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Analysis of various composite patches effect on mechanical properties of notched Al-Mg plate

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Abstract. In this study, the effect of various adhesively bonded composite patches on mechanical properties of notched Al-Mg alloy plates was analyzed. For this purpose firstly, the un-notched and notched specimens were fabricated from 5086 Al-Mg alloys which have been used in armor-plated military vehicles. The surface notches as a flaw were machined with circular cutting tool to form notch aspect ratio a/c=0.15 and notch-to-thickness ratios a/t=0.5 in the radial direction on the test specimens. Then, various composite patches which reinforced by glass, carbon and Kevlar fibers were bonded adhesively at elliptically surface notches. Finally, experimental measurements conducted by applying tensile static loading. The experimental results showed that repairing with composite patches with order of carbon, glass and Kevlar fibers have remarkable effect on tensile strength of the notched plate. Also the finite element models were developed using Abaqus/Explicit code to predict the tensile strength and elongation of unrepaired notched specimen and specimen repaired by carbon fiber composite patch. The comparison between numerical and experimental results showed good agreement between them and proved the accuracy of numerical modeling.

Keywords: composite patch repair; finite element method; adhesively bonded; tensile strength; notch

1. Introduction

Because of high strength/weight ratio and corrosion resistant, Aluminum alloys are used frequently in airplane, aerospace and military industries. Under impact and vibration loading condition, defects such as flaw, void, crash and notch can be occurred on the surface of the material. In order to prevent the progression of these surface damages and to restore or extend the service life of parts by improving the static and fatigue strength, different patches or repair techniques have been used. Welding as one of the earliest repair technique is not appropriate one due to causing local heat stress in the welding point. For instance in fuel or chemical tanks and oil pipelines under service repairing with welding is unsafe. By apply adhesively bonded composite patch on the damaged region of material it is possible to strengthen and restore the parts economically and practically (Heslehurst 2014, Rose 1982).

There are a lot of studies concerning composite bonded patch on Aluminum alloys with various size and plies orientation (Chow and Atluri 1997, Lena and Klug 1998, Young *et al*. 1992). Baker *et al*. (1984, 1988, 2002) conducted more studies on analytical methods for designing composite patches, material and adhesives selection. Ouinas *et al*. (2007) studied the performance of bonded boron and graphite composite semicircular patch on reduction of stress concentration. Also they examined the effects of patch material, thickness, radius and number of patches on the stress intensity factor of repaired crack type. Their study proved that boron/epoxy patch due to high elasticity modulus has the highest performance. Liu and Wang (2007), experimentally and numerically analyzed the effect of composite patch thickness, radius and adhesive thickness on tensile behavior of open-hole composite plates. They detected four high stress concentration locations, where damages mostly initiate. Gu *et al*. (2011) studied the effect of adhesive epoxy film, patch thickness, material and ply orientation on the stress intensity factor numerically. The results showed that by bonded composite patch repair the stress intensity factor of the notched plate is decreased about 1/6-1/20. Fekirini *et al*. (2008) proposed a new method of repair by dividing the adhesive layer into two bands with different properties. Their obtained results showed that the stress intensity factor (SIF) at the crack tip is highly reduced by the difference of properties between the two adhesive bands. Oudad *et al*. (2012) experimentally analyzed the effect of the humidity absorption on the mechanical properties of the adhesive Adekit A140 epoxy. They reported that the humidity absorption increases the repair durability but the adhesive losses its rigidity.

Benyahia *et al*. (2015) investigated the performances of aged bonded composite repair of aircraft structures experimentally and numerically. They proved that patch repairing reduced the stress intensity factor at the crack. The humidity absorption decreases the adhesive stresses and increases the stress intensity factor at the crack. Wang and Pidaparti (2002) conducted a study on monotonic tensile and fatigue crack growth of 7075-T6 Al substrates with and

