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Predicting Longitudinal Progressive Damage in Unidirectional Carbon Fiber-Reinforced Composites

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Abstract: For simplification purposes, damage in unidirectional carbon fiber-reinforced composites (CFRPs) under longitudinal tensile loading is neglected, hence maximum stress failure criterion is often used as the maximum bearing capacity. In this work, a progressive failure model focusing on predicting damage initiation and propagation associated to longitudinal loading (i.e. fiber direction) is proposed. A mathematical routine based on the classical laminate theory (CLT) and on failure criteria was developed to simulate the material behavior. This study focuses on unidirectional (UD) laminates under longitudinal tensile loading. Computational results are compared to experimental data available on the literature. The proposed approach is simple, conservative and able to offer reasonable predictions, being ideal for a preliminary analysis.

Keywords: Progressive failure analysis, Computational model, Longitudinal failure.

INTRODUCTION

One of the most ambitious goals in structural materials is to achieve exceptional mechanical properties, especially combining low weight with high strength and stiffness. Carbon fiber reinforced polymer (CFRP) composites meet these requirements and, hence, have been widely recognized as the material of choice for several automotive, aeronautical and aerospace applications, where a high strength-to-weight ratio is needed (Almeida Jr et al, 2017). The inherent anisotropy associated with CFRPs allows their properties to be somehow tailored together with geometrical and functional characteristics of a given structure in order to obtain the desired performance (Tita, 2003). Combination the strength and stiffness of a CFRP with its low density make this material as the most suitable for structural applications where weight is crucial (Almeida Jr et al, 2018).

However, the inherent anisotropy in UD CFRPs may be a positive or negative factor. On one hand, it is possible not only to select the material, but also to design it as function of a structure application, providing high efficiency. On the other hand, the anisotropy associated with the fiber heterogeneity introduces a significant difficulty to develop an efficient computational model. Therefore, it is essential to develop and analyze different constitutive and failure models to have a better predictability of a given composite under a particular loading scenario. In this context, this papers aims at proposing a fast and efficient approach focusing on the prediction of the mechanical response of UD laminates under longitudinal tensile loading by using a progressive failure model.

PROGRESSIVE DAMAGE MODEL

Based on the works performed by "Tita, 2003", "Ribeiro, 2013" and "Angélico, 2009", a novel degradation approach looking for predicting the ultimate loading and stiffness degradation of a composite sample under longitudinal tensile test is proposed. A routine in Matlab is developed to simulate the composite behavior. Later on, numerical results are compared to experimental data, and limitations and potentialities are discussed and finally modifications and improvements are proposed.

A 5-layer unidirectional CFRP ($[0]_5$) tensile specimen with fiber volume fraction (V_f) of ≈62% is herein evaluated. The elastic and strength constants (Tita, 2003 and Almeida Jr. et al, 2016) utilized as input data are shown in Table 1.

A Matlab code was developed to simulate the 2D stiffness degradation of unidirectional CFRPs under longitudinal tensile loading. At each iteration, an increment is added to the applied stress using CLT (Tita, 2011), and then the corresponding stress and strains are calculated. In parallel, non-linear strains are computed, so the shear modulus must be recomputed according to Equation (1):

$$G_{12}^{updated} = \frac{1}{\frac{1}{G_{12}} + 3\alpha\sigma_{12}^2} \quad (1)$$

where σ_{12} is the current shear stress and α is the non-linear parameter and its value is $3.98 \cdot 10^{-24}\ (Pa)^{-3}$ (Tita et al, 2008).

Table 1 – Elastic and strength properties.

	Symbol	Description	Value
Elastic properties	E_1 (GPa)	Longitudinal elastic modulus	127.0
	$E_2 = E_3$ (GPa)	Transversal elastic modulus	8.1
	$\nu_{12} = \nu_{13}$	Poisson's ratio in plane 1-2	0.34
	ν_{23}	Poisson's ratio in plane 2-3	0.35
	$G_{12} = G_{13}$ (GPa)	In-plane shear modulus	4.4
	G_{23} (GPa)	Transverse shear modulus in plane 2-3	2.10
Strengths	X_t (MPa)	Longitudinal tensile strength	1250.0
	Y_t (MPa)	Transverse tensile strength	42.5
	X_c (MPa)	Longitudinal compressive strength	930.0
	Y_c (MPa)	Transverse compressive strength	−140.3
	S_{12} (MPa)	In-plane shear strength	53.0

The next step is to verify the appearance of failures either in the matrix or in the fibers in the current iteration. In this work, it was assumed four possible failure modes: fiber failure (when the specimen is under tensile loading), matrix failure (when the matrix is under tensile loading), matrix crushing (when the matrix is under compression) and when fiber failure under compression. For each case, there is a criterion to determine the presence of a failure or not. They are the same as presented in "Tita, 2008".

