Experimental and Numerical Study of the Effect of the Presence of a Geometric Discontinuity of Variable Shape on the Tensile Strength of an Epoxy Polymer

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EXPERIMENTAL AND NUMERICAL STUDY of the EFFECT OF THE PRESENCE OF A GEOMETRIC DISCONTINUITY OF VARIABLE SHAPE ON THE TENSILE STRENGTH OF AN EPOXY POLYMER

Khalissa SAADA*,, Salah AMROUNE*,**, Moussa ZAOUI*,**, Amin Houari***, Kouider Madani***, Amina Hachaichi******

*Department of Mechanical Engineering, University of Mohamed Boudiaf-M'Sila, Algeria.
**Laboratoire de Matériaux et Mécanique des Structures (LMMS), Université de M'sila. Algérie.
***Laboratoire de Matériaux, et Mécanique des Structures (LMMS), Université SBA. Sidi Bel Abesse, Algérie.
**** Faculty of Technology, M'hamed Bougara, University, Boumerdes 35000, Algeria.

Khalissa.saada@univ-msila.dz, salah.amroune@univ-msila.dz, moussa.zaoui@univ-msila.dz, houari.latif2016@gmail.com, koumad10@yahoo.fr, a.hachaichi@univ-boumerdes.dz

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ABSTRACT:
The presence of a geometric discontinuity in a material reduces considerably its resistance to mechanical stresses, therefore reducing service life of materials. The analysis of structural behavior in the presence of geometric discontinuities is important to ensure proper use, especially if it is about a material of weak mechanical properties such as the polymer. The objective of present work is to analyze the effect of the notches presence of variable geometric shapes on the tensile strength of epoxy-type polymer specimens. A series of tensile tests were carried out on standardized specimens taking into account the presence or the absence of a notch. Each series of tests contains 5 specimens. Two notch shapes were considered, circular (hole) and elliptical. The experimental results in terms of stress-strain show clearly that the presence of notches reduces considerably the resistance of the material where the maximum stress for the undamaged specimen was 41.22MPa and the lowest stress for the elliptical-notched specimen was11.21 MPa. A numerical analysis by the extended finite element method (XFEM) was undertaken on the same geometric models; in addition, the results in stress-strain form were validated with the experimental results. A remarkable improvement was obtained (generally an error within 0.06%) for strain, maximum stress, Young's modulus and elongation values. An exponential decrease was noted in stress, strain, and Young's modulus in the presence of a notch in the material.

KEYWORDS: Tensile test, Hole-notched, Elliptical-notched, XFEM, Finite element method.

1. INTRODUCTION

In the last years, scientific researchers and industrial experts have focused their efforts on biocomposite materials due to their properties of being sustainable, renewable, biodegradable, and biocompatible [1-4].Biocomposite materials can be used in different areas of applications especially in light structures that have a bolted assembly before using. It is necessary to determine their mechanical properties through the different experimental techniques used under different types of loading such as traction [5-7], compression[8, 9] ,torsion[10-12] , fatigue[13-15] , impact [16]. The study of the geometry effect of the tensile specimens on the mechanical properties has gained importance from several authors. Notably, Baykan et al [17] were studied an experimental study on the effect of hole size and position on the mechanical properties of tensile specimens using peridynamic (PD) theory and compared them numerically using code developed on MATLAB and ANSYS. The authors noticed that peridynamic (PD) can accurately capture fracture stress, strain, and hole interaction in composite laminates.

In another study presented by Ayou Hao et al[18] plastic specimens reinforced with Kenaf fibers containing holes of different diameters were produced, these specimens were tested in uniaxial tensile, open hole tensile, tension at different strain rates, bending and in-plane shear. The obtained results indicated that the treated at higher temperature of (230° C) but with a shorter time of (60 s), had the best mechanical performance. Also, the linear elastic finite element model of KPNCs agreed well with the experimental results in the valid strain range of 0 to 0.5% for the uniaxial tensile test and 0–1% for the bending test. Tensile specimens according to ASTM D1822 were manufactured using a 3D printer by Tomislav et al [19], in this study, the authors determined the impact of three different lattice-like hollow structures considered: honeycombs, drills and scratches on the tensile strength of 3D printed samples. The test samples were prepared on a 3D printer, with variations of the geometric structure internal. The results of the tensile test revealed that the honeycomb structure and the structured samples exhibited the greatest strength.
Khosravani et al [20] found that the tensile strength of samples of polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) indicates

that increasing the diameter of the hole leads to a decrease in the strength of the part. The finite element (FE) method has been usually used in predicting the mechanical behavior of composite materials [21-23]while Reza Mohammadi et al[24] established Standard Open-Hole Tensile (OHT) laminated composites using the finite element method (FEM) to quantify the damage mechanism . Moreover, Ghezzo – Fabrizia et al [25] presented a numerical and experimental study conducted on T300/epoxy carbon fiber thin laminates with multiple cutouts subjected to in-plane loads. Liao [26] studied a new model, which is based on the geometric modeling of woven and braided fabric structures in three dimensions using a computer-aided geometric design (CAD) technique. Recently, Recement Bogrekci et al [27] analyzed the impact of modified PLA specimen geometries on structural strength using FE analysis. Moreover, several types of adhesive such as epoxy, polyester resin, phenolic and polyurethane adhesive have been used in manufacturing of sandwich joints[28, 29].

