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THEORETICAL STRENGTH PROPERTIES OF UNIDIRECTIONAL REINFORCED FIBER REINFORCED POLYMER COMPOSITES

BY

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Abstract. Available unidirectional fiber reinforced polymer (FRP) composite products have a large spectrum of properties, based on the intrinsic characteristics of the constituents and on their proportions. Mechanical properties of FRP composites can be determined experimentally but this manner may become cost prohibitive because of the large number of necessary specimens. Moreover, strength properties should be predicted during the design phase of a FRP product, in order to fulfill the requierments of its end use and to reduce the production costs. One way to calculate these properties is by using micromechanics theory. This paper presents the available micromechanical approaches utilized to determine the strength properties of unidirectional FRP composites in terms of tensile, compressive and shear loads for both longitudinal and transverse direction. The failure mechanisms for each type of loading is presented together with the triggered formulas.

Key words: micromechanics; tensile strength; compressive strength; shear strength; failure mechanism.

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1. Introduction

The mechanical properties of FRP composites depend on many factors, including the inherent characteristics of the constituents, the arrangement and the percentage of reinforcing materials, the fabrication techniques, and the in-life operating temperatures or environmental conditions.

For a precise determination of these properties, experimental tests can be carried out. The disadvantage is that one set of measurements identifies properties of a fibre-matrix system produced by a single fabrication process, any modification of the system variables implying additional measurements (FIB 40, 2007). Moreover, FRP composites have high production costs, thus testing a large number of specimens may lead to relatively high expenses.

Taking into account the abovementioned considerations, an analytical prediction of the mechanical properties of FRP composites proves to be necessary, not only as a tool that provides guidance values for experimental measurements but also during the design phase of a composite system.

One way to predict the mechanical properties of an unidirectional lamina can be performed using the micromechanical approach. Micromechanics level deals with the analysis of the effective composite properties in terms of constituent material properties, based on a certain set of simplifying assumptions.

2. Micromechanics of the Unidirectional Lamina

A lamina or a ply is the simplest element of a composite material and consists of a flat or curved arrangement of unidirectional fibers embedded in a support matrix. Unlike traditional materials, such as steel and alumina, which are homogeneous and isotropic continuous, having constant properties with respect to position and orientation, FRP composites are microscopically inhomogeneous and non-isotropic (orthotropic), their properties changing from point to point and from one direction to another (Mallick, 2007).

For the unidirectional lamina (Fig. 1) the direction parallel to the fibers is called the longitudinal direction (axis 1 or L) and the direction perpendicular to the fibers in the 1–2 plan is called the transverse direction. Any direction in the 2–3 plane is also transverse direction. Axes 1, 2, 3 are also considered as the material axes of the lamina (Hohan, 2012).

The unidirectional lamina is considered to be orthotropic with three axes of symmetry, the strongest properties being in the longitudinal direction. Because of the random distribution of the fibers in the cross-section, the transverse properties (axes 2 and 3) are approximately identical. Thus a unidirectional composite can be considered to be transversely isotropic (FIB 40, 2007).

Available micromecanics formulas used to predict strength or stiffness properties of FRP composites derive from the mechanics of materials theory. A certain set of simplifying assumptions are made in order to make this approach possible.

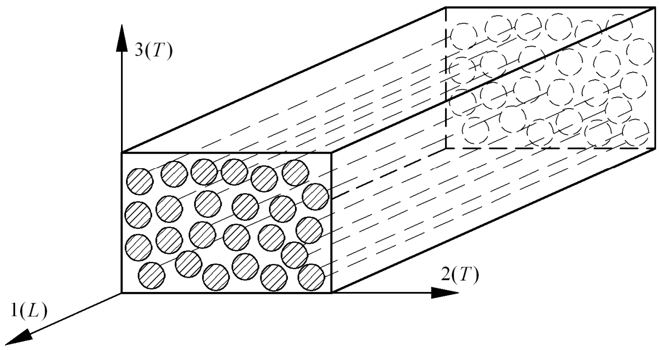

Fig. 1 – Unidirectional fibre reinforced lamina with its principal material axes.