If there is no failure, the structure is safe, and the next iteration takes place with a higher applied load. Otherwise, if at least one of the four criteria indicates failure, the material degradation starts taking place. The approach used here is that the material properties are degraded (since failure is identified) up to final failure.

Depending on the type of failure, there will be a different constitutive relation to degrade the material properties. If the matrix is damaged, the same approach established in "Tita, 2008" is employed: E_{22} and ν_{12} are updated to "0" (zero) and the other properties remain the same. However, if damage is in the fiber, a new model is herein proposed, as follows:

$$E_{11}^{dam} = E_{11}\, exp\left(\frac{-\sigma_{11}}{X_T} \cdot H\right) \tag{2}$$

$$G_{12}^{dam} = G_{12}\, exp\left(\frac{-\sigma_{12}}{S_{12}} \cdot H\right) \tag{3}$$

$$E_{22}^{dam} = 0 \tag{4}$$

$$\nu_{12}^{dam} = 0 \tag{5}$$

where the superscript "dam" stands for the damaged property, σ_{11} is the stress in the fiber direction, and H is a parameter that will be determined by simulations. The idea is to develop a simple approach that depends only on the material characteristics and the parameter H, so it can be used analytically, without the necessity to develop a numerical finite element model.

Results

The properties present an exponential behavior, where the smoothness is determined by the H parameter, as shows Figure 1. Furthermore, several simulations are performed by varying the number of increments and the values of H. The computational results are compared to the experimental data presented in "Tita, 2003" and "Tita et al., 2008".

Figure 2 shows that a good correlation between the proposed model and the experimental data is found. When 25 increments are used, the best results are for H=0.07 and H=0.06. When 40 increments are used, the best results are for H=0.06 and H=0.05. In both cases, the complete rupture happens before the computational predictions, showing that the current approach is conservative. One can remark that the results with a lower number of increments are better, since the transition between linear and non-linear regions is smoother and the predicted rupture stress is closer to the experimental one. This is in coherence with the results presented in "Tita, 2003" and "Tita, 2008". Besides, at the beginning of the simulation, in the linear region, both computational and experimental data have exactly the same stiffness. After that, there is a small divergence, which reduces at the end of the simulation.

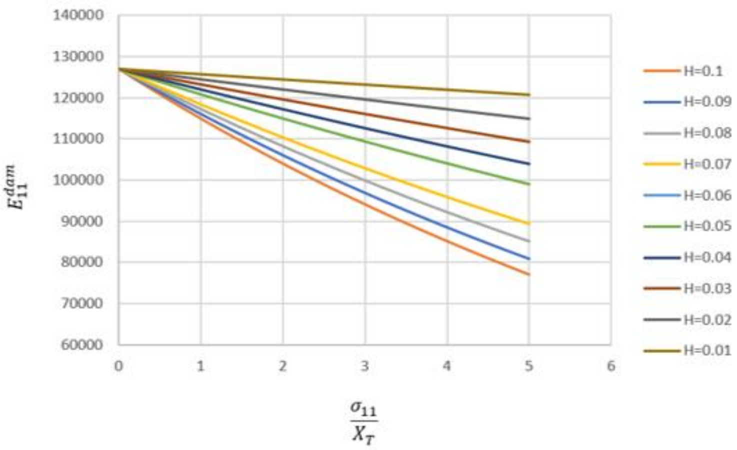

Figure 1 – Longitudinal progressive failure as function of the parameter H.

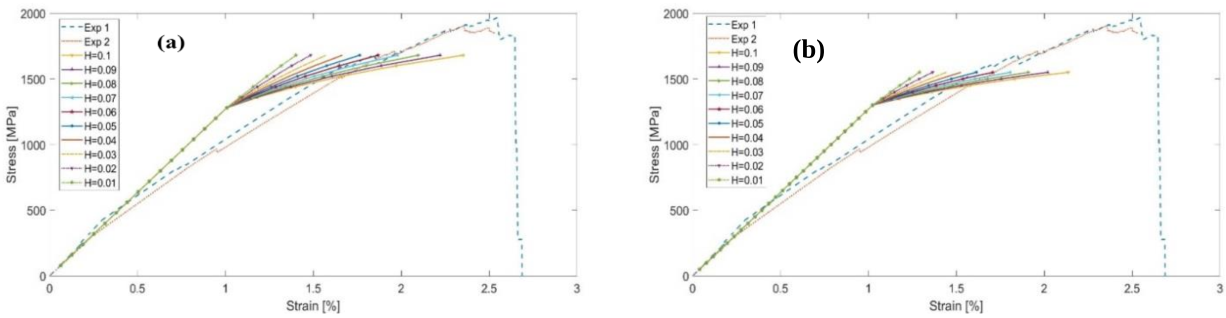

Figure 2 – Experimental and computational results with 25 (a) and 40 (b) increments.

