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A SHORT REVIEW OF RECENT RESEARCH ON THE MECHANICS OF FRACTURE AND FAILURE IN COMPOSITE MATERIALS

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Abstract: *Composite materials have excellent properties in terms of fracture toughness and low weight. These materials are used for various industrial applications in the field of wind turbine, naval, aircraft and aerospace engineering. However, composite materials usually exhibit far more complex failure mechanisms than traditional metallic alloys. These failure mechanisms involve, for example, matrix deformation, fracture of fibers, interfacial debonding and crack deflection. Extensive studies have been documented in literature using theoretical models, numerical analysis and experimental methods. The article will review the most recent trends of the research on mechanical behavior of composites materials outlining also directions for future investigations.*
Keywords*: Composite material; Fracture; Delamination; Fibre–matrix interface; Interlaminar debonding; Micro-cracking.*

1. INTRODUCTION.

Market requirements pushed people in industry to gradually improve products quality by performing a careful selection of materials and manufacturing technologies. An important example of this philosophy is represented by the use of composite materials. Automotive, biomedical, naval and aerospace industries received a great impulse from the use of composites that allowed specific stiffness of manufactured composites to be significantly improved [1].

Composite materials are comprised of a polymeric matrix including some reinforcement such as fibers. The heterogeneous nature of composite materials pushed designers towards searching the best combination of phases that allows mechanical properties of the material to be optimized. The growing interest in the use of composite materials is confirmed by the blooming of technical papers published on the mechanical behavior of these materials (see, for example, the study carried out by Gibson [2]). Data relative to the US market indicate that the request for composites is expected to grow annually by 10.3% through 2013 [3]. Figure 1, taken from Beck [4], demonstrates how the utilization of composite materials is growing exponentially in strategic fields such as, for example, the aircraft industry.

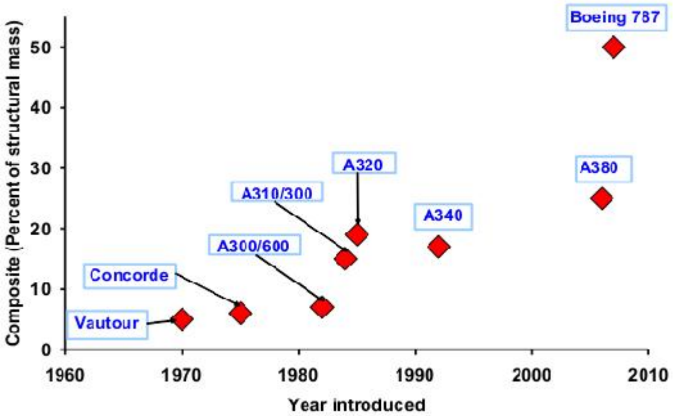

Figure1. Trend of use of composite materials in aircraft industry since 1970 (taken from [4])

However, composite materials still are less diffused than one might expect in view of their excellent mechanical properties. This is due to the limitations put by the heterogeneous nature of these materials. Material heterogeneity manifests itself in different ways and may cause a variety of failure modes during service life. For example, these problems are prominent if the composite matrix has a high degree of porosity (Figure 2) or inclusions [5]. Figure 3 shows that interface debonding will occur as the crack-tip approaches a fiber [6].

Defects may became more severe under the action of applied loads and cause changes in material microstructure that affect at different extents the mechanical behavior of the composite structure. In general, the final effect is to reduce mechanical properties and introduce various types of damage. In view of this, the paper will review the most important failure mechanisms in composite materials highlighted in technical literature.

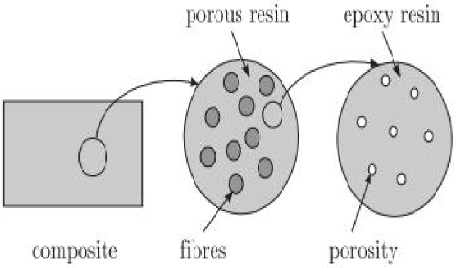

Figure 2. Porosity defect in a composite material [5].