The basic assumptions are as follows (Mallick, 2007):

1. Fibers are uniformly distributed throughout the matrix.
2. The matrix is voids free.
3. The fibers and the matrix are perfectly bonded.
4. The applied force is either parallel to or normal to the fiber direction.
5. The lamina is initially in a stress-free state, thus no residual stresses are present in either fabers or matrix.
6. Both fibers and matrix behave as linearly elastic materials.

3. Strength Properties of FRP Composites

Strength properties of the FRP composites can be predicted, applying the micromechanics principles of the unidirectional lamina, by theorethical or semi-empirical methods. The mathematical modeling of the interconnection between the strength of a composite material and the characteristics of its constituents is substantially less developed than the analysis of the elastic properties (MIL-HDBK-17-3F).

Available micromechanics formulas used to predict strength properties have a slight degree of unreliability, mainly due to the simplifying assumptions that are protruded. Another determinant factor consists of the bulk properties of the constituents which are sometimes different from the apparent ones. Therefore, one option is to perform tests at one value of fiber volume fraction and than to use the obtained strength values for back-calculating the parameters in the micromechanical formulas (Barbero, 2011).

Other factor that may influence the accuracy of the formulas is the failure mechanism. Failure is much more likely to occur in a local region due to the effect of the local values of constituent properties and the geometry in that region. This dependance upon local characteristics of high variability makes the analysis of the composite failure mechanisms much more complex than the analyses of the elastic properties.

3.1. Longitudinal Tensile Strength

In most practical composites, fibers have brittle behavior, being characterized by elastic deformations up to failure. In case of composites with polymer or metal matrices, the unreinforced matrix exhibits plastic deformation and have ultimate strains much greater than those of the fibers. By contrast, ceramic matrices are also brittle, and although much weaker than the fibers, their rigidity is simmilar to that of the latter, having smaller ultimate strains (Harris, 1999).

In case of a unidirectional composite lamina subjected to longitudinal tension, under the assumption of uniform tensile strengths of the fibers and linear behavior of both constituents, two cases arise (Daniel & Ishai, 1994), depending on the relative magnitudes of the ultimate strains of fibers and matrix.

When the ultimate tensile strain of the fiber is lower than that of the matrix, the failure of the composite will occur when its longitudinal strain reaches the ultimate strain of the fiber. At this stage, the stress in the composite defines the longitudinal tensile strength, described by eq.

$$f_{Lt} = f_{ft} V_f + \sigma_m (1 - V_f), \tag{1}$$

where: f_{ft} is the longitudinal tensile strength of the fiber, σ_m – the average matrix stress at the fiber fracture strain and V_f – the fiber volume fraction.

If the fiber volume fraction has small values ($V_f < V_{\min}$), the stress of the composite can lead to the failure of the fibers. The system is not assumed to fail because the matrix is still able to support the load until its ultimate tensile strength is reached (Harris, 1999). This phenomena is described by eq.

$$f_{Lt} = f_{mt} (1 - V_f), \tag{2}$$

where f_{mt} is the longitudinal tensile strength of the matrix.

From eqs. (1) and (2), the minimum value of the fiber volume fraction is obtained

$$V_{\min} = \frac{f_{mt} - \sigma_m}{f_{ft} + f_{mt} - \sigma_m}. \tag{3}$$

The variation of the longitudinal strength with respect to the fiber volume fraction is presented in Fig. 2 (adapted from the study performed by Barbero, (2011). The solid lines mark the regions of applicability of eqs. (1) and (2), and their intersection defines the minimum fiber volume fraction.

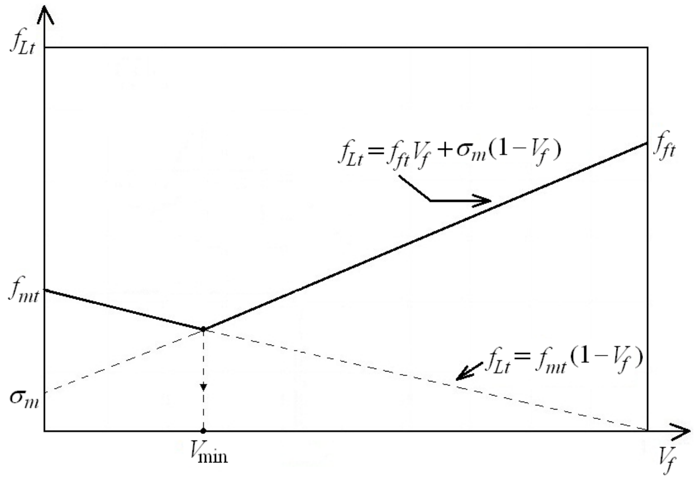

Fig. 2 – Regions of applicability of the two strength formulas.

