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Development of an integrated measurement system for CFRP components within automotive manufacture

CarbonSafe – Zbudowanie zintegrowanego systemu pomiarowego dla komponentów CFRP w przemyśle motoryzacyjnym

ABSTRACT

Overview of a German project funded by the Federal Department of Education and Research within the scope of the priority program “KMU Innovativ” (Funding No. 16ES0333).
The idea of the project was to develop a simple, but efficient SHM system for CFRP structures based on guided waves. The key milestones of the project were:
- specification of required sensors and development of sensors
- sensor characterization and application
- concept of external diagnostic equipment
- transducer self-test
- validation by generic geometries
- proof by POD and simulation of measurement results
- implementation of sensors into automotive structure
- field test.

Keywords: *Carbon fibre reinforced plastic (CFRP), automotive manufacture, guided waves, structure health monitoring (SHM)*

STRESZCZENIE

Przegląd niemieckiego projektu finansowanego przez Federalny Departament Edukacji i Badań w ramach programu priorytetowego "KMU Innovativ" (Fundusze nr 16ES0333). Ideą projektu było opracowanie prostego, ale skutecznego systemu SHM dla struktur CFRP bazującego na zastosowaniu fal prowadzonych. Kluczowymi kamieniami milowymi tego projektu były:
- specyfikacja wymagań i opracowanie czujników
- określenie charakterystyki i zastosowanie czujnika
- koncepcja zewnętrznego sprzętu diagnostycznego
- autotest przetwornika
- walidacja za pomocą ogólnych geometrii
- dowód przez POD i symulacje wyników pomiarów
- wdrożenie czujników do rozwiązań samochodowych
- test w terenie

Słowa kluczowe: *kompozyt zbrojony włóknem węglowym (CFRP), produkcja samochodowa, fale kierowane, monitorowanie stanu konstrukcji (SHM)*

1. Motivation

Today low-weight and high-strength components are used for automobile production or in aerospace sector which exhibit a high energy absorption. With respect to electromobility such materials are an excellent compensation of the heavy batteries.

However, there is one drawback: the damage behaviour of carbon fibre reinforced plastics components (CFRP) is completely different from that of materials previously used such as light metals or steel.

The structure of CFRP might be damaged upon a heavy impact. Fig. 1 shows an impact damage effect in a longitudinal CFRP structure.

Main reasons for damage are
- delaminations;
- damage of the matrix;
- fibre cracks.

Furthermore, cavities or dry spots may occur. Main cause for damage are the different component properties – fibres and resin. Damage minimise the durability of the automobile structure dramatically. Normally, that is due to crashs, hail or rock fall.

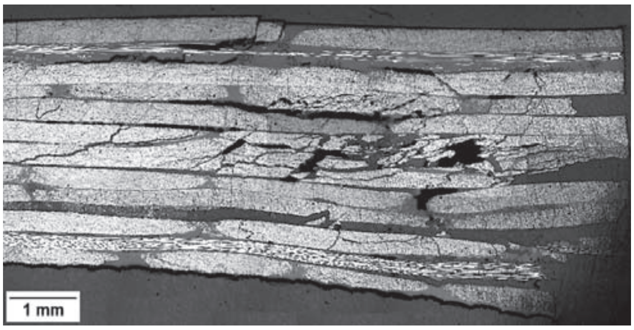

Fig. 1. Longitudinal cross section of a CFRP structure with impact damage [1].
Rys. 1. Przekrój podłużny struktury CFRP z uszkodzeniami uderzeniowymi [1].

Unfortunately, this type of damage quite often is not visible, viz. cannot be detected by visual testing. Only time-consuming pulse-echo ultrasonic testing is able to detect

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this damage non-destructively. However, one advantage is: Determination of depth as well as the extent of damage can be recorded.

Fig. 2. Pulse-echo ultrasound test device VAS 852 003, designed for Audi R8 2016 [2].
Rys. 2. Ultradźwiękowy aparat impulsowej metody echa VAS 852 003 zaprojektowany dla Audi R8 2016 [2].

Besides the long duration of the tests further drawbacks are: the structure must be well accessible to carry out the test, and the test personnel must be qualified.

