Modeling Different Repair Configurations of an Aluminum Plate with a Hole

Abdul Aabid, Meftah Hrairi, MSI Shaik Dawood

Abstract--- ***This paper investigates the influence of repair configuration on a rectangular plate with a circular hole and subjected to uniform tensile load. The fundamental idea is to study the stress created by either a composite or piezoelectric (PZT) patch on a hole along the width of a rectangular plate. Finite element ANSYS software was used to evaluate the stress concentration factor (SCF) around the hole when the plate is unrepaired, repaired with a piezoelectric patch, and repaired with single and double composite patches. The results showed that the different repair configurations were effective in improving the state of the stress concentration with the positive electric field in the PZT being the most effective in decreasing stress concentration along the width of the rectangular plate. The results also showed that the SCF reduction increased with the decrease of the hole diameter to the plate width ratio (D/W) for the composite patch repair.***

Keywords: SCF; FEM; Composite Patch; Piezoelectric Actuator.

1 INTRODUCTION

Aircraft nowadays are maintained with highest priority to maintain safety. To implement that, aircraft structures that have a slight sign that may lead to crack propagation from hole, damage, and fracture are to be replaced with new structures. Damages such as delamination, notches, and cracks in various fields of engineering are inevitable, especially in the field of aerospace, and these damages are mostly due to fatigue, corrosion, and accidents. Therefore, many studies have been carried out in either passive or active structural repair. Also, aluminum alloys and composite materials are widely used for a better enhancement and high performance of structures such as aircraft, ships, automobiles, etc. There have been numerous methods for determining SCF at the boundary of a hole or notch in an isotropic plate. A plate with a hole will generate stress or strain concentration when external load is applied and therefore will reduce the mechanical properties and could be the origin of crack initiation in materials. SCF is a dimensionless factor that is used to quantify how concentrated the stress is in a material [1]. Over the years, structures with holes integrated with composite patches have been studied by evaluating the stress around the hole [2, 3].

In recent years, simulations of center-holed rectangular plates with composite patches have been performed using finite element (FE) software ABAQUS and ANSYS for 2D and 3D analyses. Raju et al. [4] carried out a numerical study to check the effectiveness of a composite patch over a cracked structure subjected to thermal and mechanical loads. Patch material, patch size, patch shape and adhesive material were found to exhibit effects on the reduction of the stress intensity factor (SIF). Mhamdia et al. [5] repaired the crack with a bonded composite patch under thermo-mechanical load to reduce SIF. They used ABAQUS software to analyse the effect of thermal residual stresses resulting from adhesive curing on the performance of a bonded composite repair in an aircraft structure. Damghani et al. [6] analytically approached the effects of loading conditions, stacking sequences, and laminate homogenized stiffness values on the SCF at the edge of a hole [6]. Aabid et al. [7] numerically investigated the stress concentration around a hole integrated with boron-epoxy composite patch and stress intensity factor when a crack emanated from the hole [7, 8]. On the other hand, piezoelectric actuators have been used to reduce the SCF for a center-holed rectangular plate. Some theorical and experimental investigations over the last decade used piezoelectric actuators [9, 10]. Abuzaid et al. [11] reviewed active structural control and repair using piezoelectric patches. The same authors studied the effect of piezoelectric actuators on a circular hole in a plate subjected to uniform tensile load [12, 13].

In this paper, the effect of a composite patch on a hole in a rectangular aluminum plate has been studied using finite element analysis. ANSYS software is used to evaluated stress concentration on hole edges with respect to the different angles and plate lengths in X-direction from the hole.

