SOME COMPARATIVE OPINIONS REGARDING THE WORKING OF FIBERS AND MATRIX ON AXIAL STRESS LIMIT. MATRIX WITH LONGER FIBER EXTENSIONS

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Abstract. This paper falls within the current scientific and technical research concerns related to structures made of long fiber composite materials. An essential problem is the co-operation of the matrix material with that of the fibers in the composite layers under the action of external loads, until the structure is damaged. In the present case, the case is taken into account if the material of the matrix is characterized by elongations superior to those of the fibers, so that they will break before the damage of the matrix. The linear-elastic behavior of the fibers is considered until their rupture and, obviously, the destruction of the composite.

Keywords: structure, sandwich type composite, stress

1. INTRODUCTION

Due to the increasing degree of civilization and the desire to protect the external environment as much as possible, human society has been, is and will be, more and more preoccupied with obtaining new consumer goods with an increasing degree of complexity. This situation entails increasing investments for theoretical and experimental research, with high-performance equipment [1 – 15]. In the aerospace, electrical / electronic and energy fields, but also in other fields, more and more diversified materials are used in terms of quality and assortment [16 – 25].

It is recognized that composite materials fit well - deserved in the category of the most valuable, due to their physical-elastic-mechanical characteristics and technological properties, used in various technical fields [26]. Replacing metals with composite materials has the advantage of reducing weight / mass and often equal or superior functionality. At present, the industry is occupied by the "syndrome of minimization" of the masses of mechanical structures [20], with chain reactions on all stages of design, manufacture and use of products, in order to achieve lighter finished components, lower fuel and energy consumption, payload or greater autonomy (in transport, for example), longer service life, combined with lower production and operating costs, reduced pollution of the external environment.

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In general, composite structures are usually manufactured by arranging the reinforcing fibers in a predetermined way. The individual layers are arranged in such a way that the reinforcing fibers, existing in the matrix, are either parallel or cross-linked or in the form of a fabric, with equal arrangement for warp and weft (these ensuring the strength and rigidity of the structure [26, 27]. The physical-elastic and mechanical characteristics of the composite material can be estimated starting from the individual characteristics of each of the constituents (mixing rule [28]). The values of these characteristics, for a given structure, are determined by tests on specimens (with well-specified geometry) cut from the same structure, subjected to simple stresses [29].

Dif there is no connection between the fibers and the matrix at their interface, when a load is applied to the assembly, the components deform independently, in accordance with their modulus of elasticity. If there are chemical interactions between the fibers and the matrix, the assembly behaves in solidarity - similar deformation. The difference between the axial/longitudinal lengths of the two components of the composite is variable depending on the length of the fiber. The difference is zero in the middle of the fibers, reaching the maximum value at the ends of the assembly. Therefore, the longer the fibers, the greater the length difference between the two components and the more efficient the load transfer from the matrix to the fibers. The matrix tends to deform more, so that shear stresses appear between the two components, while tensile stresses are manifested in the fibers. The tangential stress in the matrix increases with increasing length of the complementary material (fibers). This process, in the case of a ductile material of the matrix, is carried out until the limit of elasticity of the material is reached, following the plastic deformation. In this phase the fiber length represents the critical length [30].

Deformation of the fiber-reinforced composite generally occurs in four stages, depending on the relative fragility or ductility of the fibers and matrix [26, 31]: a) the fibers and the matrix deform elastically; b) the fibers continue to deform elastically, but the matrix deforms plastically; c) the fibers and the matrix deform plastically; d) fiber rupture occurs, followed by the rupture of the composite.

The article presents some comparative opinions known in the literature on the behavior of a composite with long matrix and fibers under the action of external tensile loads, with limit values. Consider the same elastic deformation for both components, assuming a perfect contact between them. The expressions established for the limit tensions take into account the hypothesis of the linear-elastic behavior until the fibers break. If the length of the fibers exceeds the critical value, the material of the matrix deforms plastically at the ends of the fibers, keeping its deformation constant until the assembly is damaged.

Note: The name "*sandwich*" is given to the Englishman John Montague, Count of Sandwich (1718 – 1792), who being a big fan of card games, in order not to get up from the game table, he prefered to consume sandwiches composed of two slices of bread between which he put butter, ham, jam etc. (https://dexonline.ro/definition/sandwich).

