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Analytical method for determining the durability of fiber reinforced composite materials

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Abstract. The durability of composite materials with metallic and non-metallic matrix can be calculated using both the uniaxial and biaxial loading of the composite, following the wear phenomenon that occurs in these cases. At the same time, this mode of loading of composite material offers multiple ways of analyzing crack resistance, because the wear phenomenon characteristic of these materials is composed of both the wear of the matrix and, in particular, the sliding wear and the crack-breaking behavior of the fibers. This paper proposes to approach the procedure of solving the specific equation systems with regard to the crack resistance, using for this purpose a composite panel with a rectangular surface, with a height w = 60 mm and a thickness t = 18 mm, subjected to loads variables. The model is considered to be loaded under a tension σ_{cr} (MPa), both above and below the crack line.

1. Introduction

Due to the fact that the composite materials have a low strength-to-weight ratio, good wear and corrosion resistance, they have begun to replace traditional materials more and more [1].

The structural integrity of the composite material ensures high performance. Thus, the characteristics of laminated composite materials are reduced due to stress concentrators, as well as to metals, but also due to deterioration. These are numerous but also different from those of metals. The damages for the composite materials may be of two types [2,3]:

- damages to the composite, occurring during its realization, being related to the defects of the constituent materials, but also to the manufacturing technology.

These damages are caused by unevenness in the thickness of the layers, lack of fiber parallelism, fiber breaks, voids (air bags or gas bags) or other imperfections in the structure, delaminations, but also due to inadequate or incorrectly used tools.

- covered damage caused by the stresses that are subject parts made of these materials, the loads acting on the parts made of composite materials or environmental factors.

The damages for a fiber reinforced composite material may be: fracture or cracking of the composite matrix, increasing the gaps in the matrix, delaminating, fibers breaking, matrix separating of the fibers oriented in directions different than the loading direction, the separation matrix of the fibers oriented in the direction of loading [4,5].

These damage can occur due to static stretch-compression, bending, shearing or torsion, but also because of structural fatigue of the material [6].

2. General characterization of the modeling process

It should be noted from the beginning that in order to perform a mechanical characterization of the composite materials, laborious but also difficult work is required by the multitude of parameters that we have to consider in order to obtain even a characteristic of the material in different conditions of request [7,8].

This is due to the peculiarities of the mechanical behavior of composite material:

• the existence of several deformation mechanisms, with totally different effects on the size and nature of the deformation due to which, for the same composite placed under different stress conditions can be obtained some behaviors: elastic, visco-elastic or elasto-visco-plastic

• dependence of mechanical properties on some geometric and physical parameters - stress directions, test speed, time variation of the load, duration of application, temperature etc.;
• dependence of the mechanical properties on the conditions for obtaining the composite material, depending on the manufacturing technology and the applied thermal treatment: molded, extruded, pressed composite material etc.;
• the dependence of the mechanical properties of the nature and characteristics of the fibers (short fibers, long fibers) with which was made the metal matrix reinforcement, the arrangement of the filament fibers, the density of the filaments, the total volume of the reinforced material, the nature of the interface and the input materials introduced to modify fiber-matrix interfacial tensions.
Until now no unitary theory has been developed that can fully describe the mechanical behavior of carbon fiber-reinforced metal matrix composites and determine the mechanisms of dependence of the mechanical characteristics of the above-mentioned parameters [9].
In the theories that refer to the calculation of the composite structures, there are patterns that partially describe the properties of these materials, usually under limited conditions. The data is generally used for systematisation of tests and the structural resistance calculation [10].
Characterization of the composite structures is achieved when, from the point of view of the mechanical strength, at each point the six components of the stress and the six components of the deformation can be calculated, depending on time and temperature. If these sizes were determined, it can be said that a request is admissible or not, using a resistance theory, which defines the criteria for the occurrence of limit states in the composite material [11].