Most of these studies did not take into account in their analysis the effect of the presence of notches on a material with weak mechanical properties such as polymer. Our work is part of this context, The aim of this paper is to propose a mixed XFEM formulation for the elasto-plastic analysis of stress and strain. The objective is to see the effect of the presence of a geometric discontinuity on the tensile strength of an epoxy type-polymer and to see how its mechanical properties evolve compared to the shape of the notch and on the other hand to try to use extended finite element method to analyze the variation of the stress applied according to the deformation. Tensile tests were carried out on specimens with the presence of different shapes geometric discontinuity (hole, elliptical notch).The effect of these geometric shapes (hole and ellipse) on the mechanical properties of the polymer was examined and compared with undamaged specimen. The experimental results were compared with those obtained with the finite element numerical analysis using the ABAQUS software using XFEM. The effect of the geometric shape of the notch was evaluated in terms of maximum stress and maximum deformation. On the other hand, the calculation of the stress concentration factor Kt in the different epoxy specimens has been highlighted.

2. MATERIALS AND METHODS

2.1. Specimen geometry

The epoxy polymer specimens intended for the tensile test are shown in Fig1. The dimensions are standardized according to the ASTM D638-14 standard (Fig 1.a). Two notch shapes were considered, a circular shape (fig.1.b) and an elliptical shape (fig.1.c). The presence of the notch aims to concentrate the stresses and locate a plastification which will be a source of initiation of the damage.

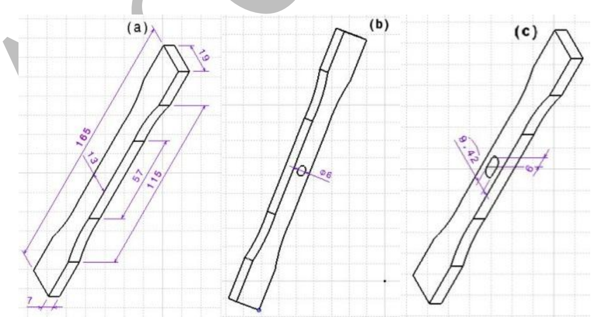


Fig .1. a)Undamaged specimen: b) Specimen with hole and :c) Specimen with elliptical notch.

The dimensions of the samples were165 ×19 ×7 mm where the hole diameter is about 6 mm and for the elliptical notch the dimension are r_1=3mm,r_2=6mm.

2.2. Test procedure

The samples were connected to the handles of the device then the displacement was measured by the computer program.The stress values relate to the force (F) and section area (S) of samples. Also, the force-displacement curves of the samples are recorded followed by the incorporation of the total energy absorption (EA) into the force-displacement curve with the relation[30]:

$$EA = \int_0^S F dS = F_m S \quad (1)$$

For displacement u and the field q to be used for the XFEM of the model [31].

$$U^h = \sum_{i\in\mathcal{M}} N_i u_i^{(\mathcal{M})} + \sum_{i\in\mathcal{H}} \tilde{N}_i H u_i^{\mathcal{H}} + \sum_{i\in\mathcal{K}} \sum_{j=1}^{4} \tilde{N}_i F_j^{(u)} u_{ij}^{(\mathcal{K})} = H\hat{u} \quad (2)$$

$$q^h = \sum_{i\in\mathcal{M}} N_i q_i^{\mathcal{M}} + \sum_{i\in\mathcal{H}} \tilde{N}_i H q_i^{\mathcal{H}} + \sum_{i\in\mathcal{K}} \sum_{j=1}^{2} \tilde{N}_i F_j^{(q)} q_{ij}^{(\mathcal{K})} = H_q\hat{q} \quad (3)$$

Where: i and j are a numbered node, $\hat{u}, \hat{q}$ is the global vectors, and N_i is corresponds to the functions of quadratic shape approximation or associated with the linear continuum While $\tilde{N}_i$ is the linear shape functions of the finite elements which construct the partition of unity. $u_i^{(\mathcal{M})}, u_i^{\mathcal{H}}, q_i^{\mathcal{M}}, u_{ij}^{(\mathcal{K})}, q_i^{\mathcal{H}}$ and $q_{ij}^{(\mathcal{K})}$ denote the unknowns at:i, H et $F_j^{(q)}$ Are the functions on the sides.

In this work we used the XFEM technique which allows us to initiate and predict the propagation of the crack in the structure to be damaged. Our structure is fixed in their extremities in order to quickly cause the damage, adding to this the mode of loading appears as an important effect which quickly causes the damage in our analysis, not only does it accumulate the load to quickly cause the damage but also it gives us a broad understanding about the behavior of our structure to analyze. The XFEM technique is implemented in the standard ABAQUS calculation code. In technique XFEM the damage is presented by the following forms:

$$u(x) = \sum_{i=N} N_i(x) u_i + \sum_{i\in N_d} N_i(x) H(x) a_i + \sum_{i\in N_p} N_i(x) \left(\sum_{j=1}^{4} F_i(x) b_i^j\right) \quad (4)$$

Where N: all the nodes of the mesh and u_i: is classical degree of freedom at node i, N_i (x): are the classical finite element shape function associated with node i. where a and b are the corresponding degrees of freedom, H(x) is a Heaviside type enrichment function and $F_i(x)$Enrichment functions represent the singularity in the vicinity of the crack front:

$$\{F_i(x)\} = \left\{\sqrt{r}\sin\frac{\theta}{2}, \sqrt{r}\cos\frac{\theta}{2}, \sqrt{r}\sin\frac{\theta}{2}\sin\frac{\theta}{2}, \sqrt{r}\cos\frac{\theta}{2}\sin\frac{\theta}{2}\right\} \quad (5)$$

In the deformation zone, there is a point (yield point) which, if exceeded by the stress value, does not return to its original value[32]:

$$\sigma = \sigma_e(1 + \varepsilon) \quad (6)$$

$$\int_0^{\varepsilon} d\varepsilon = \int_{l_0}^{l_i} \frac{dl}{l} \quad (7)$$

$$\varepsilon_{true} = \ln\left(\frac{l_i}{l_0}\right) \quad (8)$$

$$\varepsilon_{true} = \ln\left(\frac{l_0+\Delta l}{l_0}\right) \quad (9)$$

$$\varepsilon_{true} = \ln(1+\varepsilon) \quad (10)$$

In isotropic materials, have the same mechanical properties all directions in all points of the material:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ & C_{11} & 0 & 0 & 0 & 0 \\ & & C_{11} & 0 & 0 & 0 \\ & & & \frac{C_{11}-C_{12}}{2} & 0 & 0 \\ & & & & \frac{C_{11}-C_{12}}{2} & 0 \\ & sym & & & & \frac{C_{11}-C_{12}}{2} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix} \quad (11)$$

