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Using XFEM technique to predict the damage of unidirectional CFRP composite notched under tensile load

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Abstract. The composite materials are widely used in aircraft structures. Their relative rigidity/weight gives them an important advantage over the metal structures. The objective of this work is to analyze by the finite element method the mechanical behavior of composite plate type notched with various forms under tensile load. Two basic parameters were taken into consideration. The first, the form of the notch in order to see its effect on the stress and the failure load. The second, we studied the influence of the locale orientation of fiber around the plate's notch. These parameters are studied in order to see their effects on the distribution stress and failure load of the plate. The calculation of the failure load is determined numerically with the numerical code ABAQUS using the XFEM (extended Finite Element Modeling) based on the fracture mechanics. The result shows clearly that it is important to optimize the effect of fiber orientation around the notch.

Keywords: CFRP (reinforced carbon fiber polymers); XFEM (extended finite element modeling)

1. Introduction

Several mechanism of damage can occur in composite structures, such as delamination of the fiber-matrix interface, delamination of the interlayer's in the case of the laminates and or else breakage of the fibers. These mechanisms can occur simultaneously due to the effect of several parameters such as the type of loading and the boundary conditions. The necessary presence of some form of the notch in the structures causes an imbalance of resistance near the notch. Several researchers have been interested in this research axis in order to characterize this phenomenon. (Kirsh *et al.* 1898) was the first to study the phenomenon of stress concentration and distribution around a hole. Subsequently, Analytical solutions have been gradually found by various

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researchers for increasingly complex geometries. Hence the necessity of existence of these forms of notch in the conceptions, (Neuber and Peterson *et al.* 1997) contributed greatly to the knowledge of this domain by making a systematic analysis of the main geometries and forms.

Like most high-performance composites, reinforced carbon fiber polymers (CFRP) have favorable material properties of a strength-to-weight ratio and remarkable stiffness, which makes them more usable in a wide field of industries, Including aerospace, navy, armor, and other infrastructure applications (Deshpande and Tseng *et al.* 2007). In addition, The CFRP has an impressive tensile strength in the plane, resistance to traction-tension, fatigue, impact resistance, the sustainability (Seyhan *et al.* 2008) and corrosion resistance. However, CFRP composites do not have only optimum qualities, they also have several disadvantages, like poor compressive strength, tensile-compression fatigue and a limited resistance to interlaminar fiber-matrix. They also have a delamination due to the fracture toughness that is limited in the polymer matrices (Davis *et al.* 2011).

Victor *et al.* (2015) used different approaches based on tensile tests and ultrasonic characterization to determine the mechanical properties of transversely isotropic carbon fiber composite material.

The aim of all research is always to understand the phenomenon of initiation and propagation of crack, which end the lifetime of aeronautical structures. Significant efforts have been devoted to optimize for strengthening of the weakened structure part to restore structural efficiency and thus ensure the safety of the structures. These composite structures consist of complex material interactions and can be analyzed at differently sized scales. The majority of research has focused on investigating composites in a large scale, where the composite is assumed to be a homogenous material with averaged mechanical properties. Other research has focused on the random nature of individual fibers in the microscopic scale. With the XFEM, a wide range of composite materials can be evaluated. For example, (Benvenuti *et al.* 2012) applied XFEM concepts to modeling FRP-reinforced (concrete and Sosa and Karapurath *et al.* 2012) used XFEM to model delamination of fiber-metal laminate composites with orthotropic material properties. (Moreno *et al.* 2015) modeled and analyzed crack propagation inchopped glass-fiber composites under biaxial loading. (Motamedi *et al.* 2013) investigated the non-uniform nature of composites using a combination of XFEM and other commercial FEM software. Instead of using typical isotropic material properties, (Nagashima and Suemasu *et al.* 2006) developed an orthotropic material model undergoing mode I delamination.

