Influence of the reinforcement scheme on mechanical properties of 2d, 3d polymer composites

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Abstract. This work provides the results of complex study of mechanical properties of the composition materials based on carbon fiber 3D-preforms and epoxy binder (carbon fiber A-49 by AKSA + epoxy resin T26 by INUMiT CJSC), as well as the analysis of benefits, merits and demerits from the viewpoint of complex analysis of mechanical properties and structural process stability. The paper presents the values of the main mechanical characteristics for all types of materials in proportions for all types of tests. A comprehensive analysis of the mechanical behavior, patterns of damage accumulation and destruction of composite samples was carried out using additional registration means: the method of recording acoustic emission signals, the method of digital image correlation and an infrared thermal imaging system.

1. Introduction

The present-day state of technology makes it possible to manufacture 3D spatially reinforcing fillers for a wide range of polymer composition materials. 3D spatially reinforcing fillers or 3D-structures are used in composite materials in various industries for manufacture of critical parts and structural elements [1]. It provides the implementation of main benefits of multilayer fabrics – their significant strength in transversal (perpendicular to the layer plane) direction, which provides non-delaminatability of fiber plastics in the process of operation [2].

Multi-walled voluminous weaving carbon fabrics are used as a reinforcing material of carbon plastics, operating under complex and severe conditions of high-speed aerodynamic flow, vibration, high temperatures and other external exposures. The review of process and structural aspects as well as the present-day state and prospects of use of 3D fabrics in polymer composites are provided in [2, 3 and 4]. Thus, [2] considers the issues and advantages of 3D-woven structures and makes conclusion of overwhelming superiority of the so-called multinuclear weaving. The paper [3] considers the issues of utilization of various voluminous reinforced polymer composites in technical applications. The paper [4] is devoted to the study of innovative combination of front-end technologies to be implemented in automated processes of manufacture of 3D reinforced aerospace composite structures. [5, 6] provide comprehensive comparative experimental study of tensile in the plane of the composite of the samples manufactured according to VARTM technology, of E-fiberglass of two one-layer preforms 3WEAVE® of 3D orthogonal weaving on one side and the laminate reinforced with four layers of fabric weaving of E-glass fabric – on the other one. The results obtained show that the studied 3D non-
pressing orthogonal fiber composites have significantly higher threshold breaking stress and strain in the plane as well as the damage initiation strain thresholds than their composite analogue.

The papers [7, 8] study the effect of the fibers architecture on the evolution of fatigue damage in 3D woven preform-based composites with reinforcement between the layers. The comprehensive study of quasi-static and fatigue tension of Open Hole samples of orthogonal and corner interchangeable 3D woven carbon-epoxy composite is provided in the paper [9]. The paper [10] studies the effect of vascularization (VaSC) with straight and wavy canal systems of 3D-woven structures during the longitudinal and transverse direction tests. The damage evolution is controlled with acoustic emission and optical microscopy. It has been found that vascularized canals provide minimal effect on tension behavior, when the fibers direction does not change, whereas the strength and module reduction with the increase of the fractures density is observed, when the canals distort the reinforcing fiber architecture.

The paper [11] considers and analyzes the method of composite materials testing under non-trivial stress conditions. The authors solve the problems of determination of mechanical properties of composite materials under the conditions of fatigue and complex stress-strain behavior, under the effect of static loads and various temperatures. The experimental studies of the effect of operating and climatic temperatures on mechanical properties for various classes of polymer composite materials are described in the papers [12-14].

Therefore, the complex studies of materials mechanic properties based on 3D-woven structures with the use of specials methods of monitoring of strain and damage processes remain relevant. Still, equally relevant should be considered the study and development of 3D-woven reinforcing structures as well as the structural and process stability of the composites made on their basis [15, 16].

2. Research object and technology

The study used the samples, the preforms of which were made using 3D weaving technology with six different weaving methods. Besides, two types of laminated samples were used for comparison, where one set was reinforced in the transverse direction by woven wire (Tufting) method.

