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Methods of improving the detection of defects in aramid fiber-reinforced composites in non-destructive testing by pulsed thermography

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Abstract

This paper presents a comparison of the effectiveness of the non-destructive pulsed thermography method supported by image analysis methods in detecting a very thin defect inside the structure of aramid fiber-reinforced composite. The technology of making the composite was the same as in the production of composite helmets. For comparison, the result obtained using the X-ray method is also presented. The obtained results show the possibility of a significant improvement in the efficiency of the detection of defects that are not clearly identifiable in the source sequence of thermograms.

1. Introduction

In the early 1970s, Du Pont developed an aromatic organic fiber, known as Kevlar ™, with high specific tensile modulus and strength. [1]. Thanks to its properties such as low density, high tensile strength, high tensile stiffness, low compressive properties (nonlinear), and exceptional toughness characteristics, aramid fibers have become the basic material for the production of composite lightweight ballistic shields. Aramid fibre is relatively flexible and tough, thus it can be combined with resins and processed into multi-layer composites. Composite helmets, for example, are made of a layer of fabrics made of aramid fiber bonded with resin. In the work carried out at the Institute, we have shown that an effective method in detecting defects in these types of composites is infrared thermography with thermal stimulation of an ultrasonic source [2, 3, 4]. When examining samples with deliberately introduced defects in the structure of the composite, which is the material used for the production of composite helmets, the method for one type of defect turned out to be ineffective. Using various types of thermal stimulation sources in the non-destructive thermographic testing methods, the best results were achieved with the impulse method. The effectiveness of detecting and determining the dimensions of the defect is significantly increased with the use of image (thermogram) analysis methods (thermograms).

2. Experimental tests

2.1. Methods

Pulse thermography is one of the most popular methods currently used in non-destructive testing of composite materials. This type of research involves the use of a lamp, laser, etc., to generate a pulse (or series of pulses) of thermal excitation, which lasts from a few milliseconds for materials with high thermal conductivity to several seconds for materials with low conductivity [5, 6].

During the experiments using the pulsed thermography method, a thermal pulse of a power of 6 kJ and duration of 5 ms was generated by a flash lamp. Changes in the temperature field on the heated surface of the sample were recorded by an IR camera (FLIR SC 7600) in sequences consisting of 500 images with a resolution of 640×512 pixels, recorded at a frequency of 25 Hz. The tests were carried out using the reflection mode.

At the beginning, a sample test with a deliberately introduced defect was carried out using the X-ray and terahertz method.

For preliminary non-destructive testing, the YXlON X-ray diagnostic system, the MU17F model presented in Figure 1, was used. This system allows you to visualize the internal structure of the tested object in real time and enables acquisition of received images on a computer disk.

The most important components of the system are: 1 - radiation booth, 2 - control cabinet, 3 - ster control panel, 4 - monitor. The detector located in the radiation cabin is made using semiconductor technology. The X-ray tube has two foci, and its maximum operating voltage is 225 kV.

X-ray tests were performed after suspending the sample between the X-ray tube and a semiconductor detector. The largest surface of the sample was oriented perpendicular to the axis of the X-rays. The lamp operating voltage during the test was 200 kV and the lamp cathode diameter was 0.4 mm [7].

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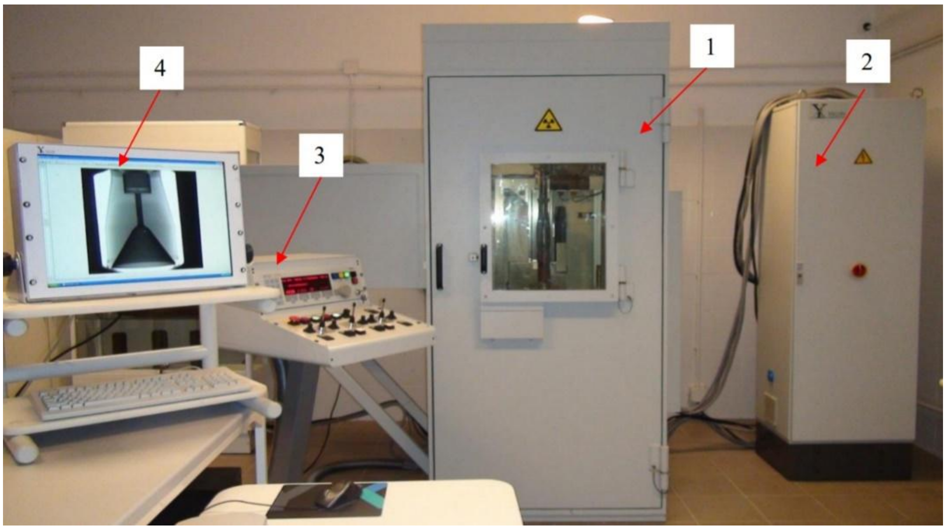


