Analysis of the mechanical behavior of spatially reinforced composites with open holes

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Abstract. The paper deals with the experimental study of mechanical behavior and the common factors of deformation of structural composites in combined use of contactless optical video system and acoustic emission analysis and registration system. The experimental studies were conducted at the electromechanical testing system Instron 5989 in compliance with ASTM 5766 recommendations for the samples of spatially reinforced and fiber-laminated carbon fiber composites with open holes. The preform-based carbon plastic samples with spatially reinforced structure are obtained by 3D-weaving methods. The paper presents the results of mechanical strain tests of open-hole samples. The authors obtained stress and strain diagrams for carbon plastic of various structures and analyzed the evolution of non-homogeneous strain fields on the surface of 3D-reinforced composite samples of the studied structure. They observed the difference in mechanical behavior of spatially reinforced and fiber-laminated carbon fiber composites. The paper presents the images of the samples with the characteristic damages in the area of the opening. Using the acoustic emission signals recording data, the authors obtained the diagrams of dependence of cumulative power, which allowed to observe the diverse nature of damage accumulation for the studied groups of samples.

1. Introduction
The mechanical behavior of the laminated samples has been extensively studied since the date of their implementation in aviaspace industry in 1960s. The obvious disadvantage of the traditional polymer composite materials in the form of textolites and laminates is their relatively low inter-layer strength [1-4]. Today, to exclude this disadvantage, it is suggested to use the spatially reinforced fillers or 3D cloths [5]. The multilayer carbon voluminous cloths are used as a reinforcing material in carbon plastics operating under complex conditions of high-speed aerodynamic flow, vibration and high temperatures. The complexities of assessment of mechanical behavior of voluminous weaving composites related to the specific features of the structure, such as non-homogeneity and anisotropy occur even during the simplest tests (uniaxial tensile/compression, shear) [6].

Obtaining the extensive experimental information is of paramount importance for assessment of 3D composites destruction process [7-9]. The optical measurement of full displacement and strain field provides obtaining further qualitative calculation and experimental data. Using the grid method, Pierron etc. assessed the effect of the gap on distribution of deformations in point-loaded composite plate [10]. The paper [11] presents the measurements of strain fields during the tensile of open-hole composite samples using moiré interferometry. Nevertheless, these studies focus on
linear elastic behavior, they did not attempt to analyze the destruction process as such. Using the measurements of full field displacement and deformations to assess the process of deformations in composite materials, the digital image correlation method is a promising and developing method (DIC) [12,13]. Despite the fact that scientific literature has a great amount of works related to acoustic emission (AE) signals for various materials and at various types of loading, the emergence of new materials necessitates the expansion of experimental basis [22-24]. The behavior and the mechanisms of composite materials damage, that can be assessed based on deformation fields using DIC method, correlate with the data obtained using acoustic emission (AE) signals registration [14-21]. This study is devoted to mathematical peculiarities of the joint application of DIC method and AE signals registration for the samples of open-hole composite materials with spatially reinforced and laminated structure during tensile.

2. Equipment, method and material
This work was carried out in Perm National Research Polytechnic University using Unique Scientific Equipment «Complex of testing and diagnostic equipment for studying properties of structural and functional materials under complex thermomechanical loading».

Spatially reinforced coal plastic composite is selected as a material, epoxy resin is used as a filler. The authors performed a number of uniaxial tensile tests of composite samples with a round hole (concentrator) in the geometric center, test strip preforms are manufactured using 3D-weaving technology by orthogonal weaving method (A) and laminated preforms (B). The central holes of the samples were drilled using vertical drills.

The loading is implemented at the multipurpose electromechanical test system Instron 5989 (± 600 kN) according to ASTM D 5766 standard with the movable grip rate \( u'_0 = 2 \text{ mm/min} \). The recording of displacements and deformations on the surface of the samples was performed using the contactless optical video system Vic-3D and the digital images correlation (DIC) method. The load was registered by a 600 kN load cell. The measurement accuracy is no lower than 0.5% of the measured value.