![Figure 1. 3D-woven preform samples.](image)

Six weave constructions of 3D-woven preforms were developed for manufacture of samples: orthogonal (Orthogonal, A); orthogonal conjoined (Orthogonalconjoint, B); with layer-to-layer reinforcement (Layer-to-layerinterlocked, C); with layer-to-layer reinforcement and a longitudinal layer (Layer-to-layerinterlockedwithwarp, D); with layer-to-layer conjoint reinforcement (Layer-to-layer interlockedconjoint, E) and with through layer-to-layer (Angleinterlocked, F).
Two types of laminated samples were manufactured: of 5/1 AKSA F49 12K satin preforms – type G - and with the use of supplementary Tufting stitching method - type H (Figure 2, 3).

![Image of G-type sample](image)

![Image of H-type sample](image)

**Figure 2.** The images of surfaces of G-type (a) and H-type (b) structure samples.

![Diagram of H-type structure](image)

**Figure 3.** The illustration of scheme of obtaining H-type structures.

Resin Transfer Molding (RTM) was the technology used for preparing samples of the composite materials. The fiber filling factor in the samples reached 55 ± 5%.

Therefore, the samples of composite materials of all investigated structures were obtained for all types of tests. Figure 4 shows longitudinal (a) and transverse sections of samples of one of the structures. Ultrasonic control and optical microscopy control suggested the conclusion that the samples have a homogeneous and continuous structure, as well as the presence and nature of microdamages and internal defects before testing.

![Longitudinal section](image)

![Transverse section](image)

**Figure 4.** Longitudinal (a) and transverse (b) sections of 3D preforms-based composite structure.
3. Complex of mechanical test methods

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».

The set of testing and measuring equipment for the implementation of the test program includes the following systems:

- Instron 5900 series electromechanical test systems with the maximum load range of 5 kN to 600 kN, additionally equipped with an Instron AVE contactless video extensometer.
- Instron CEAST 9350 electromechanical impact measuring stand-pile driver for dynamic impact tests with the maximum power of up to 1800 J.
- Instron 8850 servo-hydraulic biaxial (tension-compression /torsion) testing system, with the maximum load of 100 kN, the maximum torque of 1 kN • m, and the twist angle of ± 45°.
- Digital optical system for deformation fields analysis Vic-3D, designed for contactless measurement of deformations over the entire surface of the material in the process of sample testing or structural elements operation. The measured strain range is from 0.005% to 2000%; shooting speed 15 is frames/s; DCP cameras resolution 4.0 Mp; synchronization with the test system controller; the software mathematical apparatus is based on the digital image correlation method; “virtual extensometer” and “virtual strain gauge” integrated modules.
- Acoustic emission system Vallen-Systeme GmbH AMSY-6, designed for multichannel registration of acoustic emission signals and real-time measurements of acoustic emission parameters used for non-destructive testing, assessment of the technical condition of objects and study of the behavior of the materials under strain. It has 8 independent channels, sampling frequency 10 MHz, frequency range 5-3000 Hz.
- Infrared thermal imaging system FLIR SC7700M, with shooting speed up to 2900 Hz, frame formation time from 3 μs to 20 μs with 1 μs increment, sensitivity under 0.025°C.
- Stereomicroscope CarlZeiss SteREO Discovery V12. The microscope makes it possible to analyze the destruction surfaces in order to identify the regularities and develop the models of damage accumulation; to identify the mechanisms of destruction of composite materials under various types of loading for development of mathematical models of the processes of inelastic deformation and structural destruction of the composites, to analyze the defects of composite panels obtained after punching in order to study the issues of survivability and residual strength of structures.

The samples measurement was conducted as per the corresponding standards recommendations. The thickness of the samples was measured using digital micrometer head Mitutoyo 164-162, installed on the digital calibrator Epsilon. The measuring sensitivity of the device was 0.001 mm, the instrumental error was ±0.004 mm. The linear dimensions of the samples were measured using the caliper ShTsK-1-300-0.01. The measuring sensitivity of the device was 0.01 mm, the instrumental error was ±0.04 mm. All the devices had the appropriate calibration certificates.

