10.21611/qirt.2023.01

Methods of improving the detection of defects in thermograms on the example of GFRP testing

by W. Swiderski

* Military Institute of Armament Tchnology, 05-220, Wyszynskiego 7 Str., Zielonka, Poland, waldemar.swiderski@*wp.pl*

Abstract

In non-destructive testing using infrared thermography, we deal with disturbances of the temperature field on the surface of the tested objects, which are not caused by subsurface defects. In order for the thermograms to be free from interference and to have clearly distinguished features of interest to us, a number of image processing algorithms are used. In the article, on the example of non-destructive testing of the GFRP composite by pulse thermography, the effectiveness of various image processing algorithms was compared. In the algorithms used, there is a mechanism to increase the signal/noise ratio and thus increase the effectiveness of defect detection. It should be noted that each processing of the thermogram leads to distortion and the point is only that this distortion is beneficial from the point of view of the purpose of non-destructive testing, i.e. detection of defects and evaluation of their parameters.

1. Introduction

The development of modern composite materials began with Bakelite, the first industrially produced plastic that was produced after the synthetic resin production process had been mastered. Then, the technology of manufacturing artificial fibers was developed. The first was glass fiber produced during the Second World War, and then the carbon fiber technology (low-modulus and later high-modulus) was developed. In the next stage, aramid fibers were developed, and in recent years, basalt fibers. They are currently the most popular fibers used in a variety of applications.

Interest in composites results from their excellent mechanical and strength parameters with low specific weight, corrosion resistance, impact strength, fatigue strength, etc. [1, 2]. The simultaneous occurrence of these features occurs, in principle, only in the case of composites, hence their rapidly growing use in recent years in structures for which these features are of paramount importance. These are primarily aircraft and car structures, as well as sports equipment (boats, skis, tennis rackets, bicycles), in which composites are used for thin-walled structures.

Fiber-reinforced composites were more prominent than other types of composites for the simple reason that most materials are stronger and stiffer in fibrous form than any other form. [3] Glass fiber became commercially available in 1939 and is the most widely used fiber to reinforce polymer matrix composites and is known as GFRP (Glass Fiber Reinforced Plastics). Despite the rapid evolution of carbon and aramid fibers, glass fiber-reinforced composites are still used in many applications.

Despite many significant advantages of structures made of composite materials in comparison to analogous ones made of classical materials, they have a number of disadvantages. The most important of them is a large number of forms of failure, which are responsible both for reducing the stiffness and strength of the structure. A characteristic feature of composite materials, both for static and fatigue loads, is the gradual development of failure, which starts with local microdefects and ends with the destruction of the structure. The mechanisms by which this deterioration occurs are completely different from those responsible for the fatigue phenomena of metals. Not only these mechanisms are different, they are also more complex [4].

Damage to the composite structure may occur both as a result of technological errors in the production phase and during operation as material fatigue or as a result of an impact by a foreign body.

One of the most effective non-destructive testing methods for detecting defects in composites are infrared thermography methods.

