An Experimental Study on the Tensile Behavior of the Cracked Aluminum Plates Repaired with FML Composite Patches

A. Pourkamali Anaraki, G. H. Payganeh, F. Ashena ghasemi, A. Fallah

Abstract**—**Repairing of the cracks by fiber metal laminates (FMLs) was first done by some aeronautical laboratories in early 1970s. In this study, experimental investigations were done on the effect of repairing the center-cracked aluminum plates using the FML patches. The repairing processes were conducted to characterize the response of the repaired structures to tensile tests. The composite 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. It was observed for the lengthen cracks, the effect of increasing the crack angle on ultimate tensile load in the structure was increase. It was indicated that the situation of metal layer in the FML patches had an important effect on the tensile response of the tested specimens. It was found when the aluminum layer is farther, the ultimate tensile load has the highest amount.

Keywords**—**Crack, Composite patch repair, Fiber metal laminate (FML), Patch Lay-up, Repair surface, Ultimate load

I. Introduction

FIBER–METAL LAMINATES (FMLS) are hybrid structures based on thin sheets of metal alloy and plies of fiber-reinforced polymeric materials. These hybrid material systems combine the excellent specific strength and stiffness, and fatigue properties of composites and the machinability and toughness of metals [1] They were initially developed at the National Aerospace Laboratory in Nether-lands, after fatigue studies on the centre wings of a Fokker F-27 showed that bonded metal laminates presented promising fatigue properties [2]. Subsequent enhancement of their mechanical properties at the Technological Delft University resulted into commercially available FMLs under the trade name of ARALL (aramid fibre/aluminium) and GLARE (glass fibre/aluminium) [2].

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Current applications of FMLs include fuselages, leading edges, etc. in the Airbus A380, where weight reduction and improved damage tolerance ability are critical [3].

One of the serious shortcomings of the current-generation FML is that it has a low Young's modulus because woven glass-fabric has a fairly low tensile modulus. As a result, the modulus of glass/epoxy composite layer is low, nearly 26GPa, which is lower than that of the aluminum layer. Nevertheless, woven glass-fabric used in the current generation of the FML has a high tensile strength and strain-to-failure. The combination of lower modulus glass/epoxy layers and aluminum layer inevitably produce a laminate with a Young's modulus lower than that of the monolithic aluminum alloy [4]. This may limit the applications of the FML in aircraft structures where the stiffness is a predominant design requirement.

The lower modulus of glass/epoxy composite layer also leads to another serious concern, that is, the load carried by the aluminum layers is proportionally higher due to its higher modulus than the composite layers. The presence of high stress leads to a shorter fatigue crack initiation life of the aluminum layer [5–7]. In order to reduce the stress level and to improve the fatigue crack initiation life in the aluminum layer, it is necessary to increase the modulus of the composite layer. The beneficial effect of mingling boron and glass fibers on improving the Young's modulus and the yield strength in the hybrid boron/glass/aluminum FMLs has been successfully demonstrated in Ref. [8].

In this study, the tensile behavior of the cracked aluminum plates repaired with FML composite patches, were tested by tensile tests. In these tests, three factors are changed, i.e, crack length, crack angle and the lay-up of FML layers. Each factor contains three levels. Fourteen tests with three replicates were done. The results of tests were discussed and the effects of mentioned factors were compared.

II. Specimen Preparation

In this section, the method of specimens preparation is explained. The specimens include the cracked aluminum plates and the FML patches.

A. Cracked Aluminum Plates

In this study, the specimens were made of AL plate AA1035 having dimensions [7] as shown in Fig 1 and Fig 2. The mechanical properties of Al plate were given in table 1.

The specimens were cutted with a HYDRA jet water jet machine in principle dimensions and thereafter, using a wire cut machine, the notches by ratio a/w=0.3, 0.4 and 0.5 of specimen width were created on center of specimens. The crack width was 0.25 mm and the crack angle with respect to the width axis of specimen have three angle states, as 0°, 30° and 45°.

In order to have a complete bonding between the specimens and FML patches the surface preparation procedure according to the P2 etching process [8] was conducted on the bonding surface of the Aluminum specimens. In this method the bonding surface of the Al plate is degreased with acetone at first, and then abrades with emery cloth, then alkaline cleaning is applied, thereafter the specimen is immersed for 12 min at 65-70 °C P2etch mixture of 15% by weight FeSo4, 37% H_2So_4 and 48% water, then wash with the clean cold running water, followed by clean hot water and dry with hot air. The temperature of the hot water and air must not be greater than 65°c [9].