3. Calculation algorithm applied for modeling crack propagation and propagation

In this paper we have investigated the composite materials in terms of crack formation and propagation, using a non-proportional stress application algorithm in correlation with the finite element method. The required parameters to describe the rupture of the material impose the introduction of the load intensity, of the geometry, and direction of the loading tasks. Correspondence between the model that explains the crack propagation behavior, compositional nature and structural "homogeneity" is done by introducing a calculation algorithm based on numerical simulation [12].
Compared to the composite materials having the aluminum alloy matrix already studied and considered "classical", those with a metal matrix with reinforcing elements consisting of short carbon fibers increase the crack resistance by lowering the concentration factor at the stresses in the matrix.
For the mathematical modeling, was considered a composite with a rectangular surface with a height w = 60 mm and a thickness t = 18 mm. The model is assumed to be load under a tension σ_{cr} (MPa), both above and below the crack line. Critical load σ_{cr} is defined as the value that leads to crack propagation. If reference is made to a plane loading state, it is assumed that the composite has a zonal homogeneity and it is treated tensorally as a laminate. Calculation values are shown in table 1.

Table 1. Material properties and characteristics (Young Modullus E, Poisson coefficient ν, the breaking coefficient at internal points of the cracking surface K_{Ic}).

ξ	E(MPa)	ν	K_{IC}(MPaN $\sqrt{m}$)
0.00	3000	0.35	1.2
0.17	3300	0.34	2.1
0.33	5300	0.33	2.7
0.58	7300	0.31	2.7
0.83	8300	0.30	2.6
1.00	8600	0.29	2.6

Note: ξ - defines the coordinate point x and y of the network area; can take values between 0.00 and 1.00, as shown in figure 1.

If it is assumed that there is currently a symmetric loading leading to a matrix fracture line, parallel to it there will appear some lines of deviation and widening of the fissure, as illustrated in figure 1. In this case, the strength the material is larger, the greater the deviation of cracks.

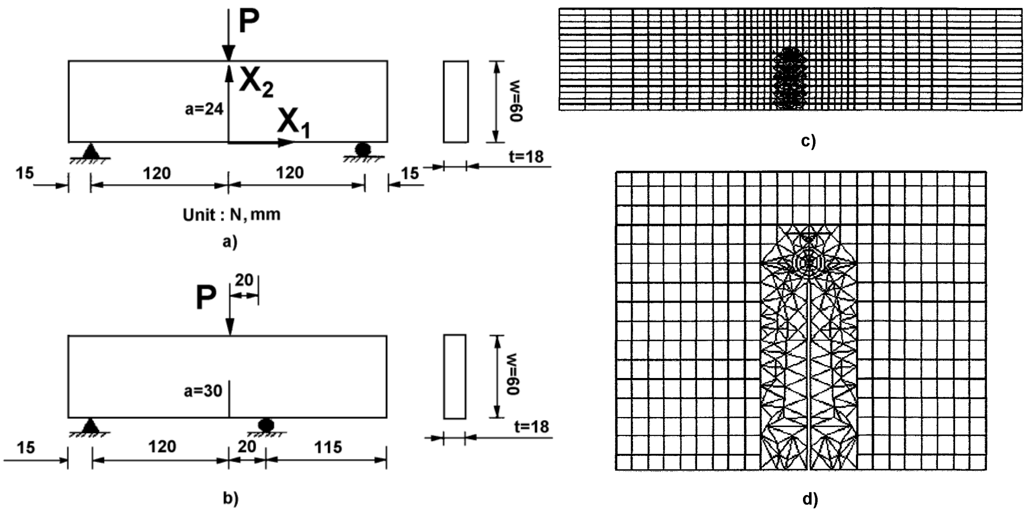

Figure 1. Representation of crack and propagation in the case of symmetrical loading.

Based on the assumption of assimilation of the composite with a material that has gradual properties but can be considered as Functional Graded Materials (FGM) but which presents local homogeneity in the crack area, was used the simulation models based on the numerical methods, but which call for a method of integrating interreactions; the method is taken from the theory of non-homogeneous materials, known in the literature as the Mori-Tanaka method [14]

Parameters describing cracking behavior include a stress intensity factor (SIFS), which is important in describing the crack direction according to the two modes of behavior K_I si K_{II}, [3].

