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EFFECT OF BONDED COMPOSITE PATCH ON THE STRESS INTENSITY FACTOR FOR A CENTER-CRACKED PLATE

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ABSTRACT: Crack propagation until fracture is an important criterion to predict a structure‘s service life. In order to increase the latter, the cracked component needs to be repaired or replaced. In the present study, a finite element analysis has been carried out to investigate the effects of adhesive thickness, patch thickness and crack length on the passive repair performance of a center-cracked rectangular aluminum plate under mode-I loading condition using finite element ANSYS package. A comprehensive parametric study shows that the stress intensity factor is influenced by the patch thickness, patch size, adhesive material, and adhesive thickness.

ABSTRAK: Penyebaran retak sehingga patah adalah kriteria penting bagi menjangka hayat struktur. Bagi memanjangkan jangka hayat struktur, komponen keretakan perlu dibaik pulih atau diganti. Kajian ini telah menjalankan analisis elemen tak terhingga bagi mengetahui kesan ketebalan pelekat, ketebalan tampalan dan panjang retak pada bahagian keretakan tengah plat petak aluminium yang dibaiki secara pasif, menggunakan pakej ANSYS di bawah beban mod-I. Kajian parametrik yang menyeluruh menunjukkan faktor tekanan intensif dipengaruhi oleh ketebalan tampalan, saiz tampalan, bahan pelekat dan ketebalan pelekat.

KEYWORDS: *stress intensity factor; center crack; composite patch; adhesive; finite element*

1. INTRODUCTION

A structure can be damaged by low energy effects and initiated cracks in its inner layer which may propagate and cause failure of the structure. Damages such as delamination, notches, and cracks are inevitable in various fields of engineering, especially in the aerospace field, and these damages are mostly due to fatigue, corrosion, and accidents. For the repair of such damaged structures, composite patches have been widely used and proven effective. Numerous studies have been reported in this type of passive structural repair in the past four decades.

Much of the earlier numerical work, reported in the literature, was based on FRANC2D/L finite element (FE) code. A circular notch in an aluminum 2024-T3 plate repaired with a graphite/epoxy composite patch was investigated using that code [1] where the developed geometry of the plate and patch were not carried out using a 3D element formulation that can be close to experimental work. Using the same FE code, another study investigated the effect of adhesive layers to repair the cracked plate with bonded composite patch in which distinct types of adhesives were used and the best one was selected to reduce the stress intensity factor (SIF) and strain energy release rate (SERR) [2]. Later, an algorithm was added to that FE code to simulate the temperature effect to determine reduction of SIF [3]. Using the same code, an investigation of composite patch use to repair a cracked plate was carried out. The effect of the thickness of the patch and adhesive were considered and the patch was designed with circular shape and implemented on an edge-cracked rectangular plate [4].

In recent years, simulation of cracked plate with composite patches has been done using ABAQUS and ANSYS software for 2D and 3D analysis. Mhamdia et al. [5] repaired the crack with bonded composite patch under thermo-mechanical load to reduce SIF. The effect of thermal residual stresses resulting from adhesive curing on the performance of bonded composite repair in aircraft structures was analysed with ABAQUS software [5]. Another study reported experimental results of applying thermal and mechanical load to check the effectiveness of a composite patch over the cracked structure. Patch material, patch size, patch shape, and adhesive material were considered effective in SIF reduction. A center crack emanating from a circular notch was employed to study the reduction in SIF [6]. A composite patch bonded to a cracked plate made of aluminum 2024-T3 under mixed-mode loading was investigated [7]. In this study, 20 noded solid186 element types were used to model the plate, patch, and adhesive bond and the geometry was developed according to the angular changes from 0% to 100% to move mode I to mixed mode. Aabid et al. [8-10] numerically analysed the results of stress concentration factor (SCF) for a center-holed rectangular aluminum plate with and without composite patch repair and SIF when a crack is emanating from the hole. It can be found from the above literature survey that much of the work has been done on edge-cracked rectangular plates. Therefore, the aim of this research is to simulate the results for center-cracked rectangular plates.