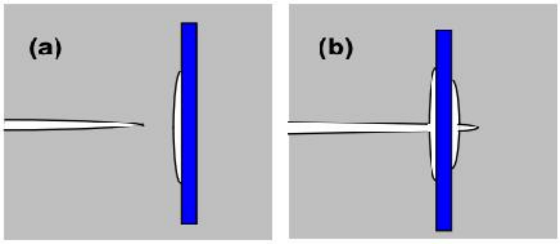

Figure 3. a) Interface debonding starts from left side of a fiber; b) matrix cracking occurs on the right [6].

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2. OVERVIEW ON DAMAGE BEHAVIOR OF COMPOSITE MATERIALS

2.1. Analytical and numerical methods

The first approach to the analysis of the mechanical behavior of a material is represented by theoretical/analytical models. These models may describe some specific damage process (for example, crack initiation or/and propagation), Progressive failure analysis ranging from the most simple load-unload cycling to complex simulations involving linear or non-linear behavior can be done as well. Ribeiroa *et al*. [7] examined the damage process of the composite matrix by defining the strain energy density parameter written in terms of effective stresses:

$$E_d = \frac{1}{2}\left[\frac{\langle \sigma_{22}^2 \rangle_+}{E_{22_0}(1-d_2)} + \frac{\langle \sigma_{22}^2 \rangle_-}{E_{22_0}} + \frac{\langle \tau_{12}^2 \rangle_+}{G_{12_0}(1-d_6)}\right] \quad (1)$$

where σ_{22} and τ_{12}, respectively, are the stress in the direction transverse to fibers and the shear stress; E_{22_0} and G_{12_0}, respectively, are the initial values of the elastic modulus in the direction transverse to fibers and shear modulus; d_2 and d_6 are damage parameters related to σ_{22} and τ_{12}, respectively.

The mechanisms of interlaminar fracture were analyzed by Krause *et al*. [8]. Fibre–matrix interface failure between plies and multiple small delaminations were modeled with Linear Elastic Fracture Mechanics (LEFM). Crack propagation in mode I from pre-existing defects was computed using the critical energy release rate. For that purpose, two main approaches can be followed: "area" methods expressed by Eq. (2) and "compliance" methods expressed by Eq. (3).

$$G_{IC} = \frac{1}{b(a_{i+1}-a_i)}\int_{P_S} P(\delta)d\delta \quad (2)$$

In the above equation, δ is the displacement of the cantilever arms loading the specimen and equals the crack opening; b is the width of the tested specimen; a_i and a_{i+1} are the crack lengths before and after crack progress; P_s is the area swept by the loading curve $P(\delta)$.

$$G_{IC} = \frac{P_C^2}{2b}\frac{dC}{da} \quad (3)$$

In Eq. (3), $C=\delta/P$ is the compliance evaluated at each point of the load–displacement curve; δ is the relative displacement between two adjacent points of the load path (i.e. corresponding to crack lengths a_i and a_{i+1}, respectively); P_c is the critical load at which fracture propagates.

For mixed mode loading, Zhang et al. [9] proposed the strain energy release rate parameter (SERR), normalized with respect to the fatigue delamination resistance (G_c) (Eq. 4).

$$G_C = \int_0^{\delta^*} \sigma_b(\delta)\, d\delta + G_0 \tag{4}$$

where: σ_b and δ , respectively, are the bridging stress and the crack opening displacement (COD); G_0 is the critical value of the SERR parameter in presence of initial delamination; δ^* is the COD at the pre-crack tip.

The above mentioned approach was utilized to determine the delamination growth rates and threshold of composite laminates subject to mixed I/II mode fatigue loading.