2 PROBLEM FORMULATION

The circular holed rectangular plate with composite patch and piezoelectric actuator is shown in figure 1. The case of the composite patch was performed in two different approaches: single side and double side composite patch as is also illustrated in figure 1. When applying a uniform tensile load on the plate, the theoretical value of the SCF, K_t, in the case without actuator is given by [1]

$$K_t = \frac{\sigma_y}{\sigma_a} \tag{1}$$

where σ_y is the maximum stress and σ_a is the applied stress in the Y-direction. For linear orthotropic material,

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the stress is directly proportional to the strain with an elastic constant. Shear-stress produced from composite material patch when force is applied in Y-direction therefore it can easily control the displacement. For the linear piezoelectric materials, Abuzaid et al. [11] described its effects and controlled by changing the electric fields.

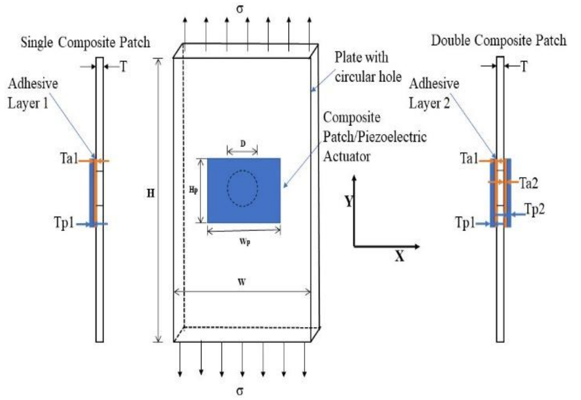

Fig. 1: Plate with circular hole integrated with composite patch/ piezoelectric actuator on the hole.

3 FINITE ELEMENT SIMULATION

3.1. FE model

The aluminum plate and the composite patch were modeled using the available structural element SOLID186 while the element SOLID226 was used to model piezoelectric actuator in ANSYS software [13]. These elements are suitable for the investigation of three-dimensional solid structures and finely meshed around the circular hole of a plate to obtain a good result.

Table 1: Dimensions of the plate, Piezoelectric Actuator/Boron-Epoxy, and adhesive

Dimensions	Aluminum plate (mm)	Piezoelectric Actuator/Boron-Epoxy (mm)	Adhesive (mm)
Height	H=200	Hp=30	Ha=30
Width	W=100	Wp=30	Wa=30
Thickness	T=1	Tp=0.5	Ta=0.03

Table 2: Properties of the plate, Boron/Epoxy, and adhesive

Parameter	Aluminum plate	Boron/Epoxy	Adhesive (Araldite 2015)
Density (ρ)	2715 kg/m3		1000 kg/m3
Poisson's Ratio (υ12)	0.33	0.3	0.3
Poisson's Ratio (υ13)		0.28	
Poisson's Ratio (υ23)		0.28	
Young's Modulus (E1)	68 GPa	200 GPa	5.09 GPa
Young's Modulus (E2)		19.6 GPa	
Young's Modulus (E3)		19.6 GPa	
Shear Modulus (G12)		7.5 GPa	1.2 GPa
Shear Modulus (G13)		5.5 GPa	
Shear Modulus (G23)		5.5 GPa	

The main material and electrical properties of the piezoelectric actuator PIC151 are: density ρ_P = 7800 kg m^{-3}, elastic compliance constant $S_{11} = 19 \times 10^{-12}\ m^2\ N^{-1}$, piezoelectric constant $d_{31} = -2.10 \times 10^{-10}$ m/V, and the electric permittivity coefficient $\varepsilon^T_{33} = 2400$.

A hole radius of D = 20 mm was used in the present study, the composite patch was integrated on the circular hole, and the applied tensile stress was 1 MPa. The model was symmetrical; therefore, only a quarter of the model was considered. The FE model of the center-holed-cracked plate with the composite patch is shown in figure 2(a). To show the clear view of the double patch on a circular hole rectangular plate with composite patches, the un-meshed model is considered as shown in figure 2(b).