The highest difference when comparing computational and experimental data is in the transition between linear and non-linear regimes. In the experimental case, the CFRP seems to have a progressive loss of stiffness before presenting a non-linear behavior, while in the computational case, the stiffness is constant until fiber failure is detected. This difference might be triggered by fiber/matrix imperfection contact. Hence, an improvement to the model would be to consider that the interphase is not necessarily perfect and so to include this effect in the simulation to achieve more realistic and precise results. The following Section explains in detail the proposed methodology.

MICROMECHANICAL MODELING

In order to understand how an imperfect interphase can affect the CFRP properties, a representative volume element (RVE) has been developed using finite element (FE) analysis (using Abaqus FE package), where the three phases of a laminate (matrix, fiber and interphase) are modelled. RVE is a numerical model used to determine a homogeneous medium equivalent to the original CFRP and comprises the smallest portion of the smart composite, which keeps the most representative combination of its main materials (Tita et al., 2015).

The first step is to determine the fibers arrangement. In this case, a square arrangement chosen: the RVE is a 1 mm^3 cube, and the fiber is a centered cylinder, as shows Figure 3. The V_f must be exactly the same as before, i.e., 62%. In addition, a thin layer is added at the boundary between the fiber and the matrix to represent the interphase. Based on "Tita et al., 2015", the interphase volume fraction (I_f) must be determined based on the following relation:

$$\frac{t}{a} = 0.001 \qquad (6)$$

where t is the interphase thickness and a is the fiber radius. It leads to an I_f of 0.12%.

The next step is to define the material properties individually. Each element (fiber, matrix and interphase) is considered as being isotropic and homogenous. Particularly in the case of the interphase, the shear modulus (G) is related to the fiber/matrix adhesion. For high G values, the contact is perfect, so the stress is transferred from the matrix to the fiber. As G decreases, the contact still exists, but it is not perfect anymore. When G reaches small values (i.e. 1), there is no contact anymore. The idea is then to vary the G values (that physically represents the transition from a perfect adhesion to a non-perfect one) in order to understand how it will affect the CFRP properties. Basically, the idea herein proposed is to incorporate the fiber/matrix adhesion characteristics obtained via the micromechanical model into the progressive damage model previously proposed in the current investigation. At the end, a micro-to-macro methodology will be proposed, in which the macro model will be able to incorporate and consider the fiber/matrix interface behavior in the analysis.

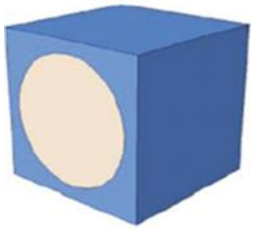

Figure 3 – Unit cell with a square arrangement.

Through combinations of loads and appropriate boundary conditions (BCs), it is possible to obtain the constitutive matrix parameters. The constitutive relation for composite materials is given by Equation (7), where the direction 1 is the one longitudinal to the fiber:

$$\begin{bmatrix}\sigma_1\\\sigma_2\\\sigma_3\\\sigma_4\\\sigma_5\\\sigma_6\end{bmatrix}=\begin{bmatrix}Q_{11} & Q_{12} & Q_{13} & 0 & 0 & 0\\Q_{21} & Q_{22} & Q_{23} & 0 & 0 & 0\\Q_{31} & Q_{32} & Q_{33} & 0 & 0 & 0\\0 & 0 & 0 & Q_{44} & 0 & 0\\0 & 0 & 0 & 0 & Q_{55} & 0\\0 & 0 & 0 & 0 & 0 & Q_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_1\\\varepsilon_2\\\varepsilon_3\\\gamma_4\\\gamma_5\\\gamma_6\end{bmatrix} \tag{7}$$

where σ_i is the stress tensor, ε_i and γ_i are the strain tensors and Q_{ij} are the stiffness coefficients, and 1 is the longitudinal direction. Since the sample was submitted to a tensile loading, it is particularly interesting to find Q_{11}. For doing that, a small displacement is imposed in the fiber direction, while the displacement on all other directions are restricted, as depicts Figure 4. It is important to apply a very small displacement, once the idea is to simulate the linear domain of the specimen.

