

Analysis of mechanical properties anisotropy of nanomodified carbon fibre-reinforced woven composites

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Abstract. The polymer binder cracking problem arises while designing and maintaining polymer composite-based aircraft load-bearing members. Some technological methods are used to solve this problem. In particular the injection of nanoagents can block the initiation and growth of microscopic cracks. Crack propagation can also be blocked if the strain energy release is not related with fracturing. One of the possible ways for such energy release is creep. Testing of the anisotropy of the woven carbon fibre reinforced plastic elastic characteristics and creep have been conducted. The samples with different layouts have been made of woven carbon fibre laminate BMI-3/3692 with nanomodified bismaleimide matrix. This matrix has a higher glass transition temperature and improved mechanical properties. The deformation regularities have been analyzed, layer elastic characteristics have been determined. The constitutive equations describing composite material creep have been obtained and its parameters have been defined. Experimental and calculated creep curves have been plotted. It was found that the effects of rheology arise as the direction of load does not match the direction of reinforcing fibres of the material.

1. Introduction

The unique physical and mechanical properties of polymer composites allow their wide use in the rocket and aerospace structures, but it is necessary to solve a number of issues related to the strength, durability, rigidity of these materials. Carbon fibre reinforced plastics (CFRP) are one of the most common materials used in aviation and space technology, they have high stiffness and strength of the material but at the same time they have a significant anisotropy of the properties, tendency to the damage accumulation, cracking, which forces engineering designers to apply an additional safety ratio. Some technological methods are used to solve cracking problem. In particular the injection of nanoagents can inhibit the initiation and growth of microscopic cracks. Crack propagation can be also blocked if the strain energy release is not related with fracturing. One possible way for such energy release is to take advantage of time-dependent effects.



It is important to analyse the patterns of the deformation processes and develop the computational and experimental methods predicting CFRP resistance to the deformation and destruction, depending on the structural and technological factors. In this paper the model predicting the creep of equally strong woven CFRP BMI-3/3692 with nano-modified bismaleimide matrix under shear loading in the layer plane is proposed.

The time-dependent effects appear under shear loading of CFRP, whereas during deformation along and across the direction of reinforcing, the rheological effects are negligible.

In [1, 2] experimental studies of CFRP deformation are conducted, and the impact of creep is studied. The change in the viscoelastic component is defined using the power law: $\varepsilon = \varepsilon_0(1+at^n)$, where $\varepsilon_0 = \sigma/E$. The essential disadvantage of this approach is the inability to take into account the history of the load [3]. The dependency between creep curves and strain rates is shown on Fig. 1 [3].

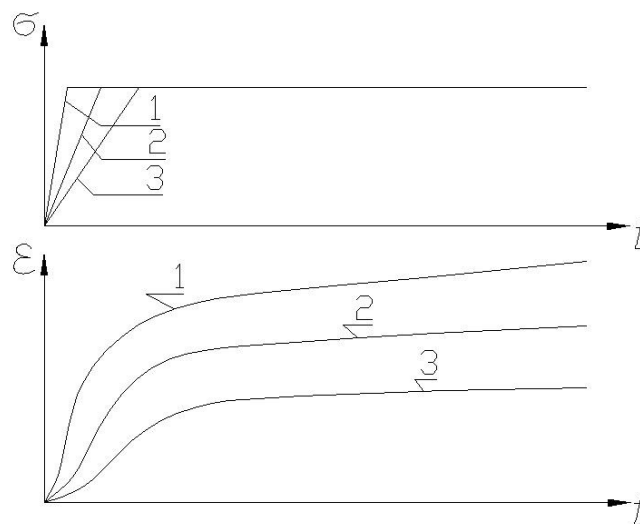


Figure 1. Creep curves obtained at different strain rates at an early stage

In [4-7] experimental studies based on carbon, glass and organic fibre reinforced plastics are conducted. It is shown that the most significant time-dependent effects arise during shear loading in the layer plane. In these works the same approach describing time-dependent effects is used. In [8] for the approximation of the experimental dependence Maxwell model is selected.

In [9-14] the relations of the linear hereditary mechanics proposed by Rabotnov are used. They have the form:

$$\varepsilon = \frac{\sigma}{E}(1 + K^*),$$

where K is the creep kernel:

$$K^*\sigma(t) = \int_0^t K(t-\tau)\sigma(\tau) d\tau.$$

Rabotnov fractional exponential function, the Abel kernel, Prony series [15] can be used as a creep kernel.