The stress intensity factor can be defined based on a equation (1):

$$\sigma_{i,j}(r,\theta) = \frac{K_1}{\sqrt{2\pi r}} f^{I}{}_{i,j}(\theta) + \frac{K_{II}}{\sqrt{2\pi r}} f_{i,j}{}^{II}(\theta) \tag{1}$$

That formula represents the SIF_s system in mode I and mode II, in which σ_{ij} defines the stress tensor, K_I and K_{II}. Respectively angled angular functions $f_{ijI}(\theta)$. The SIF_s system contains parameters for characterizing the behavior of the materials at cracking.

4. Establishing the crack propagation mode and formulating the parameters needed to describe the simulation of the phenomenon

If we consider the works of Gu and Asaro, which since 1997 attempted to describe the crack cracking and propagation of fragile materials based on the Cotterell and Rice criteria, where $K_{II} = 0$, it will be admitted that the propagation will with a gradient whose developmental direction is perpendicular to the cracking direction [13].

There are some interactive fractal description programs, such as FRANC 2D (Fracture Analysis Code 2D), which can simulate a 2D crack analysis. The analysis is based on a stepwise propagation of the cracking. The extension of the concept and non-homogeneous materials such as composites (which have up to 50% reinforcing elements) is possible in order to construct the model [1].

In the assumed situation (where we have a symmetric loading), a representation of the crack mode can be represented by the figure 2 in wich are realised a representation of the Young Modullus (E) correlated with Poisson coefficients (υ) for a restriction zone ξ, defined by a relation of the form: $0 \le \xi \le 1$.

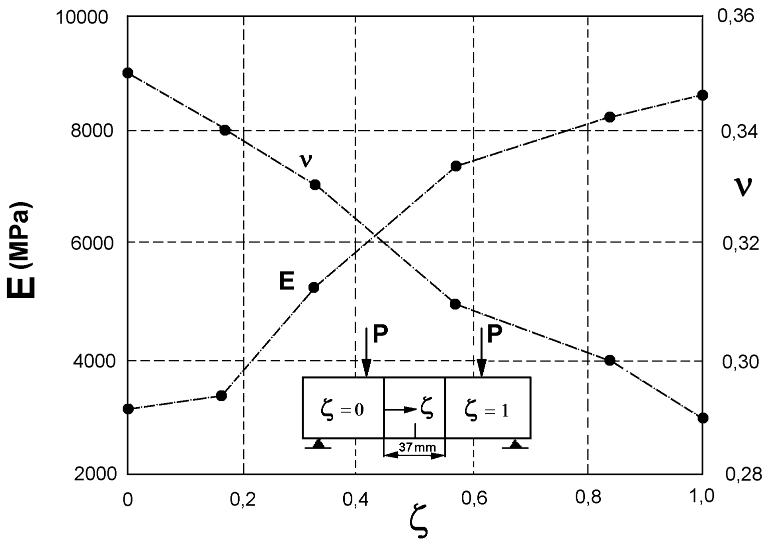

Figure 2. Graphical illustration of variation of the Young Modullus E(MPa) and the Poisson coefficient υ, for a restricted area defined by the relationship $0 \leq \xi \leq 1$.

The systematic development of the model in a network designed to simulate the crack occurrence and development by propagating it into the composite material (assumed to have homogenous zonal properties) is based on the limitation of coefficient values and numerical values for SIF_s, according to the values in table 2.

Table 2. Critical numerical values adopted in the model for the critical load value P_{cr}.

	P_{cr} (N)	$K_I(MPa\sqrt{m})$	$K_{II}(MPa\sqrt{m})$	$\psi = \tan^{-1}(K_{II}/K_I)$
0.17	253.3	2.122	-0.129	- 3.484

