Analytical and experimental research of epoxy-based glass/carbon hybrid polymer composites

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Abstract. Nowadays, the significant potential of hybrid polymer composites in terms of weight and cost has contributed to their application in different branches of industry. However, it is known that determination of unique properties of hybrid composites remains significantly challenging as laborious experimental work is usually required. This study aims to develop a numerical material model for prediction of mechanical properties of glass/carbon epoxy-based composites. To validate the material model the subsequent experimental research is proposed. It shows good agreement between numerical simulation results and experimental one.

1. Introduction
Fiber reinforced polymer composites are a well-known class of engineering materials that have proved their excellent performance in heavy-loaded aerospace structures through decades. Besides their high strength-to-weight ratio together with some other exceptional properties, fiber reinforced polymers offer a certain design freedom to developers. Thus, the fibers and matrix choice, fiber orientation and stacking sequence are the variable parameters during the composite material development. One of the possible ways to extend the design space is to use two types of fibers instead of just one, thus combining benefits of both types of fibers within one material. Composites materials, that consisted of at least two dissimilar reinforcements embedded either in thermoplastic or thermoset matrix, are called hybrid polymer composites [1-4].

Three levels of hybridization of fiber reinforced composites can be distinguished, i.e. intrayarn (fibre-by-fibre), intralayer (yarn-by-yarn) and interlayer (layer-by-layer) [5]. One of the best known types of hybrid composites is fiber-metal laminates (FMLs), that consist of thin metal sheets (usually aluminum) bonded into a laminate with intermediate thin fiber reinforced composite layers [6]. Although FMLs are widely used in aviation since 1980s and today a number of grades are commercially available [7], a bunch of challenges arises during FML manufacture and usage [7]. One of the main problems of FMLs is residual thermal stresses, that occur due to the significant difference in the thermal properties of metals and typical composite reinforcement fibers (glass, carbon, etc.). Hybrid composites reinforced with two different types of synthetic fibers are almost free from the mentioned drawback of FML, have lower density and can even exhibit so-called “hybrid effect” [1, 8]. However, fiber reinforced hybrid composites are much less studied than FMLs. Moreover, numerous combinations of the variable parameters give birth to a considerable number of hybrids with different properties. Therefore, a problem of optimum material properties combination arises during the design stage [9-11]. This problem is multilevel and requires application of different techniques to solve it in each level (optimization
methods, modelling, testing, etc.). Although, the properties of the developed material are mostly defined by experimental testing, modelling can help to eliminate the excessive number of trials and thus to reduce time, labor and financial costs.

Modern software allows to simulate material microstructure and define the material physical and mechanical properties. In this study we aimed to model the mechanical properties of hybrid polymer composite reinforced with glass and carbon fibers by means of combination of numerical and analytical methods, and validate the obtained results with the experimental ones [2, 12, 13].

In this paper to study the mechanical properties of composites, the lay-up consists of totally 16 glass and carbon monolayers that stacked with angles of orientations: [0°; ±45°; 90°] were considered. The properties of the following glass/carbon ratios in the lay-up were used: 0/100; 50/50; 100/0 in order to obtain methodology for mechanical properties determination of composites, also to investigate dependence of properties upon components volume fraction. Woven glass fibre fabric T10 [14], carbon FibArm Tape 230 [15] and epoxy resin Noapox 7510 were used for analysis and experimental research.

2. Numerical simulation of the hybrid polymer composite material properties in MSC Digimat

Over the past decades several approaches as well as software have been developed for the prediction of the behaviour of multi-component materials, especially composites. The Digimat [16] software is of particular interest for modelling a complex material microstructure by generation a representative volume element (RVE). Digimat includes several algorithms for microstructure homogenization and properties determination: the FEA-based homogenization approach (Digimat-FE) and the mean-field approach (Digimat-MF). In Digimat-MF only ellipsoidal reinforcements for homogenization can be used, also the semi-analytical Mori–Tanaka methods that is correlated with the Eshelby approach, interpolative double-inclusion scheme (Lielens’ model) and others are realized [17, 18]. Due to such constraints in this study the mechanical properties of the hybrid composites are obtained via FEA-based homogenization approach that performed in Digimat-FE that includes different types of reinforcements are implemented.

