NUMERICAL ANALYSIS OF FRACTURE MECHANICS IN COMPOSITE MATERIAL REINFORCED WITH FIBERGLASS

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Abstract. *Due the use of composite materials in structural engineering, understanding the nature and failure mechanisms for application in numerical simulations of crack propagation in these materials, it is essential to examine the approximate behavior in which the structure will be in its critical state. Thus, this paper aims to analyze computationally the crack propagation in polymeric composite material reinforced with fiberglass – polymethymethacrylate (PMMA). Performing the numerical modeling of the matrix and fiber, in order to evaluate the interaction that occurs in its interface, and using the extended finite element method (XFEM), integrated into ABAQUS software, to simulate the crack. The results obtained computationally are faced with experimental data in tensile tests, based on relations of the damage variable and normal stress with the strain in the numerical simulation*

Keywords: *Extended finite element method, composite materials, fracture mechanics, numerical analysis*

1. INTRODUCTION

With the high applications of composite materials in aerospace, aeronautics, naval and war industry, in prostheses, and various structural components, studies on its mechanical behaviors become essential for a better understanding of them. One of the fields unexplored are the studies on the process of failure of these materials, which includes analysis of the mechanisms involved in the damage and fracture, and the interaction between the matrix and fiber in critical state of the composite material. The composite material analyzed in our study is the PMMA (polymethylmethacrylate) reinforced with fiberglass. PMMA is a thermoplastic polymer that has high mechanical strength, high modulus of elasticity, low strain at break. It is widely used in various segments: industry, artifacts, medicine, dentistry, medicine and others (Netto, Wanderley, Araújo, Evêncio and Santana, 2009).

Through the development of computational tools and the use of numerical methods applied to engineering structures, numerical simulations of structural behavior of materials were possible. For the fracture analysis in materials, it was developed, and it is widely used, the Extended Finite Element Method (XFEM), which allows the analysis of crack propagation with quite accurate results compared to experimentally obtained.

This paper presents the study of the polymer composite reinforced with fiberglass E, polymethylmethacrylate (PMMA) behavior, in Mode I fracture toughness. Using the calculation code, ABAQUS, for numerical simulations with XFEM implementation in the modeling the crack. Introducing the modeling of fiber embedded in the polymer matrix, and analyzing the interactions between them in the fracture, comparing the computational results with those obtained experimentally by Oliveira Júnior (2004) in his work.

2. METHODS

2.1 Extended finite elements method

The Extended Finite Element Method (XFEM) is a very effective tool for numerical analysis of crack problems (Giner, Sukumar, Tarancón and Fuenmayor, 2008). Their use extends from modeling of mass fracture, and for application in the study of composite failure (eg, delamination) and for analyzing the crack propagation in linear and non-linear materials.

The XFEM has the advantages of easy initial setting of the crack process, because the mesh is generated independent of the crack, and the partitioning of geometry is not needed at the crack location as in the case of conventional finite element method (Krishnan, 2014).

The representation of discontinuity in modeling the crack in XFEM need, first, to incorporate in this model, a geometry that represents the discontinuity, the cut made by the crack, and a set of solutions based on the finite element method to quantify and locate this discontinuity.

The quantification of the magnitude of discontinuity, in other words, interpolation of displacement through failure faces are defined by two terms: Heaviside function H(x) and Asymptotic function $F_\alpha(x)$. As shown by Ye *et al* (2012) the Heaviside function H(x) and Asymptotic function $F_\alpha(x)$ are used to enrich the nodes on the crack path and the nodes near the crack tip, respectively to account for the displacement discontinuity and singularity at the crack tip, as shown in Eq. (1).

$$u^h(x) = \sum_{I\in N} N_I(x)[u_I + H(x)a_I + \sum_{\alpha=1}^{4} F_\alpha(x)b_I^\alpha] \tag{1}$$

where H(x) is the heavisidade distribution, a_I is the enriched node DOF to jump discontinuity, $H(x)a_I$ represents all nodes belonging to the element cut by crack, $F_\alpha(x)$ are the asymptotic functions of the crack tip, b_I is the DOF node to enrich the crack tip, $F_\alpha(x)b_I$ represents all nodes belonging to the elements containing the crack tip, as can be seen in Figure 1.

