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Application of Topological Measures in Estimation of Reinforcing Fibers Distribution in Composites

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Abstract. Roving composites are used in the production process of critical supporting structures. The mechanical properties of the composites depend on the even distribution of the fibers. Monitoring of geometrical measures of composites microstructure can be used for prediction of material strength and durability. In the paper results from the research performed on the production samples of girders of helicopter blades are presented. Some geometrical properties, like: the average fiber diameter D, matrix film thickness average G_{AB} and its standard deviation were used for specimens classification by the value of the flexural elastic modulus. The topological measure G_{AB} is intendent to evaluate of the fibers distribution. Applicability of the measure has been checked based on strength tests results. The uniformity of the fiber distribution expressed by the averaged G_{AB} measurement allows for estimation of the composite strength. Additionally the quantitative character of the measure G_{AB} take in defects occuring in the internal structure of composites.

1. Introduction

Composite materials are used in the production of machines to achieve special strength properties while maintaining their light weight. Composites containing fibers allows obtaining anisotropic properties of composites, which depend on the orientation of reinforcing fibers. The composites made of continuous fibers (filaments) achieve high resistance to transverse load to the direction of fibers.

An important property that affects the strength of unidirectional composites is the uniformity of the distribution of reinforcement in the composite matrix. This property is related to other qualities that affect the strength and impact strength of the composite. The durability of the composite depends to a large extent on the surface of the interface connecting the reinforcement phase with the warp [1-5]. Considering the thickness of the interface, the significance of the relative volume of the interface in the composite can also be considered. When the thickness of the interface reaches the minimum value, this means the presence of contacting fibers, which promote crack propagation. Cracks lead to permanent weakening of the composite. Therefore, it seems relevant to the authors of the article to assess the uniformity of the distribution of the composite reinforcing fibers, to develop a uniformity measure of the distribution allowing for the assessment of the quality of the structure and to assess the strength of the composite [6-10].

For this purpose, an experiment was conducted consisting in the preparation of composite samples builds of glass fibers and epoxy resin, in which all design parameters and quality indicators resulting from the used technology were similar and samples differed only in the distribution of fibers in the transverse plane to the fiber direction. A comparison of the overall strength and microstructural

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structure of the samples was then made. Based on these results, the analysis of the correlation of geometrical properties and results of the strength test was carried out. The results of the analysis allowed for the development of a measure of distribution in the form of an average warp thickness in a plane perpendicular to the fiber direction, surrounding individual fibers [11-15].

On the basis of the literature analysis, it was initially estimated that the impact of the reinforcement fiber distribution, although significant, would be lower than the influence of defects in the microstructural structure, such as the presence of air bubbles and contacting fibers [16-17]. Therefore, it was decided to obtain samples from the production process of responsible load-bearing structures, in which demanding quality procedures appropriate for the aviation industry are applied. With this choice, the impact of defects on the overall strength of the samples has been minimized.

2. Experiment

The study used glass fibers with a diameter of 10 μm (made at the Krosglass plant in Krosno, Poland) and epoxy resin (Epidian 5). The fibers were covered to create an interface with an epoxy resin. The fibers were rewound in strands so that the maximum glass content (relative volume) could be obtained in the composite material. Supersaturation of the fibers was carried out manually using instruments, therefore the average relative volume of glass was 51 %. Higher values of relative volume can be obtained using machine supersaturation. From such material was prepared responsible aerial supporting (load-bearing) structures and witness samples, which were used in further studies.

The samples-witness were tested on three-bending strength and short beam shear method. The following mechanical strength characteristics were determined: the force at yield point F_1, and maximum elastic deformation L_1, the maximum force F_{max} and deflection in shear test L_2, and the beam deflection angle φ. The analysis was limited to the elastic response of the composites and the value of modulus of elasticity E_f can be calculated with the following equation:

$$E_f = \frac{F_{max} L^3}{4BH^3 f} \tag{1}$$

where F_{max} is the maximal force of elastic deflection in the short beam shear test (SBST), B, H, L are width, thickness, and length of the specimen, and f the beam deflection.

Then the metallographic section from samples after strength tests were prepared and microscopic observations were made. Observations in the plane parallel to the direction of the fiber axis allowed for assumption that the distribution of fibers in the plane of transverse defects to the axis of the fibers is identical to that in the plane destroyed during the strength test. The fibers were laid parallely. On the sections of a few millimeters between both sections, the parallelism of the fibers was not observed, because it was less than measurement resolution. The cross-sections were used to develop geometric images of microstructures consisting of the position of fiber centers X, Y and diameter D.

