Visual Abstract

Finite Element analysis of the behavior of bonded composite patches repair in aircraft structures

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ABSTRACT. This paper aims to analyze the multi-effects of the glass fiber reinforced polymer (GFRP) composite patch to repair the inclined cracked 2420-T3 aluminum plate. Three-dimensional finite element method (FEM) was used to study the effect of GFRP composite patch with different stacking composite laminate sequence, $[0^\circ]_4$, $[90^\circ]_4$, $[45^\circ]_4$, $[0^\circ/45^\circ]_{2s}$, and $[0^\circ/90^\circ]_{2s}$, on the crack driving force, *J-integral*, of inclined cracked 2420-T3 aluminum plate. Furthermore, the effects of patch geometry, number of layers, single or double side patch, and crack inclination angle are described.

The present results show that the patch has a high effect in case of a crack in pure mode I. The effectiveness of the composite patch increases with increasing the crack length. Moreover, the efficiency of the composite patch has a high effect by changing the fiber orientation, the number of layers, and the single or double side patch.

KEYWORDS. Mode of mixity; J-integral; Aluminum alloy; 3-D FEM; Composite repair patch.

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INTRODUCTION

In aircraft applications, service life is very important. It is affected by structural and aerodynamic loads as landing, take off, fatigue, ground handling, and bird strikes. The repair or reinforcement method is essential to improve service life without increasing the budget. Composite patches are used over the cracked area that prevents or delays crack propagation due to the reduction in the stress intensity factor [1–9]. Fiber-reinforced polymers are used to repair the cracked structure because they have many advantages like high strength to weight ratio, fatigue resistance, corrosion resistance, and good mechanical properties [4,5]. Bouiadjra et al. [6] compared the performances of using composite and metallic patches for repairing cracked aircraft structures. They found that the composite patch is more efficient than a metallic patch for reducing the stress intensity factor of cracked aircraft structures.

Many researchers used a composite patch to repair the cracked structure and they studied different parameters to improve the efficiency of the composite patch. Ramji and Srilakshmi [4] studied single and double-sided patch on center-cracked aluminum panel. Furthermore, Madani et al. [5] used the single and double composite patch to repair the crack exerted from circular notch by using the finite element method. Brighenti et al. [7, 8] used the biology-based method to obtain the optimal shape of patch repairs for cracked plates. Huang and Feng [9] used the finite element method to study the effect of carbon fiber reinforced polymer (CFRP) repaired for edge crack under different failure modes. Sadek et al. [10] compared between carbon-epoxy and boron-epoxy patches with four different shapes: circular, rectangular, trapezoid, and elliptical.

Moreover, Ouinas et al. [11] compared boron-epoxy and graphite-epoxy patches and also studied the effects of the adhesive properties and patch size on crack propagation. Deghoul et al. [12] studied the effect of temperature and patch shapes on the bonded composite repair performance of the Aluminum plate. Gu et al. [13] studied the effect of number, material, and thickness of composite-patch repair to transfer load from cracked structures and to reduce the crack mouth opening displacement (CMOD) of cracked structures. Furthermore, Budhe et al. [14] studied the effect the environmental influence (moisture, temperature, humidity etc.) on the mechanical performance of composite repair bonded joint. Thus, Kaddouri et al. [15] used the numerical finite element method to study the effect of geometrical and mechanical of boron/epoxy composite patch to reduce the driving force stress intensity factor of the central cracked plate. They found that the stress intensity factor at the repaired crack with the composite patch is highly influenced by changing the geometrical and mechanical of boron/epoxy composite patch. Ounias et al. [16] used a bonded boron/epoxy composite patch to repair a cracked aluminum plate with imperfection in the bond between the patch and the plate. They showed that the stress intensity factor is affected by these debonds. Furthermore, the effect of welded [17] or bonded [18–22] stiffeners on the crack tip deformation was studied previously by the authors.

