Identification of defect type in non-destructive testing of polymer composite structures

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Abstract. The paper describes non-destructive testing of composite honeycomb materials, to identify the type of defect, such as delamination, non-adhesion, inclusion, etc. Practical recommendations on testing monolithic, combined, multilayer and reinforced structures and defect identification have been given.

1. Introduction
Identification of the type of defect – non-adhesion, delamination, extraneous inclusions, honeycomb filler crush, porosity in material, etc. in various types of structures (figure 1) (monolithic, multilayer structures with different fillers, reinforced structures, etc.) is one of the most difficult tasks of non-destructive testing (NDT) of structures made of polymer composite materials (PCM). When a single NDT method is used, ambiguity may arise in identification of the type of defect. The proposed integrated use of various NDT methods seems to solve the problem.

Figure 1. The main types of PCM structures.
2. Ultrasonic methods of NDT: pulse-echo and shadow

The most common methods of NDT of monolithic structures made of PCM are ultrasonic methods [1]: pulse-echo (reflection method) and shadow (pulse transmission method). Both methods find wide application for NDT of PCM products, but each of them has its own limitations, advantages and disadvantages. The main features of the pulse-echo method include: determining the presence of a defect, determining the defect depth, obtaining information about the degree of material homogeneity (based on the back wall signal), and a high method sensitivity. The shadow method, in turn, is characterized by low informational contents of the results obtained, but by a rather simple automation. Despite some disadvantages, in terms of information content the pulse-echo method prevails, which is the basic method for preliminary analysis of the type of defect.

The main task of classifying defects in monolithic structures is the ability to interpret the delamination and extraneous inclusions (residues of process materials: separating films from prepregs and film adhesives, packaging films, drainage materials, release films, paper, adhesive tapes, sealing materials, pastes, compounds, etc.). The main problem of defect identification in NDT using the pulse-echo method is the similarity of echoes from inclusions to signals from “implicit” delamination (delamination with point contacts between the edges of the defect, delamination with small openings, porosity zones, zones of multiple point delamination). Using the pulse-echo method of NDT and the preliminary analysis of the type of defect, it is possible to fix the absence of the back wall signal and the presence of the defect signal, which is a criterion for “obvious” delamination. It is also possible to fix the simultaneous presence of the back wall signal and the defect echo signal, which is the criterion of “implicit” delamination or inclusion. In the latter case, the back wall signal can be detected in the case of point contact between the edges of the delamination or in the case of partial ultrasound transmission through the material of foreign inclusion. Figure 2 shows typical A-scans obtained by a standard ultrasonic flaw detector (UD4-T) in a defect-free zone and zones with delamination and extraneous inclusion.

![Figure 2](image.png)

Figure 2. Typical A-scans: (a) – of the defect-free zone; (b) – in the delamination zone; (c) – in the inclusion zone.

The problem of identifying “implicit” delamination and inclusions is solved by the ultrasonic method with laser excitation of ultrasound, based on the optical-acoustic (OA) effect, in which, due to absorption of a laser pulse, an unsteady increase in the temperature of the near-surface layer and subsequent excitation of acoustic waves occur [5]. This method is implemented using the ultrasonic flaw detector with laser excitation of ultrasound UDL-2M, which features a high radiation resolution due to the emission of ultrashort acoustic pulses and allows detecting the presence of interfaces with a beam resolution of ~ 0.1 mm.

The identification method is based on the analysis of phase changes of signals reflected from the interface of two media having different acoustic impedances $z_1$ and $z_2$ (figure 3).
A phase reversal, characterized by a negative reflection coefficient $R$, is always observed upon reflection from an acoustically softer material [4]. The main sign of foreign inclusion is the simultaneous presence of a bidirectional signal (the resulting signal reflected from the two interfaces “PCM-inclusion” and “inclusion-PCM”) and the presence of the back wall signal over the total area of the defect. The sign of delamination with point contacts between the edges of the defect (or local porosity zones) is the presence of the signal from a defect with variable amplitude and duration, as well as a sudden jump of the amplitude of the back wall signal when scanning the defect area [3]. Figure 4 shows the results of the study of extraneous inclusion and the zone of local porosity obtained using a laser-ultrasonic flaw detector UDL-2M on real PCM products.

