# Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 12 (21): 2259-2265, 2012
ISSN 1812-5654 / DOI: 10.3923/jas.2012.2259.2265


# Numerical Analysis for Determination of the J Integral and Crack Opening Displacement in the Cracked Aluminum Plates Repaired with FML Composite Patches

Gholamhassan Payganeh, Faramarz Ashenai Ghasemi, Ali Pourkamali Anaraki and Ahmad Fallah Rahmatabadi
Department of Mechanical Engineering, Shahid Rajaee Teacher Training University, Tehran, Iran

**Abstract:** Fiber Metal Laminates (FMLs) are widely used in aerospace industries nowadays. In this study, numerical investigations of adhesively bonded FML composite patch repairs of cracked aluminum panels is reported. Pre-cracked 3035 Aluminum panels of 179×76×1.5 mm repaired with rectangular single sided FML patch were used as test specimen. The finite element analyses were performed on the test specimen using quadratic brick elements for the Aluminum panels and FML patch subjected to uni-axial tensile loading. The FML patches were made of one aluminum layer and two woven glass-epoxy composite layers. Three different crack lengths in three crack angles and different patch lay-ups were examined. The crack opening displacements and J integrals obtained show that the lay-up of the patches and the place where the metal layer was embedded in the FML patches had an important effect on the tensile response of the tested specimens. When the aluminum layer is farther, the ultimate tensile load has the highest amount and when the aluminum layer is in the middle the ultimate load has the lowest amount.

**Key words:** Crack, fiber metal laminate, patch lay-up, crack intensity displacement, J integral

## INTRODUCTION

The technique of repairing cracked metallic aircraft structures was first done by the Aeronautical and Maritime Research Laboratories (AMRL), in 1970s (Prosser *et al*., 1995). Baker *et al*. (1988) performed a mathematical approach based on an analogy with a one-dimensional lap-joint analysis has previously been used to estimate adhesive and plate stresses for simple repairs. Belason *et al*. (1994) conducted two- and three-dimensional linear elastic FEA as well as a series of laboratory tests to evaluate the performance of bonded boron/epoxy doublers for 7075-T6 aluminum aircraft sheets. They investigated stresses in adhesive, boron/epoxy patch and aluminum plate for three different and two structural boundary conditions. They observed that the shear and peel stresses in the adhesive due to the thermal loads are of about the same value, but act in the opposite direction of applied of tensile load. Sun *et al*. (1996) presented a simple analysis method to analyze cracked aluminum plates repaired with composite patch using Mindlin plate theory. The adhesive layer was modeled using of springs attached to the patch and aluminum plate. A three-dimensional finite element analysis was performed using a commercial code ABAQUS and a comparison was made between crack opening displacements obtained from both cases.

Chue *et al*. (1996) investigated the effect of composite patch size, patch length and stacking sequence on the performance of bonded repair of cracked hole in 2024-T3 aluminum plate. They used a three-dimensional finite element method, linear elastic fracture energy and strain energy density theory. They observed that the more increase in the composite patch size results the less strain energy level of the crack tip. They also demonstrated that the layer sequence of the laminate had a little effect on the strain energy distribution in the vicinity of the crack.

Schubbe and Mall (1999) successfully modeled a cracked thick metallic structure with bonded composite patch repair using a three-layer technique. The finite element model of the composite repair consisted of three layers of two-dimensional 4-noded Mindlin plate elements used to model the patch, plate and adhesive separately. The significant feature of this study was modeling of the adhesive layer. They modeled the adhesive as an elastic continuum medium between the plate and the patch. The displacements through the thickness were assumed linear and the constraints on the plate-adhesive interface and the adhesive-patch interface were based on the Mindlin plate theory. Only a quarter elements were modeled due to symmetry.