4. Uniaxial tensile test

Uniaxial tensile tests were performed at the electromechanical system Instron 5882 as per ASTM D 3039 recommendations. The selected movable grip speed was 2 mm/min. The loading was measured using a load cell with the threshold load value of 100 kN. The measurement accuracy was 0.5% of the measured value in the range of 0.2-1% of the transducer nominal limit value and 0.4% of the measured value in the range of 1-100% of the transducer nominal limit value. To measure the longitudinal deformation of the samples, the authors used a contactless video extensometer where the principle of operation was based on identification of coordinates of contrast (white or black) marks of the gauge length made on the working part of the sample (Figure 5), using a high-resolution digital video camera. The absolute error of strain measurement using a video extensometer was ±2 μm. The gauge
length was ~100 mm. To measure the transverse strain, the authors used the hinged extensometer Epsilon 3575-250M-ST with the maximally possible deviation from the measured value 0.2% (Figure 5).

**Figure 5.** The sample during the tensile test.

Based on the test results, stress and strain diagrams were built for each group of samples, and the main mechanical characteristics were obtained. The following material characteristics were determined based on the test results: breaking load (kN); breaking point (MPa); elasticity module (GPa); Poisson's ratio; longitudinal deformation (%). The characteristics were determined from the strain diagrams as per ASTM D 3039 recommendations.

### 5. Tensile and compression test of holed samples

The measurements of tensile and compression tests of the samples were conducted as per ASTM D 5766 and ASTM D 6484 recommendations according to the draft (Figure 6).

**Figure 6.** Draft of holed sample for tensile and compression tests.

The tests were conducted at Instron 5900 electromechanical test system as per ASTM D 5766 (tensile) and ASTM D 6484 (compression) recommendations (Figure 7). The movable grip speed was 2 mm/min during tensile and 5 mm/min – during compression. The loading was measured using a load cell with the threshold load value of 600 kN. The measurement accuracy was 0.5% of the measured value in the range of 0.2-1% of the transducer nominal limit value and 0.4% of the measured value in the range of 1-100% of the transducer nominal limit value.

Based on the test results, the load-displacement diagrams were built for each group of samples, and the mechanical characteristics were obtained. The following characteristics were determined from the tensile and compression tests of the holed samples: breaking load (kN); breaking point (MPa). The characteristics were determined from the load diagrams as per ASTM D 5766 recommendations under
tensile and ASTM D 6484 under compression. When calculating the breaking point, the area of the correction of the samples is calculated regardless the hole.

Figure 7. Tensile (a) and compression (b) test of holed samples.

5. Curved beam four-point bending test
Curved beam four-point bending tests were conducted at Instron 5965 electromechanical test system as per ASTM D 6415. The movable grip speed was 2 mm/min during tensile and 5 mm/min – during compression. The loading was measured using a load cell with the threshold load value of 5 kN. The measurement accuracy was 0.5% of the measured value in the range of 0.2-1% of the transducer nominal limit value and 0.4% of the measured value in the range of 1-100% of the transducer nominal limit value.

The sample was installed in a four-point bend test rig manufactured as per ASTM D 6415 recommendations (Figure 8). The distance between the centers of the lower supports was 100 mm, the distance between the centers of the upper supports was 75 mm, the diameters of the pressure rotating shafts were 9.5 mm. The samples were tested until complete breaking, however, for some structures, the test was stopped when the crosshead was moved by 17 mm due to the design feature of the equipment. The control of the samples destruction process was performed by acoustic emission method for 3 samples of each type.

Figure 8. CM sample in the form of a curved beam installed in a four-point bending test rig.

Based on the test results, the load-displacement diagrams were built for each sample, and the main mechanical characteristics were obtained. As per ASTM D 6415, in this case the beating capacity CBS measured in Newtons (N), was calculated as a mechanical characteristics [17].
6. Tests for impact and compression after impact

The tests for impact and compression after impact were performed as per the method based on the standards ASTM D 7136 and ASTM D 7137 using a tower impact measuring bench with a dropped object Instron CEAST 9350 and an electromechanical impact system Instron 5989.

![Image](image1.jpg)

**Figure 9.** CM sample installed in an impact test device (a) and a grip device for residual compression strength test after impact (b).

The potential energy of the impact (damage) varied from 30 J to 50 J, the striker weight was constant. The compression after the impact was performed at the speed of 1.25 mm/min. According to the results of testing the specimen for compression after impact, the authors built strain diagrams were constructed, the maximum value of the breaking load was determined, and the limit of residual strength at compression was calculated.