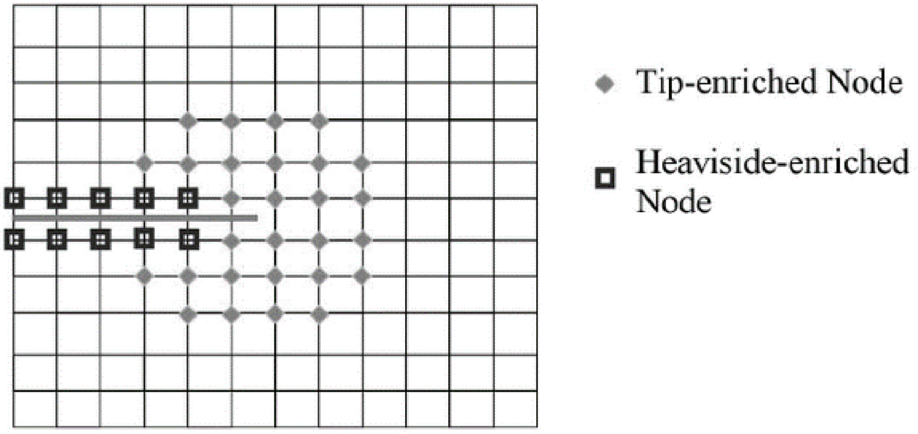


Figure 1 – enriched nodes on XFEM

The location of the crack in the model using XFEM, is based on level-set method (LSM). The level set of a real-valued function is the set of all points at which the function attains a specified value. It is a technique for represent surfaces in interface tracking problems, in this case, in the tracking the crack. Two functions are used to completely describe the crack, the Φ and Ψ functions. These functions are defined by nodal values whose spatial variation is determined by the function of the element geometry. The level set Φ = 0 represents the crack surface. The intersection between the level set Φ = 0 and Ψ = 0 denotes the crack front as shown by Krishnan (2014).

Finally, you must declare the modeling material damage. In ABAQUS software, for the damage modeling in XFEM, two types of modeling can be set: cohesive damage and damage based on fracture mechanics (mechanics of linear elastic fracture and/or elastic-plastic fracture mechanics). The first is rather applied to delamination, whereas the second is based on computing the energy released rates for normal modes and shear deformation at the crack tip.

2.2. Fracture mechanics concepts

The fracture mechanics analyzes admissible defects and the mechanisms that cause the cracks nucleation in a material, proving to be a useful tool to assess the load capacity of structures containing one or more pre-existing cracks in a given position, length and orientation (Bodnar et al, 2000). It is divided into mechanics of linear elastic fracture (LEFM) and elastic-plastic fracture mechanics (EPFM). In this study we will be addressed the LEFM analysis.

In the elastic-plastic fracture mechanics represents the cracks behavior in materials with non-linear behavior and time-independent. The fracture analysis can be made by two parameters: CTOD (crack-tip-opening displacement) and the contour integral J.

The CTOD was studied and developed by Well in 1961. This fracturing parameter proposes the opening at the crack tip as a measure of fracture toughness. The integral J, in other hand, quantifies the energy flow through a closed contour around the crack tip (Anderson, 2005).

2.2.1. Energy release rate

Considering a plane stress and with a crack propagating, the total energy E of the system is divided between the potential energy Π produced by energy due to deformation and external forces, and the work Ws required to create new surfaces as a result of crack Eq. (2).

$$\frac{dE}{dA} = \frac{d\Pi}{dA} + \frac{dW_S}{dA} = 0 \tag{2}$$

In 1956, Irwin defined the G energy release rate as the potential energy Π, which is a measure of energy available to an increase of crack extension. Where G is the rate of change in potential energy to the area A of the crack Eq (3).

$$\frac{dG}{dA} = -\frac{d\Pi}{dA} \tag{3}$$

2.2.2. Stress intensity factor

In the crack propagation process, three types distinct fracture mode may occur (Figure 2):

a) Mode I – the main load is applied to the crack plane tending to open it;
b) Mode II – It corresponds to a shear load in the plane, and tends to slide one of the crack faces in the other
c) Mode III – load shear off the plane.