In the present work, numerical simulation under linear-elastic fracture mechanics (LEFM) was carried out to establish the effect of composite patch and adhesive characteristics on a center-cracked rectangular plate subjected to a uniform tension load leading to a Mode I type of failure.

2. PROBLEM DEFINITION

2.1 Specimen

The center-cracked rectangular plate under tensile load with integrated composite material patch is considered for this study, as depicted in Fig.1. The material of the cracked rectangular plate is considered to be aluminum 2024-T3 and the adhesive material is considered to be araldite 2014. In the present study, a crack length of $2a = 30$ mm was used with an integrated composite patch on the crack length under an applied tensile load of 1 MPa. The dimension and mechanical properties of the center-cracked rectangular plate, adhesive layer, and composite material are as shown in Table 1 and Table 2. The composite patch is applied to the damaged area to cover the crack length. The dimensions of the patch are such that it completely covers the damaged area. In the present study boron/epoxy is selected as the composite patch material based on its high strength-to-weight ratio.

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2.2 Patch Shape

A patch with a skewed shape had been shown to be the most optimum patch design. However, one should be careful when designing such patch shapes to ensure the stress level in the plate remains within the design limits [11]. The rectangular shape of the patch was found to be the second best choice. Considering mechanical performances and manufacturing aspects, this rectangular shape represents a better compromise. Therefore, the patch size was chosen as the minimum patch size that completely covers the crack length and improves the mechanical behavior of the cracked plate under the mode I loading [2].

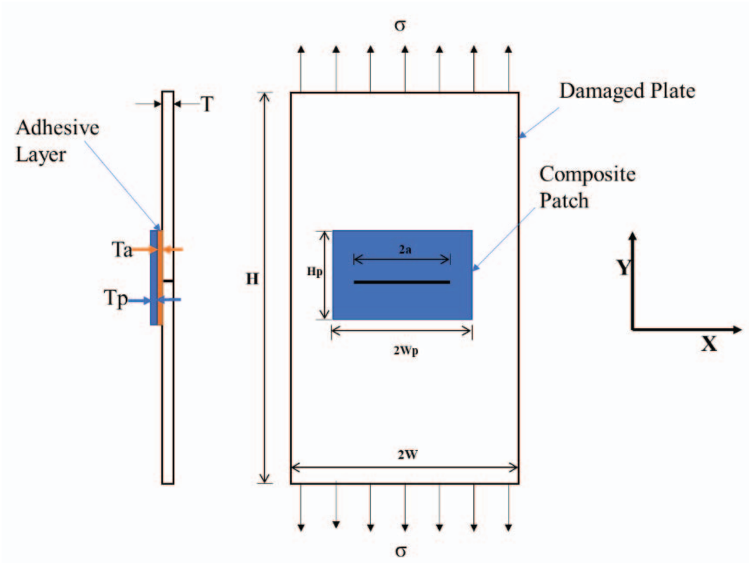

Fig. 1: Rectangular plate with a center crack and integrated composite patch.

Table 1: Dimensions of the host plate, boron/epoxy and adhesive

Dimensions	Aluminum plate (mm)	Boron/Epoxy (mm)	Adhesive (mm)
Height	H=200	Hp=40	Ha=40
Width	2W=80	2Wp=60	2Wa=60
Thickness	T=1	Tp=0.5	Ta=0.03

Table 2: Materials properties of the host plate, boron/epoxy and adhesive

Parameter	Aluminum plate	Boron/Epoxy	Adhesive (Araldite 2015)
Density	2715 kg/m^3		1160 kg/m^3
Poisson's Ratio υ_{12}	0.33	0.3	0.345
Poisson's Ratio υ_{13}		0.28	
Poisson's Ratio υ_{23}		0.28	
Young's Modulus (E_1)	68.95 GPa	200 GPa	5.1 GPa
Young's Modulus (E_2)		19.6 GPa	
Young's Modulus (E_3)		19.6 GPa	
Shear Modulus (G_{12})		7.5 GPa	
Shear Modulus (G_{13})		5.5 GPa	
Shear Modulus (G_{23})		5.5 GPa	

3. FINITE ELEMENT MODELLING

The finite element modelling (FEM) is performed using ANSYS mechanical APDL software for simulation purposes [12]. The gradient of the stress and strain fields around the crack front is very high, and to describe such behavior, the displacement extrapolation method uses the nodal displacements around the crack tip. To obtain a good representation of the crack tip displacement, singular elements are used as shown in Fig. 2(a). The nodes used for the crack tip displacements required for the equation are illustrated in Fig. 2(b).

