Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Influence of Adhesive Curing Temperature and Geometrical Parameters on Composite Patch Repair of Cracked Structures

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ARTICLE INFO

Article history:
Received 20 February 2024
Received in revised form 3 June 2024
Accepted 16 June 2024
Available online 15 July 2024

Keywords:
Crack repair; stress intensity factor; finite element analysis

ABSTRACT

Revitalizing aircraft structural components marred by damage is imperative to enhance their operational lifespan, obviating the need for wholesale replacement of parts or even the entire airframe. The application of composite patches for mending fractured structures contributes significantly to prolonging their serviceability. However, this strategy often mandates curing the adhesive at temperatures surpassing ambient conditions. Hence, the present investigation centers on the reparation of a cracked plate via a composite patch under conditions of thermo-mechanical loading. The study also delves into the repercussions of thermal stresses on the Stress Intensity Factor (SIF), engendered by elevated curing temperatures. By executing Finite Element Analysis (FEA), the SIF at the crack tip was computed, and a parametric examination was executed to scrutinize the influence of assorted parameters such as the thickness of the patch and adhesive on SIF, leveraging the ANSYS tool. Notably, the existence of a composite patch resulted in a substantial reduction of SIF, with noteworthy SIF alterations arising from parameter variations. Elevation in SIF, prompted by thermal stresses due to adhesive curing, was found to manifest markedly, a predicament that can be mitigated by effecting adhesive curing at ambient temperatures.

1. Introduction

When aircraft structural damages are identified, prompt repair processes become imperative. Swift repairs are crucial to mitigate potential hazards to flight safety and avert undesirable scenarios such as aircraft accidents. Maintenance and inspections are routinely conducted before and after flights to ensure sustained operational integrity. All damages must be meticulously addressed, as the aircraft's performance hinges on the meticulousness of these repairs. Consequently, meticulous assessment of structural impairments is essential to devise optimal repair strategies that align with aviation maintenance mandates [1].

For a variety of reasons, aircraft structures can develop cracks, and these cracks can pose serious safety risks. The two most prevalent types of reasons that lead to the onset and spread of cracks in

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https://doi.org/10.37934/arfmts.119.1.112

such structural parts are fatigue and harsh environmental conditions [2,3]. Within the aviation domain, the traditional method of addressing structural issues in aircraft still holds a prominent position. Typically utilized for the restoration of damaged metallic components in aircraft structures, this method entails the utilization of bolts, nuts, and rivets to attach the compromised metal plate to another. Nevertheless, this technique brings about additional openings, an undesirable consequence, particularly in light of the aircraft's exposure to the effects of aging. These openings have the potential to undermine the structural integrity of the aircraft [3]. Attaching the composite patch to the impaired section of the plate presents an alternative method to enhance the efficacy of mending the damaged plate. The rising adoption of composite patches in aircraft structure restoration is attributed to their advantageous attributes and user-friendly application. This trend is particularly pronounced when addressing minor fractures and other compromised structural elements. The remarkable robustness of composites, surpassing that of alternative substances, coupled with their exceptional corrosion resistance, positions them as a favored choice within aerospace contexts. These composites, formed by combining two or more materials, are engineered to impart specific functionalities [4]. Ongoing progress is being made in the realm of cutting-edge composite materials, repair techniques, simulation methodologies, and optimization strategies. The primary aim of these advancements is to manage structural impairment, reduce fracture metrics, optimize cost-effectiveness, lower energy consumption, and present innovative resolutions for repair approaches and the upkeep of compromised structures [4,5].

A study was conducted by Albedah *et al.,* [6] to study the effect of adhesive disbond on repair efficiency. Results demonstrated that increasing the initial disbond width diminishes the fatigue life of repaired structures. Interestingly, the initial length of the adhesive disbond has a limited impact on repair efficiency. Using a composite patch, Aabid *et al.,* [7] restored a structure that had a hole in the center. The results indicate a significant SIF reduction positively impacting fatigue performance. Aabid *et al.,* [8] carried out FEA to determine the SIF of a damaged plate repaired using a piezoelectric actuator and composite patch. The results showed that employing double patches enhanced the stress transfer from the damaged structure to the patch and when a high voltage was supplied to the pzt patch, a SIF drop of about 85% was achieved. Maleki and Chakherlou [9] examined a composite patch affixed to a damaged aluminum 2024-T3 structure under mixed-mode loading conditions. Notably, the geometry of the system was meticulously adjusted, ranging from 0% to 100% angular alterations, effectively transitioning from mode I to mixed mode conditions.