2. The CarbonSafe Project

The CarbonSafe Project was designed to develop a suitable Structure Health Monitoring (SHM) system based upon the application of ultrasonic guided waves for monitoring CFRP incorporate structures in automobiles. The aim was to implement the piezoelectric transducers permanantly on or in the CFRP component. All sensors should be able to perform a self-test. Test instructions should be developed, so that the monitoring could be integrated into the routine revision of the workshop.

The project was funded by the German Federal Ministry of Education and Research. The project period was 3 years. The project was completed in May 2018.

2.1 The Consortium

The consortium partners are:

- INVENT GmbH was the leader of the consortium and responsible for:
  - development of suitable sensors;
  - production of test specimens;
- Fraunhofer Institute (IKTS) in Dresden was mainly responsible for:
  - classification of damages in CFRP;
  - probability of detection investigations (POD);
  - simulations;
- University Siegen was involved:
  - in investigations concerning the capability of self-testing of the sensors;
- Autohaus ELITZSCH, a car dealer in Dresden:
  - supported the project by provision of a suitable car for the field tests;
- German Society for NDT (DGZfP e.V.) had the tasks to:
  - investigate the possibility of integration of the new technique into vocational training;
  - develop training material with regard to the functioning of the final Structural Health Monitoring System (SHM System).

Additionally, the project was accompanied by an advisory board with members from different automobile and electronic device manufacturers. Several meetings took place and the interest was quite high.

2.2 Ultrasonic guided waves

Guided waves result from reflections of longitudinal and shear waves at borders in plate-like structures. These guided waves propagate planarly along the surface or between two surfaces of a test specimen. The localisation of a defect is possible through the interaction of the guided wave with the material defect.

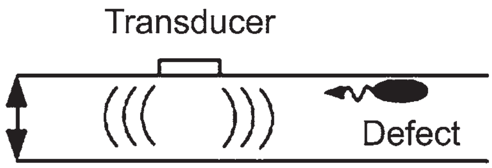

Fig. 3. Ultrasonic testing with guided waves [3].
Rys. 3. Badanie ultradźwiękowe z zastosowaniem fal kierowanych [3].

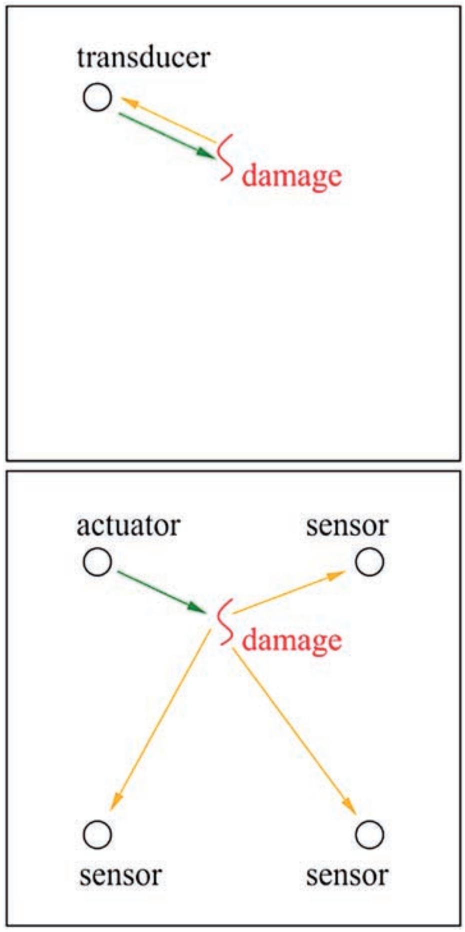

Fig. 4. Pulse-echo method (up), pitch-catch method (down).
Rys. 4. Impulsowa metoda echa (góra), metoda pitch-catch (dół).

Guided waves excel with high range. Large components and structures which are difficult to access can be tested in short time. Two different modes of application are possible: pulse-echo or pitch-catch.

Good results were already obtained by NDT in the aerospace industry. Suitable SHM systems for automobile structure were still missing.

