Development of a new experimental method for the determination of inplane shear strength and elastic characteristics of polymer composite materials based on high-modulus carbon fiber-reinforced plastics having the ±45° plies

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Abstract. A new method for the determination of shear strength and modulus of high-modulus CFRP reinforced with ±45° plies was developed. The optimal geometrical parameters of the specimen to determine shear properties of high-modulus CFRP reinforced with the ±45° plies were determined by calculation and experimental methods. A comparative analysis of the results of the experimental determination of shear properties was performed.

Key words: Shear in plane of the sheet, polymer composite materials, high-modulus CFRP, stress-strain behavior, finite element method.

1. Introduction

Today there are a large number of standards for shear modulus and strength determination. Studies [1-7] were conducted on the comparison and analysis of the main methods of determining the shear properties of polymer composite materials (PCM). The diversity in standards and methods leads to substantial differences in the characteristics observed. Moreover, current test methods for laminated composites may not always ensure reliable determination of shear strength and elastic characteristics of advanced high-modulus carbon fiber-reinforced plastics (CFRP) [8].

One of the main objectives of developing the reinforced plastic shear test methods is to provide pure shear state in the specimens, and uniform distribution of shear stresses and strains on the whole working area of the specimen.

Ultimate shear strength is provided by the ±45° lamination pattern since the strength of CFRP with this lamination pattern depends not only on the matrix characteristics, but also on high fiber rigidity. When determining shear strength stress concentrators occur in the specimen from the contact of the specimen with the test fixture, and from the holes and cutouts. When testing high-modulus CFRP reinforced with the ±45° fibers, the impact of these stress concentrators increases. [9].

2. Rib-shorting simulation method

This work was aimed at the development of a method for determining the shear strength and modulus of high-modulus CFRP reinforced with the ±45° plies. A calculation analysis of stress-strain behavior (hereafter SSB) of specimens of various configurations with the ±45° reinforcement pattern was performed.

SSB of the specimens was calculated by the finite-element method (hereafter FEM) in the NX/Nastran software application. The task was carried out using 3D Solid elements. The properties of CFRP reinforced with the ±45° plies were assigned to the elements.

The calculated SSB values were compared with the experimental data obtained during the shear test in plane of the sheet according to standards [10-14]. At the same time strain distribution in the specimens was determined both by strain gauging, and through an optical system for 3D strain measurement – VIC 3D. As a result of calculation and experimental research it was found that according to all the standards considered in the CFRP specimens reinforced with the ±45° plies there is no uniform tangential stress distribution in the...
the specimen working area. Therefore, the results of strength and elastic properties determined according to the standards which are commonly used in practice can be insufficiently reliable.

To correctly determine shear strength and elastic characteristics one should choose such geometry with which there is pure shear state in the working area, and the impact of the stress concentrators on the characteristic determined would be minimal. The tests within the work showed that the highest and most stable values of shear strength and modulus were obtained when the tests were performed by the plate distortion in relation to the narrow strip (symmetrical shear) according to GOST R 50578-93, and this specimen was used as a basis for further research.

Calculation analysis of SSB of the specimens revealed that uniform shear strain distribution was mostly affected by the working area length-to-width ratio l/b, the presence of cutouts in the specimen working area, and the spherical radius R of the cutout. Figure 1 shows the working area length l as a function of its width b.

![Figure 1 – Distribution of tangential stresses in the specimen working area](image)

When the working area length-to-width ratio l/b > 10 there are no regions with uniform distribution of tangential stresses. The ratio l/b < 5 causes higher stress concentration in the specimen working area, which results in premature failure.

When analyzing the impact of the radii on the tangential stress distribution in the specimen working area it was determined that the spherical radius R > 10 mm increased heterogeneity. The spherical radius R<5 mm causes appearance of critical stress concentrators in the cutouts, resulting in the lowered values of the mechanical properties of the material. Based on the analysis performed the specimen geometry was determined to reliably determine shear properties of high-modulus CFRP reinforced with the ±45° plies.

3. **Experimental results**

A rectangular plate specimen of 112х73 mm with protective pads was accepted for experimental research. The working area consists of two strips of material with two pairs of U-cutouts on the opposite sides of these strips.