Aabid *et al.,* [10] repaired the cracked plate using a single side patch for the crack length of 15 mm under mechanical loading conditions. The SIF of a mended plate undergoing mode-I crack propagation was determined using a 3D finite element technique [11]. Subsequently, the Design of Experiments approach was effectively employed to attain the optimal SIF value for the restoration of a centre-cracked plate made of aluminum 2024-T3. For the optimization process, a Taguchi L-9 orthogonal array was chosen. As per the findings, the minimum stress intensity factor value achieved through optimization stands at 0.0487517 MPa√m. This achievement is realized when specific parameters are combined: a patch and adhesive thickness of 1 mm and 0.025 mm, respectively, along with a shear modulus of 1022 MPa.

In their study, Mohammed *et al.,* [12] conducted an empirical investigation aimed at gauging the impact of patch shape on repair efficiency. Their approach involved employing bonded composite patches on cracked aluminum panels and subjecting them to fatigue tests. The outcomes revealed that the trapezoidal patch shape yielded a fatigue life comparable to the rectangular one, which was around 9 times greater than that of the unrepaired control. Notably, the fatigue life of the triangular patch with a left-oriented configuration closely resembled that of the unrepaired specimen. As a result, the researcher concluded that the triangular patch, when left-oriented, had negligible effects on the restored 7075-T6 specimen. Amari and Berrahou [13] carried out FEA analysis to examine the effects of complete and u-shaped composite patches on the effectiveness of mending broken composite structures. Full-shape patches helped lower the SIF value, and boron/epoxy outperformed graphite in terms of performance. The study on the influence of adhesive shear modulus repair performance of a damaged structure was carried out by Berrahou *et al.,* [14]. The author concluded that a rise in the value of shear modulus enhances the repair performance which was measured in terms of J-integral. Different patch shapes were also tested to achieve optimized performance, and the rectangular shape gave better results. Kaddouri *et al.,* [15] found that the presence of a defect in adhesive significantly impacts the repair performance of a fractured structure especially when the defect is near the fracture point. However, its impact is reduced when the fracture length is small. This research endeavor seeks to conduct finite element analysis on a centrally cracked plate subjected to both mechanical and thermo-mechanical loading scenarios. The study delves into the influence of curing temperature on SIF. Additionally, it examines significant factors impacting the effectiveness of repairs, encompassing patch thickness, adhesive thickness, and diverse patch materials, all within the context of thermo-mechanical loading conditions.

2. Geometric Model

We have considered a center-cracked plate with the following dimensions: the plate's width, 2W, is 76 mm, its height, H, is 100 mm, and its thickness, T, is 1 mm, as depicted in Figure 1. Affixed to the cracked plate is a composite patch, measuring W_p = 40 mm in width, H_p = 20 mm in height, and T_p = 1.2 mm in thickness. This patch is bonded using adhesive, which measures W_a = 40 mm in width, H_a = 20 mm in height, and T_a = 0.3 mm in thickness. The plate is deliberately designed with a 10 mm center crack, oriented perpendicular to the loading axis. For complete coverage of the damaged region, the patch spans the length of the crack. Under consideration is an axial load of 1 MPa applied to the plate. The material's elastic and thermal properties, as well as dimensions for the plate, adhesive, and patch, are outlined in Table 1 and Table 2, respectively.