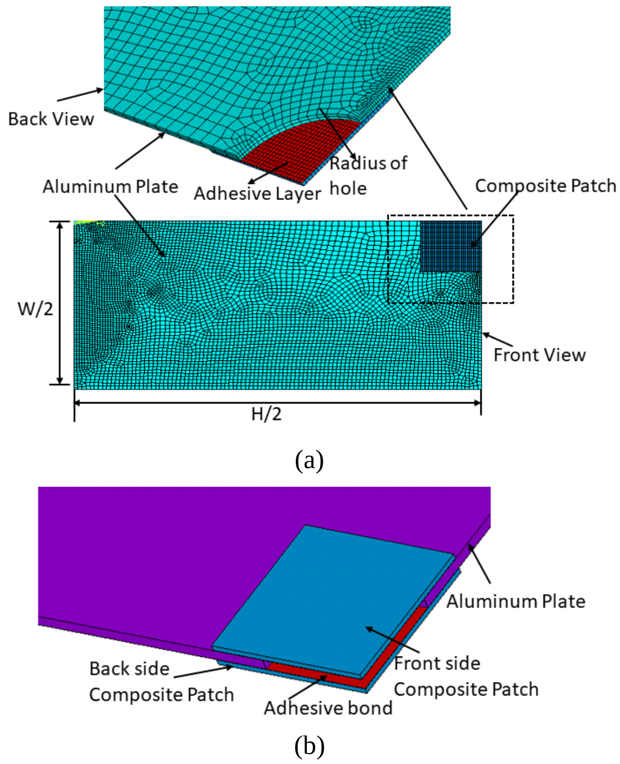

Fig. 2: Finite element model. (a) Single Patch meshed view (b) Double patch un-meshed view

3.2. Validation of FE model

Results from the literature of a circular hole in a plate with bonded composite patch [7] and piezoelectric

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actuator [11], as shown in figure 1, were used to validate the finite element results. Table 1 compares the results of the current study with those found in Ref. [7] and [11]. A good agreement between these results has been observed.

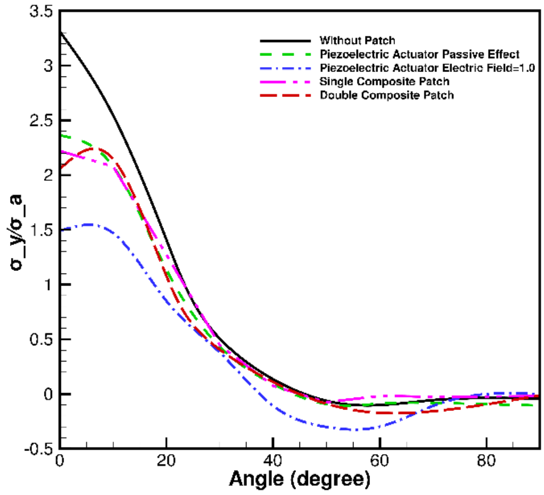
Table 3. Validation of FE model results

Condition	Applied electric field	SCF Reference Results	SCF Present Results
Without Repaired	-	3.16 [7]	3.21
With actuator	-E0	1.68 [11]	1.61
Composite Patch		2.21 [7]	2.22