For the ellipse shape which is parallel to the axis and the plate α=0 or α=π/2, that indicated the concentration of stresses around the ellipse and the concentration of stress at the edge of the given hole[33]:

$$\overline{\sigma} = \sigma^{\infty} \frac{1-m^2-2m+2\cos 2\theta}{1-2m\cos 2\theta+m^2} \quad (12)$$

So that $0 \leq m \leq 1$

The maximum stress equals:

$$\sigma_{max} = k_t \sigma_{nom} \quad (13)$$

The stress concentration factor kt:

$$k_t = 1 + 2\sqrt{\frac{a}{R}} \quad (14)$$

R: Curve radius

2.3. Materials tested

Three sample types of epoxy resin with and without fibers were prepared, and the notches. were created in the shape of elliptical holes (Fig2). During the manufacturing process, the samples were exposed to a polymerization temperature of 70° and for five hours in order to improve their mechanical properties. The testing conditions were as follows: These samples will be subjected to a tensile test under a displacement speed estimated at F= 1mm/min. and diameter of the hole was droll = 6 mm for hole-notched specimen and the dimensions of the samples were165 ×19 ×7 mm.

2.4. Design of experiments

The purpose of determining the tensile curves for the different specimens was to take into account the location of rupture of the specimens by the presence of notches. The different geometric notch shapes have the purpose of defining the sensitivity of the specimen with respect to the tensile loading. For this, five specimens were considered for each type as shown in Fig2.

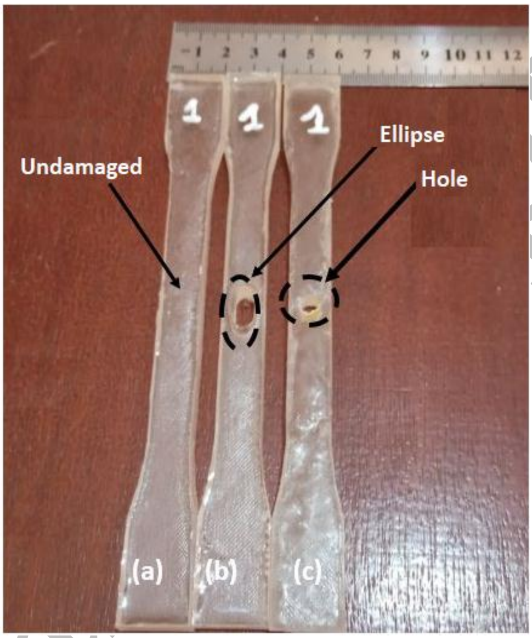


Fig.2. a) The undamaged sample of epoxy, b) Epoxy specimens with ellipse, c) Epoxy specimens with hole

3. EXPERIMENTAL ANALYSIS

The experimental results obtained refer to five samples for each of the specimens, complete Fig 3-(a), hole-notched specimen Fig 3-(b) elliptical-notched specimen Fig3-c.obtaining a reproducibility of the results was a little difficult especially for the samples in the presence of elliptical notch. Machining this shape was a bit difficult. For the other specimens the shape of the curves was the same. We notice a variation of the tensile curves for the three specimens. Where the mechanical properties of resistance (stress and Young's modulus) as well as the deformation were influenced by the presence of notches. A considerable drop in these properties is noted compared to the results of the solid samples (Fig 4). The maximum stress is dropped from 40MPa to 21.06MPa (a reduction of almost 50%) for the samples with holes and 11.21MPa (a reduction of almost 75%) for the samples with elliptical notch.