In the case of the fissure model development of the composite material, for which the cracking propagation is believed to occur as a result of a non-homogeneous material loading (figure 3), the fissure propagation simulation steps can be transcribed by a relationship of the form:

$$P_i(t) + \alpha_1(t) \cdot P_1^0, i = 1,2,3,..., n \quad (2)$$

where i represents a number (n) of variable loadings of the composite material, the P_i^o - iteration i the charge to be applied to the composite, and $P_i(t)$ - the final load to be applied after iteration t.
The procedure for choosing the Critical Charging Value also applies to SIF_s, which sum up all the load values.
Figure 4 is a comparative example of the cracking traces resulting from data processing, experimental values and math simulation results for a homogeneous (a) and a non-homogeneous (b) load.
To fully determine the state of the composite load, general equations apply to define the plane of deformation. These data should be described in a system, imposing a limitation on a matrix of conditions, with which to analyze the phenomenon of tensions.
In this context, the equilibrium refers only to the values of the variables determined by a set of conditions, and it is always possible to develop a system in equilibrium without any real significance. This method of comparing statics is a particular case of the deduction method, according to which the behavior of a system is defined by an ensemble of functional equations determined by the initial conditions [7,8].
In a working hypothesis, either a composite where its quality is given by the intersection of the matrix type (metallic or nonmetallic) and the amount of carbon fiber of the composite, the parameters given by p = matrix type and q = the amount of fiber carbon for reinforcement.
Let α = length parameter (α represents the displacement of a curve in one direction or another and is different from the displacement on the curve, in which case α is constant); this may be, for example, the length of the reinforcing fibers, p and q being the variables, the equations of equilibrium will be:

$$D(q, a) - p = 0 \quad (3)$$
$$S(q, a) - p = 0 \quad (4)$$

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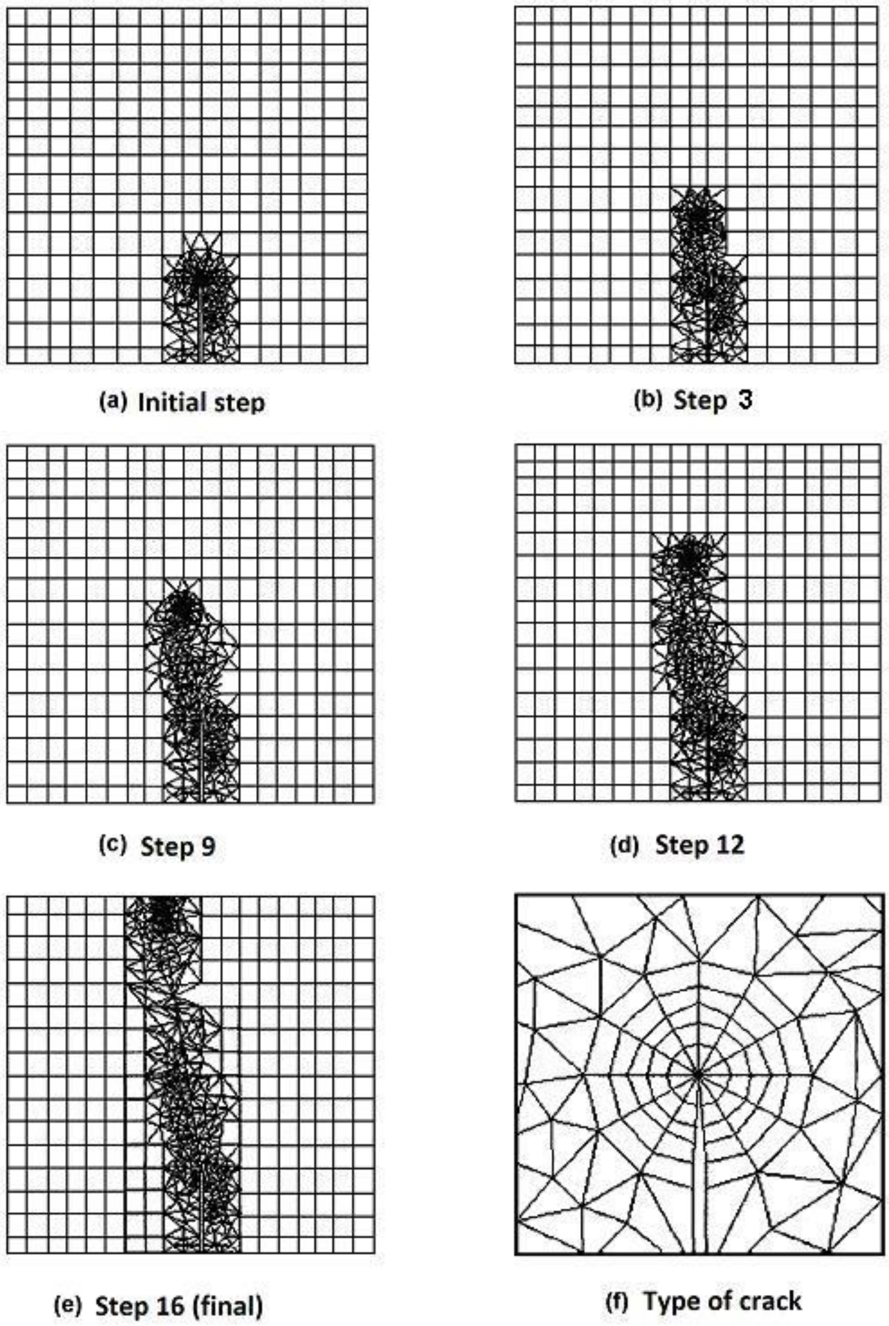