When the ultimate tensile strain of the matrix is lower than that of the fiber, the composite fails when its longitudinal strain reaches the ultimate strain of the matrix. The longitudinal tensile strength of the composite is calculated with relation

$$f_{Lt} = \sigma_f V_f + f_{mt}(1 - V_f), \tag{4}$$

where σ_f is the average fiber stress at the matrix fracture strain.

3.2. Longitudinal Compressive Strength

In case of longitudinal compressive stresses, the most important function is carried out by the matrix, which has to provide lateral support and stability for fibers.

The behavior of the unidirectional FRP lamina subjected to longitudinal compressive stresses is often different than that of longitudinal tensions stresses, due to the various modes of failures. Depending on the fiber volume fraction and on the behavior of the matrix, either elastic or plastic, four distinct modes of failures have been identified (Rosen, 1965; Daniel & Ishai, 2006; Nielsen, 1974).

In case of elastic behavior of the matrix, two possible microbuckling modes of fibers are supposed to occur (Rosen, 1965): the extensional microbuckling, for low fiber volume fractions (V_f < 0.2), creating extensional strain in the matrix because of the out-of-pahase buckling of fibers (Fig. 3 *a*) and the shear microbuckling, for higher volume fractions, creating shear strain in the matrix because of the in-phase buckling of fibers (Fig. 3 *b*).

The longitudinal compressive strength, in case of extensional mode of microbuckling, is calculated with eq. (5) using the energy method (Timoshenko & Gere, 1961)

$$f_{Lc} = 2V_f \sqrt{\frac{V_f E_m E_f}{3(1-V_f)}}, \tag{5}$$

where E_m and E_f are the Young's Moduli for matrix and fibers.

For the shear mode of microbuckling, the longitudinal compressive strength is calculated with relation (Rosen, 1965)

$$f_{Lc} = \frac{G_m}{(1-V_f)}, \tag{6}$$

where G_m is the matrix shear modulus.

Most of the fiber-reinforced composites available on market contain fiber volume fraction >30%, making the shear mode of microbuckling more important than the extentional one. Eq. (6) shows that the longitudinal compressive strength is controlled by the shear modulus of the matrix and by the fiber volume fraction.

Compressive strength predictions from eqs. (5) and (6) are higher than the experimentally measured values. The differences between theoretical and experimental results is attributed to preexisting fiber misalignment, which reduces the strength appreciably (Daniel & Ishai, 1994). Flexural stresses in a misaligned fiber due to shear microbuckling lead to the formation of kink zones which can conduct to large deformation in ductile fibers, or fracture planes in brittle fibres. Assuming an elastic-perfectly plastic shear stress-shear strain relationship for the matrix, Budiansky & Fleck, (1993), have determined the stress in which the kink is initiated as

$$f_{Lck} = \frac{\tau_{my}}{\varphi + \gamma_{my}}, \tag{7}$$

where: τ_{my} is the shear yield strength of the matrix, γ_{my} – the shear yield strain of the matrix and φ – the initial angle of fiber misalignment.

Shear failure mode, without microbuckling of fibers, occurs at high values of the fiber volume fraction (Fig. 3 *c*). Daniel & Ishai, (2006), came up with the following eq. for determining the compressive strength of the unidirectional lamina, under shear failure mode:

$$f_{Lc} = 2 f_{fs} \left[V_f + (1 - V_f) \frac{E_m}{E_f} \right], \tag{7}$$

where: f_{fs} is the shear strength of the fiber.