Fig. 1. *MU17F X-ray diagnostic system*

There was also an attempt to use terahertz radiation by transmission method. The terahertz band includes waves in the range from 0.1 to 10 THz. Electromagnetic waves in this spectral range are strongly attenuated in electrically conductive substances such as metals, as well as in water and electrolytes, while they are very poorly attenuated in dielectrics. Therefore, they can be used for non-destructive testing of metal-free composites.

The terahertz setup consisted of a line scanner Linear (512×1 pixels image resolution with pixel pitch of 0.5 mm and frequency of ~300 GHz), and terahertz source in a form of generator THz IMPATT (frequency 292 GHz ± 5 GHz and power of ~10 mW). This source includes novel reflective THz optics based on specially configured high-gain horn antenna in combination with a metallic mirror. This generator considerably improves the THz imaging capabilities of our linear scanner by increasing the amount of power reaching the sensor array.

This equipment was sourced from the company Terasense Development Labs. Investigations were performed in transmission mode where the emitter and scanner are on the opposite sides of the sample. Fig. 2 presents schematical representation of experimental setup. The sample placed on the displacement device was moving along the scanner which scans the sample linearly. The shift was carried out with the speed selected in such a way to possibly reduce the disturbances caused by the movement of the sample in reference to scanner. The data were registered using dedicated software [8].

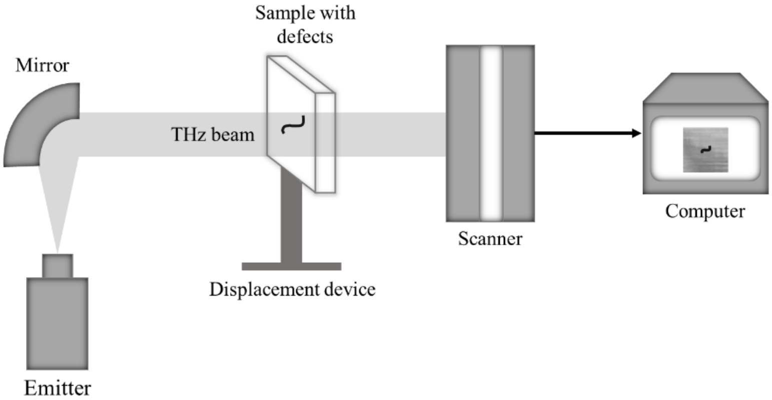


Fig. 2. *Schematic representation of the investigation setup in transmission mode*

2.2. Sample

Composite samples made with the same technology as is used in the production of composite helmets were used for the tests. A flat sample with dimensions of 200×200×10 mm consisted of 25 layers of aramid fabric connected by layers of resin (Fig. 3). In the internal structure of the sample, there was a defect in the form of a cut fragment of one layer of aramid fabric with dimensions of 20×20 mm. This defect was located at a depth of 2 mm under the heated surface during the tests and in the center of this sample.

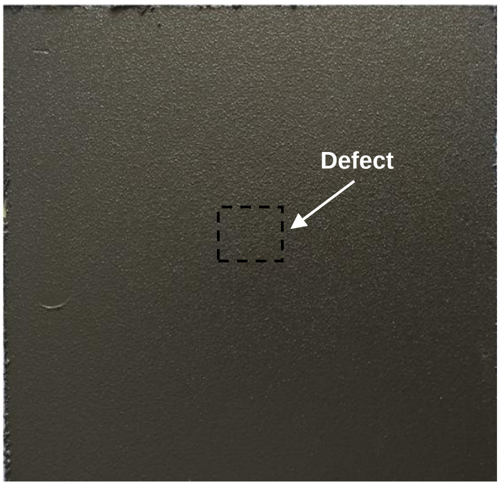


Fig. 3. *Tested composite sample*

3. Methods of analysis

The thermogram sequences recorded during the experimental tests did not allow for unequivocal detection of the defect in the tested composite sample. In order to improve the visualization of this defect, the impulse-phase thermography algorithm [9] and image analysis methods such as principal components analysis and wavelet analysis were used.