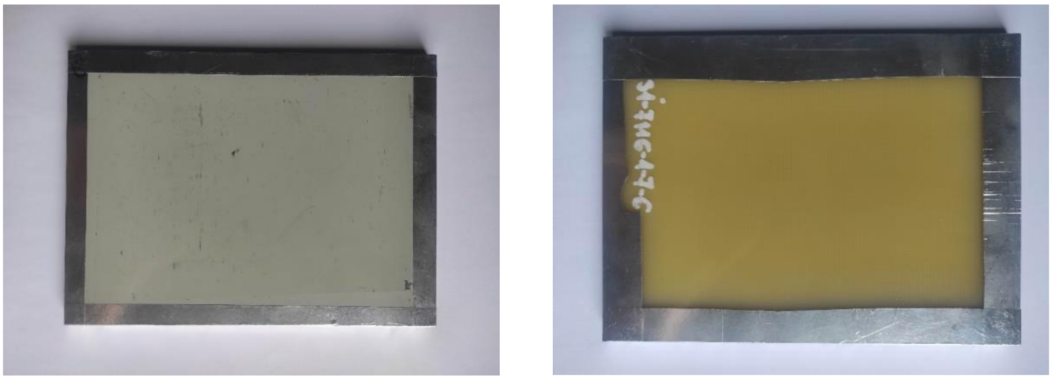
2. Method

Pulse thermography is one of the most popular methods currently used in non-destructive testing of composite materials. This type of test 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 (e.g. metals) to several seconds for materials with low conductivity [5 - 11]. You can also use a pulse cooling the surface of the test object (e.g. a stream of cold air, liquid nitrogen, etc.). Pulse thermography can be performed using both the reflection and transmission approaches. A sequence of images (thermograms) is recorded with equal intervals between images. After switching off the radiation source, the object cools down to the ambient temperature. In the cooling phase, the temperature distribution on the surface of the tested object is determined and analysed. Depending on the thermal characteristics of the test material and occurring in the defects in the crust of the areas of higher or lower temperatures at the surface will indicate areas where there may be material defects. Often, special techniques for processing thermograms must be used to identify areas with defects.

In our tests, we used a flash lamp. Using this lamp, a thermal pulse of 6 kJ and a duration of 5 ms was generated. Changes in the temperature field on the surface of the sample were recorded with an IR camera in sequences consisting of 500 images with a resolution of 640×512 pixels, recorded with a frequency of 25 Hz. The tests used the reflection method in which both the radiation source and the camera recording changes in the temperature field on the tested surface are located on the same side of the tested sample.

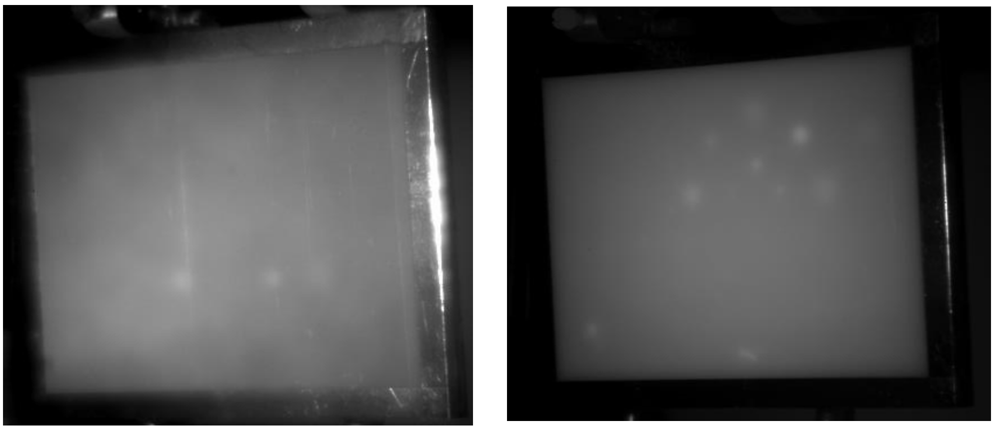
3. Infrared reflection test results

For tests, the Air Force Institute of Technology in Warsaw/Poland made 7 samples of glass fiber-reinforced composites. The material from which the samples were made was a typical material used in aviation applications. All samples measuring 140×190 mm and a thickness of about 10 mm consisted of two plates of equal thickness of about 5 mm. Blind holes of various diameters and depths were milled in the front plate (Fig. 1a). When examining the samples, we did not know how many defects in the form of holes or where they were located in individual samples. The front surfaces of these plates were covered with a layer of varnish to mask the location of the defects. The back plate (Fig. 1b) was glued on the side of the holes and ensured masking of their location.



a) *b)*

Fig. 1. *View of the GFRP composite sample a) front side, b) back side*



a) *b)*

Fig. 2. *Source best thermogram from the saved measurement sequence a) sample No 6, b) sample No 7*

Figure no. 2 shows an example result obtained for two of the tested samples (No 6 and No7). The best thermogram from the recorded sequence is shown.