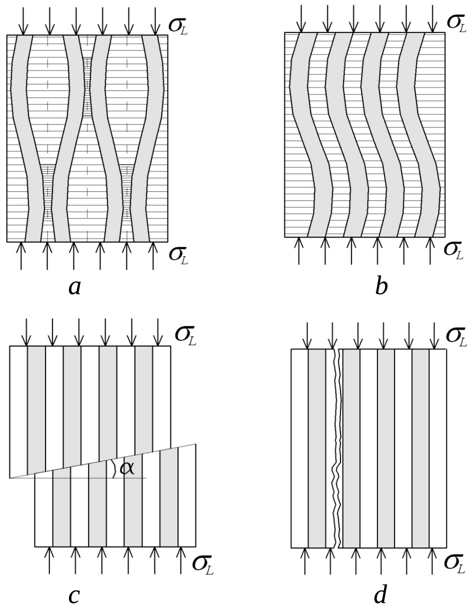

Fig. 3 – Failure modes of unidirectional lamina subjected to longitudinal compression: *a* – extensional microbuckling, *b* – shear microbuckling, *c* – shear without microbuckling, *d* – longitudinal matrix failure due to Poisson's effect.

Beside microbuckling and shear, another important failure mode is the longitudinal splitting in the matrix due to Poisson's effect. When a unidirectional FRP lamina is subjected to longitudinal compression, strains appear in the transverse direction, leading to failure once their maximum values are reached.

The ultimate transverse strain of the composite can be calculated using eq., (Nielsen, 1974)

$$\varepsilon_{Tu} = \varepsilon_{mu} (1 - V_f^{1/3}), \tag{8}$$

where ε_{mu} is the ultimate transverse strain of the matrix.

Based on eq. (8) the longitudinal compression strength of the unidirectional FRP lamina, under the longitudinal splitting failure mode, can be predicted using eq., (Agarwal & Broutman, 1990)

$$f_{Lc} = \frac{[E_f V_f + E_m(1-V_f)](1-V_f^{1/3})\varepsilon_{mu}}{\nu_f V_f + \nu_m(1-V_f)}, \tag{9}$$

where, ν_f and ν_m are the Poisson's coefficients of the fiber and matrix, respectively.

3.3. Transverse Tensile Strength

The transverse tensile loading is the most critical loading of a unidirectional composite, turning fibers into hard inclusions that decrease the deformations of the matrix instead of acting as principal load-carrying elements (Gibson, 1994; Mallick, 2008). Some of the factors that influence the tensile strength are: the matrix strength and modulus of elasticity, the fiber volume fractions, the fiber-matrix interface properties and defects in the matrix such as microcraks and voids.

The first empirical approach for the prediction of tensile transverse strength (Nielsen, 1974) leads to eq.

$$F_{Tt} = \frac{E_T F_{mt}}{E_m}(1-V_f^{1/3}), \tag{10}$$

where: F_{mt} is the transverse tensile strength of the matrix.

Under the hypothesis of perfect adhesion between fibers and matrix, eq. (10) leads to the failure of matrix near or at the interface of the phases. Also, eq. (10) does not take into accout the existence of voids into the composite. In order to account for voids, the transverse tensile strength calculated with eq. (10) can be affected with a reduction coefficient, determined with eq., (Barbero, 2011)

$$C_V = 1 - \sqrt{\frac{4V_V}{\pi(1-V_f)}}, \tag{11}$$

where: V_V is the void volume fraction.

Another empirical prediction of the transverse tensile strength is given by eq., (Barbero, 2011)

$$F_{Tt} = F_{mt} C_v \left[1 + \left(V_f - \sqrt{V_f}\right)\left(1 - \frac{E_m}{E_f}\right)\right], \tag{12}$$

where: E_m and E_f are the transverse modulus of the matrix and fiber, respectively.