The present work is an attempt to investigate numerically the effect of patch geometry, the number of patch layers, single or double patch, stacking composite laminate sequence of repair patch, and crack inclination angle that can improve the composite repairing patch of a cracked plate. The GFRP is used to repair a plate with an inclined crack with different crack lengths. Furthermore, the inclination angle is changed to cover the effect of the composite repairing patch on the mode I or mixed mode fracture of the cracked plate. Moreover, the stacking composite laminate sequence and geometry of the patch are changed.

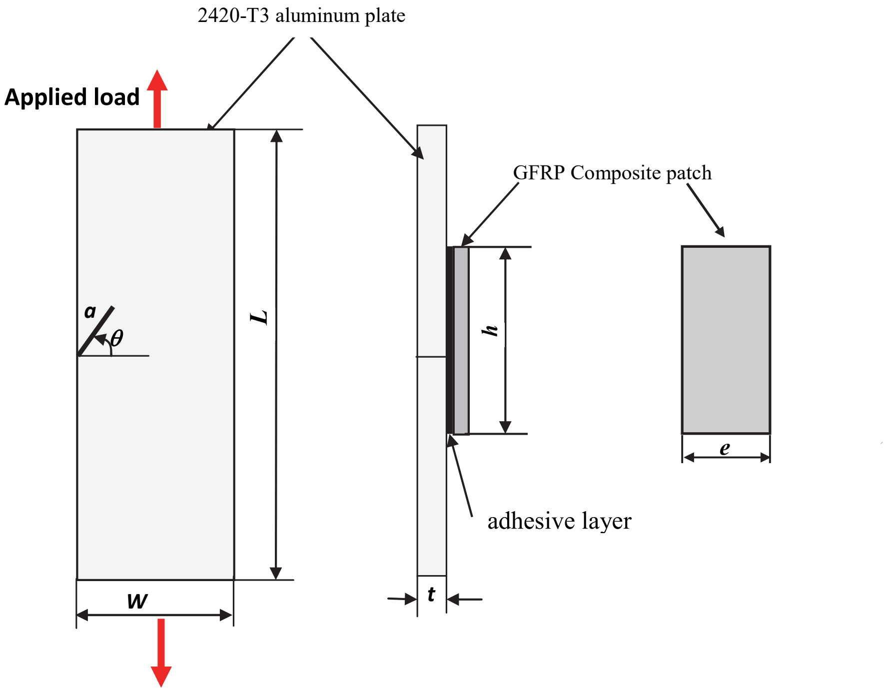

Figure 1: Specimen details-cracked plate, adhesive and patch

GEOMETRICAL MODEL

Fig. 1 shows the main plate, adhesive, and patch geometry analyzed in this work. The main plate contains an inclined crack with different crack length, *a*, and inclined angle, θ,. GFRP composite patch consists of many layers with different stacking composite laminate sequence (where: 90^{o} fiber angle means the fiber is perpendicular to the load direction as shown in Fig. 1) to study the effect of the number of layers, *N*, and stacking composite laminate sequence on the efficiency of the patch. Furthermore, the height of the patch, *h*, has several values to show if it has any effect on the efficiency of the patch. The patch width, *e*, is selected to be less than the maximum crack length to study the effect of the repair if the crack length exceeds the width of the patch. It is worth noting that the efficiency of the patch may be depending on the patch width, patch position on the cracked plate, and the thickness of the adhesive material. All these parameters will be taken into consideration by the authors in future work. The GFRP composite patch is bonded to the main plate by using the adhesive layer with the same cross-section of the patch and has a thickness of 0.1 mm. All geometric data for the main plate, adhesive layer, and composite patch can be shown in Tab. 1.

FINITE ELEMENT MODELING

The three-dimensional finite element method (3D-FEM) is utilized to show the effect of GFRP patch on repairing the cracked aluminum plate under static load. ABAQUS/Standard code [23] is used to simulate the present model to study the effectiveness of a composite patch on the driving force of a cracked aluminum plate. The validation and accuracy of the present models were checked previously by the authors [18, 19, 22].

