Study and quantitative assessment of the structural inhomogeneities parameters of composite materials

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Abstract. The possibility of determining the size of the delamination region and the depth of its location in non-metallic multilayer weakly conductive materials using a unique pulsed eddy-current equipment by scanning the sample and registering the region of increasing amplitude of the differential signal has been practically confirmed. The nonstationary thermal and holographic interferometry method is used to obtain information on the shape and size of the bundles. For experimental testing, samples were used made of carbon fiber composite materials with artificially created defects in the structure of the material in the form of delaminations of various sizes and shapes.

1. Introduction

Currently, polymer layered composites are widely used in the creation of structural elements for various technical objects [1–3]. For the manufacture of high-strength elements of composite structures, special sheet semi-finished products - prepregs are used [4, 5].

During the production or operation of products which have been made of laminated composite materials (CM), in the depth of the material local structural abnormalities of various types can occur. The most dangerous of them are non-adhesives, delamination and splitting. Disruption of the bond between the layers of the composite material or their partial destruction can lead to a significant decrease in the strength characteristics of the product [6]. To solve the problem of ensuring the strength of a product at the entire stage of its life cycle, it is necessary to conduct a comprehensive study, an integral part of which is an accurate and reliable determination of the true boundaries of structural defects, their areas and location along the thickness of the composite package.

2. Samples for experimental testing

The objects for the tests of the study were rectangular plates with artificial defects. The plates were made from unidirectional prepreg with high strength carbon fiber and polymer binder. A composite package with dimensions of 100×150 mm² consisted of 36 monolayers with a thickness of 0.113 mm.

During the laying of the composite package, imitators of defects were placed between the layers. These imitators were fragments of a fluoroplastic film having similar electrical properties to the
transport film used to protect prepregs at the appropriate technological stage. Fragments of the film differed in shape and size, but had the same thickness equal to 0.12 mm. Imitators were located in the center of the sample at different distances from its front surface. In total, four samples were made with the following variations in the shapes and sizes of defect simulators (figure 1):

- rectangular shape, the size of the imitator is 55×83 mm$^2$, the distance from the surface to the defect is 0.678 mm (sample 1);
- round shape, imitator diameter ø 31 mm, distance from the surface 0.678 mm (sample 2);
- round shape, imitator diameter ø 62 mm, distance from surface to defect 0.678 mm (sample 3);
- round shape, the diameter of the imitator is ø 62 mm, the distance from the surface to the defect is 1.356 mm (sample 4).

![Figure 1. General view of samples with artificial defects, mm.](image)

3. **Instrumentation and methodology of eddy current testing with experimental determination of the defects boundaries**

To obtain information on the shape and depth of defects on composite samples with artificial discontinuities, the pulsed eddy current method was used. It’s hardware implementation included a pulse voltage generator of a special shape, flat-pancake eddy-current probes with a system for recording and analyzing signals [7, 8]. At the same time, a new procedure was applied [7, 8], which was based on the first identified additional informative parameters of differential eddy current signals (figure 2). These parameters include the time to reach the maximum signal amplitude, the maximum signal amplitude, the signal value at a point of 16 µs, the signal value at two points in time according to the criterion proposed in [9, 10]. The measured value are abscessas and ordinates of characteristic points, the position of which on the state plane is compared with the nodes of the calibration grids reflecting the simultaneous change of several unrelated parameters of the test object.

The developed procedure allows for the numerical determination of several key parameters of layered composites at once and thus provides a comprehensive evaluation of their state.

It should be noted that during evaluation of composite objects consisting of thin low conductive layers, the main technical difficulty is the need to reduce the value of the initial penetration depth of eddy currents in the object by forming rectangular current pulses with a short leading edge in an inductive load. Most of the modern high-current switching elements used in the output stages of pulsed eddy-current generators provide the duration of the switching processes about 20 ns. However, due to the fact that the generator load is inductive, the rise time of the excitation current in it is longer than the rise time of the applied voltage. With the duration of the leading edge of the excitation voltage equal to 20 ns, the duration of the exciting current in the sensor (with an inductance value of about 10 µH and a resistance of about 10 Ohm) is at least 1.3 µs, which is unacceptable when evaluating thin-layer objects. In this regard, to reduce the duration of the front of the exciting pulse, a voltage generator of a special shape was developed [9].
The low electrical conductivity of the considered materials also determines a number of increased requirements for the quality of differential eddy current probes containing at least two measuring coils connected in opposite directions. The uncompensated value of the differential voltage and the value of the supply voltage of the amplifying channel of the system directly determine the possible multiplicity of the applied amplification, and, consequently, the level of sensitivity of the entire measuring channel. In this case, the value of the differential signal corresponding to the region without structural changes is the smaller, the smaller the difference in the basic and parasitic parameters of the exciting and measuring coils.