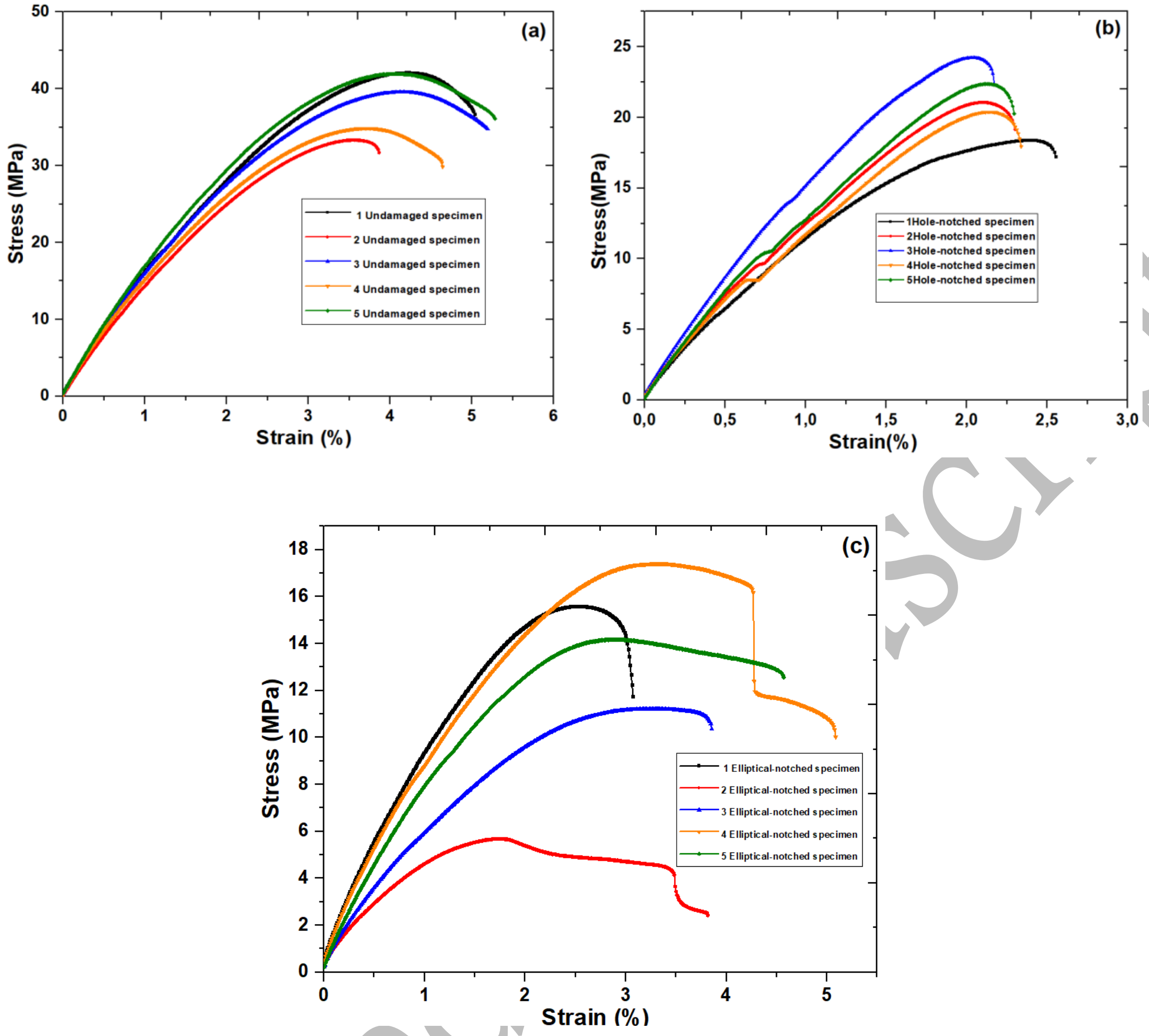
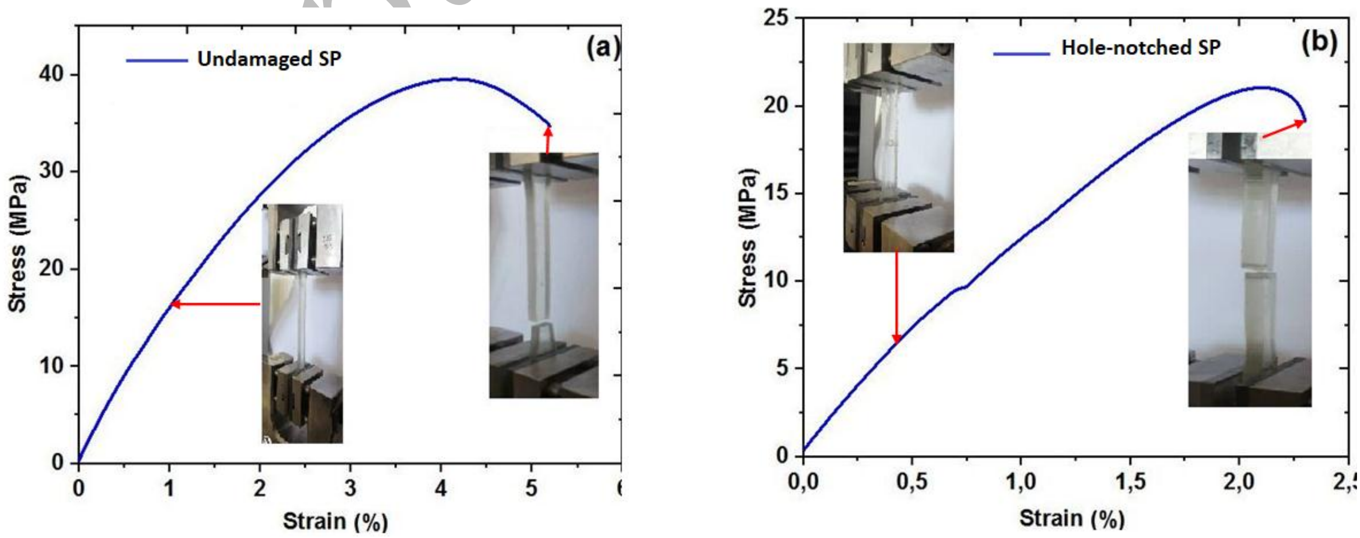


Fig. 3. Different experimental results for the five samples a) The five undamaged specimen b) The five hole-notched specimen c) The five elliptical-notched specimen).



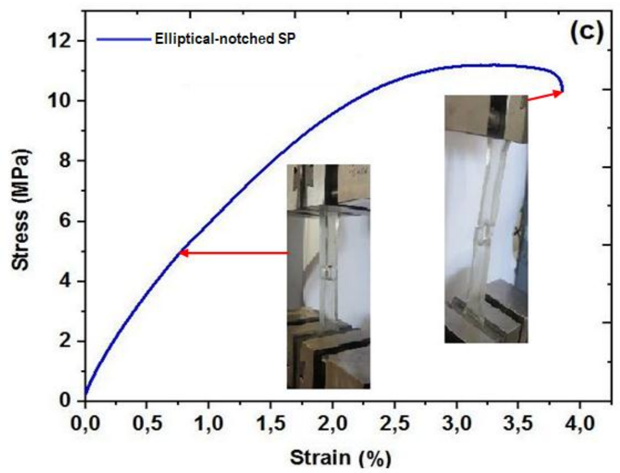


Fig .4. Comparison the experimental results of the mean of the three specimens: a) The undamaged sample: b) The hole-notched specimen : c) The elliptical-notched specimen.