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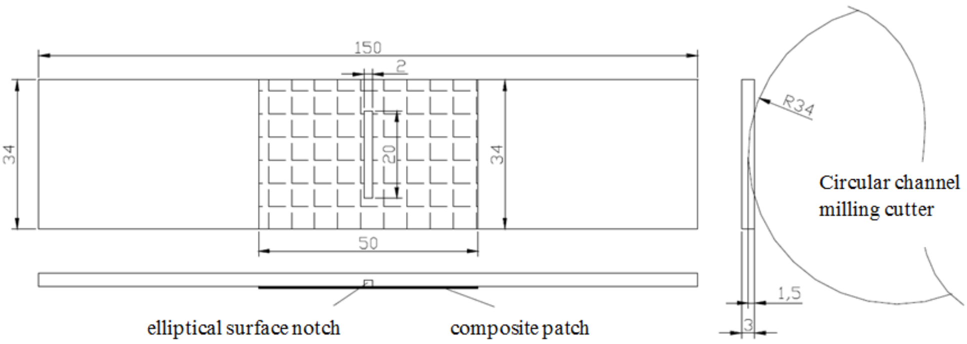

Fig. 1 Views and dimension of test specimen with elliptical surface notch and composite patch

without bonded boron/epoxy patches. Their experimental results proved that the bonded composite patches influenced the static strength and fatigue life of the repaired aluminum substrates significantly. Also by examining the different repairs they found that the patch-ply improved the fatigue life about 5-14 times and decreased the stress intensity factor about 2-4 times.

Umamaheswar and Singh (1999) experimentally and numerically studied the effect of patch material, patch size, patch symmetry and adhesive thickness on adhesively bonded repair performance. As a result of their study parametric model was established for numerical study of Stress Intensity factor in the crack region. Campilho *et al*. (2009) analyzed tensile behavior of adhesively bonded strap repairs numerically and experimentally. They evaluated the failure mode, elastic stiffness and strength for different overlap lengths and patch thicknesses experimentally. Cetisli and Kaman (2014), numerically researched the stress intensity factors on plates joined with single side composite patch. On one side patch due to the eccentricity, bending events may appear in main material. The double-sided patch prevents the bending effect of the patch (Benchiha *et al*. 2016). The bonded composite patch can be used to repair the ductile cracked structures in probabilistic elastic plastic fracture mechanics application (Mechab *et al*. 2016). A reported probability study on fatigue crack growth behavior of a cracked aluminum plate repaired with a bonded composite patch showed that uncertainties related to mechanical and geometrical properties during the manufacturing process affect the optimized patch design (Errouane *et al*. 2017).

In published literature concerning adhesively bonded composite patches on Aluminum alloy, it is noticed that there is no reported study focused on effect of various composite patches on mechanical properties of repaired metallic plates. Motivated by this fact, this study is initiated to investigate the influence of various adhesively bonded glass/epoxy, carbon/epoxy and Kevlar/epoxy composite patches on mechanical properties of 5086 Al-Mg with notched specimen. For this purpose, experimental analysis was conducted on specimens repaired with various adhesively bonded composite patches. The obtained experimental results in terms of tensile strength, ultimate strength and elongation values for various repairing material proved the effectiveness of composite patches on load carrying capacity and tensile strength of defected material. It is also observed that mechanical properties, fiber direction of composite patch and adhesive type are determining parameters. It is worthy to notice that experimental analysis of various parameters of adhesively bonded composite patches require equipment that are expensive and time consuming. Finite element method (FEM) as a numerical method is so useful one to analysis various parameters effecting adhesively bonded composite patches in reasonable time and facilities. In this study addition to experimental measurements, finite element analysis was conducted using ABAQUS software. By comparison the experimental and numerical results, it was observed that there is good agreement between experimental measurements and numerical results, which indicate that the model accurately represents the real tensile test pattern.

2. Materials and methods

The specimens used in the experiments were fabricated from 5086 Al-Mg aluminum alloy plates. The dimension of un-notched and notched test specimens was 3 mm thickness, 150 mm length and 34 mm width. The notched specimens were fabricated by using circular channel milling. The diameter and thickness of milling cutter were d=68 mm and t=1 mm respectively. The elliptical notch was created on the middle of plate with 20 mm length, 2 mm width and 1.5 mm depth as shown in Fig. 1.

