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INFLUENCE OF POLYMER COATING THICKNESS ON DAMAGE TOLERANCE AND RESIDUAL STRENGTH OF COMPOSITE MATERIAL

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Abstract. The low impact resistance of laminated polymer composites is a significant problem. Even barely visible impact damages can significantly decrease the residual strength of the composite. In this article, the effect of the thickness of a polymer coating based on hollow glass microspheres on the damage tolerance and residual strength of glass fibre-reinforced plastic (GFRP) was studied. 4 mm thick GFRP specimens with polymer coatings of different thicknesses were prepared. The thickness of the coatings varied from 0.4 mm to 1.2 mm. The specimens were tested on a vertical drop tower system with impact energies up to 25 J. The dimensions of the obtained defects were determined using infrared thermography. The residual strength of the specimens was determined using the Flexure-After-Impact protocol. It was found that the 1 mm thick coating with a surface density of 650 g/m² made it possible to reduce the damaged area by 35% and to increase the residual flexural strength of the GFRP specimens by 27% in comparison with the uncoated ones.

1. Introduction

Aerospace structures made of polymer composite materials can be subject to transverse low-velocity impacts (tool fall, hail, bird impact, runway debris) throughout their entire service life. When the energy threshold is exceeded, low-velocity impact loading can lead to barely visible damages in the composite, for example, delamination, which significantly decreases the residual strength of the entire structure [[1], [2]].

A large number of works are devoted to improving the impact resistance of composite materials. First, the use of hybrid composites is an effective technological method that allows to achieve the reduction of impact damage size and to increase residual strength. The following studies of impact behaviour of hybrid composites should be mentioned:

- using various types of reinforcement fibres and their stacking sequence in the laminate [3-7];
- combination of unidirectional and woven layers [8];
- intermediate layers based on thermoplastics, elastomers and metal foil [9, 10].

The disadvantages of hybrids include a decrease in the weight efficiency of the material. In several works, the authors noted a significant positive effect of interlayer polymer veils on the mechanical behaviour of composites upon impact and their residual strength. [[11]-[15]]. At the same time, the use of polymer veils often leads to a reduction of flexural stiffness due to a decrease in the reinforcement volume fraction. The most radical way to increase the transverse strength of the composite and its impact resistance is transversal reinforcement. In many works, the authors noted a decrease in the damaged area and an increase of residual strength due to the use of three-dimensional woven/braided preforms [16-



18], stitching [19-22], and tufting [23, 24]. However, transversal reinforcement leads to a decrease in the elastic and strength properties of the composite, significantly increases the cost and complicates the manufacture of the composite element.

In several articles, researchers have studied the possibility of using various protective layers to reduce the impact damages in the composite. During et al. [25] considered composite specimens with protective layers based on steel foil and EPDM elastomer. Rahme et al. [26] carried out experimental studies of impact loading of composite specimens with a protective layer based on hollow polymer spheres and an outer layer of aramid fibre-reinforced plastic. In both cases, the specimens with a protective layer had a significantly smaller damaged area compared to the original specimens at the same impact energy. On the other hand, the coatings had a rather complex configuration. Moreover, the coating based on hollow polymer spheres increased the panel weight by more than 90%. Thus, protective coatings having a relatively simple configuration and low weight are of interest.

In the previous work [27], it was found that the indicator coating with the thickness of 0.4 mm based on hollow glass microspheres (HGMs) and epoxy resin not only simplified the search of the impacted place but also contributed to an increase of residual strength of the composite by 15-20% compared to uncoated specimens. This work aimed to study experimentally the effect of the thickness of the polymer coating on the size and nature of the composite impact damage, as well as on its residual flexural strength.

2. Materials and specimens

Commercially available GFRP STEF® (PJSC «Electroizolit») with the thickness of 4.2 ± 0.1 mm and with the density of 1.77-1.79 g/cm³ was chosen as a material for studying the effect of the indicator coating thickness on the residual strength of the composite in bending. The mechanical properties of the material are given in [27]. The indicator coating was based on highly flowable ETAL-INJECT epoxy resin (TETA in a ratio of 10/1 by weight was used as a hardener) filled with HGMs. The average sphere diameter was 40 µm, average wall thickness was 2 µm. The HGMs volume fraction was about 60%, and the density of the cured coating was 0.65-0.66 g/cm³. A detailed description of coating preparation and application could be found in [27]. The coating thickness was varied in the range from 0.4 mm to 1.2 mm with a step of 0.2 mm.