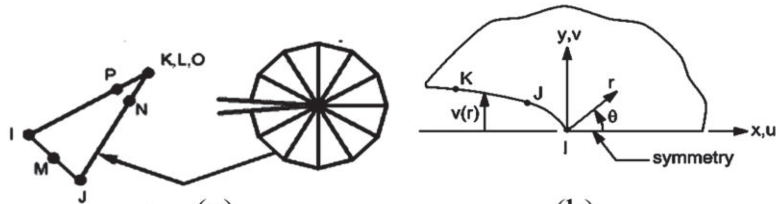

Fig. 2: (a) The singular element near the crack tip and (b) nodes used for the approximate crack tip displacements.

In this work, the SIF is calculated using ANSYS finite element analysis (FEA) software with reasonable accuracy. The displacement near the crack tip is obtained from finite element (FE) analysis, and then the SIF is calculated according to equation (1).

$$K_I = \sqrt{2\pi}\frac{2\mu A}{1+k} \tag{1}$$

3.1 Mesh Sensitivity Analysis

To study the mesh effect on the computational results, three mesh sizes were considered as illustrated in Table 3. The processor, which used to run the different cases of the simulation, was an Intel(R) Core i7-3770 CPU @ 3.40 GHz, 16.0 GB RAM, and a Windows-10 64-bit operating system. The parameters selected to run the simulations are: crack length of 10 mm, width of the adhesive bond and the composite patch of 30 mm, height of the adhesive bond and the composite patch of 20 mm, thickness of the adhesive bond of 0.03, mm and thickness of the composite patch of 0.5 mm. The grid structured mesh was used to mesh the adhesive bond and composite patch by applying the size of elements based on mesh type. For the damaged plate, the elements were divided by picking each line, and the generated mesh is of an unstructured type.

As shown in Table 3, it was found that the refinement of the mesh, from intermediate to fine, slightly improved the solution accuracy of the SIF value, leading to a maximum relative difference of 4 %. This comparison indicates that the intermediate mesh provides sufficient resolution and accuracy with around half the computational time, and hence, this mesh size was used for the rest of the simulations.

Table 3: Mesh independence test

Mesh Type	No. of Elements	CPU Runtime (seconds)	SIF (MPa)
Coarse	6,832	300	0.0691
Intermediate	33,180	660	0.0667
Fine	68,920	1322	0.0640

3.1 Modelling of the Integrated Structure

In this case, a boron/epoxy composite patch was used, and a SOLID186 element type was used to model the damaged plate, adhesive layer, and composite patch. SOLID186 contains a 20-noded higher order element with 5 degrees of freedom. A typical FE model for the center-cracked plate integrated with a composite patch is shown in Fig. 3. Due to symmetry, only a quarter of the plate was modeled. A total of 10 singular elements were employed to model the crack front. The adopted FE mesh consisted of 7910 coupled-field elements used to model the composite patch, while 21,580 and 3690 high-order reduced integration solid elements were used to model the damaged plate and adhesive bond, respectively.

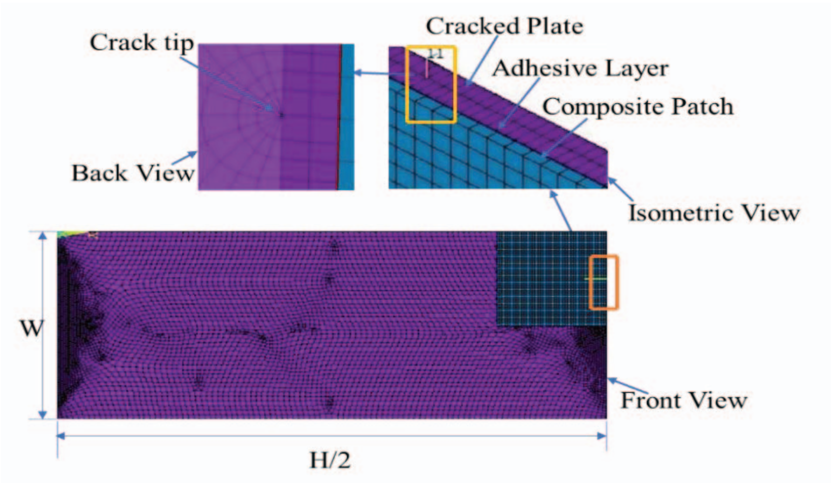

Fig. 3: Finite element mesh and the location of the singular element.