Hosseini-Toudeshky *et al*. (2005) used finite element fatigue crack growth method to see the effects of using

**Corresponding Author:** Gholamhassan Payganeh, Department of Mechanical Engineering,
Shahid Rajaee Teacher Training University, Tehran, Iran Tel:+98-021-22970052

asymmetric repaired panels to predict the actual crack front shape and crack growth life of the repaired panels with various patch and panel thicknesses. Lee and Lee (2004) performed numerical and experimental crack growth analyses of centrally cracked aluminum panels repaired with graphite/epoxy composite material. They showed that there is a good agreement between the crack front shapes obtained from finite element analysis and those obtained from experiments for various repaired panels.

Bouiadjra *et al.* (2007) and Fekirini *et al.* (2008) demonstrated that the quality of the adhesives is a very important factor affecting the stress intensity factor at repaired crack tips. The patch technique with two adhesive bands consists in used of two adhesive bands with different mechanical properties: the band of adhesive with higher shear modulus is used on the crack region for repair and the second band with lower shear modulus is used beyond the crack region to avoid the adhesive failure between the aluminium plate and the composite patch.

In this study, the tensile behavior of the cracked aluminum plates repaired with FML composite patches, were studied by obtaining crack opening displacement and J integral for test specimens. To this purpose three factors are changed, i.e., crack length, crack angle and the lay-up of FML layers. Each factor contains three levels. The results in tow state LEFM and EPFM were presented. The results were discussed and the effects of mentioned factors were surveyed.

## MODELING OF THE STRUCTURE

The structure contains three parts, (1) Aluminum panel (2) Adhesive layer and (3) FML patch. Here, the adhesive layer was not modeled and the patch has been attached to the specimen using Tie technique. The Aluminum panel were made of AL AA1035 having dimensions of 179×76×1.5 mm. The crack angle with respect to the width axis of specimen have three angle states, as 0, 30 and 45° and by ratio a/w = 0.3, 0.4 and 0.5 of specimen width were modeled on center of specimens (a = crack length and w = specimen width).

The FML composite patch was fabricated with two woven glass-fabric (T(90°)/M200-E10) layer ass the fiber layers (GFRP) and one thin Aluminum sheet (AA1035, 0.3 mm) as the metal layer that having dimensions of 80×50×0.7 mm . The lay-up of the FML patch vary in different make up so that the metal layer can be near or far from the repair surface. In specimens the lay-up of the patch was F-F-AL in bottom-up direction, in second repaired specimens the lay-up was F-AL-F and finally in patches the lay-up was AL-F-F. The direction of warp and fill fibers in the patch lay-up are equally along 0 and 90° in all patches. The mechanical properties of Aluminum plate and GFRP layer were given in Table 1.

## FINITE ELEMENT ANALYSIS

The behavior of the cracked aluminum specimen under the tensile load is ductile. As a result, as soon as, the growth of the crack starts, a huge area of the crack front enters the plastic area, therefore, EPFM (Elastic-Plastic Fracture Mechanic) should be used to model the crack. But due to two reasons, it is better to use LEFM (Linear Elastic Fracture Mechanic) instead of PEFM. (a) the main purpose of numerical modeling is to compare the influence of using different patches in different crack angles and lengths. So, it is not necessary to obtain exact experimental results in the process of modeling; it is just enough to see which patch in what crack length and what crack angle has a better function. (b) The time for running LEFM is much less than PEFM. Therefore, in this study LEFM method was used.

To observe the behavior of specimens, integral J and crack opening displacement have been chosen from different parameters of fracture mechanic. The patch has been attached to the specimen using Tie technique. All the freedom degrees of one side of the specimens have been restrained and the other side, because of load application, is free. In order to model the elements of crack front singular elements have been used. Elements around the crack front are quadratic wedge elements, type C3D15, and the technique of meshing in this area is Sweep. All the other elements used in the other area of the Aluminum specimen and FML patch are quadratic brick elements, type C3D20R (Fig. 1, 2). Figure 1 shows a schematic view

Table 1: Properties of plate and patch material

| Materials | Stiffness $E_1 = E_2$ (GPa) | Ultimate tensile strength $S_1 = S_2$ (MPa) | Poisson's ratio (ν) |
|---|---|---|---|
| Aluminum AA1035 | 69 | 167 | 0.3 |
| GFRP layer | 26 | 230 | 0.25 |