If probes are machine wound, the final balancing factor usually does not exceed -40 dB (the ratio of the maximum uncompensated value of the differential voltage to the total voltage of each of the measuring coils). In order to increase the sensitivity of the measuring system, a series of transducers was developed, with a high balancing coefficient from -78 to -98 dB (figure 3).

A number of experiments were performed on the samples. By measuring the differential eddy current signal, taking into account the fixed coordinates of the probe position, diagrams of the electromagnetic response of the longitudinal sections of the sample were obtained. When the probe approaches the defect, the amplitude of the differential signal increases nonlinearly, and when it approaches the defect, it practically does not undergo changes, forming a plateau (figure 4) corresponding to the maximum voltage value. The location of the real boundaries of the defect corresponds to the phase of the change in the character of the increase in the differential voltage on its spatial distribution. The accuracy of determining their boundaries depends on the size of the exciting section of the eddy current sensor. For the probe used in the experiments, this parameter is 1.5 mm. When scanning samples 2 and 3, which differ in the depth of the defect, the maximum of the differential signal received from the deeper defect is shifted to the right along the time axis [11]. The boundaries of defects with the diameter exceeded the dimensions of the probe are reliably determined by the presented eddy-current procedure, however, the spatial resolution provided for defects with a diameter comparable to the linear dimensions of the probe may be insufficient; this fact was used to
construct a diagram of finding the defects (figure 5). So on samples 2 and 3 the defects had a smaller area, the signal amplitude from the defect boundary was blurred and it is difficult to reliably determine the defect edge and measure its geometric parameters. This determines the need for the combined use of methods based on other physical principles.

**Figure 4.** Identification of defects shape in the structure of layered composites using a pulsed eddy current method of non-destructive testing, depending on the signal amplitude.

**Figure 5.** Visualization of defects in the structure of layered composites obtained using a pulsed eddy current method of non-destructive testing.

4. **Experiment on identification of the boundaries of structural defects using holographic interferometry**

Holographic interferometry method was used to clarify the actual boundaries of defects, their shape and location over the thickness of the samples. The determination of the natural mode and the corresponding vibration frequencies was carried out in a real time. When carrying out the research, the scheme of the holographic interferometer by E. Leith and J. Upatnieks was used. It implements the principle of beam splitting along the front (figure 6).
The studies were carried out in the vibration frequency range from 0 to 12 MHz. During the experiment, attempts were made to determine the current modes of vibrations of the plates by the positions of the nodal lines on the surface of the object. However, it was not possible to fix the influence of the presence of defects on the natural forms and vibration frequencies of the plates. The vibration behavior of plates with structural defects did not differ significantly from the deformation of defect-free samples.

The lack of deformation response of the defect area can be explained by the presence of partial adhesion between the binders and the defect simulator. This circumstance is indicated by the similar physical and mechanical characteristics of the polymer and fluoroplastic, from which the samples and simulators are made, as well as the results of experimental studies [12]. To establish the reliability of this statement, numerical calculations were carried out using the finite element method with different characteristics of the amount of adhesion between the simulator and the composite material of the plate.

Samples and defect simulators were modeled in the «MSC.Patran» software package. Despite the fact that the geometric shape of the samples is simple, in order to improve the accuracy of the results obtained, three-dimensional finite elements were used. In the process of carrying out a numerical study, a series of calculations was performed aimed at determining the deformation and vibration characteristics of the object under study. The first 10 natural modes of vibration and the corresponding frequencies were determined. Boundary conditions - rigid fastening of the plate along the bottom edge.

![Figure 6. Schematic of a holographic interferometer with beam splitting along the front.](image)

**Figure 6.** Schematic of a holographic interferometer with beam splitting along the front.

![Figure 7. Vibration characteristics of a structure with maximum (a), (c) and minimal (b), (d) adhesion in the zone of the structural defect.](image)

**Figure 7.** Vibration characteristics of a structure with maximum (a), (c) and minimal (b), (d) adhesion in the zone of the structural defect.
The change in the adhesion force was modeled by transforming the relationships between the boundaries of the defect area. In a numerical experiment, the deformation response of the structure was determined in the range from the initial (while maintaining the integrity of the material structure) to the limiting state (the occurrence of fracture in the form of the absence of bonds between the edges of the defect) states. The resulting reaction spectra, corresponding to the initial and secondary information, are shown in pairs in the form of displacement patterns in figure 7.

Comparing the results of the calculation of the initial structure with the data in which the magnitude of the relationships in the defect area changes, it can be noted that, with significant adhesion, its effect on the frequencies and the corresponding vibration modes is not significant and is mainly reduced to the distortion of the lines of the original pattern of displacement fields (figure 7(a) and 7(b)). This phenomenon is due to the fact that the change in the stiffness of the plate in the region of the defect is insignificant in comparison with the stiffness characteristics of its initial state.