To determine the properties, the RVEs of a carbon tape and a glass fabric are generated. The initial characteristics of the carbon and glass monofilaments and the epoxy matrix are presented in Table 1.

| Parameter | CFRP | GFRP |
|-----------|------|------|
| Reinforcement architecture / type | UD tape/ AKSA A-49 24K4 | Satin fabric 8/3 /T10 |
| Geometric model of representative volume element (RVE) generated using Digimat-FE (matrix is hidden for clarity) | | |
| RVE dimensions (mm) | 0.04 x 0.04 x 0.4 | 4 x 2.2 x 0.24 |
| Fiber diameter (μm) | 10 | 8 |
| Reinforcement volume fraction (vol.%) | 60 | 60 |
| Modulus of elasticity in longitudinal / transverse directions (GPa) | 240 / 50 | 80 / 80 |
| Modulus of rigidity (GPa) | 42 | – |
| Density (kg/m³): reinforcement /epoxy matrix | 1 790/1 300 | 2 520/1 300 |
As the result of the simulation the mechanical properties of the GFRP and CFRP monolayers are obtained. In order to conduct more accurate calculation, the properties are calculated for various orientation angles: 0°, 45°, -45°, and 90° in MSC Digimat (table 2).

**Table 2.** Mechanical properties of GFRP and CFRP monolayers for various orientations obtained in MSC Digimat and user for subsequent analytical calculation.

| Property                             | GFRP (0°) | GFRP (±45°) | GFRP (90°) | CFRP (0°) | CFRP (±45°) | CFRP (90°) |
|--------------------------------------|-----------|-------------|------------|-----------|-------------|------------|
| Modulus of elasticity in longitudinal direction $E_1$ (GPa) | 29.8      | 23.5        | 23.6       | 122.2     | 12.4        | 8.5        |
| Modulus of elasticity in transverse direction $E_2$ (GPa)  | 24.5      | 25.2        | 29.4       | 9.4       | 12.4        | 116.9      |
| Modulus of rigidity $G_{12}$ (GPa) | 5.8       | 12.2        | 6.0        | 3.8       | 9.4         | 3.4        |
| Poisson's ratio $\nu_{12}$         | 0.19      | 0.29        | 0.20       | 0.27      | 0.40        | 0.02       |
| Poisson's ratio $\nu_{21}$         | 0.16      | 0.30        | 0.15       | 0.02      | 0.40        | 0.27       |

Unfortunately, the RVE size of a glass fabric is considerably larger than the RVE of a carbon tape. For savings in computational time the calculation of the mechanical properties of composites are defined in analytical form using the expressions of composite mechanics. Based on the known values of the technical elastic constants, the coefficients of the stiffness matrix for each layer in its natural coordinate system are obtained [19-22] using following expressions:

\[
g_{11}^i = \frac{E_i^i}{1-\nu_{12}^i \cdot \nu_{21}^i} \quad (1)
\]

\[
g_{22}^i = \frac{E_2^i}{1-\nu_{12}^i \cdot \nu_{21}^i} \quad (2)
\]

\[
g_{12}^i = \nu_{12}^i \cdot g_{22}^i = \nu_{21}^i \cdot g_{11}^i \quad (3)
\]

\[
g_{66}^i = G_{12}^i \quad (4)
\]

where $g_{11}^i, g_{22}^i, g_{12}^i, g_{66}^i$ are the coefficients of the stiffness matrix of each layer; $E_1^i, E_2^i$ are the modulus of elasticity in longitudinal and transverse directions respectively, Pa; $\nu_{12}^i, \nu_{21}^i$ are the Poisson’s ratio; $G_{12}^i$ is the modulus of rigidity, Pa.

For the determination of the coefficients of the stiffness matrices of each of 16 layers in the coordinate system of multilayer material we have used the following formulas [19-22]:

\[
g_{xx}^i = g_{11}^i \cdot \cos^4 \varphi_i + g_{22}^i \cdot \sin^4 \varphi_i + (2 \cdot g_{12}^i + 4 \cdot g_{66}^i) \cdot \sin^2 \varphi_i \cdot \cos^2 \varphi_i \quad (5)
\]

\[
g_{yy}^i = g_{11}^i \cdot \sin^4 \varphi_i + g_{22}^i \cdot \cos^4 \varphi_i + (2 \cdot g_{12}^i + 4 \cdot g_{66}^i) \cdot \sin^2 \varphi_i \cdot \cos^2 \varphi_i \quad (6)
\]