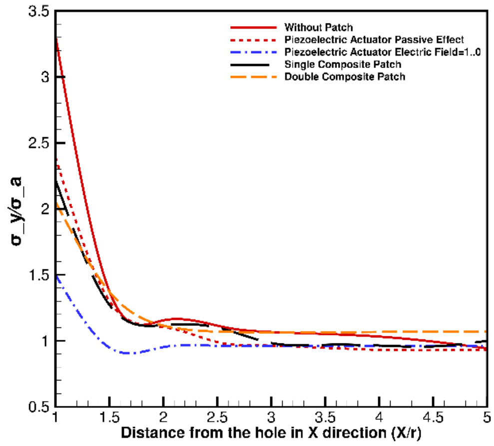
4 RESULTS AND DISCUSSION

4.1. Stress Concentration Factor on a Plate with and Without Patch

The stress concentration in the Y-direction, as described by Eq. 1, has been computed. Figure 3 illustrates the stress concentration on a plate in two different ways which are; stress around the hole angle and from the hole to the X-direction with the effect of piezoelectric actuator for electric field 0.0 and 1.0, and the effect of composite patch for single side and double side and without any configuration. The piezoelectric actuator for electric field 1.0 is more effective to reduce stress concentration in the Y-direction compared to composite patch since the actuator had produced a high level of strain with positive electric field. It has also been noticed that for the compression stress zone around the hole at a 90-degree angle, the curves for all cases intersect each other, as shown in figure 3(a). Similarly, stress concentration with respect to the length of the plate at X-direction close to each other at end location is depicted in figure 3(b). Moreover, Abuzaid et al. [11] identified the effect of the piezoelectric actuator for different voltages and electric fields.



(a)



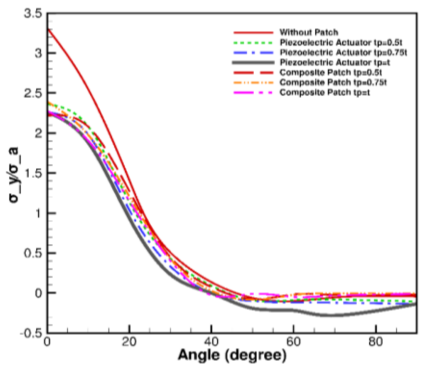
(b)

Fig. 3: Stress concentration in a plate, (a) around hole (b) from the hole in X-direction

4.2. Effect of Patch Dimension

Figure 4 illustrates the effect of the composite patch and piezoelectric actuator thickness for reducing the stress concentration around the hole angle and from the hole to the X-direction of the plate. For the hole angle, the piezoelectric actuator with positive electric field 1.0 is slightly higher to reduce stress concentration for the thickness of 1mm. It is also noticed that the points are close to each other at the position of a 90-degree angle as shown in figure 4(a). Similarly, for the case of X-direction of the plate, results show approximate close performance in all cases, as shown in figure 4(b).

Figure 5 illustrates the effect of the composite patch width on the reduction of the stress concentration around the hole angle and from the hole to the X-direction of the plate. As we found, the piezoelectric actuator performance is higher to reduce the stress concentration therefore, this case considered only the composite patch to identify its effect with different parameters. From the results, it has been observed that for a hole angle, if the width of the patch increases, the stress concentration slightly increases between a 20 to 40-degree angle as shown in figure 5(a). Similarly, for the case of the X-direction of the plate, if the width of the patch increases it will result in a decrease of stress concentration as shown in figure 5(b).



(a)

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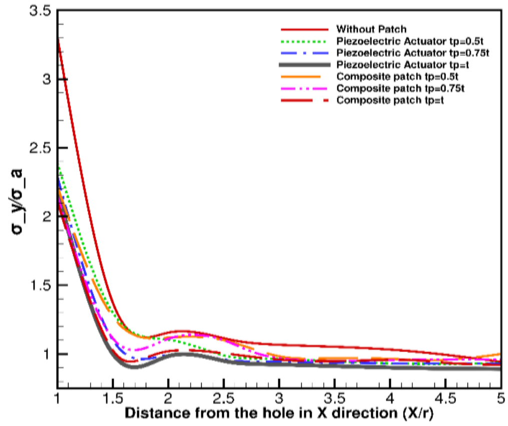
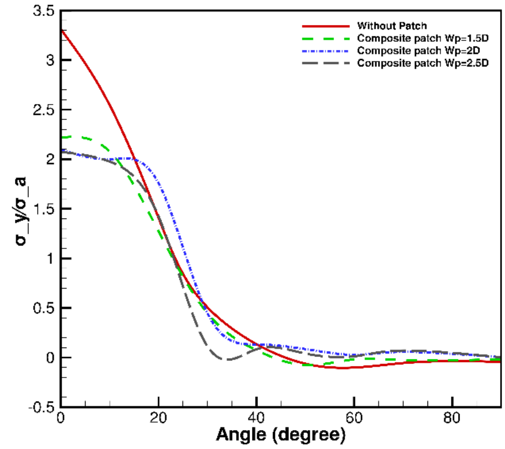
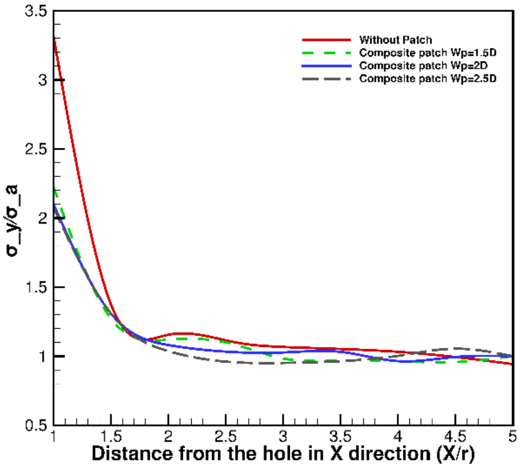