Figure 2 shows the diagrams of SSB of the selected specimen determined by FEM and an optical method using the Vic-3D system.

![Figure 2 – Diagrams of SSB of the specimen obtained by calculation and experimental methods](image)

a) Distribution of tangential stresses determined by FEM in NX/Nastran

b) Distribution of shear strains experimentally determined by an optical method
It should be noted that in this specimen there is uniform tangential stress distribution nearly on the entire strip surface area. The specimen shape developed enables to fix it in the test device without fixing holes in the gripping portion, which provides a minimal impact of the stress concentrators on the specimen, and a more uniform strain and stress distribution in the area of transition from the gripping portion to the test portion of the specimen.

After the calculation analysis the comparative mechanical tests for shear in plane of the sheet were conducted by the method developed and the most common standards [10-14]. The test specimens were fabricated by autoclaving from high-modulus CFRP VKU-25 (carbon filler HTS 40 and binder VSE1212) reinforced with the ±45° plies. The thickness of the test specimens was ≈2 mm.

The comparative analysis of the results of experimental determination of the advanced high-modulus CFRP shear properties showed that the method developed provides proper determination of the material shear properties and low coefficients of variation of shear modulus (CV=1.79%) and ultimate shear stress (CV=1.14%) values.

4. Conclusions

Thus, the method developed provides a reliable and precise strength and elastic modulus determination in shear in plane of the sheet through the uniform stress and strain distribution in the specimen working area. This is due to the specific geometrical shape of the specimen that is the presence of U-cutouts on the test specimen with the length and width of the specimen working area. This geometrical shape of the specimen is selected so that over the whole specimen working area that is between the U-cutouts the “pure” shear state is at most realized. The test method using this specimen was protected by the RF patent [15].

References

[1] Tarnapolsky Yu M and Kintsis T Ya Metodi staticheskikh ispitaniy armirovannykh plastikov Khimiya Publ (Moscow) 272
[2] Polilov A N 2016 Experimental Mechanics of Composites Bauman Moscow State Technical University Publ 121-131.
[3] Arnautov A and Bach T 1996 Determination of In-plane Shear Characteristics of Composites with the ±45 lamination. Mechanics of Composite Materials 32 256-254.
[4] Adams D O, Moriarty J M, Gallegos A M, and Adams D F 2003 Development and Evaluation of the V-Notched Rail Shear Test for Composite Laminates, U.S. Department of Transportation Federal Aviation Administration. National Technical Information Service (NTIS) (Springfield, Virginia 22161) 90
[5] Gusenkov A P and Polilov A N 1992 Modern Test Methods for Composite Materials, IMASH RAN Publ (Moscow) 247
[6] Hodgkinson J M 2000 Mechanical Testing of Advanced Fibre composites ed Corporate Blvd pp. 100-122.
[7] Adams D F 2000 Comprehensive Composite Materials 5 pp. 113-148.
[8] Popov A G and Matyushevsky N V 2013 Abstracts of the XX Int. scientific and technical conf. Structures and technologies of production from nonmetallic materials (Obninsk) pp.146-148.
[9] Matyushevsky N V and Popov A G 2016 Proceedings of the 2nd International conference Deformation and Failure of Composite Materials and Structures Stolitsa Publ (Moscow) pp.219 – 220.

[10] GOST R 50578 ‑ 93: Plate distortion shear test

[11] Standard Test Method for In-Plane Shear Properties of Polymer Matrix Composite Materials by the Rail Shear Method ASTM D4255/D4255M 15 A

[12] Standard Test Method for Shear Characteristics of Composite Materials by the V-Notched Beam Method ASTM D5379/D5379M 12

[13] Standard Test Method for Shear Properties of Composite Materials by V-Notched Rail Shear Method ASTM D7078/D7078M 12

[14] Methods of shear strength determination in plane of the sheet, 12 p GOST 24778-81

[15] Matyushevsky N V, Popov A G and Lisachenko N G Description of the RF patent no. 2617776 Specimen for the determination of shear elastic modulus and ultimate strength of high-modulus CFRP in plane of the sheet IPC G01N 1/28 (2006.01), G01N 3/24 (2006.01). Application no. 2016100524 of 11.02.2016