2. MATRICES OF MATERIALS WITH MAXIMUM LENGTHS LONGER THAN FIBERS (POLYMERIC OR METAL MATRICES)

Note: In the following, at the lower index of the specified quantities, the paper indicates the stress along the reinforcing fibers (respectively the x-axis of a triorthogonal reference system), and the letter - c the composite.

Appreciating that the fibers, with the same resistance/mechanical tension, fragile compared to the matrix, do not support the same elongation at the tensile stress, they break first, compared to the matrix material [26, 27]. If *the same elastic deformation* is considered for both components of the composite (assuming an excellent contact between the matrix material and the fibers), the stress developed in the composite has the expression (1) [31, 32 - 38]:

$$\sigma_{1c} = \sigma_{1f} \cdot p_{vf} + \sigma_{1m} \cdot p_{vm} = \sigma_{1f} \cdot p_{vf} + \sigma_{1m} \cdot \left(1 - p_{vf}\right), \tag{1}$$

while the allowable tensile strength $(\sigma_c)_M$, *along the direction of the fibers*, can be approximated with the equation [26, 27, 31]:

$$\left(\sigma_{1c}\right)_M = p_{vf} \cdot \left(\sigma_{1f}\right)_M + \left(1 - p_{vf}\right) \cdot \left(\sigma_{1m}\right)_M , \tag{2}$$

where $(\sigma_{1f})_M$ represents the allowable tensile strength of the fibers; $(\sigma_{1m})_M$ maximum tensile strength of the matrix material at the time of fiber breakage [1, 39]:

$$\left(\sigma_{1m}\right)_M = E_m \cdot \left(\varepsilon_{1f}\right)_M , \tag{3}$$

in which, in addition to the modulus of longitudinal elasticity of the matrix material, the maximum specific linear deformation of the fibers occurs $(\varepsilon_c)_M$.

Note: In establishing the expressions for the evaluation of the limit stresses, the hypothesis of the linear-elastic behavior until the breaking of the fibers is taken into account [31]. Note that the matrix material would have a nonlinear variation of the specific linear deformation developed by the applied stress, only in the area where its deformation is greater than the maximum linear specific deformation of the fibers.

By appropriate processing the equality (3) can also be presented in the form [31]:

$$\left(\sigma_{1c}\right)_M = \left[1 + \left(E_m / E_f\right) / \left(p_{vm} / p_{vf}\right)\right] \cdot p_{vf} \cdot \left(\sigma_{1f}\right)_M . \tag{4}$$

Notations were used: E_f, E_m are the modulus of longitudinal elasticity for the fiber material, respectively of the matrix; p_{vf}, p_{vm} the volumetric percentage of the fibers, respectively of the matrix.

Relation (4) allows the determination of the critical volumetric percentage of fibers, in the form [37, 40]:

$$p^{\bullet}_{vf} = \left[\left(\sigma_{1c}\right)_M - \left(\sigma_{1m}\right)_M\right] / \left[\left(\sigma_{1f}\right)_M - \left(\sigma_{1m}\right)_M\right], \tag{5}$$

percentage that can lead to an excess of fibers to obtain a certain strength of the composite [27].

Note: The paper [36] presents the following correlation between the tensions developed in the fibers and the matrix, in the conditions of accepting a solidary transfer (of the hardening) of the external loads between them:

$$\sigma_{1f} / \sigma_{1m} = \left(E_f / E_m\right) \cdot \left(p_{vf} / p_{vm}\right), \tag{6}$$

with the corresponding volumetric participations. The relation expresses the fact that the fibers in the composite will be more stressed, the higher their modulus of longitudinal elasticity than that of the matrix and the higher the volume fraction of the fibers in the mixture.

The tensile stresses, developed in fibers, increase from their extremities to the central region, where their maximum value is manifested [41]. If the fiber length exceeds the *critical value*, l_{cf}, the material of the matrix deforms plastically at the ends of the fibers, keeping the deformation constant until the assembly is damaged.

Note: If the fiber length is greater than the critical length, the tensile stress at the fiber ends increases to the maximum value, over a distance equal to the difference between the actual fiber length and the critical length [41]. Increasing the fiber length above the critical value no longer affects the value of the tensile stress [33]. In this phase the material of the matrix deforms plastically in the extreme areas of the fibers, keeping the value of its yield strength limit $(\tau_m)_c$.