2.3 Components of SHM system

Piezo-electric transducers

The requirements were:

- Ready-to-integrate into typical automobile's manufacturing processes e.g. by RTM (resin transfer moulding) injection method based on preforms:

1) Placing the preform (non-impregnated semi-finished product) into the two-piece injection tool
2) Injecting resin with constant volume stream and pressure into the closed tool
3) Hardening by, e.g., air jet
4) Removing the component from the tool

During this process transducers and cables can already be placed at the predetermined locations. So they can join with the structure during the hardening process (Co-Bonding).

- over an area of 1 m^2 not more than 10 transducers should be distributed with efficient coupling;
- because the transducers have to be integrated into the surface during the production period of the component, they must be of very flat design;
- furthermore, they must be of similar fatigue strength and resistance as the component.

Fig. 5. DuraActTM transducer (series design).
Rys. 5. Przetwornik DuraActTM (wykonanie seryjne).

Characterisation of transducers

For characterisation of the transducer beam characteristic in generic components the wave field was measured with a 3D laser vibrometer [4] (see Fig. 6). Suitable measurement frequencies were determined by impedance analysis.

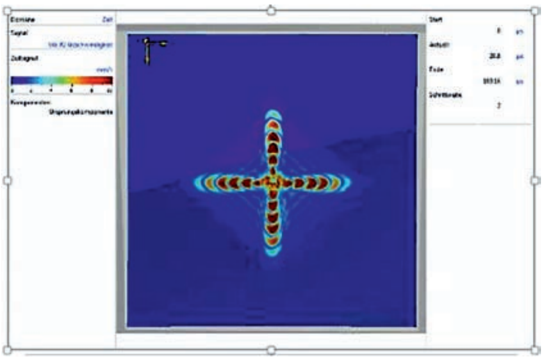

Fig. 6. Measurement of wave fields with 3D laser vibrometer (RC5-impulse, 200 kHz).
Rys. 6. Pomiar pola fali za pomocą wibrometru laserowego 3D (RC5-impulse, 200 kHz).

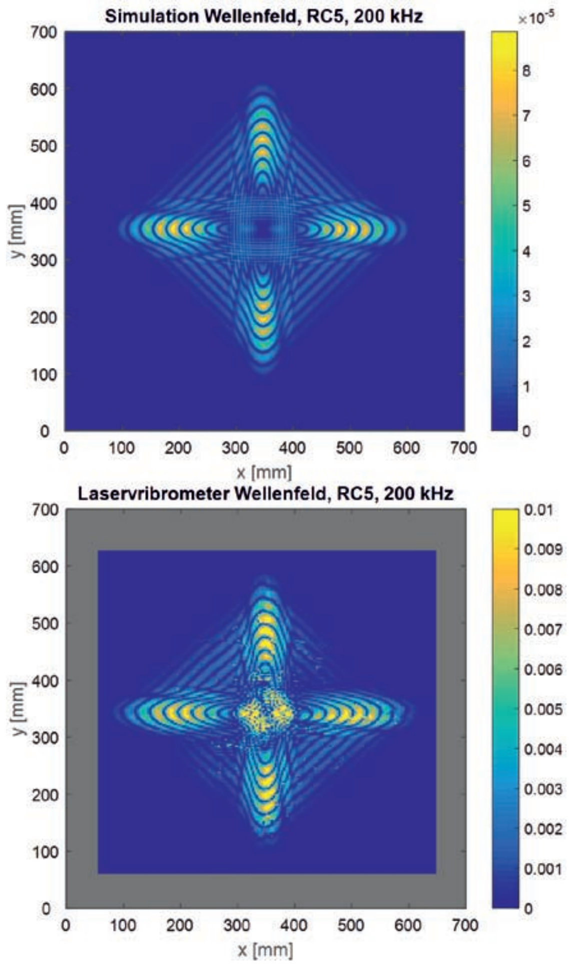

Fig. 7. Comparison of results: Simulation of the wave field (up), laser vibrometric measurement of the wave field (down).
Rys. 7. Porównanie wyników: Symulacja fali (góra), laserowy pomiar wibrometryczny pola falowego (dół).

The resonance behaviour of the transducer and the adjacent structure can be recognised by measurement of the impedance. The transducer should not operate at a frequency range, in which resonance appears. This would hamper the later signal evaluation significantly. Furthermore, it is necessary for the later measurement method to identify a frequency range, in which the transducer shows a uniform vibration behaviour.