By using the technique of XFEM, our study consists to a direct use of global composite failure property given in table (3). A key advantage of XFEM is that in such problems the finite element mesh does not need to be updated to track the crack path and also it does not require to follow a predefined path. Subsequent research has illustrated the more general use of the method for problems involving singularities, material interfaces, regular meshing of micro structural features such as voids. It's why other researchers use this technique for patch repair (Marlett *et al.* 2011). Actually, cracks can grow freely within a bulk region of a material without the requirement of the mesh to match the geometry of the discontinuities neither remeshing near the crack (Koerber *et al.* 2009) and (Camanho *et al.* 2007), however, for highly curved cracks the software needs to perform some minimum re-meshing.

The purpose of this work is to conduct a systematic investigation of the orientation effect of the fibers at the side of the notch on the resistance of composites structure with different notch geometries. To obtain the stress distributions and failure load under mechanical with damage behaviour, the finite element analysis was investigated by tensile loading of several plates with notches of various forms and varied dimensions.

2. XFEM technique

The X-FEM uses the concept of partition of finite element unity and enrichment function. The enrichment functions are expressed as follows (Moes *et al.* 1999)

$$Uxfem(X) = \sum_{i \in \Gamma} Ni(X)_{ui} + \sum_{i \in J} Ni(X)H(X)_{ai} + \sum_{i \in K} [Ni(X) \sum_{\alpha=1}^{4} F\alpha(X)_{bi\alpha}] \tag{1}$$

Where (Γ) is the set of all nodes in the mesh, (Ni (X)) is the nodal shape function and (ui) is the standard (degree of freedom) DOF of node (i) (ui represents the physical nodal displacement for non-enriched nodes only). The subsets (J) and (K) contain the nodes enriched with Heaviside Function (H (X)) or crack-tip function (F_α(X)), respectively, and (ai, biα) are the corresponding DOFs. The first and second term on the right-hand side is applicable to all nodes in the model; the third term is valid for nodes whose shape function support is cut by the crack interior and the third term is used only for nodes whose shape function support is cut by the crack tip (Qian *et al.* 2012).

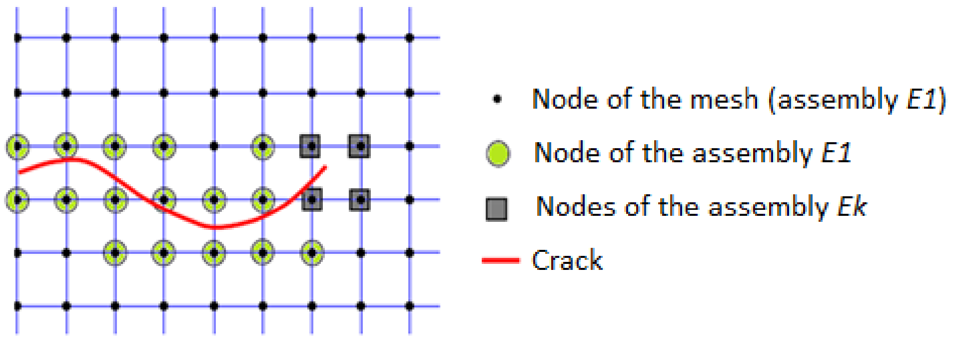

Fig. 1 Description of the E1EJEK sets of the displacement field approximation enriched finite element

The Heaviside function (H (X)) is defined as follow

$$H(x) = \begin{cases} -1, & if\ x > 0 \\ 1, & if\ x < 0 \end{cases} \tag{2}$$

The crack-tip function (F_α(X)) contains the enrichment functions (branch functions) used to increase the accuracy of the numerical solution around crack tip and their formulation depends on the nature of the problem to be solved. For LEFM problems, these functions are chosen based on the asymptotic behavior of the displacement field at the crack tip (Belytschko *et al.* 1999)

$$F_\alpha(X) = [\sqrt{r}\ \sin\frac{\theta}{2}, \sqrt{r}\ \cos\frac{\theta}{2}, \sqrt{r}\ \sin\theta \sin\frac{\theta}{2}, \sqrt{r} \sin\theta \cos\frac{\theta}{2} \tag{3}$$

Where (θ, r) are a polar coordinates system with its origin at the crack tip and when (θ = 0) it is tangent to the crack at the tip, $\sqrt{r}\sin(\theta/2$ takes into account the discontinuity across the crack face. This function has a lot of applications including biomaterial and elastic-plastic power law hardening material.