In this study, the effect of various composite patches on mechanical properties of notched Aluminum alloy plate was investigated. Seven notched specimens were prepared for adhesively composite bonded tests. In bonding process, pretreatment of surfaces plays an important role. Quality of an adhesive bonded repair is highly depended on the surface (Yoo *et al.* 2016). To ensure proper adhesion, the plate surface around notch was cleaned with acetone. The composite patches approximately with 0.15 mm thickness, 50 mm length and 34 mm width bonded on the notched surface of plates by using chemical and applying compression. The specimens were cured in autoclave at 185℃ two hours then, cooled at room temperature. The specification of composite materials and adhesives which were used in repair process are presented in Table 1. The static tensile experiments were carried out by universal tensile test machine subjected to 1 mm/min tensile velocity at room temperature.

Table 1 The composite materials and adhesives used in repair process

Specimen no.	Composite patch material	Adhesive chemical material	Description
1	non	non	without notch
2	non	non	notched, without patch
3	HEXEL unidirectional carbon fiber	AS4/8552 RC 34 AW194	notched and patched
4	CYTEC 970 PWC T300 3K carbon fiber text	HENKEL HYSOL EA 9396	notched and patched
5	CYTEC 970 PWC T300 3K carbon fiber text	METLBOND1515-4M film	notched and patched
6	CYCOM 919 K285 kevlar text	HENKEL HYSOL EA 9396	notched and patched
7	CYTEC MXB 7668/7781 glass fiber text	METLBOND1515-4M film	notched and patched
8	CYTEC MXB 7668/7781 glass fiber text	HENKEL HYSOL EA 9396	notched and patched
9	CYTEC MXB type 171glass fiber text	HENKEL HYSOL EA 9396	notched and patched

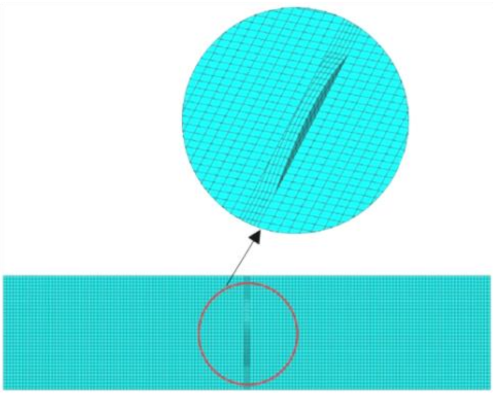

Fig. 2 Full-scale finite element model

Table 2 Mechanical properties of carbon fiber composite

Properties	Values (GPa)	Description
E_1	160	Young's modulus in fiber direction
E_2	8.9	Young's modulus in the transverse direction
G_{12}	6.2	In-plane shear modulus
T_1	2.8	Tensile strength in the fiber direction
C_1	1.55	Compressive strength in the fiber direction
T_{12}	0.060	Tensile strength in the transverse direction
C_{12}	0.167	Compressive strength in the transverse direction
S_{12}	0.095	In-plane shear strength
v_{12}	0.28	Poisson's Ratio

3. Numerical simulation

The Finite Element (FE) simulations were carried out at two stages. At the first stage, the elastic-plastic behaviour of 5086 Al-Mg aluminium alloy plate with notched was simulated. The simulation results of the notched specimen were compared to the experimental results. In second stage, the behaviour of repaired specimen with adhesively bonded by using AS4/8552 RC 34 AW194 type of adhesive and HEXEL unidirectional carbon fiber composite material was simulated.

3.1 First stage: FE simulation of notched specimen

Full scale FE model of specimens have been generated by using ABAQUS as shown in Fig. 2. The plate with 3mm thickness and 150×34 mm dimension and notched at the middle was created as solid part. The elastic-plastic material properties and ductile damage parameters of Al-Mg alloy which were obtained by experimental measurement assigned to the plate. In order to simulate the accurate tensile test, the displacement of specimen in one end was restricted in all directions and axial displacement has been applied to the other end of the specimen. Different mesh sizes were employed to guarantee the convergence of numerical results. In order to obtain smooth hexahedral element shape, especially around notch, the solid part was divided to some partitions. The solid explicit element type of C3D8R with eight node and hour glass control was assigned to the plate. The FE analysis results of plate under tensile test in different elongations and Von Mises stress distribution were presented in result and discussion section. The comparison between the experimental measurement and FE results of tensile strength and elongation of notched specimens revealed that there is a good agreement between FE and experimental results. This proved the accuracy of FE model and in next step adhesively bonded composite patched was simulated.