The hereditary approach is the most common and appropriate form of the relationship between stress and strain under variable loads [9]. This approach also makes possible the

identification of a number of related functions characterizing the material. Thus, the expression for the description of the relaxation can be written as: $\sigma = E(1 - R^*)\varepsilon$, where R^* is the relaxation kernel having the following interrelation $(1 + K^*)(1 - R^*) = 1$, $R^* = K^*/(1 + K^*)$.

Paper [16] is devoted to the analysis of the time-dependent properties of CFRP and determination of the hereditary type constitutive equations of the of laminated CFRP KMU-4L. The rheological properties of the tensile specimens with layup $[\pm 40^\circ]$, $[\pm 50^\circ]$ are studied experimentally. These properties are determined primarily by the rheological properties under shear loading. Testing of the samples with the layup $[\pm 40^\circ]$ under time-varying loads makes it possible to determine the time-dependent relations [17]. It has been found that this relationship can be represented as a hereditary type constitutive relation with Abel kernel [4].

2. Description of the experiment

The samples were cut from the 14-layer twill weave plate using computer marking and diamond wheel cutting with CNC machines. All layers were oriented in the same direction. Stress/strain curves for flat tensile specimens were obtained under loading in the Instron test machine. The strains along and across the longitudinal axis of the sample were measured using strain gages (Fig. 2) and strain gauge station SIIT-4. Test specimens were produced with longitudinal axis having an angle of 0° , 30° , 45° and 90° to the direction of the base (Fig. 3). The cross-sectional area of the samples was $2 \times 18 = 36 \text{ mm}^2$.

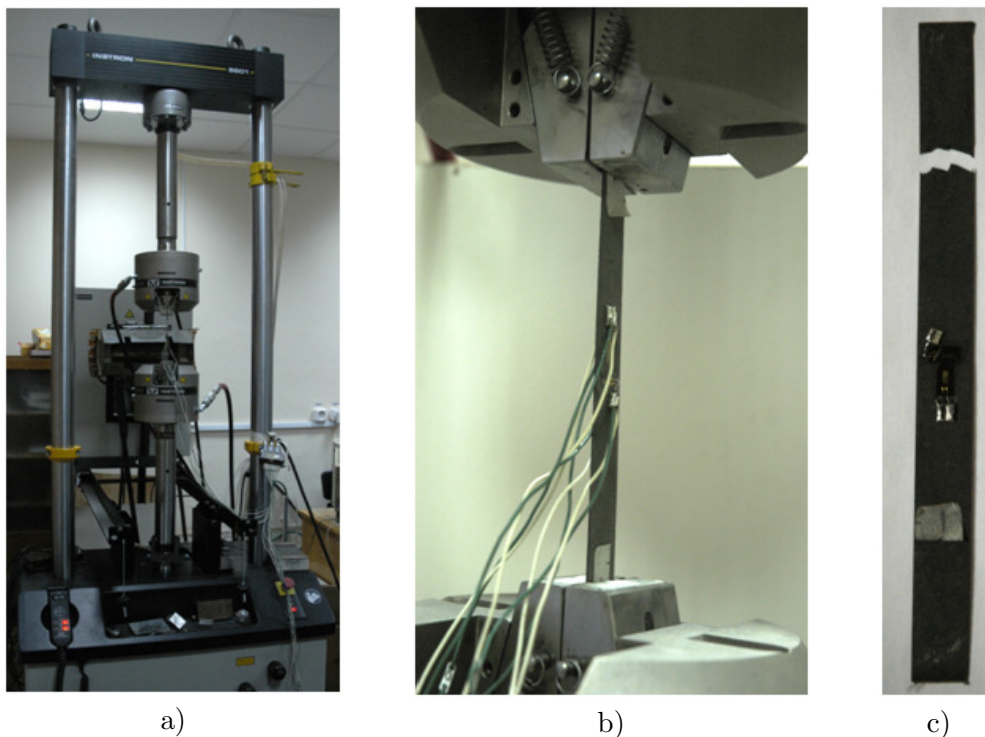


Figure 2. a) The test machine; b) The sample in the grips; c) The sample after the test

Samples of each cutting direction were loaded at a speed corresponding to the quasi-static load with a subsequent discharge. Loading rate for each sample was varied in the 2-3 times. The final loading was carried out until the destruction. Three strain gauges were pasted onto each sample: two in the longitudinal direction and one in the transverse direction.