3. XFEM input parameter

The plate domain is created as a solid part of the solid section, The X-FEM enrichment domain function is input as follows:

*Enrichment, name=Crack-1, type=PROPAGATION CRACK, activate= ON

The solid composites section is used for the X-FEM domain, whereas the thickness section is created as one single solid composites section. Therefore, this domain section serves the X-FEM purpose. The evaluated damage is maximal at crack opening and is calculated using the following equation (ABAQUS 2009)

$$\left(\frac{G_I}{C_{IC}}\right)+\left(\frac{G_{II}}{G_{IIC}}\right)+\left(\frac{G_{III}}{G_{IIIC}}\right)=1 \tag{4}$$

The following analysis uses the elastic properties of Carbon fiber reinforced polymer that are listed in Table 2. The maximum principal stress is the value of the un-notched nominal strength which is measured as (2560) MPa in first direction and 64 MPa in the second direction. In addition, the damage evaluation criterion is maximum traction energy (maximum crack opening of the composite specimen is experimentally measured as 81.5, 106.3, 106.3). Therefore, the input file of the order line in the software becomes as follow:

*Damage Initiation, criterion=MAXS 2560. 2560. 500.

*Damage Evolution, type=ENERGY 81.5, 0.277, 0.277

*Damage Stabilization 1e-5

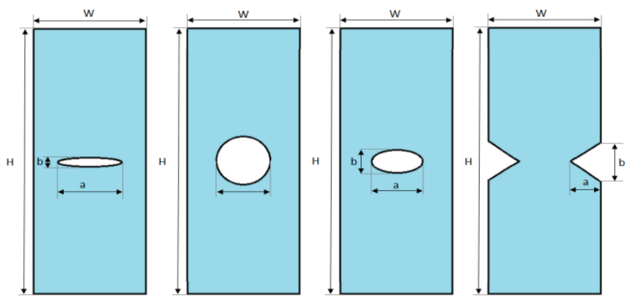

Fig. 2 Plate with different notch geometry, thickness of 2 mm and the applied tensile displacement U of 2 mm

4. Analysis

4.1 Geometrical specimens and materials

The present study consists in a three-dimensional numerical analysis of tensile loaded with four geometrical notch model (Fig. 2). A linear material and geometrical analysis was performed. (Fig. 3) shows a detail of the mesh used at a different edge.

In tensile behavior the restraining and loading condition consists on applying a restraint in the edge and tensile displacement at the opposite edge.

Table 1 Dimension of different notch geometry

B(elliptical)	e(circular)	c(elliptical)	f (V lateral)
H = 140 mm	H = 140 mm	H = 140 mm	H = 140 mm
W= 50 mm	W = 50 mm	W = 50 mm	W = 50 mm
a = 20 mm	D = 20 mm	a = 20 mm	a = 20 mm
b = 1/4 a	b = 20 mm	b = 1/2a	b = a

The mesh subjectivity of the proposed model is illustrated by simulating the response of a notched GFRP composite which is loaded in tension. The simulated specimen has 2 mm in thickness, 140 mm in length and 50 mm in width. Its contains in the first case, different dimension of a central notch. In the second, it has three modification of fiber orientation. On the other hand, Table 3 lists the used properties. The meshes were constructed with bias effects and swept technique using (C3D8R) element type, to generate dense mesh in region around the notch in order to capture the peak stresses which practical presented concentration stress and initiation of crack grow, whereas coarser structure meshing is used for the other domain region, to reduce the calculations time. The section through thickness is simulated using only one dependent section to help node set convergence.