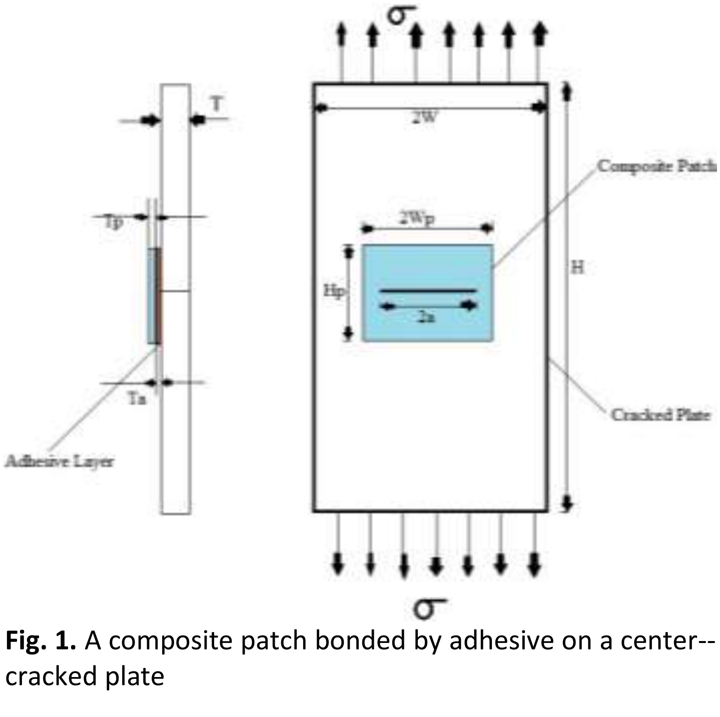


Fig. 1. A composite patch bonded by adhesive on a center--cracked plate

Table 1
Material Properties

Parameters	Aluminium plate	Composite patch	Adhesive
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}		0.3	
Poisson's Ratio υ_{23}		0.35	
Young's Modulus (E_1)	68.95 GPa	13.78 GPa	5.1 GPa
Young's Modulus (E_2)		13.78 GPa	
Young's Modulus (E_3)		3.57 GPa	
Shear Modulus (G_{12})		5.3 GPa	
Shear Modulus (G_{13})		5.3 GPa	
Shear Modulus (G_{23})		1.32 GPa	
α_{12} (10^{-6}°C)	22.5	15	
α_{13} (10^{-6}°C)		15	
α_{23} (10^{-6}°C)		55	

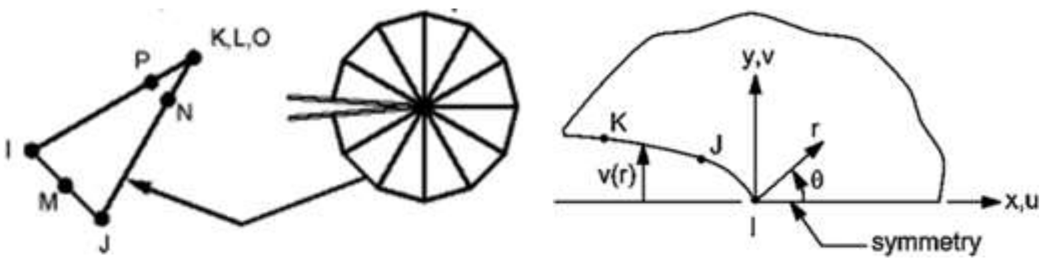
Table 2
Material dimensions

Dimensions	Aluminium plate (mm)	Composite patch (mm)	Adhesive (mm)
Height	H=200	H_p=20	H_a=20
Width	2W=76	$2W_p$=40	$2W_a$=40
Thickness	T=1	T_p=1.2	T_a=0.03

Aluminium 2024-T3, Araldite 2014, and Fibreglass/epoxy were selected for plate, adhesive, and patch respectively.

3. Finite Element Modelling

To facilitate simulation, the ANSYS mechanical APDL program is utilized for finite element modeling (FEM). To capture the specific behavior accurately, a displacement extrapolation method is employed. This technique leverages the nodal displacements near the fracture tip. This decision is based on the crack front's surrounding stress and strain fields, which have a markedly higher gradient. Singular elements are included, as shown in Figure 2(a), to precisely describe the displacement at the fracture point. Figure 2(b) shows the nodes used to calculate the necessary fracture tip displacements.



(a) (b)

Fig. 2. (a) singular element near fracture point and (b) nodes used to calculate the displacements of the fracture tips roughly

3.1 Geometry and Modelling

The evaluation of a 3D finite element model was performed utilizing the ANSYS software. The fractured plate, composite patch, and adhesive were all subject to analysis, employing the 3D SOLID186 element type. SOLID186 falls within the category of higher-order elements, incorporating 20 nodes that enhance its suitability for solid-structural analysis. To compute SIF, singular elements were integrated at the fracture point during the plate meshing process. A free mesh option was employed. For both the adhesive bond and patch, a structured rectangular mesh with an element size of 0.0005 m was adopted. Due to symmetry considerations, just one-fourth of the repaired plate was taken into account. Figure 3 illustrates the mesh model for the repaired plate.

