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Experimental Study of Failure Analysis in Notched and Repaired Fiberglass Epoxy Composite

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ABSTRACT
The composite materials are remarkably increasing in many industry sectors like aircraft, automobiles, oil pipes, and marine boats. This attention comes from their excellent properties, such as lightweight and high strength. However, these materials expose many damages like fiber-matrix debonding, matrix crack, and delamination. The composite structures risked damage through the service life and therefore need to repair to achieve their function with a good performance. This paper focuses on the analysis during the tensile test of samples of fiberglass epoxy composite materials exposed to damage before and after repair. Experimental and numerical investigations are performed to determine and identify mechanical properties and failure analysis between repaired and unrepaired composite plates. Five samples are selected: without hole, 4 mm hole-repaired, stepped hole from 4 to 8 mm, and stepped hole from 4 to 8 mm-repaired. Simulation models are created using the finite element (FE) method to compare them with Abaqus's practical experiments to predict damage during the tensile test. To simulate damage models, interlaminar and intralaminar damage, were used to study initiation and propagation of the samples failure. Results show that the experimental and numerical investigations of the repaired samples have a significant effect on the mechanical properties and failure behavior of the holed and stepped plates compared with unrepaired samples. Also, maximum stress and strain are concentrated around and on both sides of the hole, while the most significant damage occurs around the hole and the axial direction.

Keywords: damage analysis, repaired GFRP, open-hole tensile test, finite element analysis.

INTRODUCTION

Composite materials have a wide application in many other engineering fields because of their strength higher than traditional materials, such as automobile, commercial aircraft, shipbuilding, sports, civil infrastructures industries. Therefore, composite materials are not used to manufacture the secondary parts but rather to manufacture essential parts. For example, composite materials have taken half a percent in the Boeing 787 and Airbus A350 airplane (fuselage and wings). As is known, the structure of automobiles and airplanes consists of many parts. The joins between the pieces contain holes used for connecting the elements, so when the load is applied to the composite materials, many types of failure or damage occur. Therefore, the forces, stress, and strain analysis are significant in the industrial field to avoid failure [1–5]. Some problems occur when using parts made of composite materials, such as holes, cracks, etc. Sometimes damaged area isn't preferred to replace because it is big or located in a critical area. Therefore, the companies urgently need to find the best way to repair the parts that were damaged during usage.

Furthermore, typical damage happens from impact, animal strike, moisture, fluid, and aerodynamic [6, 7]. One of the ways to repair the damage is to use the adhesive material mixed with some materials to strengthen the repaired material used for fixing. The adhesive material used to maintain the damaged area has reasonable cost, high efficiency, and does not require many tools for preparing and using. In addition, designing the best material to repair the affected areas should be reliable and straightforward to obtain a high resistance and long-lasting repair efficiency.

Many researchers have been worked on and analyzed composite materials with open-hole. The following paragraphs reviewed the related papers about specimens' analysis to check mechanical properties with various conditions. Rajkumar et al. [1] studied the mechanical properties of composite materials that consist of a hybrid combination of synthetic glass fiber-laminate and fibers human hair-coconut coir. Two types of tests, applied with eight sets of various sizes specimens and holes drilled in the center, were tensile and impact tests. Furthermore, FEM is used to study the stress distribution of samples. The FEM results proved high stress was along the tensile loading direction. Wei et al. [2] investigated three models of specimens' damage using Puck's criterion. A scaling algorithm is suggested in the model to modify and differentiate the shear automatically. In addition, the modified shear was used to estimate and capture the tensile strengths and failure of CFRP specimens with a hole in the center. The results pointed out have a significant influence on the specimen failure when changing the stacking scheme of panels. Zhang et al. [3] worked on damage analysis fiber kinking and shear nonlinearity by applying a longitudinal load of open-hole composite laminates. Some FEM and practical experiments were used in this paper to determine the effective model. Results revealed the first damage was matrix tension damage of open-hole tension (OHT). Almeida Jr et al. [4] studied the unnotched and open-hole tensile of the fiber-steered variable-axial composite laminates. An optimization process of the fiber manufacturing (angle and thickness) used Tailored Fiber Placement (TFP) method to produce the specimens. The longitudinal tensile loading test was applied to measure the strain and failure. Results showed the notched strength-to-weight by fiber optimization of the open hole had higher strength than the unnotched specimen. Azadi et al. [5] worked on standard samples under tensile loading to analyze stress, strain, mechanical properties, and failure behavior of carbon fiber reinforced polymer composites with open-hole in the center, pure resin, pure fiber, and composite samples. Results proved the maximum strain decreased and maximum stress increased when increasing the tensile loading rate in open-hole composite specimens.

The research objective is to analyze and study stress, strain, and damage mechanism through experimental and numerical methods for composite materials samples (holed in different shapes and sizes) before and after the repairing process and to understand the damage mechanism of composite materials samples to use composite materials correctly in various engineering fields.