Table 2 Elastic, strength and fracture properties of the composite used

Longitudinal Young’s modulus	$E1$ (GPa)	162
Transverse Young’s modulus	$E2$ (GPa)	8.96
Poisson’s ratio	$v12$	0.316
Shear modulus	$G12$ (GPa)	4.69
Shear modulus	$G13$ (GPa)	4.69
Shear modulus	$G23$ (GPa)	3.973
Longitudinal tensile strength	XT (MPa)	2560
Transverse tensile strength	YT(MPa)	64
Longitudinal fracture energy	GI (kJ/m^2)	81.5
Transverse fracture energy	GII=GIII(J/m^2)	277

As shown in the following figure, several local marks were surrounded by the different types of notches to guide the orientation of the fibers according to the shape of the notch. The area away from this notch was attached only by a single mark oriented in the direction of loading (unidirectional composite). We use Assigning Material Orientation. This technique can be done either by “Create Geometric Part” or by “Create Mesh Part” in order to sweep the structure by local marks that indicate the orientation of the fibers.

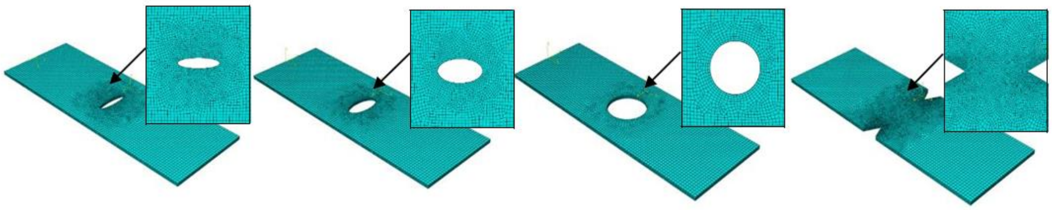

Fig. 3 Detail of the mesh of different geometrical notch

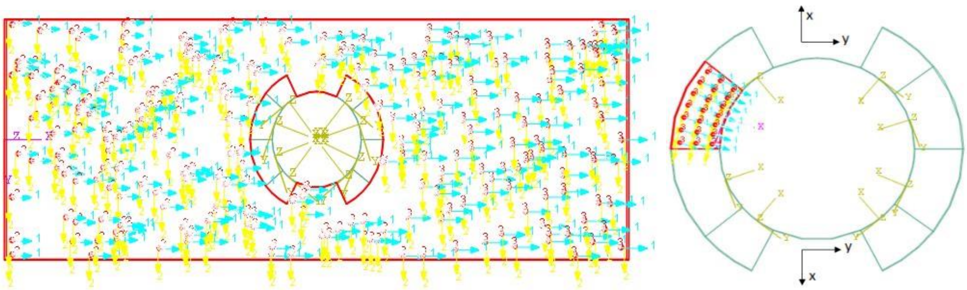

Fig. 4 Schematizations of the local marks for the modification 3 of the circular notch shap