The critical length of the fibers can be determined by expression *Kelly A. - Tyson W. R.* [32 - 34, 41 - 43]:

$$l_{cf} = 0{,}5 \cdot d_f \cdot \left[\left(\sigma_f\right)_M / \left(\tau_m\right)_M\right], \tag{7}$$

where d_f is fiber diameter, in mm; $(\sigma_f)_M$ - the tensile stress of the fiber material, in N/mm^2; $(\tau_m)_M$ - the shear stress of the matrix material, in N/mm^2.

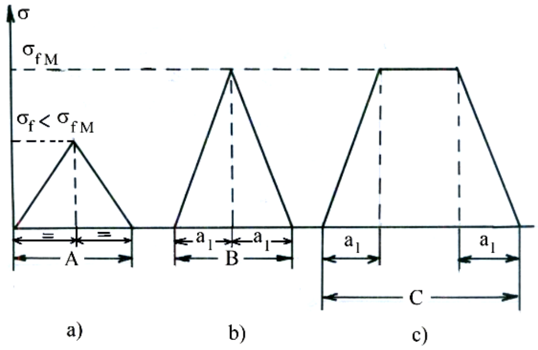

Fig. 1. Fiber stresses, depending on their length [37, 42]:
a – case A where $l_f < l_{cf}$; b) – case B where $l_f = l_{cf}$; c) case C where $l_f > l_{cf}$.

Were: $a_1=0.5 \cdot l_{cf}$; σ_f - the tensile stress in the fiber below the yield strength of its material; σ_{fm} - maximum limit in the fiber material – yield stress.

Figure 1 indicates the stress along the reinforcing fibers. At fiber lengths greater than the critical length (Figure 1, c), the average stress $(\sigma^{\bullet}_f)_M$ developed in them is higher, according to the relationship [32, 33]:

$$\left(\sigma^{\bullet}_f\right)_M = \left(\sigma_f\right)_M \cdot \left[1 - \left(1 - \beta_m\right) \cdot \left(l_{cf} / l_f\right)\right], \tag{8}$$

where β_m is a coefficient dependent on the behavior of the matrix [37, 38]. Iin case of a plastic deformation of the matrix, βm = 0.5, equation (8) becomes [32]:

$$\left(\sigma^{\bullet}_f\right)_M = 2 \cdot \left(\sigma_f\right)_M \cdot \left(2 - l_{cf} / l_f\right). \tag{9}$$

It is easy to see that when the fiber length is greater than the critical length $l_f > l_{cf}$ or even $l_f >> l_{cf}$ [42], transferring the load from the matrix to the complementary material/fibers is more efficient (Figure 1, c). In this case, the expression of the normal stress in the composite is [37]:

$$\sigma_c = \sigma_{fM} \cdot \left[1 - l_{cf} / \left(2 \cdot l_f\right)\right] \cdot p_{vf} + \sigma_m \cdot \left(1 - p_{vf}\right) \tag{10}$$

It is noted, in the same order of ideas, that the bearing capacity of the composite can be increased (stress (σ_c), without changing the length of the fibers, if the value of the shear stress increases τ_{fm} between the fibers and the matrix material [37]:

$$\sigma_c = \tau_{fm} \cdot \left(l_f / d_f\right) \cdot p_{vf} + \sigma_m \cdot \left(1 - p_{vf}\right). \tag{11}$$

Note: In the papers [36, 42, 44, 45] the following relation is presented for the calculation of the critical length of the continuous fibers in the composite:

$$l^{\bullet}_{cf} = d_f \cdot \left[\left(\sigma_f\right)_M / \left(\tau_m\right)_M\right], \tag{12}$$

which leads to observation $l^{\bullet}_{cf} = 2 \cdot l_{cf}$.