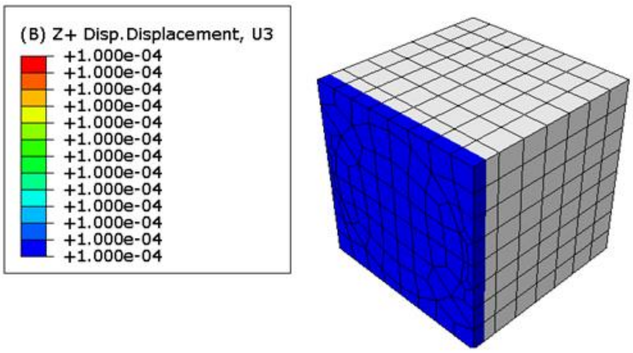

Figure 4 – Boundary conditions applied to the RVE.

Finally, Q_{11} is computed according to Equation (8), where $\overline{\sigma_i}$ and $\overline{\varepsilon_i}$ denote stress and strain average values, respectively.

$$Q_{11}=\frac{\overline{\sigma_1}}{\overline{\varepsilon_1}} \tag{8}$$

Following the methodology presented above, it is possible to determine how Q_{11} is affected by the interphase. Figure 5 shows the results. If G increases infinitely, the fiber/matrix adhesion is perfect. When it reaches about $10^{10}\ Pa$, the interface is not perfect anymore, so Q_{11} starts to reduce. It drops significantly until the moment it reaches its minimum value, which represents a case with a weak interphase. Figure 6 illustrates how the stress distribution (σ_1 specifically) changes with the interphase.

After doing the microscale analysis, the obtained results must be integrated to the macroscale analysis. The idea is to take the fiber-matrix interphase into the degradation law account, where the reduction of the CFRP stiffness and its subsequent failure are caused by both fiber failure and interphase degradation. The theory of this new model consists of two steps: **i) the first modification** refers to the CFRP behavior before detection of a fiber failure. In the experimental results, it is seen that before the first failure, there is a drop of E_{11}, which can be associated to damage in the interphase. In the beginning of the test, the applied stress is low, the fiber/matrix adhesion is still perfect, and that is why the computational and experimental data match perfectly. The results start diverging because damage in the interphase starts taking place, however they were not taken into account in the numeric model. Thus, to compensate this feature, at each increment, E_{11} is updated as follows:

$$E_{11}^{update} = \gamma\, E_{11} \tag{9}$$

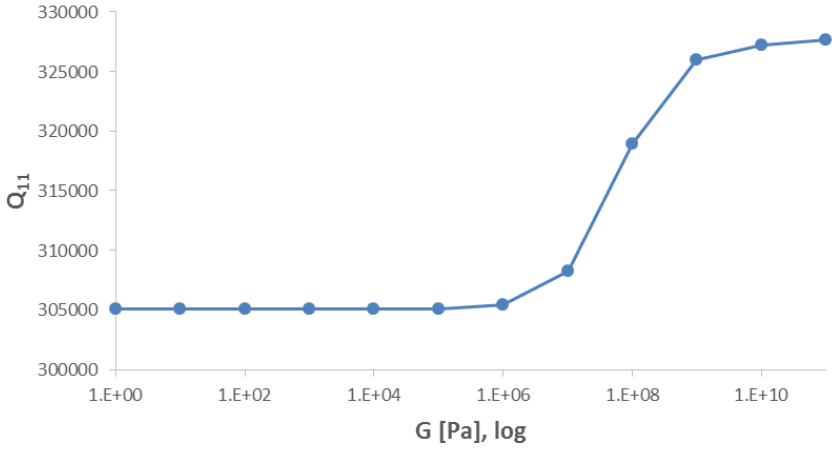

Figure 5 –Q_{11} coefficient as function of the fiber/matrix interphase contact imperfection parameter.

The parameter γ varies from 0 to 1, indicating that E_{11} is used in the new iteration is a fraction of the previous one. The parameter γ can be obtained from its variation according to the interphase parameter G (Figure 7), that shows the same result as Figure 5, but now the results are normalized by its highest value. The curve presented will be divided in the same number of increments as the simulation itself, then for each value of the applied stress in the tensile test, there will be a corresponding γ value.

