The new indicator coating to detect the place of barely visible impacts on aircraft composite structures

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Abstract. There was developed indicator coating made of epoxy resin filled with hollow glass spheres of the volume fraction up to 50% on GFRP substrates. This coating has a high sensitivity to local impacts changing light reflection by the failure of epoxy and glass spheres in the contact area. Mechanical behaviours of the coating are close to the pure epoxy resin but the density is twice less. We also provided experimental data concerning the contact traces under barely visible impact and the numerical model to predict residual traces onto indicator coating with GFRP substrate.

1. Introduction
During aircraft maintenance, staying on the airfield or the movement, various damages can occur in the polymer composite material (PCM) elements due to falling of the tool, hits of gravel from the runway, collision with birds, hail impacts, etc. Composite structures can have both small dents, delamination, and fibre breaks [1-3] depending on the impact speed, size, shape, and material of the indenter. The most dangerous composite damage is considered to be the barely visible impact (BVI) which can decrease more than half the strength of the structure [4-6] under compression or tension. In this regard, to ensure flight safety, it is crucial to detect operational defects on time and assess their danger.

Visual methods are the fastest and cheapest for detecting operational defects in PCM aircraft structural elements. In the scientific literature, it is proposed various functional coatings for this purpose. Such coating (often called 'smart'), as a rule, consists of a polymer matrix into which capsules with a dye are embedded, which reacts to mechanical stress by changing their colour [7-9]. For the case of an impact, the microcapsules are destroyed, and the coating colour is changing. The wall thickness of the microcapsule determines the sensitivity of the coating to impacts. The disadvantage of such coatings is that the accuracy of diagnosing places of impact damage to a structure depends significantly on the uniformity of distribution of the initiator, dye and inhibitor in the coating, and, consequently, on the quality of mixing in the process of creating a polymer composition.

There are 'smart' mechanochromic coatings [10-12] which react to external pressure, stretching or friction by changing colour. The phenomenon of mechanochromy has a reversible nature, and the duration of the colour change of the material can take from several minutes to several hours, depending on the operating conditions. The mechanochromic properties of a polymer are manifested when exposed to a force of a strictly defined value, which depends on the chemical nature of the mechanophore contained in the polymer.

Recently, coatings have become widespread, which are called 'damage indicators' [13-15]. This type of coating consists of a polymer matrix with capsules of a phosphor that exhibits fluorescent properties when exposed to a specific wavelength light. The disadvantages of this method for detecting damage is
the lack of sensitivity of the capsules to low-energy impacts, and, therefore, this prevents the detection of BVI damage to the structure. Also, it is impossible to adjust the thickness of the walls of microcapsules filled with different fluorescent indicators, which give different colours when irradiated, to determine the impact force accurately. Constant monitoring of structures with their illumination with specific wavelength radiation and registration of the glow using a digital video camera is required. It complicates the control procedure, increases the time of its conduct, and also requires the appropriate qualifications of the service personnel.

In this work, we propose a new type of indicator coating (IC) based on a polymer matrix and hollow glass microspheres (a close analogue is a syntactic foam [16]) taking into account the disadvantages of the above 'smart' coatings. On impact, the IC irreversibly changes the reflection coefficient due to polymer deformation and failure of microspheres and is easily detected without specific sources of illumination.

It is important to note that the trace on the IC indicates the place of impact and makes it possible to estimate the residual strength of the composite after appropriate calibration.

2. Experimental investigations

2.1. Indicator coating material and manufacturing technology

A dispersed-filled composite based on hollow glass microspheres and ED20/TETA epoxy polymer was used as an impact-sensitive IC. Hollow glass microspheres (manufactured by ForeSphere [17], Fig. 1a) have a bulk density of 36 kg/m³ and a hydrostatic compression strength about 150 bar. The spread of diameters of microspheres obeys a logarithmically normal distribution, (Fig.1b), with an average diameter ~40 μm and a wall thickness ~ 2 μm, determined from the bulk density.

![Figure 1](image1.png)

**Figure 1.** Glass microspheres: image in a scanning electron microscope (a) and histogram of diameters (b).

The manufacturing technology of the IC was as follows:

1. mixing ED20 epoxy resin with TETA hardener in a ratio of 10/1 by weight;
2. mixing the prepared polymer with glass microspheres in a ratio of 8/1 by weight;
3. coating (notched trowel) on the composite specimen;
4. curing at room temperature for 24 hours;
5. post-curing at 80°C for 5 hours.