Paper [34], considering the shear stress between the fibers and the matrix, τ_{fm}, and the specific linear deformation of the composite, ε_c, specifies the following expression for the critical fiber length (*Bowyer H. W. – Bader G. M.*):

$$l^{\bullet}_{cf} = 0{,}5 \cdot E_f \cdot \varepsilon_c \cdot d_f / \tau_{fm}. \tag{13}$$

In the papers [26, 28, 31, 41, 46] the following relation is also presented for determining the admissible tensile strength of the composite material:

$$\left(\sigma_c\right)_M = \left(\sigma_f\right)_{max} \cdot \left[p_{vf} + p_{vm} \cdot \left(E_m / E_f\right)\right], \tag{14}$$

with the same consideration for equal deformations of fibers and matrix (and for volumetric percentages of fibers) $p_{vf} > 0,2$ [31]). It is also mentioned that equality (2) leads to obtaining higher values of resistance $(\sigma_{lc})_M$ compared to the experimental results. This occurs because the fibers in the manufacturing process are not uniformly tensioned, under the action of external stress breaking differently, a state that ends with the rupture of the matrix. In the previous analysis it was agreed that the fibers behave linearl - elastic to rupture, as well as the matrix material. Exceeding the maximum deformation of the fibers, the behavior of the matrix is nonlinear - elastic. These behaviors lead to the application of the equation (2).

Paper [31] specifies the approximation $(\sigma_c)_M \approx (\sigma_f)_{max} \cdot p_{vf}$, with the condition specified before $p_{vf} > 0,2$.

Paper [35], addressing the problem of a hybrid composite with epoxy matrix and glass and carbon fibers, presents the following equality for the evaluation of its tensile strength σ_{rch}:

$$\sigma_{rch} = \sigma_{rs} \cdot \left(1 - p_{vm}\right) + \left(\sigma_{rc} - \sigma_{rs}\right) \cdot p_{vc}, \tag{15}$$

where σ_{rc}, σ_{rs} represent the tensile strength of carbon and glass fibers, respectively p_{vc}, p_{vm} - the volumetric percentage of carbon fibers and that of the matrix.

We further admit that the fibers are equally stretched, in which case two types of tensie limits are possible: once the fibers break and once the matrix material breaks. If we denote by $(\sigma_c)_{el}$ ***the yield strength of the composite***, then you can write [26, 31]:

$$\left(\sigma_c\right)_{el} = \left[p_{vf} + p_{vm} \cdot E_m / E_f \right] \cdot \left(\sigma_f\right)_{el} \approx p_{vf} \cdot \left(\sigma_f\right)_{el} \text{, for } p_{vf} \rangle\ 0,2. \tag{16}$$

For very high volumetric percentages, the matrix no longer transmits the efforts to the fibers, then, taking place, a decrease of the load-bearing capacity of the composite.

Paper [36] indicates the following expression for composite strength σ_{lc}, along the fibers:

$$\sigma_{1c} = \sigma_{rf} \cdot \left\{ \left(\frac{E_f - E_m}{E_f} - \frac{\sigma_{rf}}{\tau_{fm}} \cdot \frac{d}{2 \cdot l_f} \right) \cdot p_{vf} + \frac{E_m}{E_f} \right\}, \tag{17}$$

where σ_{rf} represents the ultimate tensile strength of the fibers; τ_{fm} - the shear stress between the fiber and the matrix.

Paper [47], considering the behavior of a unidirectional reinforced composite, under external load, distinguishes two situations:

- The case in which the destruction of the matrix material occurs first (Figure 2 a and c), when the value of the stree is reached σ_{mr} is reached (the specific linear deformation being ε_{mr}), the composite continuing to withstand external stress until the tensile stress value is reached (when the corresponding specific linear deformation is ε_{fr} in accordance with the law (Figure 2 a):

$$\sigma^{\bullet}_{fr} = \sigma_f \cdot p_{vf} \ \langle\ \sigma_{fr}. \tag{18}$$

