# A study on the Charpy impact response of the cracked aluminum plates repaired with FML composite patches

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## Abstract
Fiber metal laminates (FMLs) are widely used in aerospace industries nowadays. Repairing of the cracks in these advanced materials was first done by some aeronautical laboratories in early 1970s. In this study, experimental investigations were done on the effects of repairing the edge-cracked aluminum plates using the FML patches. The repairing processes were conducted to characterize the response of the repaired structures to the Charpy impact tests. The composite patches were made of one aluminum layer and two woven glass-epoxy composite layers. Three different crack lengths, crack angles, and patch lay-ups were examined. It was indicated that for the lengthen cracks, the effect of increasing the crack angle on energy absorption in the structure was more. When the ratio of crack length to the specimen width, i.e. a/w is 0.5, the energy absorption per unit area of the specimens having different crack angles but the same patch lay-ups was so different. It was also observed that the percentage of the absorbed energy of 45° cracked angle specimens were about %25 higher than the 0° ones. Also it was observed 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 impact response of the tested specimens. The more the metal layer of the patches is far from the interfacial surface of the aluminum plate and the FML patches, the less energy absorbs in the structure.

## 1. Introduction

Composite patches are used most commonly to repair cracked components [1]. There are lots of advantages to use adhesively bonded composite patches, such as high corrosion properties, good specific strength and stiffness, facility of fabrication, lightweight, etc. These structures also show different properties in different directions by changing the lay-up sequence of their plies and amount of their reinforcement. Crack growth behaviour of engineering components has been studied by many researchers. The positive effect of using composite patches to improve the mechanical behaviour of cracked-components was first studied by the Aeronautical and Maritime Research Laboratory [2]. Chue et al. [3] discussed the effect of laminated composite patch with different stacking sequences on repairing an inclined central cracked plate under biaxial loads. They showed that the use of different stacking sequences for the patch does not affect the energy distribution near the crack tip significantly. Naboulsi et al. [4] involved nonlinear analysis of the adhesively bonded composite patch to investigate its effects on the damage tolerance of the repaired structure. They showed that the crack-opening displacement of the crack in the repaired plate is smaller for the geometrically nonlinear analysis than its counterpart from linear analysis. Hence, the stress intensity factor of the repaired structure computed from geometrically nonlinear analysis is less than its counterpart from geometrically linear analysis.

Chung et al. [5] performed experimental investigations on the effect of composite material patch repairing to characterize the fatigue crack growth behaviour in a thick Al6061-T6 (6 mm) panels with a single sided fiber reinforced composite patch. They showed that the fatigue life of patched plate increases about 4–6 times compared to the un-patched plate. They also demonstrated that the stress intensity factor value decreases rapidly at the end of patch. Okafor et al. [6] studied on the design, analysis and durability of adhesively bonded composite patch repairs of cracked aircraft aluminum panels. They found that the maximum skin stress decreases significantly after the application of the patch and the region of maximum skin stress shifts from the crack front for an un-patched panel to the patch edges for a patched one. They also showed that the maximum skin stress for the patched specimen was reduced by 83–85% from that of the un-patched specimen. Sabelkin et al. [7] studied several parameters/factors related to mechanical and fatigue behaviours of a cracked 7075-T6 aluminum panel repaired with one-sided adhesively bonded composite patch by a combined experimental–analytical approach. They showed that the disbond does not affect the out-of-plane deformation and in-plane strain except in their vicinity. They also investigated that the crack length has a small effect upon the in-plane strain and out-of-plane deformation. They observed that the bonded patch repair of a cracked panel provides a considerable increase in the residual strength as well as fatigue

life. Cheng et al. [8] demonstrated that applying the adaptive control of the electric field to the surface bonded piezoelectric patch could significantly decrease the lateral deflection of laminated composite beam, and, in turn, increase its dynamic buckling capacity. They observed that the application of the externally applied electric field to the surface bonded piezoelectric patch could effectively enhance the dynamic buckling capacity of the laminated beams. They also demonstrated that a non-alternating electric field applied to the patch could more effectively enhance the dynamic (pulse buckling) response of the beam. Khalili et al. [9] investigated edge-cracked aluminum plates repaired with one-sided composite patches experimentally for their response to Charpy impact test. They observed that carbon patches are more effective in reinforcing the cracked plates than glass patches. They showed that when the ratio of crack length to specimen width is constant, carbon fiber patches show better characteristic than glass ones.
In this paper, experimental investigations were done on the effect of repairing the single-sided cracked aluminum plates using the single side three layers of FML patches. The repairing processes were conducted to characterize the response of the repaired structures to Charpy impact tests. The composite patch was made of one metal layer and two woven fiber-reinforced composite layers. Three different crack lengths, angles and patch lay-ups were examined. Some experiments were done to study the energy absorption mechanism of repaired and un-repaired cracked specimens and to see the effects of patch lay-up, crack angle and length in reinforcing of the cracked structures too.

