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*State University “Kyiv Aviation Institute”, Ukraine***DAMAGE OF CARBON PLASTICS FROM LOW-VELOCITY IMPACT AND THEIR RELAXATION**

*The damage assessment of carbon plastics with different filler structures based on the same epoxy matrix HexPly M 21 from low-velocity impact was carried out. The purpose of the research was to determine the difference between the depths of dents and the diameters of damage of carbon plastics that had two different fillers, namely bidirectional fabric and unidirectional carbon tape. Low-velocity impact tests were carried out with the same energy of 6.7 J per 1 mm of sample thickness. Immediately after the impact, damage parameters such as the depth of the dent and the maximum size (diameter) were measured, with the latter being determined from both the front and back sides. The depth of the dent was measured immediately after impact and after 7 days to determine the degree of damage relaxation, which reached 17%. The results of the studies are presented in the form of histograms of dent depths and damage diameters on both sides of the samples. It was found that the damage diameters for carbon plastics of both performances on the back side are significantly larger than on the front side.*

**Keywords:** *damage, carbon fiber, low-velocity impact, epoxy matrix, dent, relaxation degree.*

**Introduction.** The use of the modern polymer composite materials (PCM) has allowed replacing traditional metals in advanced military aircraft designs. The weight of PCM elements reaches 50% or more in the designs of modern passenger aircraft Boeing 787 and Airbus 350, which provides a significant increase in their economic efficiency. In the advanced designs of these passenger aircraft, carbon plastics are mainly used, these are PCM, which allow the manufacture of structures up to 40% lighter in weight compared to similar metal ones and are significantly more technological than metal ones. Carbon plastics are the most common in aircraft designs due to their significant rigidity and low weight, but, at the same time, they are sensitive to shock actions that are possible during their operation. Damage, which is a barely visible consequence of low-speed impacts on the front side of the sample (Fig. 1,*a*), is significant on the back side (Fig. 1,*b*) [1].

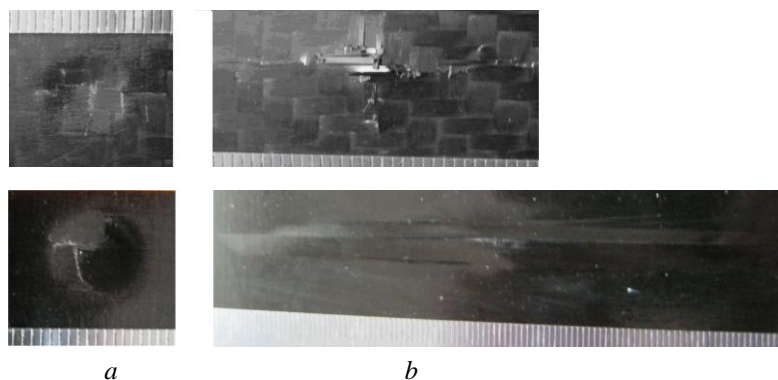


Fig. 1. View of damage on the front (*a*) and back (*b*) sides of the carbon fiber composites.

In the standard [2] dedicated to the study of PCM damage during low-velocity impact with low energy, the concept of - Berely Visible Impact Damage (BVID). The presence of such damage on the front surface of the carbon fiber can lead to significant damage on its back side (see Fig. 1).

Currently, tests are underway on the UltraFan engine, which has composite blades and a fan housing, which will reduce the weight of a twin-engine aircraft by 700 kilograms [3]. The 140-inch (3.55m) UltraFan fan has a set of 18 composite blades made of 500 layers of Hexcel HexPly M91 epoxy prepreg reinforced with high-strength and impact-resistant carbon fiber. A thin titanium shell is attached to the leading edges of the blades, protecting them from erosion, foreign objects and collisions with birds, but this does not completely protect the composite part from possible impact damage.

The results of studies on damage caused by impacts with energy from 4 to 40 J in samples of various carbon plastics, the dimensions of which were determined by the methods of computer tomography, optical thermography and ultrasonic control, were presented in [4]. Comprehensive studies of the resistance to damage of carbon plastics with different matrices and different fiber content are presented in [5]. The results of low-velocity impact tests with energy from 2 to 25 J of three different PCMs, which had a thickness of 1.0 mm to 1.8 mm, showed that for a qualitative comparison of damage and assessment of PCM sensitivity to impact, the samples should have approximately the same thickness [6]. Comparative studies of damage depths and diameters based on the results of tests of samples with a thickness of  $2.00 \pm 0.05$  mm made of carbon fiber and fiberglass based on epoxyphenolic binder and thermoplastic PCM based on polypropylene at different impact energy were presented in [1].