3. Definitions of applied topological measures for estimation of fibers distribution

Voronoi tessellations were used during microscopic measurements. There were measured: the surface area of the matrix surrounding any individual fiber A_m, fiber diameter D_f, the distance between neighboring fibers G_{1i}, where i is a number of neighboring fibers, $G_{2j}(\varphi)$ is the radial thickness of voronoi polygon (figure 1) measured with angular intervals ($\Delta\varphi$ = 5 deg), where j varies from 1 to 360 with 5 degree angle, G_{AD} is the average film thickness G_2 calculated from the matrix area A_m and the fiber diameter D_f:

$$A_m = \frac{\pi}{4}\left[\left(D_f + 2G_{xx}\right)^2 - D_f^2\right] \tag{2}$$

$$G_2 \approx G_{AD} = \frac{1}{2}\left(\sqrt{D_f^2 - 4\frac{A_m}{\pi}} - D_f\right) \tag{3}$$

G_{AB} is the fractional of the Voronoi polygon with matrix area A_m by the circuit fiber.

$$G_{AB} = \frac{A_m}{\pi D_f} \tag{4}$$

4. Analysis of results

Figure 2 presents the distributions describing the dispersion of thickness G_{1i}, G_{2j}, and figure 3 presents distributions describing the dispersion of averaged G_{AB}. The presented exemplary results were calculated for a sample comprising 187 composite fibers.

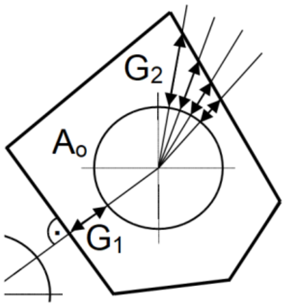

Figure 1. The local thickness of the matrix separated around a single fiber with Voronoi polygon.

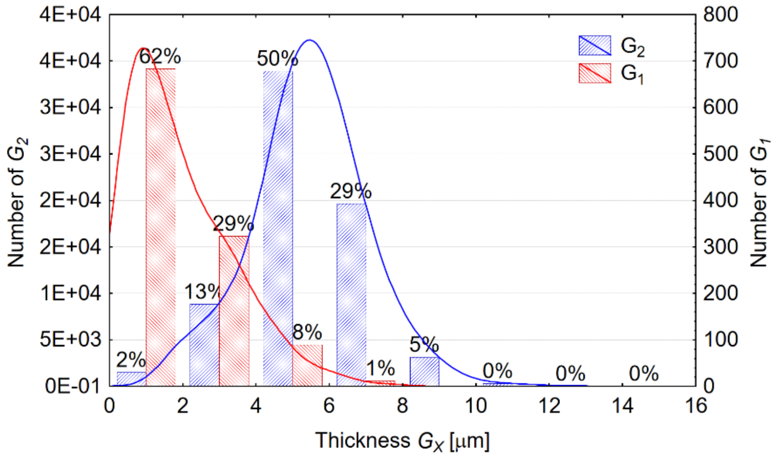

Figure 2. Example of distributions describing the local thickness spreads G_{1i} and G_{2j} measured for a sample image of a composite cross-section comprising 187 fibers.

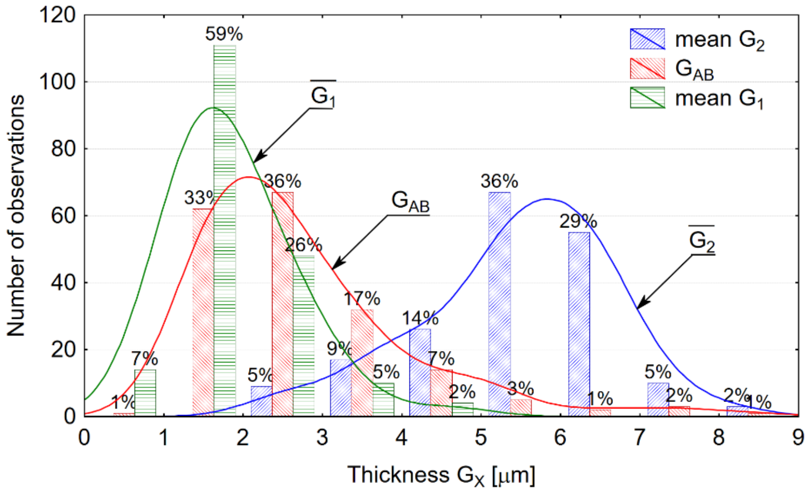

Figure 3. The distributions describing the dispersion of fibers within the average thickness $\bar{G}_1$, $\bar{G}_2$ and $\bar{G}_{AB}$ calculated for 187 fibers.

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The quoted results make it possible estimation of the actual micro constructions of the tested composite. This model is presented in the form of randomly spaced parallel reinforcing fibers having random value of diameters, surrounded by a matrix of annular shape and the random thickness G_X. On the basis of figure 2 and figure 3, various types of deviations from a homogeneous model structure of the composite may be determined by a global mean and medians values. For example, from figure 3 follows that in the sample considered, about 7 % of the fibers were surrounded by a layer of resin with an average thickness of less than 1 μm, which practically means the contact between the fibers. Left skewed distribution of the thickness G_1 (figure 2) proves the advantage of smaller thickness than the mean value calculated for this set. This conclusion confirms the thickness distribution G_{2j}, which in turn is characterized by right-side skewness.

Averaging the local film thicknesses within individual fibers leads to the expected effect in the form of reduced skewness, making the dispersion size of G_1, G_2 and G_{AB} more closely related to the normal distribution.