The testing scheme (a) and the draft of the “open-hole” sample (b) are presented in the Figure 1. Videorecording of the deformation process was performed with Q-400 cameras with objectives Limess 2.0/28/0901. The shooting speed was 15 frames per second with the set cameras resolution of 4.0 MP. The total number of the tested samples was 10 per each group. To calculate the fields of longitudinal \( (\varepsilon_{yy}) \), cross \( (\varepsilon_{xx}) \) and shear deformations \( (\varepsilon_{xy}) \), the authors used the finite strain tensor in the sense of Lagrange \( \varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i} + u_{k,i}u_{k,j}) \). Here, the Oy axis is directed along the sample (along the tensile axis), the Ox axis – perpendicular to the load axis in the plain of the sample. To build the load diagrams, the authors used an additional module of the video system software “virtual extensometer”, where the principle of operation is based on tracking the mutual displacement between the two points of the sample surfaces according to the applied force.

![Figure 1](image-url)  
Figure 1. Uniaxial tensile test of a sample with a hole (a), draft of a sample with a hole (b).
3. The experimental study results

According to ASTM D 5766, the following characteristics are determined from the test: the destructive load (kN); the tensile strength (MPa). To calculate the tensile strength, the area of the samples cross-section is calculated regardless the hole. The “load-displacement” diagrams (Figure 2) were built for each group of samples based on the test results, and the mechanical characteristics presented in the Table 2, were obtained in relative units.

| №  | Marking specimens | Destructive load | Tensile strength |
|----|-------------------|------------------|------------------|
| 1  | A                 | 1.00             | 1.00             |
| 2  | B                 | 0.37             | 0.38             |

Figure 2 presents load diagrams which are characteristic for each carbon plastic reinforcement scheme (A, B). The polymer composite samples with orthogonal (A) weaving scheme feature with higher values of the load limit in comparison with the laminated samples (B). The breaks related to structural failure are observed for the carbon plastic sample with orthogonal weaving scheme. Figure 2 presents the images of the samples with characteristic damages in the hole area.

![Figure 2](https://via.placeholder.com/500)

**Figure 2.** Diagram of loading of carbon plastic samples with orthogonal reinforcement scheme (A) and laminated one (B).

The assess the non-homogeneous strain fields obtained with the help of the video system, the Figure 3 and Figure 4 present the fields of cross, shear and longitudinal strain on the surface of A and B reinforcement type samples at various load levels.
The presented longitudinal strain fields at maximal load clearly demonstrate the place of the localization of the defects that result in complete destruction of the sample. The material deformation

**Figure 3.** Fields of cross $\varepsilon_{xx}$ (a), shear $\varepsilon_{xy}$ (b) and longitudinal strains $\varepsilon_{yy}$ (c) on the surface of a specimen of reinforcement type A at a load of $P1 = 89$ kN, $P2 = 114.6$ kN, $P3 = 126.8$ kN.

**Figure 4.** Fields of cross $\varepsilon_{xx}$ (a), shear $\varepsilon_{xy}$ (b) and longitudinal strains $\varepsilon_{yy}$ (c) on the surface of specimen B at a load of $P1 = 47.4$ kN, $P2 = 49.6$ kN, $P3 = 51$ kN.

The presented longitudinal strain fields at maximal load clearly demonstrate the place of the localization of the defects that result in complete destruction of the sample. The material deformation
process is non-homogeneous, the areas of localized damages in the form of longitudinal strips are recorded on the surface of the sample, that, in turn, reflect the material structure.

Besides, using the data obtained from the video system, the authors performed an assessment of longitudinal strain $\varepsilon_{yy}$ distribution on the surface of the sample (Figure 5) along the line $L$ drawn from the hole to the edge of the plate. The strain diagrams are built at certain strain levels of 10%, 40% and 70% of the threshold value $\sigma_{\text{max}}$.