7. Crack (nonuniform breaking) test for mode I

Mechanical crack tests were performed using ASTM D 5528 recommendations at Instron 5965 electromechanical impact system equipped with 5kN load cell. The crack length increase recording was performed using the digital microscope Dino-Lite Dicital Microscope AM4013 MTL Series, with zoom shooting function (Figure 10). For shooting and optical control of length, a graph paper was stuck at the butt end of the sample, and it was painted white. The gauge length was 100 mm. The selected load rate during the test was 1 mm/min.

![Image](image2.jpg)

**Figure 10.** Sample for crack resistance test installed in the test grip.

The following characteristics of interlayer crack growth were determined during the test: breaking load (kN); opening value (mm); crack resistance parameter G1 (kN/mm). Based on the test results, the “load-displacement” diagram was built and mechanical characteristics were obtained for each group of samples.
8. In-plane shear tests
The tests were conducted at electromechanical system Instron 5882 as per ASTM D 5379 recommendations. The movable grip speed was 2 mm/min. The loading was measured using a load cell with the threshold load value of 100 kN. The measurement accuracy was 0.5% of the measured value in the range of 0.2-1% of the transducer nominal limit value and 0.4% of the measured value in the range of 1-100% of the transducer nominal limit value. To perform the shear test, the authors used a specialized device recommended by ASTM D 5379. The sample was installed into the device and centered using a centering device. The shear deformations were determined using a 3D digital optical system Vic-3D (Figure 11).

![Figure 11. The sample during in-plane shear test.](image)

The deformation was registered using a supplementary module of the video system software “virtual extensometer”. The principle of its operation is similar to that of the hinged extensometer, it involves the tracking of mutual shear between two points of the surface of the samples according to the force applied. To assess the shear deformations, two “virtual extensometers” were installed at the angle of ±45° to the load axis. The gauge length was 1.5±1 mm as per ASTM D 5379 recommendations.

During the test, the authors determined ultimate shear stress $F'_u$ (MPa), ultimate breaking strength $\gamma'^a$ (%), shear module $G$ (GPa) and nominal shear strength $F'^o$ (MPa). Based on the tests, “stress-strain” and “load - lifting beam displacement” diagrams were built, and the main mechanical characteristics were determined for each group of samples as per ASTM D 5379 [18].

9. Uniaxial compression test
The tests were conducted at electromechanical system Instron 5882 as per ASTM D 3410 recommendations. The movable grip speed was 1.5 mm/min. The loading was measured using a load cell with the threshold load value of 100 kN. The measurement accuracy was 0.5% of the measured value in the range of 0.2-1% of the transducer nominal limit value and 0.4% of the measured value in the range of 1-100% of the transducer nominal limit value. The strain was determined using a 3D digital optical system Vic-3D. The appearance of the test rig with the installed sample for compression test as per ASTM D 3410 is presented in Figure 12.
Based on the test results, the “load-displacement” diagram was built and mechanical characteristics were obtained for each group of samples. The following characteristics were determined during the test: maximal compression load (kN); ultimate compressive strength (MPa), compression module (GPa), breaking classification as per ASTM D 3410. The characteristics were determined from load diagrams as per ASTM D 3410 recommendations.

10. High-cycle fatigue test
The authors conducted the tests of flat samples of composite materials of various structures under cyclic impacts. Fatigue tests were performed at multi-purpose servo-hydraulic testing systems Instron 8801 and Instron 8802 using the samples of two types of structures selected according to the quasi-static test results. Cyclic pulsating tensile tests were performed using the samples of A and D series composite materials. High-cycle fatigue tests of composite materials were performed as per ASTM D 3479 recommendations. The cyclic loading program was selected so that to meet the following conditions: the loading frequency should not exceed 30 Hz; the maximum number of test cycles for one sample should be $5 \times 10^6$ cycles; smooth loading (where the set parameters is the applied load, the controlled parameter is the movement of grippers); pulsating, sinusoidal load change law; the minimum stress level is 1% of the static ultimate strength, the maximum stress level varies; the test program was aimed at building of the $\sigma$-N dependence, at various load levels, using 3 samples per load level; at significant (10%) change of hardness of the sample in the direction of the load application, the tests were suspended, the sample was examined for damage (cracking, delamination), the description of the damages was recorded in the test records, after that the tests continued.

