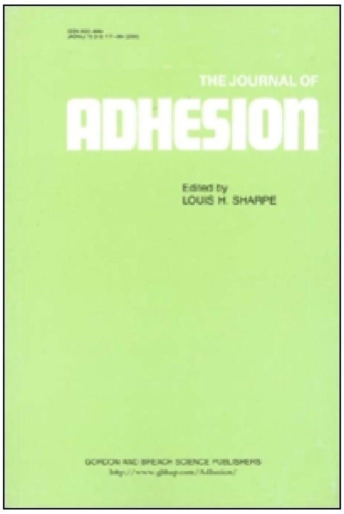

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Effect of Patching on Charpy Impact Response of Repaired Notched Plate – Experimental Study

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Charpy impact tests were conducted on repaired notched aluminum specimens and the absorbed energy and fracture behavior of the specimens were investigated. The aluminum specimens contained a single-edge notch and were repaired with a metal sheet, composite, and fibre metal laminate (FML) hybrid composite patches on one of the side faces of the specimens. Some of the specimens were repaired on two sides. A metal sheet, laminated glass fibre reinforced polymer (GFRP), and carbon fibre reinforced polymer (CFRP) composite and FML patches with three and five layers were used to repair the aluminum specimens. The metal patches were made by phosphor-bronze, the composite patches were composed of woven glass and woven carbon fibre laminates, and the FML patches were fabricated from a combination of woven glass or woven carbon fibre laminates with phosphor-bronze metal sheet. The aluminum specimens had three different notch lengths. The results showed that the specimens repaired with FML patches of the same number of layers, irrespective of fibre type, absorbed almost the same energy level. The results also showed that the notched specimens repaired with single and double-sided FML patches with carbon fibre absorbed more energy than the other specimens. Generally, as the notch length increased, the absorbed energy by the notched aluminum specimen with or without any patch decreased. The effective role of patching in the repaired specimens was found to be substantial with the bigger notch lengths.

Keywords: Absorbed energy; Charpy impact; Composite; FML; Notched plate; Patching

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1. INTRODUCTION

Repairing of cracked metallic aircraft structures by high strength advanced composite materials was first tested by the Aeronautical and Maritime Research Laboratories (AMRL) for the Royal Australian Air Force (RAAF) in the early 1970s [1]. Advantages that make advanced composite materials ideal reinforcements for structural repair are: high specific strength and stiffness, lightweight, resistance to corrosion, and directional dependence of the material properties.

Generally, mechanical fastening and adhesive bonding are the techniques used to attach the composite reinforcement patch to the damaged or weakened structure. The use of adhesively bonded composite patches as a method of repair has several advantages over mechanically fastened repair methods. They include reduced installation cost, increased strength and fatigue life and, hence, effective crack retardation, elimination of unnecessary fastener holes in an already weakened structure and consequent reduction of stress concentrations, good corrosion resistance, high stiffness, and lightweight [2]. Bonded repair patches are an effective method to deviate stress concentration from the crack region, as the stresses are transferred from the cracked plate to the composite patch, slowing down or completely arresting crack growth under the applied load. This extends the life of a cracked structure or machine component at an economical cost.

Many researchers investigated the effects of patching on the repair of cracked plates in various loading conditions. Xiong and Shenoi [3] experimentally investigated the effectiveness of bonded composite patches to repair cracked aluminum alloy panels based on static and fatigue strength concepts. Their experimental results showed that the effects of repairing vary, depending on the thicknesses of the patch and the fibre/epoxy prepreg materials. Also, the results indicated that the patches would increase the tensile residual strengths of the repaired specimens compared with un-repaired cracked specimens. Chung and Yang [4] investigated experimentally the fatigue crack growth behavior in thick (6 mm) Al 6061-T6 panels repaired with a single-sided fibre reinforced composite patch. Their results demonstrated that the size of the composite patches affects the fatigue life. In addition, Pastor *et al.* [5] concluded from their experimental study that the shear strength of the adhesive used to bond the patch on the parent material plays an important role in determining the fatigue response of the patched specimen. Lee and Lee [6] performed numerical and experimental crack growth and crack-front shape analyses of centrally cracked aluminum panels (Al 7075-T6) repaired with a graphite/epoxy composite patch. A good agreement was achieved between the crack-front shapes obtained from the finite element analysis and those obtained from the experiments for various repaired panels.

Furthermore, some researchers investigated the effect of double-sided patches. Bouiadjra *et al.* [7] used the finite element method to investigate the advantage of a double-sided patch repair over the single-sided equivalent in the reduction of the stress intensity factor at the crack tip. They observed that the adhesive properties must be optimized in order to increase the advantage of the double-side patch and to avoid adhesive failures. The numerical results also showed that the patch properties have a significant effect on the beneficial effects of the double-sided symmetric patches. Madani *et al.* [8] numerically analyzed single-sided and double-sided composite patch repairs on Al 2024-T3 aluminum plate, designed to reduce the concentration of stresses at circular notches and cracks. The authors emphasized the considerable reduction in the asymptotic value of the stress-intensity factors and the normal stresses at the crack tip with these repairs. They also showed that the use of a double-sided patch suppresses the bending effect due to the eccentricity of the patch only on one side and reduces the shear stresses in the adhesive. In addition, Megueni and Lousdad [9] compared the performance of a double-sided and a stepped patch. Their investigation was accomplished *via* a two-dimensional finite element analysis of a centrally cracked metallic panel repaired using an externally bonded composite patch. They showed that a stepped patch yields better results. The recommended course of action was to use symmetrical double patches, which offer the best guarantee and a better stability.

Some of the most recent research papers focused on a new type of structure named fibre-metal laminates (FMLs), based on the combination of thin layers of metal and fibre-reinforced composite, investigating the mechanical properties of these structures [10–12]. FMLs combine the good characteristics of metals such as ductility, impact, and damage tolerance with the benefits of fibre composite materials such as high specific strength and stiffness, and good corrosion and fatigue resistance. Khalili *et al.* [13] observed experimentally that the FMLs behave better under tensile, impact, and bending loadings than GRPs (glass reinforced polymers). Experiments were carried out on new hybrid FML composites made by bonded steel/aluminum/glass fibre-epoxy. Vlot *et al.* [12] conducted impact tests on GLARE (glass aluminum reinforced epoxy), a monolithic aluminum alloy and carbon fibre reinforced PEEK (polyether ether ether ketone). Their results indicated that the damage threshold energy for this multi-layered material was significantly greater than the values offered by traditional engineering materials.