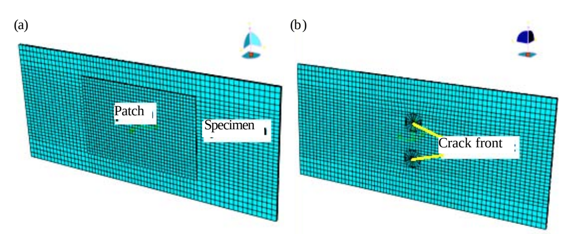


Fig. 1(a-b): (a) Meshed Patched and (b) un-patched specimen

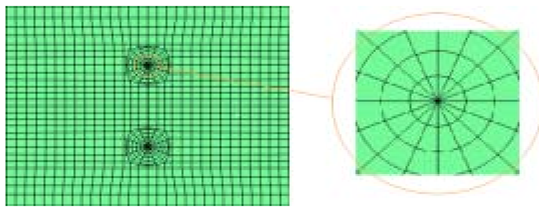

Fig. 2: Elements around the crack front

of the meshed patched and un-patched specimen and Fig. 2 shows the used elements around the crack front.

## RESULTS AND DISCUSSION

**Comparing of J integral in nods of crack front:** As shown in Fig. 3 and 4, for the specimens without repair, the highest J integral is related to the middle node of the crack front and for the repaired specimens this integral is related to the furthest node from the repaired surface. Accordingly, when presenting the results, the results related to these nodes will be discussed. It is observed that the amount of J integral for the node that places on the repaired surface is incorrect.

**Crack opening displacement (COD):** Here, the nodes displacement of crack mouth were studied. As Fig. 5 shows $U_1$ displacement of nodes were calculated and compared. $U_2$ and $U_3$ displacements for all of nodes are nearly zero.

**Effect of crack length on the COD:** In the un-patched specimens that having same crack angle but different crack length, can valuated the effect of crack length on the COD. In Fig. 6, the amounts of COD were shown. It is found with increasing crack length the COD was increased.

**Effect of crack angle on the COD:** In the un-patched specimens that having same crack length but different crack angle, can valuated the effect of crack length on the COD. Figure 7 shows that with increasing crack angle the COD was decreased.

**Effect of FML patch on the COD:** Figure 8 indicates the comparison of COD of specimen with a/w = 0.5 and $\theta = 0°$ that by three type of patches had repaired. It is found that COD of patched specimens as compared to un-patched specimens is less. Maximum loss occurs in the side that repaired. Gradually with moving toward another side, the displacement increase. Almost three lay-up of patch has the same effect on COD. One sees that F-F-AL patches have more effect on decreasing of COD.