Symbol	Value	Description
L	100	The height of the main plate, (mm)
W	50	The width of the main plate, (mm)
t	2	The thickness of the main plate, (mm)
a/W	0.02, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6	Inclined crack length ratio (mm/mm)
θ	0^{o}, 15^{o}, 30^{o}, 45^{o} and 60^{o}	Inclined crack angle
e	20	GFRP composite Patch width, (mm)
h	30, 40, 50 and 60	GFRP composite Patch height. (mm)
t_p	0.2	The thickness of each layer of the patch (mm)
t_a	0.1	The thickness of the adhesive (mm)
	[0], [0/90], [90], [45], [0/45]	Stacking composite laminate sequence
N	0, 2, 4, 6	Number of patch layers

Table 1: GFRP composite repaired inclined cracked 2420-T3 aluminum plate geometry.

A 2024-T3 aluminum alloy has been selected for material of the main plate and it was simulated as isotropic material with mechanical properties tabulated in Tab. 2. The glass fiber reinforced epoxy polymer, GFRP is used as a material of the patch and it was modeled as a composite layup in the property module in ABAQUS/Standard [23]. The GFRP composite material's unidirectional stiffness properties were listed in Tab. 2. Furthermore, the adhesive layer simulated as isotropic material with mechanical property described in Tab. 2. The mechanical properties of the 2024-T3 aluminum alloy, Glass epoxy composite repair wrap material and film adhesive epoxy FM 73 are taken from ref. [12]. Uniform axial tensile stress of 120 MPa was acting on the plate as shown in Fig. 1. The Composite patches are bonded on the surface of the plate covering crack. The layers of the composite patch are assumed as a complete bond on each other. Furthermore, film Adhesive epoxy was used to bond the composite patch on the aluminum plate by using the tie contact option in the ABAQUS/Standard.
The Contour Integral method is used to compute the value of *J-integral* [17, 18]. In the present model, C3D8R: an eight-node linear brick was used to mesh each element of the main plate, adhesive, and the composite patch. The refining process of mesh was carried out to assure that results are not dependent upon the size of the element. A complete mesh of a composite repaired aluminum plate model is shown in Fig. 2.

Symbol	Value	Property
Glass epoxy composite repair wrap material's properties		
E_{11}	27.82	Young's modulus in fiber direction (GPa)
E_{22}	5.83	Young's modulus in the transverse direction (GPa) (In Y direction)
E_{33}	5.83	Young's modulus in the transverse direction (GPa) (In Z direction)
G_{12}	2.56	In-plane shear modulus (GPa) (X-Y plane)
G_{13}	2.56	In-plane shear modulus (GPa) (X-Z plane)
G_{23}	2.24	In-plane shear modulus (GPa) (Y-Z plane)
ν_{12}	0.31	Poisson's Ratio (X-Y plane)
ν_{13}	0.31	Poisson's Ratio (X-Z plane)
ν_{23}	0.41	Poisson's Ratio (Y-Z plane)
Aluminum 2024-T3 material's properties		
E	71.02	Young's modulus (GPa)
ν	0.3	Poisson's ratio
Film adhesive FM 73 material's properties		
E	1.83	Young's modulus (GPa)
ν	0.33	Poisson's ratio

Table 2: Material properties of 2024-T3 aluminum alloy, adhesive layer and glass/epoxy composite patch [12]