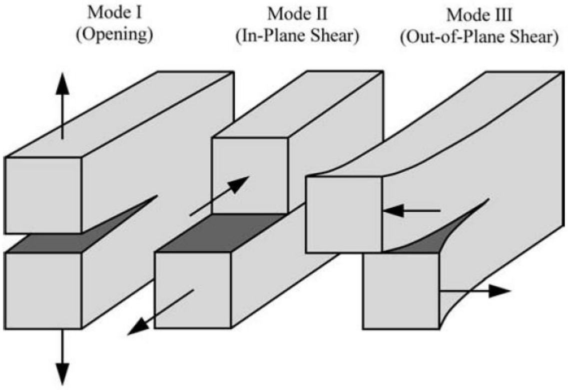


Figure 2 – Three modes of fracture: Mode I, Mode II and Mode III

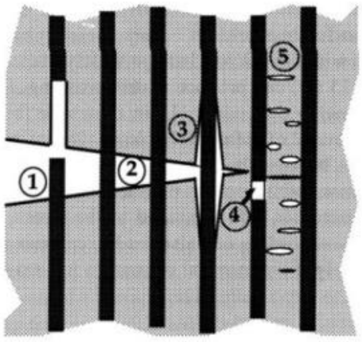
The stress intensity factor completely defines the increase in the crack tip in the ratio of K, serving as a scale factor to characterize the magnitude of the stress field. According to applied load mode, K will present a distinct value for Mode I, Mode II and Mode III (K_I, K_{II} e K_{III}, respectively). This study will explore the Mode I in numerical modeling.

2.3. Fracture mechanics of composite materials reinforced with fibers

Composite materials, as shown by Reinhart & Clements *apud* Oliveira Júnior (2004), are defined as a macroscopic combination of two or more distinct materials having a recognizable interface between them. In this combination, the constituents retain their identities, or rather, they do not dissolve completely, or mischaracterize and act together making the composite properties are higher than those of each individual constituent.

The fracture of composites reinforced with glass fibers are often controlled by numerous microcracks distribution through the material, rather than a simple macroscopic crack. There are situations where the fracture mechanics is suitable for composites, but it is important to recognize the limitations of the theories that were assigned to homogeneous materials (Anderson, 2005).

According to Veiga (2014), the composite materials rupture can be divided into two categories, intra-laminar breakage and interlaminar (Figure 4). In the case of intra-laminar breakage, the rupture occurs in the layers of the composite which can be at the matrix level, break of fibers and interfacial decohesion fiber/matrix, friction fiber/matrix after decohesion, and pullout of fibers. The interlaminar fracture or delamination, is a displacement between two adjacent layers, normally occurring between layers with different orientations, this type of fracture is common in continuous fiber materials.



1. Fiber pull-out
2. Fiber bridging
3. Decohesion fiber/matrix
4. Rupture of fibers
5. Cracking of the matrix

Figure 4 – Representation of the failure mechanisms of composite material

2.3. Numerical analysis

In numerical analysis was used the software based on the finite element method, ABAQUS, with implementation of XFEM for analysis of simulation of crack propagation. In the modeling of fiber embedded in the matrix, we used a Representative Volume Element (RVE), by submitting the tensile stress to verify the Mode I fracture in the composite (Figure 5).