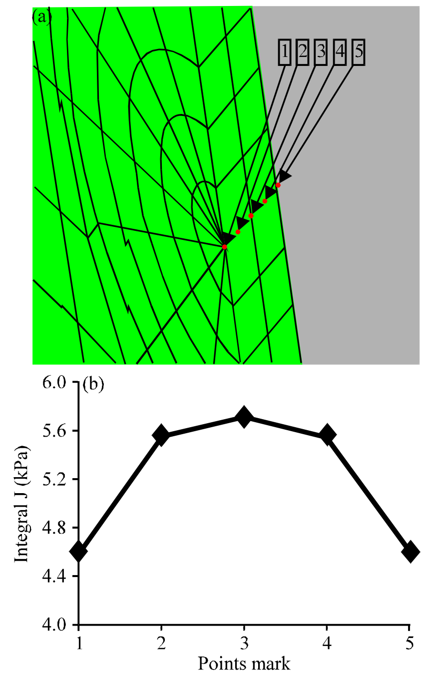


Fig. 3(a-b): J integrals in nodes of crack front of un-patched specimen

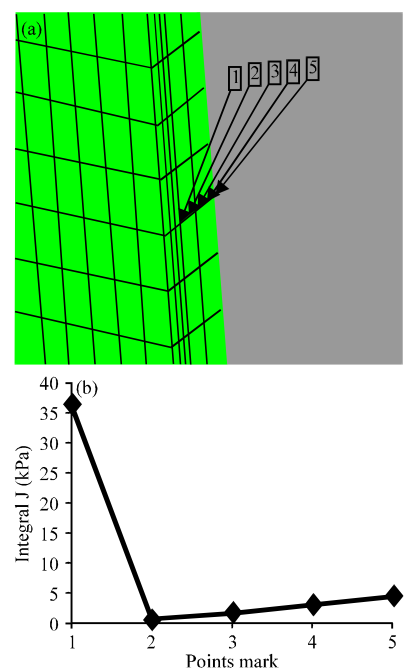


Fig. 4(a-b): J integrals in nodes of crack front of patched specimen

**J integral:** Here, In order to understand the results better, at first the results related to different angles

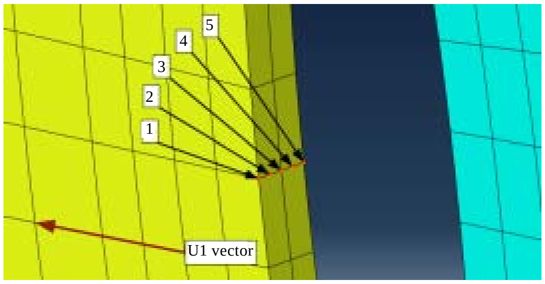


Fig. 5: Nodes of crack mouth and direction of displacement measurement

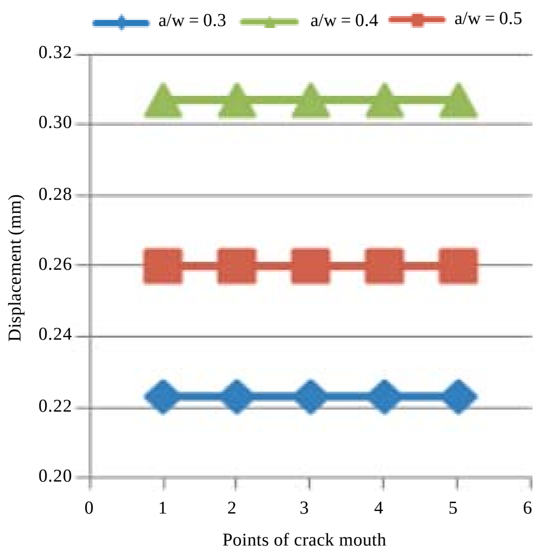


Fig. 6: The effect of crack length on the COD

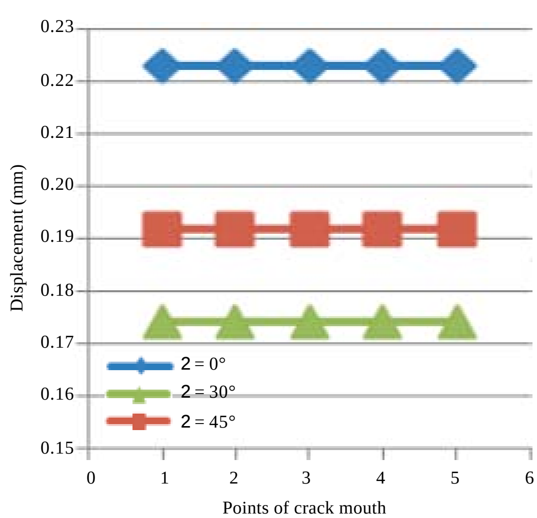


Fig. 7: The effect of crack angle on the COD

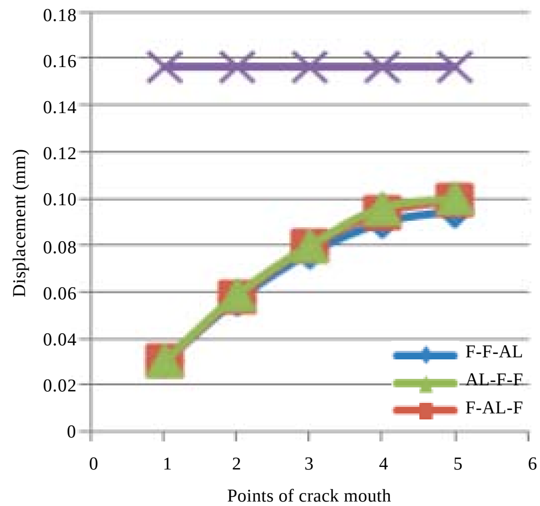


Fig. 8: The effect of patch lay-up on the COD

of the crack will be discussed separately. Then, will compare them together.