Principal Component Analysis (PCA) is a transformation that turns a large amount of information contained in the interrelated input data into a set of statistically independent components according to their importance. It is therefore a form of lossy compression, known in information theory as the Karhuen-Loev transform [10]. It is used in statistical procedures, which in recent years have become more and more popular in the issues of image recognition and data compression, especially data of very large volumes [11].

The principal components method has been used relatively recently in thermographic tests. The PCA uses the decomposition method to extract both spatial and temporal information from a thermographic data matrix. Three-dimensional matrix (the sequence of thermal images recorded) is converted into two-dimensional, wherein the time values are arranged in columns a spatial data in rows. Thereafter, the two-dimensional matrix is decomposed and the resulting matrix can again be represented as an image sequence [12].

The most common use of this method is to reduce the size of the data set. The task is to describe large-dimension data (high number of features) with fewer features, while keeping maximum information. In the case of PCA, this information is measured by variance, which in statistics is a classic measure of volatility. Principal components analysis allows to describe multivariate data with a small number of uncorrelated coordinates (determined by the eigenvectors of the covariance matrix), maintaining the dispersion between the data. The dimension of the new space will depend on how much of the features we want to keep [13].

The wavelet analysis or wavelet transforms was developed in the 1980s as a tool for seismogram analysis. In thermographic tests, the wavelet analysis was first used by the team of X. Maldague as an alternative to the Fourier transform [13, 14].

The wavelet transformation enables a simultaneous representation of time and frequency signals and it leads to the approximation of the signals by isolating their characteristic structural elements. In contrast to the Fourier transform, the wavelet transform decomposes the signal into elementary signals called wavelets, which are continuous waveforms of a different duration and different spectra [15]. The disadvantage of the Fourier transform, which is the most popular method of analysing temperature signals, is that switching from time-value to frequency-value results in the loss of time information. On the other hand, the wavelet transform enables the analysis of the signal frequency change as a function of time. The wavelet analysis is a useful tool for analysing short time signals, transient data or complex images.

In thermographic tests, the basic Morlet function is used, which is a sinusoidal function modulated with Gaussian functions. The distribution parameters are called translation ratio Tr and scale factor S. Then the wavelet transformation formula (W) has the form:

$$W(S,Tr)=\int_{-\infty}^{+\infty}T(\tau)\,h_{S\,Tr}(\tau)d\tau \tag{1}$$

where h_{STr} is the wavelet function related to the parent function by the compound:

$$h_{STr}(\tau)=\frac{1}{\sqrt{S}}h(\frac{\tau-Tr}{S}) \tag{2}$$

Since the scaling factor is related to the frequency and the translation factor to time, the wavelet function method does not lose the time information necessary to assess the depth of the defect location.

As in the case of the Fourier image, the wavelet image contains both the real and the imaginary part, therefore it is possible to define phase characteristics in the image space (which allows this method to be transferred to the pulsed phase thermography). Wavelet images have the same properties as Fourier images. Wavelet transform phases are used for defect detection, with defect segmentation being performed by the Sobel operator. Calibrating the translation factor (difference of pixel values Tr) allows to assess the depth of the location of defects [16].

The translation factor, which is in fact an analogue of time, ensures the maximum «visibility» of defects of a given dimension at a given depth. Therefore, in order not to introduce double calibration to the dimensions of the defect and the depth, it has been proposed to use early observation times, in which the temperature signals weakly depend on both the transverse dimensions of the defects and their thickness, while maintaining a strong dependence on the depth of position.