In addition to the works related to experimental studies of the damage resistance of various PCMs, it is worth noting numerous studies of similar problems using special computer programs. A hybrid composite laminate containing three glass/epoxy (G) layers and two carbon/epoxy (C) layers under the action of ballistic impact loading based on numerical calculations is investigated in the article [7]. The ability of the hybrid composite laminate to absorb energy at different impact velocities (from 400 m/s to 500 m/s) and with different layer combinations was also analyzed using the ANSYS-Explicit Dynamic module. The results show that the sequence of laying [G-C-G-C-G] provides the best characteristics under impact loading caused by perforation.

The listed sources, as well as many others, explain the relevance of research into the resistance of PCM to impact damage, and especially carbon plastics, to low-velocity impact with low energy. This is also confirmed by the presence of various existing standards for testing PCM under low-velocity impact loads. The main standards are the following: ASTM D7136 and ASTM D7137, ISO18352, DIN 65561, prEN 6038, NASA RP 1092 ST-1, Boeing BSS 7260 - Type II, Airbus AITM 1.0010, SACMA SRM 2R-94 and CRAG Method 403. Detailed analysis of installations, samples and test methods according to these standards given in the presentation [8]. In almost all standards, test specimens have dimensions of  $100 \times 150$  mm<sup>2</sup>, are fixed on a base with a rectangular cutout of  $75 \times 125$  mm<sup>2</sup>, and only the CRAG 403 standard specifies a hole diameter of 140 mm. All the mentioned standards have practically similar testing methods. The impact load is applied by dropping from a height  $H$  [m] a load with a mass  $m$  [kg], which differs in different standards and is in the range of 1÷6.8 kg. The load has a spherical tip with a diameter of 16 mm, and the impact energy is calculated by the formula:

$$E = mgH,$$

where  $g$  is the free fall acceleration [ $9.81 \text{ m/c}^2$ ].

**Materials and methods of research.** In this work, the research is devoted to testing samples of carbon fiber plastics of 2 performances based on the same highly effective and durable epoxy matrix HexPly M21 for low-velocity impact with the same energy per unit thickness. Carbon fiber plastics of each of the 2 performances had different filler structures, namely bidirectional carbon fabric and unidirectional carbon tape. Further, after applying low-velocity impacts to the samples, measurements of the diameters of impact damage and their depth were carried out, and the relaxation of damage after 7 days of exposure after their application was also studied.

The samples of the first performance were made of carbon plastic M21/40%/268T2/AS4C-6K, which had an average thickness of 2.50 mm and was made by prepreg technology based on the HexPly M21 epoxy matrix with a curing temperature of  $180^\circ\text{C}$ , which is used in the main aerospace structures, and a filler based on bidirectional carbon fabric twill weave unidirectional carbon harness AS4C-6K. The samples of the second performance had an average thickness of 2.10 mm and were cut from the material M21/34%/UD268/AS7-12K, which was made on the basis of the same epoxy resin M21 using prepreg technology, but a unidirectional carbon tape from the AS7-12K tow was used as a filler. The carbon plastic of both performances had a quasi-isotropic structure that was balanced relative to the median plane.

The samples were tested in accordance with the ASTM D7136 standard [2] on a special test rig, the design of which was described in [6]. Standard tests of samples of both versions with a size of  $100 \text{ mm} \times 150 \text{ mm}$  are carried out by causing damage by impact with a falling load with a spherical 16 mm tip striker with a given energy and subsequent determination of such parameters of the resulting damage as the depth of the dent and the diameter of the damage. Before testing, the samples were fixed using special clamps on the upper support part above a rectangular hole  $75 \text{ mm} \times 125 \text{ mm}$ . The impact was caused by a falling load with a mass  $m = 2.248 \text{ kg}$  from a height  $H$  [m] with an impact energy that was calculated by the formula:

$$E = C_E h,$$

where:  $E$  – potential energy of the falling load before impact,  $J$  [N m];

$C_E$  – ratio of impact energy to sample thickness  $J/\text{mm}$ , which in these tests is  $6.7 J$  per 1 mm of thickness, which corresponds to the standard [2];

$h$  – nominal sample thickness.