With a dynamic change in the characteristics of adhesion, an increase in the effect of the defect on the patterns of the bands and the vibration frequency is observed. The tendency of displacement of the areas of maximum displacements, as well as the nodal lines corresponding to each of the shapes, is revealed. The intensity of concentration and the value of the maximum displacements are directly related by the force of interaction of the boundaries of the defect - with a decrease in adhesion, the distortion of the bands increases, causing a change in the vibration response of the structure (figure 7(c) and 7(d)).

The conducted research and the results obtained demonstrate that the presence of adhesion between the boundaries of the defect in the form of non-gluing, delamination or splitting causes a change in the deformation and vibration characteristics of the structure. In the future, studies using the holographic interferometric method will be continued, including after loading the samples and obtaining a sharper boundary of the transition of the defective region to the defect-free region.

5. Application of the non-stationary thermal method

To clarify the position and shape of defects, a non-stationary thermal inspection method with pulsed heating was used. The setup design is provided in figure 8. The samples were heated with a 500 W halogen lamp. The distance from the research object to the heating source was 30 mm. The duration of thermal irradiation of the samples varied in the range from 0.5 to 6 seconds and was controlled by an electronic timer TDM SO1506-0002, which applied voltage to the lamp. Thermograms were recorded with an NEC TH9100 PWV thermal imager with a temperature resolution of 0.02 °C. Its distance from the object was 500 mm. Thermograms were analyzed and recorded using NEC Image processor 4.7 software. During the tests, a significant dependence of the temperature contrast in the defect zone on the heating duration Δt was found. At its optimal value Δtp, the recorded thermograms made it possible to reliably detect subsurface structural defects (figure 9). Experimentally, it was found that for the available samples with depths of defects in the range of 0.678–1.356 mm, the optimal heating time, depending on the depth of occurrence, was 2.5–3.5 s.

![Figure 8](image-url)

**Figure 8.** Components of thermo inspection system: 1 – timer for the heating source, 2 – heating source, 3 – research object, 4 – thermal imager, 5 – personal computer.
Sample № 1, $\Delta t_{opt} = 3.5$ s

Sample № 2, $\Delta t_{opt} = 2.5$ s

Sample № 3, $\Delta t_{opt} = 3.5$ s

Sample № 4, $\Delta t_{opt} = 2.5$ s

$\Delta t_{opt}$ – optimal heating time

**Figure 9.** Thermograms of samples and determined optimal heating times.

**Figure 10.** Image processing procedures: original image (a), saturation channel selection (b), binarization (c), parameters calculation of the defect shape in the image (d).

To calculate the size of the defective zones, an automated algorithm was used, created using the National Instruments Vision Assistant software package. The algorithm included the following steps: the procedure for extracting the saturation channel from the color image, smoothing the image with a $3 \times 3$ averaging mask, binarizing the color image using an adaptive threshold. In this case, the threshold was selected as a value in the region of the minimum of the color image brightness histogram separating the peak of the brightest pixels corresponding to the defective area and pixels belonging to
the object from the non-defective area. The image processing results are shown step by step in figure 10.

The resulting binary image was processed to obtain the parameters of the defective area by calculating the area and dimensions of the defective zone shape when calibrating using the known linear dimensions of the samples – figure 10(d).

The experiment showed that – when processing the thermograms, it was possible to identify defects in all samples, while the shape and size of the defect in samples 2 and 3, which have small defects with an error of no more than 10%, were determined, for samples with large defects the error was 20%. At the same time, in comparison with the eddy current pulse inspection method, the image of the defect and the shape of its projection onto the front surface were obtained without scanning.

6. Conclusion

For samples with artificial defects that simulate delamination, the parameters of defects are obtained - shape, area, depth. For this, special equipment and a new methodological approach to the implementation of the pulsed eddy current method for testing carbon fiber composite materials have been proposed. The thermal non-stationary inspection method and the holographic one were also used to obtain images and shapes of defects.

From the results of the experiments, it was obtained that for the effective solution of the tasks set, the combined use of the thermal and eddy current method is necessary. At the same time, the holographic method of interferometry with vibration loading did not allow obtaining a contrast pattern, the non-stationary thermal method makes it possible to accurately determine the boundaries of small defects, due to the optimal selection of the heating time, and the pulsed eddy current method provides the ability to accurately determine the boundaries and determine the shape of large defects. At the same time, thanks to the use of special circuit solutions, the sensitivity and resolution in the plane and in depth were increased, due to which the location of the delamination in depth was determined, which is critically important for predicting the nature of the destruction of parts under load. Thanks to the combined use of pulsed eddy current and non-stationary thermal methods, it is possible to compensate for the loss of sensitivity, the nature of the detected defects expands and the accuracy of determining their key parameters: area, shape, thickness, depth of occurrence when inspecting composite products made of carbon fiber reinforced plastic is increased.

The results of the studies carried out can be used in the development of complex highly efficient methods for diagnostics of new composite materials based on carbon fiber reinforced plastic.

Acknowledgements

This work was supported by the Russian Science Foundation (project № 20-19-00769).

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