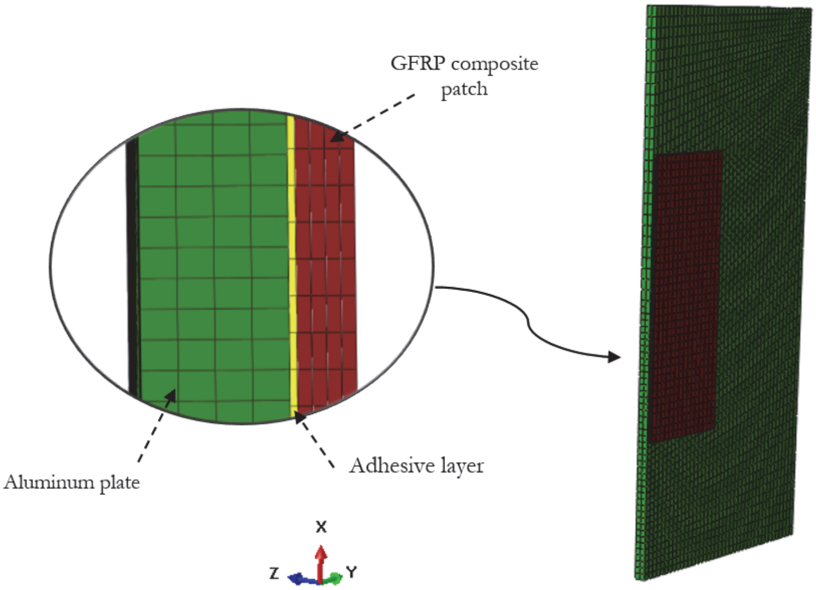

Figure 2: Typical mesh of the present model.

RESULTS AND DISCUSSION

The main objective of the present work is to study the efficiencies of the repaired bonded GFRP composite patch on the reduction of the crack tip driving forces, J-integral value. Therefore, in the present figures, the values of J-integral are presented in normalized form, i.e. the values of the repaired joints divided by the unrepaired ones. Fig. 3 shows the effect of stacking composite laminate sequence of the repaired patch on the values of normalized *J-integral* of the inclined crack with a constant number of layers, $N = 4$, and at $h = 50$ mm with different crack length. The value of normalized *J-integral* decreases by increasing the value of crack length ratio, a/W, as shown in Fig. 3. That means the efficiency of the composite patch increases by increasing the values of crack length. This may be attributed that when the crack length increases, the composite patch can more close the crack. Moreover, the best effect of stacking composite laminate sequence of the repaired patch is at uniaxial direction $[0]_4$ whatever the value of the inclined crack angle. On the other hand, the composite patch which has stacking composite laminate sequence $[90^o]$ is the lowest efficiency as shown in Fig. 3. When a/W reaches 0.4, crack length (a) is equal to the width of the patch (e), i.e. a vertical dash line is drawn at $a/W = 0.4$. After that the curves show the effect of the patch on the cracked plate when the crack length is higher than patch width. The effect of the patch is still very high till the end of the curves. This means that the patch has a higher efficiency to reduce the value of crack tip driving force, *J-integral*, even if the crack length exceeds the width of the patch. From Fig. 3, it can be concluded that the GFRP composite patch is a good method to repair the cracked plate regardless its crack length.