In addition, a few studies were carried out to investigate the resistance of materials under impact loadings. Marouf *et al.* [14] studied the effect of the number of layers and the interface strengths on the impact behavior of aluminum/epoxy laminates. It should be noted that although the overall thickness did not change, the individual layers decreased in thickness when the number of layers increased. Experiments showed that the impact resistance of the laminate increases with the number of layers, while the interface strength has a less pronounced influence on the impact resistance of the laminate. Lee and Jang [15] experimentally investigated the effect of glass fibre content on the mechanical properties of a glass fibre mat/polypropylene composite. The authors showed that the tensile and flexural modulus and impact absorption energy increased with the glass fibre content. However, the properties exhibited maximum values and showed a decrease for high glass fibre content. Harsoor and Ramchandra [16] investigated the deformation and failure of clamped beams with and without notches (at mid span/quarter span) subjected to mid span and quarter span impact. Results showed that notch width does not have a significant influence on the dynamic response of the beam as compared with notch depth and location. Beams without notches suffer more deformation when impacted at mid span as compared with quarter span impact. However, beam specimens having a notch at mid span and subjected to quarter span impact suffer more deformation as compared with beams having a notch at quarter span and impacted at mid span. This shows that deformation is more sensitive to notch location rather than to impact location.

In this paper, notched aluminum specimens repaired by metallic, composite, and FML patches were studied using the Charpy impact test configuration. The aluminum specimens had three different single edge notch lengths. The specimens were reinforced by single-sided and double-sided patches. The composite and FML patches consisted of three and five layers. The FMLs were composed of 2/1 and 3/2 woven glass or woven carbon fibres and phosphor-bronze metal. 2/1 FML composite consisted of three layers in which its outer layers were phosphor-bronze and the middle layer was made of fibre composite, either GFRP or CFRP, and 3/2 FML composite consisted of five layers in which the outer and middle layers were phosphor-bronze and the other two intermediate alternative layers were fibre composites, either GFRP or CFRP. A phosphor-bronze metal sheet with a thickness of 0.2 mm was also used as a one-layer metallic patch to reinforce the notched aluminum plate. The effect of various parameters such as the patch material, number of patch layers, single-sided or double-sided configuration, and notch length on the absorbed energy in the Charpy impact test was investigated.

2. SPECIMENS AND PATCHES FABRICATION

2.1. Specimen

Aluminum alloy plate (Al 1050) with a thickness of 2 mm was used for the notched specimens. The properties of the aluminum [17] are given in Table 1.

The aluminum specimens were cut and prepared to the final dimensions of $70 \times 15.2 \times 2$ mm. Thereafter, using a wire cut machine, slots of 1.45, 4.6, and 7.52 mm long were machined on one edge of the specimens. For making the slots, the specimens were kept together and then wire cut. Therefore, the samples of a given case had the same notch length and shape. The ratio of notch length to the specimens' width, *i.e.,* l/w, for the different specimens is 0.1, 0.3, and 0.5. The radius of the notch tip was 0.19 mm. The specimens with different notch lengths are shown in Fig. 1. The specimen's surface, on which the patch was bonded, was prepared according to the standard procedure [18]. The bonding surface was first sanded with 240- and 1000-grit silicon carbide paper and then cleaned with acetone. After that, it was rinsed in deionized water and dried. Finally, it was immersed in sodium dichromate sulfuric acid solution at 70°C for 12 min and then rinsed with deionized water and dried.

2.2. Patch

For the fabrication of composite patches, the epoxy resin AE510 (NARME Co., Fullerton, CA, USA) with the following properties was used: density = 0.8–1.1 g/cm^3, viscosity = 680–750 MPa s, tensile

TABLE 1 Mechanical Properties of Aluminum Plate, Phosphor-Bronze, and Adhesive [18,22]

	Tensile strength (MPa)	Yield strength (MPa)	Shear modulus (GPa)	Young's modulus (GPa)	Specific weight (g/cm^3)
Aluminum plate	105	80	26	69	2.7
Phosphor-bronze	752	680	40	109	8.8
*Adhesive	30	–	–	1.85	1.4

*Adhesive lap shear strength = 18–22 MPa.

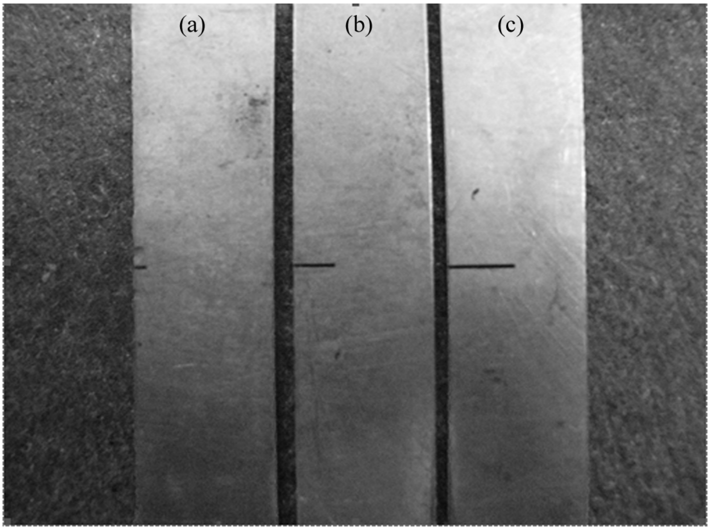


FIGURE 1 Specimens with different notch lengths (a) $l/w = 0.1$, (b) $l/w = 0.3$, (c) $l/w = 0.5$.

strength = 88–90 MPa, tensile modulus = 3.1–3.3 GPa, curing time = 7 h (at 25°C). The composite patches were made by three or five layers glass/epoxy and carbon/epoxy laminate patches (GFRP and CFRP patches) fabricated by the hand lay-up technique with glass or carbon fibres as combined with the above-mentioned epoxy resin. The glass and carbon fibres are woven fabrics with an average fibre content of about 50% in all the GFRP and CFRP layers. The patches were made in the molds with specified thicknesses and allowed to cure for 24 h at ambient conditions, after the lay-up procedure. The properties of the GFRP and CFRP patches were obtained from the density measurement and tensile tests [19] and are listed in Table 2. For the FML patches, phosphor-bronze metal sheets with a thickness of 0.2 mm were used; its mechanical properties are listed in Table 1. Two types of FML lay-ups were fabricated by the hand lay-up technique. To bond the layers of FML strongly, the phosphor-bronze metals were surface treated according to the standard procedure [20]. The bonding surface was first sanded with 240- and 1000-grit silicon carbide paper and then cleaned with acetone. It was then immersed for 10 min at 66°C in the aqueous ferric sulfate/sulfuric acid solution (1:75 by wt. + 8 parts water) and then rinsed in deionized water and dried. After that, it was immersed in sodium dichromate sulfuric acid solution at room temperature and then rinsed. Finally, it was dipped in the ammonium