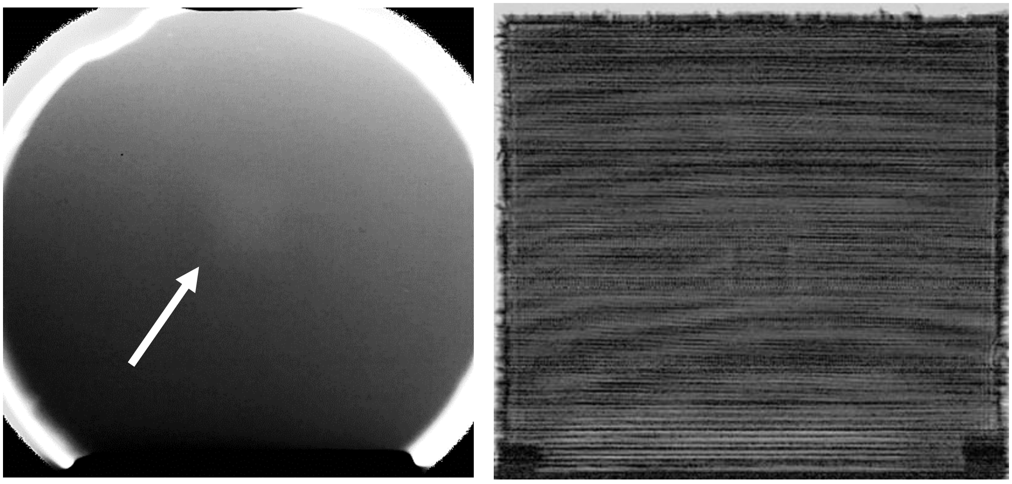
Wavelet analysis is some generalization of Fourier analysis where the signal is decomposed into a sum or integral of sinusoidal signals, the physical meaning of which is relatively easy to interpret. Unfortunately, these sine waves are homogeneous over time, while the output signal not always is. In particular, it can take the form of oscillations, the amplitude and frequency of which change with time, and this heterogeneity is not clearly reflected in the transform.

Use of the wavelet function method in thermographic tests, has been relatively poorly examined, and its superiority is questionable, because changes in the differential signals $\Delta T(\tau)$ over time are non-impulsive and smoothed.

Image analysis was performed with ThermoFit ™ Pro software developed by Vavilov [17]. ThermoFit ™ Pro is primarily intended for processing infrared (IR) images obtained as a result of pulsed (in some cases – thermal wave) Thermal Non-destructive Testing (NDT).

4. Results

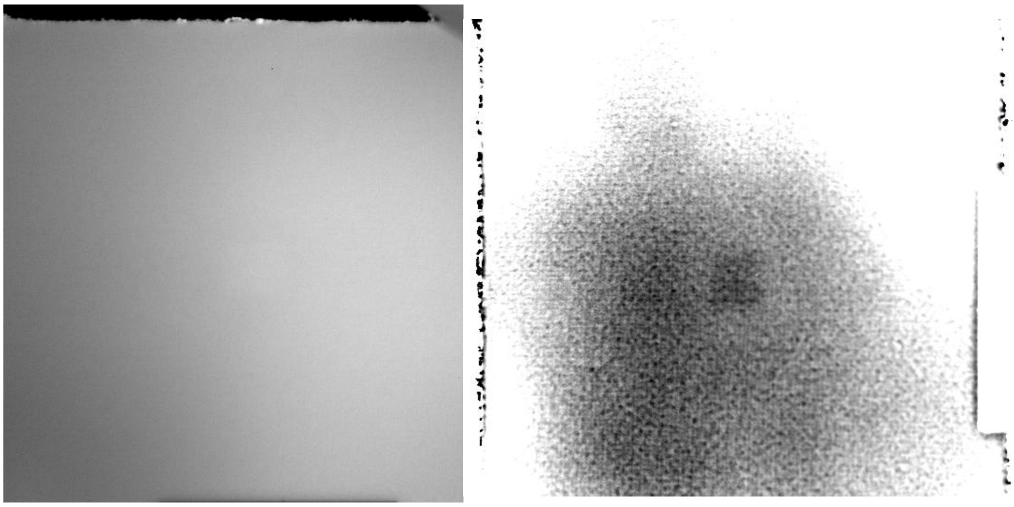
The selected results are shown in Figures 4-7. The results obtained from non-destructive tests by X-ray and impulse methods were compared. The X-ray image presented in Fig. 4a shows a very faint defect (marked with a white arrow). Figure 4b shows the obtained test result from the use of terahertz radiation. Both tests were performed with the transmission method. There is a fundamental difference in visualizing the defect. In the terahertz method, the contours of the defect are clearly visible, despite the visible disturbances in the image. In the X-ray image, the defect is very difficult to see. You can practically identify its location by knowing where it may be.