## 2. Specimens and patches preparation

### 2.1 Specimens preparations

The specimens were made of aluminum AA1035 [10] having dimensions of 70mm ×15.3mm×3 mm as shown in Figure 1 . The mechanical properties of aluminum plate are determined by tensile test (Figure 2 and Table 1). The specimens were cut with a water jet machine in principle dimensions and thereafter, using a wire cut machine, the notches were created. Three different crack lengths to specimen width ratios, i.e., a/w=0.1,0.3, and 0.5 were created on one edge of the specimens (Figure 1). The value of the crack angles with respect to the width axis of the specimens were chosen as 0°, 30°and 45° (Figure 3). The specimens with same crack configuration in length and angle were kept together and then wire cut.
In order to have a complete bonding between the specimens and FML patches the surface preparation procedure according to the P2 etching process [11] was conducted on the bonding surface of the aluminum specimens. In this method the bonding surface of the aluminum plates were first degreased with acetone, and then abraded with emery cloth. Finally alkaline cleaning was applied. Thereafter the specimens were immersed for 12 min at 65-70 °C P2 etch mixture of 15% by weight $FeSo_4$, 37% $H_2So_4$ and 48% water. They were washed with the clean cold running water, followed by clean hot water and then were dried with hot air. The temperature of the hot water and air must not be greater than 65°C [12].

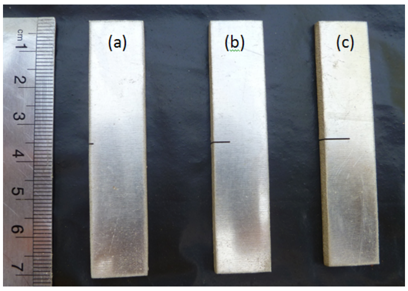



Figure 1: Cracked specimens with different crack lengths to specimen width ratios:
a) a/w=0.1, b) a/w=0.3, and c) a/w=0.5

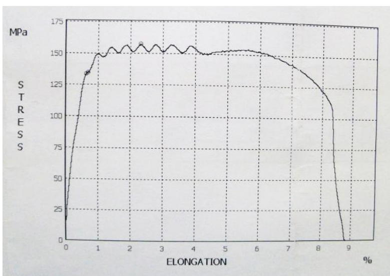


Figure 2: Stress-Elongation curve of aluminum plates

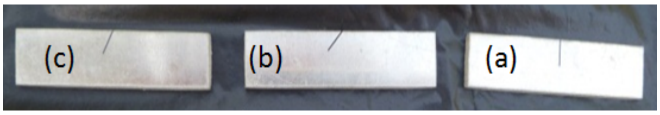



Figure 3: Specimens with three different crack angles: (a) $\theta$ = 0°, (b) $\theta$ = 45°, and (c) $\theta$ = 30°

### 2.2 Patches preparation

The FML composite patches were fabricated with two woven glass-fabric (T(90°)/M200-E10) layer as the fiber (F, hereinafter) layers and one thin aluminum (A, hereinafter) sheet (AA1035,0.3mm) as the metal layer. The lay-up of the FML patches varied in different make up so that the A layer could be near of or far from the cracked surface. Different codes were chosen to simplify presenting the results. For the un-repaired cracked specimens, code B was supposed. Three different repair types of patch lay-ups were conducted on the cracked specimens. The code C1 means that the lay-up of the patch is F-F-A, from bottom to up direction. The code C2 demonstrates that the lay-up is A-F-F and finally the code C3 shows that the lay-up is F-A-F. This means that in C1 patches, the A layer of the patch is far from repaired surface, in C2 ones, the A layer is exactly bonded to the cracked specimen and in C3 ones, the A layer was in the middle of the patches. The direction of fibers in the patches lay-ups are equally along 0° and 90°. To bond the F and the A layers strongly, the surface preparation procedure for bonding the surfaces of A layer was done according to ASTM E 23 – 02a [13]. The epoxy (LY5052) was used as the matrix because of its efficiency for the aerospace applications [14]. The content of fiber was about 55% by weight in glass-epoxy layers. The composite was made by hand and then the curing procedure according to the recommended cure schedule in two stages was done [14]. The patches dimensions were 40mm×10mm and after curing their thickness was 0.8mm. Figure 4 shows the specimen that is not cracked (a), it is cracked but not repaired (b) and finally it is cracked and repaired with a patch (c). Araldite2015 was used for bonding the FML patches to the cracked plates [15]. The thickness of the adhesive layer was about 0.2mm. Before bonding the patches to the cracked plates, surface preparation procedure of A layer of patch was applied according to the P2 etching process (as mentioned before). For bonding F layer, the surface preparation was done according to the procedure recommended for thermoset materials [16]. Table 1 shows the mechanical properties of the aluminum plate, the patches, and the bonding material.