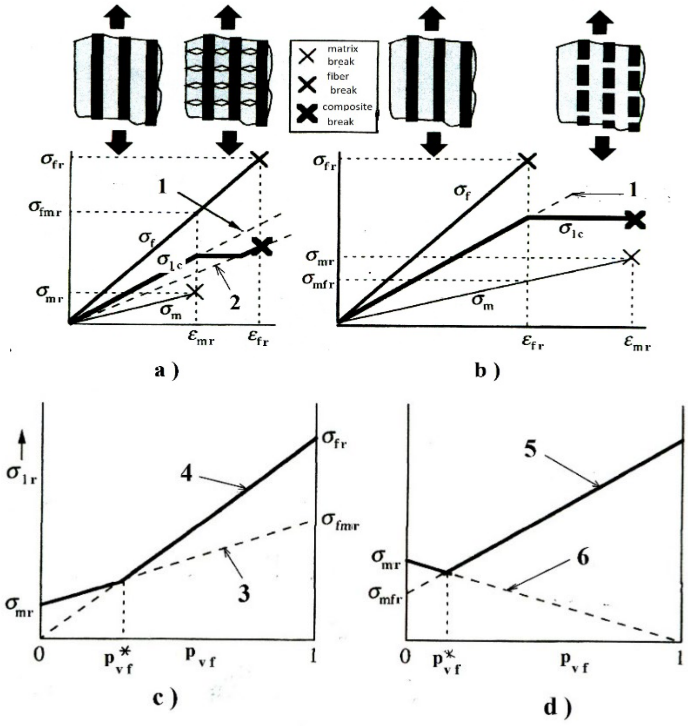

Fig. 2. Schematic representation of the behavior of a composite under external load [47 – 52]:
a, c – the case when the matrix material breaks before the fibers; b, d – the case when the fibers break before the matrix material.

Were: 1 – curve: $\sigma_f \cdot p_{vf} + \sigma_m \cdot \left(1 - p_{vf}\right)$; 2 – curve: $\sigma_f \cdot p_{vf}$; 3 – curve: $\sigma_{fmr} \cdot p_{vf} + \sigma_{mr} \cdot \left(1 - p_{vf}\right)$; 4 curve: $\sigma_{fr} \cdot p_{vf}$; 5 – curve: $\sigma_{fr} \cdot p_{vf} + \sigma_{mfr} \cdot \left(1 - p_{vf}\right)$; 6 – curve: $\sigma_{mr} \cdot \left(1 - p_{vf}\right)$;

The law governing the behavior of the composite, in the case of the collaboration of the two components is [37, 47, 49]:

$$\sigma_{1c} = \sigma_f \cdot p_{vf} + \sigma_m \cdot \left(1 - p_{vf}\right). \tag{19}$$

The intersection of the graphs of the expressions of the two laws, previously specified, leads to the specification of the volumetric fiber content:

$$p^{\bullet}_{vf} = \sigma_{mr} \Big/ \left(\sigma_{fr} + \sigma_{mr} - \sigma_{fmr}\right), \tag{20}$$

where the tension developed in the fibers is inserted when the matrix material breaks.

Note: The paper [49] presents the following equality for the evaluation of the critical value of the volumetric percentage of fibers:

$$\left(p_{vf}\right)_{cr} = \left(E_f \cdot \sigma_{mr} - E_m \cdot \sigma_{fr}\right) \Big/ \left[\left(E_f - E_m\right) \cdot \sigma_{fr}\right], \tag{21}$$

with notations *$(\sigma_f)_M$, $(\sigma_f)_M$* - tensile strength of the fiber and matrix material.

For the minimum value of the volumetric percentage of ***fragile fibers***, the expression [49]:

$$p^{\bullet}_{vf} = \left(E_f \cdot \sigma_{mr} - E_m \cdot \sigma_{fr}\right) \Big/ \left[\left(E_f - E_m\right) \cdot \sigma_{fr} + E_f \cdot \sigma_{mr}\right], \tag{22}$$

as shown in Figure 2 d, respectively for the *fragile matrix* [48]:

$$p^{\bullet}_{vf} = E_m \cdot \sigma_{mr} \Big/ \left[\left(E_m - E_f\right) \cdot \sigma_{mr} + E_m \cdot \sigma_{fr}\right], \tag{23}$$

as seen in Figure 2 c.

– The possibility of the composite fibers breaking before the matrix material is destroyed (Figure 2 b and d), the law that patronizes the behavior of the composite has the same form (19). The volumetric percentage corresponding to the intersection of the curves of the two laws, specific to the case, indicated in Figure 2 d, can be determined by the same equation (20).