Another technique for predicting the damage of fiber-matrix composite structures is the progressive failure analysis. Different models were developed by Fan et al. [10] and Liu et al. [11]. The most important approach followed to detect the micromechanical damage of composite pressure vessels is the modified Mises failure criterion:

$$\left(\frac{\sigma_{eq}}{\sigma_{eq}^{cr}}\right)^2 + \frac{J_1}{J_1^{cr}} = 1 \tag{5}$$

where: $\sigma_{eq} = \sqrt{\frac{3}{2} S : S}$ is the Mises effective stress, $J_1 = tr(\sigma)$ is the first stress invariant; $S = \sigma - tr(\sigma)/3I_2$ is the deviatoric stress tensor; I_2 is the second-order unit tensor; $\sigma_{eq}^{cr} = \sqrt{T_m C_m}$ and $J_1^{cr} = C_m T_m / (C_m - T_m)$ are critical values.

Sun *et al*. [12] applied the progressive failure analysis approach to assess mechanical behavior of fiber-reinforced composites. They mentioned two conditions for micromechanics-based failure: one refers to the fiber failure state, Eq. (6); the other refers to matrix (inter-fiber) failure, Eq. (7).

$$\frac{\sigma_{f1}^2}{T_f C_f} + \left(\frac{1}{T_f} - \frac{1}{C_f}\right)\sigma_{f1} = 1 \tag{6}$$

$$\frac{\sigma_{VM}^2}{T_m C_m} + \left(\frac{1}{T_m} - \frac{1}{C_m}\right) I_1 = 1 \tag{7}$$

In the above equations, T_f, C_f, T_m and C_m are the tensile and compressive strengths of fibers and matrix, respectively (all these entities are calculated from ply strengths); σ_{f1} is the micro-longitudinal stress in the fibre; σ_{VM}, I_1 and I_2, respectively, are the von Mises stress, the first and second stresses invariant computed for the composite matrix;

$$\begin{cases} \sigma_{VM} = \sqrt{I_1^2 - 3I_2} \\ I_1 = \sigma_1 + \sigma_2 + \sigma_3 \\ I_2 = \sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1 - \left(\tau_{12}^2 + \tau_{23}^2 + \tau_{31}^2\right) \end{cases} \tag{8}$$

In order to define the damage model, Sun *et al*. [12] used a non-iterative element-failure method criterion based on the equivalent stress:

$$\sigma_{eq} = \frac{(\beta_m - 1) I_1 + \sqrt{(\beta_m - 1)^2 I_1^2 + 4\beta_m \sigma_{VM}^2}}{2\beta_m} \tag{9}$$

where $\beta_m = C_m / T_m$.

Pemberton *et al*. [13] developed another model that predicts the fracture energy of ceramic–matrix composites. In this approach, fracture is caused by pull-out and/or plastic deformation of fibres bridging the crack plane. The contribution of pull-out to the fracture energy is expressed as:

$$G_{cpo} = \left(\frac{f}{2\pi R^2}\right)\pi R x_0^2 \tau_{i*} = \frac{f s_{po}^2 R \tau_{i*}}{2} \tag{10}$$

where the fiber protrusion aspect ratio, s_{po}, is equal to x_{0po}/R (see Figure 4b) or, equivalently, can be expressed by the ratio of δ_{po} (average length of fiber protruding beyond the crack plane), to R.

A model involving both plastic deformation and fiber rupture should assume that the interfacial debonding is an extension of crack plane (Figure 4c). The resistance to fracture debonding can be expressed in terms of energy as:

$$G_{cfd} = 2x_{ofd}\left(\frac{f}{2\pi R^2}\right) W_{fd} \pi R^2 = x_{ofd} f W_{fd} \tag{11}$$

where: $2x_{ofd}$ is the initial length of fiber; U_{fd} and W_{fd} are the deformation work for the fiber expressed per fiber unit length (J/m) or unit volume (J/m^3), respectively. The fracture process is schematized in Figure 4.