The experimental results in Fig 4, including Young's modulus and maximum stress value, indicate that the highest value for them is at the undamaged specimen (1793.80 MPa and 41.22MPa) respectively. The value of the hole-notched specimen is lower with Young's modulus of 1423.36MPa and a maximum stress equal 21.06 MPa and the smallest of them is the elliptical-notched specimen with a maximum stress of 11.21 MPa and a Young's modulus of 547.59 MPa.
The experimental results indicate that the elasticity area of the undamaged specimen is larger than the elasticity area of the hole-notched specimen and the elliptical-notched specimen.

3.1. Analysis of tensile test specimens

The three-epoxy specimens were analyzed by performing a fig 4 tensile test to obtain the mechanical properties and entering the values for numerical analysis using the Abaqus program, the results are shown in Tab 1

Tab.1. Mechanical properties of Epoxy specimen under tensile test.

Features	Young's modulus (MPa)	ε-Fmax (%)	εBreak (%)	σBreak (MPa)	Maximal stress (MPa)
Undamaged specimen	1793.80	4.12	5.19	34.74	39.58
Hole-notched specimen	1423.36	2.11	2.30	19.15	21.06
Elliptical-notched specimen	547.59	3.30	3.86	10.36	11.21

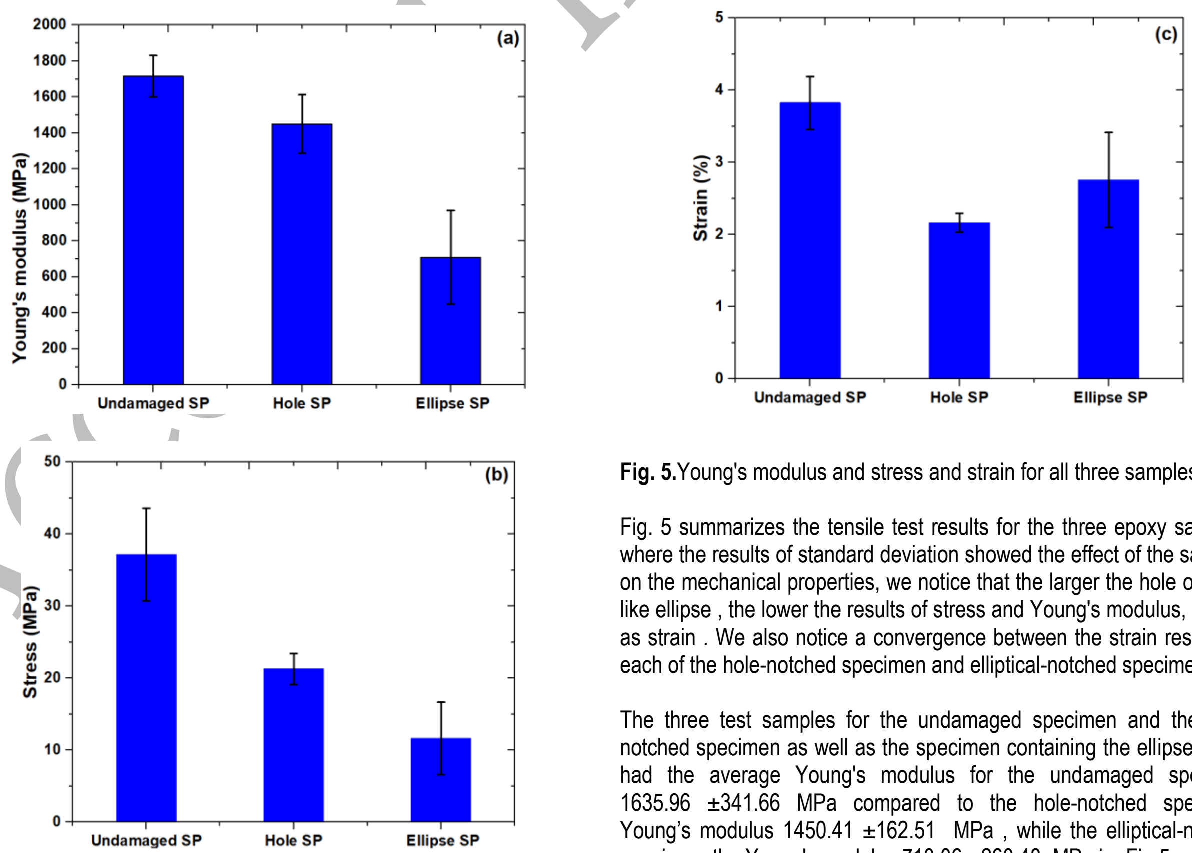


Fig. 5. Young's modulus and stress and strain for all three samples.

Fig. 5 summarizes the tensile test results for the three epoxy samples, where the results of standard deviation showed the effect of the samples on the mechanical properties, we notice that the larger the hole opening like ellipse , the lower the results of stress and Young's modulus, as well as strain . We also notice a convergence between the strain results for each of the hole-notched specimen and elliptical-notched specimen.

The three test samples for the undamaged specimen and the hole-notched specimen as well as the specimen containing the ellipse shape had the average Young's modulus for the undamaged specimen 1635.96 ±341.66 MPa compared to the hole-notched specimen, Young's modulus 1450.41 ±162.51 MPa , while the elliptical-notched specimen the Young's modulus 710.06 ±260.48 MPa in Fig 5–a. while in Fig 5-B of the average stresses for the three samples, which were 35.68±8.60 MPa and for the undamaged specimen, and stress

21.28±2.17 and 12.81±4.58 MPa for each of the hole-notched specimen and elliptical-notched specimen respectively. Fig 5-C presents the deformation for the three samples. It showed less strain for the hole-notched specimen with an average strain of 2.16±0.13%, followed by the elliptical-notched specimen with an average strain of 2.75±0.65% and the largest of these was the undamaged specimen with an average strain of 3.68±0.48% .The standard deviations of the three test samples for the undamaged specimen, the hole-notched specimen and the elliptical-notched specimen in the range 6–37%.