Table1: Material properties of the aluminum plate, the patches, and the adhesive

| | Stiffness | Shear modulus | Ultimate tensile strength | Density | Poisson's ratio |
|---|---|---|---|---|---|
| | $E_x=E_y$ (G[illegible] | [illegible] | [illegible]Pa) | $P$ (g/cm$^3$) | $v_{xy}$ |
| Aluminum-AA1035 | 69 | [illegible] | [illegible] | 2.7 | 0.3 |
| Epoxy-LY5052 | 3.5 | [illegible] | [illegible] | 1.16 | 0.35 |
| GFRP layer | 16 | [illegible] | [illegible] | 1.6 | 0.25 |
| Araldite-2015 | 2 | [illegible] | [illegible] | 1.4 | ------ |

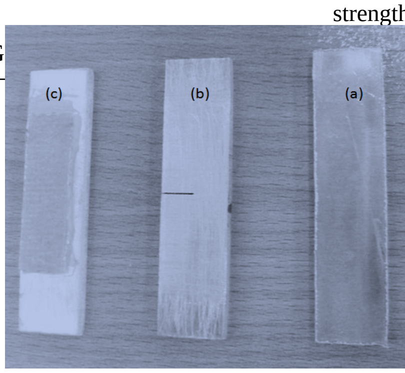
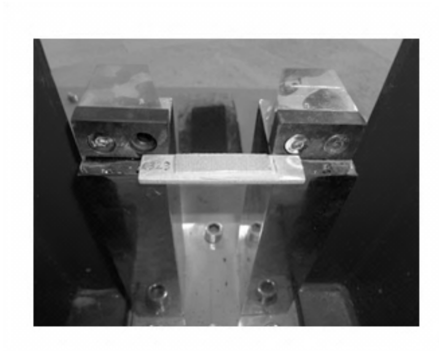



Figure 4: Specimens: (a) without a crack, (b) with a crack but not repaired and (c) with a crack and repaired with a composite patch

## 3. Impact test

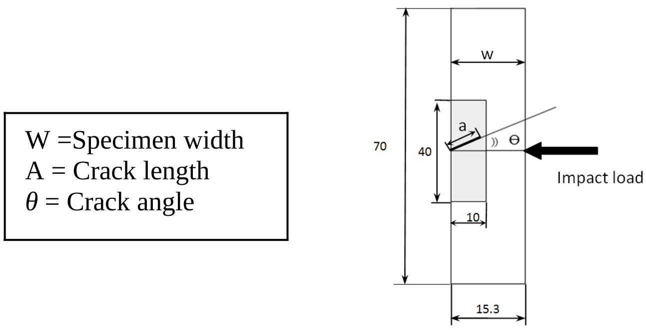
Charpy is a dynamic three point bending experiment of a beam. The experimental setup consists of the specimen, the fixture where the specimen is freely supported, and a pendulum with a defined mass attached to a rotating arm. The pendulum falls following a circular trajectory and hits to the test specimen at the middle span length and transfers its kinetic energy to it [17]. In this research a Charpy test device (Figure 5 (a)) was used for impact testing of all specimens according to ASTM E 23 – 02a [13]. The pendulum hammer had a mass of 15.200 kg and a disc radius of 150mm. The swing arm length and mass were 520mm and 5.270 kg respectively, leading to a speed at impact point of around 5.033 m/s and a stored energy of 218.5 J. The friction energy losses were about 1.9 J and the energy losses due to air resistance was neglected. The span distance in the test setup was 45mm.The final energy absorption of each specimen was the average value of the three same tested samples. Figure 5 (b) Shows a typical impact test specimen that is prepared to test. Figure 6 shows the schematic view of geometry and loading of repaired specimens.

