Theoretical and practical justification of high-precision of defects in multilayer polymer honeycomb structures by the honeycomb filler height reduction method

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Abstract. A method of non-adhesion defect simulation in multilayer honeycomb structures from polymer composite materials is discussed. This simulation method is particularly relevant for honeycomb structures with large cells. An experimental model for the comparison of two simulation methods, a new one and a flat-bottom hole simulation method, was fabricated.

1. Introduction
Non-destructive testing (NDT) of multilayer honeycomb structures made of polymer composite materials is an integral part of ensuring the reliability of parts in the aircraft and rocket and space industries. The acoustic impedance method [1] is the main testing method of such structures. Additionally, the following NDT methods are applied: ultrasonic [3, 4], thermal [5, 6], X-ray [7, 8] and others.

To adjust and check the operability of flaw detectors, as well as verify the testing sensitivity, work standard samples (WSS) with defect imitators made in them are used [1]. The WSS are manufactured in accordance with the manufacturing technology of the tested item and have an identical structure with it. For adjustment, the defect-free and defective zones on the WSS are used.

The most important task is to imitate a defect with the area corresponding to the area of the minimum allowable defect and the specifications closest to the real defect. However, the features of the methods of defect imitation in multilayer honeycomb structure are not considered in sufficient detail in publications. For a number of honeycomb structures with a honeycomb core area exceeding 0.8 cm², the existing methods of non-adhesion defect imitation [1, 2] do not provide the necessary accuracy and reproducibility of defect imitation on a given area [9]. As compared to existing analogues, the application of the method of non-adhesion defect imitation (the so-called “rib-shortening” method) developed by the authors and described in [9-11], allows imitating defects with a strictly specified area and provides 100% reproducibility of the imitation results. In the present work, a mathematical simulation of WSS with defect imitation using the developed method is performed, and the process of the NDT of the WSS with this type of defect is described. The imitation of delaminations in the skin is not considered in this paper.

2. Main results. Theoretical justification of the method’s reliability
To theoretically confirm the advantages of the method developed by the authors against the currently available analogues, a three-dimensional model of the sample was constructed, which is a three-layer
structure with honeycomb filler. The model has defect imitators that structurally correspond to the
defect imitators made using the honeycomb filler height reduction method by circular milling,
described in [1, 2], as well as using the rib-shorting method. Figure 1 shows the model of a
honeycomb structure with performed defect imitators.

![Figure 1](image1.png)

**Figure 1.** A part of a honeycomb structure model with defect imitators using the honeycomb filler
height reduction method by circular milling and rib-shorting method. In the right part of the figure, the
detail without an external skin is shown. The location of the imitator is circled in red.

To study in detail the effect of various area defects on the strength of the honeycomb structure, as
well as to predict the detection of defects by NDT methods, the imitation of the stress condition of the
WSS in the Nastran environment was performed. The load value was selected in accordance with the
part’s workload specified in the design documentation. First, the structure loading was carried out,
with a defect imitator performed in it using the honeycomb filler height reduction method by circular
milling. Figure 2 shows models of defect imitators made using the honeycomb filler height reduction
method by circular milling, with equal theoretical areas of defects, but performed on different sections
of the honeycomb filler.

Based on the results of imitation, the theoretical confirmation of the difference in the areas of
imitated defects, depending on the place of their location, with equal areas of the milled imitators was
obtained.

![Figure 2](image2.png)

**Figure 2.** Models of the stress condition of the sample with defect imitators made using the
honeycomb filler height reduction method by circular milling.
The diameter of the milled imitators is 16 mm.
The following conclusions can be drawn from these models:
1) the forms of the obtained defect imitators have significant differences;
2) the areas of the obtained imitators are not equal to each other;
3) the areas of the obtained imitators exceed the theoretical ones.

It should be noted that in the zone around the defect imitator, there is a reverse deflection that compensates for the deflection of the skin in the centers of the cells. This stress condition can cause an increase in the defect area during the operation of the honeycomb structure.

Next, the stress condition of the sample was imitated using the rib-shorting method. The resulting models are shown in figure 3.

![Figure 3](image)

Figure 3. Models of the stress condition of the sample with defects imitators performed using the rib-shorting method. The height of the 1 (a), 3 (b), 5 (c) and 12 (d) cell faces is reduced, respectively.