The tests were performed until the maximum number of cycles constituted $5 \times 10^6$ or until the residual hardness of the sample was less than 50% of the initial value. As a result, the experimental dependences of the limiting number of cycles before destruction on the values of the maximum stresses in the cycle were obtained. The authors built the diagrams of dependence of changes in the amplitude of the gripping parts displacements on the number of cycles during loading.

11. A set of methods for supplementary studies of deformation and destruction processes
For the purpose of comprehensive analysis of mechanical behavior of composite samples during mechanical uniaxial tension tests, the authors studied the processes of strain, damage accumulation and material destruction using supplementary recording means. They studied the non-homogeneous strain and temperature fields, as well as the acoustic emission response according to the loading process for each type of samples. The study of the regularities of accumulation of damages and the formation of fracture conditions in strip samples was performed on the basis of the analysis of a set of
experimental data: the diagrams of loading, non-homogeneous strain and temperature fields, acoustic emission signals.

Figure 13 and 14 show the examples of time dependences of loading (P, kN), cumulative energy (CE, B²с) and temperature changes (ΔT, °C), recorded on the surface of type A and type E samples, respectively. The load values are obtained from the built-in load cell of the test system. The energy parameter $E$ (B²'s) and the number of registered signals during the registration time ($N_{sum}$) are used as informative parameters of acoustic emission. The values of the energy parameter are calculated by the formula:

$$E = \int_0^T U(t)^2 dt,$$

where $U(t)$ is the electric voltage of the signal at the output of the acoustic emission transducer, the time constant $T = 6.5$ ms. Summing up the values of the energy parameter, we obtain the value of the cumulative energy of the acoustic emission signals, which was interpreted as the degree of accumulation of defects in the material.

Based on the analysis of non-homogeneous temperature fields, the authors obtained the data on the change of temperature on the surface of the samples, the maximum value of ΔT was considered at each time point. The temperature change is obtained by subtracting the first frame (unloaded sample) from the subsequent ones. Due to local destruction of the sample structure elements and, accordingly, the increase in internal friction and dissipation of mechanical energy, a sudden heating of the material is observed at the site of the defect, and a vertical spike is formed on the curve of the time dependence of ΔT on t. Analyzing the number of such spikes and their amplitude, it is possible to assess the intensity of the process of damage accumulation and the formation of macrodestruction of the sample.

![Figure 13](image.png)

**Figure 13.** Time dependences of load (1), cumulative energy (2) and temperature change (3), obtained for sample strip A-1.

It should be noted that the increase of the slope of the curve 2 in Figure 14 is the evidence of high activity of the process of damage accumulation in the material, the sample “cracks”, the increase of temperature spikes frequency is observed on the curve ΔT on t.
Figure 14. Time dependences of load (1), cumulative energy (2) and temperature change (3), obtained for sample strip E-1.

Therefore, the authors could perform qualitative and quantitative comparison of complex analysis parameters obtained for a group of samples with various weave patterns of reinforcement structure [19]. The Table 1 presents the parameters on the basis of which the study of the effect of composite samples weaving pattern was studied.

Table 1. The parameters of complex analysis of composite sample strips with various weave patterns.

| Sample | $P_{\text{max}}$, kN | $U_{\text{max}}$, mm | $\Delta T_{\text{max}}$, °C | $N_{\text{cykl}}$, units | $K\Theta_{\text{max}}\cdot10^{-5}$, V²s⁻¹ |
|--------|---------------------|---------------------|---------------------|---------------------|---------------------|
| A-1    | 6.46                | 8.75                | 21.42               | 31325               | 2.94                |
| B-1    | 6.92                | 8.48                | 25.11               | 26902               | 5.40                |
| C-1    | 3.98                | 6.17                | 24.12               | 30970               | 4.07                |
| D-1    | 4.75                | 6.82                | 23.33               | 27814               | 3.91                |
| E-1    | 3.49                | 6.13                | 23.75               | 32100               | 9.41                |
| F-1    | 3.10                | 5.65                | 26.03               | 34220               | 8.40                |
| G-1    | 2.18                | 4.33                | 23.96               | 14512               | 9.57                |
| H-1    | 2.31                | 4.54                | 25.09               | 15748               | 7.26                |

When carrying out fatigue tests, the results are in the form of graphs of changes in the amplitude of displacements of the gripping parts versus the number of cycles during loading. The data presented in the form of a diagram of dependence of the displacement amplitude on the number of loading cycles in Figure 15, provide information on the change in the sample hardness during cyclic tension. The vertical lines correspond to suspension and continuation of the test.

