Effect of strain rate on strength of unidirectional CFRP

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Abstract. An analysis of the anisotropy of failure stress envelopes for unidirectional carbon fiber reinforced plastic at different strain rates, including dynamic loading, is carried out. Based on the study of transverse compressive and shear strengths, a peak of the failure stress envelopes is observed, which is described by using the parabolic function approximation. It is shown that with an increase in the strain rate, not only an increase in strength but also a shift of the peaks to the area of higher transverse compressive stresses are observed.

1. Introduction

In recent times, more and more publications related to the study of sensitivity of polymeric CFRPs to strain rate and other time-varying loads have appeared [1-5]. To a large extent, this is associated with the study of mechanisms of resistance to cracking, ability to absorb energy which does not cause degradation of material properties and, as a result, to the problem of ensuring the reliability and service life of critical structural components made of polymer composites. In particular, researches continue despite the fact that some airframe components made of polymeric composites have been launched into mass production.

A review of the regularities of deformation and fracture of polymer composite materials [6] notes that, in the overwhelming majority of cases, there is an increase in Young’s modulus and strength with an increase in strain rate. Only in two cases relating to glass/epoxy and glass/polyester composites, the strength decreases with increasing strain rate. Most studies were carried out in a wide range of strain rates, including dynamic loading, which were realized using a split-Hopkinson pressure bar (SHIPB). It should be noted that when studying elastic and rheological properties, a weak sensitivity of Poisson's ratio to strain rate is observed, which is explained by fiber properties.

A detailed study of the regularities of mechanical behavior of IM7/8552 unidirectional carbon fiber reinforced plastic was carried out [7, 8]. It is noted [7] that due to the effect of transverse compressive stress, modification of the known failure criteria of unidirectional composites, such as Tsai-Wu, Tsai-Hill, Hashin-Rotem, etc., is required. The sensitivity of mechanical properties to strain rate requires taking into account the influence of the viscoelastic properties of the matrix under transverse stresses and in-plane shear. It is also noted that an increase in resistance to cracking with an increase in strain rate is observed under dynamic loading. Using high speed camera images made it possible to analyze
and measure the fracture angles. The phenomenon of fiber rotation due to deformation of specimens was observed under off-axis loading [7]. An analysis of the strain-rate curves of off-axis specimens shows the sensitivity to strain rate as well as the appearance of nonlinearity in such curves. Along with this, any change in Young’s modulus in the direction of reinforcement due to strain rate can be neglected. Attempts [7, 9] were made to use the well-known Puck criterion [10] which generalizes the well-known Mohr-Coulomb law, allowing the effect of normal stresses on shear stresses in the fracture plane to be taken into account. A consequence of this approach is the ability to describe a shear strength peak in the presence of normal stresses. In this case, the well-known Hashin-Rotem criterion with Sun’s correction takes the following form

\[ \frac{\sigma_2}{\sigma_z^*} + \frac{\tau_{12}^*}{(\tau_{12}^* - \eta \sigma_z^*)} = 1, \]

where \( \eta \) is an experimentally determined parameter that allows the effect of friction forces caused by normal stresses to be taken into account, \( \sigma_z^* \) is the transverse compressive strength, and \( \tau_{12}^* \) is the in-plane shear strength.

The lamina plastic flow criterion [11] representing a simplified one-parameter version of the anisotropic theory of plasticity of a lamina caused by a certain combination of stresses reaching some yield point is widely used. Adding two more additional parameters to such theory made it possible to expand the field of application of the theory to the case of taking into account the effect of strain rate as well as describing the viscoplastic deformation of unidirectional CFRPs [12-14]. A study of the effect of fiber orientation on the mechanical properties of unidirectional IM7/8551-7 CFRP specimens under loading at various strain rates [15] shows that the dependence of the ultimate strain on the direction of fiber orientation is non-monotonic. In the range from 45° to 75°, peaks of the ultimate strain values were observed, and the relationship between the strength values under quasi-static and dynamic loading was determined using a correction factor being an off-axis angle polynomial and including the natural logarithm of strain rate as a multiplier. A similar method was used in [16]. The effect of fiber rotation in IM7/8552 angle-ply laminates under tensile and compressive loading in the area of large strains was studied in [17]. Model constructions of constitutive relations using the linear viscoelasticity relations based on the Maxwell bodies connected in parallel with an elastic spring was performed in [18] where the stiffness matrix components are considered as functions of time in a hereditary form. A criterion taking into account the predominance of one or another fracture mechanism and making it possible to describe the intra-laminar strength peak in the area of transverse compression was proposed in [19].