4. NUMERICAL ANALYSIS

4.1. Mesh view

The numerical model was realized by finite element under the code Abaqus. A fine mesh has been undertaken for the different models.
There are two types of mesh: a mesh around the hole and a uniform 3×3 mesh as shown in Fig 6. The mesh around the circular hole and around the elliptical hole has been refined. The mesh optimization provides accurate values compared to the normal mesh in the finite element method and thus gives better results to ensure the convergence between the experimental results and the numerical results. The tried to model the three specimens with the same number of mesh elements as shown in Fig 6.

Tab.2. Input parameters of numerical simulation

Specimen	Total number of nodes	Displacement speed	Mesh type	Young's modulus (MPa)
Undamaged	1008	1	Hexagon (C3D8R)	1793.80
Hole-notched	1050	1	Hexagon (C3D8R)	1423.36
Elliptical-notched	1050	1	Hexagon (C3D8R)	547.59

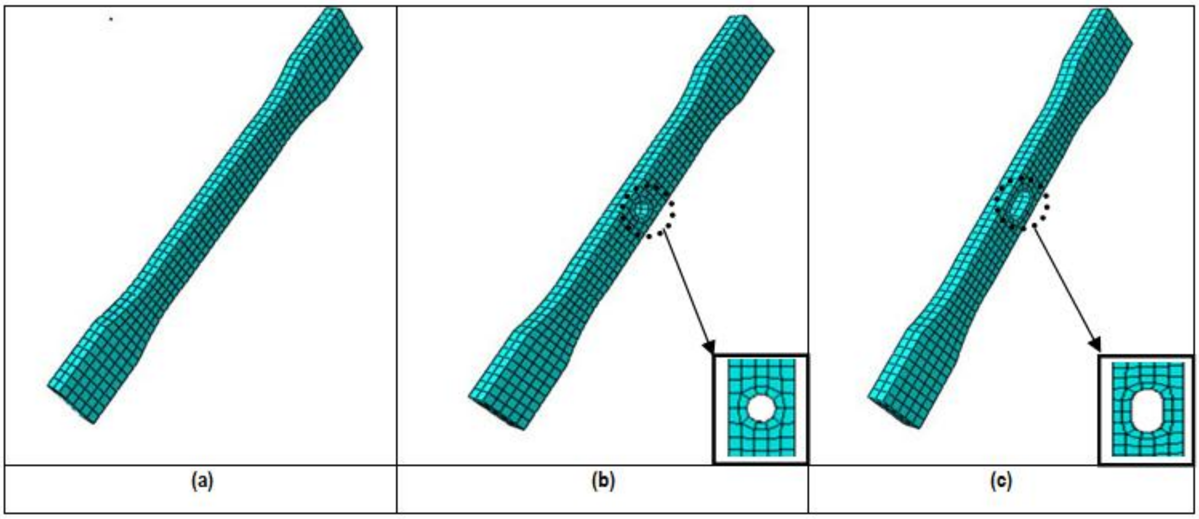


Fig.6 . Mesh view. a) The undamaged specimen b) The hole-notched specimen c) The elliptical-notched specimen).

In order to be close to the real loading conditions in the traction machine, the following boundary conditions have been assumed, one end of the specimen was embedded and the other subjected to an applied stress. Application of force perpendicular force F = 1 mm/min to the tensile samples as in Fig 7.

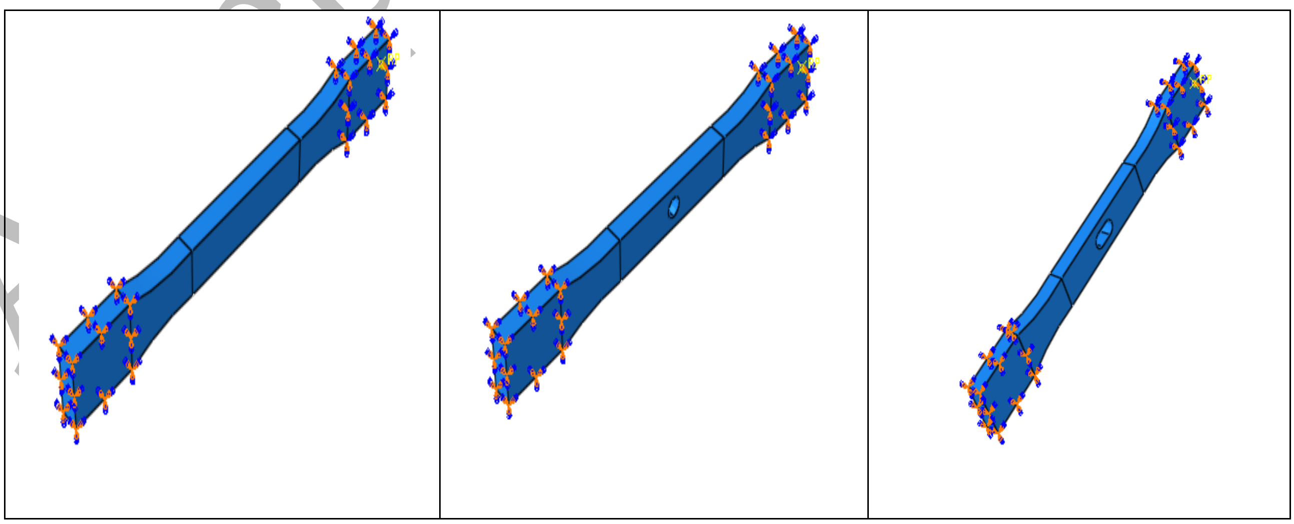


Fig.7. Application of force to specimens in ABAQUS program.