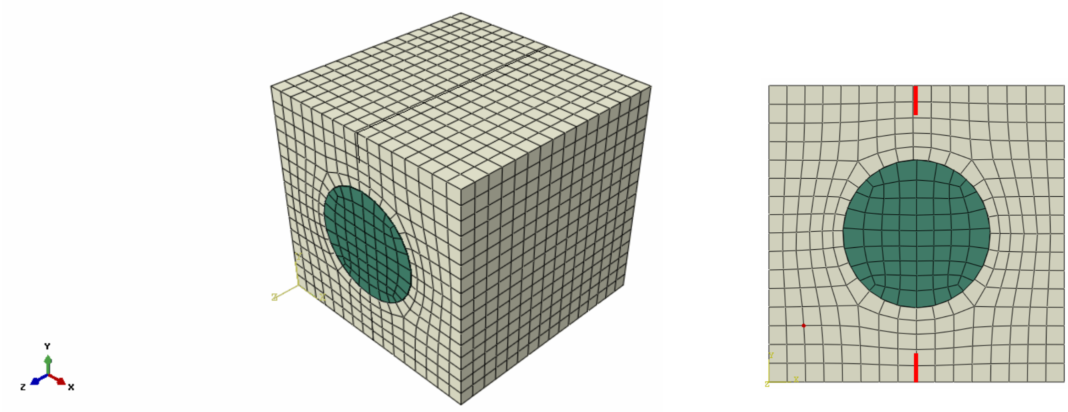


Figure 5 – Model for analysis of fracture. RVE modeling with fiber embedded in matrix submitted to fracture Mode I with initial cracks (red line).

The mechanical properties of the matrix (PMMA) and fiber (fiberglass E) have been defined from the data presented in the work of Oliveira Junior (2004) and materials tables at the Massachusetts Institute of Technology (Table 1). In the PMMA was considered the modeling of the non-linearity, in addition to modeling of damage initiation and damage evolution in the polymer matrix.

Table 1 – Definition of mechanical properties of the polymeric matrix PMMA and Fiberglass E

Properties Mechanics - Elasticity	PMMA	Fiberglass E
Young's Modulus (MPa)	2500	72400
Poisson's ratio	0.35	0.2
Fracture Criterion – Interaction		
Critical energy release rate G_{Ic} (kJm^{-2})	500	-

In the contact definition, the surface of the fiber was declared as the *master surface* while the matrix surface in contact with the fiber was declared as *slave surface*, adopting *small sliding* to restrict movement between the nodes of contact surfaces. The fiber-matrix interface was defined as *cohesive behavior* so that only the nodes, fiber and matrix, initially connected submit this behavior. All *slaves nodes* outside of this set will experience only compressive contact forces during the analysis. In this model was not defined the criteria for initiation and evolution of damage in the interface.

The mesh was assigned with C3D8 elements (hexahedral element with 8 nodes) throughout the model. It was used the medial axis mesh control algorithm, to minimize the mesh transition when it moves from a coarse mesh to a fine mesh. Overall, it was adopted medium mesh in the model not to present inconsistent results and to avoid a high computational effort in processing.

The boundary conditions were set so that the model suffers only tensile stresses and that the pure Mode I fracture was observed.

3. RESULTS

According to the RVE model suggested, the numerical simulation results were analyzed in order to observe the crack propagation, the stresses acting on the crack itself and the fiber-matrix interface in critical condition.

The numerical results of the von Mises stress can be seen in Figure 6. We can see the crack propagation to the meeting of the fiber-matrix interface, and where we have stresses between 390 MPa and 440 MPa, featuring the rupture of the composite. Very similar values to those found experimentally by Oliveira Junior (2004) in his work, with ultimate stress of 451.56 MPa for the composite reinforced his tensile tests (Figure 7).

