [7]. The propagating Lamb- and Rayleigh-waves interact with defects such as delaminations or stringer debondings in case of stringer stiffened CFR panels, which represent one main field of application in the aerospace industry. This interaction leads to a change in the propagation pattern compared to the undisturbed wave propagation and can be used to detect and localize defects.

This method produces good results for large flat and curved structures, but an increase in geometrical complexity (stringers, cutouts, etc.) has a significant influence on the detection ability. A further disadvantage is that every single sensor of a sensor network has to be connected separately to an amplifier. These connectors and the amplifier itself increase the total system weight significantly.

Fiber Bragg Grating (FBG) sensor network

In order to decrease the number of connectors, FBG sensors [8] can be used as an alternative approach. Multiple FBG sensors can be monitored using a single connection unit. A FBG sensor network consists of optical fibers with multiple FBG sensors and is a strain based monitoring system. It uses the differences in the strain field due to flaws or defects in comparison to an ideal structure to detect and to locate defects. Furthermore, they can be integrated into composite materials as shown in [9].

Comparative Vacuum Measurement (CVM)

The CVM method is a distributed sensor network that can either act as a conventional SHM method to monitor the state of a CFRP structure in service or can be used during maintenance. It is based on leakage measurements of small volumes (see e.g. [10]). In most cases, multiple manifold sensor patches are combined to generate a sensor network. In case of CFRP structures, hole patterns are required to detect delaminations in the structure.

Figure 3 presents a schematic side-view of a self-adhesive, elastomeric sensor with fine channels etched on the adhesive face mounted on a CFRP structure.

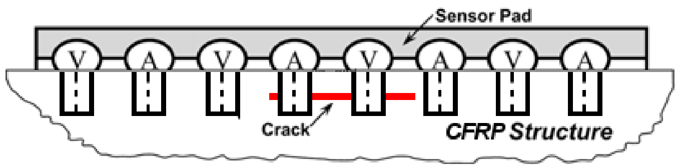

Figure 3. Schematic side-view of a self-adhesive, elastomeric sensor mounted on a CFRP structure (according to [10]).

The CFRP structure is equipped with a hole pattern of stud holes. In case of an undamaged structure, there is no leakage between two or more stud holes. If a crack or a delamination is present, air flow occurs between two or more holes, which can be detected and localized.

Due to the high flexibility in the geometry of the sensor patches, also complex geometries can be equipped with CVM sensors. The sensors can be mounted on different materials and structures and do not require electrical amplifiers or transducers as it is the case for AU, which results in a reduction in weight of the whole system. Another advantage is that a large number of sensors can be monitored using a single pressure connector. The main drawback of this method is the mechanical treatment that is required to detect defects in CFRP structures.

INFLUENCE OF MECHANICAL TREATMENT FOR CVM MEASUREMENT TECHNIQUE

As described before, the CVM technique has a large number of advantages compared to other SHM methods. Focus is given on the main disadvantage, the mechanical treatment. The influence of the hole patterns regarding the mechanical properties of the structure is investigated. Therefore CFRP specimens with different lay-ups are used.

Test specimen

The test specimen for the influence of the mechanical treatment for the CVM-sensors are standard sized tensile test specimen and have been fitted with a single row of holes in the center of the specimen to achieve symmetric stress distribution. The hole diameter has been taken from the requirements for CVM-sensors. The distance between the holes is 20mm and has been derived from the requirements for the detection of impact damages on a CFRP-breadboard where the minimum size of a detectable defect should be 40mm.

Strain measurement

Strain measurement for all specimens is conducted with the help of a stereo correlation measurement system (GOM Aramis) as it is not possible to measure the strain distribution around the holes required for the CVM measurement system using a strain gauge. Additional benefits of the stereo correlation system are:

- Specimen surface is not damaged
- Local strain distribution can be visualized
- Adjustable size of monitored area to task at hand
- Strain resolution between 0,01% and 100% of surveyed area

For the strain measurement during tensile tests, an optical pattern – of black and white dots – is spray-painted on the specimen surface. The pattern is monitored by two CCD-cameras throughout the test to calculate the changing distances between the dots' positions caused by the specimen's elongation. During post processing, the data of both cameras is combined thus creating a 3D-deformation image and to calculate strain and displacements of the surveyed area.