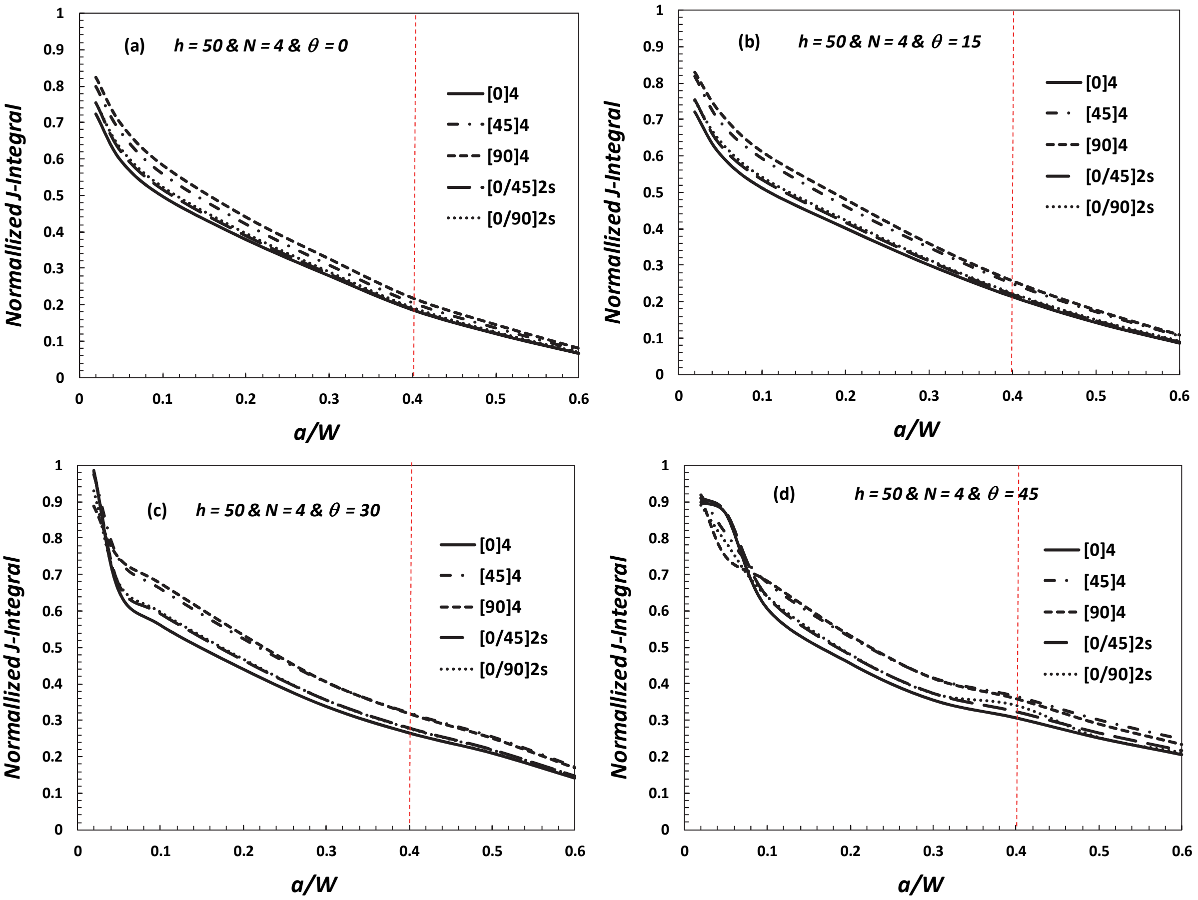

Figure 3: The effect of stacking composite laminate sequence of repair patch on the values of Normalized *J-integral* of edge repaired cracked plate with: (a) $\theta = 0^o$, (b) $\theta = 15^o$, (c) $\theta = 30^o$ and (d) $\theta = 45^o$

Fig. 4 *a* and *b* depict the effect of the inclined crack angle, θ, on the value of normalized *J-integral* of edge repaired cracked plate for different stacking composite laminate sequence of repair patch $[0]_4$ and $[0/45]_{2s}$ respectively, with a constant value of h and N. From Fig. 4 it can be concluded that the composite patch has the highest efficiency when
$\theta = 0^o$, while it has the worst efficiency when $\theta = 45^o$.

Fig. 5. shows the effect of patch height, h, on the values of normalized *J-integral* of edge repaired cracked plate with stacking composite laminate sequence $[0]_4$. From Fig. 5 it can be seen that the height of the patch does not considerably affect the efficiency of the repair.

Fig. 6 illustrates the effect of numbers of patch layers N, on the values of normalized *J-integral* of edge repaired cracked plate versus a/W at $h = 50$, $\theta = 0^o$ and stacking composite laminate sequence [0]. As expected, it can be shown that the effect of composite patch increases with increasing the numbers of layers. As described in Fig. 6 the number~~s~~ of layers improve the efficiency of the composite patch so that if another patch put at the other side of the composite patch can improve the effect of composite patch. Fig. 7 shows a comparison between the effect of single and double patch on the values of normalized *J-integral* of edge repaired cracked plate versus *a/W*. The use of a double composite patch has a higher effect than using a single composite patch as shown in Fig. 7.