The ratio of the amplitude and phase of the back wall signal to the defect signal and the determination of ratio of the reflection and transmission of ultrasound at the PCM-inclusion interface, in some cases allow not only to identify the inclusion, but also to obtain information about its material. Data on the type of discovered defect and its material are extremely important for the design, process

Figure 3. Phase changes of signals at the interface (a) and typical signals from foreign inclusions (b).

Figure 4. A- and B-scans of foreign inclusion (a) and local porosity zones (b).
and production services of the enterprise, as they allow to correctly assess the degree of risk and influence on the structural ability, the ability to conduct and select repair methods for the discovered defect, help in analyzing the technological process, labour discipline and developing measures to reduce the likelihood of such defects in the future. To estimate the material of the detected inclusion, it is necessary to manufacture a comparative sample made according to the technological process of the tested item, in which it is necessary to install fragments of materials that are potentially possible to enter the product during its manufacture.

3. X-ray method of NDT

Despite rather high informational content of the integrated application of the pulse-echo and ultrasonic method with laser excitation, in the problem of identification of extraneous inclusions there is a number of materials that cannot be distinguished from delamination. To solve this problem, the x-ray method is applied, which provides information about the presence of a defect based on the change of the X-ray density of the material being X-rayed.

For example, the use of phosphoric X-ray plates, followed by digitization and computer processing of the obtained X-rayograms, allows to achieve the best results in determining the inclusion, which is a separating film lying between the layers of the prepreg, which prevents the prepreg from sticking together during storage. The application of the X-ray film for such a task is practical; however, it requires a careful development of the X-ray diffraction modes, as well as the measurement of the degree of blackening of the zones of the X-rayogram corresponding to the defective and defect-free zones using a densitometer.

Figure 5 shows X-rayograms of products that have the inclusion type defects. Sections of images that have a high degree of blackening and are marked with lead marks correspond to the places where the separating film lies between the layers of the prepreg.

![Figure 5](image)

**Figure 5.** X-rayograms of PCM products with an inclusion type defect.

The application of the X-ray diffraction method is most effective for differentiation of the inclusion type and delamination type defects.

4. Low-frequency acoustic methods of NDT: impedance and free oscillation

For NDT of PCM multilayer structures, the layers of which consist of various materials (monolithic skin, honeycomb filler, plastic foam, etc.), one of the most common NDT methods are: acoustic impedance [2] using dry point contact with the tested item and shadow ultrasound (using computer-
aided procedures) with a jet input of the ultrasonic signal or the NDT in the scanning tank. Additionally, the local free oscillation method (FOM) is used as an expert method) [2, 8–10]. One of the distinguishing features of PCM multilayer structures is the presence of a large number of interfaces between dissimilar materials. The high attenuation ratio of elastic acoustic oscillations of some layers of these structures leads to the need to apply the above methods.

The solution to the problem of identifying the type of defects in multilayer structures is more complex than in monolithic ones. The acoustic impedance flaw detector ID-91M [2] (amplitude-frequency signal processing) together with the single probe (SP) and the dual probe (DP) can indirectly distinguish near-surface delamination in the skin due to the non-adhesion defect between this skin and the honeycomb filler or the honeycomb filler crush as the method is based on recording changes in mechanical impedance $Z$, which is equally influenced by the presence of each of the listed defects. The SP is used to detect defects located close to the surface at a depth of up to 4 mm, and the DP - to detect deep-lying defects located at a depth of up to 10 mm (the sensitivity of testing of complex multilayer structures is determined empirically using samples with simulated defects in them [11]). The features of the operation of these probes (when testing with two types of probes) can be used to solve the problem of identifying delamination and non-adhesion defect using the impedance method. Table 1 shows the nature of changes in the signal amplitudes of the ID-91M flaw detector when various anomalies are detected in the tested item (the NDT was performed from the external skin) by the example of the conventional three-layer PCM structure with skins of 3 mm thick and honeycomb filler 10 mm high.