**J integral for specimens with θ = 0°:** Figure 9-11 compare the results of specimens with θ = 0°. Scrutinize the obtained amounts in each figure separately, it is found that the patch type F-F-AL has the most effect and the patch type F-AL-F has the least effect on the increase of J integral.

Also comparing figures of specimens with different crack length, it is observed that the effect of using patches in longer crack lengths is greater. In order to understand this issue better, must be calculated the proportion of the J integral of the repaired specimen, with one type of patch, to the J integral of that specimen but without repair. Now must be obtained the above-mentioned proportion for specimens with different crack lengths and compare them together. The less this amount, the more the effect of patch in the related crack length will be. For instance, this proportion for specimen with crack angle θ = 0° and crack length a/w = 0.3 (repaired with the F-F-AL patch) will be 0.66 and for specimen with same crack angle and patch but crack length a/w = 0.5 will be 0.55. As a result, the effect of using patches in the crack length a/w = 0.5 is more than a/w = 0.3.

**J integral for specimens with θ=30°:** Figure 12-14 compare the results of specimens with θ = 30°. The results of scrutinize the obtained amounts in these figures is similar to obtained results in previous section. However, it is found that changing the patch lay-up, make partly little change in the J integral (relation to specimens with θ = 0°).

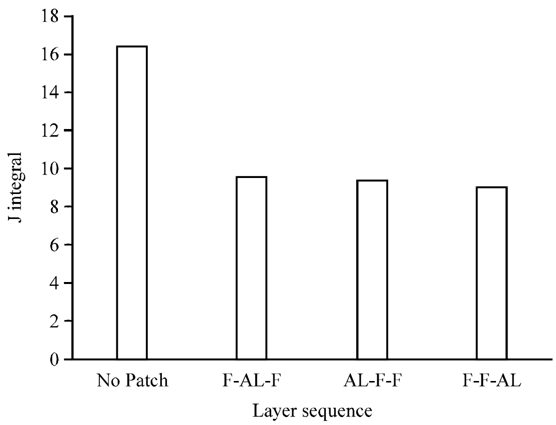


Fig. 9: Comparison of J integral for specimens with a/w = 0.3 ($\theta$ = 0°)

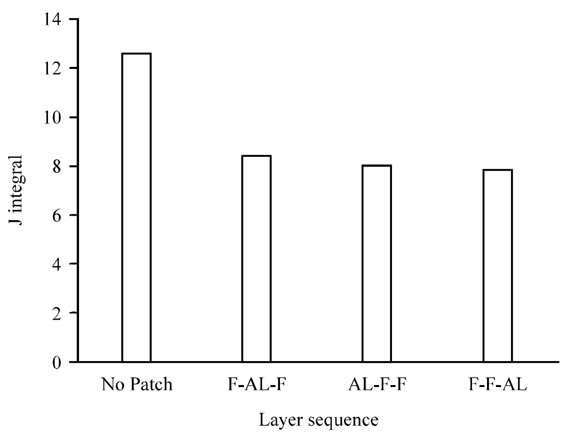


Fig. 10: Comparison of J integral for specimens with a/w = 0.4 ($\theta$ = 0°)

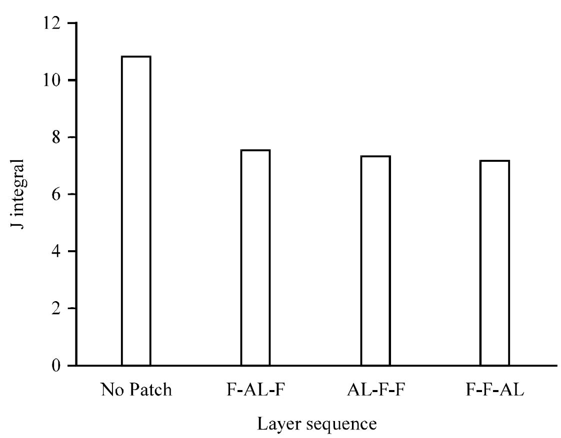


Fig. 11: Comparison of J integral for specimens with a/w=0.5 ($\theta$ = 0°)