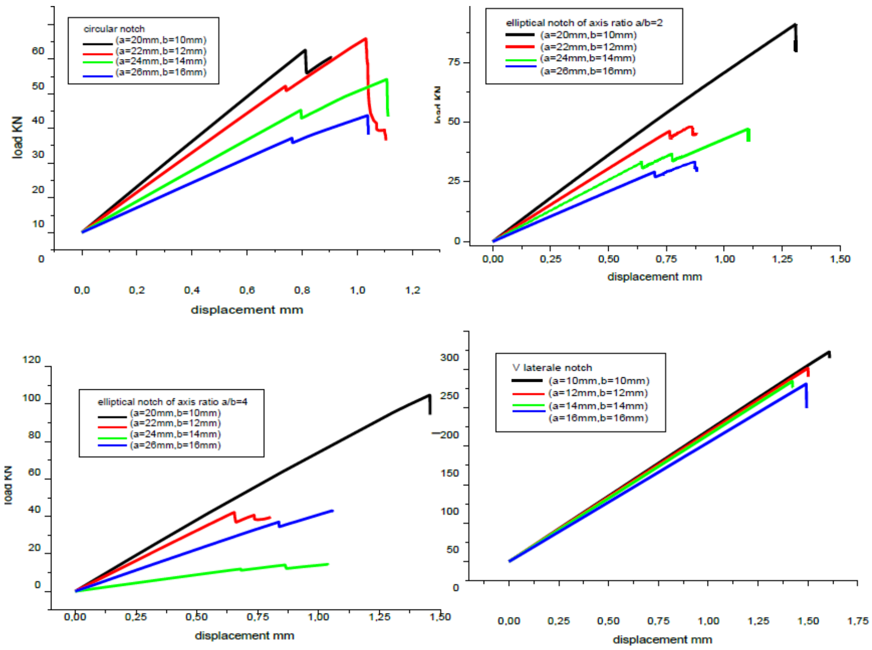

Fig. 5 XFEM load displacement curve of (a) circular, (b) elliptical of a/b=2 and (c) elliptical of a/b=4 and (d) lateral V, for different deferent notch size

The presence of the notch in the structures weakens its resistance. This leads to a concentration of stresses leading to the formation of a crack. The solution of this problem can be done by a geometric reinforcement.

4.2 Effect of the size of different geometrical notch type on the damage of the plate

The Objective oriented in this section it's to canceled the property effect then to keep the same rapport (W/ H, a/ W). Another objective is to intervener only on the effect of the size of each notch form upon the predicted the failure that occur in the plate configurations. Thus, it can be demonstrated the robustness of this type of analysis.

The desired magnitude to be evaluated in these curves is the resistance of the plates to the damage represented by the load-displacement curves. The overall response during the loading of the plates to the damage is ensured by the reaction of the force at the level of the embedment and the displacement at the level of the surface where applies the load. This is to illustrate the overall response of our notched plate.

In the figure, it is clear that there is a proportionality between the dimensioning of the notch and the damage force in an order of value of 10 KN in average between each dimension of the notch. It is also evident that the values are also proportional to the rupture parameter of the damaged composite. These values do not exceed 160 KN. Depending on the shape of the notch, it is found that the plates with a small notch are more resistant than those with a large notch. This can be reflected in the fact that the plate with an oversized notch will extend even further, resulting in a decrease in the damage force. So, the longer the plate has an ability to lie, the less resistant it is.

The same applies to other forms of notches with different values except for the V-shaped notch which presents itself with high values and the same pitch between these different dimensions. This is due to their positioning which makes them more resistant (edge effect), despite the fact that this sharp shape favors the initiation and rapid propagation of the crack.

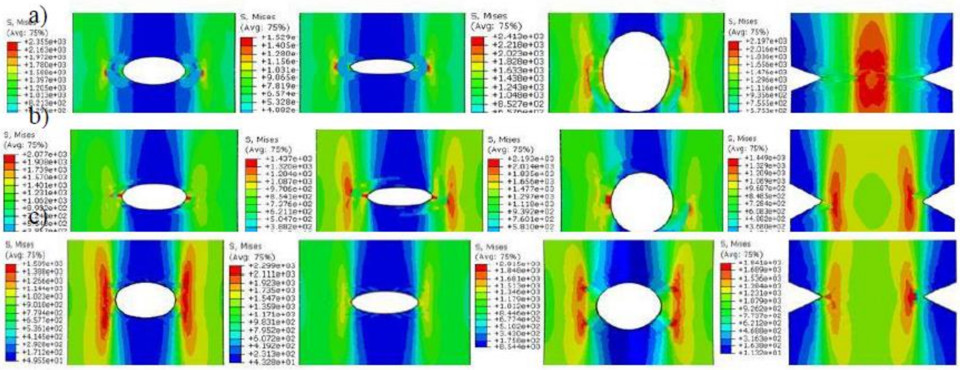

Fig. 6 Stress distribution of each form of notch under (a) modifcation1 and (b) modification 2 (c) modification3

4.3 Effect of the modification of the fiber orientation on damage of plate

Let us start from the idea that these modifications move a part of the concentration zone of the stresses towards the zones of discontinuity of the fibers.