3.2 Second stage: FE simulation of repaired specimen with the adhesively bonded composite patch

There are cohesive elements for 2D and 3D simulation in ABAQUS element library (2010). For analysis of adhesively bonded composite patch, the element type COH3D8 used, which is an eight-node brick element with one stack direction corresponding to the thickness of the interface. The response of the cohesive elements is specified through the cohesive section definition as a traction-separation response type. The elastic properties of the cohesive bond are specified in terms of the traction-separation response with stiffness values E=2.75 GPa, G_1=2.75 GPa, G_2=2.75 GPa and 35.2 MPa tensile strength. For damage initiation in the cohesive elements, the quadratic traction-interaction failure criterion is selected. Because the thickness of the patch in comparison with two other dimensions is very small and the change of the analyzed feature across the thickness direction is negligible, the first-order S4R shell element is used to model the composite patch in Abaqus/Explicit. By using shell element the number of finite elements consequently the number of

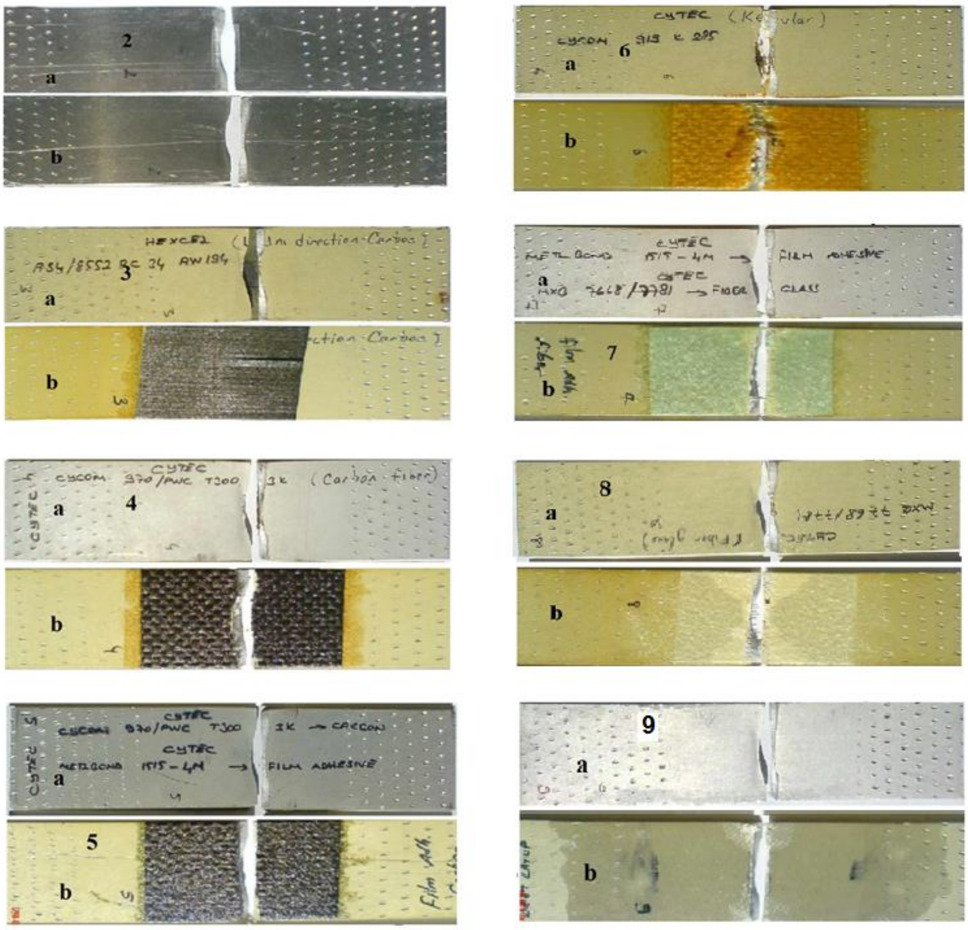

Fig. 3 (a) front views and (b) back views of specimens after tensile test

equations must be solved is decreased. Therefore, it is reasonable to use shell elements due to the CPU time advantages it creates. A composite shell section is defined and the material, thickness, number of integration points and orientation of fiber are specified. The assigned material properties of carbon fiber composite are given in Table 2. Hashin damage criteria is selected for composite failure simulation. By using Tie constraint the cohesive elements are connected to the main plate and composite patch. During the analysis, the cohesive elements carry loads to bond the main plate and composite patch until the failure of composite patch.