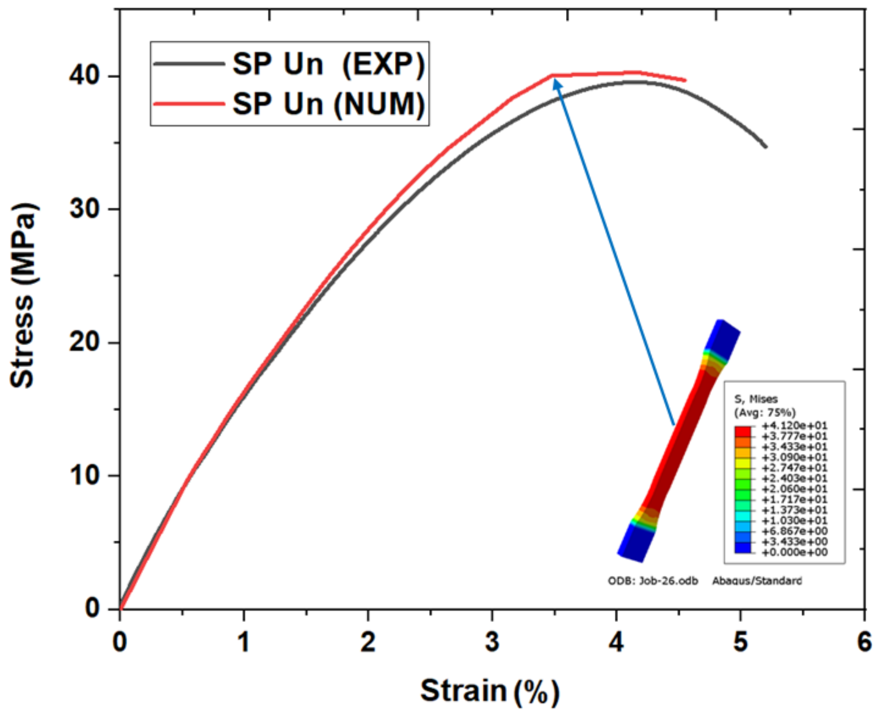


Fig. 8. Comparison between the experimental results and the numerical for the undamaged specimen.

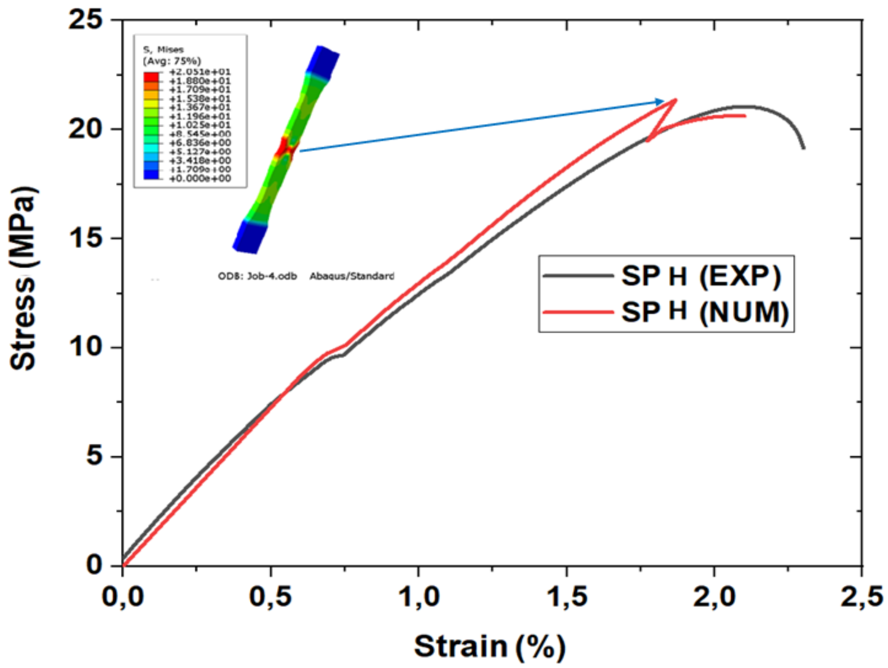


Fig.9. Comparison between the experimental results and the numerical for hole-notched specimen.

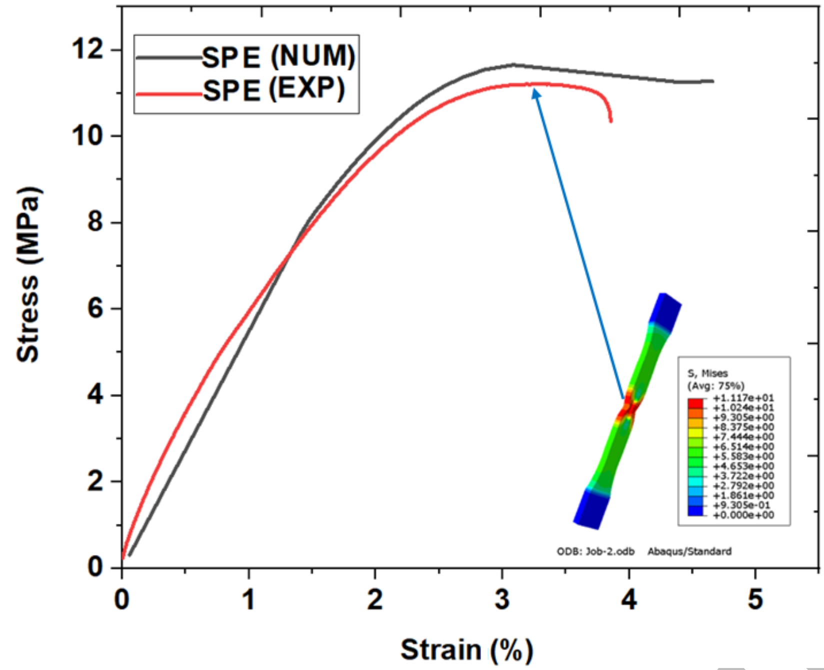


Fig. 10. Comparison between the experimental results and the numerical for elliptical-notched specimen.