The difference in the change in the signal amplitudes during the testing by the SP and the DP allows indirectly identifying near-surface delamination, but does not allow distinguishing the deeper delamination in the skin due to the non-adhesion defect of this skin or the honeycomb filler crush.

**Table 1.** Changes in signal amplitudes and mechanical impedances during the testing of various sections of the tested item by means of the ID-91M flaw detector.

| Tested zone                                                                 | Probe          | Mechanical impedance, $Z$ |
|---------------------------------------------------------------------------|----------------|----------------------------|
| A regular defect-free (tuning) zone: external skin, honeycomb filler, internal skin. | $\sim 85\ \mu A$ | $\sim 40\ \mu A$ | No change |
| A zone with the increased thickness of the external skin, and/or with a honeycomb filler filled with paste, or a PCM insert instead of a honeycomb filler. | $\uparrow$ | $\downarrow$ | $\uparrow$ |
| A zone with a reduced thickness of the external skin.                      | $\downarrow$ | $\uparrow$ | $\downarrow$ |
| A zone with near-surface delamination in the skin (depth up to 0.5 mm*).  | $\downarrow$ | $\downarrow$ | $\downarrow$ |
| A zone with delamination in the skin (depth more than 0.5 mm*).           | $\downarrow$ | $\uparrow$ | $\downarrow$ |
| A non-adhesion zone of the honeycomb skin/honeycomb filler crush.         | $\downarrow$ | $\uparrow$ | $\downarrow$ |

* - the value of 0.5 mm is conditional, as it depends on the specific material.  
$\uparrow$ - the value increases, $\downarrow$ - the value decreases.
Impedance flaw detectors with amplitude-phase signal processing (DAMI-S, BondMaster), where the tuning takes place using a zone of friction noise, do not allow identifying the type of defect and their use is only possible to determine the presence of a defect.

Due to the influence of the surface roughness of the tested item on the value of the signal amplitude in the impedance method, an additional FOM can be used. In the spectral case [2, 8–10] of this method or in the case with the analysis of the impact duration [12–15] of the striker of the flaw detector probe for FOM with the tested item, surface delamination in PCM products are steadily detected, the NDT of multilayer structures with thin (less than 0.5 mm) skin is possible. In addition, there is no phenomenon of “collapsing” (or “closing” [2]) of such defects in the FOM, which is typical for the impedance method, since the probe is tightly pressed to the surface of the tested item.

Thus, the testing sensitivity of PCM multilayer products using low-frequency acoustic methods often remains quite low due to the influence of various factors: the complexity of structures consisting of three or more layers, the small thickness of the skin, the small value of the material Young's modulus, the high surface roughness, the presence of perforation of the skin etc. Defects that do not have a discovery in the form of a gas-filled gap (inclusion) are not detected by low-frequency acoustic methods. In fact, the NDT of multilayer structures made of PCM, where these methods are applied, requires an individual approach, and the identification of each type of defect often requires the application of additional NDT methods.

5. NDT thermal method
Along with the X-ray method, the thermal method [16-19] is characterized by the visualization of the presentation of the testing results, but compares favorably with the high testing performance and safety. The testing of honeycomb structures by the active thermal method is of our main interest. Compared to the low-frequency acoustic testing, the thermal method allows distinguishing the delamination and the non-adhesion defect.

There are a large number of ways of thermal stimulation of the tested item, for example, the method of heating with a halogen lamp, a xenon flashtube, a stream of hot air, microwave, ultrasonic. Among the simplest methods to implement is the heating method with a halogen lamp with a one-sided control circuit.

