Study of the tensile behaviour of unidirectional hybrid composites by means of an improved fragmentation model

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Introduction

Composites can be more damage resistant and thus less brittle if different reinforcements are combined to obtain hybrid configurations.

The mixture can be done at the macro scale (layers stacked sequentially, woven roving, etc.) or at the micro scale (filaments in a tow). The mechanical properties of hybrid composite materials have been often predicted with the rule of mixtures, assuming that the contribution of each component is proportional with its volume fraction.

This work develops an analytical expression to predict the mechanical behavior under tensile stresses of a unidirectional hybrid composite of two different fibers. The approach followed is based on an improved fragmentation model.

Theoretical background

Around a break, the fibers slide in the matrix and recover they full stress level over a load transfer length, due to an interfacial sliding strength, τ_i, which is assumed to be constant. The net stress over any cross-section of the composite containing sufficiently many contributing fibers is obtained from the mean stress in a long (fragmented) fibers subjected to the same strain (Fig.1).

The fiber strength was assumed to follow two parameters Weibull distribution. A damage variable w was introduced, defined as [1]:

$$w_{A,B} = \left(\frac{\sigma_f}{\sigma_{R_{A,B}}}\right)^{\beta_{A,B}+1} \qquad (1)$$

where σ_f is the unimpaired fiber stress which is used as measure of strain ($\sigma_R = E \cdot \varepsilon$). By other hand, each reinforcement has a proportion R_A, R_B and following the rule of mixtures the Young modulus is defined by:

$$E = E_A \cdot R_A + E_B \cdot R_B \qquad (2)$$

In the same, way for each type of fiber included in the hybrid, the reference stress is given by Eq. 3 [2]:

$$\sigma_{R_{A,B}} = \sigma_{0_{A,B}} \left(\frac{2 \cdot L_{o_{A,B}} \cdot \tau_i}{d_{A,B} \cdot \sigma_{0_{A,B}}}\right)^{\frac{1}{\beta_{A,B}+1}} \qquad (3)$$