TABLE 2 Properties of Metal Sheet, CFRP, and GFRP Layers and Different Patches

Material	Density ρ (g/cm^3)	Stiffness (GPa) $E_1 = E_2$	Specific stiffness (GPa cm^3/g)	Ultimate tensile strength (MPa) $S_1 \approx S_2$	Specific strength (MPa cm^3/g)
Phosphor-bronze	8.8	109	12.4	752	85.4
GFRP	1.64	18	11	200	121.9
CFRP	1.1	140	127.3	600	545.4
2/1 FML with glass fibre	5.42	71.7	13.2	511	94.3
3/2 FML with glass fibre	5.09	65.6	12.9	475	93.3
2/1 FML with carbon fibre	5.23	110.4	21.1	615	117.6
3/2 FML with carbon fibre	4.82	112	23.2	605	125.5

hydroxide and then rinsed and dried. The dimensions of all patches were 40 mm length and 10 mm width, while the patch thicknesses were 0.9 and 1.4 mm for three-ply and five-ply patches, respectively (for both glass and carbon fibres). Table 2 gives the mechanical properties (density, stiffness, and strength) of the constitutive materials as well as the patches with the different lay-ups obtained experimentally [19] (the same procedures used for FML patches). The patch surface, on which the specimen has to be bonded, was prepared according to the standard procedure [20,21]. For GFRP and CFRP patches, the bonding surface was first cleaned with acetone, and then sanded with 240- and 1000-grit silicon carbide paper. It was then immersed in dichromate sulfuric acid solution for 60 min at 20–30°C and cleaned with acetone again and wiped in dry air at 40°C with lint-free paper to remove any foreign particles [21]. For the FML patches, the bonding procedure [20] mentioned earlier was used.

2.3. Adhesive

The two-part epoxy adhesive Araldite 2015 (Huntsman Inc., Basel, Switzerland) was used to bond the patches to the notched aluminum plates. This adhesive makes a strong adhesion between phosphor-bronze sheet and aluminum plates. The properties of the adhesive [22] are listed in Table 1. The thickness of the adhesive layer was kept to 0.2 mm using shims and molded fixtures.

TABLE 3(a) Codes for the Specimens with $l/w = 0.1$

Patch		
Patch configuration	No. of layers	Specimens' codes
Phosphor-bronze	1	101
GFRP	3	113
GFRP	5	115
CFRP	3	123
CFRP	5	125
2/1 FML with glass fibre	3	133
3/2 FML with glass fibre	5	135
2/1 FML with carbon fibre	3	143
3/2 FML with carbon fibre	5	145
Double 3/2 FML with carbon fibre	10	1445

For a quick labeling of the specimens and proper reference to them in subsequent results and discussions, each tested configuration was assigned a code. The code for single-sided patch specimens consists of three digits, while the code for double-sided patch specimens consists of four digits. The first digit in both codes indicates the ratio of the notch length to the specimen width (l/w) without the decimal point. For example, 1 means the specimen with $l/w = 0.1$, 3 for the specimen with $l/w = 0.3$, and 5 for the specimen with $l/w = 0.5$.

The last digit in both codes defines the number of layers in the patch. The central digit in the code for single-sided patch specimens and the two central digits in the code for double-sided patch specimens

TABLE 3(b) Codes for the Specimens with $l/w = 0.3$

Patch		
Patch configuration	No. of layers	Specimens' codes
Phosphor-bronze	1	301
GFRP	3	313
GFRP	5	315
CFRP	3	323
CFRP	5	325
2/1 FML with glass fibre	3	333
3/2 FML with glass fibre	5	335
2/1 FML with carbon fibre	3	343
3/2 FML with carbon fibre	5	345
Double 3/2 FML with carbon fibre	10	3445

TABLE 3(c) Codes for the Specimens with $l/w = 0.5$

Patch		
Patch configuration	No. of layers	Specimens' codes
Phosphor-bronze	1	501
GFRP	3	513
GFRP	5	515
CFRP	3	523
CFRP	5	525
2/1 FML with glass fibre	3	533
3/2 FML with glass fibre	5	535
2/1 FML with carbon fibre	3	543
3/2 FML with carbon fibre	5	545
Double 3/2 FML with carbon fibre	10	5445
Double 3/2 FML with carbon fibre and 3/2 FML with glass fibre	10	5435
Double 3/2 FML with glass fibre	10	5335
Double 3/2 FML with carbon fibre and 5 layer carbon fibre	10	5425
Double 5 layer carbon fibre and 5 layer glass fibre	10	5215

indicate the material used in the patch. The metal patches were assigned 0, the glass fibre composite patches 1, the carbon fibre composite patches 2, the FML with glass fibres 3, and finally the FML with carbon fibres 4. For example, the code 5425 indicates a specimen reinforced with double-sided patches with a l/w ratio of 0.5, one of the patches of FML with carbon fibres and the other of composite with carbon fibres, both of them with five layers. The type of the specimens with their patches and the corresponding codes used to define them are shown in Table 3. This table is divided into three parts (a), (b), and (c), according to the l/w ratio.

3. IMPACT TEST

All specimens were subjected to the Charpy impact test (ASTM D 256) conducted on an Avery-Denison Charpy impact testing machine (Leeds, England). For each assigned code, three specimens were tested. A sketch of the impact test specimen showing the location of the impact point is shown in Fig. 2. Also, the Charpy impact testing machine fixture with a notched repaired aluminum specimen and the impact loading direction is shown in Fig. 3. The results of the experiments are discussed according to the ratio of the notch length

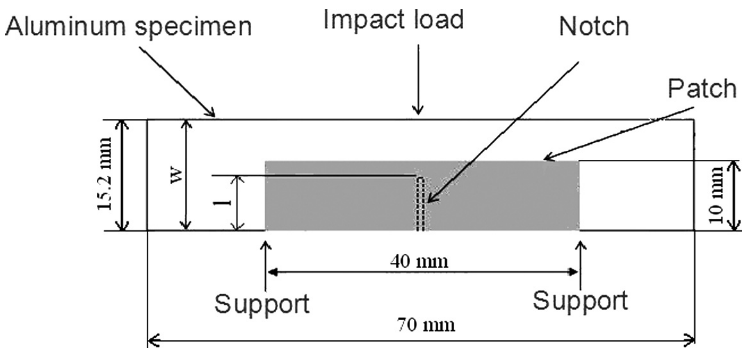


FIGURE 2 Schematic diagram of a repaired specimen for impact loading.

to the specimen width (l/w). The pendulum height, mass, and also length are, respectively: H = 140 cm, M = 19 kg, L = 82 cm. So, a maximum of 300 J could be imparted to the specimens. The tests were conducted in ambient conditions. The height of the pendulum before and after tests was recorded and the energy absorbed by the specimens was calculated.

