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Damage identification and assessment in composite structures

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Abstract

The paper presents multidisciplinary methods and techniques oriented towards damage identification and assessment in composite structures. Two types of materials have been used: carbon and glass fibres reinforced composites. Particularly the paper is dedicated to elastic waves propagation phenomenon, scanning laser vibrometry, electromechanical impedance and terahertz spectroscopy. It also includes a variety of techniques being related to diagnostics (damage size estimation and damage type recognition) and prognostics. Selected numerical aspects of the phenomena related to the mentioned methods are addressed.

Moreover it covers the main disciplines which are related to above mentioned techniques as piezoelectric sensors and transducers, and signal processing. The signal processing approach is crucial allowing extracting damage related features from the gathered signals.

Investigated damage is in the form of mechanical failures as cracks, delaminations, debonding, voids. Also methods dedicated to thermal degradation, moisture and chemical contamination are shown. Presented methods are also suitable for performance of bonded joints assessment. Problem of external factors on investigated methods is also discussed in this paper. The characteristic of each method is summarized by a critical look.

The laser vibrometry is a non–contact technique that allows to measure vibrations of structure excited by shaker or piezoelectric transducer. In guided waves–based technique, the interaction of elastic waves with failures can be seen after appropriate signal processing.

The electromechanical impedance method is based on electromechanical coupling of piezoelectric transducer with a

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host structure. Damage in structures caused frequency shift of certain resonance frequencies visible in resistance characteristic.

The terahertz spectroscopy method is based on an electromagnetic radiation in the range: 0.1–3 THz. It allows for reflection and transmission measurements. Reflection mode is more feasible for real structures where access to the structure is only from one side. During current research time signals as well as sets of signals creating B–scans have been analysed.

Authors address also the problem of adhesive bonding in the case of CFRP samples. Techniques for detection of weak bonds are presented together with signal processing approaches. The reported investigations concern contaminated bonds caused by both manufacturing (e.g. release agent) and in–service contaminations (e.g. de-icer).

Promising combination of selected techniques should lead to an innovative approach to ensure safety operation of structures. Local and global methods have been applied and validated by experimental studies.

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Keywords: Composite structures; Damage identification

1. Introduction

Fiber reinforced composite materials are utilized in many branches of industry. They have large strength to weight ratio, they are chemical resistant and can be simply formed in complex shapes. Beside of many advantages they are vulnerable to barely visible mechanical damage like delamination. Therefore, problem of damage assessment in the case of composite materials is very important from the point of view of safety of its exploitation.
There are many non-destructive testing NDT techniques that can be utilized for damage assessment in composite materials. In this purpose such techniques like ultrasound testing [1], active infrared thermography [2], eddy currents [3], X-ray tomography [4], terahertz spectroscopy [1],[5], guided wave GW based technique as well as electromechanical impedance [5] are utilized.
In this paper authors focused attention on guided wave propagation method, electromechanical impedance method and terahertz spectroscopy.

2. Scanning Laser Doppler Vibrometry

Scanning Laser Doppler Vibrometry SLDV is non-contact technique dedicated to measurements of vibrations and guided wave propagation in structures. In presented research Polytec PSV-400 system was utilized for measurements of guided wave propagation. Measurements were taken at dense mesh of measuring points spanned over the area of investigated structure. Guided waves were excited using piezoelectric transducer in the form of disk with diameter 10 mm and thickness 0.5 mm made out. This transducer was made out of NCE51 piezoelectric material.

One of the full wavefield signal processing method is based on calculation of damage maps based on weighted root mean square (WRMS). As consequence map of energy distribution related to guided wave propagation in the structure is obtained. This map shows all forms of interaction of waves with any kind of discontinuities in the structure. This algorithm is extension of conventional RMS map algorithm. In WRMS algorithm a weight factor which decreases the importance of the time samples at the beginning when excitation is applied and increases the importance of the samples closer to the end of signal where waves amplitudes are small due to damping. The WRMS can be calculated as:

$$WRMS = \sqrt{\frac{1}{N}\sum_{k=1}^{N} w_k s^2} \tag{1}$$

where the weighting factor w_k is defined as follows:

$$w_k = k^m, \quad m \geq 0 \tag{2}$$

It can noticed that for the case of weighting factor equal $w_k = k^1$ the importance of particular time samples increases linearly with the time. When the weighting factor is defined as $w_k = k^2$ this importance (weight) increases as a square function of time.