\[
g_{xy}^i = (g_{11}^i + g_{22}^i - 4 \cdot g_{66}^i) \cdot \sin^2 \varphi_i \cdot \cos^2 \varphi_i + g_{12}^i (\sin^4 \varphi_i + \cos^4 \varphi_i) \quad (7)
\]

\[
g_{yx}^i = (g_{11}^i + g_{22}^i - 2 \cdot g_{12}^i) \cdot \sin^2 \varphi_i \cdot \cos^2 \varphi_i + g_{66}^i (\sin^4 \varphi_i - \cos^4 \varphi_i)^2 \quad (8)
\]

where $g_{xx}^i, g_{yy}^i, g_{xy}^i, g_{yx}^i$ are the coefficients of the stiffness matrix of monolayers in the coordinate system of multilayer material.

The coefficients of the stiffness matrix for laminate structure are defined:
\[ g_{xx} = \sum_{i=1}^{n} g_{xx}^{i} \cdot \tilde{h}_{i}; \quad (9) \]
\[ g_{yy} = \sum_{i=1}^{n} g_{yy}^{i} \cdot \tilde{h}_{i}; \quad (10) \]
\[ g_{xy} = \sum_{i=1}^{n} g_{xy}^{i} \cdot \tilde{h}_{i}; \quad (11) \]
\[ g_{ss} = \sum_{i=1}^{n} g_{ss}^{i} \cdot \tilde{h}_{i}, \quad (12) \]

where \( \tilde{h} \) is the relative thickness of a monolayer.

The resulting technical constants of the laminate structure of hybrid composite are obtained:

\[ E_x = \frac{g_{xx}^2 - g_{xy}^2}{g_{yy}}, \quad (13) \]
\[ E_y = \frac{g_{yy}^2 - g_{xy}^2}{g_{xy}}, \quad (14) \]
\[ G_{xy} = g_{ss}, \quad (15) \]

where \( E_x \) and \( E_y \) are the modulus of elasticity of the longitudinal and transverse directions respectively, Pa; \( G_{xy} \) is the modulus of rigidity, Pa.

3. Validation of the numerical results via experimental research

Several samples of hybrid composite are manufactured and have the following glass/carbon ratios: 0/100; 50/50; 100/0. For statistical processing, 5 samples of each type of material are made. Photos of the used materials are presented in Figure 1.

![Figure 1](image)

**Figure 1.** Photos of the (a) UD tape/ AKSA A-49 24K4 (b) satin fabric 8/3 /T10 used for samples fabrication

To manufacture the composite samples, the vacuum infusion is applied. The scheme of the manufacturing process is presented in Figure 2 [23, 24]. For the production of the flat samples the dry preforms are placed into the aluminum mold that stowed in the vacuum bag [24].
Samples with the rectangular cross section with the end tabs made of orthogonally-reinforced GFRP are used for tensile tests (Figure 3a). Five samples of GFRP, CFRP and hybrid composite are applied for each trial. As an example, the GFRP sample is presented in Figure 3b.

For the proposed lay-up the hybrid FRP samples (GFRP/CFRP = 50/50) as well as neat CFRP and GFRP samples are manufactured. The experiments are conducted at room temperature. As the results of the tensile testing the relation between elastic modulus and GFRP/CFRP ration and the relation between ultimate tensile strength and GFRP/CFRP ration are obtained (Figure 4). The experimental results are compared with the numerical ones.
The experimental results of the dependencies of the elastic modulus on the volume content of the components have good agreement with the numerical results. The numerical results are slightly overestimated than the experimental, that is due to the fact that the structural defects were not considered during the modelling. However, this can be taken into account in the further research, as Digimat provides such a possibility. The dependence of the ultimate tensile strength on the GFRP/CFRP ratio illustrates the hybrid effect, as when 50% of the CFRP are added to GFRP the strength of the composite is almost doubled.

4. Conclusion

In this study an approach to determination of the mechanical properties of composites, including hybrids, is implemented. As the result of numerical simulation by means of MSC Digimat the mechanical properties of composites with different reinforcing ratios are obtained. To validate the numerical analysis results the experiment is conducted. The simulation results are compared with experimental data and have shown good agreement that confirms the feasibility of the approach [21-22, 24].

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Figure 4. (a) Comparison of the mechanical properties obtained in MSC Digimat (1) with experimental ones (2) in dependence on components ratios; (b) Ultimate tensile strength in dependence on components ratios.
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