(b)

Fig. 4: Effect of patch thickness, (a) around hole of plate (b) from the hole in X-direction of plate



(a)

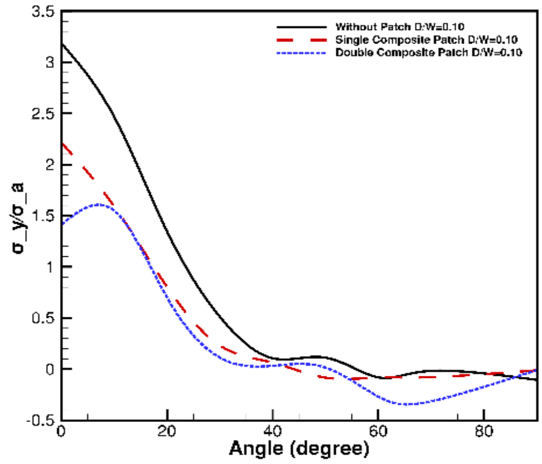


(b)

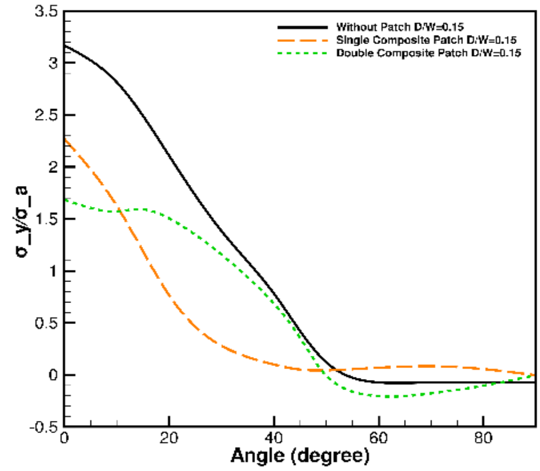
Fig. 5: Effect of patch width, (a) around hole of plate (b) from the hole in X-direction of plate.

4.3. Effect of the Patch for Different Diameter to Width Ratios

The effect of diameter to width ratio with fixed composite patch width on the stress concentration in the Y-direction along the plate length in the X-direction with single and double patches are displayed in figures 6 and 7, respectively. It can be seen, from figure 6 that the reduction of SCF increases when diameter to width ratio decreases, in case of double patch. However, figure 7 shows that the stress concentration reduction at a far distance from the hole is very small for both single and double composite patch.