In addition, the interaction of the wave field with defect locations was simulated and compared with laser vibrometric measurement. The results shows a very good coincidence between simulation and laser vibrometric measurement (see Fig. 7). Finally, measures to protect the system against electromagnetic disturbances (EMC) were untertaken.

The number of transducers required for a given structure under consideration of fail of one transducer can be determined with this procedure, as well as the locations where the transducers should be placed on the structure.

Transducer self-test

The SHM system must be able to identify damaged transducers through a self-test and exclude them from the system. Exchange of damaged transducers is not possible. The self-test is based on measurement of the electromechanic impedance spectrum which depends on the temperature. It compares the actual condition with the measured baseline under same temperature of the environment or by compensation of the temperature difference. [5].

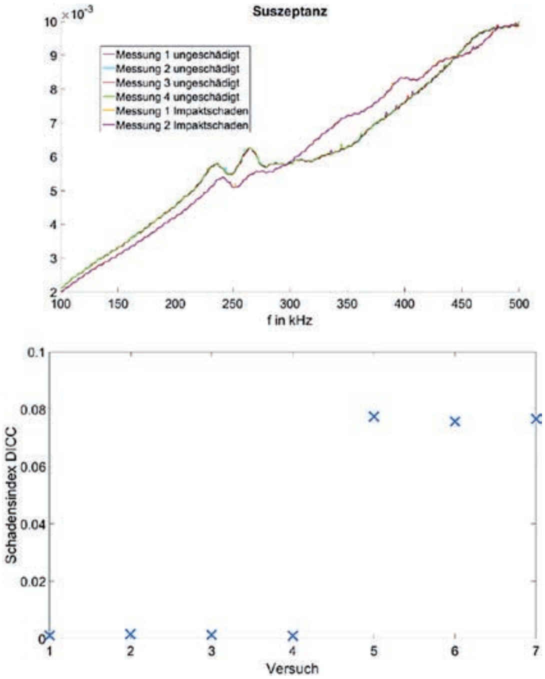

Fig. 8. Susceptance (up) and damage index (down).
Rys. 8. Zużycie (góra) i wskaźnik uszkodzeń (dół).

By this procedure damaged transducers can be clearly identified. Their malfunction can be considered in the evaluation.

SHM system and field test

During the progress of the project a CFRP component with an integrated transducer network was developed using the RTM method and co-bonding. The diagnostics equipment consists of the measurement electronics, a preamplifier and a small PC built in a housing (see Fig. 9).

Fig. 9. Open diagnostics equipment.
Rys. 9. System diagnostyczny otwartego dostępu.

For function proof of the SHM system a generic crash reinforcement structure was produced as reference structure using the RTM method. In the final version transducers were integrated in the component.

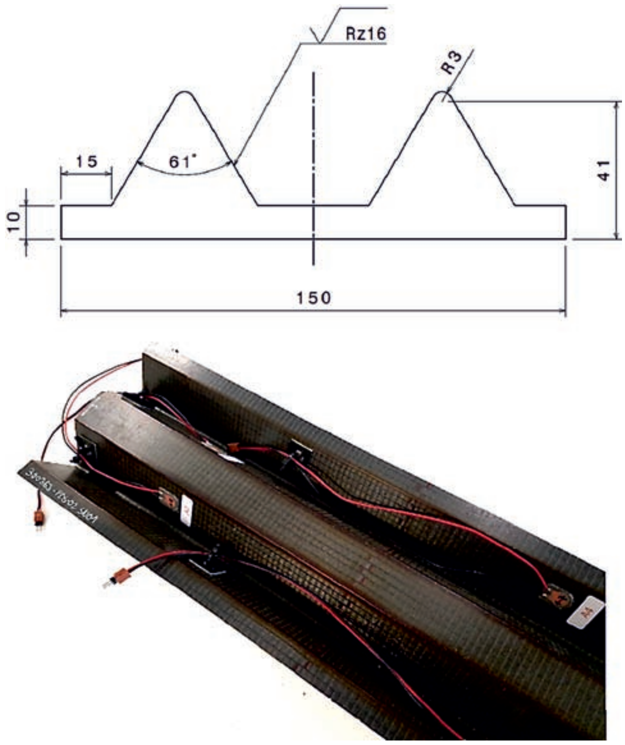

Fig. 10. Reference structure.
Rys. 10. Struktura odniesienia.