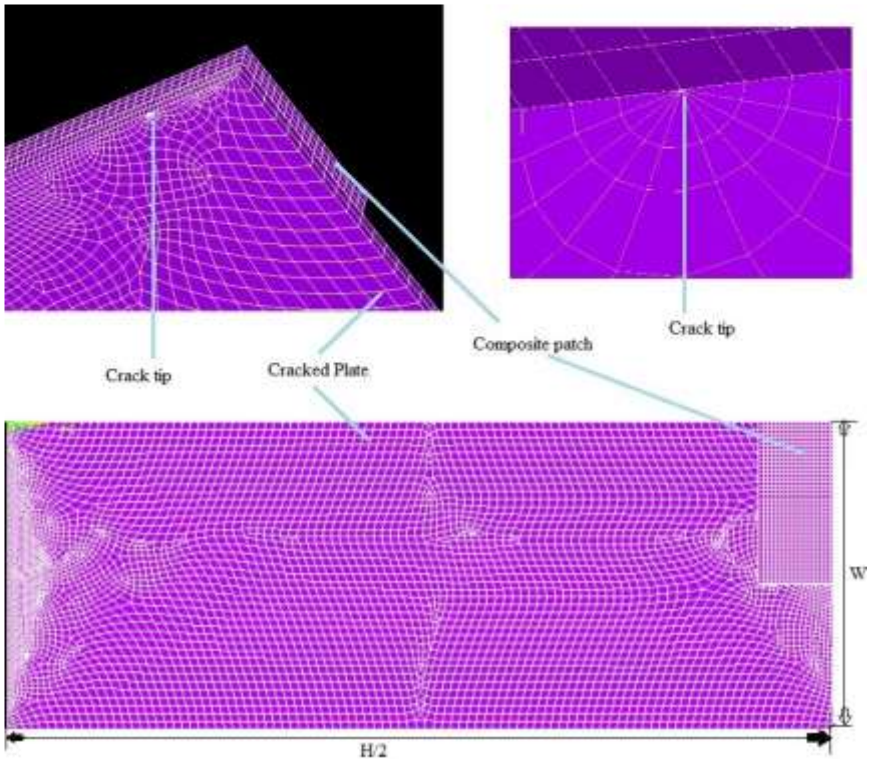


Fig. 3. Mesh model

3.2 Mesh Sensitivity Analysis

Three different mesh sizes were considered to explore the impact of mesh resolution on computational results, as shown in Table 3. The subsequent simulations were conducted using the following parameters: a 5 mm crack length, a 20 mm width for both the composite and adhesive, a 10 mm height, a 0.03 mm thickness for the adhesive bond, and a 1.2 mm thickness for the composite patch. The sizing of the elements was determined based on the mesh type, with a grid-structured mesh employed for meshing adhesive bonds and patches. To segment the parts of the damaged plate, each line was individually selected, resulting in the generation of an unstructured mesh configuration.

Table 3
Mesh sensitivity analysis

Mesh type	No. of elements	CPU runtime (seconds)	SIF (MPa√m)
Coarse	7150	75	0.062902
Intermediate	23522	180	0.057893
Fine	56184	450	0.054633

Refining the mesh, transitioning from intermediate to fine, marginally increased the precision of the computed SIF values, as demonstrated in Table 3, revealing a maximum relative variation of 6%. Subsequent simulations opted for the intermediate mesh size due to this comparison. It was chosen based on the sufficient balance it struck between clarity and precision, all while having less than half the computational time compared to the fine mesh option.

3.3 Validation of the Model

For validation, a model was employed with the following measurements: H = 200 mm, 2W = 80 mm, and T = 1 mm. The adhesive and patch possessed identical dimensions: H_p = H_a = 40 mm, $2W_p$ = $2W_a$ = 60 mm, with a patch thickness of T_p = 0.5 and an adhesive thickness of T_a = 0.03 mm. This model represented a centre cracked plate, featuring a crack of length a = 5 mm, subjected to a tensile load of 1 MPa, as portrayed in Figure 4. Material characteristics for the cracked plate, patch, and adhesive were meticulously documented in Table 4. Notably, the SIF results obtained through the present simulation for both the unrepaired cracked plate and the repaired one exhibited a commendable concurrence with findings in prior literature, as eloquently showcased in Table 5.