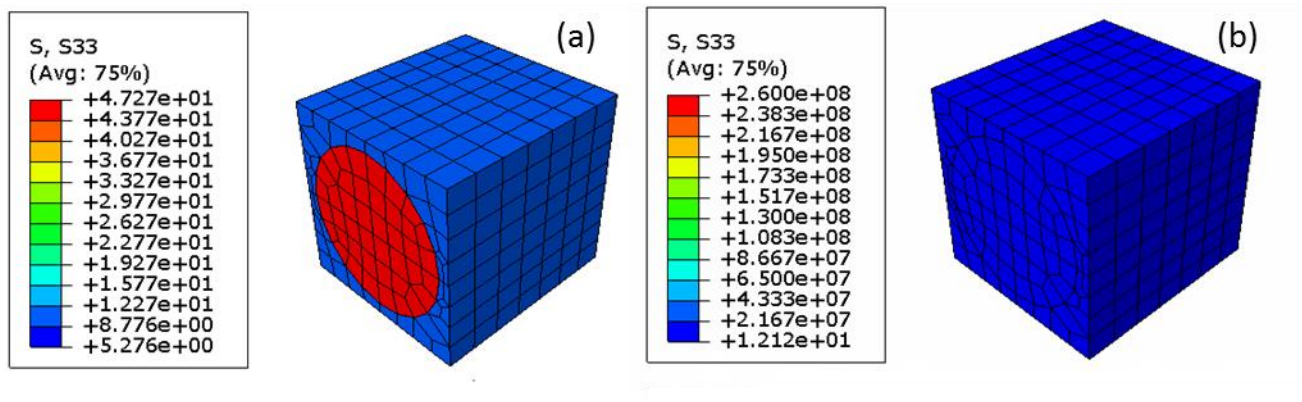

Figure 6 – Longitudinal stress (σ_1) distribution for (a) G=1000 Pa and (b) G= 10^{10} Pa.

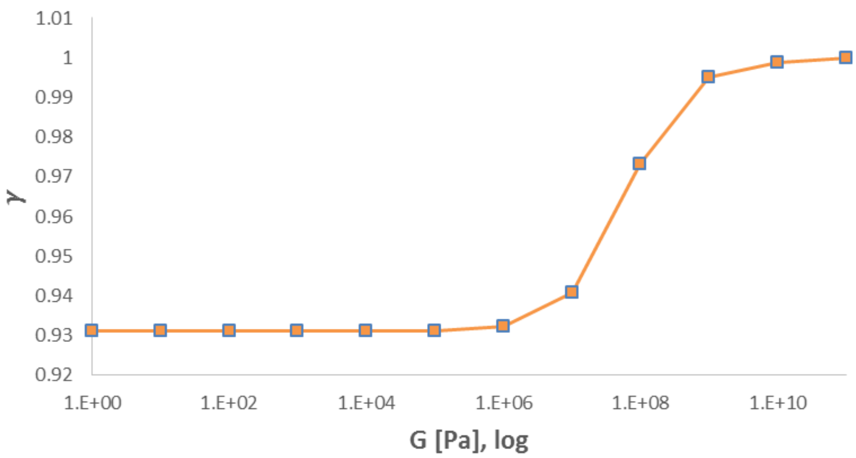

Figure 7– Parameter γ as function of G parameter.

This procedure is interactively performed until detection of the first failure. Then, **ii) the second modification** takes place: a change in the degradation law is implemented, as follows:

$$E_{11}^{dam} = E_{11}\left(\exp\left(\frac{-\sigma_{11}}{X_T}\cdot H\right) + \beta\right) \quad (10)$$

$$G_{12}^{dam} = G_{12}\left(\exp\left(\frac{-\sigma_{12}}{S_{12}}\cdot H\right) + \beta\right) \quad (11)$$

$$E_{22}^{dam} = 0 \quad (12)$$

$$\nu_{12}^{dam} = 0 \quad (13)$$

If compared to Equations (2-5), β parameter has been introduced. It is a fitting parameter to incorporate the influence of the fiber/matrix interphase in the constitutive law.

The theory of the model is developed and implemented as herewith presented and the results are promising. Further analyses are currently being carried out.

CONCLUSIONS

This work proposed a novel, fast and efficient approach for predicting longitudinal degradation of CFRPs. A major advantage is that the model does not require complex and time-consuming codes and provides good predictions when compared to experiments. In order to improve the results, it was developed a micromechanical model in order to incorporate the effect of the fiber/matrix interphase. For that, a RVE has been modeled and the interphase effect coupled to a macro analysis of the problem. In the final version of this article further results and deeper discussion will be included.

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