(a)



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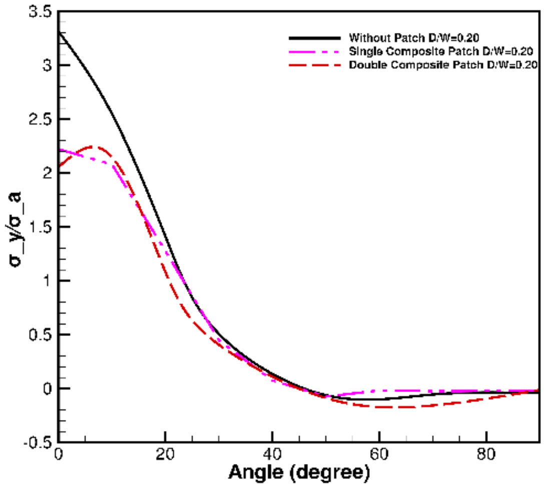

(c)

Fig. 6: The stress concentration around the hole of plate, (a) D/W=0.10 (b) D/W=0.15 (c) D/W=0.20

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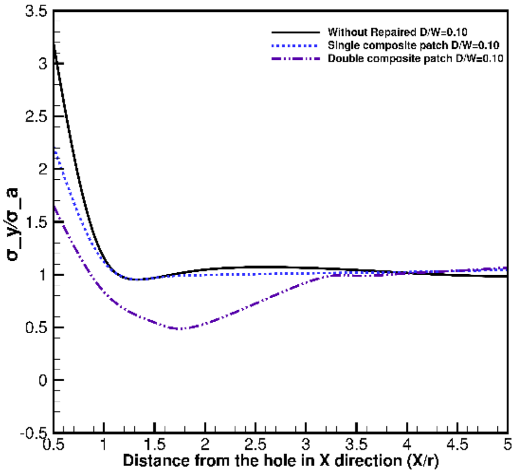
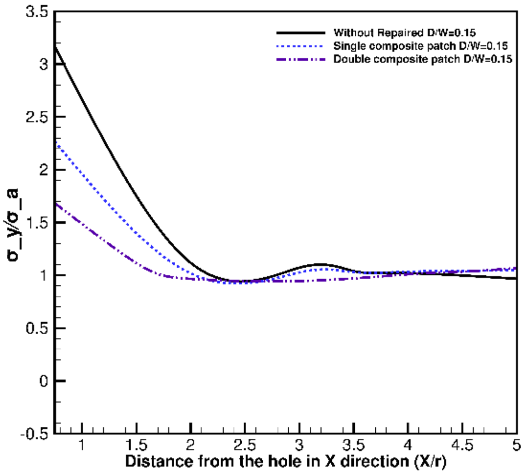


(a)



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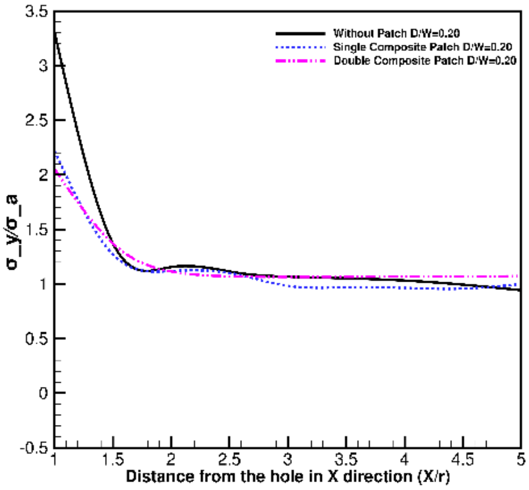

(c)

Fig. 7: The stress concentration from the hole in X-direction of plate, (a) D/W=0.10 (b) D/W=0.15 (c) D/W=0.20

4.3. Stress Distribution from the Patch

Figure 8 shows the stress concentration distribution in the Y-direction in the composite patch and piezoelectric actuator with positive applied electric field 1.0. It can be observed that applying a positive electric field does increase the compression stress. Therefore, the composite patch is less effective compared to piezoelectric properties. Moreover, from the results, the piezoelectric actuators with positive electric field are more effective for reducing SCF compared to composite patches.