The tensile stress of the matrix material, in the direction transverse to the direction of the fibers, can be established with the expression [47]:

$$\sigma_{2r} = \sigma_{mr} \cdot \left(1 - 1{,}129 \cdot \sqrt{p_{vf}}\right), \tag{24}$$

established by imagining that there is a minimum area, fictitiously removing the longitudinal fibers, in their place remaining the corresponding gaps (Figure 3). In reality, the respective fibers cannot be eliminated, at most one can imagine the fact that they no longer have intimate contact with the matrix material, which is why, analyzing the micromechanics of the structure, another relationship for the evaluation of σ_{2r} stress, has the form:

$$\sigma_{2r} = \sigma_{mr} \Big/ k_{\sigma 2} = \left(E_{2r} / E_m\right) \cdot \left[\left(2 \cdot r_f / s_f\right) \cdot \left(E_m / E_f - 1\right) + 1\right] \cdot \sigma_{mr}. \tag{25}$$

In the previous equation is present the concentration coefficient of normal voltages $k_{\sigma 2}$; r_f - cylindrical fiber radius; the effective modulus of the longitudinal elasticity of the structure/lamina in the normal direction on that of the fibers; sf - the distance between two uniformly distributed cylindrical fibers (Figure 3), whose formula is [47]:

$$s_f = \left[2 + \left(\sqrt{\pi / p_{vf}} - 2\right)\right] \cdot r_f. \tag{26}$$

<u>Note:</u> It is taken into account that the strength of the fibers is much higher than that of the matrix material, that the elasticity of the components is linear and that the rupture is fragile.

Another relation for calculating the distance between two fibers / wires (in the case studied being the case of concrete reinforced with "steel”) is given by the paper [53]:

$$s_f = 13{,}8 \cdot d_f \cdot \sqrt{1 / p_{vf}}. \tag{27}$$

<u>Note:</u> The paper [37] presents for the evaluation of the normal stress in the composite a relation of the kind shown by equation (26), in which, the concentration coefficient of the normal stresses has the form:

$$k^{\bullet}_{\sigma 2} = \frac{1 - p_{vf} \cdot \left[1 - \left(E_m / E_f\right)\right]}{1 - \left[1 - \left(E_m / E_f\right)\right] \cdot \sqrt{1{,}274 \cdot p_{vf}}}. \tag{28}$$

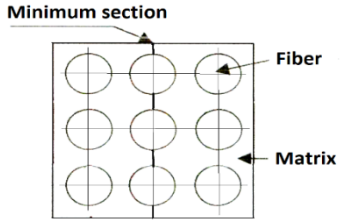

Fig. 3. When calculating the transverse stress to the fibers – schematic representation [47].

To evaluate the shear stress when the material breaks τ_{23r}, it is proposed [47]:

$$\tau_{23r} = \tau_{mr} \Big/ k_{\tau 23} = \left(G_{23r} / G_m\right) \cdot \left[\left(2 \cdot r_f / s_f\right) \cdot \left(G_m / G_f - 1\right) + 1 \right] \cdot \tau_{mr}, \qquad (29)$$

where k_{r23} represents a concentration coefficient of shear stresses; τ_{mr} - shear stress at rupture of the matrix material; G_{23t} - the effective modulus of the transverse elasticity (shear) of the lamina.

Note: The paper [47] draws attention to the fact that the previously expressed relationships cannot be guaranteed for the actual design of the sheets, without adequate experimental research, whether or not to find manufacturing defects (fiber geometry, their arrangement, contact between them and matrix material , possibly changes etc.).

3. CONCLUSIONS

The appearance of composites during human existence has allowed the gradual replacement of metallic, traditional materials, used in structures of great technical and economic importance. The advantages, but also the disadvantages, required special research to impose them justified where they belong. The detailed analysis regarding the cooperation between the matrix material and the other reinforcement/filling materials (of organic - synthetic or artificial nature, of vegetable or animal nature, respectively inorganic) is fully justified.

The present paper discusses the cooperation of matrix material and reinforcing fibers, under the action of external loads, the phases when damage occurs to one component or another. There are different opinions of researchers in the field, which is reflected by the content of this article, but it does not exclude the recommendation to make concrete experiments for practical conditions. Different comparative mathematical expressions are specified for the evaluation of the limit resistance of composite structures characterized by matrix materials with maximum lengths higher than those of fibers (polymeric or metallic matrix).

A subsequent paper, with the same orientation, will present the results offered by the scientific literature regarding the matrix of materials with maximum lengths lower than those of fibers. This category includes, for example, refractory composites, in which case the rupture is influenced by the elongation of the matrix material (assuming a perfect adhesion between the fibers and the matrix). In this sense, comparative results will be presented for the tensile elastic limit for a certain direction in relation to the direction of the long fibers or in a direction perpendicular to the long fibers. At the same time, the compression behavior along the fibers or perpendicular to their direction will be discussed.

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