Adhesive technology for composite materials repairing

Adhesive technology is a way used to repair damaged areas of composite materials. Therefore, before using adhesive material to improve damaged areas, some procedures are followed to be repairing process in the right way. Cutting the damaged area in a circular hole and then cleaning the place where the cutting is done. Furthermore, following these procedures should be done before the repairing operation. To avoid the failure of the adhesive material used to repair the damaged part, the repairing material used must be inspected during the same working conditions of the piece, such as tensile force, compression force, torsion, etc. Also, the repaired area should not be excessively thick as pointed or convex or concave, but rather should be at the same surface as the part surface to avoid concentrations of stress on the area affected. In the repair process, the main concerns are identifying and preparing the damaged area, preparing the adhesive material, and predicting the repair area's strength, efficiency, and reliability [7]. In general, the adhesive is used significantly to repair various damages of composite materials. Figure 1 shows the typical shapes of bonded joints used for repair. Two bonded methods are widely used for the repair process in different industrial fields, namely patch repair, and scarf repair. Furthermore, the significant experiments proved the scarf repair is used for the thick composite material, and patch repair is used for an easy or simple repair.

PROBLEM DESCRIPTION AND EXPERIMENTS

There is an essential relationship between the sample variables (hole size, hole shape, repair method, adhesive type, etc.) and the maximum stress that the specimen can bear before the failure [8]. In this research, the applied load

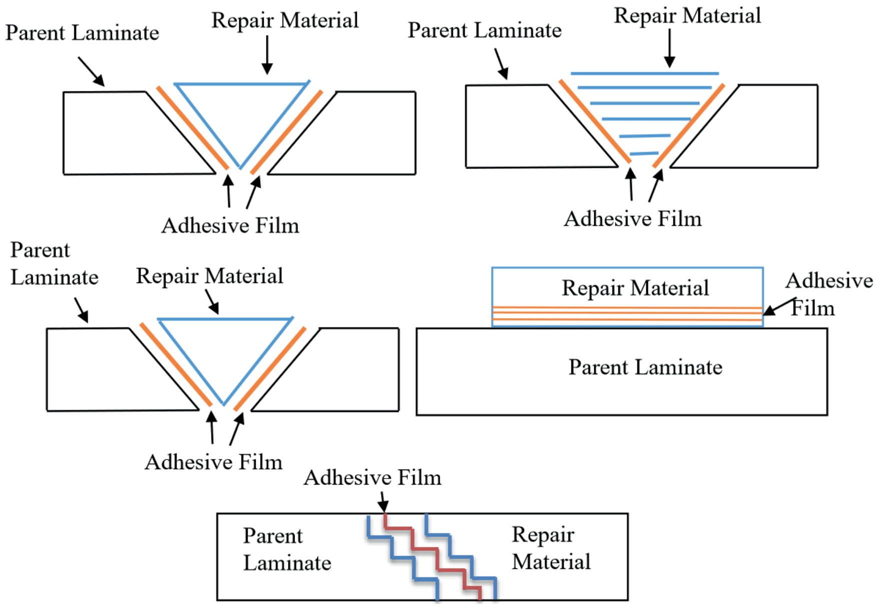


Fig. 1. Type of composite repair bonded joints, a) scarf repair, b) stepped scarf repair, c) scarf double-bonded repair, d) patch repair, e) stepped lab repair [8]

effect (axial direction) is studied on the fiberglass epoxy composite material specimens that have already been damaged with a hole in the center of the sample with different forms. Therefore, some specimens are taken for damage analysis. The specimens are without hole, circle hole in the center of sample, stepped circle holes from 4 to 8 mm with a step 1 mm in the center of the piece, circle hole in the center of specimen-repaired, and stepped circle holes from 4 to 8 mm with a step 1 mm in the center of specimen-repaired, see Table 1 and Figure 2.

Table 1. The specimens view without hole, with hole, and stepped holes

Specimen	Length L (mm)	Width W (mm)	Hole diameter D (mm)	Thickness t (mm)	Repair material
SP. 1	250	25	Without hole	6	-
Sp. 2	250	25	4	6	-
Sp. 3	250	25	Scarf from (4 to 8 mm)	6	Fiberglass-epoxy