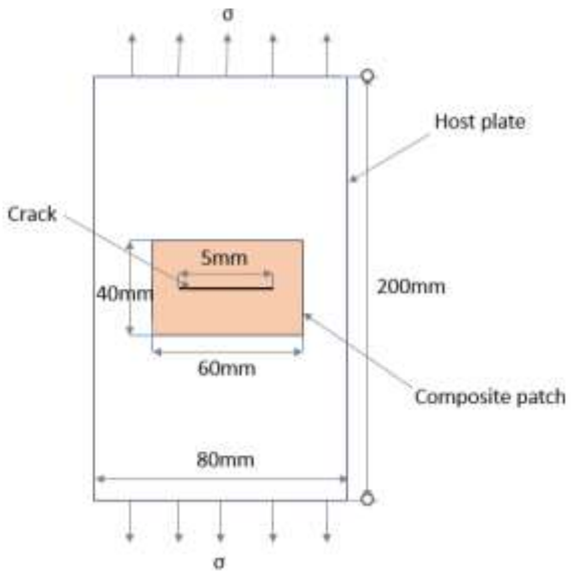


Fig. 4. Validated model

Table 4
Material characteristics of cracked plate, patch and adhesive

Parameters	Aluminium plate	Boron/epoxy	Araldite 2014
Density	2715 kg/m^3		1160 kg/m^3
υ_{12}	0.33	0.3	0.345
υ_{13}		0.28	
υ_{23}		0.28	
E_1	68.95 GPa	200 GPa	5.1 GPa
E_2		19.6 GPa	
E_3		19.6 GPa	
G_{12}		7.5 GPa	
G_{13}		5.5 GPa	
G_{23}		5.5 GPa	

Table 5
Validation of simulation work with literature

Case	[12](MPa√m)	Present results (MPa√m)	Relative error (%)
Cracked plate without repair	0.115	0.120	4.25
Cracked plate with repair	0.059	0.06	1.68

4. Results and Discussions

Within this segment, the outcomes derived from the finite element analysis are explored. Following the resolution of the SIF, the analysis delves into magnifying the crack tip vicinity to establish the path of the crack face. Furthermore, a local coordinate system is formulated through the utilization of three nodes. Ultimately, the Mode-I SIF is ascertained by employing the KCALC command.

4.1 Mechanical Loading

In this segment, only a mechanical load was employed perpendicular to the crack axis on the damaged plate. As depicted in Figure 5, it becomes evident that the presence of the patch substantially diminishes the SIF due to the adhesive's role in transferring load from the cracked plate to the patch. Remarkably, there was a noteworthy 70% reduction in SIF upon employing the patch for the repair of the damaged plate. In cases where no repair was conducted, there was a noticeable exponential escalation in SIF in direct proportion to the increase in crack length. In contrast, for the repaired scenario, SIF showcased an asymptotic trend with the extension of the crack length. This behavior arises from the patch's ability to endure the load as the crack extends. It's worth noting that the asymptotic SIF pattern upon lengthening the crack in the repaired scenario might shift if the plate's thickness is decreased, possibly resulting in structural failure. Consequently, initiating repairs on the plate during the initial stages of crack formation is a recommended course of action.

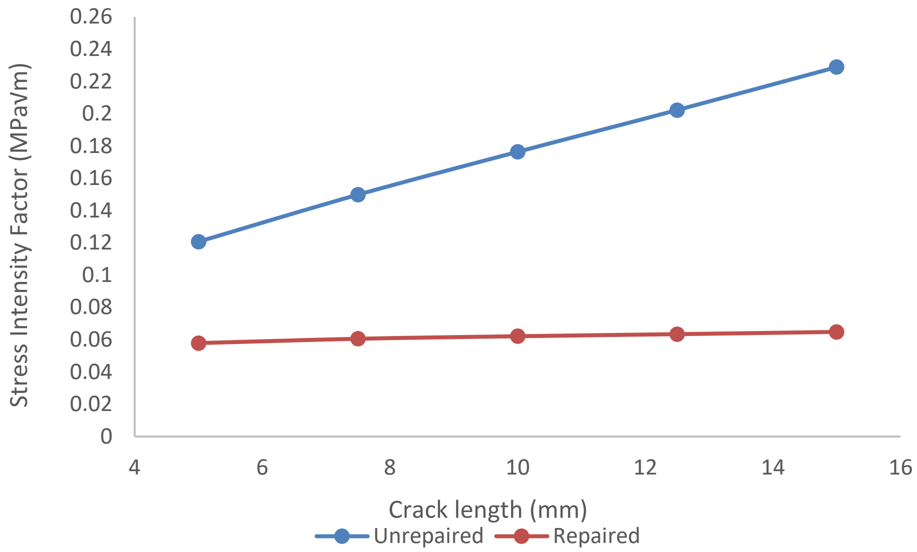


Fig. 5. Effect of composite patch and crack length on SIF

4.2 Effect of Adhesive thickness on SIF

Observing Figure 6 reveals a clear trend: a slight augmentation in adhesive thickness leads to a rapid upsurge in the SIF at the fracture tip. This action is explained by the fact that while a thicker adhesive increases adhesion strength, it also makes it more difficult for loads to be effectively transferred to the patch, lessening the benefits of the patch. Conversely, opting for a thinner adhesive shifts stress towards the patch, amplifying the chance of the adhesive failing. Hence, there exists a need to judiciously optimize the adhesive thickness.