A more theoretical and elaborated approach of the transverse tensile strength was achieved by analysing the stress and strain concentration in the matrix and interface/interphase. When a transverse tensile stress is applied to the unidirectional FRP lamina, local tensile stresses concentrate near the fibers, having greater magnitudes than the external ones. In case of square array of fibers, the peak stress in the matrix is the normal stress at the interface, along the loading direction. The ratio between the peak stress and the applied mean stress is defined as the stress concentration factor, k_σ, and can be calculated with eq. (Daniel & Ishai, 2006)

$$k_\sigma = \frac{1 - V_f\left(1 - \frac{E_m}{E_f}\right)}{1 - \left(\frac{4V_f}{\pi}\right)^{1/2}\left(1 - \frac{E_m}{E_f}\right)} . \tag{13}$$

Also, the strain concentration factor, k_ε, can be calculated with eq. (Daniel, 1974)

$$k_\varepsilon = k_\sigma \frac{E_T}{E_m} \cdot \frac{(1+\nu_m)(1-2\nu_m)}{1-\nu_m} , \tag{14}$$

where: E_T is the transverse modulus of the composite and ν_m – the matrix Poisson’s ratio.

For the maximum tensile stress criterion, the transverse tensile strength of the unidirectional FRP lamina can be calculated using eq. (15) (Daniel & Ishai, 2006), assuming linear behavior to failure for the matrix and stiff, perfectly bonded fibers

$$F_{Tt} = \frac{1}{k_\sigma}(F_{mt} - \sigma_{rm}) , \tag{15}$$

where: F_{mt} is the transverse tensile strength of the matrix and σ_{rm} – the radial maximum residual stress (if present).

Under the same assumptions listed above, the transverse tensile strength for the maximum tensile strain criterion can be calculated using eq. (Daniel & Ishai, 2006)

$$F_{Tt} = \frac{1-\nu_m}{k_\sigma(1+\nu_m)(1-2\nu_m)}(F_{mt} - \varepsilon_{rm}E_m) , \tag{16}$$

where ε_{rm} is the radial maximum residual strain (if present).

3.4. Transverse Compressive Strength

Composite laminae subjected to transverse compressive loads usually fail under matrix shear combined with the crushing of the fibers. It is difficult to give an accurate micromechanical prediction of the transverse compressive strength because, unlike the case of composites loaded longitudinally where the fiber and matrix behavior follows very closely the isostrain or isostress approximation until the initiation of failure, composites loaded transversely do not follow the isostrain or isostress approach (Gonzales & Lorca, 2007).

An empirical formula for estimating the transverse compressive strength is given by Weeton *et al*., (1986), namely and Stellbrink, (1996),

$$F_{Tc} = F_{mc} C_v \left[1 + \left(V_f - \sqrt{V_f} \right) \left(1 - \frac{E_m}{E_f} \right) \right], \tag{17}$$

where F_{mc} is the compression strength of the matrix.

Kaw, (2006), and Gibson, (2012), framed a theoretical approach for the transverse compressive strength but under certain assumptions: perfect bond between constituents, uniformly distributed fibers, full elastic behavior of the matrix and fibers and no initial residual stresses. Thus, the transverse compressive strength can be predicted using relation

$$F_{Tc} = E_T \varepsilon_{Tu}^{c}, \tag{18}$$

where: E_T is the transverse modulus of the composite and ε_{Tu}^{c} – the ultimate transverse strain of the composite, determined with eq.

$$\varepsilon_{Tu}^{c} = \left[\frac{d}{s} \cdot \frac{E_m}{E_T} + \left(1 - \frac{d}{s} \right) \right] \varepsilon_{mu}^{c}, \tag{19}$$

where: d is the fiber diameter, s – the distance between fibers (calculated with respect to V_f) and ε_{mu}^{c} – the compressive ultimate strain of the matrix.

3.5. In-Plane Shear Strength

Under in-plane shear stresses, the failure of the unidirectional FRP lamina can occur by matrix failure, due to extensive propagation of cracks, by fibers debonding, due to shear stress concentrations, or by a combination of the two.

An empirical formula to calculate the shear strength was given by Stellbrink, (1996), and it is similar to relation

$$F_{LTs} = F_{ms} C_v \left[1 + \left(V_f - \sqrt{V_f} \right) \left(1 - \frac{G_m}{G_f} \right) \right], \tag{20}$$

where: G_m and G_f are the shear modulus of the matrix and fiber, respectively, and F_{ms} – the shear strength of the matrix.