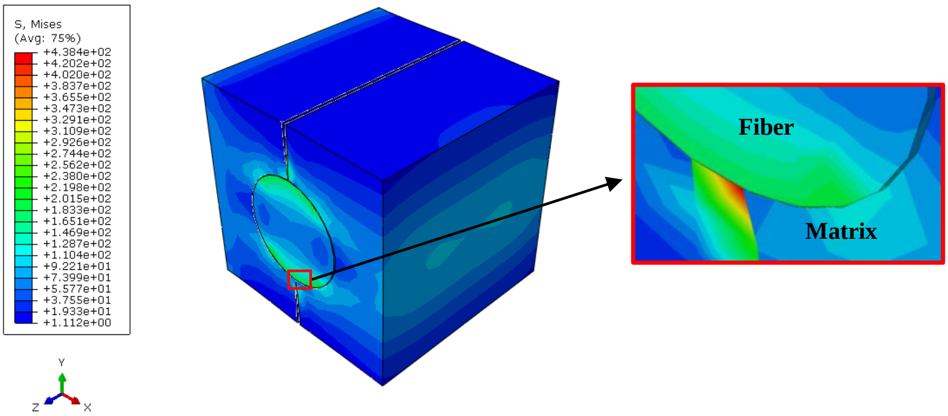


Figure 6 – Von Mises stresses in the RVE

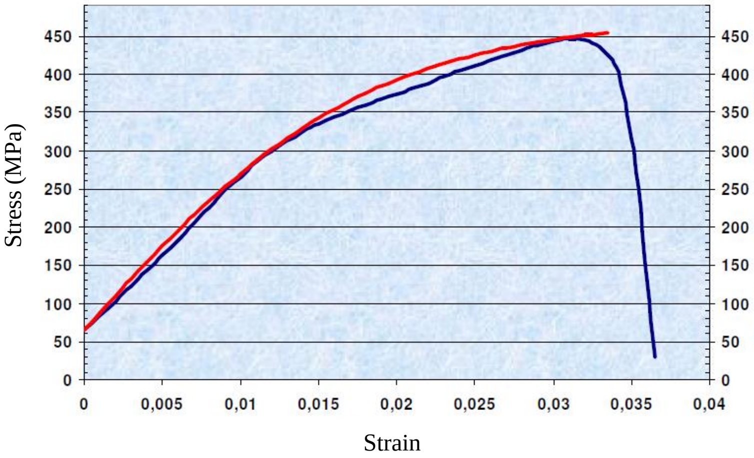


Figure 7 – Stress x strain diagram obtained in tensile testing (blue line) in PMMA reinforced with fiberglass by Oliveira Júnior (2004). On the red line, we have an approximation of the behavior of composite material through a hyperbolic tangent function.

Analyzing the numerical results to observe the mode I in the RVE (Figure 8), we see the tensile stresses break of the matrix PMMA at the crack tip with values between 52 MPa and 92 MPa, consistent values with those found in the literature, values of tensile strength between 48.3 MPa and 79.6 MPa (Cambridge University Engineering Department, 2003). It was also verified in the fiber/matrix interface, tensile stress of 170 MPa in the RVE. Thus, it was examined in software Abaqus the CSMAXUCRT, in order to understand the damage in cohesive surface of fiber/matrix interface (Figure 9), where 0 means interface no damage, and 1 interface totally damaged. We observed in the fiber/matrix interface, largely on the contact surface in the interface, totally damaged areas (see Figure 9), which we characterize as the separation fiber/matrix for the propagation of cracks in polymer matrix.