The density of the finished material was 0.96 g/cm³. Specimens were made in the form of beams (100x20x4 mm) or cubes (10x10x10 mm) for bending or compression tests, respectively to determine the elastic and strength characteristics of the IC. The tests were carried out on an INSTRON 5882 universal testing machine at room temperature. The crosshead speed was set at 5 mm/min.

During compression, the IC behaved non-brittle (Fig.2a) with properties close to those of epoxy resin: elastic modulus 3.70 GPa, Poisson's ratio 0.34; however, the ultimate compressive strength was significantly higher than that of pure epoxy polymer and equal to ~ 170 MPa. According to the results
of tests for three-point bending (span 60 mm), the tensile strength of the material was ~ 120 MPa. The failure of the coating occurred mainly in the matrix (Fig. 2b).

![Figure 2](image)

**Figure 2.** Compressive stress-strain diagram for SP (a) and SEM of fracture surface (b)

2.2. Low-Velocity Impact testing

LVI tests of composite specimens were provided to assess the indicator capabilities of the proposed IC. These tests were carried out on plates (100×100×4 mm) cut from a GFRP sheet. Half of the specimens were coated with IC ~ 0.4 mm thick. GFRP (STEF™, manufacturer "Electroizolit" [21]) had 20 layers of plain-weave fabric and phenolic epoxy matrix. The volume fraction of fibres and the density of GFRP were equal to 42% and 1.76 g/cm³ correspondingly. The elastic and strength characteristics of the material were determined using standard specimens. The data obtained are presented in Table 1 and Table 2. The ± sign everywhere below is followed by the standard deviation measured on a series of specimens.

**Table 1.** Elastic properties of the GFRP.

| Young's moduli (GPa) | Shear moduli (GPa) | Poison's ratios |
|----------------------|-------------------|----------------|
| $E_1$                | $E_2$             | $G_{12}$       |
| $E_3$                | $G_{13}$          | $G_{23}$       |
| $\mu_{12}$           | $\mu_{13}$        | $\mu_{23}$     |
| 23.7±0.6             | 22.9±0.6          | 9.5±0.1        |
| 4.6±0.3              | 4.2±0.2           | 3.7±0.2        |
| 0.19                 | 0.19              | 0.18           |

**Table 2.** Strength properties of the GFRP.

| Ultimate tensile strength (MPa) | Compressive strength (MPa) |
|---------------------------------|----------------------------|
| $F_{11}$                        | $F_{21}$                   |
| 403±14                          | 304±10                     |
| 500                              |                            |

Impact tests were done on an INSTRON CEAST 9350 drop tower. In all tests, the specimens were placed on a rigid support (Fig. 3), which provided more significant damage to the composite structure in comparison with a simply supported plate. This case is the most dangerous in the design of the fuselages of new aircraft with a lattice structure [19, 20]. The aerodynamic skin of them is glued to the ribs and cannot bend in these places and dampening the impact. In our experiments, we used an INSTRON 7529.841 steel tip with a hemisphere with a radius of 12.7 mm. The falling weight was 5.095 kg, the impact energy was varied in the range of 5 ... 25J. A total of 30 samples were tested with and without coating.

![Figure 3](image)

**Figure 3.** Support of the specimen during testing.
Upon impact, a distinctly noticeable imprint appeared on the IC (Fig. 4a), the diameter of which increased with increasing impact energy (Fig. 4b).

![Image of an impacted coating after LVI with the energy of 5J (a) and the dependence of the indentation diameter on the impact energy (b).](image)

**Figure 4.** Image of an impacted coating after LVI with the energy of 5J (a) and the dependence of the indentation diameter on the impact energy (b). Line - calculation (see below).

According to the test results, the dependence of the area of damage in GFRP plate vs the impact energy was obtained (Fig. 5). It has been found that the indicator coating also functions as a bumper layer, reducing the damage of the GFRP. At impact energies up to 10 J, no visible damage or delamination was found in the GFRP. At impact energies over 15 J, the use of an indicator coating made it possible to halve the area of the damaged zone in the GFRP.

![Dependence of the damaged area on the impact energy](image)

**Figure 5.** Dependence of the area of the damaged zone in the composite on the impact energy.

2.3. Residual strength of specimens with defects

Beams 40 mm wide were cut out from specimens with impact defects (Fig. 6), which were tested for three-point bending; the span was 40 mm.

![Specimen cutting scheme for determining residual flexural strength](image)

**Figure 6.** Specimen cutting scheme for determining residual flexural strength.
According to the test results, the dependences of the residual strength in bending on the impact energy were obtained (Fig. 7). It can be seen that the residual bending strength of the coated specimens does not change up to impact energy of 20 J. The residual strength of the uncoated specimens decreased by 15-20% at the same impact energy.