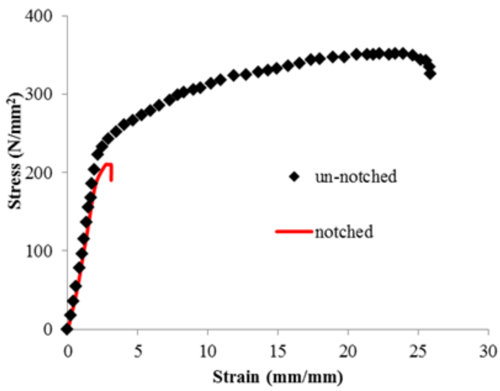

Fig. 4 The stress-strain curves of the un-notched and notched specimens

4. Result and discussion

Tensile tests were performed on un-notched, notched specimens and specimens with adhesively bonded glass/epoxy, carbon/epoxy and Kevlar/epoxy composite patches. The applied force and elongation of specimens under tensile tests were measured. Fig. 3 demonstrates the specimens after tensile test. As a result of stress concentration around notch on elliptical surface notched test, the capillary cracks being developed and sudden crack propagation happens then brittle fracture occurs. By analysis of fracture section this condition is recognizable. To study the effect of various composite patches on mechanical properties of repaired Al plate stress-strain curves were extracted. The stress-strain curves are an extremely important graphical measure to evaluate a material's mechanical properties. In order to obtain stress-strain curves of the specimens during tensile test, the measured force and elongation data were used. Nominal stress is defined as $\sigma=F/A$ and strain is defined as $\varepsilon=\Delta L/L_0$, where F is the tensile force, A is the gross cross-sectional area of Al plate, ΔL is the elongation and L_0 is the initial length of Al plate. The stress-strain curves of the un-notched and notched specimens under tensile loading are

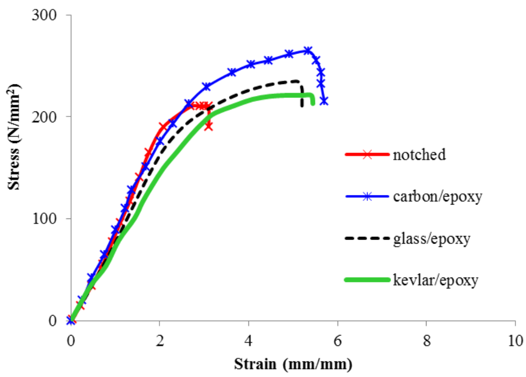

Fig. 5 The stress-strain curves of the repaired specimens

Table 3 The tensile yield strength, ultimate tensile strength and elongations values of specimens

Specimen No	Tensile yield strength (N/mm^2)	Ultimate tensile strength (N/mm^2)	Elongation (%)
1	240	355	26.0
2	190	211	3.1
3	230	262	5.8
4	222	251	5.3
5	232	254	5.4
6	202	231	5.2
7	212	240	5.1
8	216	235	5.3
9	209	242	4.9

shown in Fig. 4. It can be seen that, the tensile and ultimate strength of un-notched specimen are nearly 26% and 68% higher than notched specimen strength respectively. Elongation of notched specimen is near to one eighth of the un-notched specimen ones. The reasons of more declines on the notched specimen strength value are cross-section area reduction and the stress concentration on the sharp corners of the notch. The un-notched specimen by 26% elongation demonstrated quite ductile behavior. The ultimate tensile strength of un-notched specimen is 355 N/mm^2 while this value decreased to 211 N/mm^2 for the notched specimen. The tensile yield stress of un-notched specimen is 240 N/mm^2 while for notched specimen the tensile strength decreased to 190 N/mm^2. Fig. 5 gives the stress-strain curves of the repaired notched Al plates. It shows that all the patches advanced the load carrying capability of the repaired plates more or less. The tensile yield strength, ultimate tensile strength and elongation before fracture values of all the specimens were extracted using stress-strain curves as presented in Table 3.