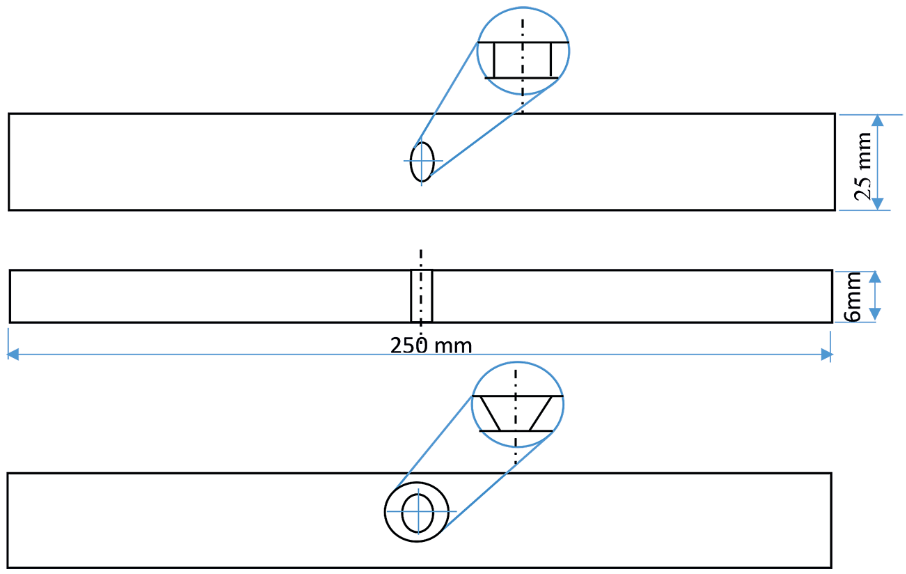


Fig. 2. The shapes and dimensions of specimens

The variables that affect the durability of the repair zone are the shape of the damaged area and the repair material used for fixing. Furthermore, the repair material is prepared by mixing the epoxy with the fiberglass (cutting it into small pieces); then placing the repair material inside the specimen hole; after that, the repair area is left for a while to dry to conduct the inspection process. In addition, the results are compared with the identical specimens that are repaired by using Fiberglass-Epoxy. The researchers [9, 10] suggested and clarified the failure criteria for composite materials.

EXPERIMENTAL PROCEDURE

Specimens materials

The fiberglass epoxy composite is used in the research made of mixed materials: 50% a reinforcing material (fiberglass) and 50% a matrix (epoxy). The fiberglass material is prepared, and then the epoxy material is used with the compression of the material; after that, the air is removed by a vacuum to produce high-quality composite material.

Tensile test

The tensile strength of the composite material samples depends on several factors: the fiber-reinforced, the fiber matrix, the orientation of distribution of the fibers, and the sample thickness. Therefore, if any of the factors change, the resistance of the composite material will increase or decrease, depending on the factor type. Five experiments are carried out for the samples of the composite materials to obtain practical results of the stress and damage behavior that occur in the samples. A tensile testing device (Model WDW-200E) with a constant velocity 5 mm/min is used to test the pieces, as shown in Figure 3a. Figure 3b indicates the samples after the tensile test process, where the failure process happened in the middle of the pieces. As for the maintained samples, the failure started from the sample center, passed through the circumference of the material used for maintenance, and returned to the center.

By noting the samples after the tensile process, the failure of all the pieces occurred in the middle region. Also, checking the failure area seemed that it was not straight but tortuous and

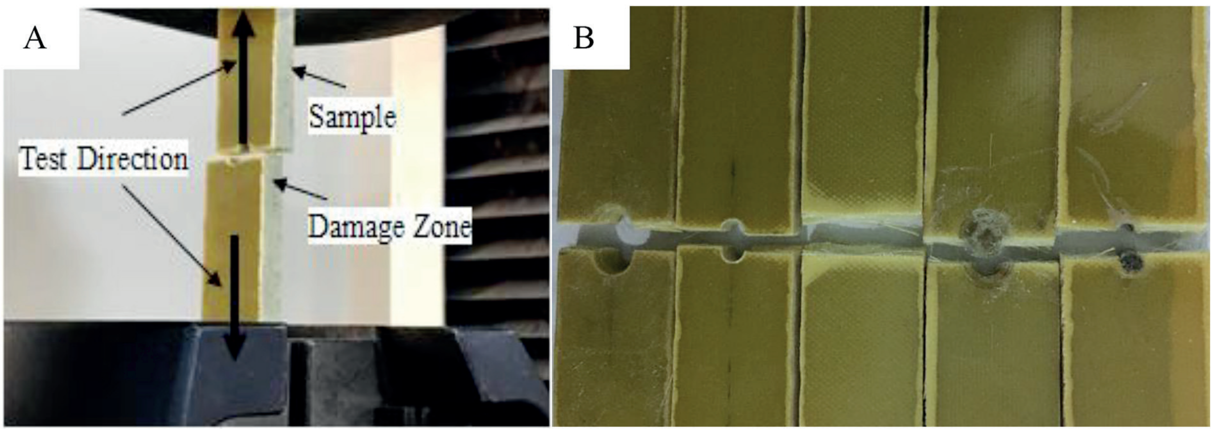


Fig. 3. (a) Tensile test operations (b) Comparison of damage morphologies between the samples

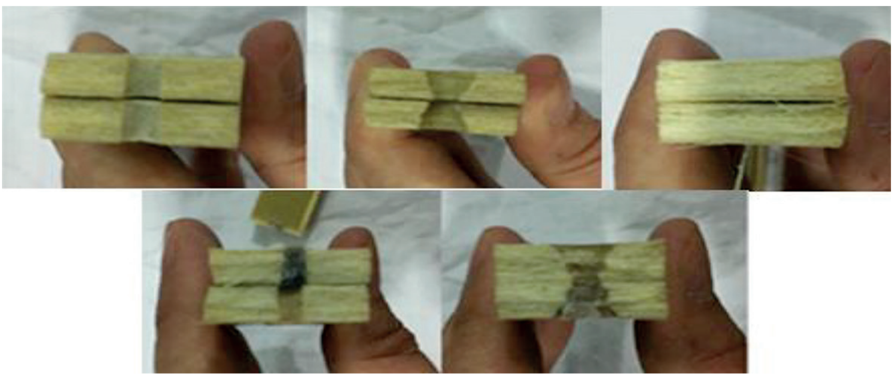


Fig. 4. Damage zones of the samples

irregular, and the fibers were torn. Furthermore, the failure of the repaired samples occurred in the area where the repair material adhered to the sample, see Figure 4.