The results of studying the calculated and experimental characteristics of deformation and failure of unidirectional and layered composite materials under quasi-static loading are summarized in [20] where the predictions using different models and mechanical properties of unidirectional specimens [21] were compared with test results. A criterion for the adequacy of the models was the proximity of predicted and experimental data. A data analysis is given in [22] where a significant scatter of the predicted data is noted and the number of input parameters introduced into the proposed theories is discussed. Taking into account the influence of variable loads is, to some extent, a continuation of the above-mentioned works providing for the variation of parameters that allow the effect of time and physical nonlinearity of properties to be described. In particular, during the rate deformation of specimens made of unidirectional material, the dependence of the stress-strain curves on rate and the physical nonlinearity are observed. An analysis of the regularities under quasi-static loading and the effect of the strain rate on the rheological properties are considered in [23, 24].

2. Strain rate dependence of failure envelopes

Let us consider the application of the well-known Tsai-Wu failure criterion in relation to the fracture of unidirectional material loaded at an off-axis angle (see figure 1)
where $\sigma^\pm_2$ are the transverse tensile and compressive strengths, $\tau_{12}^*$ is the in-plane shear strength. The Tsai-Wu criterion describes a failure envelope in the form of an ellipse but does not allow of describing the experimentally observed strength peak associated with an increase in shear strength in the presence of transverse compressive stresses. Similarly, other criteria, with the exception of the Sun criterion, do not allow of taking this factor into account. The Northwestern University (NU) criterion [1, 2] allows the strength peak to be described by associating it with a change in the nature of failure, namely, with an increase in compressive stresses, when the shear nature of failure is replaced by the prevalence of compressive stresses.

\[
\left( \frac{1}{\sigma^+} - \frac{1}{\sigma^-} \right) \sigma_2^2 + \frac{\sigma_2^2}{\sigma_1^2 \sigma_2^2} + \frac{\tau_{12}^*}{\tau_{12}^*} = 1,
\]

Figure 1. Schematic illustration of off-axis loading: directions 1 and 2 are the major orthotropy axes, $\theta$ is off-axis angle.

Let us introduce a parabolic dependence of the shear strength on transverse stresses

\[
\tau_{12}(\sigma_2) = a\sigma_2^2 + b\sigma_2 + c
\]

Let us propose an approach based on a quadratic least squares approximation of the failure stress envelopes for IM7-8552 unidirectional CFRP specimens tested at different off-axis angles and at three strain rates: quasi-static, intermediate, and dynamic [2]. The test results digitized from the figures in [2] were approximated by the following curves

\[
\begin{align*}
\tau_{12} &= -0.0039\sigma_2^2 - 0.9046\sigma_2 + 88.98 \\
\tau_{12} &= -0.0031\sigma_2^2 - 0.946\sigma_2 + 104.64 \\
\tau_{12} &= -0.0029\sigma_2^2 - 0.961\sigma_2 + 121.68
\end{align*}
\]

The first equation describes the failure envelope corresponding to quasi-static loading at the strain rate equal to $10^{-4}$ s$^{-1}$. The second equation corresponds to the intermediate strain rate equal to 1 s$^{-1}$, and the third to dynamic loading at the strain rate $\dot{\varepsilon} = 800$ s$^{-1}$. R-squared values ($R^2$) for the respective strain rates were 0.9144, 0.8529 and 0.8806 accordingly.

An analysis of the experimental data shows that the failure envelopes do not intersect each other and the curves corresponding to higher strain rates lie higher (see figure 2). In addition, it can be seen that the parabola peaks shift to the left with increasing strain rate.

The resulting curves allow the peaks of the failure envelopes under shear and transverse compressive stress conditions to be described. It is obvious that, when $\sigma_2 = 0$, the curves make it possible to estimate the values of in-plane shear strength, i.e. in the absence of transverse stresses. For the corresponding strain rate, the shear strength is equal to the free term in the respective parabola equation. For example, the in-plane shear strength equal to 90 MPa is given in [21], while the free
term in the respective failure envelope equation is 88.98 MPa. The maximum shear strength values under compressive stress conditions are \( \tau_{\text{max}} = -\frac{b^2}{4a} + c \) with \( \sigma_z = -\frac{b}{2a} \) as a parabola axis of symmetry. It should be noted that there are some regularities in changing the parabola parameters depending on the strain rate. With an increase in the strain rate, these changes, on the one hand, characterize the shift of the parabola peak to the left and, on the other hand, raise the parabola up.

![Figure 2. Strain-rate dependent failure envelopes for IM7-8552 unidirectional composite: ▲ - 800 s\(^{-1}\), ■ - 1 s\(^{-1}\), ♦ - 10\(^{-4}\) s\(^{-1}\).](image)

3. Conclusions

To describe the strength of unidirectional CFRP, a simple parabolic dependence is proposed, which make it possible to describe the failure envelopes at different strain rates as well as the experimentally observed peak in the shear strength. The free terms in the parabola equation allow us to estimate the in-plane shear strength.

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