It is observed that in specimens' no. 3, 4 and 5 repaired with adhesively bonded carbon/epoxy patch tensile yield strength, ultimate strength and elongation values increased approximately 20%, 21% and 78% respectively in comparison by notched specimen as showed in table 3. In the specimens (no. 7, 8 and 9) repaired with adhesively bonded glass/epoxy patch, tensile yield strength, ultimate strength and elongation values increased 12%, 13% and 65% respectively. In the specimen (no. 6) repaired with adhesively bonded kevlar/epoxy patch, 6% increase in yield

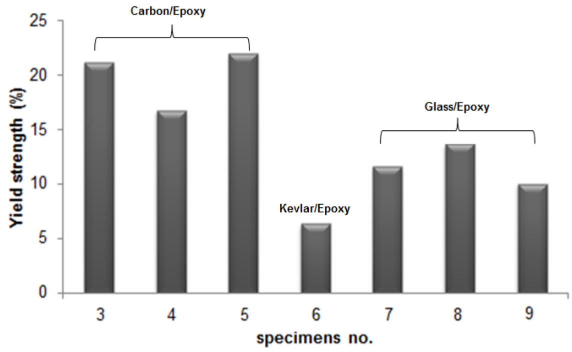

Fig. 6 The percentage increase of the tensile yield strength of repaired specimens in comparison to unrepaired specimen

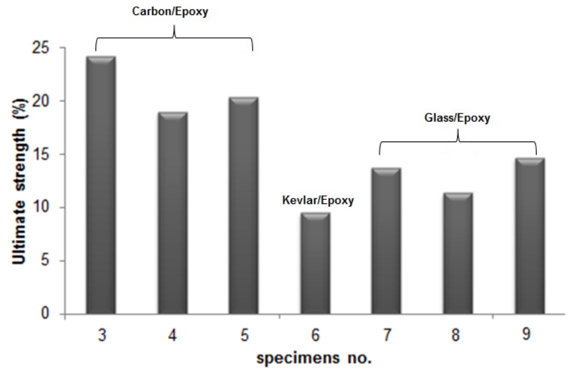

Fig. 7 The percentage increase of the ultimate tensile strength of repaired specimens in comparison to unrepaired specimen

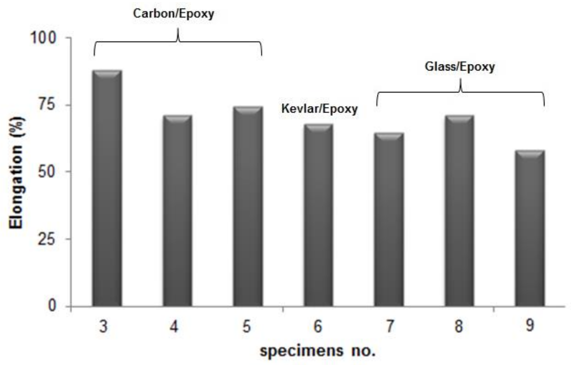

Fig. 8 The percentage increase of elongation of repaired specimens in comparison to unrepaired specimen

strength, 9% increase in ultimate tensile strength and 68% increase in elongation value were observed. In the specimen with unidirectional carbon fiber reinforced patch (no. 3), due to fibers and tensile force being in same direction, the strength of specimen increased but bonding force on repaired surface did not compensate the applied force and the patch was debonded. In this specimen, the fiber was not ruptured. In this condition it is required to extend the dimensions of patch or high strength adhesively must be applied.