In this section, the effects of the fiber orientation (d/b ratio) on the ultimate failure load of a unidirectional composite plate with an elliptical, circular and lateral v notch are shown in Fig. 4.

XFEM failure criterion is used to predict the ultimate failure load in this analysis. Fig. 3 indicates that the ultimate load decreases when the cutout size increases i.e., d/b ratio increases the reduction in ultimate failure load is 26%, 42% and 54%, respectively.

From the Fig. 3, it is also observed that, reduction rate in ultimate failure load decreases, as the cutout size increases.

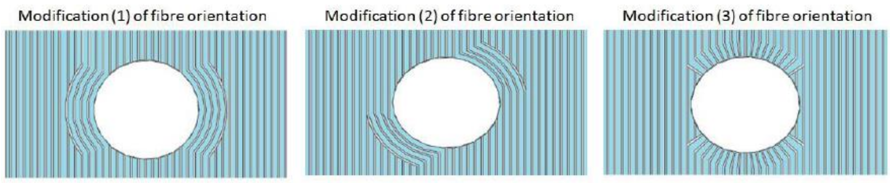

Fig. 7 The fiber orientation form of composite around the notch

The effect of fiber orientation of each plate under tensile strength is investigated by changing its orientation around the notch. The notch size is held constant at the baseline values, also the property of CFRP. The variation of tensile strength of the plate with different form of notch is shown in Fig. 6.

We have limited ourselves only to the presentation of the circular shape of the notch. The other geometric shapes follow these same three types of modification. The only problem posed in these modifications is the discontinuity of the fibers, which are well illustrated in these schematizations and these zones of concentration of the stresses.

-For the first modification, the notch must be tried symmetrically and in the transverse zone of the surrounded plate notch by the fibers.

-For the second modification, the notch may be symmetrically surrounded along the diagonal of the plate.

-For the third modification, the fibers are vertical at the notch along the longitudinal zone of the plate. These three modifications made appear fibers that are not continued in the notched plates.

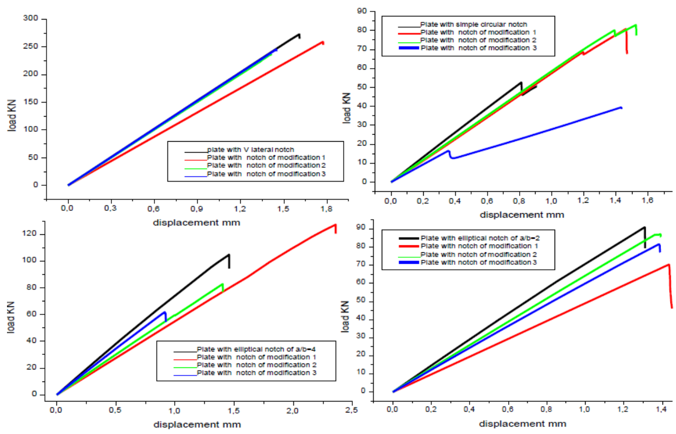

Fig. 8 XFEM load displacement curve of (a) circular, (b) elliptical of a/b=2 and (c) elliptical of a/b=4 and (d) lateral V, for different modification of fiber orientation

These modifications are approaches to the resolution of the problems of rapid damage of the notched plates but which are sometimes limited due to the discontinuity that occurs at the level at each modification. At first places the effect of these modifications is conditioned by the shape of the notch. We notice that the curves are close to one another. Since the effect is only on the fiber orientation with the same size of the notch. This is not the case for the other curves. It is also noted that the modifications do not have much effect except for the circular and elliptical shape for a/b = 4 which improves its resistance.