2.1 Experimental results

In this subsection selected results of delamination localisation in composite honeycomb plate were presented. Investigated plate was made out of glass fibre reinforced polymer GFRP with internal aluminium honeycomb core (Fig. 1). Both of plate skins were made out of VV 192T 202 IMP503 glass pre-preg. The bottom skin consisted of four layers with total thickness about 1 mm whereas top skin consisted of two layers of pre-pregs with total thickness about 0.5 mm. Internal core cell size was 3.2 mm with height 10 mm. Delamination was simulated by square Teflon insert with 20 mm x 20 mm. Teflon insert was located between honeycomb core and GFRP skin. Piezoelectric transducer was placed on the bottom skin whereas guided wave propagation measurements were performed on the top panel layer. Measurements were taken only for part of surface above the honeycomb core.

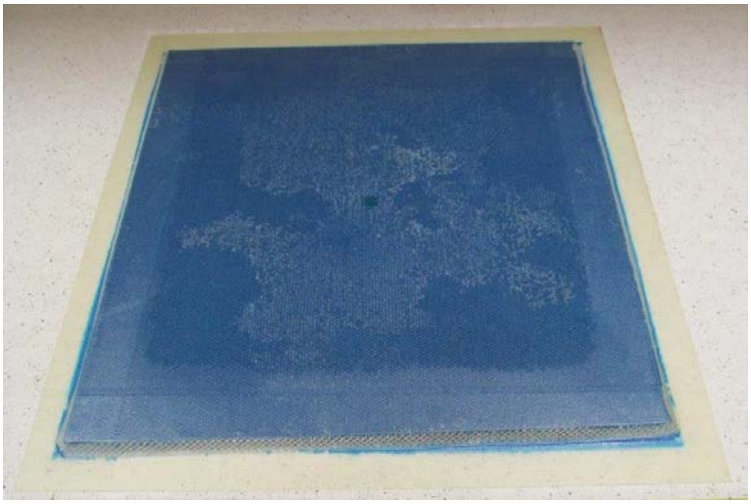


Fig. 1 Honeycomb plate utilized in experiments

In Fig. 2 results of delamination localisation were presented. In the case of Fig. 2a) WRMS map for exponent m=0 was presented. In this case calculations are performed in the same way like for conventional RMS map. The drawback of this approach is indication of the point of guided wave excitation (bottom edge) and delamination location (at the middle). Due to large amplitude of excitation sometimes, damage location could not be distinguished due to its much smaller amplitude. In order to solve this problem WRMS algorithm was developed. In the Fig. 2b) WRMS map calculated for exponent m=1 was presented (linear importance of sample with distance). In this case the indication related to excitation was reduced and damage location is much better visible. In the case of exponent values m=2 (square importance of sample with distance) and m=3 (cubic importance of sample with distance) see Fig. 2c,d) – the indication related to excitation was significantly removed. Results for m=3 are very similar to the results obtained for m=2, in both cases location of delamination is clearly visible.

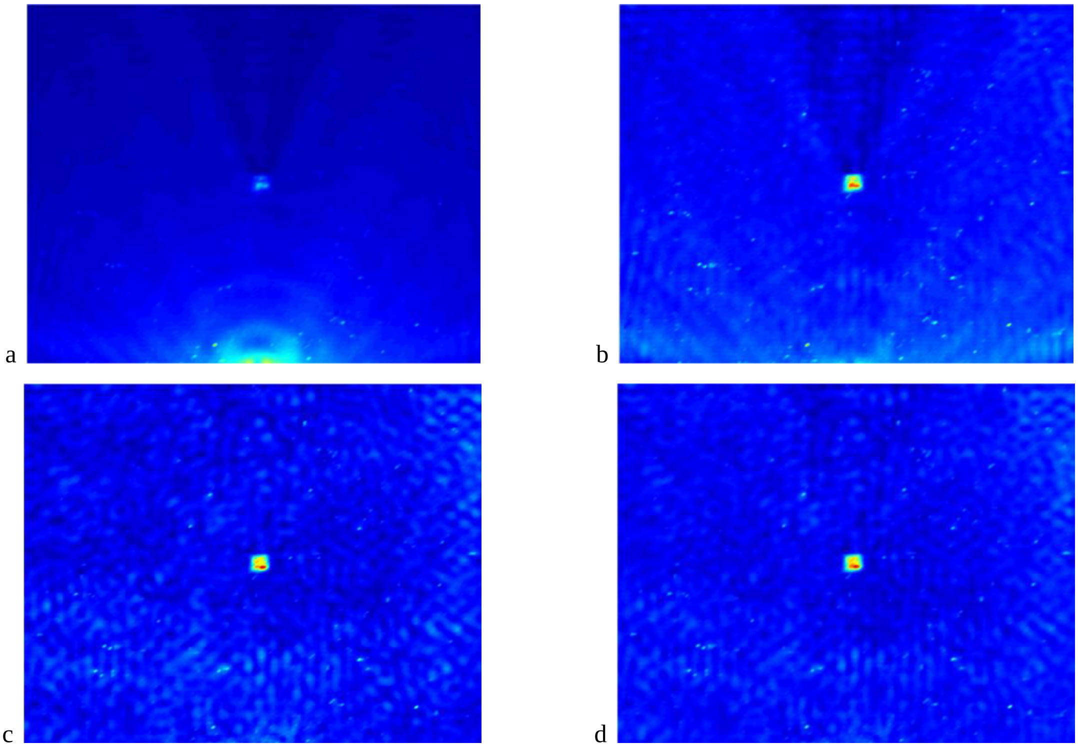
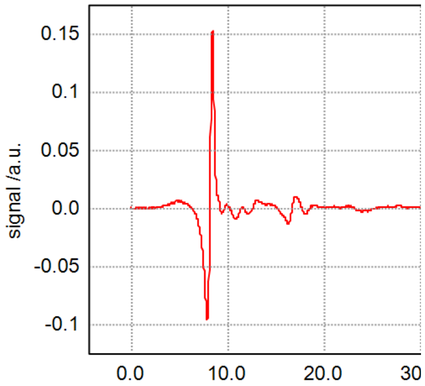