a) The Charpy test device

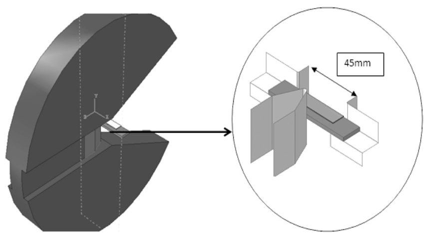


b) Specimen set up before testing

Figure 5: The Charpy test device and the specimen set up for testing




a) Schematic view of geometry of stiffened cracked panel repaired with a FML patch




b) Schematic view of impact time

Figure 6: Schematic view of geometry and test configuration of specimens

## 4. Results and discussions

At first, the un-cracked specimen was tested and the energy absorption was acquired 53.00j for it. Then the un-repaired cracked specimens were tested .The results of these tests are depicted in Figure 7 and Table 2. Figure 7 shows that the more increase in crack angle, the more increase in absorbed energy no matter what the crack length is. One also sees that in specimens with 45° crack angle, the most energy is absorbed in the structure. This is due to the change of the crack growth path that forces the crack to go in mode I of the fracture. This change in direction leads to a more energy absorption (Figure 7). Also it is shown that by increasing the crack length, the energy absorption increases when the crack angle changes from 0° to 45°. For instance, according to Table 2, the percentage of increasing of energy absorption of un-repaired specimens with a crack length ratio of a/w=0.5, is about 21% when the crack angle changes from 0° to 45°. Similarly this difference for the ratios of a/w=0.3 and a/w=0.1 are equal to

9% and 2% respectively. The reason for this behaviour is that by increasing the crack length, the distance that the crack must go to reach to the mode I of fracture becomes longer. Therefore, the amount of energy absorption increases too.

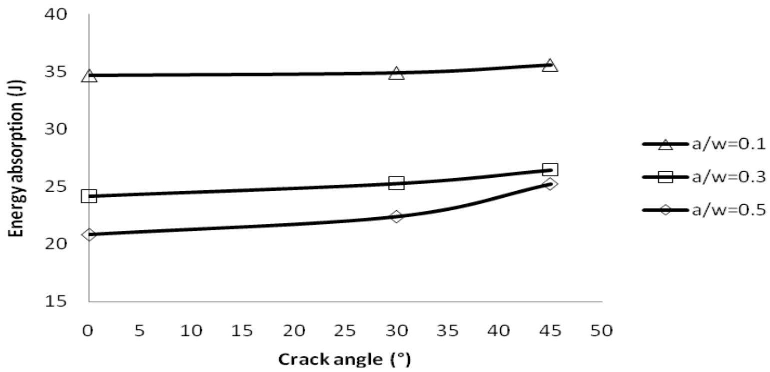



Figure 7: Energy absorption of the un-repaired cracked specimens

Table 2: Energy absorption of the un-repaired cracked specimens

| Crack angle | a/w ratio | | |
|---|---|---|---|
| | 0.1 | 0.3 | 0.5 |
| 0° | 34.7 | 24.19 | 20.83 |
| 30° | 34.93 | 25.3 | 22.4 |
| 45° | 35.61 | 26.47 | 25.24 |

In next step, selected patches were adhered to the specimens having different crack angles and lengths that mentioned earlier. They were tested to see how the effects of patch lay-up and crack characteristics are in the strength of the repaired structures. Table 3 shows the results of the repaired specimens having a crack length ratio of a/w=0.1 with some selected patch configurations. The amount of the energy absorption of the specimens having ratios of a/w=0.3 and a/w = 0.5 are presented in Tables 4 and 5 too, respectively.

Table 3: Energy absorption (J) of specimens with a crack length ratio of a/w=0.1

| Crack angle | Repair type | | |
|---|---|---|---|
| | C1† | C2†† | C3††† |
| 0° | *** | 36.5 | *** |
| 30° | 35.34 | *** | 36.91 |
| 45° | *** | 40.61 | *** |

† C1: A patch with the F-F-A lay-up.
†† C2: A patch with the A-F-F lay-up.
††† C3: A patch with the F-A-F lay-up.