FAILURE CRITERIA

Composite materials failure occurs when the force applied exceeds the ultimate load of the composite material. After that, cracks begin to form, which is considered the beginning of material damage. As is known, the composite material consists of matrix and fibers, so the failure begins in the areas of bonding between the fibers and the matrices. Therefore, when increasing the applied load, the cracks start growing, leading to acceleration of the composite materials damage. The finite element explicit Abaqus software is used to study and analyze the damage in all samples using Hashin criteria. In addition, the Hashin criterion is one of the methods used to predict and quantify damage in unidirectional composite materials. The equations are shown below (1–4) represent the complete description of the failure analysis for composite materials based on the Hashin method.

Fibre tensile failure:

$$(f_{ft}) = \left(\frac{\sigma_{11}}{X_t}\right)^2 + \alpha\left(\frac{\sigma_{12}}{S_L}\right)^2 \geq 1\ (\sigma_{11} \geq 0) \quad (1)$$

Fibre compression failure:

$$(f_{fc}) = \left(\frac{\sigma_{11}}{X_c}\right)^2 \geq 1\ (\sigma_{11} < 0) \quad (2)$$

Matrix Tensile Failure:

$$f_{mt} = \left(\frac{\sigma_{22}}{Y_t}\right)^2 + \left(\frac{\sigma_{12}}{S_L}\right)^2 \geq 1\ (\sigma_{22} \geq 0) \quad (3)$$

Matrix Compression Failure:

$$(f_{mc}) = \left(\frac{\sigma_{22}}{2S_t}\right)^2 + \left(\left(\frac{Y_c}{2S_t}\right)^2 - 1\right)\frac{\sigma_{22}}{Y_c} + \left(\frac{\sigma_{12}}{S_L}\right)^2 \geq 1\ (\sigma_{22} < 0) \quad (4)$$

where: σ_{11} is the tensile stress in the longitude direction and x_t is the longitude tensile strength of unidirectional laminates. σ^m_{ij} and τ^m_{ij} are misaligned coordinate systems of the stresses. Also, Y_t is transverse tensile strength, S_{12} is longitudinal shear strength, and S_{23} is transverse shear strength. Figure 5 shows a kink-band diagram of the composite material sample to illustrate the fibers' kink, taking into account the direction of the angle of the fibers [3].

The damage evaluations equations are shown below (5–12) represent the complete description of the four-damage of equivalent displacement and stresses.

Fiber tension ($\grave{\sigma}_{11} \geq 0$):

$$\delta_{eq}^{ft} = L^C\sqrt{\langle\varepsilon_{11}\rangle^2 + \alpha\varepsilon_{12}^2} \quad (5)$$

$$\sigma_{eq}^{ft} = \frac{\langle\sigma_{11}\rangle\langle\varepsilon_{11}\rangle + \alpha\tau_{12}\varepsilon_{12}}{\delta_{eq}^{ft}/L^C} \quad (6)$$

Fiber compression ($\grave{\sigma}_{11} < 0$):

$$\delta_{eq}^{fc} = L^c\langle-\varepsilon_{11}\rangle \quad (7)$$

$$\sigma_{eq}^{fc} = \frac{\langle-\sigma_{11}\rangle\langle-\varepsilon_{11}\rangle}{\delta_{eq}^{fc}/L^c} \quad (8)$$

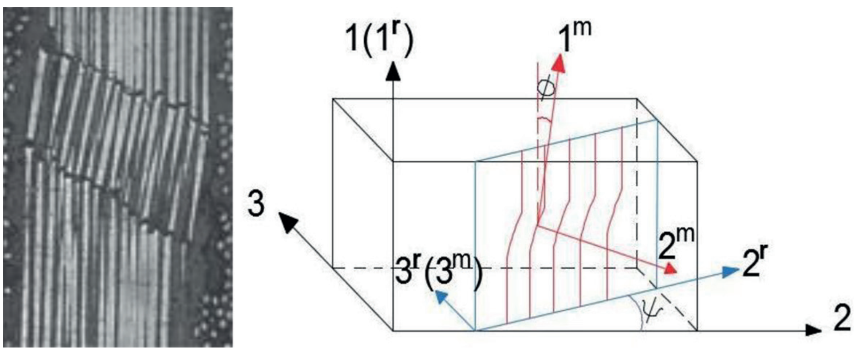


Fig. 5. Schematic of fiber kinking model [3]