Another approach for the prediction of the shear strength consists in estimating the ultimate angular deformation of the composite using eq., (Fib, 2007)

$$(\gamma_{LT})_c = \left[\frac{d}{s} \cdot \frac{G_m}{G_f} + \left(1 - \frac{d}{s} \right) \right] (\gamma_{LT})_m, \tag{21}$$

where $(\gamma_{LT})_m$ is the ultimate angular deformation of the matrix.

Further, based on eq. (21) the shear strength is calculated with

$$F_{LTs} = (\gamma_{LT})_c G_{LT}, \tag{22}$$

where G_{LT} is the in-plane shear modulus.

4. Case Study

The following case study consists in determining the strength properties of a unidirectional FRP composite made up of *E*-glass fibers and epoxy matrix. The characteristics of the constituents are listed in Table 1.

Table 1
Elastic and Strength Properties of the Constituents

Property	*E*-glass fibers	Epoxy matrix
Volume fraction (V_f,V_m)	0.4	0.6
Young's modulus (E_f, E_m)	72,000 MPa	4,000 MPa
Tensile strength (f_t)	1,950 MPa	100 MPa
Ultimate tensile strain (ε_{fu}, ε_{mu})	2.7%	4.4%
Compressive strength (f_{fc}, f_{mc})	–	110 MPa
Shear strength (f_{ff}, f_{mf})	34 MPa	35 MPa
Poisson's coefficients (ν_f, ν_m)	0.22	0.38

The strength properties of the unidirectional composite are calculated using the eqs. presented in section 3 of this paper and the results are presented in Table 2.

Table 2
Strength Properties of the E-glass – Epoxy Unidirectional FRP Composite

1. Longitudinal Tensile Strength	
Since $\varepsilon_{fu} < \varepsilon_{mu}$, the longitudinal tensile strength is calculated with eq. (1). $f_{Lt} = 845$ MPa	
2. Longitudinal Compressive Strength	
Extensional microbuckling – eq. (5) $f_{Lc,1} = 6{,}400$ MPa	Shear microbuckling – eq. (6) $f_{Lc,2} = 2{,}415$ MPa
Shear without microbuckling – eq. (7) $f_{Lc,3} = 30.33$ MPa	Poisson's effect – eq. (9) $f_{Lc,4} = 649$ MPa
3. Transverse Tensile Strength	
Empirical approach by eq. (10) $f_{Tt,1} = 42.49$ MPa	Assuming $C_V = 0$, using eq. (12) $f_{Tt,2} = 78.04$ MPa
Maximum tensile stress criterion, assuming no residual stresses – eq. (15) $f_{Tt,3} = 52.63$ MPa	Maximum tensile strain criterion, assuming no residual strains – eq. (16) $f_{Tt,4} = 98.02$ MPa
4. Transverse Compressive Strength	
Empirical approach by eq. (17) $f_{Tc,1} = 85.85$ MPa	Applying Hook's Law – eq. (18) $f_{Tc,2} = 129.16$ MPa
5. In-Plane Shear Strength	
Empirical approach by eq. (20) $f_{LTs,1} = 27.73$ MPa	Applying Hook's Law – eq. (22) $f_{LT,2} = 19.69$ MPa

Strength properties of the undirectional FRP lamina are also represented graphically in Fig. 4.

5. Conclusions

This paper presents the available micromechanical determining of the short term strength properties of FRP composites, from both theoretical and empirical point of view. Most of the abovementioned formulas have a slight degree of unreliability, due to the simplifying assumptions that are imposed and also because of the apparent properties of the constituents which are different from the bulk ones. This fact can also be observed for the worked example in section 4 of this paper. The longitudinal compressive strengths (Fig. 4 *a*) have the most scatter values, ranging from 33.33 MPa to 6,400 MPa because of the different failure criteria that can occur. By contrast, the in-plane shear strengths

(Fig. 4 *c*), obtained either by empirical or by theoretical formulas, have the closest values (19.69 MPa and 27.73 MPa).