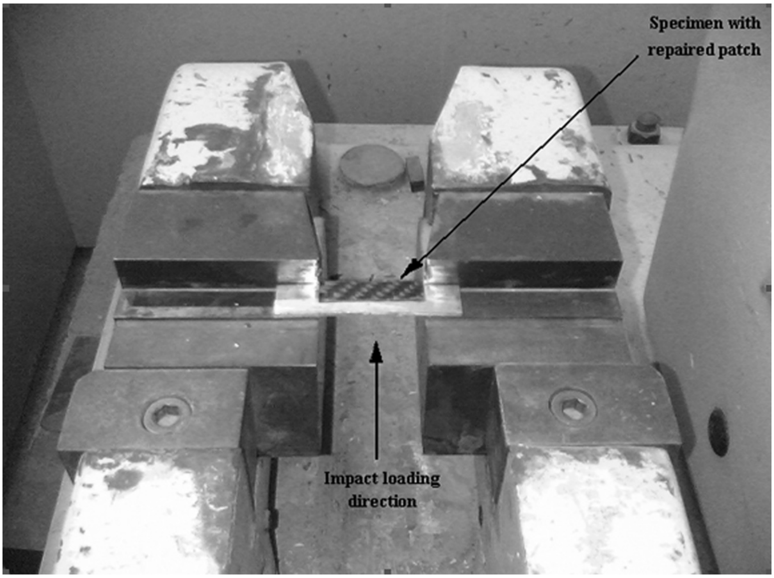


FIGURE 3 Charpy impact testing machine with notched repaired aluminum specimen and impact loading direction.

4. RESULTS AND DISCUSSION

4.1. Specimens with a Ratio of Notch Length to Specimen Width $l/w = 0.1$

The repaired aluminum specimens with a ratio of $l/w = 0.1$ were first examined. Table 4(a) shows the results obtained from the Charpy impact test on these specimens. For comparison purposes, Table 4(a) also shows the results of Charpy test for the un-notched specimen and the notched un-repaired specimen. The GFRP patches have low strength and stiffness compared with the CFRP patches and, therefore, show less resistance to impact loading. Khalili *et al.* [13] observed experimentally that glass reinforced epoxy has low energy absorption capabilities and, therefore, does not perform well in Charpy impact tests, despite showing some good characteristics under static and fatigue loadings [23]. Table 4(a) shows that the capability of energy absorption of the notched aluminum specimens did not improve much from three to five layer GFRP patches. The three-layer GFRP patch (Specimen 113) increased the absorbed energy of the notched specimen by 4 J (17.4% increase compared with the notched un-repaired

TABLE 4(a) Energy Absorption Capability for Specimens with $l/w = 0.1$

Sample	Absorbed energy (J)	Standard deviation	Percentage increase in absorbed energy compared with the un-repaired notched aluminum specimen	Energy absorption capability as a percentage of the energy for the un-notched specimen	Absorbed energy per weight of the specimen (J/g)
Un-notched specimen	38	0	–	–	6.61
Un-repaired notched specimen	23	0.1	–	60.5	4
Specimen 101	30	0	30.4	78.9	4.51
Specimen 113	27	0.2	17.4	71	4.13
Specimen 115	29	0.18	26.1	76.3	4.23
Specimen 123	33.5	0.2	45.6	88.2	5.23
Specimen 125	36	0	56.5	94.7	5.43
Specimen 133	36.5	0.15	58.7	96	4.55
Specimen 135	40.5	0.1	76.1	106.6	4.6
Specimen 143	38.5	0.24	67.4	101.3	4.92
Specimen 145	42.5	0.32	84.8	111.8	4.91
Specimen 1445	59	0.08	156.5	155.3	5.11

specimen). Changing the patch from three-layer to five-layer GFRP (Specimens 113 to 115) increased the absorbed energy by only 2 J and the percentage improvement of the energy absorption changed from 17.4 to 26.1% compared with the notched un-repaired aluminum specimens. Although the GFRP composites have good specific tensile strength and specific stiffness, they are not widely used in primary structures. This is due to the low energy absorption property of GFRP during bending and impact loading [13]. As can be seen, when the patch changes from five-layer GFRP (Specimen 115) to five-layer CFRP (Specimen 125), the absorbed energy increased by 7 J and the percentage of increase in energy absorption, by changing the patch from GFRP to CFRP as compared with the notched un-repaired specimen, changed by approximately 30%. The percentage increase of the absorbed energy (compared with the notched un-repaired specimen) for Specimen 125 is over 2 times that of Specimen 115 and approximately 3.2 times as compared with Specimen 113.

Glass and carbon fibres perform better under impact loadings when they are combined with a stiff metal to make FMLs [13]. As it is shown in Table 4(a), when two layers of glass fibre composite are combined with three layers of phosphor-bronze metal (Specimen 135), the absorbed energy changes from 29 J for Specimen 115 (five layers of GFRP) to 40.5 J for Specimen 135, and the percentage increase in energy absorption changed from 26.1 to 76.1% (192% increase). Also, it is shown that when two layers of carbon fibres are combined with three layers of phosphor-bronze metal (Specimen 145), the absorbed energy changed from 36 J for Specimen 125 (five layers of CFRP) to 42.5 J for Specimen 145, which means that the percentage of energy absorption increased by 18%.

Phosphor-bronze has good mechanical properties such as high tensile properties, specific strength, toughness, and stiffness. By increasing the number of phosphor-bronze layers in the patches, the percentage improvement of energy absorption increases, resulting in more effective patches.