It is also remarkable that the rupture is similar to the level of the discontinuity of the composite's fibers and the propagation of the crack is oriented towards the least resistant path which is in the cross-section of the plate. As against the antisymmetric orientation (modification2) the propagation path takes the diagonal whatever the shape of the notch, for the main reason that the outbreak of the crack follows the fiber discontinuity zone which is already antisymmetric.

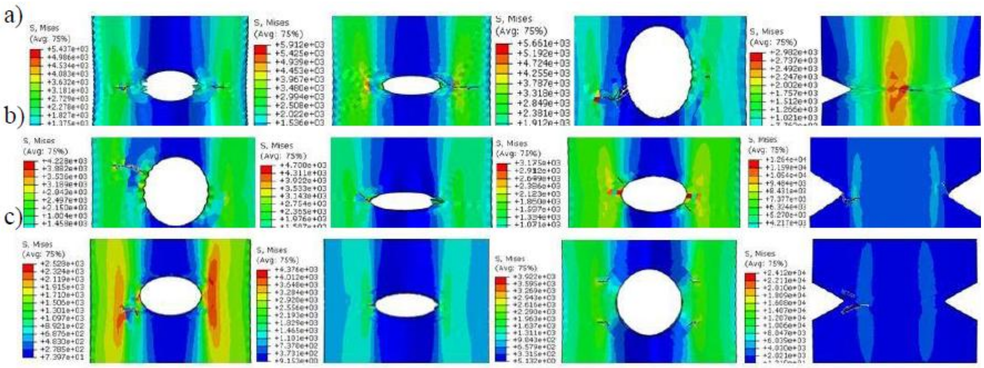

Fig. 9 Stress distribution of each form of notch under (a) modifcation1 and (b) modification 2 (c) modification3

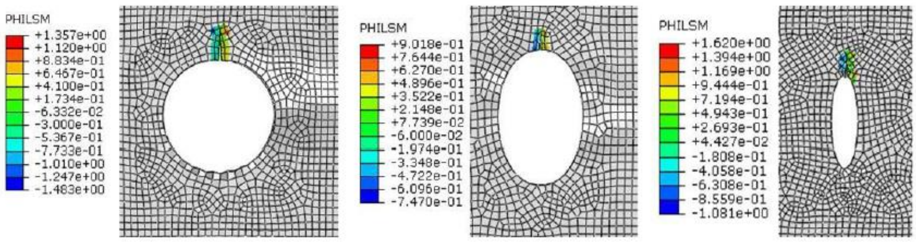

Fig. 10 Contours of PHILSM of the XFEM technique

Fig. 11 shows the PHILSM contour of the carbon fiber unidirectional composites with holes. It shows also the location of the signed distance function which is used to represent the crack surface.

5. Conclusions

Based on the progressive failure analysis of a unidirectional CFRP rectangular composite plate with a central elliptical, circular and lateral V of notch cutout under uniform uniaxial tensile loading, the following conclusions are drawn:

- XFEM is demonstrated to be a very capable technique to predict the fracture action during the crack propagation to failure of unidirectional CFRP composite.
- The presence of the notch weakens the structure and causes a reduction in the stiffness of the structure.
- The rigidity of the plate is disturbed by the presence of a geometrical defect; the reduction in rigidity varies with the shape and the dimension of the notch.
- The stress concentration increases with the shape and size of the notch and can be reduced by the presence of an introduced fiber orientation change.
- For a rectangular unidirectional CFRP composite plate with a central elliptical, circular and lateral V notch, ultimate failure loads magnitudes are decreased by increasing the size of notch.
- Ultimate failure loads magnitudes can be increased despite the discontinuity of unidirectional fiber and this by the appropriate between the type of modification and shape of the notch, case of circular and elliptical notch.
- The position of the notch in the uniaxial load structure influences on the value of failure load, the case of the V-shaped lateral notch, so the notch at the side of the plate if it does not exceed its critical size is less dangerous to that of the central notch.
- The birth of crack and its propagation depends directly on the orientation of the fibers at the tip of the notch.

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