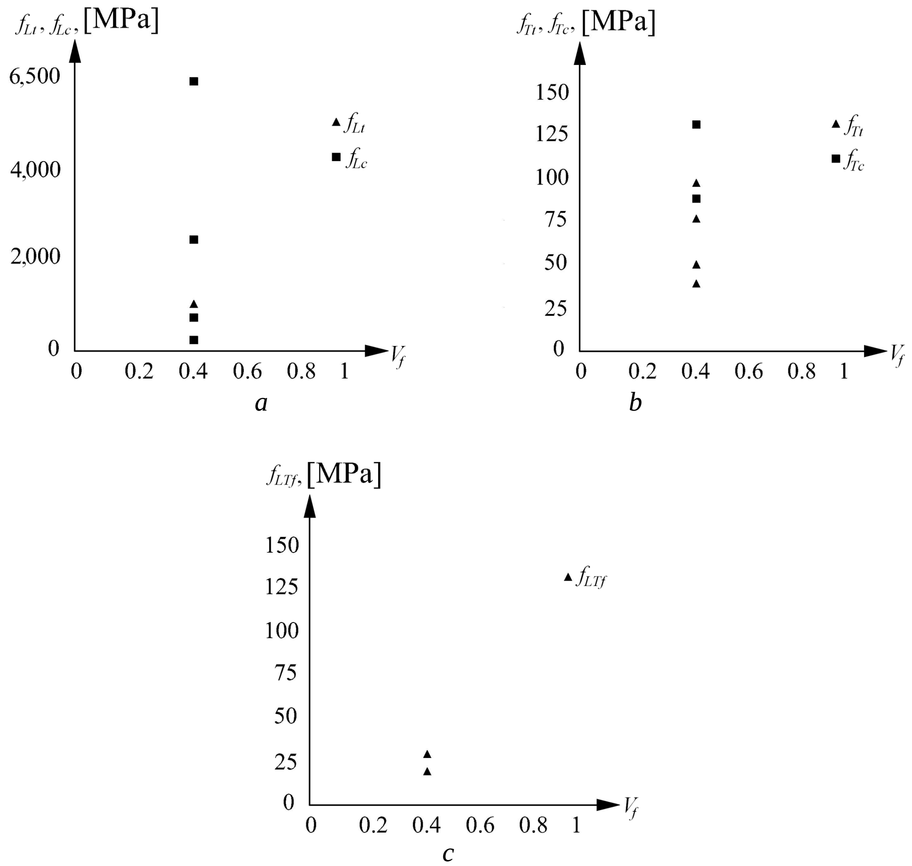

Fig. 4 – Strength properties: *a* – longitudinal strengths;
b – transversal strengths; *c* – shear strength.

It seems appropriate that inherent properties of the consituents, also called apparent properties, should be back-calculated using micromechanics formulas based on experimental determinations at one value of fiber volume fraction. Once these values are determined, they can be used for determining strength characteristics at other fiber volume fractions as long as the constituents and the fabrication procedure are the same.

The manner in which a composite failes also controls the availability of micromechanics formula, and for this reason, failure mechanics theory should be extended and applied in order to predict, based on the properties of constituents, the failure mechanism.

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REZISTENȚE MECANICE TEORETICE ALE COMPOZITELOR POLIMERICE ARMATE CU FIBRE UNIDIRECȚIONALE

(Rezumat)

Materialele compozite unidirecționale sunt caracterizate de o gamă variată de proprietăți, ce au la bază caracteristicile intrinseci ale elementelor constituente şi proporțiile în care acestea intră în sistemul compozit. Proprietățile mecanice ale materialelor compozite pot fi determinate experimental dar, de cele mai multe ori, această metodă implică costuri ridicate pentru fabricarea unui număr rezonabil de probe.

Determinarea proprietăților mecanice ale materialului compozit este necesară încă din faza de proiectare, astfel încât sistemul să poată satisface cerințele de performanță impuse de utilizarea sa finală, fără a presupune costuri suplimentare aferente testării experimentale a unui număr ridicat de probe. O modalitate de a calcula proprietățile mecanice ale materialelor compozite constă în aplicarea teoriei micromecanicii. Această lucrare prezintă modurile în care, folosind teoria micromecanicii, se pot calcula rezistențele la întindere, compresiune şi forfecare ale materialelor compozite unidirecționale, atât în direcție longitudinală cât şi transversală. De asemenea, pentru fiecare tip de solicitare se evidențiază principalele moduri de cedare, împreuna cu expresiile matematice care le caracterizează.