The results of Table 4(a) can also be interpreted in terms of the percentage recovery of energy absorption of the repaired specimens compared with the un-notched specimen (3rd column). A notch with $l/w = 0.1$ results in approximately 40% loss of energy absorption (a notched un-repaired specimen with $l/w = 0.1$ absorbed 60.5% energy compared with the un-notched specimen), but recovers additionally 34.2% when a five-layer CFRP patch is bonded to the specimen (Specimen 125 absorbed 94.7% energy compared with the un-notched specimen). The usage of 2/1 FML patch with carbon fibres in Specimen 143 changes the absorbed energy to 101.3% compared with the un-notched specimen, which means that the repairs almost act as un-notched specimens with all the energy absorption capabilities lost having been recovered. The usage of single-sided 3/2 FML patch with carbon fibres (Specimen 145) not only repaired the notched specimen, but also reinforced the specimen by approximately 10% as compared with the un-notched specimen. In the case of double-sided repair by 3/2 FML patches (Specimen 1445), the reinforcement reaches over 50% (59 J compared with 38 J).

As can be seen in Table 4(a), the absorbed energy by Specimen 145 is 4.9% more than specimen 135. However, this value is 10.3% when Specimen 145 is compared with Specimen 143. This shows that the absorbed energy by different FML patches in impact loading is more dependent on the number of layers of the FML patches, and less dependent on the fibre type of the FML patches.

4.2. Specimens with a Ratio of Notch Length to Specimen Width $l/w = 0.3$

For the specimens with $l/w = 0.3$, the results obtained from the Charpy impact test are given in Table 4(b). It can be concluded that, similarly to the results described in Section 4.1, the three-layer and five-layer GFRP patches (Specimens 313 and 315) do not contribute much to improving the energy absorption for the notched aluminum specimens. A similar trend to the one for $l/w = 0.1$ was observed concerning the increase of absorbed energy for the repaired specimens using various patches. Since the absorbed energy of the notched un-repaired specimen was lower in the case of $l/w = 0.3$ (notched un-repaired specimens with $l/w = 0.1$ and 0.3 absorbed 60.5% and 44.7% energy, respectively, as compared with the un-notched specimen), the role of the reinforcing patches is more evident. In fact, by increasing the notch length, the percentage improvement of the absorbed energy compared with the notched un-repaired specimen increases. On the other hand, changing the patches from CFRP and GFRP to FMLs shows a significant effect. The percentage increase of the absorbed energy (compared with the notched un-repaired specimen) for Specimen 345 is approximately 3.5 times that obtained with Specimen 315 and approximately 1.6 times as compared with the Specimen 325. As can be seen in Table 4(b), the 3/2 FML carbon patch (Specimen 345) repaired and reinforced the notched specimen better than the other single-sided patches and it absorbed approximately 95% energy as compared with the un-notched specimen.

No single-sided patch allowed the full recovery of the absorbed energy compared with the un-notched specimen (38 J). However, in

TABLE 4(b) Energy Absorption Capability for Specimens with $l/w = 0.3$

Sample	Absorbed energy (J)	Standard deviation	Percentage increase in absorbed energy compared to the un-repaired notched aluminum specimen	Energy absorption capability as a percentage of the energy for the un-notched specimen	Absorbed energy per weight of the specimen (J/g)
Un-notched specimen	38	0	–	–	6.61
Un-repaired notched specimen	17	0.08	–	44.7	2.96
Specimen 301	23.5	0.14	38.2	61.8	3.53
Specimen 313	21	0.09	23.5	55.3	3.21
Specimen 315	22.5	0.09	32.3	59.2	3.28
Specimen 323	27	0	58.8	71	4.22
Specimen 325	29	0.13	70.6	76.3	4.37
Specimen 333	29	0.08	70.6	76.3	3.67
Specimen 335	34.5	0.15	102.9	90.8	3.92
Specimen 343	32	0.21	88.2	84.2	4.09
Specimen 345	36	0.08	111.8	94.7	4.16
Specimen 3445	54	0.01	217.6	142.1	4.67

the case of a double-sided 3/2 FML patch with carbon fibre (Specimen 3445), not only was all the absorbed energy lost by the notch recovered, but also an approximately 42% reinforcement was also achieved.

4.3. Specimens with a Ratio of Notch Length to Specimen Width $l/w = 0.5$

In the third stage of this work, the ratio of the notch length to the specimen width was 0.5. The results of the absorbed impact energy by the Charpy tests are given in Table 4(c). It can be found that, equally to the studies in the previous sections, the three-layer and five-layer glass patches (Specimens 513 and 515) are not effective in restoring the energy absorption capabilities of the notched aluminum specimens as compared with the other patches. When $l/w = 0.5$, the benefit of using carbon and FML patches over glass patches is notorious, resulting in a much larger percentage increase of the absorbed energy. The percentage improvement in absorbed energy of Specimen 545 (compared with the un-repaired notched specimen) is nearly 8.7 times as great as that of Specimen 513 and 6.5 times as great as Specimen 515.

TABLE 4(c) Energy Absorption Capability for Specimens with $l/w = 0.5$

Sample	Absorbed energy (J)	Standard deviation	Percentage increase in absorbed energy compared to the un-repaired notched aluminum specimen	Energy absorption capability as a percentage of the energy for the un-notched specimen	Absorbed energy per weight of the specimen (J/g)
Un-notched specimen	38	0	–	–	6.61
Un-repaired notched specimen	8	0.08	–	21	1.39
Specimen 501	13	0.06	62.5	34.2	1.95
Specimen 513	11	0.09	37.5	28.9	1.68
Specimen 515	12	0	50	31.6	1.75
Specimen 523	19	0.21	137.5	50	2.97
Specimen 525	24	0.19	200	63.2	3.62
Specimen 533	25	0.09	212.5	65.8	3.16
Specimen 535	32	0.15	300	84.2	3.64
Specimen 543	29	0.18	262.5	76.3	3.70
Specimen 545	34	0.08	325	89.5	3.93
Specimen 5445	49	0.04	512.5	128.9	4.24

Table 4(c) indicates that a notch with $l/w = 0.5$ results in approximately 79% loss of energy absorption compared with the un-notched specimen. Similarly to Section 4.2, no single-sided patch could fully re-establish the strength of the un-notched specimen, but in the case of a double-sided 3/2 FML patch with carbon fibre (Specimen 5445), not only was all the energy lost recovered, but also the un-notched specimen was reinforced by 28.9%.