3.2 Validation of Finite Element Model

Most of the previous work has been done for the edge cracked plate as it can be easily verified through experimental work. Therefore, an edge-cracked plate was selected to validate the present finite element model. The meshes that are used to model the center and edge cracked plates are almost identical except for their boundary conditions. To verify the simulation results of passive repair, the case study reported in [13] was simulated using the FE model developed in the present work. The edge-cracked rectangular plate integrated composite patch is shown in Fig. 4.

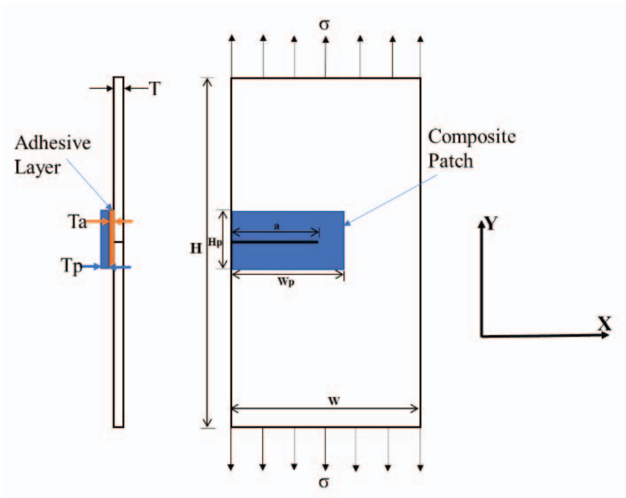

Fig. 4: Rectangular plate through an edge-crack integrated composite patch.

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The dimensions and mechanical properties of the cracked plate, adhesive layer and composite material are mentioned in Tables 4 and 5. Applied tensile stress is 58.33 MPa, and the crack length is 30 mm. The results obtained from the current numerical simulation were compared with that reported in [13] and there was a very good agreement as shown in Table 5.

Table 4: Dimensions of the host plate, boron/epoxy patch and adhesive (FM-73)

Dimensions	Host plate (mm)	Boron/Epoxy (mm)	Adhesive (mm)
Height	H=254	Hp=75	Ha=75
Width	W=254	2Wp=130	2Wa=130
Thickness	T=4.76	Tp=2.28	Ta=0.15

Table 5: Material properties of the host plate, boron/epoxy patch and adhesive (FM-73)

Parameter	Aluminum plate	Boron/Epoxy	Adhesive (FM-73)
Plate Strength	350 MPa		
Poisson's Ratio $\upsilon 12$	0.33	0.3	0.32
Poisson's Ratio $\upsilon 13$		0.28	
Poisson's Ratio $\upsilon 23$		0.28	
Young's Modulus (E1)	72 GPa	200 GPa	2.55 GPa
Young's Modulus (E2)		19.6 GPa	
Young's Modulus (E3)		19.6 GPa	
Shear Modulus (G12)		7.2 GPa	
Shear Modulus (G13)		5.5 GPa	
Shear Modulus (G23)		5.5 GPa	

Prior to repair validation, the FE model of the unrepaired plate (cracked plate without a patch) was also validated using a fracture mechanics analytical solution [14]. Comparing the results gained by Tada's analytical solution [14] according to equation (2) and the present finite element results, there is a good agreement, as shown in Table 6.

$$K_I = \sigma\sqrt{\pi a}\sqrt{\frac{2b}{\pi a}tan\frac{\pi a}{2b}}\frac{0.752+2.02\left(\frac{a}{b}\right)+0.37\left(1-sin\frac{\pi a}{2b}\right)^3}{cos\frac{\pi a}{2b}} \quad (2)$$

Where a is the crack length, and b is the width of the damaged plate.