Matrix tension ($\grave{\sigma}_{22} \geq 0$):

$$\delta_{eq}^{mt} = L^t \sqrt{\langle \varepsilon_{22} \rangle^2 + \varepsilon_{12}^2} \tag{9}$$

$$\sigma_{eq}^{mt} = \frac{\langle \sigma_{22} \rangle \langle \varepsilon_{22} \rangle + \tau_{12} \varepsilon_{12}}{\delta_{eq}^{mt} / L^t} \tag{10}$$

Matrix compression ($\grave{\sigma}_{22} < 0$):

$$\delta_{eq}^{mc} = L^c \sqrt{\langle -\varepsilon_{22} \rangle^2 + \varepsilon_{12}^2} \tag{11}$$

$$\sigma_{eq}^{mc} = \frac{\langle -\sigma_{22} \rangle \langle -\varepsilon_{22} \rangle + \tau_{12} \varepsilon_{12}}{\delta_{eq}^{mc} / L^c} \tag{12}$$

where: L^c is element geometry (length of a line across an element), $\langle \ \rangle$ is the Macaulay bracket operator, δ_{eq}^{xx} is equivalent displacement, σ_{eq}^{fc} is fiber equivalent stresses (tension or compression), δ_{eq}^{mX} is matrix equivalent stresses (tension or compression), ε_{xx} is strain, τ_{12} is shear stress, α is coefficient to determine the shear stress contribution of the fiber tensile initiation, and $\langle \alpha \rangle = (\alpha + |\alpha|)/2$.

FINITE ELEMENT MODELING

Finite element modeling is used to analyze the samples damage of composite materials by using the Abaqus-finite element tool, taking into account entering the sample dimensions and the mechanical properties of the samples. Before starting work on the sample stress analysis using the Abaqus tool, some information about the samples must be prepared to be provided to the Abaqus tool to obtain correct results. The information are the pieces must be drawn with the same shape and dimensions as the actual samples, mechanical properties of the sample material as shown in Table 2, displacement used to test the models (0.5 mm/s), and type of mesh (Hex type is used for the samples). The pieces have drawn with dimensions 250×25×6 mm by connecting eight layers (cohesive contact) with 0.75 thickness of each layer. After drawing, all the model's mechanical properties and displacement values are added.

Table 2. Elastic and strength properties of the composite plate [11]

Longitudinal Modulus (E_{11})	40 (GPa)
Transverse Modulus (E_{22}=E_{33})	10 (GPa)
Shear Modulus (G_{12}=G_{13})	3.15 (GPa)
Shear Modulus (G_{23})	4.32 (GPa)
Volume fraction of fiber (Vf)	0.54
Poisson's ratio (μ_{12} =μ_{13})	0.3
Poisson's ratio (μ_{23})	0.21
Density	1780 (kg/m^3)
Longitudinal Tensile Strength (XT)	988 (MPa)
Transverse Tensile Strength (YT=ZT)	44 (MPa)
Longitudinal Compressive Strength (XC)	1432 (MPa)
Transverse Compressive Strength (YC=ZC)	285 (MPa)
In-plane Shear Strength (S_{12}=S_{13})	60.6 (MPa)
Interlaminar Shear Strength (S_{23})	22 (MPa)

The samples are divided into two parts, the first part is near the hole, and the second part is the remaining sample. Therefore, the mesh element size is 2 mm, but the area around the hole was a refined mesh to obtain accurate results and decrease time running, see Figure 6.

Figure 7a shows the comparison force between experimental and numerical results (stepped hole-repaired). It was noticed that the

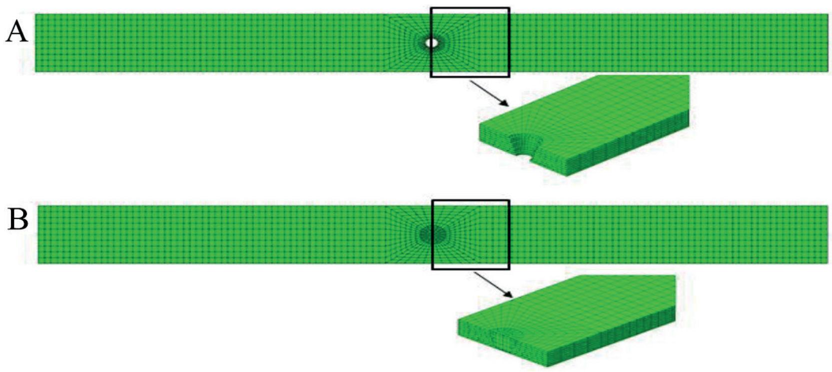


Fig. 6. Finite element model of the sample (a) Before repairing (b) After repairing