Table 4: Energy absorption (J) of specimens with a crack length ratio of a/w=0.3

| Crack angle | Repair type | | |
|---|---|---|---|
| | C1 | C2 | C3 |
| 0° | 26.61 | *** | 27.63 |
| 30° | *** | 31.69 | *** |
| 45° | 31.46 | *** | 34.56 |

As can be seen in Tables 3, 4, and 5, there is a meaningful correlation between length and the angle of crack with the amount of specimens' energy absorption. By increasing of crack length, the fracture energy of the structure decreases. But, by increasing of crack angle, the strength of the specimens increases. In this section the important point to be taken into account is the difference of energy absorption of various repairs. The reason for this behaviour is that by changing of the patch lay-up, the amount of energy absorption of the structure changes too. By looking at the obtained results, it can be conclude that the location of the A layer in the patch lay-up has a significant role upon the efficiency of the repair. The more the location of the A layer is near of the base structures (repair type C2), the more energy will be absorbed in the structure and vice versa. The more the A layer is far from the repaired surface (repair type C1), the less energy will be absorbed in the structure.
The reason of this behaviour is changing of the fracture mechanism of the patch. Whenever the A layer is near of the repaired surface, the ductility of the whole structure becomes more. Therefore, the structure can be able to absorb the more energy by the plasticity behaviour of the A layer. When the A layer is placed in the middle of patch lay-up or even more far from the repaired surface, nearly the brittle fracture occurs. The reason of this behaviour is that the F layer is less ductile. I.e., if the F layer fails, the A layer fails suddenly too. One should be noted that the amount of the loading and the required time of A layer plasticity is too low. Therefore, the more the A layer is far from the repaired surface, the more the structure shows a brittle behaviour and vice versa. It can be concluded that if the structure is repaired with the C2 type patches, no matter what the crack angle or length is, its strength becomes the most.

Table 6: % Energy absorption of cracked specimens compared to an un-cracked one

| Crack length | Repair type | % Energy absorption for different crack angles | | |
|---|---|---|---|---|
| | | 0° | 30° | 45° |
| a/w=0.1 | B[†] | 65.47 | 65.91 | 67.19 |
| | C1 | ------ | 66.68 | ------ |
| | C2 | 68.87 | ------ | 76.62 |
| | C3 | ------ | 69.64 | ------ |
| a/w=0.3 | B | 45.64 | 47.74 | 49.94 |
| | C1 | 50.21 | ------ | 59.36 |
| | C2 | ------ | 59.79 | ------ |
| | C3 | 52.13 | ------ | 65.21 |
| a/w=0.5 | B | 39.3 | 42.26 | 47.62 |
| | C1 | ------ | 45.45 | ------ |
| | C2 | 44.3 | ------ | 55.66 |
| | C3 | ------ | 49.34 | ------ |

[†]B: un-repaired cracked specimen

Table 6 shows the percentage of the energy absorption of various repaired cracked specimens respect to energy absorption of an un-cracked specimen. In other words, the % energy absorption shows that every cracked specimen without a patch (B) or each of the repaired specimens with different types of patches (types C1, C2, or C3) are able to absorb the more energy compared to the un-repaired cracked specimens. The results also shows that in the un-repaired cracked specimens, the maximum energy absorption belongs to the specimen having the minimum crack length ratio (i.e., a/w=0.1) and the maximum crack angle (i.e., θ=45°), and is equal to 67.19%. By increasing of the crack length, the energy absorption decreases and finally in the specimens having the maximum crack length ratio (i.e., a/w=0.5) and the minimum crack angle (i.e., θ=0°), the percentage of the energy absorption value becomes the minimum (i.e., 39.3%). The effect of crack length ratio and crack angle of the repaired specimens is similar to un-repaired ones.

## 5. Conclusions

In this paper the effects of using the FML patches on strengthening of cracked aluminum plates were studied. The specimens were repaired with single-sided FML patches and then they were subjected to Charpy impact test. The following conclusions can be drawn:

1) When the crack length ratio is constant, the more the crack angle is, the more energy absorbs in the structure.
2) By increasing of the crack length ratio, the strength of specimens decreases, no matter they are repaired or not.
3) No matter what the type of the crack is, the strength of the repaired structures depends on the type of patch lay-up. The more the metal layer of the patch structure is close to the repaired surface, the more energy absorbs in the structure.

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