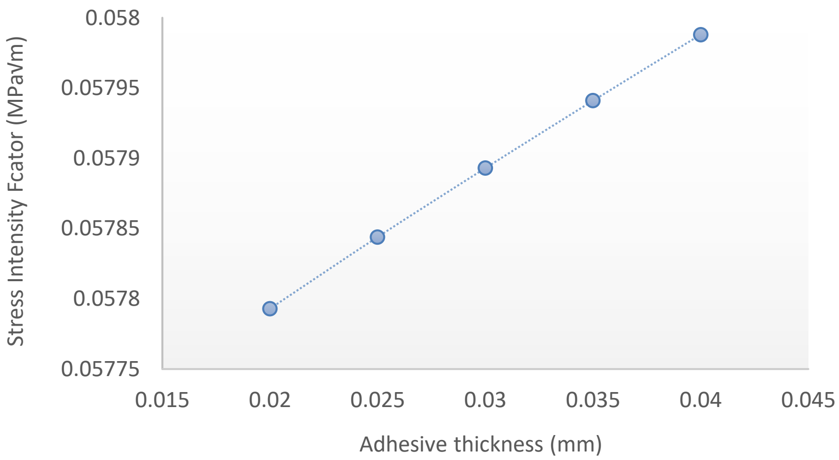


Fig. 6. Effect of Adhesive thickness on SIF

4.3 Effect of Patch Thickness

The thickness of the patch is a significant factor in influencing the restorative effectiveness of the compromised structure. Figure 7 depicts how alterations in patch thickness impact the SIF. Patch thickness and the decrease in SIF are directly correlated. This is because thicker patches can distribute the load of the plate more evenly, which reduces the stress concentration around the crack and can prevent further propagation of the crack. Hence, to improve repair performance, patches of thicker size should be employed. Additionally, to enhance the distribution of stresses when patching cracks, multi-layered composite patches are used.

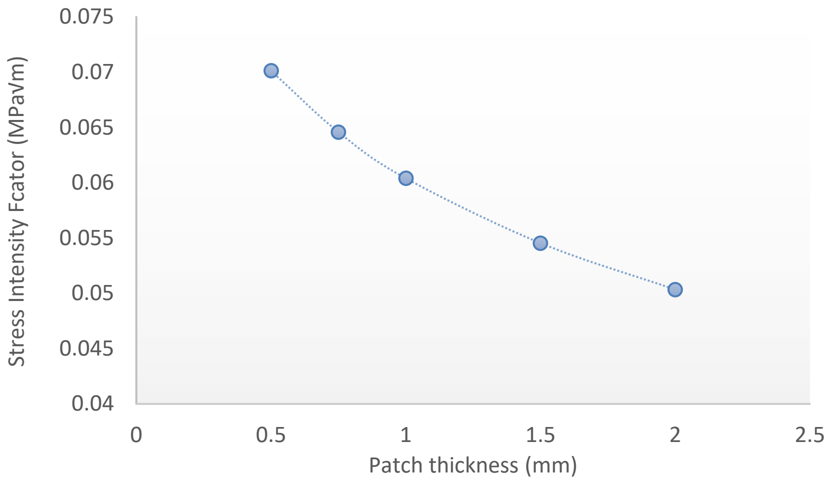


Fig. 7. Effect of Patch thickness on SIF

4.4 Thermo-Mechanical Loading

The utilization of strong structural adhesives in adhesive bonding typically involves the need to cure the adhesive at temperatures higher than the surrounding environment. In the initial bonding phase, the specific region of the plate is heated to an elevated temperature denoted as Ti during the curing procedure. The effectiveness of attaching the composite patch to the mended panel is notably impacted by the curing temperature. However, the curing process also induces thermal residual stresses, which ultimately undermine the efficiency of the repair. Eq. (1) can be employed to calculate these stresses.

$$\sigma = -\frac{1}{2}\alpha.\mathrm{E}\,\Delta\mathrm{T} \tag{1}$$

To evaluate the potential impact of these stresses on repair efficacy, the Stress Intensity Factor (SIF) is calculated under two conditions: one accounting for thermal residual stress and the other without it. A mechanical force of 130MPa was applied to the mended plate in conjunction with the thermal stress component. The curing temperature is taken as 120°C, while the ambient temperature is set at 20°C.