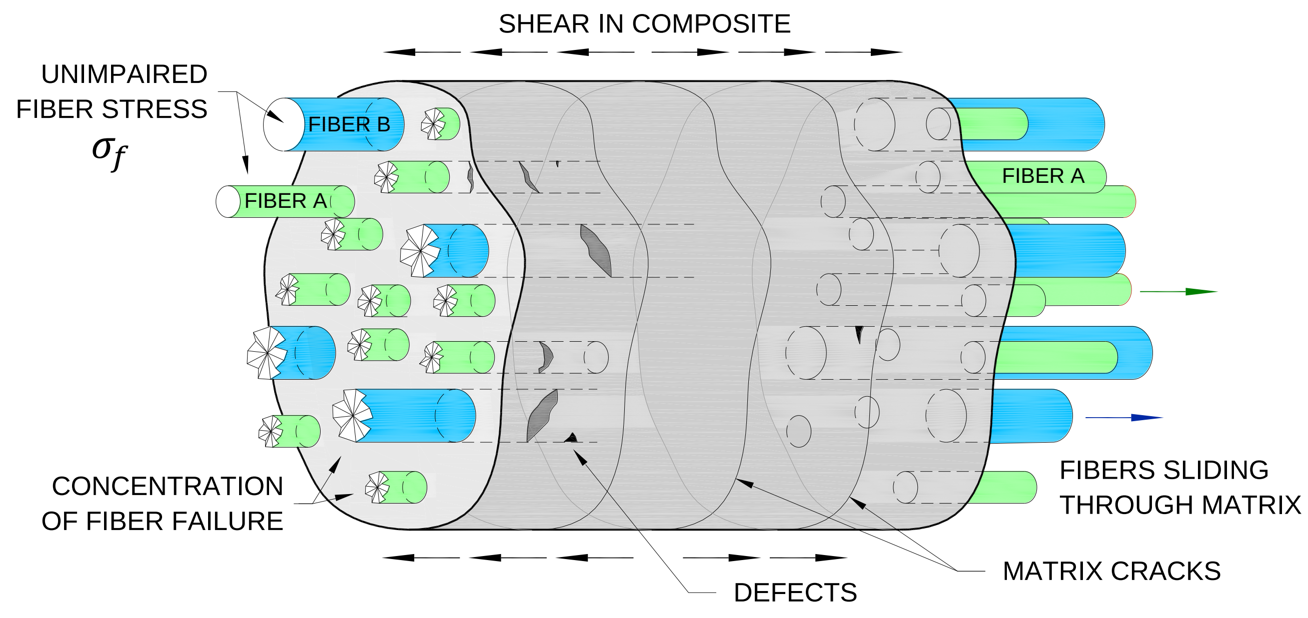

Figure 1. Conditions for bundle of fiber and matrix surrounding failed fibers

Here, $\sigma_{0_{A,B}}$ is the characteristic strength at gauge length $L_{o_{A,B}}$, $\beta_{A,B}$ is the Weibull modulus and $d_{A,B}$ is the diameter the of the each kind of fiber. The model to compute the behaviour of the hybrid under tension (Fig. 2), can be computed by using the following expression:

$$\sigma_\infty = V_F \cdot E \cdot \varepsilon \left\{ R_A \left[\frac{1}{w_A+1} + \frac{1}{2 \cdot ln(w_A+1)} \left(\frac{w_A}{w_A+1}\right)^2 \right] \right\} + \left\{ R_B \left[\frac{1}{w_B+1} + \frac{1}{2 \cdot ln(w_B+1)} \left(\frac{w_B}{w_B+1}\right)^2 \right] \right\} \qquad (4)$$

Results and discussions

According to the experiments carried out by Diao et al. an unidirectional Hybrid with carbon fibers (CF) and glass fibers (GF) reinforced epoxy composite were manufactured by resin film infusion from these commingled fibers, exhibiting a more gradual tensile failure strain (increased by 14%) [5].
In order to evaluate our model, we use the same properties of components, materials and proportions (Table 1). The comparison between analytical and experimental results are shown (Table 2). Finally, The mechanical response and the improvement of a pseudo-ductile curve is also depicted (Fig. 2).

Table 1. Reinforcement data for model validation

Ref.	Fiber ID	σ_0 MPa	L_0 mm	β	d µm	E MPa	References
TORAYCA T700SC-12K	A	2700	100	9,03	6,9	294,000	[4,5,6,7]
AGY 5744-735	B	1649	5	3,09	14,9	72,000	[4,5,8]

Table 2. Tensile strength, modulus and strain

Configuration	Fragmentation model					Experimental [4]		
	σ_U MPa	E^* GPa	ε_u %	$\Delta\varepsilon_H$ %	$\Delta\sigma_H$ MPa	σ_U MPa	E^* GPa	ε_u %
CF/Epoxy	1086,3	88,2	**1,35**	0,40	250,9	1055 ± 167	73,0 ± 8,8	**1,34 ± 0,06**
GF/Epoxy	501,7	21,6	**2,50**	-	-	458 ± 14	22,9 ± 0,9	**2,34 ± 0,14**
Hybrid	**849,5**	**37,8**	**1,90**	**1,25**	**449,5**	**719 ± 103**	**51,7 ± 5,0**	**1,52 ± 0,05**

Notes: $\tau_i = 23\text{MPa}$. $V_F = 0{,}30$. $V_{CF}:V_{gGF} = 1{,}55:1$. Proportion of fibers: $R_A = {}^{V_{CF}}/_{V_{CF}+V_{GF}}$, $R_B = {}^{V_{GF}}/_{V_{CF}+V_{GF}}$. $E^*$from slope in each curve.