4. Image processing methods

Standard methods used in digital image processing are used to improve the quality of thermograms, the main of which are [12]:

- tone scale modification (changing the histogram);
- choice of colour palette;
- improving the sharpness of the thermogram;
- smoothing;
- separating the boundaries of areas;
- morphological filtration;
- reconstruction of the thermogram;
- subtraction and division of thermograms.

If the methods presented above are ineffective, more advanced methods are used, described in detail in [12]. Belong to them:

- thermal tomography;
- Fourier transform;
- wavelet analysis;
- reconstruction of the thermographic signal;
- normalization in dynamic thermography;
- principal component analysis;
- neural networks.

Layer-by-layer imaging of the material under study is called the tomography method, which was used as a method of X-ray tomography (computed tomography) - one of the methods of medical diagnosis. The idea of the thermal tomography method and its application in non-destructive thermographic test was established in the 1980s [13]. In 1986, Vavilov and Shiryaev proposed to use the so-called Dynamic Thermal Tomography (DTT) [14].

A special feature that distinguishes the Fourier transform used in thermographic research from standard two-dimensional imaging processing procedures is its "one-dimensionality" because it adapts to changes in signals over time. The Fourier transform in thermographic tests is used to study the dynamics of temperature changes in thermogram sequences. The difficulty in interpreting the phase (phasograms) and amplitude (amplitudograms) images in the Fourier analysis is due to the fact that the results of the Fourier transform depend both on the size of the interval $\Delta\tau$ between images of temperature data and the number of these intervals [15].

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 [16]. 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 one-sided pulsed thermographic tests, the temperature signals over typical defects in the cooling stage change slower than in defect-free areas, due to less intense heat dissipation into the sample (due to the presence of the defect). For this reason, as well as the analysis of temperature functions $T(\tau)$, it is interesting to analyse the changes in time of the first ($\partial T(\tau)/\partial\tau$) and second ($\partial^2 T(\tau)/\partial\tau^2$) temperature derivatives. The superiority of derivative analysis over the analysis of temperature functions as a mathematical operation is obvious, nevertheless S. Shepard et al. attempted to explain their role from the point of view of thermal diffusion analysis [17]. They developed the concept of "synthetic processing" of impulse thermographic data, which is carried out with commercial equipment from Thermal Wave Imaging. Recently, the term "Thermographic Signal Reconstruction" (TSR) has also been used [18].

In thermographic tests, the term "normalisation" means the mathematical operation of dividing thermograms to suppress the effect of uneven heating. This term appeared in work [19]. We distinguish the following types of normalisation:

1. Normalisation of all thermograms from the sequence by the selected display, which is called "normalising ";
2. Three-dimensional (3D) normalisation that involves splitting two sequences, one of which is experimental and the other is computational.

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 [20]. 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 [21].

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.

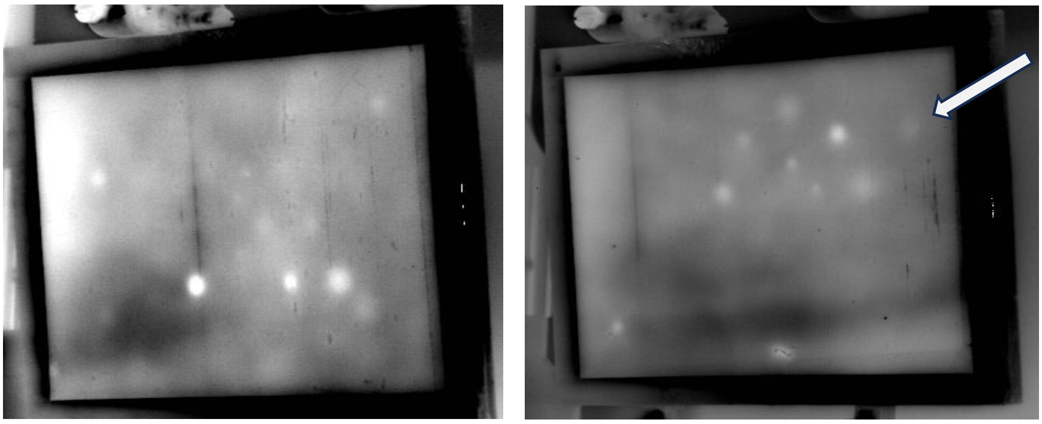
The most common use of this method is to reduce the size of the data set. The task is to describe large-dimension data (high number of features) with fewer features, while keeping maximum information. In the case of PCA, this information is measured by variance, which in statistics is a classic measure 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 [22].