The results obtained indicate the high efficiency of using the coating not only to show the place of impact but also to mitigate the damage of the composite with it.

**Figure 7.** Dependence of the residual strength of STEF in bending vs the impact energy.

### 3. Numerical modelling of indicator coating

The coating was modelled using the finite element method in the commercial version of the ANSYS WB / Static Structural. An elementary cell is considered, which is a cube containing a part of a hollow sphere (Fig. 8); the volume fraction of the glass sphere in the model was 30%. This model made it possible to obtain quite a reasonable estimation of the elastic and strength properties without considering the complex stochastic distribution of microspheres of different diameters in the volume of the polymer.

**Figure 8.** Unit cell UP with a finite element mesh (a) and the calculated stress-strain diagram of cell compression (b).

In the model, quadratic finite element SOLID186 was used, which allow considering the linear change in deformations and stresses along the element body. Elastic and strength (yield point) properties of epoxy polymer and microspheres are taken from the ANSYS library of standard materials [18], table. 3. Outside of elasticity, the polymer material is assumed to be bilinear with a hardening modulus $E_t = 500$ MPa.

| Material           | $E$, MPa | $\mu$ | $\sigma_Y$, MPa | $E_t$, GPa |
|--------------------|---------|------|----------------|----------|
| Epoxy resin        | 3780    | 0,35 | 60             | 500      |
| Glass microspheres | 71000   | 0,3  | -              | -        |
The boundary conditions on the surface of the periodicity cell corresponded to the planes of symmetry. The loading was kinematic (the displacement of the upper face of the cube was set), and the corresponding force was determined and, then, the average compression stress. With the elastic behaviour of materials (the von Mises equivalent stresses in the polymer did not exceed 60 MPa), the values of the IC elastic modulus and Poisson's ratio were obtained: $E = 3.57$ GPa, $\mu = 0.34$, which is in good agreement with the experimental data (Section 1.1).

With further compression, inelastic deformations develop in the polymer, the load increases, Fig. 8b. With a total strain of the IC model of 10%, it was found that the compressive stresses were 170 MPa. It is in full agreement with experimental observations (marked * in Fig. 2a). Calculations with other volume fractions of microspheres (10 ... 50%) showed a weak sensitivity of the mechanical properties of the IC. Thus, when operating on a substrate made of STEF, the IC can be considered a pseudo-isotropic elastoplastic material with an elastic modulus of 3.57 GPa, Poisson's ratio of 0.34, the yield stress of 115 MPa, and a hardening modulus of 600 MPa (bilinear behaviour up to the strain of 10%).

4. Numerical modelling of the IC on the GFRP substrate

In the calculations, the elastoplastic behaviour of the IC and the elastic work of the STEF with the properties noted in Table 1 were considered. The scheme of finite element modelling in ANSYS WB (explicit) is shown in Fig. 9. There is ¼ part due to symmetry; friction on the contacting surfaces of the indenter and the coating was neglected.

The indenter weighted ~5 kg and fell on a STEF plate on a rigid base with initial velocities from 1.41 to 3.16 m/s, which corresponded to energies from 5 to 25 J. In the process of dynamic contact, the coating elements experienced significant inelastic deformations and failed upon reaching the value of the first principal strain of 10%. Failure was simulated by the excluding of the corresponding finite element from the mesh.

As a result of dynamic calculations, the configurations of the coating failure zone were obtained (Fig. 9b). The diameters of these zones as a function of impact energy are shown in Fig. 4b by the line. Up to an energy of 15 J, the calculations are in good agreement with the experiment. At high energies, the STEF is damaged, and the indentation diameter practically does not change, while in the calculations the contact force increases with the indentation diameter. Nevertheless, the error in the calculated estimate of the indentation diameter does not exceed 10%.

5. Conclusion

Indicator coatings (IC) based on epoxy resin and hollow glass microspheres can be used for visual detection of subtle damages that occur in aircraft structural elements under the local impact.
The volume fraction of glass microspheres in IC insignificantly affects the mechanical characteristics of the coating. The IC can also act as a damping layer, drastically reducing the GFRP damage zone under LVI.

For rigid support during impact the nature of GFRP damage does not depend on the impact energy: a zone with intense cracking appears, without noticeable delamination. The numerical model of the IC was developed and showed that the coating could be replaced by a homogeneous isotropic elastoplastic material to predict the indentation diameter and then for the estimation of the composite residual strength.

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