For the field test a hood was selected because of good accessability and relatively high stress e.g. (temperature, rock fall). Three areas were selected for application with transducer networks.

As demonstrator component a hut profile was constructed which illustrates a typical reinforcement structure with representative dimensions. It serves for the baseline measurement.

As defect simply two magnets were fixed at the component, although they do not represent a typical defect but the active principle is comparable.

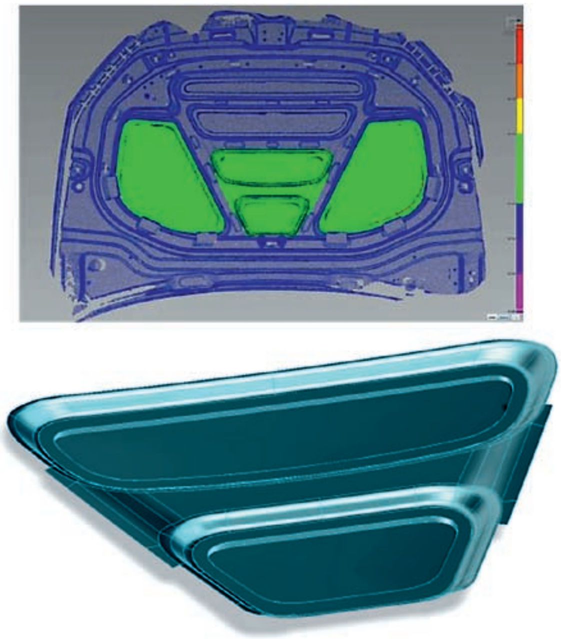

Fig. 11. Hood (field test).
Rys. 11. Pokrywa (testy terenowe).

Fig. 12. Hut profile, upper with integrated SHM network.
Rys. 12. Profil, górny ze zintegrowaną siecią SHM.

The field test is still ongoing. The measurement results are shown on a tablet. First results demonstrate that the SHM system is operating reliable. Recording of data is performed easily in the workshop.

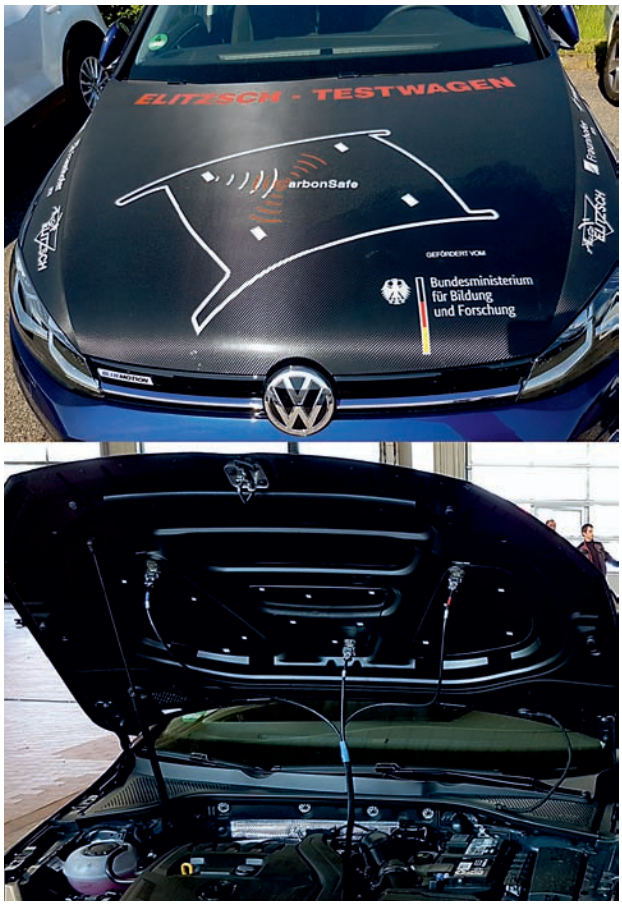

Fig. 13. Field test car.
Rys. 13. Samochód do testów terenowych.

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