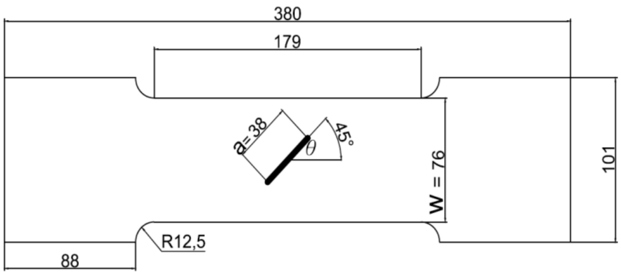

Fig.1 Specifications of an unpatched aluminum specimen, all dimensions in mm

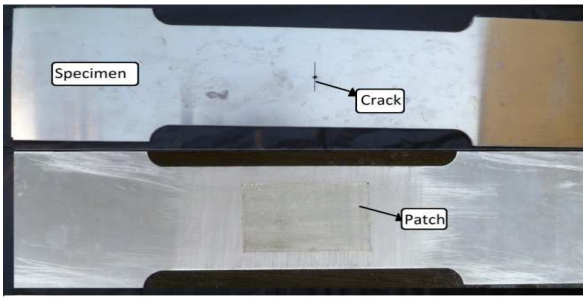

Fig. 2 Cracked and patched specimens

B. FML Patch

The FML composite patch was fabricated with two woven glass-fabric (T(90°)/M200-E10) layer as the fiber layers (GFRP), and one thin Al sheet (AA1035,0.3mm) as the metal layer. 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-A in bottom-up direction, in second repaired specimens the lay-up was F-A-F, and finally in patches the lay-up was A-F-F. The direction of warp and fill fibers in the patch lay-up are equally along 0° and 90° in all patches. For strong bonding between fiber layers and thin metal layer in the patch lay-up the surface preparation procedure for bonding surfaces of metal layer was done according to the standard [10]. For matrix, epoxy (LY5052) was used because it's efficiency for the Aerospace usages [11]. The content of fiber was about 55% by weight in glass-epoxy layers. The composite lay-up was made by hand and then the curing procedure according to the recommended cure schedule in two stages were done [11], at the first the patches were cured in 60°C for 2hr and then in 80°C for 4hr. The patch having dimensions of 80mm×50mm and after curing the thickness of the patch was 0.7mm. Table 1 shows the mechanical properties of patch material as well as the bonding materials.

The adhesive Araldite 2015 was used for bonding the FML patches to the cracked plates [11], and the thickness of the adhesive layer maintained about 0.2mm. Before bonding patches to the cracked plates, for bonding the metal layer to specimen, surface preparation procedure for metal layer of patch according to the P2 etching process that mentioned before was applied.

In this study, three factors are discussed, i.e, crack length, crack angle and the lay-up of FML layers. In order to compare the obtained answers together we should calculate the proportion of the ultimate load of repaired specimens to the ultimate load of same specimens but without repair. Table 2 shows fourteen experiments must be done (Table 2).

TABLE I
PROPERTIES OF PLATE AND PATCH MATERIAL

	Stiffness	Shear modulus	Ultimate tensile strength	Density	Poisons ratio
	E_1=E_2(Gpa)	G(GPa/MPa)	S_1=S_2(MPa)	ρ(g/cm^3)	ν
Aluminum AA1035	69	26(Gpa)	167	2.7	0.3
Epoxy-LY5052	3.5	------	60	1.16	0.35
GFRP layer	26	------	230	1.6	0.25
Araldite-2015	2	10-20MPa	30	1.4	------

TABLE II
EXPERIMENTS THAT WERE DONE

Trials	Crack angle	Crack length(a/w)	Patch lay-up
1	0°	0.3	F-F-AL
2	0°	0.3	F-AL-F
3	0°	0.3	NO patch
4	45°	0.3	F-F-AL
5	45°	0.3	F-AL-F
6	45°	0.3	No patch
7	30°	0.4	AL-F-F
8	30°	0.4	No patch
9	0°	0.5	F-F-AL
10	0°	0.5	F-AL-F
11	0°	0.5	No patch
12	45°	0.5	F-F-AL
13	45°	0.5	F-AL-F
14	45°	0.5	No patch

III. TENSILE TESTS

A. Experimental Setup

After the Specimens preparation, some experimental tests were performed. Tensile tests were conducted on specimens on the Instron 8802 tension- testing machine [14], which has a maximum load capacity of 250KN (25 Ton); The specimens were loaded in tension at a rate of 2 mm/min up to failure. The data of the tests were acquired and stored into a computer and were later plotted as a load vs. displacement curve.

Fig. 3 Specimen positioning before test

B. Experimental Results

Fig 4 and 5 shows some of tests results of patched and unpatched specimens. It was found that the stiffness of patched specimens with different crack lengths and angles was equal. In this study, due to the brittle behavior of specimens (repaired and without repair), the parameter that is studied is ultimate tensile load. Therefore, in this section the proportion of the ultimate load of repaired specimens to the ultimate load of specimens without repair is presented and compared. In order to better uptake of results, we apportion the results to three parts that each part explains the effect of each factor on the ultimate load of specimens. Before go into the parts, it is needful that be discussed about the result of specimens without patch.