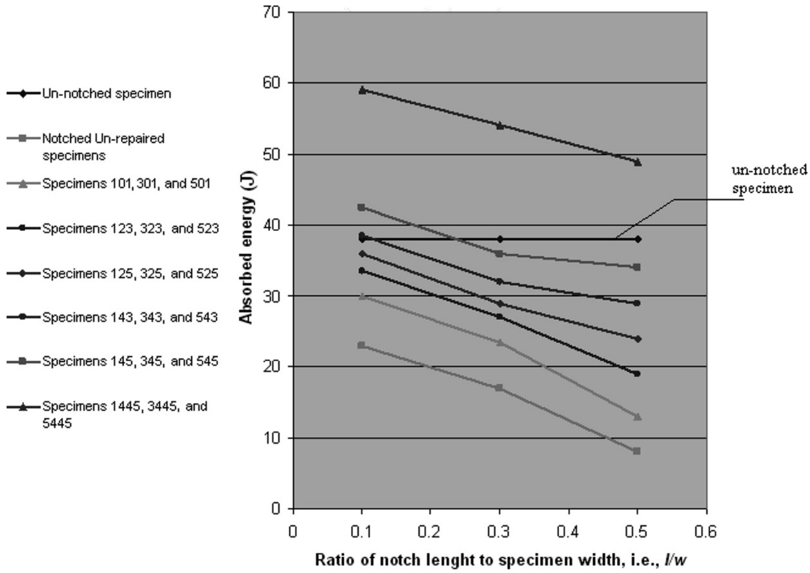
Although the energy absorption increases by repairing the specimen using FML and composite patches, the weight of the structure would also equally increase. The last column in Tables 4(a)–(c) shows the specific absorbed energy (absorbed energy/weight of the specimen with patch). In this work, the metal used for the fabrication of the FML is phosphor-bronze which is a heavy metal. For specimens with $l/w = 0.1$, the specific absorbed energy for the specimens repaired by FML patches with carbon fibres (Specimens 143 and 145) is lower than that of specimens repaired with CFRP composites patches (Specimens 123 and 125). But this also depends on the notch length. In Table 4(b), *i.e.*, for $l/w = 0.3$, the specific absorbed energy is almost the same for composite and FML patches with carbon fibres (Specimens 343 and

345 compared with Specimens 323 and 325), but in Table 4(c), *i.e.,* for $l/w = 0.5$, this quantity shows bigger values for FML patches with carbon fibres (Specimens 543 and 545) than for CFRP patches (Specimens 523 and 525).

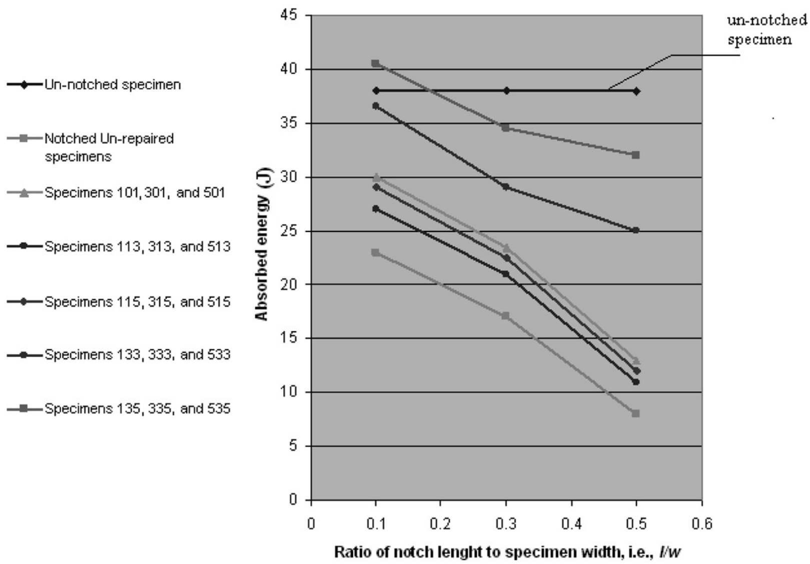
The specific absorbed energy of specimens repaired by FML patches with glass fibres is larger than that of specimens repaired with GFRP composite patches in all l/w ratios. Nonetheless, by increasing the notch length, the differences between their absorbed energy also increase. This difference is about 0.37 J/g for Specimens 115 and 135. However, it increases to 0.64 and 1.89 J/g for Specimens 315/335 and 515/535, respectively. The reason for this behavior is the dependency of the patch strength on the ultimate strength of the constituent materials. The strength of the CFRP composite is almost the same as that of the phosphor-bronze metal, but the ultimate strengths of the GFRP composites are one-third those of the metal sheet.

Figure 4(a) shows the energy absorbed by the specimens repaired with composite and FML patches with carbon fibres and Fig. 4(b) shows the energy absorbed by the specimens repaired with composite and FML patches with glass fibres. In both figures, the energy absorbed by the specimens repaired with a one-layer metallic patch is also shown. As can be seen in both figures, the repaired specimens with single-sided 2/1 and 3/2 FML patches with carbon fibres (Specimens 143 and 145) and the 3/2 FML patch with glass fibres (Specimen 135) for $l/w = 0.1$ absorbed more energy than the un-notched specimen which is 38 J. In addition, Fig. 4(a) shows that for all l/w ratios, the repaired specimens with double-sided FML patches with carbon fibres (Specimens 1445, 3445, and 5445) absorbed more energy than the un-notched specimen. Also, these figures indicate that by increasing the l/w ratio, the absorbed energy decreases for similar patches.

It can be concluded that by increasing the ratio of l/w, the energies absorbed by the notched un-repaired specimens decrease almost steadily, but the relation of absorbed energies (J) with the l/w ratio for repaired specimens with single-sided patches is not linear. Figure 4(a) shows that by increasing the l/w ratio, the slope of the curves for the specimens repaired with single-sided composite and FML patches with carbon fibres (except the specimens repaired with 3-layer CFRP patch) decreases. On the other hand, Fig. 4(b) shows that by increasing the l/w ratio, the slope of the curves for the specimens repaired with GFRP patches increases (except the slope for the specimens repaired with FML patches with glass fibres). Generally, by increasing the l/w ratio, the single-sided FML patches reduce the rate of decrease in absorbed energy (curve's slopes) by the repaired specimens.



(a)



(b)

FIGURE 4 (a) Energy absorbed (J) by un-repaired and repaired specimens with phosphor-bronze, CFRP patches, and FML patches with carbon fibres; (b) Energy absorbed (J) by un-repaired and repaired specimens with phosphor-bronze, GFRP patches, and FML patches with glass fibres.