Fig. 2. Weighted RMS energy maps (WRMS) for the case of delamination; excitation frequency 50 kHz: a) m=0,b) m=1, c) m=2, d) m=3

3. Damage detection with terahertz spectroscopy

The terahertz spectroscopy method is based on an electromagnetic radiation in the range: 0.1–3 THz. It allows for reflection and transmission measurements. Reflection mode is more feasible for real structures where access to the structure is only from one side.

A rectangular GFRP plate was investigated with a Teflon insert put during the manufacturing process. The plate size was 500 mm x 500 mm x 4.3 mm. One surface of the sample was smooth and two layer under it a 10 mm x 10 mm Teflon patch was located. The second surface was rough casing the dispersion of the radiation, so the measurements were conducted from the smooth side. The time signal registered at the defect position comprises a reflection at about 16 ps (Fig. 3a) that is not visible in signals measured outside of the detect region (Fig. 3b).



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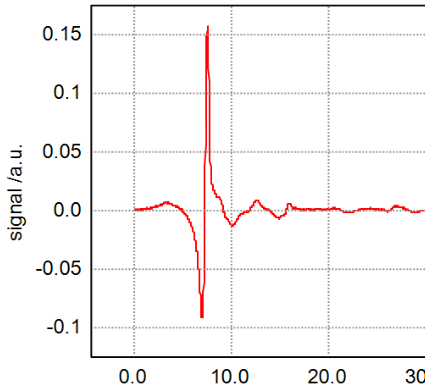
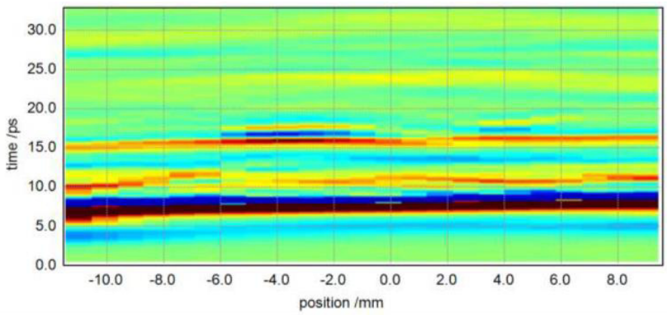


b

Fig. 3. Terahertz time signals registered at defect region (a) and undamaged region (b) of the sample.

The presence of Teflon insert is even more apparent if one investigates the B-scans (time signals plotted along chosen section). The section that passes through the defect region indicates reflections at about 16.5 ps for positions from -6.00 mm to 5 mm (Fig. 4a). If one compares this with a section passing other region of the sample, the reflections are not present (Fig. 4b).

The position of the Teflon insert along the depth of the sample can be determined investigating the time signals. The sample begins at 8.5 ps, where large reflection form the surface is observed (figure). The reflection from the bottom (not shown in the figures) is observed at 68.5 ps. It means that the thickness of the sample (4.3 mm) is within 60 ps. The defect reflection is observed 8 ps after the surface reflection giving the depth ot the defect equal to 0.6 mm.