The specific features of the delamination are:
- a short delay time of the demonstration of the defective zone on the thermogram;
- strongly marked interfaces of the defective zone;
- significant temperature difference between the defective and non-defective zones.

The thermogram of the sample with an artificial imitator of the delamination type defect is shown in figure 6. The defect imitator is made in the form of an embedded wedge-shaped element installed between the layers of the prepreg of the external skin of the sample and extracted after forming the sample.

The specific features of the non-adhesion defects are:
- a longer delay time of the demonstration of the defective zone on the thermogram compared to the delamination;
- absence of honeycomb filler zone demonstration in the place of the non-adhesion defect;
- the temperature difference between the defective and non-defective zones is absent or insignificant.
Figure 6. The thermogram of the sample with an artificial imitator of the delamination type defect.

Figure 7. The thermogram of the sample with an artificial imitator of the non-adhesion defect.

The thermogram of the sample with the artificial defect imitator of the non-adhesion defect type is shown in figure 7. The defect imitator is made in the form of a wedge-shaped embedded element installed in the adhesive layer between the outer skin of the sample and the honeycomb filler and extracted from the sample after its remolding.

Thus, the application of the active thermal method allows simplifying the process of identifying defects in three-layer structures with honeycomb fillers made of polymer composite materials. The advantages of application of the method for identifying the type of defects are its contactlessness, safety and ease of interpretation of the testing results.
6. Conclusion

The capabilities and features of the methods for identifying defects are shown in Table 2.

### Table 2.

| Method                        | Monolithic structures | Multilayer structures |
|-------------------------------|-----------------------|-----------------------|
|                               | delamination          | non-adhesion defect   |
|                               | (layer-to-layer       | (layer-to-layer       |
|                               | connection)           | connection)           |
|                               | foreign inclusion     | a delamination in the |
|                               |                       | skin                  |
|                               |                       | non-adhesion defect   |
|                               |                       | (connection of the    |
|                               |                       | skin with the filler) |
|                               |                       | honeycomb filler      |
|                               |                       | crush                 |
| Impedance, FOM                | ±                     | +                     |
|                               | ±                     | +                     |
|                               | –                     | –                     |
| Low sensitivity of testing.   |                       |                       |
| Near-surface delamination are |                       |                       |
| steadily detected. Reduced   |                       |                       |
| sensitivity when increasing   |                       |                       |
| the thickness of the structure. |                       |                       |
| Ultrasonic shadow             | +                     | +                     |
|                               | ±                     | –                     |
| A steady detection of delamina|                       |                       |
| tion and non-adhesion defects. |                       |                       |
| It is impossible to detect   |                       |                       |
| the type of defect. It is     |                       |                       |
| difficult to detect           |                       |                       |
| inclusions. Poor performance  |                       |                       |
| of the testing in manual mode. |                       |                       |
| Ultrasonic pulse-echo         | +                     | –                     |
|                               | +                     | +                     |
|                               | ±                     | –                     |
| In the presence of the back   |                       |                       |
| wall signal (materials with   |                       |                       |
| an ultrasonic attenuation     |                       |                       |
| ratio of no more than 1.5 dB/mm), all considered |                       |                       |
| defects are steadily detected |                       |                       |
| and identified.               |                       |                       |
| Thermal                       | ±                     | –                     |
|                               | ±                     | –                     |
|                               | –                     | –                     |
| Restrictions on the thickness |                       |                       |
| and material of the product.  |                       |                       |
| A high labour intensity of   |                       |                       |
| the NDT.                      |                       |                       |
| X-ray                         | –                     | –                     |
|                               | –                     | –                     |
|                               | ±                     | –                     |
| Only inclusions from materials |                       |                       |
| with a high X-ray absorption  |                       |                       |
| rate are steadily detected. A |                       |                       |
| high labour intensity of the  |                       |                       |
| NDT.                          |                       |                       |
|                               |                       |                       |

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