Low-velocity impact (LVI) tests were carried out on specimens with in-plane dimensions of 100×100 mm at different thicknesses of the indicator coating. After impact tests, the damaged area of the specimens was assessed by flexural strength, beam specimens with dimensions of 100×40 mm were cut from damaged plate specimens with the warp direction aligned to the longitudinal axis of the beam.

3. Methods

3.1. Low-velocity impact tests

Low-velocity impact (LVI) tests were performed on INSTRON CEAST 9350 drop-weight tower system. The steel ring with the outer/inner diameters of 100/72 mm was used as a support fixture. The plate specimens were placed on the support fixture without additional clamping.

A cone impactor INSTRON 7529.841 with a hemispherical tip (12.7 mm radius) was used in all impact tests. Specimens were tested at energies of 10J, 17.5J and 25 J. The drop weight was 5.095 kg in all cases.

3.2. Infrared thermography

The method of active infrared thermography was used to assess the composite damaged area. The scheme of the experimental setup is shown in Figure 1. The impact side of the specimens after LVI tests was covered with black matte enamel to prevent glare from entering the lens of the thermal camera. A painted specimen with an impact defect was installed in a special heat-insulating frame. The back of the sample was heated for 15 seconds by a halogenic lamp. The TESTO 882 thermal camera was used to record the temperature fields.

The resulting thermograms were converted to grayscale. The image was considered as a two-dimensional matrix, where each pixel was assigned a value from 0 to 255, where 0 is purely black, and 255 is purely white. Then, using the developed software, the damaged area was estimated.

The developed program is based on an algorithm for searching areas whose grey colour value exceeds the threshold value. An example of the program's operation to determine the damaged area of the impacted specimen on a thermogram in grayscale is shown in Figure 2. The threshold value (240 in the present study) that provides the best defect detection is determined empirically depending on the material and test conditions.

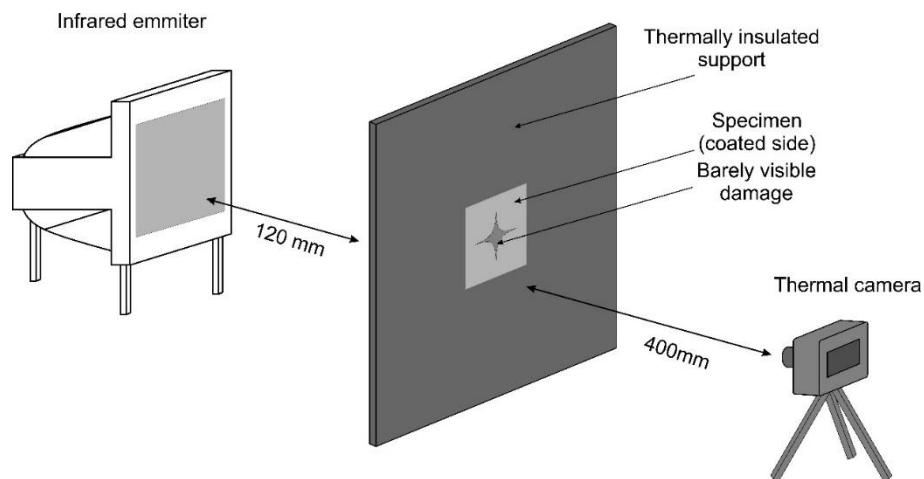


Figure 1. Scheme of the experimental setup being used for active infrared thermography of the specimens with impact damages.