The sample 0° was loaded to stress 220 MPa, 440 MPa and 660 MPa, with subsequent discharge (Fig. 4), and then to the destruction that occurred at 836 MPa. The sample 90° was



The graph plots yield stress σ_x' in MPa against equivalent strain ϵ_v, ϵ_x in percent. The data points form a vertical line at zero strain for stresses up to about 680 MPa, indicating a yield point phenomenon. Beyond this point, the stress increases linearly with strain.

Strain ϵ_v, ϵ_x (%)	Yield Stress σ_x' (MPa)
0.00	0
0.00	50
0.00	100
0.00	150
0.00	200
0.00	250
0.00	300
0.00	350
0.00	400
0.00	450
0.00	500
0.00	550
0.00	600
0.00	680
0.05	50
0.15	120
0.25	220
0.35	280
0.45	390
0.55	450
0.65	500
0.75	610
0.80	680

The graph plots yield stress σ_x' in MPa against strain ϵ_v, ϵ_x in percent. The data points for positive strains (tension) form a straight line starting from the origin (0,0) and extending to approximately (0.55, 380). For negative strains (compression), the yield stress increases rapidly, reaching about 380 MPa at a strain of -0.02%.

Figure 5. The experimental stress-strain curves of the sample 90°

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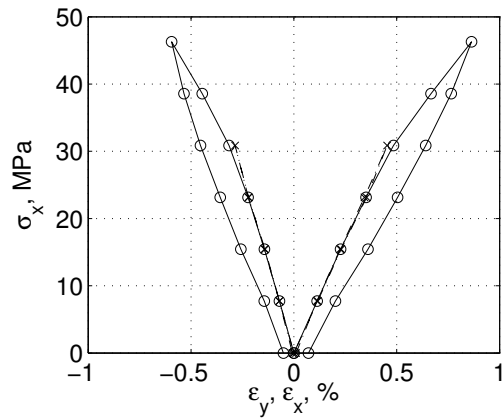


Figure 6. The experimental stress-strain curves of the sample 30°

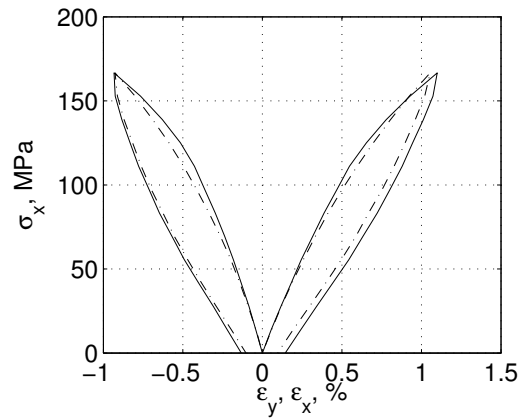


Figure 7. The experimental stress-strain curves of the sample 45°

The shear modulus was identified by solving the inverse problem for the linear part of the stress-strain curve for the specimens cut at angles 30° and 45°, $G_{12} = 7.5$ GPa.

The other samples cut at 45° were tested for creep. The longitudinal and transverse strains have been registered throughout the test. The first sample was loaded to 172 MPa in 15 seconds and held at this stress for 75 seconds, after that the failure occurred (Fig. 8). The maximum longitudinal strain before failure was 1.9%. Fig. 8 shows the dependence of the stress and strain on the time for this sample. Another sample was loaded up to 158 MPa in 15 seconds, and then for 1.7 hours was kept at this load without visible signs of destruction. The maximum longitudinal strain registered was 1.8%.