The height of the load (impactor) fall  $H$  was determined by the formula:

$$H = E / m_d g,$$

where:  $m_d$  – mass of falling load ( $m_d = 2.248 \text{ kg}$ ) and  $g = 9.81 \text{ m/s}^2$ .

These studies present the results of tests of 8 carbon plastic samples, 4 samples of each of two performances. The first and second samples of each performance had no coating on the surface of impact damage, and the third and fourth samples of each performance had a paint coating typical of aircraft structures on the front surface, on which the impact was applied.

**Analysis of results and discussion.** After impact, each sample was fixed in a special fixture and within 15 minutes after testing, measurements of the depth  $d_0$  of damage (dent) of the sample were made using a specially designed depth gauge, which included a watch-type indicator with a measurement accuracy of up to 0.001 mm. Next, the damage to the sample after impact was visually recorded, the type of damage was determined and the maximum linear size (diameter according to the standard) of the damage on the front side  $D_f$  and on the back side  $D_b$  was measured using a digital caliper. In order to avoid subjective influence on the results of determining the depths of dents and diameters of damage, measurements of all samples in this study were made by one specialist. Histograms of damage diameters on the front and back sides are presented in Fig. 2.

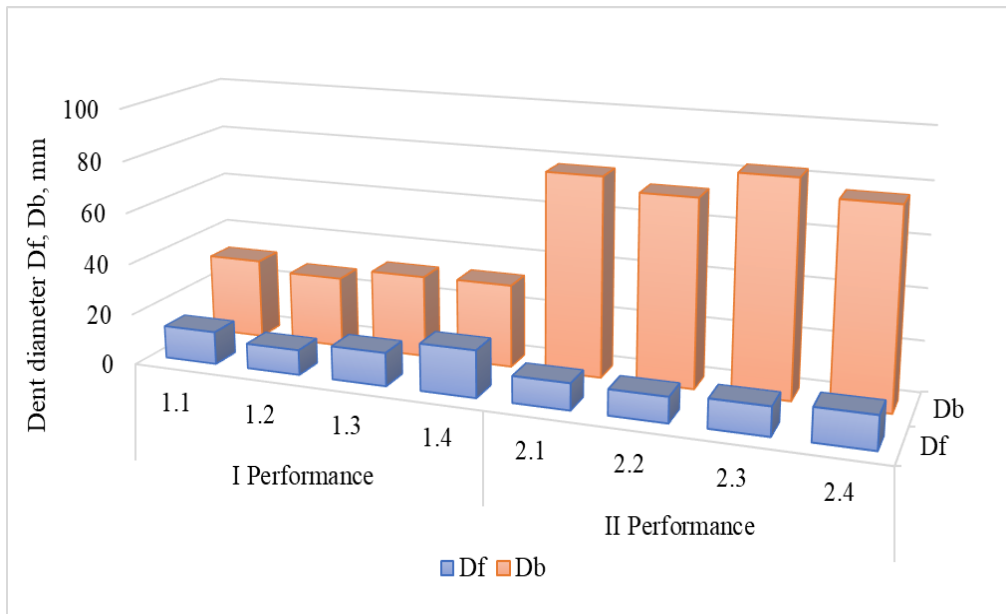


Fig. 2. Histograms of front  $D_f$  and back  $D_b$  dent diameters of samples of both performances.

Analysis of the results presented in Fig. 2 shows that the diameters of damage on the front sides of the samples of both performances without a paint coating are approximately the same, and for the samples of both performances with a paint coating, the diameters of damage are larger, and for the samples of the I performance from a unidirectional carbon tape they are significantly larger. It can also be noted that the diameters of damage on the back sides of the samples of each performance are approximately the same and are significantly larger for the samples of the II performance from a unidirectional carbon tape compared to the samples of the I performance from a bidirectional carbon fabric.

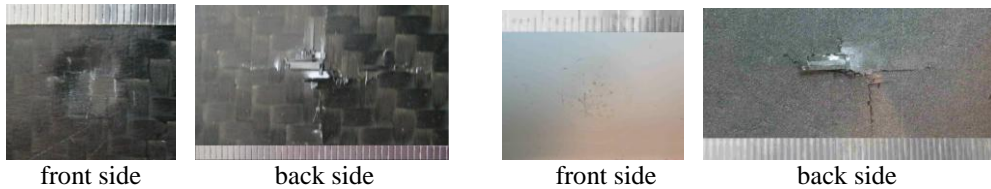
After the impact tests and the completion of the damage parameters measurements, photos of the resulting damage of each sample were taken from both the front and back sides using a special magnifying webcam. Typical photos of damage to samples of two performances from the front and back sides are presented in Fig. 3.