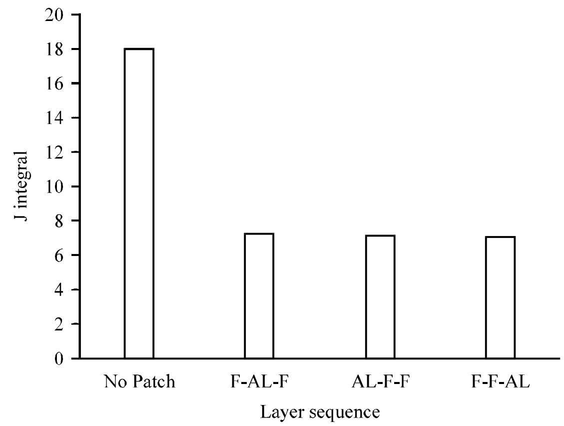


Fig. 12: Comparison of J integral for specimens with a/w=0.3 ($\theta$ = 30°)

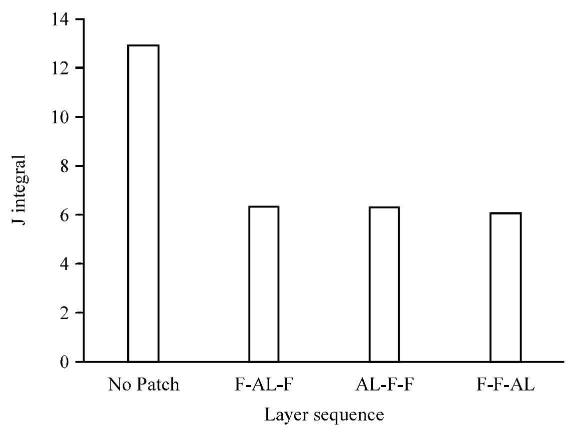


Fig. 13: Comparison of J integral for specimens with a/w=0.4 ($\theta$ = 30°)

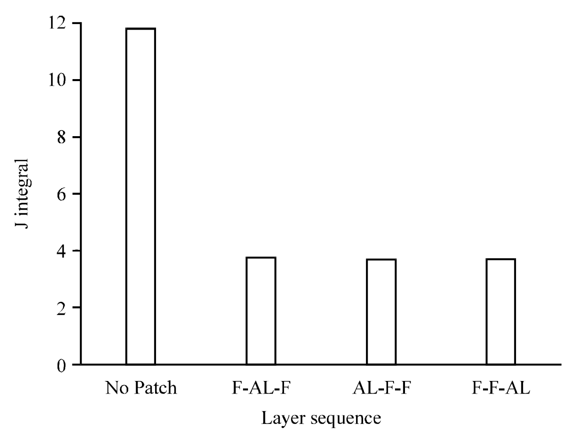


Fig. 14: Comparison of J integral for specimens with a/w=0.5 ($\theta$ = 30°)

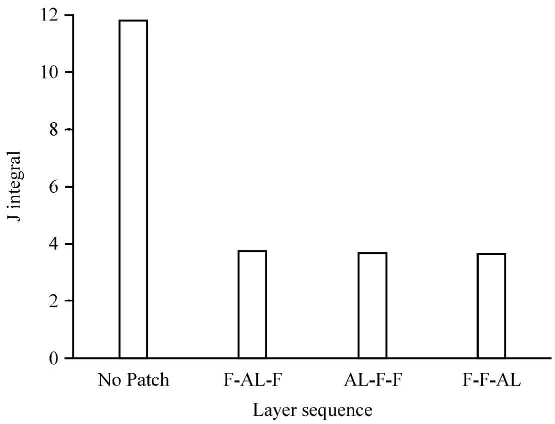


Fig. 15: Comparison of J integral for specimens with a/w=0.3 ($\theta$ = 45°)