a) b)

Fig. 4. *The results of non-destructive tests of a sample of a composite reinforced with aramid fiber with a defect inside the composite structure a) radiograph, b) terahertz method*

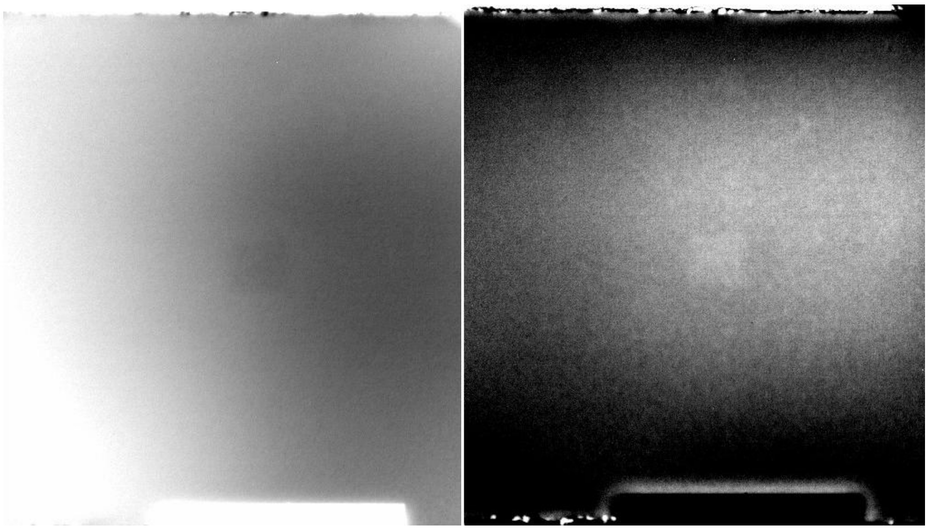
Figure 5a shows a selected thermogram from the recorded sequence of 500 thermograms in which the defect is best visible. It is a thermogram recorded within 1.2 seconds after the end of heating the test sample with a thermal pulse. A much better result was obtained after the phase analysis, which is shown in Figure 5b. The defect is clearly visible, but its contours are blurred.



a) b)

Fig. 5. *The results of non-destructive tests of a sample of a composite reinforced with aramid fiber with a defect inside the composite structure a) the best source thermogram, b) phase image*

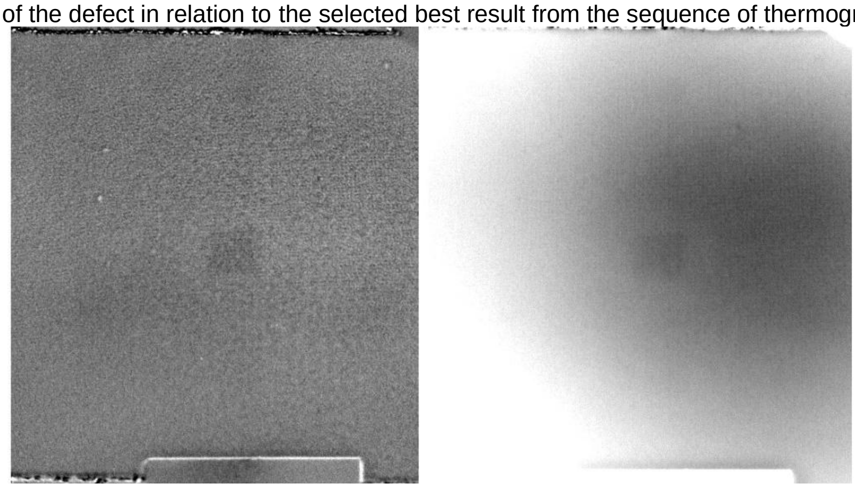
In order to improve the defect visualization, PCA and wavelet analysis were performed. The PCA results are shown in Figures 6a and 6b and 7a. The best visible defect contours are visible after the second component analysis (Fig. 6a). In the third and fourth component analysis (Figures 6b and 7a), the image of the defect is more contrasting to the area of the sample without the defect, but its contours are blurred. The image quality deteriorates significantly when analyzing further components.