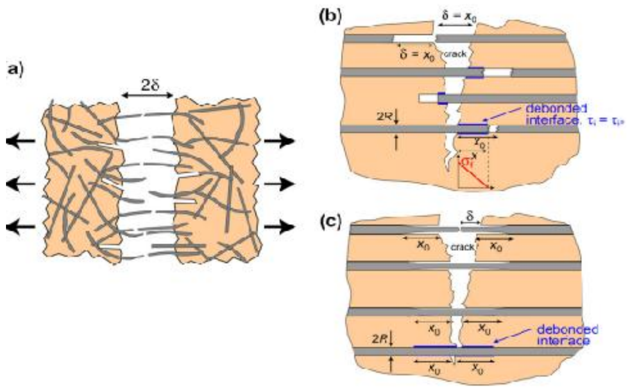


Figure 4. Representation of the fracture process [13]: a) general fracture geometry;
b) debonding at matrix-fiber interface causing fracture and then frictional pull-out;
c) fibers undergoing debonding, plastic deformation and then fracture.

Patrícioa and Mattheij [14] developed an incremental algorithm to predict the evolution path of pre-existing cracks in composite materials. They utilized the maximum circumferential tensile stress criterion: crack growth occurs when the maximum of $K_{\theta\theta}(\theta)$ reaches the value of the critical stress intensity factor K_{IC}:

$$\max_{\theta} K_{\theta\theta}(\theta) = K_{IC} \tag{12}$$

The angle defining the direction of propagation of the crack was computed with Eq. (13) once that the propagation mechanism was defined (see Figure 5). Figure 6 shows how the crack will propagate between composite layers.

$$\theta_p^{(K)} = 2\arctan\left(\frac{K_I - \sqrt{K_I^2 + 8K_{II}^2}}{4K_{II}}\right) \tag{13}$$

where K_I and K_{II}, are the stress intensity factors for modes I and II, respectively.

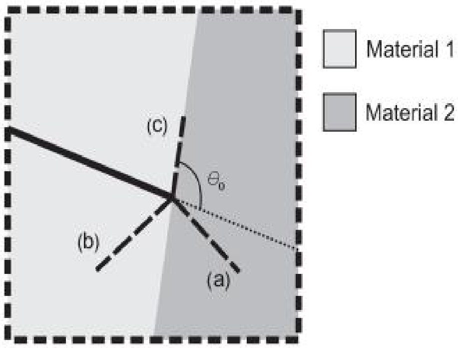


Figure 5. a) Penetrating crack; b) reflected crack; c) crack deviated along the interface [14].

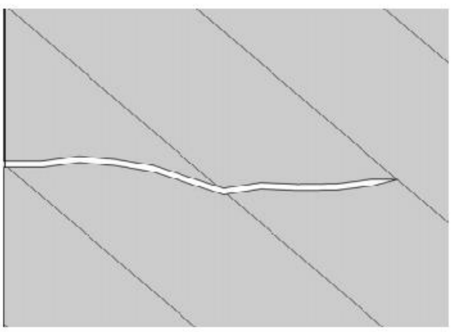
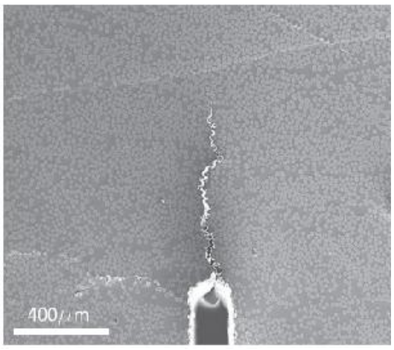


Figure 6. Crack propagating through layers [14].

2.2. Experimental methods

Analytical and numerical models of fracture must be corroborated by experimental evidence. Researchers focused their attention on nondestructive methods. In particular, we should mention: optical microscopy, scanning electron microscopy (SEM), nano-indentation, Eddy currents, Dye penetrant inspection (DPI) (also called liquid penetrant inspection (LPI)), ultrasonic tests, magnetic particle methods and acoustic emission.