Table 6: Validation of numerical simulation results

Condition	Ref. [9] $MPa\sqrt{m}$	Ref. [10] $MPa\sqrt{m}$	Present Results $MPa\sqrt{m}$	Relative Error
Without Repair	-	20.049	20.432	**1.874%**
Passive Repair	9.789	-	9.623	**1.695%**

3.3 Boundary Conditions for Center and Edge Cracked Plate

Figure 5 shows the applied boundary conditions for the edge and center cracked plate. Due to symmetry, the model used for the center-cracked plate is a quarter of the plate and for the edge-cracked plate is half the plate. The dimensions of the adhesive bond and composite patch are illustrated in Table 1 for the center cracked plate, and Table 4 for edge cracked plate.

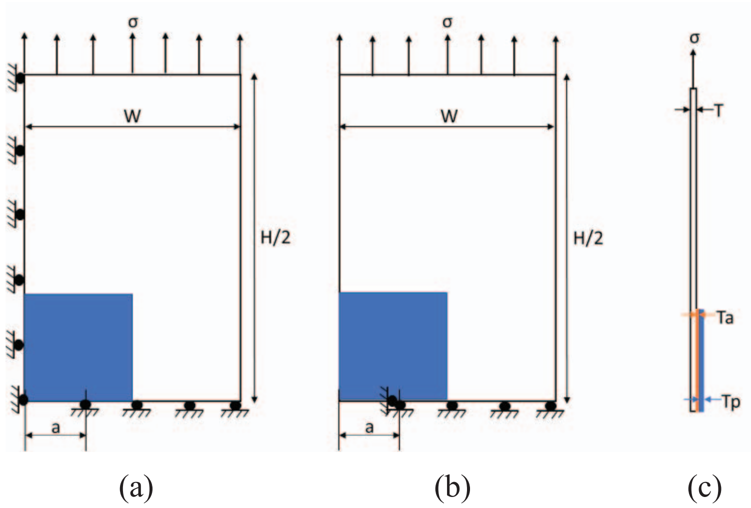

Fig. 5: Applied Boundary conditions (a) center-cracked (b) edge-cracked (a) side view of plate.

4. RESULTS AND DISCUSSION

In this section, finite element analysis was carried out to study the effect of a composite patch placed on the damaged area of a rectangular plate under uniform uniaxial tension load for the problem shown in Fig. 1.

4.1 Comparison between Unpatched and Patched Crack

The variation of mode I stress intensity factor is plotted in Fig. 6 for five different values of crack length in the unpatched and repaired cracked plates. It can be seen that SIF strongly decreased when employing the patch repair and more so for bigger crack lengths since the patch carried the load as the crack grew. This is because the stress singularity around the crack tip is reduced due to the composite patch induced shear force on the crack area. Indeed, the SIF reduction reached a maximum value of 68% compared to a 60% reduction for the glass/epoxy patch as obtained in [6]. Therefore, boron/epoxy patches are more effective for reduction of SIF. Furthermore, Fig. 6 shows that for the repaired plate and as the crack length increases, the SIF exhibits an asymptotic behavior.

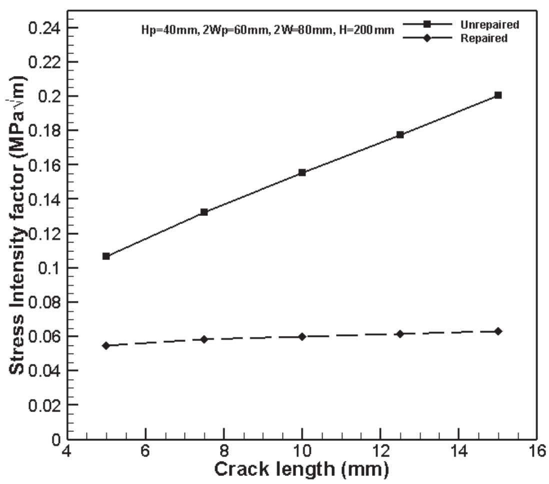

Fig. 6: Crack length variation with and without patch.