Figure 3. Evolutionary representation propagation in steps of the cracking phenomenon by applying modeling for values $\xi = 0.17$ and increment $\Delta a = 1$ mm.

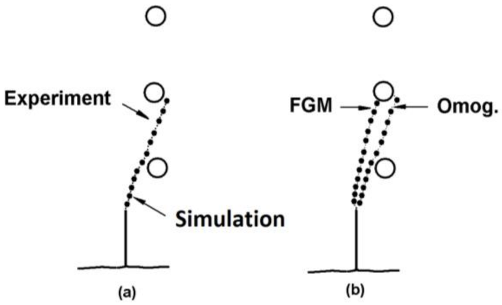

Figure 4. The evolutionary representation of carbon fiber fissure modeling.

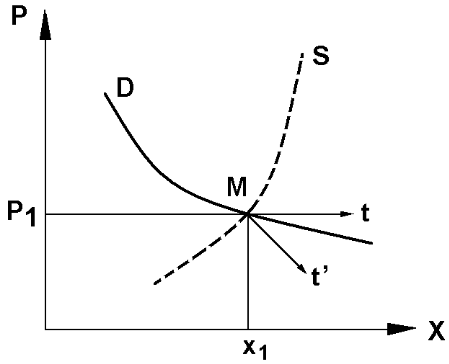

Figure 5. A graph obtained by using the method of presenting an optimal point by the intersection method.

Descriptively, the classical equilibrium conditions are: a positive slope of the mechanical resistance curve of the matrix and a negative slope of the quantitative carbon fiber curve used to reinforce:

$$\frac{\frac{\partial S}{\partial q}}{\frac{\partial D}{\partial q}-\frac{\partial S}{\partial q}} \prec 0 \tag{5}$$

In order to establish an optimum between the matrix type and the reinforcement elements, some conditions for limiting the analyzed range can be set. The equilibrium state of figure 5 is performed if the matrix resistance curve is above the curve of the reinforcement elements, being represented by the formulas:

$$\begin{gathered} \frac{\partial S}{\partial q} \succ \frac{\partial D}{\partial q} \Rightarrow \left(\frac{\partial q}{\partial \alpha}\right)^0 \succ 0 \\ \frac{\partial S}{\partial q} \succ 0 \Rightarrow \frac{\partial q}{\frac{\partial D}{\partial q}-\frac{\partial S}{\partial q}} \prec 0 \end{gathered} \tag{6}$$

5. Conclusions

The fracture analisys is used to assess the durability of a model, having variable geometry defined by the finite elements, when the simultaneously or sequentially loads are applied to it. There is possible to run analyses which are linear or nonlinear.

The model presented in this article can archieve further development as modeling and verification of transient fatigue of composites. This approach can be used to calculate the dynamic stress and the specific effort, thus being able to estimate the wear lifetime of industrial products.

The proposed model offers efficient and flexible tools in order to generate, modify and didsplay the mechanical and thermal properties, necessary for product design, simulation and manufacturing

The analysis of a model with errors can consume a lot of time and money, and often, errors are not detected even after analysis. The proposed model provides a complete set of mathematical and graphical tools for checking and correcting of the model before its use in simulation.

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