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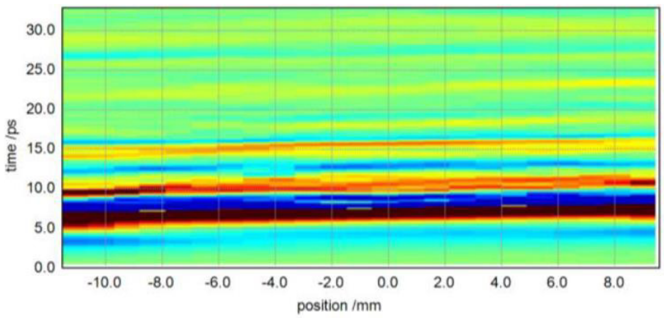

b

Fig. 4. Terahertz B-scans registered at section passing through the defect region (a) and undamaged region (b) of the sample.

4. Assessment of adhesive bonding of CFRP samples

It is expected that the joints between structural elements are robust. One of the joining techniques for composites is adhesive bonding. It is used both in manufacturing and repairs. It is important to assess the quality of the bonds. For this purpose electromechanical impedance (EMI) method is investigated in this section. The lower quality of the bond may be a result of improper preparation of the surfaces to be bonded or mistake in the bonding process. The attention here is focused on two cases of improper surface preparation, namely the contamination with moisture (MO samples), and release agent (RE samples) on the surface to be bonded, and the lowered temperature of curing (CS samples). The investigated samples comprise of two CFRP plates bonded together with adhesive film. The amount of moisture was expressed but mass increase of the plate that was held in humid conditions in environmental chamber before bonding to a dry plate. The amount of release agent contamination was expressed by atomic content of silicon on the surface after dip coating of one of the plates before bonding.

The electromechanical impedance signatures gathered by the sensor were measured in the 3-5MHz band, where the sensors thickness resonance is observed. The resonance is represented by a strong conductance peak and this conductance characteristic was taken for the analysis. The changes in registered spectra caused by transducer bonding were observed and analyzed. The frequency of the peak was tracked in relation to peak for the reference sample. Also the RMSD (root mean square deviation) value was calculated for the 305 MHz band. The RMSD is a relative quantity calculated in relation to the spectrum of the reference sample. The results were depicted in Fig. 5. The results plane was divided into three areas. Each of the area is separated by dashed line. It can be noticed that as the curing temperature get lower the RMSD value and the peak frequency increase. In the case of release agent contamination the higher the contamination level the higher the RMSD value. Also beginning from RE2 sample the frequency of the peak begins to drop with increasing amount of contamination. In the case of moisture contaminated samples one do not observe an increasing or decreasing trend for frequency of the peak or RMSD value. It can be related to the face that moisture has different influence on the adhesive bond.

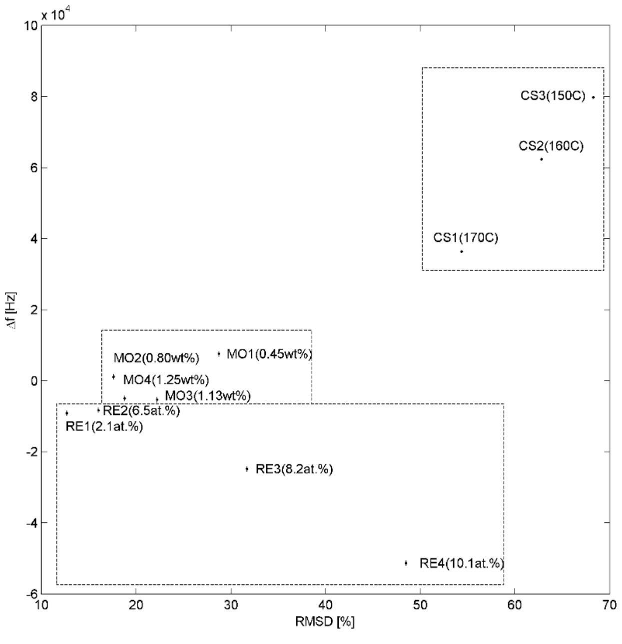

Fig. 5. Results of the adhesive bonds assessment of CFRP samples. The assessment was made using EMI method. Maximum of the frequency peak of conductance and RMSD values were compared. Results for samples with moisture (MO) and release agent (RE) are depicted together with results for samples cured with lower temperature (CS).

5. Conclusions

In this paper selected nondestructive testing (NDT) and (SHM) techniques have been presented. The focus was put on three methods that can be used for damage identification and assessment in composite structures. The vibrometry and terahertz methods were tested on artificially delaminated samples with Teflon inserts. The electromechanical impedance method was applied to samples manufactured with simulated adhesive bonds defects. It should be mentioned that the above mentioned methods are also used for damage detecting in metallic structures. The exception is terahertz spectroscopy.

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