a) b)

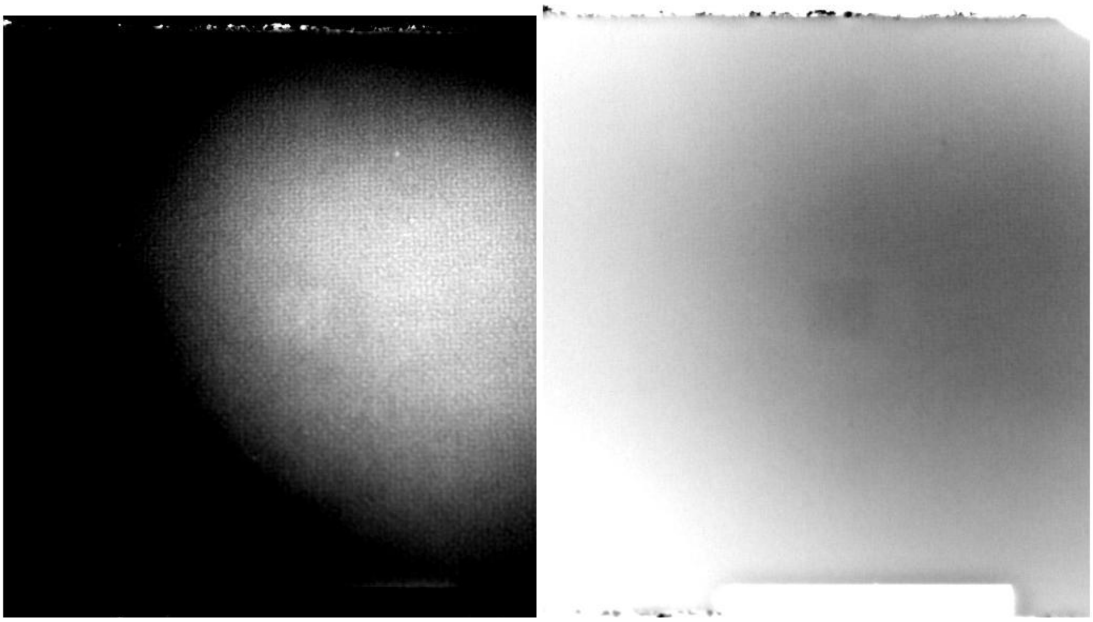
Fig. 6. *The results of non-destructive tests of a sample of a composite reinforced with aramid fiber with a defect inside the composite structure a) PCA analysis – showing the second component, b) PCA analysis – showing the third component*

The presented results obtained using the wavelet analysis (Figures 7b, 8a and 8b) show that it is possible to improve the visualization of the defect in relation to the selected best result from the sequence of thermograms (Fig. 5a).



a) b)

Fig. 7. *The results of non-destructive tests of a sample of a composite reinforced with aramid fiber with a defect inside the composite structure a) PCA analysis – showing the fourt component, b) wavelet analysis - Morlet*



a) b)

Fig. 8. *The results of non-destructive tests of a sample of a composite reinforced with aramid fiber with a defect inside the composite structure a) wavelet analysis - Gaussian b) wavelet analysis - Paul*

5. Conclusion

The obtained results indicate that the defect visualization can be significantly improved with the use of PCA and wavelet analysis. Due to the not very favorable thermo-physical parameters of the composite reinforced with aramid fiber, the detection of a very thin defect (lack of material) is limited by the depth of its location under the surface of the tested material. With the applied pulse method, these are 2 mm.

The best result was obtained with the use of terahertz radiation. Since the transmission method was used, the terahertz radiation had to pass through the entire thickness of the material (10 mm). It follows that the detection of the defect was not influenced by the depth of its location below the surface of the sample, and it would be equally well detected at any depth. This result shows that in cases where the thermo-physical parameters of the material are not favorable, the tests with infrared thermography using the terahertz method can obtain better results.

In further works, we plan to compare these methods when testing different composite materials.

6. Acknowledgements

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