The choice of the test frequency for each stress level was made taking into account the heating of the samples, controlled by registering the temperature fields with an infrared thermal imaging system. The use of this system made it possible to reveal the specific features of heating the samples of each series.
Figure 15. The diagrams of changes in the amplitude of displacements along the built-in sensor of the test system on the number of loading cycles of sample A-2 (a), D-2 (b).

The paper analyzes the evolution of non-homogeneous fields of strain components, as well as the intensity of strains on the surface of composite sample strips according to the loading process. As an example, the Figure 17 show the patterns of fields of longitudinal (εyy), shear (εxy) and transversal (εxx) deformations at the specified load level.
12. Conclusions

Based on the tests, the “load-displacement”, and, where applicable, “stress-strain” diagrams were built, and mechanical characteristics were determined, including the mean values, mean-square deviations and variation coefficients were determined for each group of samples. The values of the main mechanical characteristics in shares for each type of tests are provided in the Table 2.

Based on conducted uniaxial tensile tests, the “load-displacement” diagrams were built for each group of samples. The test results suggest that the samples of A and B-groups have the highest mechanical characteristics in comparison with other groups C, D, E and F of samples 3D-PCM and groups G and H of laminated composites.

The results of compression tests of carbon plastic samples suggest that the samples of A and B-groups have the highest values of tensile strength and elasticity module in comparison with the other groups. The ultimate compression strength for group B is 10% higher than for group A, and the elasticity module values are comparable. Besides, it is possible to conclude that the samples of groups A and B have the highest mechanical properties in comparison with the other groups C, D, E and F of 3D-PCM samples, as well as the groups G and H of laminated composites.

Based on uniaxial tensile test results for open hole sample strips, the authors conclude that the samples of groups A and B have the highest ultimate characteristics in comparison with the other groups C, D, E and F of 3D-PCM samples, as well as the groups G and H of laminated composites. It is worth mentioning that the values of strength limits for groups A, B, F, G and H are comparable,
within the standard deviation, with the values of ultimate strength during tensile tests under ASTM D 3039. For groups C, D and E the ultimate strength values in comparison with tensile tests under ASTM D 3039 were 30, 15 and 26% lower correspondingly.

The following conclusions are made from the open hole sample strips compression tests: the highest strength value was identified for B-group of samples, the maximal strength reduction during the boring of the hole (43%) – in F-group samples, and the 7.5% strength increase is registered in H-group samples where there is a hole.

The curved beam four-point bending test results suggest that the samples of groups А, В, D and H have the highest mechanical characteristics. In D-group samples the destruction occurs with the lower variation coefficient in comparison with the other tested groups.

In the process of the study the authors have tested the CM sample plates for resistance to dropped object damage and the tests for assessment of residual compression strength of the damaged sample strips. Based on the results of compression after impact tests, the A and B-series samples have the highest values of residual strength at compression after impact at various levels of preliminary damages among 3D-weaving samples. Among the laminated sample-plates of G and H series, the H-series have the highest survivability.

According to the test results, it should be noted that due to the destruction of A-series samples of under the linings, the experimental data obtained may be underestimated. In general, for A and D-series samples, it is necessary to note a significant statistical scatter characteristic of composites. And to conclude that the results are of approximate (estimates) nature.

The authors conducted the fatigue tests at pulsing cyclic tension of flat samples of A and D series of composite materials at various levels of maximal stress in the cycle and obtained the experimental