Artificial neural networks, called neural networks for short, are an intensively developing field of knowledge used in many areas of science. They have properties desirable in many practical applications: they are a universal approximation system reflecting multidimensional data sets, they have the ability to learn and adapt to changing environmental conditions, the ability to generalize the acquired knowledge, constituting in this respect an artificial intelligence system. The basis of the operation of neural networks are learning algorithms that enable the design of an appropriate structure of the network and the selection of parameters of this structure, tailored to the problem to be solved. The most commonly used types of networks are: unidirectional single-layer, unidirectional multilayer and recursive (in which there is feedback between the input and output layers) [23]. A neural network can be an effective tool in recognizing and qualifying defects [24] thanks to its learning ability to determine small differences between the identified classes, which is obtained as a result of training on appropriate training (reference) samples, which can be obtained experimentally or by means of computer simulation [25].

The use of the above-mentioned imaging improvement methods is possible thanks to the ThermoFit^{TM} Pro software developed by prof. V. Vavilov. This software was also used in this work.

5. Results of image processing

Figures 2 and 3 show the characteristic results for two selected samples No 6 and No 7. In the thermogram(Fig. 2a) of sample No 6, three defects are clearly visible but after image processing using PCA (the second component – Fig. 3a) can be identified by detailed analysis that there are 14 defects in this sample. Most defects are located much deeper than the defects visible in best thermogram (Fig. 2a). The thermogram of sample No 7 (Fig. 2b) allows the detection of 9 defects. After applying image processing using PCA (the second component), one more defect was detected (Fig. 3b), marked with a white arrow.



a) *b)*

Fig. 3. *Images after processing with PCA – second component a) sample No 6 b) sample No 7*

6. Conclusions

Using the ThermoFit^{TM} Pro software, image (thermograms) processing was carried out using methods such as Fourier transform, wavelet analysis and principal component analysis. A significant improvement in detection results was achieved using PCA. This type of composite is probably largely influenced by its not very favorable thermophysical parameters for thermal excitation of material with a lamp and reflection of radiation from the sample surface. The obtained results do not mean that the PCA method is superior to other image analysis methods. When testing other composites or using a different infrared thermography method, other image processing algorithms may be more effective.

REFERENCES

[1] Kar K. K., Composite Materials Processing, Applications, Characterization, Springer-Verlag, 2017
[2] Seo D-C., Lee J-J., “Damage detection of CFRP laminates using electrical resistance measurement and neural network”, Composite Structures; 47: pp. 525-530, 1999