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4.2 Effect of Patch Thickness

Patch thickness represents one of the best means for improving patch repair performance. Thus, many researchers investigated the patch thickness effect on the repair performance in damaged structures [4,5,15]. Mhamdia et al. [16] achieved almost 50% decrease in the crack tip SIF by increasing the patch thickness to repair a cracked plate under mechanical loading.

Figure 7 displays this effect on the normalized SIF variation. It is clearly illustrated that the normalized SIF at the crack tip is reduced proportionally as the patch thickness increases. Indeed, the size of the patch is important to transfer shear load at the damaged area. An increase of 45-50% of the patch thickness reduces the normalized SIF by the same order. Hence to increase the repair performance, the size of the patch should be thicker. Moreover, for repairing cracks, it is preferable to use multi-layered composite patches to improve the distribution of stresses.

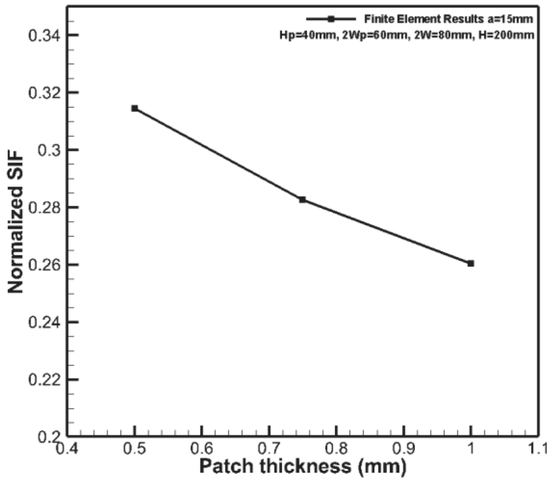

Fig. 7: Effect of patch thickness for passive repair.

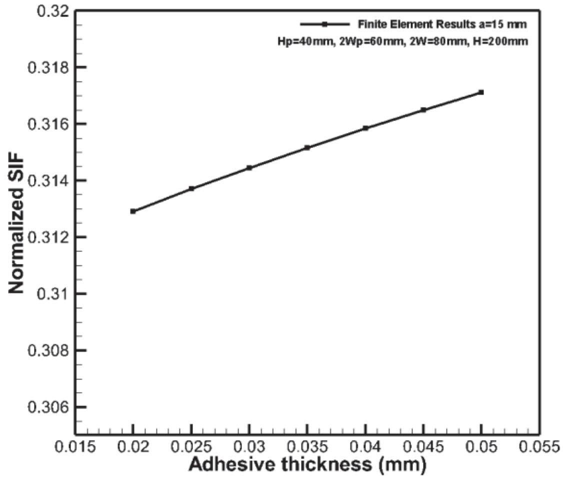

Fig. 8: Effect of adhesive layer thickness for passive repair.

4.3 Effect of Adhesive Thickness

Figure 8 shows the variation of the normalized SIF as a function of the adhesive thickness. It can be seen that a very small increment in the adhesive thickness increases the normalized SIF. Therefore, when repairing cracked structures, it is desirable to use smaller adhesive thickness. This finding correlates well with the results highlighting this effect in [15]. Thus, the adhesive thickness should be chosen carefully as on the one hand, a bigger value of thickness will reinforce adhesion but dissipate the transfer of the loads towards the patch, which decreases the favorable effects of the patch. On the other hand, smaller thickness will transfer the load towards the patch but increases the risk of adhesive failure.

4.4 Effect of Adhesive Materials

The mechanical stresses between the composite patch and the host cracked plate increase significantly with the increase of the shear modulus of the adhesive. However, it is not recommended to increase the adhesive shear modulus indefinitely as this will reduce the adhesive strength, which can increase the risk of the adhesion failure. Thus, the adhesive choice should compromise between allowing stress transmission to the patch while preventing the failure of the adhesion.

The variation of the SIF as a function of four different adhesive materials, shown in Fig. 9, confirms the above statement. The mechanical properties of adhesive materials are illustrated in Table 7. It can be seen in Fig. 9, that when a crack length increases, the normalized SIF will decrease. This means that when the crack length increases, there is a chance that the material will fail drastically if not repaired. Therefore, to control this, the composite patch has been used and the adhesive material properties create effective shear loads that depend on shear modulus, as was highlighted in Ref. [5]. The araldite 2014 outperforms the other adhesives as it better transfers the load towards the patch, as highlighted by the higher reduction in normalized SIF.