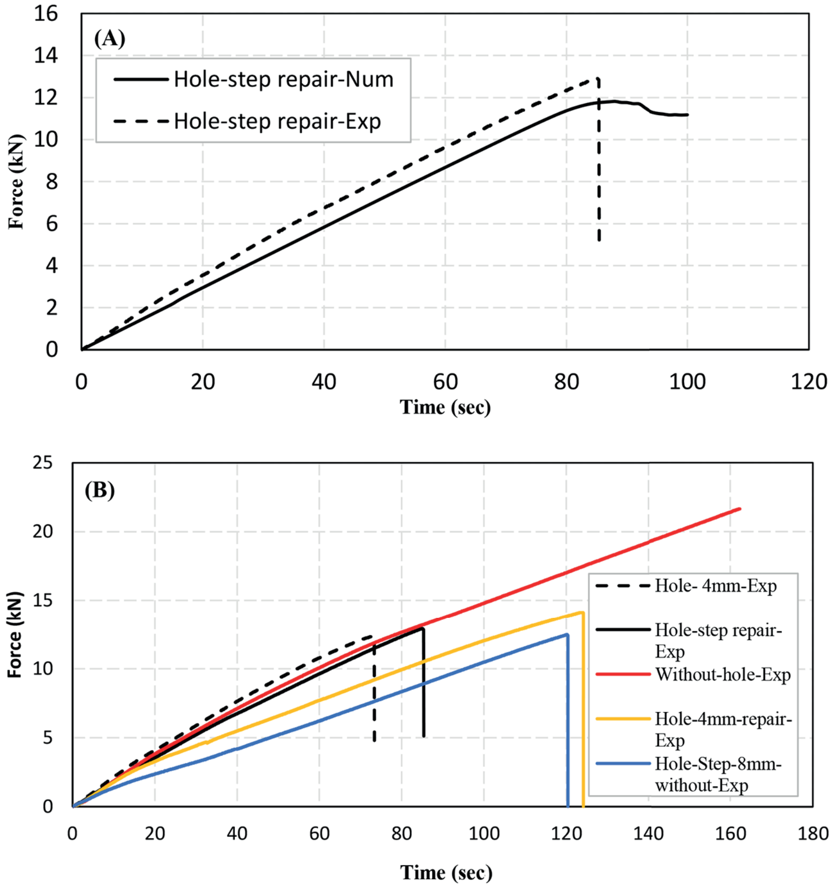


Fig. 7. Difference experiments (a) Experimental values (b) Difference between the experimental and numerical test of stepped hole repaired

behavior and the amount of difference between the numerical and experimental results was small during the test. The relationship between the samples types and the force applied to check the sample. The checking process of the samples was carried out using a tensile test device with fiber orientations 0^o. So, the time (sec) taken to fail during the tensile test of samples that have been repaired longer than that unrepaired samples. The deviation gradually increased from the standard sample line (without hole sample) due to the increase in the damaged area. The resistance observed varies from one sample to another depending on the size and shape of the hole, see Figure 7b.

Figure 8 shows the relationship between five samples and the force (KN) taken to damage during the tensile test. Logically, there is a difference between the results of the process and the theory, resulting from the difference between the conditions and variables of experiments between the

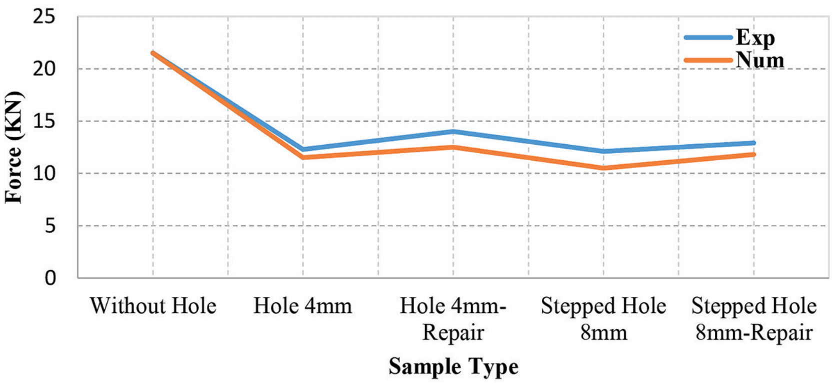


Fig. 8. Difference between all experimental and numerical tests

numerical and experimental. Also, it has been observed that the value of deviation increases as the size of the hole increases.

Damage initiations analysis

The composite laminate consists of a matrix, and fibers bind together. Hence, cracks begin to form in the matrix and then grow between layers (delamination), leading to stiffness degradation of laminate. The laminates of composite materials start to initiate damage when the applied load exceeds the ultimate strength of the laminates. After that, the damage propagates until failure occurs. To predict the damage onset for the intralaminar failure of the composite material, the numerical model evaluates the stress state that meets the Hashin failure criteria. Figure 9 shows the numerical results. The stress concentrations were around the hole for unrepaired and repaired stepped samples. In addition, the effect increases closer to the area where the repair material meets the sample.

Figure 10 shows the numerical results, the stress state satisfied Hashin's criteria, and damage initiation closed to both samples' holes. In addition, the damage increases close to the repair area.

Damage progressive analysis

One of the essential points is to study the damage behavior of laminate samples before and after a repair operation. After satisfied with the initiations criteria, the damage propagation will occur. It seems that the first damage (cracks) that happened to the composite materials was in the matrix. Also, this damage grows and propagates, leading to reach to the fibers and to all layers, which leads to stiffness degradation of the laminates. Therefore, Figure 11 shows all the fundamental analyses of the samples during the tension and compression processes of the damage propagation. It was observed that the most significant effect occurs in the area around the holes and the repaired area due to the stress concentration.