The results obtained demonstrate that the behavior of the A-reinforced samples with the holes remains linearly elastic up to the very destruction. For B-reinforcement at higher tensile loads the strain peak appears at some distance from the hole. It has been observed that the higher the applied load is, the greater is the maximal strain value, and the strain variation increases.

The wide set of experimental data obtained using the contactless optical video system Vic-3D and the digital image correlation method, provides the assessment of composite material behavior all over the strain process. The data obtained provide the assessment of strain stages, the mechanisms of damages and localization of composite objects defects.

To study the acoustic-emission response of the samples studies, the authors used the acoustic emission measurement system AMSY-6 (VallenSysteme GmbH, Germany). AMSY-6 - it is a multi-channel AE-system of 8 parallel completely synchronized measurement channels. The analogue measurement chain of each channel includes: a piezoelectric AE sensor; pre-amplifier; acoustic signal preprocessor located in the body of the system; specialized software Vallen Systeme (Figure 6).
Figure 6. The composition of acoustic emission measurement system AMSY-6: piezoelectric AE sensor (a), pre-amplifier (b), AE signal preprocessor unit (c).

The broadband sensors AE105A with frequency range 450÷1150 kHz, AE-signal amplifiers AEP4 with amplification coefficient 34db were used in the work. A continuous mode with the true energy assessment and the absolute registration time recording was selected for AE signals recording. The test method includes the preparatory stage, when the AE sensors are installed on the surface of the experimental prototype in the working part with the help of a rubber and a high-vacuum silicone grease; Ae-sensor calibration using SuNielsen source or automatic calibration function; setting the necessary parameters in the software (discretization frequency, threshold value, digital filter parameters, duration limitation time, refitting time) for AE recording system. It should be noted that AE sensors are installed on the reverse side of the sample so that their fixtures does not come into the view of the optical systems shooting the front side of the sample (Figure 7). The power parameter was used in the work as an AE information parameter (1 eu = 1·10^{-18} J). The summing of this parameter provided the value of cumulative power (E_{cum}), reflecting the degree of defects accumulation in the material under the effect of the loading all over the test [19,21].

Figure 7. The photo of the front side (on the left) and rare side (on the right) of the sample with the AE sensors installed.

AE signal recording starts simultaneously with the beginning of the loading and is performed continuously all over the loading process. The obtained results processing is performed using the Vallen Systeme software with the help of VisualAE program.

The Figure 8 presents the typical diagrams of cumulative power dependence combined with load schedules for spatially reinforced (type A) and fiber-laminated (type B) composites. These groups of samples present the diverse nature of the damage accumulation for these groups of samples. Thus, in
A-samples (Figure 8, a) it is observed that the cumulative power growth occurs as early as at the initial load stage. After that, the growth slows down, however lasting up to the moment preceding the final destruction of the sample. For fiber-laminated composites (Figure 8, b), it could be observed that the cumulative power growth starts at approximately 60% of the maximal load. Besides, it should be noted that at the both diagrams the smooth growth of cumulative power is not accompanied with the breaks at the load diagram, and, vice versa, the drops at the load diagram is observed at step fast growth of cumulative power value.

![Graphs](image)

**Figure 8.** Graphs of the cumulative energy of acoustic emission signals versus displacement for open hole samples of type A (a) and type B (b).

4. **Conclusions**

Therefore, the work presents the results of experimental study of mechanical behavior and the regularities of deformation of composite open-hole samples with spatially reinforced and fiber-laminated structure during the tensile using digital image correlation methods and acoustic emission signals registration. The combined use of additional registration systems for composition materials samples provides obtaining a greater number of high-quality calculation-experiments data. The non-homogeneous strain fields obtained on the surface provide monitoring of defect localization sites as
well as the regularities of the materials strain process. The use of additional video system instruments provides a more detailed analysis and assessment of strain distribution on the sample surface.

The simultaneous recording of acoustic emission signals with the load make it possible to obtain the combined load diagrams with cumulative power, which, in turn, provides the assessment of the nature and the stages of accumulation of damages for the studied group of samples.

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