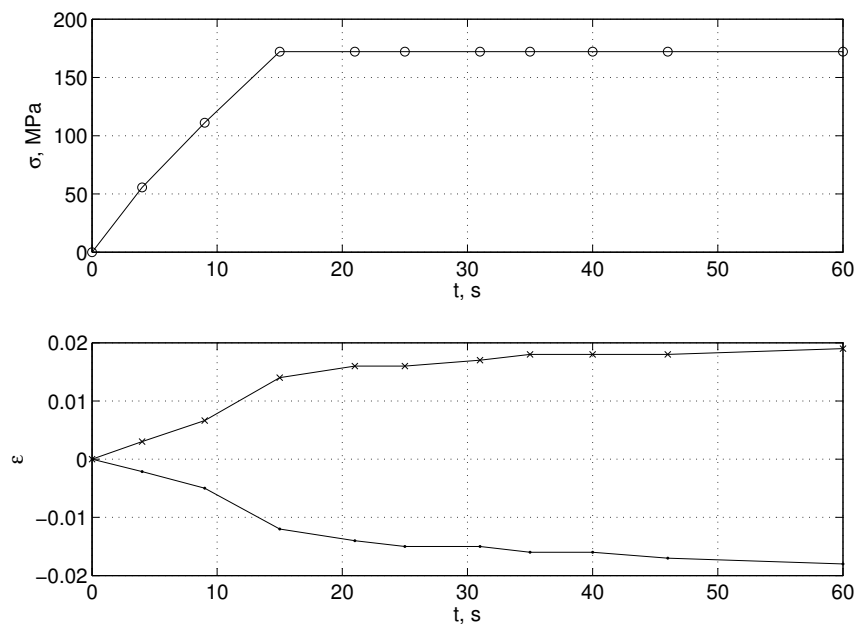


Figure 8. The experimental stress and strain curves of the sample cut at an angle of 45°

3. Model Description

It was shown [15] that the dependence between the stress and the strain can be represented as a hereditary type constitutive relation:

$$\gamma_{12} = \frac{1}{G_{12}^0} (1 + K^*) \tau_{12}.$$

Using the expression for the resolvent, an expression for the stresses calculated by the known history of strain was obtained [5]:

$$\tau_{12} = G_{12}^0 (1 - R^*) \gamma_{12}.$$

Constitutive relations for the layer can be written in the following matrix form:

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} \frac{E_1}{1 - \nu_{12}\nu_{21}} & \frac{\nu_{21}E_1}{1 - \nu_{12}\nu_{21}} & 0 \\ \frac{\nu_{21}E_1}{1 - \nu_{12}\nu_{21}} & \frac{E_2}{1 - \nu_{12}\nu_{21}} & 0 \\ 0 & 0 & G_{12}(1 - kR^*) \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix},$$

$$\{\sigma_{12}\} = [G_{12}^0 - G^0 R^*] \{\varepsilon_{12}\},$$

where $[G_{12}^0]$ is the stiffness matrix, $[G^0]$ is the matrix taking into account creep effect,

$$[G^0] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

The stiffness matrix of the package can be calculated as:

$$[G_{xy}] = [T][G_{12}][T]^T = [G_{xy}^0] - [\tilde{G}]R^*,$$

where $[G_{xy}^0] = [T][G_{12}^0][T]^T$ is the stiffness matrix of the package without taking into account the time-dependent properties, $[\tilde{G}] = [T][G^0][T]^T$ is the correctional matrix, $[T]$ is the rotation matrix,

$$[T] = \begin{bmatrix} c^2 & s^2 & -2sc \\ s^2 & c^2 & 2sc \\ sc & -sc & c^2 - s^2 \end{bmatrix},$$

where $s = \sin(\theta)$, $c = \cos(\theta)$, $\theta = 45^\circ$ in this case.

To obtain the compliance matrix it is necessary to invert the stiffness matrix:

$$\begin{aligned} [S_{xy}] &= [G_{xy}]^{-1} = [G_{xy}^0 - \tilde{G}R^*]^{-1} = \\ &= \left[[G_{xy}^0] \left([I] - [S_{xy}^0][\tilde{G}]R^* \right) \right]^{-1} = \left[[I] - [S_{xy}^0][\tilde{G}]R^* \right]^{-1} [S_{xy}^0], \end{aligned}$$

where $[S_{xy}^0] = [G_{xy}^0]^{-1}$ is the compliance matrix of the package without taking into account time-dependent properties. Let $[A] = [S_{xy}^0][\tilde{G}]$. After diagonalisation we finally have $[A] = [Q] \text{diag}(\lambda_i) [Q]^{-1}$, where $\text{diag}(\lambda_i)$ is a diagonal matrix of A eigenvalues, and columns of $[Q]$ are the corresponding right eigenvectors.