Including the influence of thermal residual stresses is crucial when predicting the fatigue longevity of revitalized aircraft structures. As the cured plate cools down, the aluminum material, which possesses a higher coefficient of thermal expansion than the fiberglass/epoxy composite, undergoes tensile thermal stress. In contrast, the composite patch experiences compressive stress. The complete curing of the repair gives rise to thermal residual strains during the cooling process from an elevated temperature. This is due to the typical scenario where composite patches exhibit a lower thermal expansion coefficient compared to the cracked structure being repaired. Figure 8 illustrates that the SIF sees a growth of approximately 47% across the entire crack length when both thermal and mechanical loads are applied. This elevation in SIF has the potential to curtail the structural fatigue life.

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
Volume 119, Issue 1 (2024) 1-12

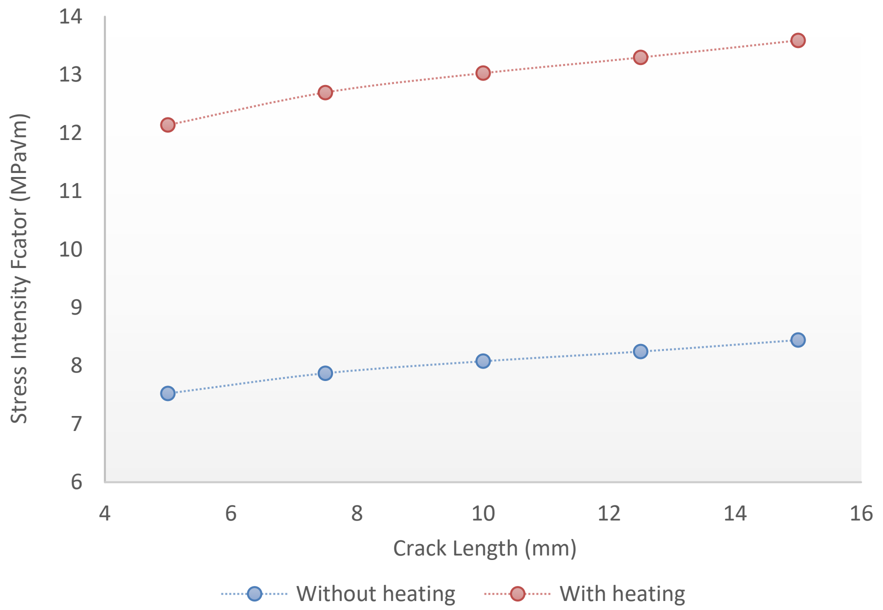


Fig. 8. Effect of Thermal heating on SIF

4.4.1 Different patch materials under thermo-mechanical loading

In this section, different patch materials such as boron/epoxy, graphite/epoxy, and e-glass/epoxy were employed for repairing the damaged plate under thermo-mechanical loading to study their effect on repair efficiency. The mechanical and thermal properties of boron/epoxy, glass/epoxy, and graphite/epoxy have been listed in Table 6.

Table 6
Different patch material properties

Parameters	Poisons ratio			Youngs modulus (GPa)			Shear Modulus (GPa)			α (10^{-6}°C)		
Material	υ_{12}	υ_{13}	υ_{23}	E_1	E_2	E_3	G_{12}	G_{13}	G_{23}	α_{12}	α_{13}	α_{23}
Boron/epoxy	0.3	0.28	0.28	200	19.6	19.6	7.2	5.5	5.5	4.5	23	23
Graphite/epoxy	0.33	0.33	0.33	134	10.3	10.3	5.5	5.5	3.2	-1.2	34	34
E-glass/epoxy	0.33	0.33	0.33	50	14.5	14.5	2.56	2.56	2.24	5.5	15	15

The lowest SIF was observed in the case of boron/epoxy, graphite/epoxy, and e-glass/epoxy as depicted in Figure 9. Among these, the boron/epoxy exhibited the lowest SIF, followed by graphite/epoxy, and finally e-glass/epoxy. When substituting boron/epoxy with graphite/epoxy, there was a notable 26% increase in SIF. This shift can be attributed to the superior strength-to-weight ratio of boron/epoxy in comparison to the other composite materials. Moreover, the use of e-glass/epoxy instead of boron/epoxy led to a significant additional increase of about 45% in SIF.