Results proved that the maximum matrix tension damage (DAMAGEMT) and matrix compression damage (DAMAGEMC) are around the hole area and longitudinal direction of the unrepaired and repaired samples, while fiber tension damage (DAMAGEFT) is around the hole area samples of the unrepaired and repaired samples.

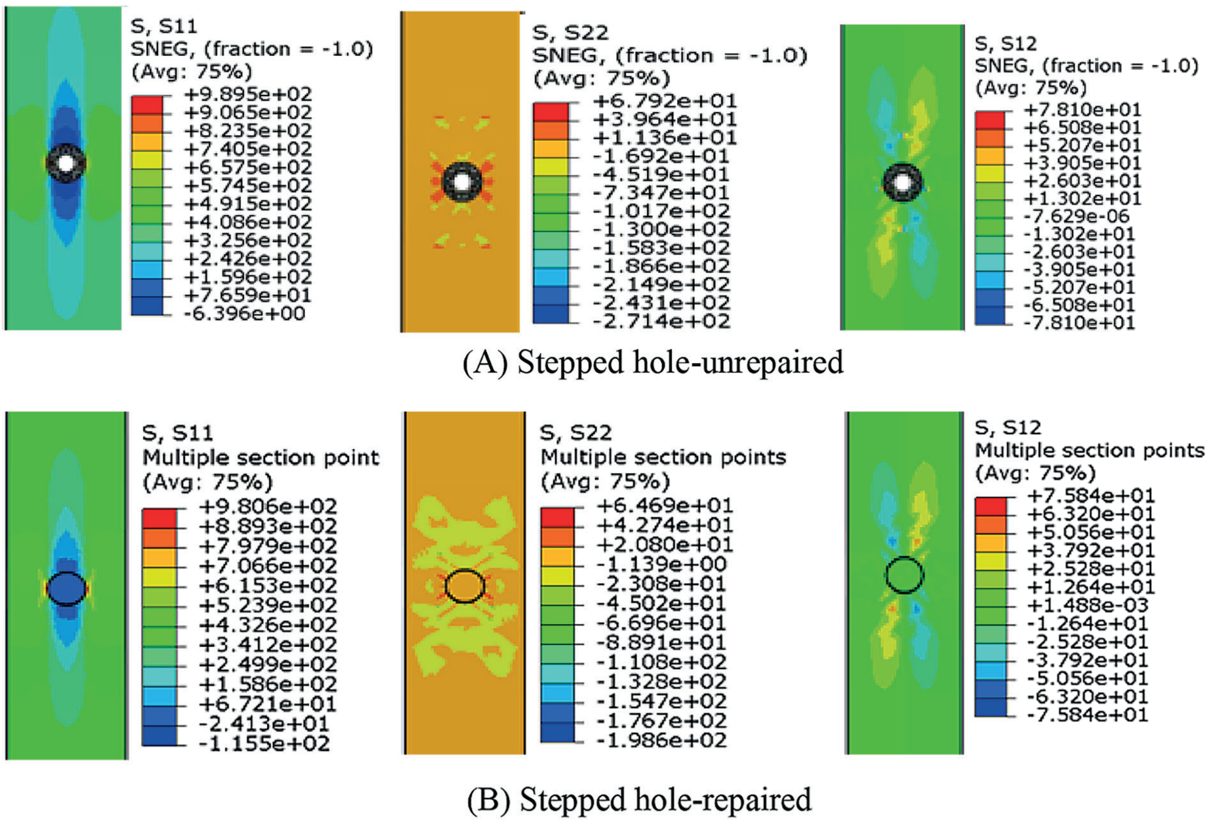
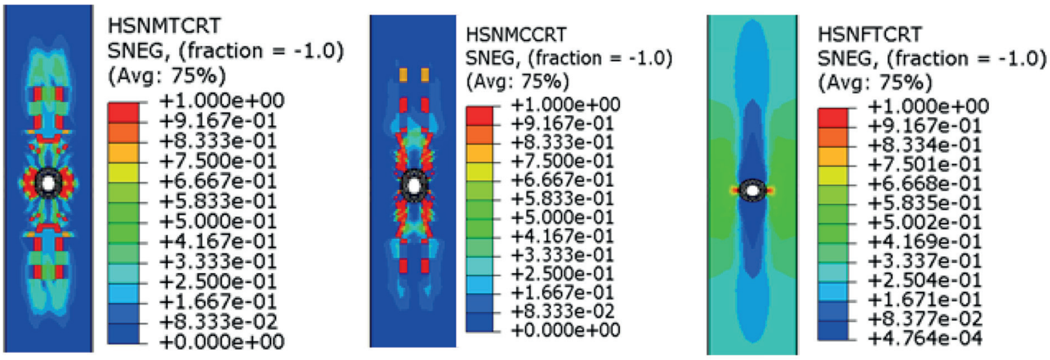
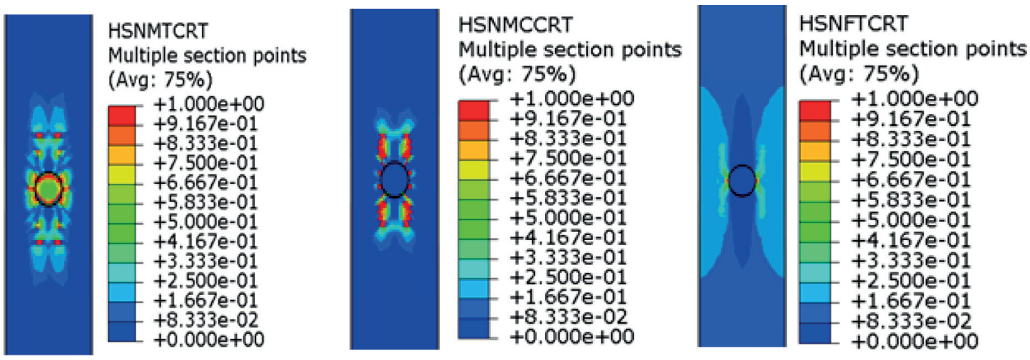