TABLE 4(d) Energy Absorption Capability for Specimens with Double-Sided Patches and $l/w = 0.5$

Sample	Absorbed energy (J)	Standard deviation	Percentage increase in absorbed energy compared to the un-repaired notched aluminum specimen	Energy absorption capability as a percentage of the energy for the un-notched specimen	Absorbed energy per weight of the specimen (J/g)
Un-notched specimen	38	0	–	–	6.61
Un-repaired notched specimen	8	0.06	–	21	1.39
Specimen 5445	49	0.08	512.5	128.9	4.24
Specimen 5435	48	0.11	500	126.3	4.10
Specimen 5335	47.5	0.07	493.7	125	4.01
Specimen 5425	45	0.05	462.5	118.4	4.72
Specimen 5215	26.5	0.08	231.2	69.7	3.42

The energies absorbed by the double-sided patches are listed in Table 4(d). As it can be seen in this table, the absorbed energy for Specimens 5445, 5435, and 5335 is at the same level, which shows that the effect of FMLs' number of layers is more important than the effect of FMLs' fibre type in impact loading. In addition, Specimens 5445, 5435, 5335, and 5425 absorbed more energy than the un-notched aluminum specimen, allowing the reinforcement of 28.9, 26.3, 25, and 18.4%, respectively.

4.4. Comparison of the Natures of Fracture

The fracture surfaces were carefully examined to find out the failure mechanism. Some typical examples of specimens with composite patches are shown in Figs. 5 and 6. Whereas the GFRP patches showed fibre pull-out, the CFRP patches mainly failed by fibre-breakage. This is due to brittle behavior of advanced carbon fibres and also the good adhesion of fibres and adhesive in these patches.

In addition, some typical examples of the specimens with FML and phosphor-bronze patches are shown in Figs. 7–9. In Fig. 8, the carbon fibre FML patch exhibits a limited amount of fibre pull out across the fracture surface, but Fig. 7 shows the glass fibre pull out across the fracture surface of the patch which explain why the specimens did

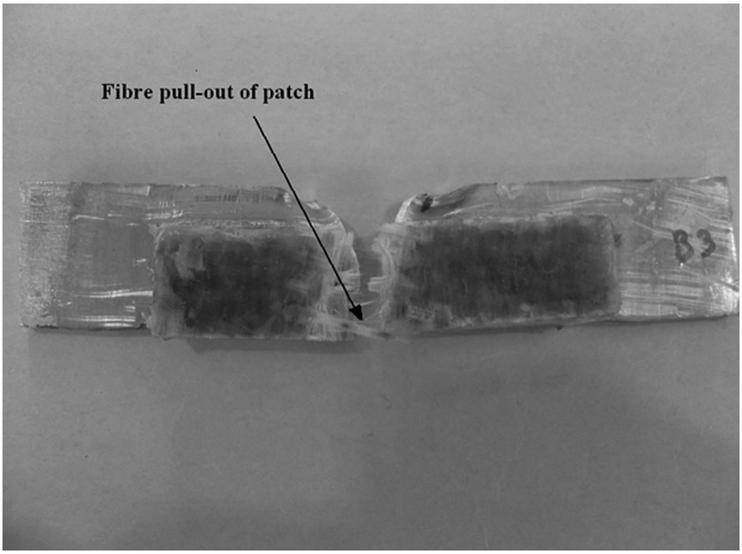


FIGURE 5 Specimen 315 after impact test (top view).

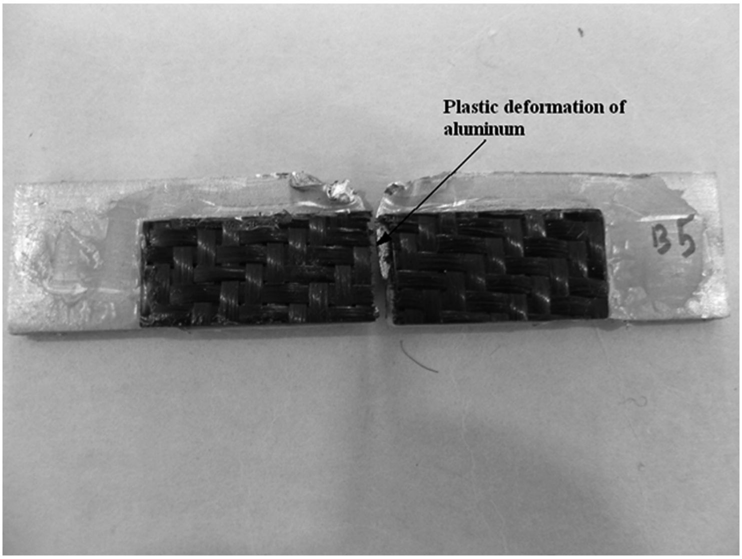


FIGURE 6 Specimen 325 after impact test (top view).

FIGURE 7 Specimen 133 after impact test (front view of fracture surface).

not break completely. In Fig. 9, the metal patch shows limited plastic deformation as compared with the aluminum specimen.

The fracture appearance of the aluminum specimens, either notched un-repaired or notched repaired, were similar. The failure mechanism was plastic deformation around the notched area. No debonding, either complete or partial, was visually detected in the layers of the patches and also between the patches and the aluminum specimens.

Figures 10 and 11 show that increasing the notch length did not have any significant effect on the fracture behavior of the un-repaired notched aluminum specimens as well as the repaired specimens.

(a) (b)

FIGURE 8 (a) Top view of Specimen 145 after impact test, (b) Front view of fracture surface.