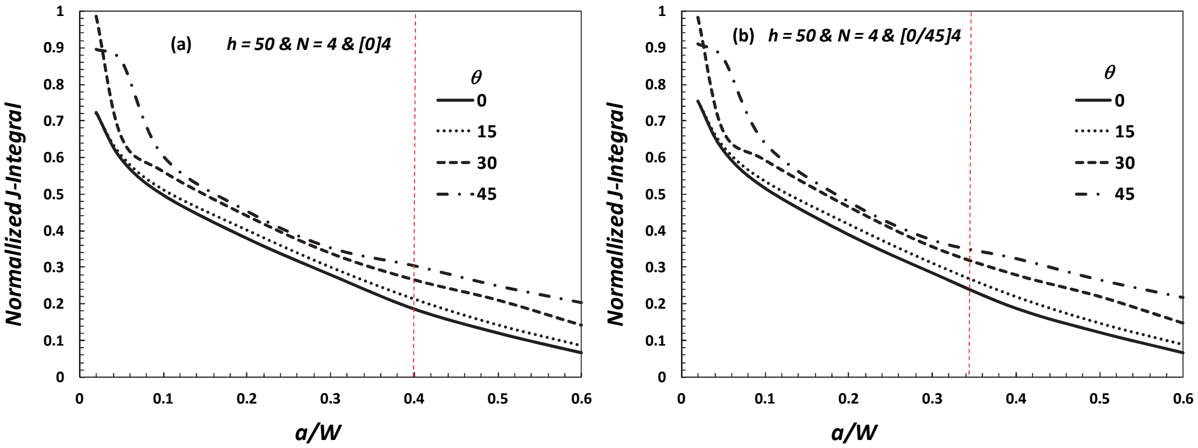

Figure 4: The effect of inclined crack angle, θ, on the values of normalized *J-integral* of edge repaired cracked plate with: (a) $[0]_4$ and (b) $[0/45]_{2s}$.

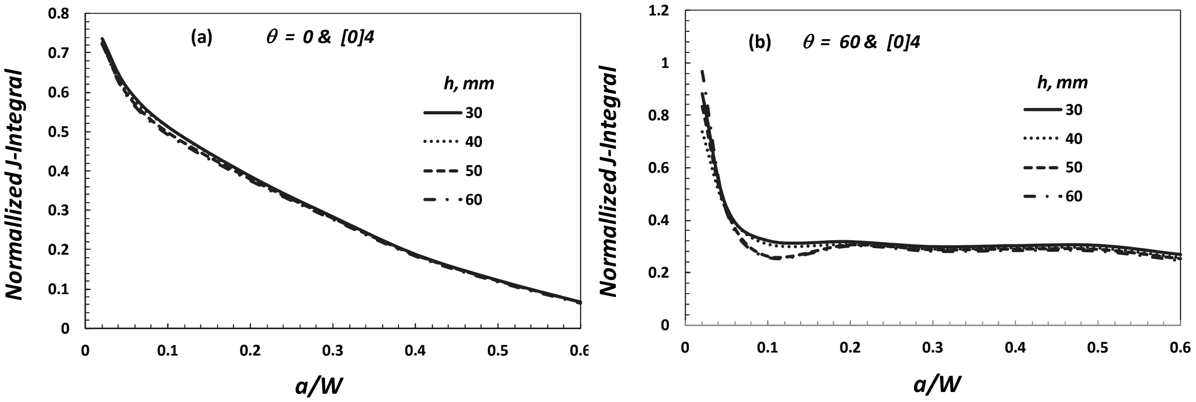

Figure 5: The effect of patch height length, *h*, on the values of normalized *J-integral* of edge repaired cracked plate with: (a) $\theta = 0^{\circ}$ and (b) $\theta = 60^{\circ}$.