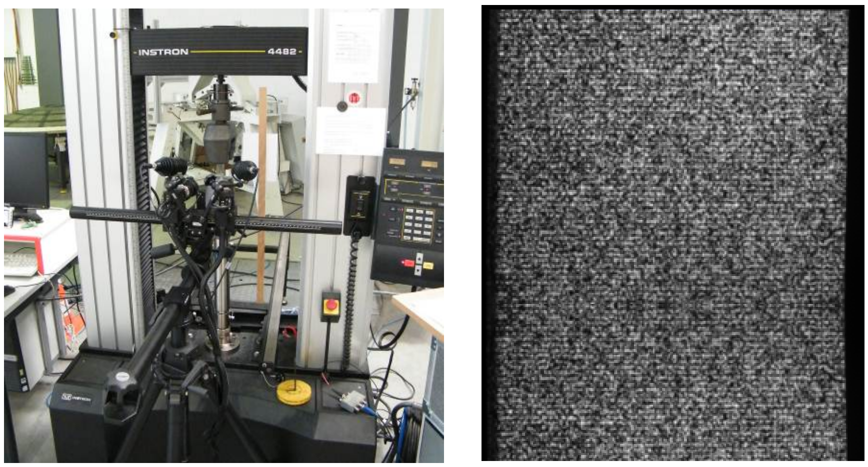

Figure 4. Test-bed for tensile tests with stereo correlation measurement system (left) and detail of optical pattern on specimen (right).

Results for the different stacking sequences show a local increase in the strain level that is caused by the holes in the specimen and influenced by the orientation of the outer layer.

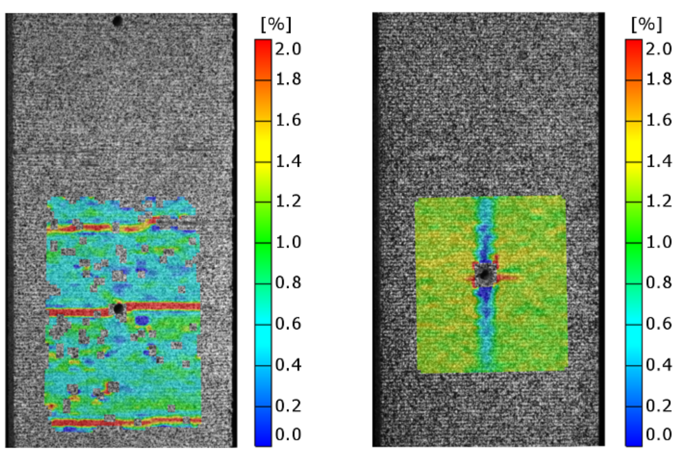

Figure 5. Maximum axial strain levels for orthotropic (50% 0°/ 50% 90°) specimen with 90° outer layer (left) and orthotropic (60% 0°/ 40% 90°) specimen with 0° outer layer (right).

Figure 5 shows that the CVM-holes cause two local strain maxima perpendicular to the applied stress for the specimen with 90° outer layer and four local maxima parallel to the applied stress for the specimen with 0° outer layer with two sections of relatively low strain levels at the top and bottom side of the holes. These two sections with low strain levels are caused by the CVM-holes as the fibers in these locations have been cut during drilling and therefore do not transfer loads.

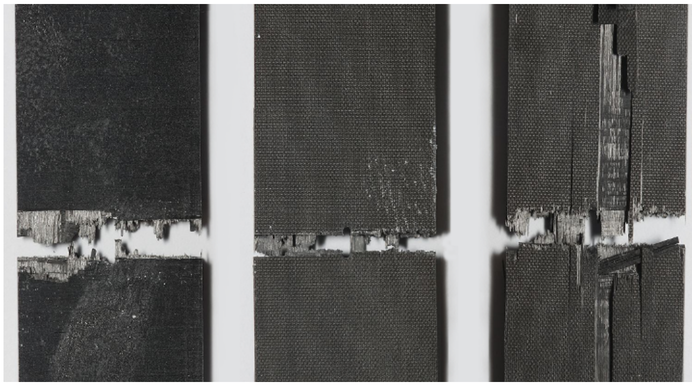

Figure 6. Fracture patterns of different orthotropic stacking sequences: 50% 0° / 50% 90° with 90° outer layer (left), 50% 0° / 50% 90° with 0° outer layer (middle) and 60% 0° / 40% 90° with 0° outer layer (right).

Correlation of strain data from the GOM Aramis measurements and the fracture patterns (see **Figure 6**) of the specimens proves that for specimens with CVM-holes, failure always occurs at the holes. The local strain maxima recorded with the stereo correlation system indicate the position of the fracture as well as the type of fracture that will occur at an early stage of the test whereas for specimens without CVM-holes the local strain maxima indicating the position of the fracture will only appear directly before the fracture.

Influence of mechanical treatment

The tensile tests on the different specimens show that regardless of the stacking sequence or the orientation of the outer layer of the specimens, the introduction of the hole pattern for the CVM-sensors results in a significant reduction of ultimate stress levels (see **Figure 7**).