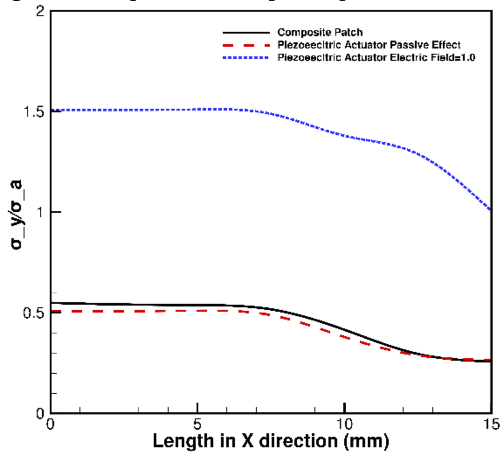

Fig. 8: Stress distribution from the Length of patches

5 CONCLUSION

The effects of composite patches and piezoelectric actuators bonded on a circular hole in a rectangular plate subjected to uniform tensile load have been investigated. The results showed that the SCF reduces with the composite patch. However, when applying a high positive electric field on the piezoelectric actuator, a higher reduction of SCF is achieved. It was also found that the reduction of the SCF is significantly affected by the composite patch diameter to width ratio. Finally, it wass concluded that the piezoelectric actuator with positive electric field is more effective compared to the composite patch for single and double patches in many of the cases.

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REFERENCES

1. W.D. Pilkey, Peterson's Stress Concentration Factors, John Wiley, New York, 2008.
2. E.S. Folias, J.J. Wang, On the three-dimensional stress field around a circular hole in a plate of arbitrary thickness, Computational Mechanics 6 (1990) 379–391.
3. K. Madani, S. Touzain, X. Feaugas, M. Benguediab, M. Ratwani, Stress distribution in a 2024-T3 aluminum plate with a circular notch, repaired by a graphite/epoxy composite patch 29 (2009) 225–233.
4. N.L.V. Raju, H. Pathak, A. Singh, Composite patch repair modelling by FEM, in Proceedings of First Structural Integrity Conference and Exhibition (SICE-2016), Bangalore, India, July 4-6 July, (2016) 4–9.
5. R. Mhamdia, B. Serier, A. Albedah, B.B. Bouiadjra, K. Kaddouri, Numerical analysis of the influences of thermal stresses on the efficiency of bonded composite repair of cracked metallic panels, Journal of Composite Materials 51 (26) (2017) 3701–3709.
6. M. Damghani, C. Harrison, D. Kennedy, The effects of composite laminate stiffness and loading on stress resultant concentration factor around a hole, Journal of Mechanical Engineering Science 232(6) (2018) 1033-1049.

7. A. Aabid, M. Hrairi, J.S.M. Ali, A. Abuzaid, Stress concentration analysis of a composite patch on a hole in an isotropic plate, International Journal of Mechanical and Production Engineering Research and Development 6 (2018) 249–255.
8. A. Aabid, M. Hrairi, J.S.M. Ali, A. Abuzaid, Numerical analysis of cracks emanating from hole in plate repaired by composite patch, International Journal of Mechanical and Production Engineering Research and Development 6 (2018) 238–243.
9. A. Abuzaid, M.S.I.S. Dawood, M. Hrairi, Effects of adhesive bond on active repair of aluminium plate using piezoelectric patch, Applied Mechanics and Materials 799–800 (2015) 788–793.
10. A. Abuzaid, M. Hrairi, M.S.I.S. Dawood, Survey of active structural control and repair using piezoelectric patches, Actuators 4(2) (2015) 77–98.
11. A. Abuzaid, M. Hrairi, M.S.I.S. Dawood, Estimation of stress concentration factor of plate with hole using piezoelectric actuator and finite element method, IOP conf. Series: Materials Science and Engineering 184(3) (2017) 1–7.
12. A. Abuzaid, M.S.I.S. Dawood, M. Hrairi, The effect of piezoelectric actuation on stress distribution in aluminum plate with circular hole, ARPN Journal of Engineering and Applied Sciences 10(21) (2015) 9723–9729.
13. ANSYS Inc, "ANSYS FLUENT 18.0: Theory Guidance," Canonsburg PA, 2017.