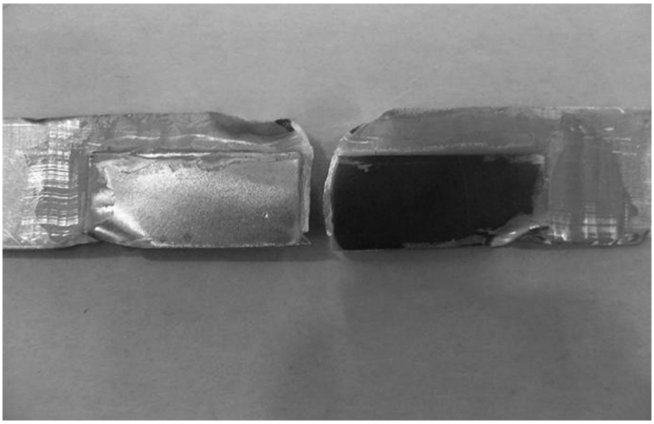
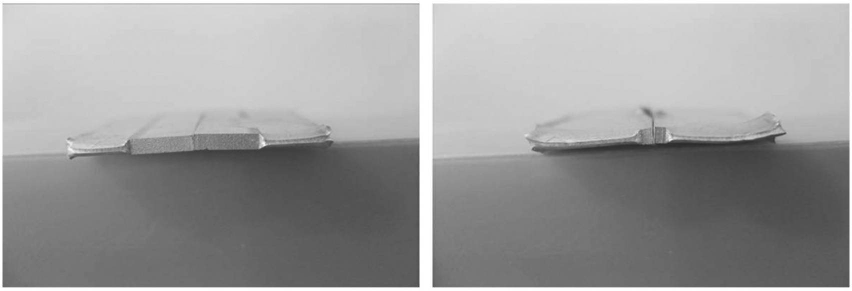
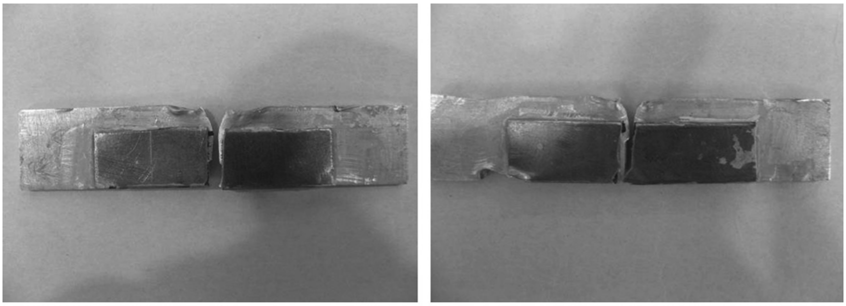


FIGURE 9 Specimen 101 after impact test (top view).



(a) (b)

FIGURE 10 Fracture surfaces of notched un-patched specimens after impact test (front view of fracture surface) (a) $l/w = 0.1$, (b) $l/w = 0.5$.



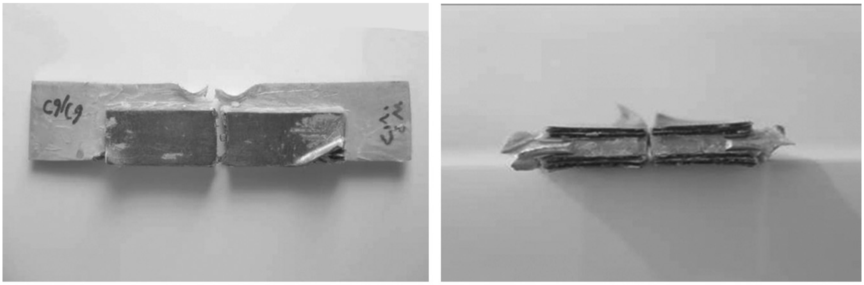
(a) (b)

FIGURE 11 Notched specimens repaired by 2/1 carbon fibres FML patches after impact test (top view) (a) $l/w = 0.3$, (b) $l/w = 0.5$.

FIGURE 12 Specimen 5215 after impact test (a) Top view, (b) Back view.

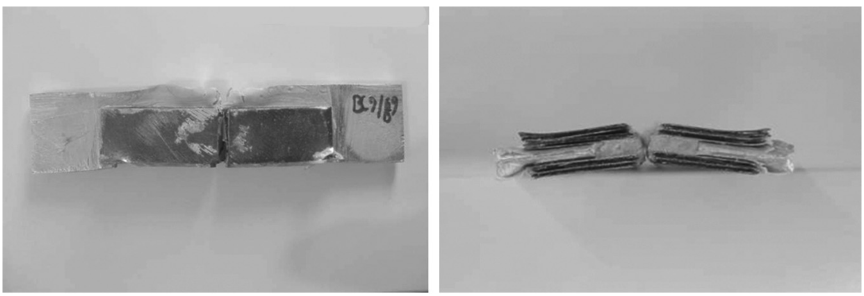
The fracture mechanisms of the repaired specimens with double-sided patches are similar to the single-sided patches. Figure 12 (Specimen 5215) shows the breakage of carbon fibres on one side and pull-out of glass fibres on the other side of the aluminum specimen. In addition, as can be seen in Figs. 13 and 14, the FML patches with carbon fibres exhibited a limited amount of fibre pull out across the fracture surface of the patch. In contrast, the glass fibre FML patches showed evidence of a greater amount of fibre pull out. All double-sided patches were broken completely from the notch region and, as shown in Figs. 14 and 15, increasing the notch length did not have a significant effect on the fracture mechanisms of the specimens.

FIGURE 13 Specimen 5335 after impact test (top view).



(a) (b)

FIGURE 14 (a) Top view of Specimen 5445 after impact test (top view), (b) Front view of fracture surface.



(a) (b)

FIGURE 15 Specimen 3445 after impact test (a) Top view, (b) Front view of fracture surface.

5. CONCLUSIONS

In this paper, the absorbed energy of edge notched aluminum plates, repaired with single-sided and double-sided composite and FML patches, was investigated experimentally with the Charpy impact tests. The composite and FML patches with woven glass and carbon fibres were used for reinforcing notched aluminum specimens. Phosphor-bronze metal sheet was used in FML patches. By comparing the results obtained, the following conclusions can be drawn:

1. FML patches are more effective in reinforcing the notched specimens than GFRP and CFRP patches. The effect of FML patches is more evident in the case of greater notch lengths.

2. When the ratio of notch length to specimen width is constant, the 3/2 FML patches with carbon fibres used in both single-sided and double-sided repair showed better characteristics than the other patches.
3. By increasing the notch length, the absorbed energy of the un-repaired specimens decreased. Also, in the case of similar patches, increasing the notch length leads to a reduction of the absorbed energy. However, the percentage improvement of the energy absorption compared with the notched un-repaired aluminum specimen increased, which shows the predominant role of the repair patches.
4. In the specimens with composite patches, independently of the number of layers, the fibre type has a significant role in the energy absorption, although with the FML patches, a bigger number of layers is to be recommended.
5. There is no difference in the fractured surfaces of the aluminum specimens repaired by the various patches, either composite or FML, subjected to Charpy impact loading, but some differences could be found in the fracture of the fibres of the composite patches. In addition, the fracture surfaces of the specimens with double-sided patches are similar to the specimens with single-sided patches.
6. Double-sided FML patches are more effective than single-sided FML patches in respect to energy absorption and also in terms of weight.

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