Visual analysis of the photos of impact damage, which are presented in Fig. 3 and others, shows that damage at the same impact energy per unit thickness of the material

on samples with a paint coating on the front side is less visible, even despite the larger diameter of the damage.

The purpose of this study is also to determine the relaxation of carbon plastic damage after a week (7 days) of exposure of the samples after applying impact damage in order to test the hypothesis of the possibility of "self-healing" of this material.

### I Performance



### II Performance

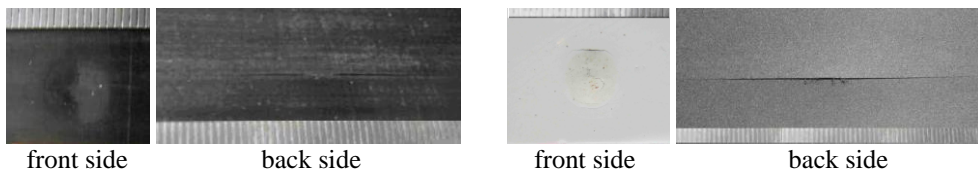


Fig. 3. View of impact damage to carbon plastic from the front and back sides.

Since carbon plastic has a sufficiently high stiffness, one can expect significant dissipation of the energy that was transferred to the sample during the impact process and caused damage, but over time this may lead to a decrease in the depth of the damage. Therefore, to study this process, in addition to measuring the depth of the dent  $d_0$  immediately after the impact, in this study, the depth of the dent  $d_7$  was measured again in all selected samples 7 days after the moment of testing the sample in order to further determine the relaxation of the damage.

From the point of view of physics, **relaxation** is the process of reducing the magnitude of a disturbance in a physical system due to energy dissipation, a gradual transition of a physical system to a state of equilibrium. It is often characterized by a relaxation time. In relation to a physical system, it is the process of gradual transition from a non-equilibrium state caused by external influences to a state of thermodynamic equilibrium or to a certain stationary state. Relaxation of rock stresses is considered in detail in a fundamental work [9], by analogy, impact damage can be considered a kind of disturbance in a physical system, which is a carbon-plastic sample.

Part of the energy is spent on the destruction of the material, but some part of the energy accumulates in the sample material and, due to energy dissipation, a partial reduction in damage can be expected until a certain state of equilibrium is reached over time. In this study, a period of 1 week was chosen to determine the degree of reduction of the initial damage. To determine the degree of damage relaxation within 7 days after the moment of testing the sample  $\eta$  in percent, the following formula was proposed:

$$\eta = \frac{d_0 - d_7}{d_0} \cdot 100\%$$

where:  $d_0$  – dent depth determined within 15 minutes after testing;  
 $d_7$  – dent depth determined 7 days after testing of this sample.

The generalized results of measurements of dent depths  $d_0$  after impact and 7 days after testing  $d_7$  are presented in the form of histograms in Fig. 4, and this figure also presents the results of damage relaxation calculations in the form of corresponding curves.