A comparison was performed to evaluate the effect of various composite patches on mechanical properties of notched AL alloy plate. In Fig. 6 to 8 are shown the increase

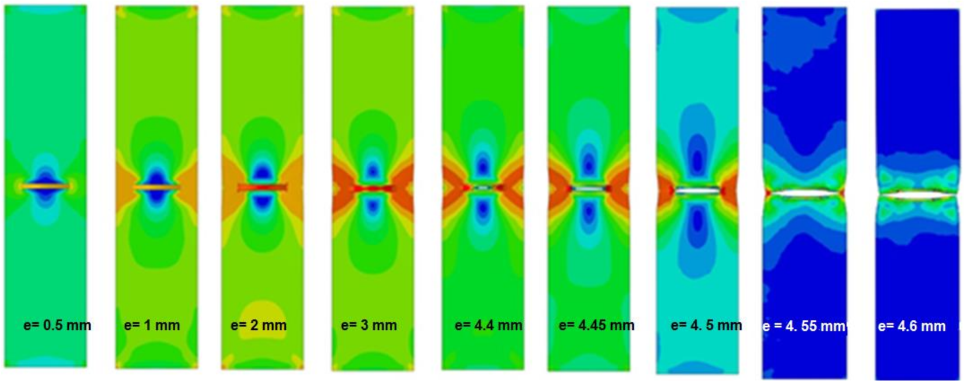

Fig. 9 The FE analysis results: Von Mises stress distribution in different elongations

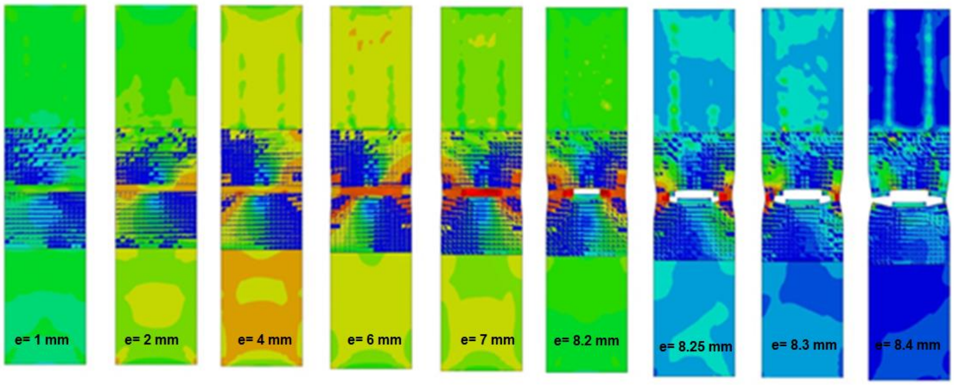

Fig. 10 The FE analysis results of specimen with adhesively bonded composite patch in different elongations

percentage of yield strength, ultimate tensile strength and elongation values belong to repaired specimens in comparison to unrepaired specimens' values.

It was observed that the carbon fiber, glass fiber and kevlar patch increased the tensile yield strength of notched specimen about 21%, 12% and 6% respectively as shown in Fig. 6. The repairing treatment with carbon fiber, glass and Kevlar text have about 21%, 13% and 9% contribution to the tensile ultimate strength of specimens respectively as shown Fig. 7.

As it can be seen in Fig. 4 and 5 the stress-strain curves of the specimens are formed of two region; linear and nonlinear region. The slope of the linear region is the elasticity modulus of specimen material. The curves show a little difference between the elasticity modulus of the specimens. Although the disparity is little, it is worthwhile to discuss the reasons here. The disparity between the elasticity modulus of un-notched specimen and notched one was by stress concentration on sharp corners of notch area. Based on the rule of mixtures in composite material, elasticity modulus of a composite material can be obtained by Eq. (1)

$$E_c = (v_f E_f + v_m E_m) \quad (1)$$

where v_f and v_m are volume fractions of fiber, matrix respectively. E_f and E_m are elasticity modulus of fiber and matris respectively.

By assuming $v_f = v_m = 50\%$, $E_{glass} = 70$ GPa and $E_{epoxy} = 6$ GPa. The elasticity modulus of glass/epoxy is obtained $E_{glass/epoxy} = 38$ GPa. By considering that the elasticity modulus of Al is $E_{Al} = 70$ GPa and patch thickness is 0.15 mm the elasticity modulus of the notched specimen repaired by glass/epoxy patch is obtained $E = 68.5$ GPa. In the same way the elasticity modulus of the notched specimen repaired by carbon/epoxy patch and kevlar/ epoxy are determined as $E = 69.1$ GPa and $E = 67.2$ GPa .It is clear that because the thickness of patch is small, the stiffness of Al plate was affected a little. If the thickness of patch increases the influence on stiffness of material will be sharp.