### Table 2. The results of the tests conducted.

| Sample type | 3D-weaving | Laminate G | Laminate+ stitching H |
|-------------|------------|------------|----------------------|
| Characteristic | A | B | C | D | E | F | G | H |
| 1. Uniaxial tensile test | | | | | | | | |
| Strength, units | 1.00 | 0.98 | 0.64 | 0.81 | 0.53 | 0.49 | 0.34 | 0.36 |
| Elasticity module, units | 0.90 | 1.00 | 0.66 | 0.81 | 0.51 | 0.59 | 0.56 | 0.56 |
| Poisson’s ratio | 0.16 | 0.14 | 0.63 | 0.09 | 0.47 | 1.00 | 0.42 | 0.44 |
| 2. Tensile test of holed samples | | | | | | | | |
| Strength, units | 0.82 | 1.00 | 0.37 | 0.57 | 0.33 | 0.40 | 0.32 | 0.32 |
| 3. Compression test | | | | | | | | |
| Strength, c.a. | 0.90 | 1.00 | 0.28 | 0.50 | 0.23 | 0.33 | 0.52 | 0.43 |
| Elasticity module, units | 0.97 | 1.00 | 0.67 | 0.90 | 0.65 | 0.78 | 0.76 | 0.76 |
| 4. Compression test of holed samples | | | | | | | | |
| Strength, units | 0.89 | 1.00 | 0.22 | 0.36 | 0.20 | 0.20 | 0.48 | 0.49 |
| 5. Curved beam four-point bending test | | | | | | | | |
| Beating capacity, units | 0.60 | 0.65 | 0.45 | 0.65 | 0.38 | 0.54 | 1.00 | 0.51 |
| 6a. Tests for impact and compression after impact 30 J | | | | | | | | |
| Maximal compression load, units | 1.00 | 0.92 | 0.36 | 0.74 | 0.37 | 0.38 | 0.67 | 0.84 |
| 6b. Tests for impact and compression after impact 40 J | | | | | | | | |
| Maximal compression load, units | 1.00 | 0.99 | 0.36 | 0.74 | 0.37 | 0.38 | 0.69 | 0.83 |
| 6c. Tests for impact and compression after impact 50 J | | | | | | | | |
| Maximal compression load, units | 1.00 | 0.97 | 0.36 | 0.71 | 0.36 | 0.38 | 0.56 | 0.76 |
| 7. Crack (nonuniform breaking) test for mode I | | | | | | | | |
| Breaking load, units | 0.68 | 0.79 | 0.75 | 1.00 | 0.91 | 0.60 | 0.25 | 0.24 |
| 8. In-plane shear tests | | | | | | | | |
| Ultimate shear stress, units | 0.38 | 0.39 | 0.43 | 0.46 | 0.45 | 0.45 | 0.91 | 1.00 |
| Shear module, units | 0.21 | 0.22 | 0.24 | 0.30 | 0.28 | 0.33 | 1.00 | 0.96 |
dependence of the ultimate number of cycles before destruction on the values of maximum stresses in the cycle. They built the diagrams of changes in the amplitude of displacements of the gripping parts versus the number of cycles during the loading.

As a result of complex analysis of mechanical behavior, the regularities of accumulation of damages and destruction of composite samples with the use of supplementary registration devices during the tensile tests it is possible to make a conclusion of high efficacy of multiparameter analysis method. The combination of test and diagnostic equipment provide a significant improvement of experimental database and the accuracy of results. This field of investigation is promising and needs further study.

The comparison of the experimental data obtained during the implementation of a complex of additional studies of deformation and fracture processes, is presented with the help of a radar diagram (spider diagram) (Figure 16).

The authors considered the maximum load \( (P_{\text{max}}, \text{kN}) \), the ultimate elongation of the sample \( (U_{\text{max}}, \text{mm}) \), the heating of the material at the moment of macro-destruction of the sample \( (\Delta T_{\text{max}}, \text{°C}) \), the maximum value of the cumulative energy attained at the moment of destruction \( (KE_{\text{max}} \times 10^{-5}, \text{В}^2\text{с}) \), as well as the number of registered emissions of the AE signal \( (N_{\text{sum}}, \text{Units.}) \). The values in Figure 16 are presented in relative terms. This presentation of the results provides a qualitative and quantitative comparison of the characteristics of samples with different weaving patterns. It can be noted that the samples with the similar structure are grouped, for example, the samples with the laminated structure (G-4 and H-3) feature with low values of the ultimate load and a relatively low number of \( N_{\text{sum}} \). The samples with orthogonal weave (A-3 and B-3) are characterized with high strength, high values of \( KE_{\text{max}} \) and \( N_{\text{sum}} \). Therefore, based on multivariate analysis, it is possible to select the optimal set of material properties during its development according to the necessary operating conditions [19].

Figure 17. Multiparameter analysis of the effect of composite sample strips weaving pattern [19]: A-2, B-2, C-1, D-1, E-1, F-3, G-4, H-3 [19].
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