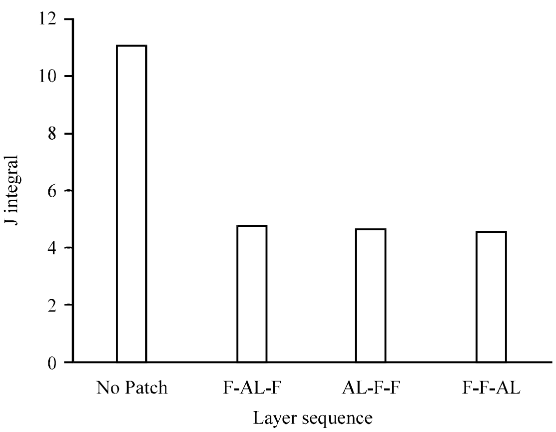


Fig. 16: Comparison of J integral for specimens with a/w = 0.4 ($\theta$ =45°)

**J integral for specimens with $\theta$ = 45°:** Figure 15-17 compare the results of specimens with $\theta$ = 45°. With comparing these figures with previous figures, found that increasing the angle of the crack, the effect of changing the patch lay-up on the J integral will be less. For example, in the specimen with crack length a/w = 0.3 and crack angle $\theta$ = 0°, with changing the patch from type of F-AL-F to F-F-AL, the amount of J integral increase nearly 7%. While this value for crack with angle $\theta$ = 45°, is 2%. This criterion for specimens with crack length a/w = 0.4 and 0.5 is truthful too.

Finally, in order to compare the effect of patches with different angles, the proportion of the J integral of the repaired specimen with one type of patch and those specimens having no patches must be calculated. The above-mentioned proportion has obtained for specimens with different crack angles and then compare together. The less this amount, the more the effect of patch in the

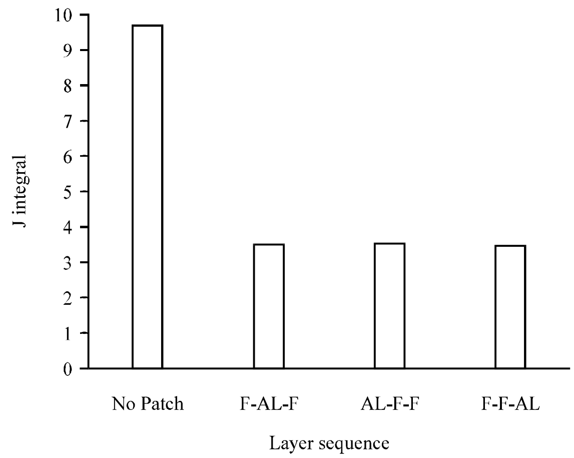


Fig. 17: Comparison of J integral for specimens with a/w=0.5 ($\theta$ = 45°)

related crack angle will be. For instance, this proportion for specimen with crack angle $\theta$ = 0° and crack length a/w = 0.3 (repaired with the F-F-AL patch) will be 0.66 and for specimen with same crack angle and patch but crack angle $\theta$ = 45° will be 0.35. As a result, the effect of using patches in the crack angle $\theta$ = 45° is more than $\theta$ = 0°. Therefore, in the greater crack angle the effect of using patch is more.

## CONCLUSIONS

From the study, the following conclusion has been drawn:

- In the un-patched specimens, the highest J integral is related to the middle point of the crack front while this amount for patched specimens is related to the furthest node from the repaired surface
- With increasing crack length and decreasing the crack angle the crack opening displacement was increased
- All of the patches have the same effect on the crack opening displacement
- When the Al layer of the patch structure is located far from the repair surface of AL plate, amount of J integral will be more and when the AL layer is in the middle of other layers the J integral has the lowest amount
- Comparison of J integral of repaired specimens and J integral of same specimens but without repair, indicates the more effect of using patches, in more crack length and more crack angle
- The effect of changing the patch lay-up on the increment of J integral, with increasing the crack angle, is less

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