Canal *et al*. [15] carried out nano-indentation tests on matrix pockets. The tested specimens are fiber-reinforced composites applied to notched beams. The interface strength was measured by means of push-out tests done on thin slices of material. Specimens were inspected with a SEM microscope. Figure 7 shows the typical pattern obtained in the experiments including a number of decohesed interfaces connected by matrix ligaments.

a) 

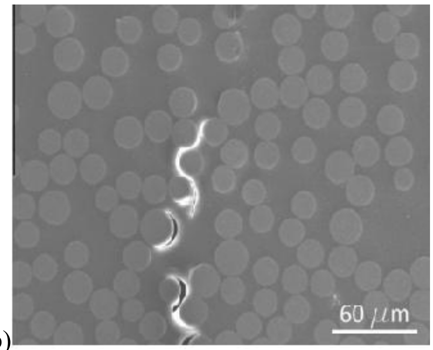
b) 

Figure 7. Damage processes by interface decohesion and matrix failure in front of the notch tip [15].

Okoli and Abdul-Latif [16] considered the pullout of fibers to depend on the matrix-fiber bond strength and load transfer mechanisms. The progress of damage depend on the interaction between the increasing in loading rate and the interfacial bond strength. As fibers are pulled out, matrix debonding occurs and produces cracking and disintegration of matrix (Figure 8).

a) 

b) 

Figure 8. a) Tufnol 10G/40 laminate showing fibre-matrix delamination and debonding (×1140); b) Tufnol 10G/40 laminate showing brittle failure with fiber breaking (×541) [16]

Abdizadeh and Baghchesara [17] observed that fracture is controlled by the inter-dendritic cracking of the matrix. In addition, a number of dimples were observed on the fractured surfaces of all samples. This may be due to void nucleation and subsequent coalescence during the fracture process.

Sabirov and Kolednik [18] analyzed the effect of matrix strength and the mechanism of void initiation. Maximum principal stresses generated in the matrix structure at the moment of void initiation are not constant, but show a dependency on the yield strength of the composite material. Local changes in material properties depend on the void initiation, but may also be caused by debonding rather than matrix fracture.

Amato de Campos *et al*. [19] used a conventional optical microscope combined with the extended depth-of-field 3-D reconstruction method to detect intense fiber decohesion in warp and interlaminar fracture mechanisms in a plain-weave carbon/epoxy composite. Furthermore, during tests, resistance to delamination failure was measured with high-speed video photography by recording the specimen displacement and crack length history [20].

Xu *et al*. [21] carried out seawater tests over a period of about 29 months. The level of degradation of matrix and fibers caused by the exposure to seawater was around 10%. Several failure mechanisms including interlaminar debonding, microcracking and sublaminate buckling were detected.

3. CONCLUSIONS

This paper presented a short review of state-of-the-art failure models and experimental investigations on the fatigue and fracture behavior of composite materials and structures recently published in literature. It appears that the fracture process starts with void nucleation and is followed by crack growth, matrix debonding, delamination and fiber breaking. Special cares should be taken to keep under control the rate of reduction of mechanical properties which may occur during life service. This requirement brings a number of issues relatively to experimental testing and numerical modeling. In fact, either experimental techniques for real time monitoring of damage evolution should be available or multi-scale analyses of damage mechanisms should be performed. These multi-scale models must be corroborated by experimental evidence and may be multi-fidelity models entailing different level of complexity in the same analytical/numerical framework. Parametric studies may help analysts to tune multi-scale models as well as to design the experimental set up best suited for the particular problem dealt with.