Table 7: Mechanical properties of adhesive materials

Material Type	E (GPa)	υ	G (GPa)	ρ kg/m^3
Araldite 2014	5.1	0.345	1.89	1160
EPON422J	3.49	0.29	1.10	
FM-47	2.106	0.3	0.81	
FM-73	1.83	0.33	0.688	875

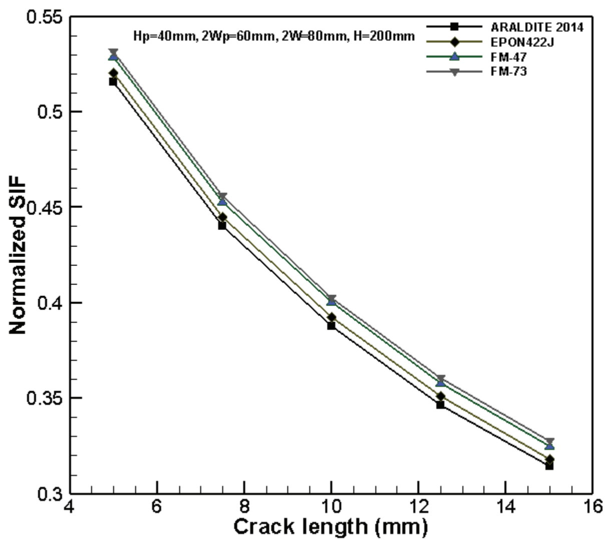

Fig. 9: Effect of adhesive materials for passive repair.

4.5 Effect of Crack Length

Figure 10 displays the normalized SIF variation as a function of crack length. It can be seen that the reduction of normalized SIF is higher for larger crack lengths. Indeed, the normalized stress intensity factor is maximum for smaller cracks, and then it decreases and stabilizes towards an asymptotic value for larger cracks. This behaviour leads us to state that the patch stress absorption is less significant for short cracks.

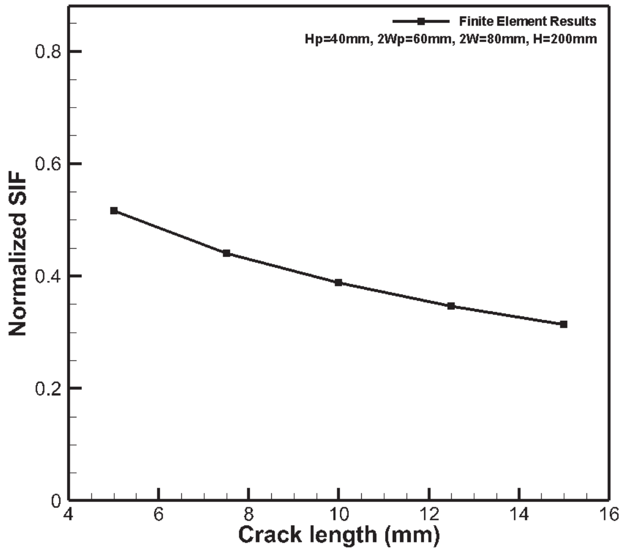

Fig. 10: Effect of crack length for passive repair.

5. CONCLUSION

This work describes the numerical simulation of the composite patch for a damaged rectangular plate under structural load by a finite element analysis ANSYS package. A substantial reduction in SIF is observed with an integrated composite patch. Based on present simulations, the following conclusions are drawn;

- About 68% SIF reduction is observed for single side patch repairs for boron/epoxy patches and a crack length of 15 mm.
- Increases of patch thickness reduce the SIF at the crack front.
- Increase in adhesive thickness results in a decrease of SIF reduction at the crack front.
- It has been proven that araldite 2014 adhesive material has a good mechanical property to reduce maximum SIF at the crack front.

The effect of the composite patch on the reduction of SIF on a center-cracked rectangular plate subjected to uniaxial load is simulated, and the results demonstrated that the SIF decreases linearly with the effect of the composite patch.

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