[3] Krishan K. Chawla K.K., Composite Materials, Science and Engineering,Springer Science+Business Media, New York , 2012
[4] Wicaksono S., Chai g. B., “A review of advances in fatigue and life prediction of fiber-reinforced composites”, Journal of Materials: Design and Applications, 2012
[5] Vavilov V. P., Burleigh D.D., “Review of pulsed thermal NDT: physical principles, theory and data processing”. NDT E Int;73: pp. 28–52, 2015
[6] Swiderski W., “Detection of Very Thin Defects in Multi-Layer Composite Made of Carbon Fibre with IR Thermography Methods”, Nondestructive Testing of Materials and Structures, Part1, Springer, pp. 633-639, 2013
[7] Zheng K., Chang Y-S., and Yao Y., “Defect detection in CFRP structures using pulsed thermographic data enhanced by penalized least squares methods”, Composites Part B: Engineering, vol. 79: pp. 351–358, 2015
[8] Poelman G., Hedayatrasa S., Segers J., Van Paepegem W. and Kersemans M., “Application of Flash Thermography and Advanced Post-Processing Techniques for Rapid NDT of CFRP Aircraft Component”: A Case Study, 11th Symposium on NDT in Aerospace, PARIS-SACLAY – Nov 13 to 15, 2019
[9] Yang, R. and He Y., “Optically and non-optically excited thermography for composites”: A review. Infrared Physics & Technology, 75: pp. 26-50; 2016
[10] Ibarra-Castanedo C., Genest M., Piau J-M., Guibert S., Bendada A. and. Maldague X. P. V., Active infrared thermography techniques for the nondestructive testing of materials, Chapter X Ultrasonic and Advanced Methods for Nondestructive Testing and Material Characterization, pp.325 – 348, 2007
[11] Vavilov V.P., Pulsed thermal NDT of materials: Back to basics, Nondestr. Testing & Evaluation 22(2-3), pp.177-197, 2007
[12] Świderski W., Vavilov V., “Processing of thermograms and data processing in nondestructive testing with infrared thermography methods”, PTU; 3: pp.57÷81, 2009 (in Polish)
[13] Rosencwaig A., Gersho A., Thermal-wave imaging, Science, Vol. 218, Washington, D.C., American Association for the Advancement of Science, pp. 223-228, 1982
[14] Maldague X. P. V. Theory and practice of infrared technology for nondestructive testing. John Wiley&Sons, Inc. New York, p. 78, 2001
[15] Vavilov V. P., Marinetti S. C., Pulsed phase thermography and thermal tomography based on Fourier transform, Defectoscopy, 2, C: pp. 58-72, 1999 (in Russian)
[16] Białoszewski J. T., Wavelets and approximations, WNT, Warszawa, 2000 (in Polish)
[17] Shepard S., “Advances in pulsed thermography” Proc. SPIE “Thermosense-XXIII”, 4360: pp. 511-515, 2001
[18] Shepard S., Lhota J., Hou Y., Ahmed T., “Gold standard comparison of thermographic sequence data”, Insight, Vol. 46, No 4: pp. 210-213, 2004
[19] Pawar S.S., Vavilov V.P., “Applying the heat conduction – based 3D normalization and thermal tomography to pulsed infrared thermography for detect characterization in composite materials”, Int. Journal of Heat and Mass Transfer, Vol. 94: pp. 56-65, 2016
[20] Cichocki A., Unbehauen R., Neural Networks for Optimization and Signal Processing, J. Wiley, New York, 1993
[21] Hermosilla-Lara S., Joubert P.-I., Placko D. et al., “Enhancement of open-cracks detection using a principal component analysis/wavelet technique in photothermal nondestructive testing”, Intern. Conf. Quant. Infrared Thermography QIRT’02, Dubrovnik (Croatia), pp. 12-13, 2002
[22] Vavilov V. P., Ivanov A. I., “Pulse thermal control of multilayer products”, Defektoscopy,№ 6. C. pp. 39-47, 1984 (in Russian)
[23] Osowski S. Neural networks in an algorithmic approach, WN-T, Warszawa, 1996 (in Polish)
[24] Bharara M., Cobb J. E., Claremont D. J., “Thermography and thermometry in the assessment of diabetic neuropathic foot: a case for furthering the role of thermal techniques”, The International Journal of Lower Extremity Wounds. Vol. 5, No. 4, pp. 250-260, 2006
[25] Halloua H. et al. “An intelligent method using neural networks for Depth detection by standard thermal contrast in active thermography” Conference QIRT 2016, Gdansk (Poland), pp. 697-704, 2016