In order to evaluate the homogeneity of the geometrical structure, the measure is proposed in the form of the G_{AB} index (equation 5), which determines the average thickness of the matrix surrounding the single fiber. This indicator can be both random, i.e. it can be calculated for individual samples taken at random from the composite cross-section, as well as global calculated from several samples selected representatively of the cross-section of the composite. A negative value of the skewness of the distribution indicates the occurrence of left-sided asymmetry. A positive value of the skewness coefficient indicates the occurrence of right-sided asymmetry (extended right arm of the distribution). The proposed G_{AB} measure does not provide accurate quantitative information on possible defects, such as the number of contacting fibers, nevertheless, on the basis of this ratio can be inferred the number of such defects.

5. Influence of the composite structure on its strength

The results of SBST tests allowed to choose two groups of samples, which differ with results of the tests, while quantitative indicators describing the geometrical properties of the samples were identical and the samples were devoid of air bubbles and other defects. The factor differentiating the structure of the samples was fiber arrangement. A discriminant analysis was conducted, which distinguished three main features of the microstructure of the samples that influenced the diversification of strength properties.

In the figure 4, the difference between groups of samples-witnesses was characterized according to the value of the maximum force F_{max} [N] obtained during the SBST tests. Figure 5 shows the values of the geometric parameters highlighted during the discriminant analysis, characterized by two groups of samples. Thus in the prepared space the two groups of samples are distinctly separable.

$$D_1 = 14.357 + 1.649\ G_{AB} - 16{,}944\ G_{1\min} - 0.396\ V_f \quad (5)$$

The significance level of the discriminant function, calculated by the chi-square test used to gave the p-value below 0.0001 and the coefficient of canonical analysis R reached high value (0.915). These values proved strong correlation of the discriminant function with the separated groups of specimens.

In order to determine the individual contribution of characteristics in building a discriminatory function, coefficients of the factor structure were calculated. G_{AB} (0.837) characteristics and V_f (0.810) have a similar, high values of coefficients, but the higher value of the correlation coefficient reaches G_{AB}. The third factor reached the small value of G_{1min} = 0.188, what means the lack of significant effect of fiber diameter in our analysis. This result is a confirmation of the plan for obtaining samples of the same fiber diameter. However, the significant influence of the volume fraction of V_f glass in this group of samples makes difficulty in analysis of the fibers distribution effect.

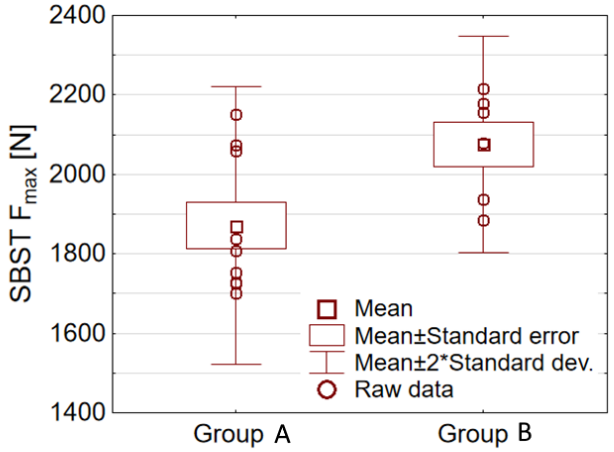

Figure 4. Statistics of maximum force values F_{max} [N] during short-beam strenght test in group A and B [18].

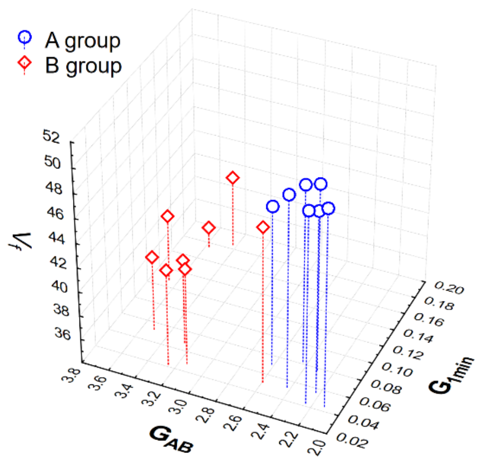

Figure 5. Average values of V_f, G_{AB} and G_{1min} for individuals specimens in groups A and B [19].

6. Summary and conclusions

In this paper we proposed several topological measures to estimate fibers distribution in the polymer matrix composites. In particular, we analysed defects occuring in the internal structure of composites. The topological measure G_{AB} allows to evaluate the distribution of fibers. The uniformity of the fiber distribution expressed by the averaged G_{AB} measurement allows for estimation of the composite strength. The proposed measures find application in monitoring of composites quality. In further studies, it is advisable to collect the results allowing for determination of the regression function of all features characterizing the uniformity of fiber distribution with respect to strength characteristics. The model can be extended by inclusions of damage or cracking processes, as it was done for other composite materials, e.g. [20-30].

7. References

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