The tensile test of the specimens was carried out numerically and the behavior of the specimens was studied according to the presence of the notch. In the numerical analysis in the ABAQUS software, it showed a convergence between the experimental results and the results of the numerical analysis for the three specimens Fig 8, 9 and 10.Moreover, the maximum stress value(red color) was 41.20MPa and minimum stress (blue color) was around 0 MPa for the undamaged specimen as shown in Fig .8,the maximum stress value(red color) was 20.51MPa and minimum stress (blue color) was around 0MPa for the hole-notched specimen Fig .9, and the maximum stress value(red color) was 11.17MPa and minimum stress (blue color) was around 0MPa for the elliptical-notched specimen Fig .10.
A high concentration of stress is noted in the vicinity of the notch which reduces the resistance of the specimen. However, for the specimen

without notch, the stresses are distributed uniformly along its useful length. The elliptical notch represents a higher concentration of stress than that in the presence of a circular notch. The stresses in the complete sample are greater than in the other samples. A comparison of the results was made with respect to the Young's modulus, maximum stress and deformation between experimental results and those obtained numerically (see Tab 5). There is clearly a slight difference between the different properties between the simulation results and the experimental results.

Tab.3. Experimental and simulation result with error for the stress.

Specimen	Experimental	ABAQUS	Error (%)
Undamaged	41.20	41.22	0.04
Hole-notched	20.51	21.06	2 .61
Elliptical-notched	11.17	11.21	0.35

Tab. 4. Experimental and simulation result with error for the Young's modulus.

Specimen	Experimental	ABAQUS	Error (%)
Undamaged	1793.80	1650.01	8.08%
Hole-notched	1423.36	1185.92	16.89%
Eliptical-notched	547.59	474.47	13.35%

It can be seen in Tab 3 that the effect of stresses is higher in the undamaged specimen and lower in the elliptical-notched specimen. Stresses in the undamaged specimen 41.20 MPa and stresses in the elliptical-notched specimen 11.17 MPa. While the results of PEMAG (the magnitude of equivalent plastic strains) and PEEQ (equivalent plastic strain) In the Abaqus software, the results were close and similar in the perforated and elliptical-notched specimen and slightly higher in the undamaged specimen.

Tab5 shows, comparing the results of the reactions generated in the three specimens along the steepest region, that the highest value of RF Magnitude is 310.7 N in the undamaged specimen, 83.49 N in the hole-notched specimen and 55.26 N in the elliptical-notched specimen. The displacement is close for the hole-notched specimen and the undamaged specimen of 5.993 mm and 4.580 mm respectively, and it is lower for the elliptical-notched specimen of 1.421 mm.

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Tab.5. Comparison between numerical results for the three specimens on ABAQUS.

Specimen	STRESS MAX (MPa)	E MAX(%) principal	PEMAG MAX (%)	PEEQ MAX	RF Magnitude MAX(N)	U Magnitude MAX(mm)	STATUSXFEM MAX
Undamaged	41.20	0.05828	0.03739	0.03740	310.7	4.580	1.000
Hole-notched	20.51	0.04016	0.02635	0.02640	83.49	5.993	1.000
Elliptical-notched	11.17	0.04185	0.02660	0.02660	55.26	1.421	0.4001
	STRESS min (MPa)	E MIN (%) principal	PEMAG min (%)	PEEQ min	RF Magnitude min(N)	U Magnitude min(mm)	STATUSXFEM min
Undamaged	3.333	4.86	0.003116	0.003116	25.89	0.3816	0.0800
Hole-notched	1.709	0.003347	0.002.196	0.002200	6.958	0.499	0.0833
Elliptical-notched	0.9305	0.003488	0.002261	0.0002217	4.602	0.1184	0.03334

Fig .11 shows that the cracks propagated directly from the edge of the hole to the nearest edge of the samples, due to the quasi-isotropic characteristic of the samples of the epoxy composites. While this; can be clearly seen in the optical images included in Fig 11, the tensile specimens after fractures for all three types (undamaged , circular and elliptical). The damage occurred across the width of the specimen on either side of the hole at the notched specimen and the ellipse notched specimen, while different damage could be observed at various locations on solid specimens, the fracture of the destroyed specimen occurred along the plane perpendicular to the direction of maximum tensile stress

Fig. 11. Tensile specimens after fractures

5. CONCLUSION

The study undertaken in this work aims to use the XFEM technique in modeling the behavior of an epoxy type polymer to see the influence of the presence of notch on the tensile response. The obtained experimental results indicate that undamaged specimen has ultimate tensile strength of 41.22MPa and young's modulus of 1793.80 MPa which are the strongest part among the studied specimens. Comparison of the ultimate tensile strength indicates that an increase in hole diameter leads to a decrease in the strength of the part. The ultimate maximum stress is decreased of of 11.21 MPa and a Young's modulus of 547.59 MPa for elliptical-notched specimen. The weakest examined is elliptical-notched specimen. The standard deviations of The three test samples for the undamaged specimen, the hole-notched specimen and the elliptical-notched specimen in the range 6–37%.The comparison of the numerical results with the experimental values revealed a good agreement and that the error ratios are less than 3% for the maximum stress while the error rate is less than 17% for the Young's modulus.

The finite element analysis using the XFEM technique is efficient and presents good results if the mesh of the specimen is well optimized.

The high stress concentration is noted around the elliptical and circular notches. These geometric discontinuities reduce the width of the plate and provide a considerable drop in the value of the maximum tensile stress.

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Khalissa Saada: https://orcid.org/0000-0002-3025-1287
Salah Amroune: https://orcid.org/0000-0002-951935
Kouider Madani: https://orcid.org/ 0000-0003-3277-1187
Amina Hachaichi : https://orcid.org/0000-0002-4905-7599