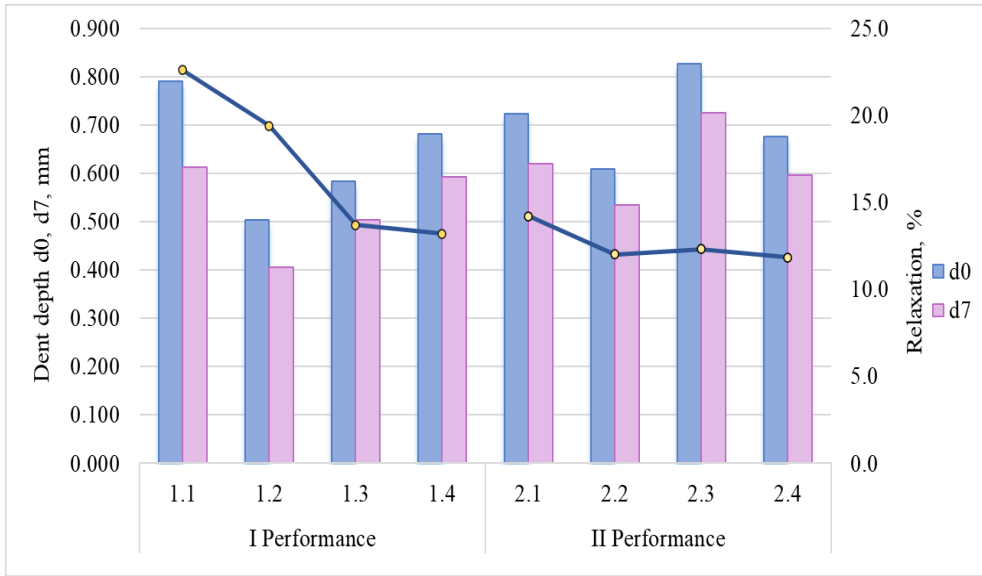


Fig. 4. Histograms of dent depth measurements immediately after impact  $d_0$  and 7 days post impact  $d_7$  with damage relaxation curves.

Analysis of the test results, which are presented in the form of histograms and curves in Fig. 4, allows us to conclude that during the week in all samples there was a decrease in the depth of the dents compared to the initial  $d_0$ . That is, as expected, the so-called relaxation of damage occurred, and in carbon fiber based on bidirectional fabric it was more likely due to the cross-woven fabric structure of the reinforcing component compared to carbon fiber based on unidirectional tape.

### Conclusions

1. Carbon fiber samples based on bidirectional carbon fabric (I performance) compared to carbon fiber based on unidirectional carbon tape (II performance) after impact with the same energy of 6.7 J per 1 mm of thickness have a smaller dent depth  $d_0$  on average by 10.7%, but a larger diameter of damage  $D_f$  on the front side on average by 18.4%.

2. The diameters of damage on the front sides of the samples of both performances without paint coating turned out to be approximately the same, and for the samples of both performances with paint coating the diameters of damage are larger, and for the samples of the I performance from unidirectional carbon tape they are significantly larger. But at the same time, the damage on the samples with paint coating is visually less visible, even despite the larger diameter of the damage.

3. On the back side of the carbon plastic samples, the diameters of the damage  $D_b$  for both performances are significantly larger compared to the diameters of the damage DP on the front side, and for carbon plastic based on bidirectional fabric the difference is 1.7 times, and for carbon fiber based on unidirectional tape the difference is more than 7 times.

4. The diameters of the damage on the reverse side  $D_b$  for carbon plastic based on bidirectional fabric are on average 2.5 times smaller than for carbon plastic based on unidirectional tape.

5. The reduction in the depth of dents  $d_0$  (the so-called degree of relaxation) in carbon plastic based on bidirectional fabric is on average 17.2%, and in carbon fiber based on unidirectional tape 12.6%, which is approximately 1.4 times smaller, which indicates the presence of relaxation. An increase in its value should be expected with increasing sample holding time, which may be a direction for further research.

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## ПОШКОДЖЕННЯ ВУГЛЕПЛАСТИКІВ ВІД НИЗЬКОШВИДКІСНОГО УДАРУ ТА ЇХ РЕЛАКСАЦІЯ

Проведена оцінка пошкоджень вуглепластиків з різними структурами наповнювача на основі однакової епоксидної матриці HexPly M 21 від низькошвидкісного удару. Мета досліджень полягала у визначенні різниці між глибинами вм'ятин та діаметрами пошкоджень вуглепластиків, які мали два різних наповнювача, а саме двоспрямовану тканину та односпрямовану вуглецеву стрічку. Випробування на низькошвидкісний удар проводились з однаковою енергією 6,7 Дж на 1 мм товщини зразка. Відразу після нанесення удару вимірювались параметри пошкоджень, такі як глибина вм'ятини та максимальний розмір (діаметр), причому останній визначався як з передньої, так і зворотної сторони. Глибина вм'ятини вимірювалась відразу після нанесення удару та після 7 днів, щоб визначити ступінь релаксації пошкоджень, яка досягала 17%. Результати досліджень надані у вигляді гістограм глибин вм'ятин та діаметрів пошкоджень з обох сторін зразків. Встановлено, що діаметри пошкоджень для вуглепластиків обох виконань із зворотної сторони є значно більшими, ніж на передній, причому для вуглепластика на основі односпрямованої стрічки різниця більше ніж 7 разів.

**Ключові слова:** пошкодження, вуглепластик, низькошвидкісний удар, епоксидна матриця, вм'ятина, ступінь релаксації.

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