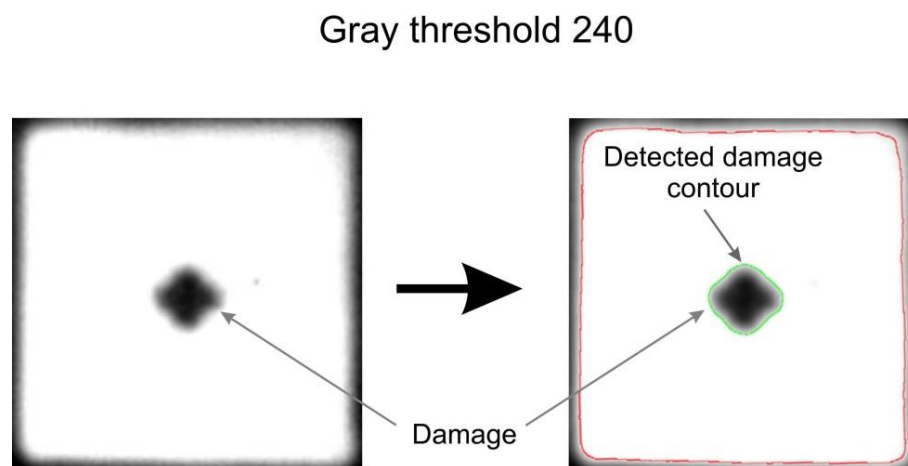


Figure 2. Determination of the specimen damaged area based on thermogram using the developed software.

3.3. Flexure-after-Impact tests

Flexure-After-Impact tests were carried out on an INSTRON 5900R universal testing machine. The distance between the support pins was 40 mm. The diameter of the loading and support pins was 10 mm, the loading speed was 10 mm/min.

The flexural strength of undamaged specimens was determined from the results of three-point bending tests up to failure with the same loading conditions.

4. Results

Figure 3 shows the dependence of the average damaged area of GFRP specimens on the impact energy for different thicknesses of the coating. It can be seen that the application of an indicator coating of any of the considered thicknesses can reduce the composite damaged area. For specimens with the coating thickness of 1.2 mm at impact energies of 10 J, 17.5J, and 25J, the decrease in the damaged area was maximum and equal to 64%, 76%, and 46%, respectively.

Figure 4 shows the dependence of the energy absorbed by the composite on the coating thickness for the impact energy of 25J. In comparison with uncoated specimens, a decrease in the absorbed energy by 34% and 24% was observed for coatings with thicknesses of 1 mm and 1.2 mm, respectively. The decrease in the absorbed energy is associated, first of all, with a reduction of the cracks density in the composite that is noticeable when analysing the cross-section of the composite.

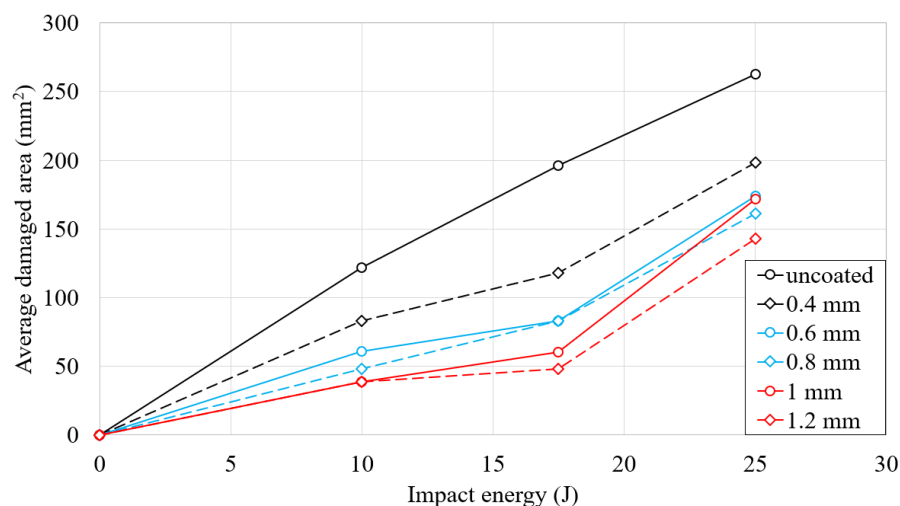


Figure 3. Averaged damaged area of composite specimen vs impact energy for different coating thicknesses.