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REFERENCES

[1]. Automotive Plastics & Composites. *Worldwide Markets and Trends to 2007*. Elsevier Science Ltd. (1999).
[2]. R.F. Gibson. A review of recent research on mechanics of multifunctional composite materials and structures. *Composite Structures* 92 (2010) 2793–2810.
[3]. http://www.reinforcedplastics.com/view/13565/composites-2011-looking-to-the-us-industry-s-future/
[4]. A.J. Beck, A. Hodzic, C. Soutis, C.W. Wilson. *Influence of Implementation of Composite Materials in Civil Aircraft Industry on Reduction of Environmental Pollution and Greenhouse Effect.* University of Sheffield (UK) (2008).
[5]. H. Welemane, H. Dehmous,. Reliability analysis and micromechanics: A coupled approach for composite. *International Journal of Mechanical Sciences* 53 (2011) 935–945.
[6]. R. Zhou, Z. Li, J. Sun. Crack deflection and interface debonding in composite materials elucidated by the configuration force theory. *Composites: Part B* 42 (2011) 1999–2003.
[7]. M.L. Ribeiroa, V. Tita, D. Vandepitte. A new damage model for composite laminates. *Composite Structures* 94 (2012) 635–642.
[8]. T. Krause, K. Tushtev, D. Koch, G. Grathwohl. Interlaminar Mode I crack growth energy release rate of carbon/carbon composites. *Engineering Fracture Mechanics* (2012) (In press).
[9]. J. Zhang, L. Peng, L. Zhao, B. Fei. Fatigue delamination growth rates and thresholds of composite laminates under mixed mode loading. *International Journal of Fatigue* 40 (2012) 7–15.
[10]. X. L. Fan, T. J. Wang, Q. Sun. Damage evolution of sandwich composite structure using a progressive failure analysis methodology. *Procedia Engineering* 10 (2011) 530–535.
[11]. P. F. Liu, J. K. Chu, S. J. Hou, J. Y. Zheng. Micromechanical damage modeling and multiscale progressive failure analysis of composite pressure vessel. *Computational Materials Science* 60 (2012) 137–148.
[12]. X. S. Sun, V. B. C. Tan, T. E. Tay. Micromechanics-based progressive failure analysis of fibre-reinforced composites with non-iterative element-failure method. *Computers and Structures* 89 (2011) 1103–1116.
[13]. S. R. Pemberton, E. K. Oberg, J. Dean, D. Tsarouchas, A. E. Markaki, L. Marston, T. W. Clyne. The fracture energy of metal fibre reinforced ceramic composites (MFCs). *Composites Science and Technology* 71 (2011) 266–275.
[14]. R.M.M. Mattheij, M. Patrícioa. Crack paths in composite materials. *Engineering Fracture Mechanics* 77 (2010) 2251–2262.
[15]. L.P. Canal, C. González, J. Segurado, J. LLorca. Intraply fracture of fiber-reinforced composites: microscopic mechanisms and modeling. *Composites Science and Technology* 72 (2012) 1223–1232.
[16]. O. Okoli, A. Abdul-Latif. Failure in laminate composites: overview of an attempt at prediction. *Composites. Part A* 33 (2002) 315-321.
[17]. H. Abdizadeh, M.A. Baghchesara. Investigation on mechanical properties and fracture behavior of A356 aluminum alloy based ZrO_2 particle reinforced metal-matrix composites. *Ceramics International* (2012) (In Press).
[18]. Sabirov, O. Kolednik. Local and global measures of the fracture toughness of metal matrix composites. *Materials Science and Engineering* A527 (2010) 3100–3110.
[19]. K. Amato de Campos, J. Augusto, T.A. Pereira, L.R. de Oliveira Hein. 3-D reconstruction by extended depth-of-field in failure analysis – Case study II: Fractal analysis of interlaminar fracture in carbon/epoxy composites. *Engineering Failure Analysis* 25 (2012) 271–279.
[20]. B.R.K. Blackman, A. J. Kinloch, F.S. Rodriguez-Sanchez, W.S. Teo. The fracture behaviour of adhesively-bonded composite joints: Effects of rate of test and mode of loading. *International Journal of Solids and Structures* 49 (2012) 1434–1452.
[21]. L. Roy Xu, A. Krishnan, H. Ning, U. Vaidya. A seawater tank approach to evaluate the dynamic failure and durability of E-glass/vinyl ester marine composites. *Composites: Part B* 43 (2012) 2480–2486.