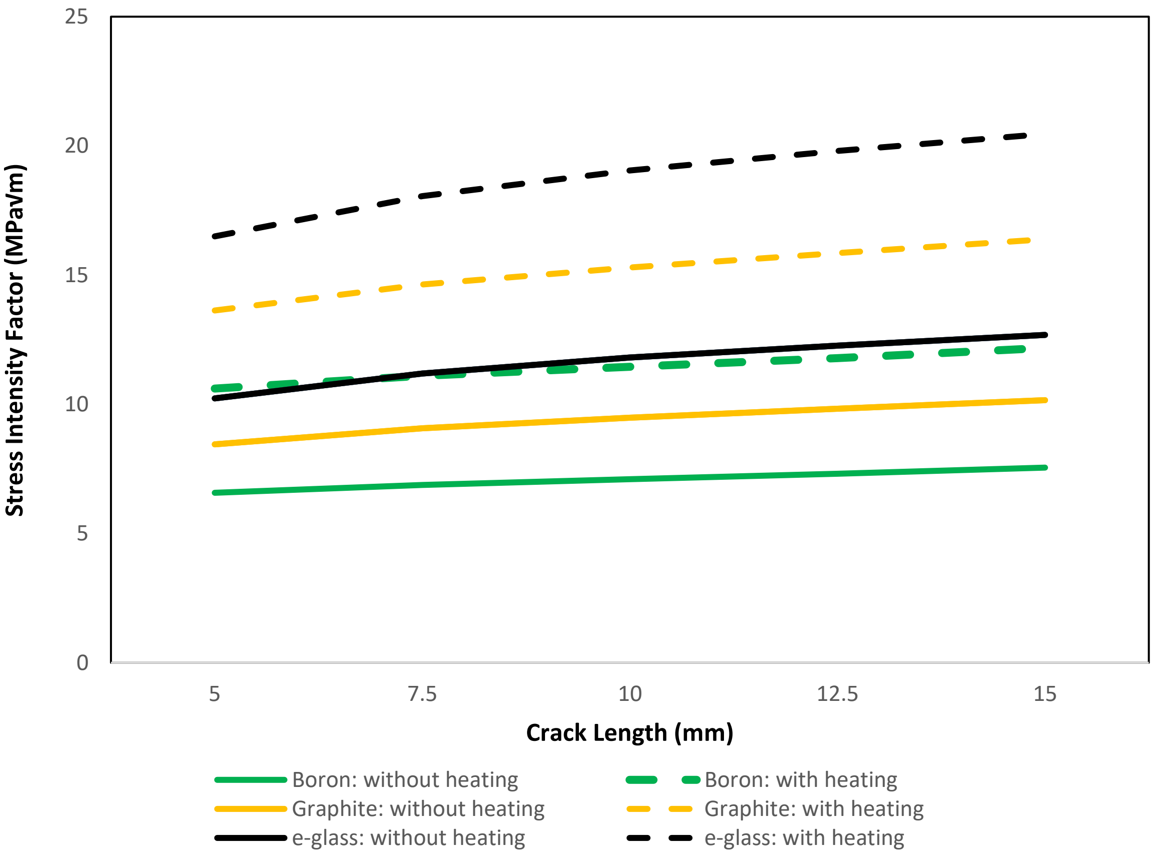


Fig. 9. SIF vs thermal heating for different patches

The disparity in SIF between mechanical and thermo-mechanical loading remains consistent across all patch materials, demonstrating a relative difference of approximately 46%. This similarity holds for all types of patch materials. Therefore, adopting boron/epoxy for repair work can effectively diminish the SIF and subsequently enhance repair efficiency. It is advisable to account for the impact of curing temperature when devising patch designs.

5. Conclusion

The present investigation was conducted to assess the impact of mechanical and thermo-mechanical forces on a damaged plate that underwent repair using a composite patch. Taking advantage of a patch led to a noteworthy 70% decrease in stress intensity factor (SIF). Enhanced reduction in SIF was observed with thicker patches possessing optimized adhesive thickness. Notably, when a locally stiffened structure is allowed to cool post complete curing and patching, thermal stress inevitably develops within both the plate and the reinforcement. This effect is particularly pronounced if the patch used for reinforcement has a lower coefficient of thermal expansion than the structure being repaired. The results underscore that elevated curing temperatures give rise to thermal stresses, causing an approximately 47% rise in SIF compared to SIF under mechanical loading alone. These thermal stresses profoundly compromise the repair effectiveness of the mended plate. Consequently, it is advisable to employ adhesives that can cure at ambient temperatures to mitigate the influence of thermal stress. Among the options of boron/epoxy, graphite/epoxy, and glass/epoxy, choosing boron/epoxy for the repair work holds the potential for reducing SIF due to its advantageous strength-to-weight ratio.

Acknowledgment
This research was supported by the Ministry of Higher Education of Malaysia (MOHE) through the Fundamental Research Grant Scheme (FRGS/1/2021/TK0/UIAM/01/5). The author acknowledges and thanks Kulliyyah of Engineering, International Islamic University Malaysia, for offering the KOE Postgraduate Tuition Fee Waiver Scheme.

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