Figure 5 shows photographs of the cross-section of uncoated specimens and specimens with 1 mm coating after impact tests at different impact energies. For clarity, the contact area of the specimen with the cone impactor was treated with a dye solution. It can be seen that the presence of a coating led to a significant decrease in the number of broken fibres at impact energies of 17.5J and 25J. At the energy of 10J, the fibres fracture was not observed at all on the coated specimen.

Figure 6 shows the dependences of the indentation diameter on the indicator coating on the impact energy for different coating thicknesses. It is seen that the coating thickness does not significantly affect the damage detectability, especially at high impact energies.

Figure 7 demonstrates the dependences of the relative residual flexural strength of uncoated and coated GFRP specimens on the impact energy. In the entire range of impact energies under consideration, a positive effect of the coating on the residual strength was noted. Thus, a decrease in residual strength by 30% was observed for uncoated GFRP specimens at the impact energy of 17.5 J, while the decrease in residual strength was no more than 3% for specimens with 1 mm and 1.2 mm coatings. For specimens with 1 mm and 1.2 mm coatings at the impact energy of 25 J, residual flexural strength increased by 23% in comparison with uncoated specimens.

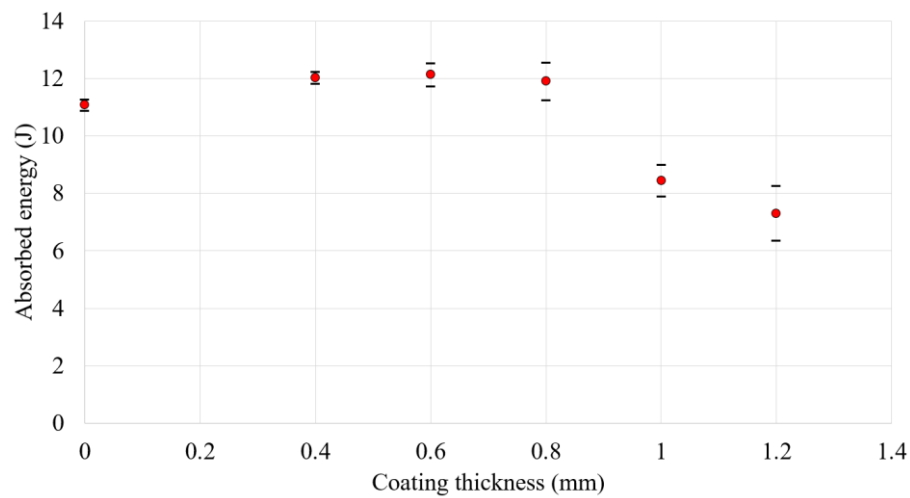


Figure 4. Absorbed energy vs coating thicknesses for impact energy of 25J.

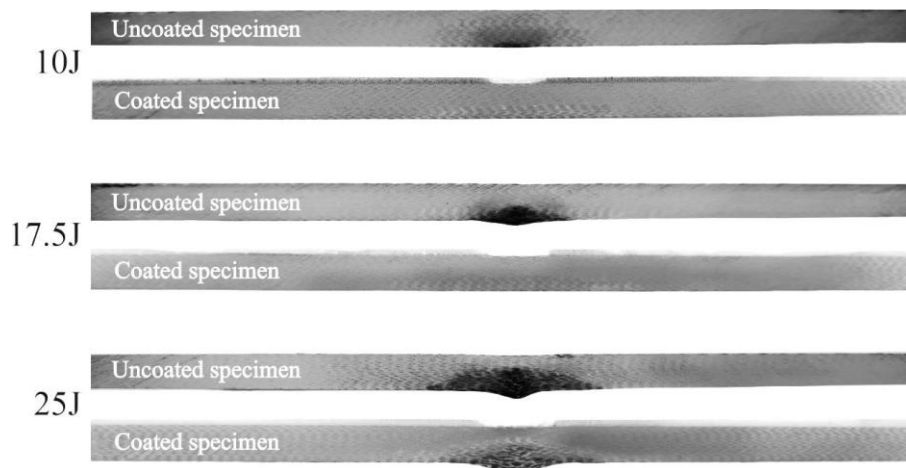


Figure 5. Cross-sections of uncoated specimens and specimens with 1 mm coating impacted with different energies.