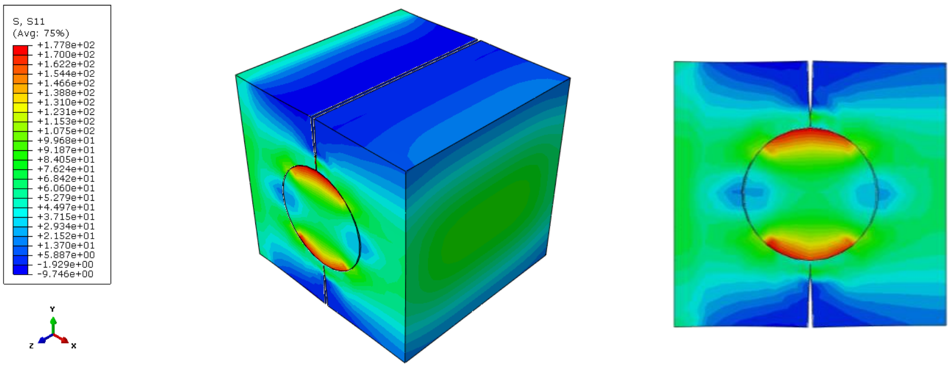


Figure 8 – Tensões de tração (σ_{xx}=S11) no RVE

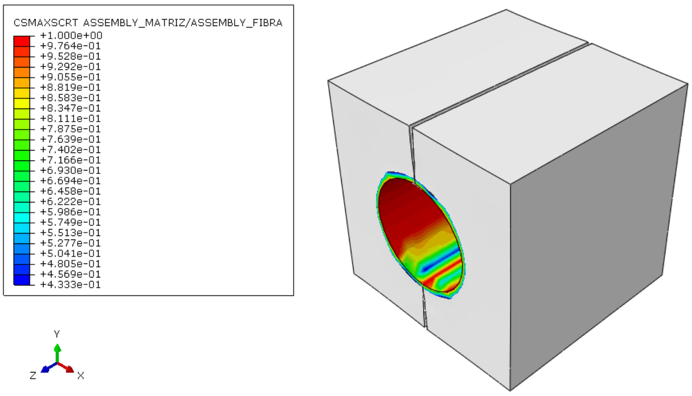


Figure 9 – Stress x strain diagram obtained in tensile testing in PMMA reinforced with fiberglass by Oliveira Júnior (2004)

In addition, we observe the matrix PMMA surrounding the fiber, the crack propagation and its complete fracturing, as can be seen in STATUSXFEM (Figure 10), which shows the conditions of the nodes enriched, where the value 0 is the matrix in its healthy state, and 1 represents the fully cracked material. For intermediate values, we are partially fractured matrix. We observed that there was decohesion the fiber/matrix interface due to the polymer matrix fracturing.

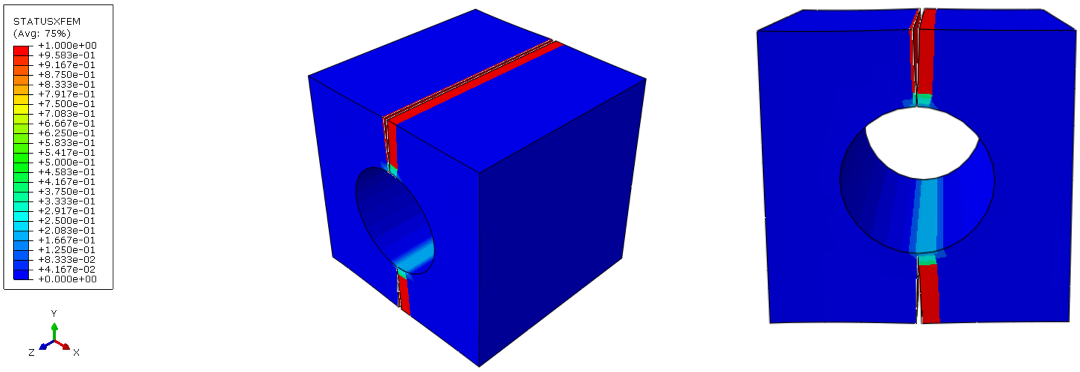


Figure 10– The numerical results STATUSXFEM. The conditions of the enriched element nodes.

4. CONCLUSIONS

We realized in our analysis, quite similar results between the numerical simulation and in assays. What highlights the importance of good modeling techniques to analyze the behavior of materials in their break states, which would help in the design and development of engineering structures.

We conclude that analysis of the polymer composite with multiple fibers in the matrix would be required to relate to the experimental results obtained numerically and validate in this paper. As well as consider the initial and evolution damage criteria in the contact properties in the fiber-matrix interface, which will be titles for future studies to be developed.

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