Compared to the imitation using the method of honeycomb filler height reduction by circular milling, the area of the defect imitators performed on the model using the rib-shorting method is completely within the theoretical boundaries of the imitator. The shape of the skin deflection zones inside the defect imitators corresponds to the shape of the performed imitator. The area of the skin deflection zones inside the imitator is less than the sum of the cells areas of the honeycomb filler inside the defect imitator.

The results of modelling of the developed defect imitation method showed its advantages over the currently available analogues: the ability to predict the area of the obtained defect imitator, the absence of a zone around the imitator with a reduced load-bearing capacity of the honeycomb filler, the deflection of the skin as close as possible to the real defect.

3. Main results. Practical confirmation of the method’s reliability

The experimental verification of the reliability of the developed imitation method and of the proof of its advantages over existing analogues was carried out on a sample, which was a three-layer structure with a honeycomb filler. The defects imitators in the form of flat-bottomed holes were performed on the sample, as well as the rib-shorting method was applied (figure 4). The imitation in the form of a flat-bottomed hole was similar to the imitation of honeycomb filler height reduction by circular milling. The difference is that in a flat-bottomed hole, the material is removed completely up to the lower skin (figure 6). The error of forming defect imitators with a certain area is identical for these two methods of imitation.
Figure 4. The sample diagram with two types of defects imitation: flat-bottomed holes (1) and height reduction using the rib-shorting method (2).

Figure 5 shows a general view of the imitators made using the developed method on the honeycomb filler of the sample, before the installation of the outer skin.

Figure 5. Defects imitation using the method of honeycomb filler height reduction (a rib-shorting method). View before gluing the outer skin. The following have the reduced height: (a) 1 face, (b) 3 faces.

Figure 6. The imitator of the non-adhesion defect in the form of a flat-bottomed hole. View from the side of the lower skin (the NDT is performed from the opposite side).
Non-destructive testing of the sample was carried out by the impedance method using the ID-91M flaw detector with the SP. Table 1 shows a comparison of the design parameters of defects with the parameters determined as a result of testing.

Table 1

| Defects imitators | I    | II   | III  | IV   |
|-------------------|------|------|------|------|
| The sum of the areas of all cells, cm² | 1.57 | 2.36 | 3.14 | 5.5  |
| Diameter of a circle with an area equal to the sum of the areas of all cells, mm | 14.15 | 17.33 | 20.01 | 26.47 |
| The area of the inscribed circle, cm² | 0.24 | 0.95 | 1.66 | 3.8  |
| Diameter of the inscribed circle, mm | 5.5  | 11   | 14.55| 22   |
| The area of the defect imitator determined using the impedance flaw detector, cm² | *    | 1.6  | 2.2  | 3.8  |

* - minimal defect, detected pointwise.

A characteristic trend is observed: with an increase in the number of honeycomb filler cells of reduced height, the area of the defect detected during the testing using the impedance method becomes equal to the area inscribed in the circle defect. For imitator of type IV, these areas are equal (3.8 cm²). Smaller imitators of types I-III generate interest, since the detection of such defects in products is most difficult.

The additional X-ray testing of the sample did not discover any honeycomb filler crushes. This confirms the reliability of the testing results using the impedance method.

The sample was also subject to the NDT using the active thermal method. The conversion of testing results was performed according to the method described in [12]. The testing results in the form of an “artificial” thermogram of the sample are shown in figure 7. Similar results can be obtained using the conversion methods described in [13-15].

![Figure 7](image)

Figure 7. The thermogram of the sample with defect imitators made in the form of flat-bottomed holes (upper row) and using rib-shorting method (lower row).

The areas of defect imitators in the form of flat-bottomed holes, detected during the testing using the active thermal method, exceed the areas designed in the theoretical calculations. The areas of defects performed by the rib-shorting method strictly correspond to the theoretical ones.
4. Discussion of results

The results of modelling of the developed defect imitation method, as well as the NDT of the sample manufactured in accordance with the developed imitation technology, showed its advantages over the currently available analogues: the ability to predict the area of the defect simulator obtained, the absence of a zone around the simulator with a reduced honeycomb load bearing capacity, and the skin deflection as close as possible to a real defect. The developed imitation method shows good results of reliability and reproducibility of defect imitators. The effectiveness of the method has been proven for adjustment of flaw detectors that implement impedance, thermal, shadow ultrasonic, and free oscillation methods.

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