Finally the contribution of various composite patch materials on elongation of specimens before rupture was demonstrated in Fig. 8. The carbon fiber, glass and kevlar increased the elongation percentage of the specimens about 78%, 65% and 68%. Unlike the tensile strength, Kevlar effect on elongation is bigger than glass fiber patch ones. It is obvious that carbon fiber is the optimum option for adhesively bonded composite patch.

The FE analysis results of notched specimen and specimen with adhesively bonded composite patch have been demonstrated in Fig. 9 and 10. The comparison between the experimental and finite element method results in terms of tensile strength, ultimate strength and elongation are presented in Table 4. For specimen no. 2 tensile yield strength, ultimate tensile strength and elongation before rapture from FE method were extracted as 188 N/mm^2, 209 N/mm^2 and 3.07% respectively. Also from experimental measurement for specimen no. 2 aforementioned data are 190 N/mm^2, 211 N/mm^2 and 3.1% respectively.

The differences between FE results and experimental measurements are about 1.5-2.5%. For composite bonded

Table 4 Comparison between the experimental and finite element method results

Specimen no	Method	Tensile yield strength (N/mm^2)	Ultimate tensile strength (N/mm^2)	Elongation (%)
2	FE	188	209	3.07
	Experimental	190	211	3.1
3	FE	224	258	5.6
	Experimental	230	262	5.8

specimen no. 3 tensile yield strength, ultimate tensile strength and elongation before rapture from FE method are extracted as 224 N/mm^2, 258 N/mm^2 and 5,6% respectively. Also the obtained corresponding data from experimental measurement are 230 N/mm^2, 262 N/mm^2 and 5.8%. It is observed that the disparities between the FE results and experimental results are about 1.5-11%. Approximately high range of these disparities emerged from parameters that affecting maximum load and the progressive damage process of cohesive elements. These parameters are shear toughness, position of cohesive elements, elastic stiffness that was set by using ABAQUS software guidance and experimental data. Fig. 9 shows the stress concentration happened around notch area and final failure took place in this area. Crack initiation and crack progressing and final failure is same as experimental results. This indicates that FE model represents accurately the experimental results. As shown in Fig. 9, the crack initiation in notched model happened in 4.4 mm elongation. Whereas in composite bonded repaired model crack initiation happened in 8.2 mm elongation (see Fig. 10). This proved composite patch improved the load carrying capacity of notched plate.

5. Conclusions

The present study investigated the effect of various composite patches (glass, carbon and Kevlar) on notched strength of specimens of 5086 Al-Mg alloy material (armored vehicle body material) experimentally and numerically. It was revealed that;

• The machined elliptical surface notch on ductile material (Aluminum alloy) resulted in approximately one-third decrement in yield stress and ultimate tensile strength and almost eight times decrement in elongation of main material.

• Repairing with composite patch (carbon, glass and Kevlar fibers) increased the tensile yield strength of notched plate nearly 20%, 12% and 6% respectively. Also improved the ultimate tensile strength about 21%, 13% and 9% respectively. Therefore it can be concluded that repairing with carbon fiber reinforced composite patch is useful whereas repairing with kevlar fiber reinforced composite patch is not so effective. The elasticity modulus of repairing or reinforcement material must be higher than the elasticity modulus of main material.

• Unidirectional carbon fiber reinforced patch due to fibers and tensile force being in same direction, the strength of specimen increased but bonding force on repaired surface did not compensate the applied force and the patch was debonded. In this condition it is required to extend the dimensions of patch or high strength adhesively must be applied.

• The main advantage of composite patch is to apply patch in desired orientation. If the applied force on main structure is just in one direction, instead of text composite patch the unidirectional patch will be appropriate.

• In order to achieve accurate FE model of adhesively bonded composite patch by usage cohesive elements, parameters of these elements must be calibrated by experimental data and finally FE modeling must be validated by experimental results.

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