Fig. 9. FEA of the composite material samples (stress concentrations); (a) Stepped hole-unrepaired; (b) Stepped hole-repaired

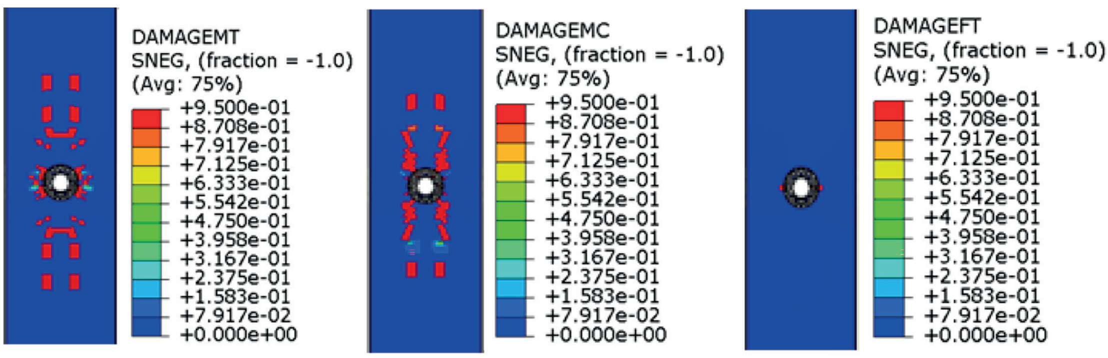


(A) Stepped hole-unrepaired

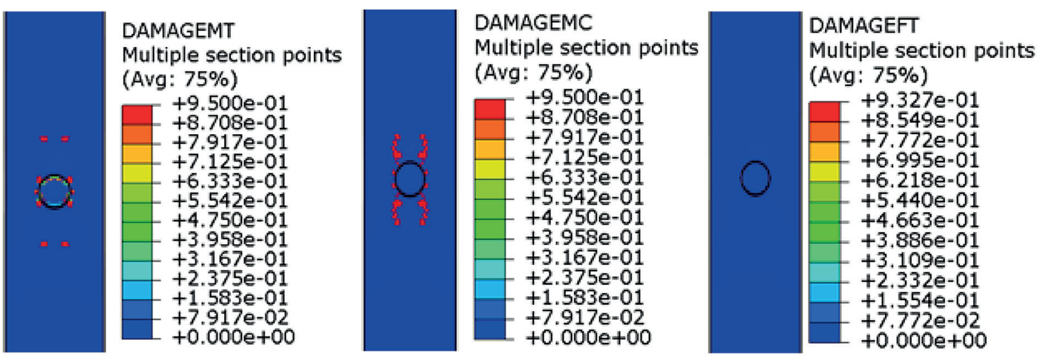


(B) Stepped hole-repaired

Fig. 10. FEA of the composite material samples-Hashin criteria initial; (a) Stepped hole-unrepaired; (b) Stepped hole-repaired



(A) Stepped hole-unrepaired



(B) Stepped hole-repaired

Fig. 11. Finite element results for damage evaluation of the samples; a) Stepped hole-unrepaired; b) Stepped hole-repaired

CONCLUSIONS

In this paper, the experimental and numerical analysis have been investigated for the open hole of the laminate composite material, especially for repairing the stepped hole state. The tensile device is used to achieve the experiments studies, and the FEA-Abaqus program is used to analyze the composite material samples. The following points were concluded:

- The stepped sample that has been repaired had more resistance compared to the unrepaired sample.
- It was observed that the damage behavior of the samples occurred in the matrix close to the hole, which led to propagate cracks between the layers. The propagation between layers reduced the stiffness, leading to rupturing the laminate.
- Two damage modes (interlaminar and intralaminar) in the numerical model are used to study the damage initiation and propagation behavior.
- The numerical model used for prediction and damage analysis of the samples provided accurate results of the matrix and fiber damage assessment.

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