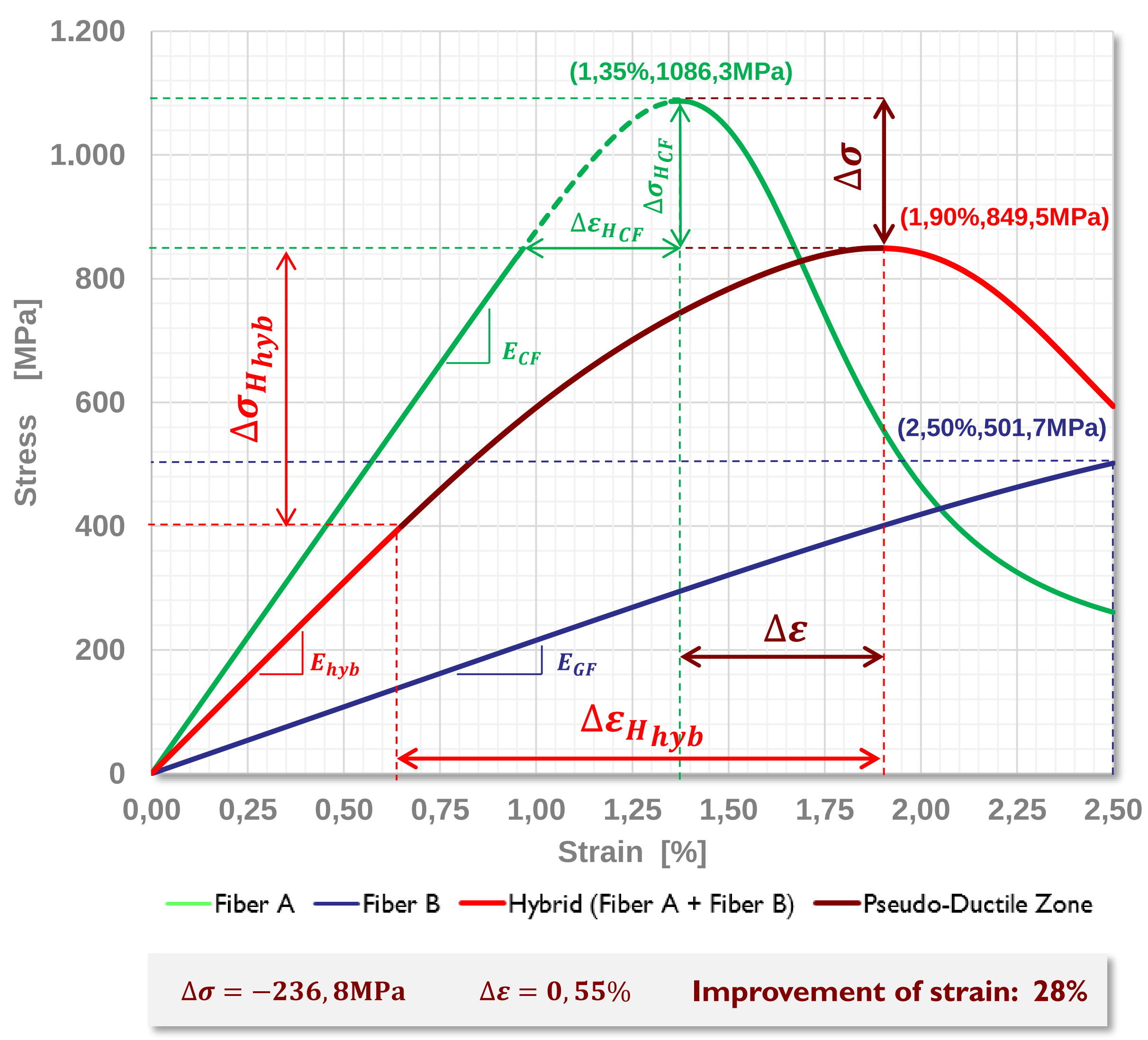

Figure 2. Tensile stress-strain curves

Conclusions

A fragmentation model to predict the behavior of a composite hybrid at microscale level was developed. The hybrid composite exhibited improved tensile failure strain, $\Delta\varepsilon = 0{,}55\%$ (28% more), compared with the non-hybrid carbon fiber composite, retaining the strength (with a slightly decrease $\Delta\sigma = -236{,}8\text{MPa}$) and stiffness properties. Therefore, the hardening in the CF-Epoxy was improved from $\Delta\varepsilon_H = 0{,}4\%$ and $\Delta\sigma_H = 250{,}9\ MPa$ to $\Delta\varepsilon_H = 1{,}25\%$ and $\Delta\sigma_H = 449{,}9MPa$ offering a more gradual damage in the hybrid composite. To sum up, the combination of materials shows the benefits of the hybridization offering a pseudo-ductile behavior and mitigating the catastrophic failure present in brittle materials.

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