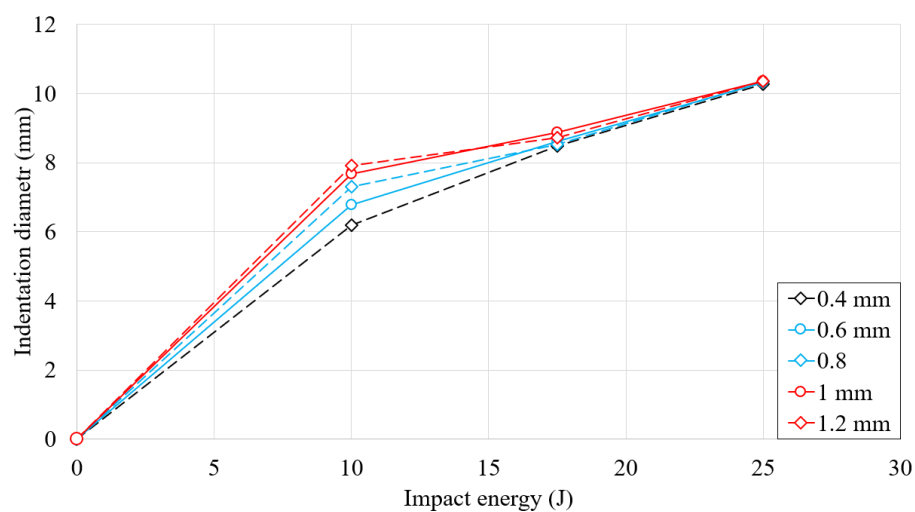


Figure 6. Indentation diameter vs impact energy for different coating thicknesses.

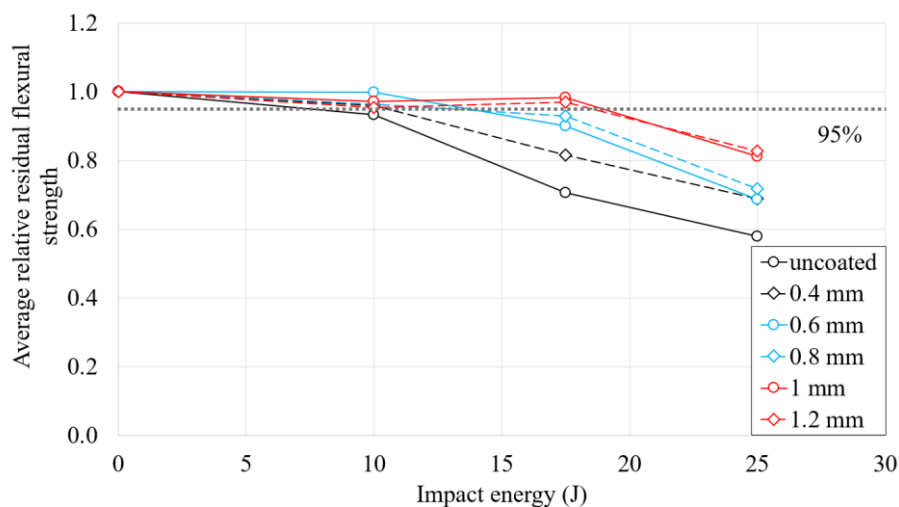


Figure 7. Average relative residual flexural strength vs impact energy for different coating thicknesses.

5. Conclusion

The article presents the results of the experimental study of the effect of the polymer indicator coating thickness on damage and residual strength of GFRP. Low-velocity impact tests showed that the composite damaged area decreased in the entire considered range of impact energies with an increase in the coating thickness. The presence of 1 mm and 1.2 mm coatings led to a reduction of the damaged area at the maximum impact energy of 25 J by 69% and 76%, respectively. In this case, the residual flexural strength of the coated specimens increased by 27% compared to the uncoated ones.

Even though specimens with 1.2 mm coating showed the highest reduction in the damaged area, the difference in the residual flexural strength for specimens with 1 mm coating did not exceed 1.5%. Thus, among the variants considered, 1 mm coating was the most balanced by the ratio of the added surface density and residual strength of the composite. At the next stage of research, it is planned to carry out low-velocity impact tests of CFRP specimens with the coating and compare results with ones obtained for GFRP.

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