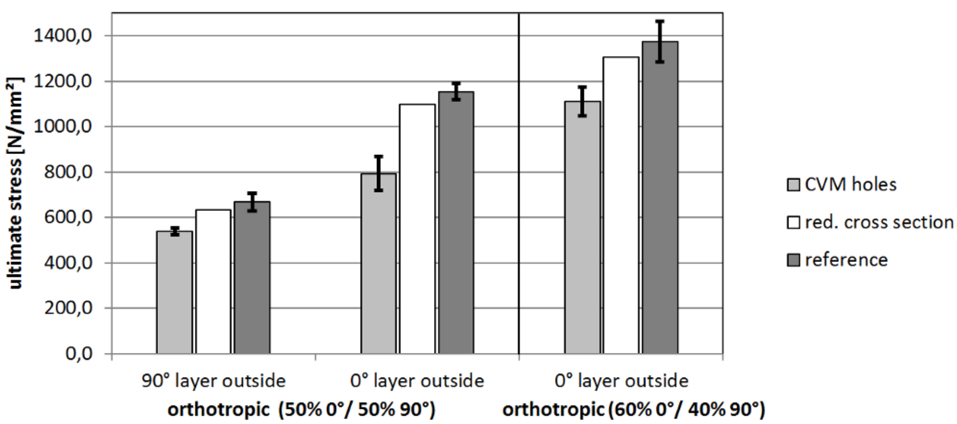

Figure 7. Influence of CVM holes on the ultimate load of orthotropic CFRP structures.

Additionally to the ultimate stress levels for specimen with and without holes, **Figure 7** plots the expected levels for the reduced cross sections, thus neglecting the area occupied by the holes.

Due to local strain maxima at the edges of the holes the effect of the holes on the ultimate stress levels is higher than anticipated when using a reduced cross section. The test data indicates that directly next to the holes the maximum strain before failure of the specimen reaches levels of over 1,5% for all tested specimen with 0° and 90° outer layer (see **Figure 5**) causing fiber cracks in the area next to the holes and in consequence fracture of the specimen itself.

CONCLUSION AND OUTLOOK

The obtained results indicate a significant influence on the mechanical properties as well as the damage pattern when a hole pattern for CVM is present. In order to characterize the influence of this mechanical treatment for real applications, larger structures have to be used and a 2-D pattern has to be applied. The mechanical behavior of this CFRP structure (e.g., CFRP Panel) with and without hole pattern has to be investigated. Also the influence of the hole pattern on the initial damage behavior of the structure itself is of interest. That is why impact tests should be performed with CFRP panels with and without hole patterns. Thereafter the resulting damage has to be measured using a NDT system, mentioned in this paper.

A further issue for future research is the fatigue behavior of the structure itself as well as the CVM Sensor and the Sensor-structure interface.

REFERENCES

1. M. Perterer, H. Baier, F. Höchtl. Cost-Effective, Phase-Based Thermography Method for Ultrasonic Investigation of defects in CFRP Structures. *SAMPE Journal*, Vol. 47, No. 6. (2011), p 46-52.
2. A. Puck. *Festigkeitsanalyse von Faser-Matrix-Laminaten: Modelle für die Praxis*. Carl Hanser Verlag München Wien. 1996.
3. M. Perterer, F. Höchtl, A. Kiefmann, H. Baier, V. Senner. Kosteneffiziente phasenmodulierte Thermographie zur Schadensdetektion an flachen und stark gekrümmten Bauteilen aus CFK. *DGZfP-Jahrestagung 2011*. Berichtsband 127-CD 2011. Bremen.
4. K.-J. Langenberg, R. Marklein, K. Mayer. *Theoretische Grundlagen der zerstörungsfreien Prüfung mit Ultraschall*. Oldenbourg Verlag München. 2009.
5. X. Maldaque. *Infrared Methodology and Technology*. Gordon and Breach Science Publishers. 1994.
6. X. P. V. Maldaque. *Theory and Practice of Infrared Technology for Nondestructive Testing*. John Wiley & Sons. Inc. 2001.
7. U. Berger. *Überwachung von Bauteilen mit Hilfe von Schwingungen und Festkörperwellen*. Technische Universität München, Fakultät für Maschinenwesen. Dissertation. München. 2006.
8. U. C. Müller. *Structural Monitoring and Displacement Field Estimation based on Distributed Fiber Bragg Grating Sensors*. Technische Universität München, Fakultät für Maschinenwesen. Dissertation. München. 2010.
9. W.J. Staszewski, C. Boller, and G.R. Tomlinson. *Health Monitoring of Aerospace Structures - Smart Sensor Technologies and Signal Processing*. Wiley & Sons, Chichester, U.K. 2004.
10. Roach, D.: Real time crack detection using mountable comparative. *Smart Structures and Systems*. Vol. 5, No. 4 (2009), p. 317-328.