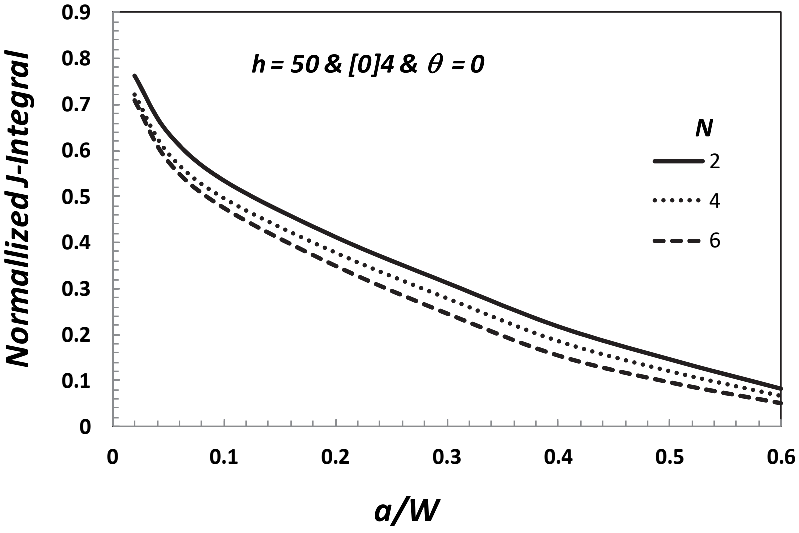

Figure 6: The effect of patch number of layers, *N*, on the values of normalized *J-integral* of edge repaired cracked plate.

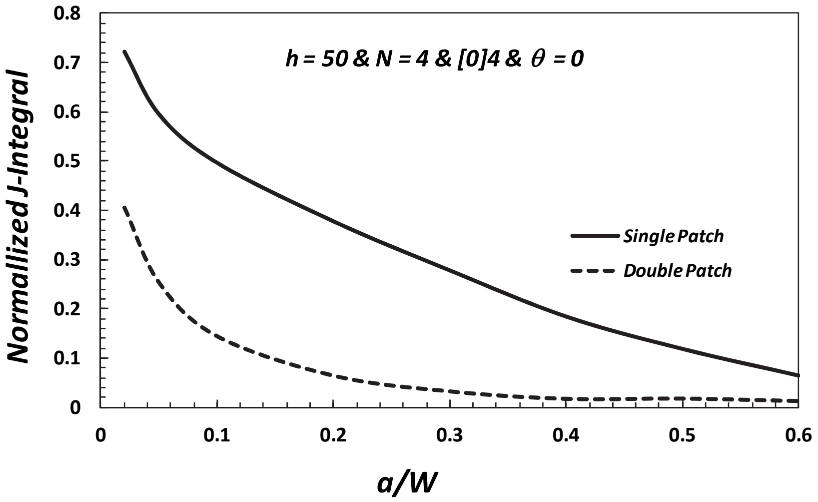

Figure 7: Shows a comparison between the effect of single and double patch on the values of normalized *J-integral* of edge repaired cracked plate.

CONCLUSION

From the present numerical work, it can be concluded that:

- The efficiency of the composite patch is depend on the fiber orientation with respect to the load direction, where the higher efficiency of composite repaired patch happens when it has a higher stiffness in the direction parallel to the load direction (Mode-I), whatever the value of the inclined crack angle.
- The patch has the highest efficiency in case of a crack in pure mode I for the present study.
- The GFRP composite patch is a good candidate method to repair the cracked plate even if the crack length exceeds the width of the patch.
- The efficiency of the composite patch improves when the number of layers increases.
- The use of a composite patch on the other side of the cracked plate increases the efficiency of the composite patch to restrain the crack propagation.
- The height of the composite patch does not considerably affect the efficiency of the repair of the cracked plate.

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