Thus, after transformation, the following expression was finally obtained:

$$[S_{xy}^*] = [Q] \text{diag}(1 - \lambda_i R^*(\mu - \lambda_i)) [Q]^{-1} [S_{xy}^0].$$

Constitutive equations for the package are written in the following form

$$\{\varepsilon(t)\} = [S_{xy}^*]\{\sigma_{xy}(t)\},$$

where $[S_{xy}^*]$ is a compliance matrix, $\sigma_{xy}(t)$ is a function describing the loading history.

A satisfactory approximation of the experimental data may be obtained using the sum of exponential functions as a kernel [15]. We have determined the parameters of the kernel by minimizing the discrepancy between the calculated and experimental values of the strain:

$$R(t) = 5.0 - 4.7 \left[1 - \exp \left(-\frac{t}{10} \right) \right].$$

Calculated and experimental creep curves of CFRP with the layup of 45° are shown in Fig. 9.

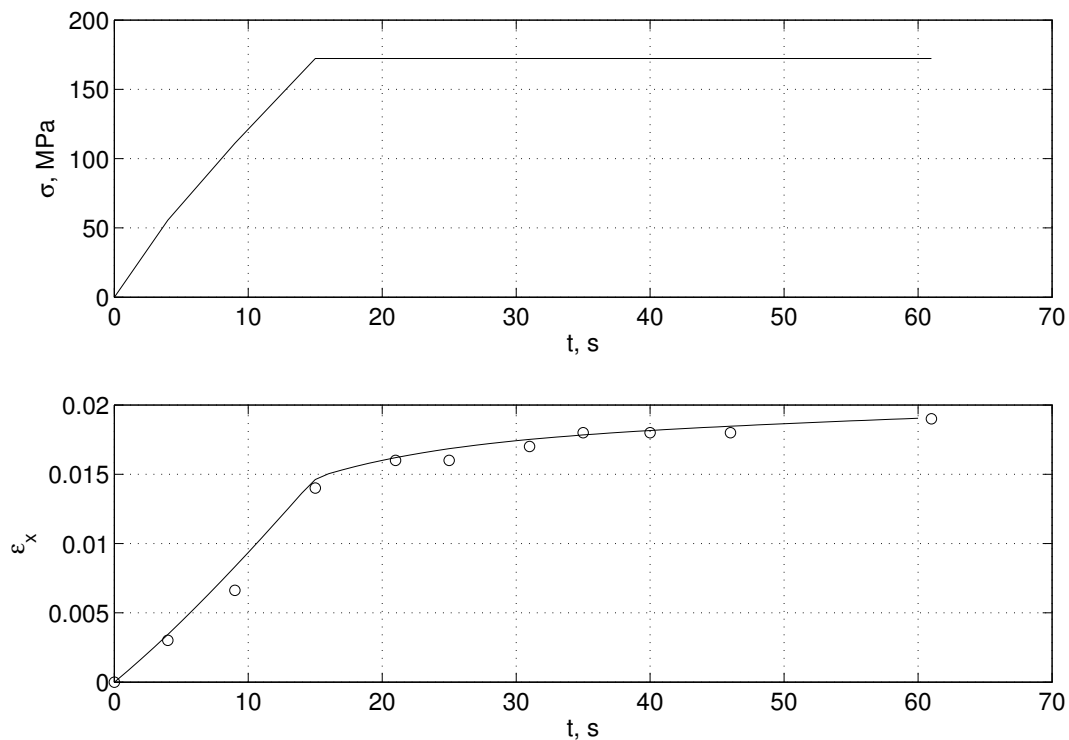


Figure 9. The calculated creep curve of CFRP and the experimental points of the 45° sample.

4. Conclusions

The analysis of mechanical properties anisotropy of woven CFRP with nano-modified high-temperature polymer matrix has been done.

Quasi-static tests have been conducted on specimens cut at different angles from the plate. The elastic and strength characteristics of the material in the longitudinal and transverse directions have been determined.

Creep tests have been conducted to identify the rheology effects. A hereditary model has been obtained, and the parameters of the model have been determined.

A satisfactory agreement between the calculated and experimental data has been shown.

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