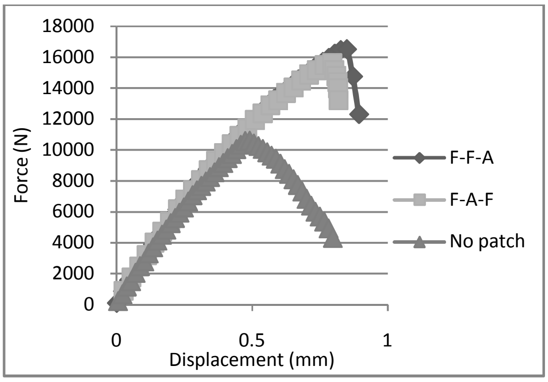

Fig. 4 Comparison of load vs. displacement curve for specimens with a/w=0.3, ϴ =0°

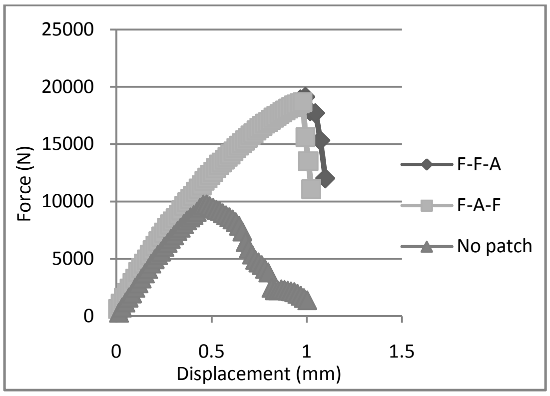

Fig. 5 Comparison of load vs. displacement curve for specimens with a/w=0.5, ϴ =45°

1. Result of Specimens Without Repairing

At the first, the cracked specimens without patch were tested. The results of these tests were depicted in Table 3. As it is shown a positive increase of the ultimate load by increasing the crack angle in three state of crack length is seen.

TABLE III
ULTIMATE LOAD OF UN-REPAIRED SPECIMENS

Crack angle	Crack length(a/w)		
	0.3	0.4	0.5
0°	10688	-------	7474
30°	-------	9998	-------
45°	12722	-------	9761

2. The Effect of Crack Angle

The obtained results show that by augmentation of crack angle the ultimate load of the repaired specimens is increased. For example, when a/w=0.3 and F-F-AL patch is used, by increasing the angle from 0° to 45° there would be almost a 27-precent increase in the ultimate load. It's because of change in the growth path of crack, in loading time, which forced it to be in direction that crack was placed in mode1. Then this change in direction lead to more strength. (Fig 6)

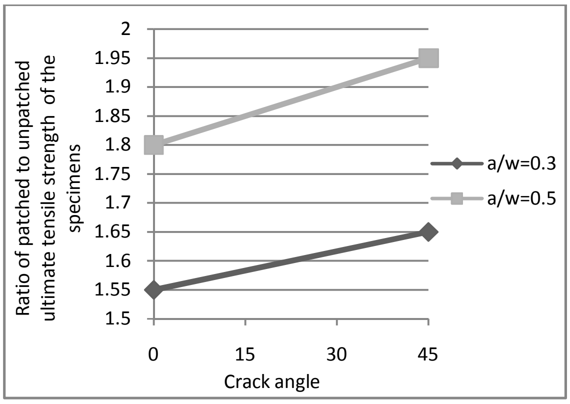

Fig. 6 Comparison of increment of ultimate load of specimens with different crack angle, repaired by F-F-A patch

3. The Effect of Crack Length

The second factor is crack length. AS augmentation of crack length, the amount of ultimate load is decreased. But, the more the crack length, the greater the effects of the patch on the ultimate load will be. This matter is important for us. For example when the crack angle is 0° and the patch of type F-AL-F is used and a/w=0.3, the augmentation of the ultimate load of the specimen with respect to the specimen without patch is 48%, while if a/w=0.5 this value is 68%. By increase in crack length, passed path by crack until reach to mode1 will be more long and the amount of ultimate load increases, too. (Fig 7)

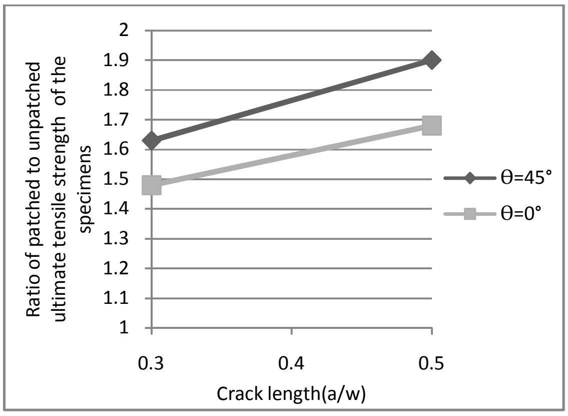

Fig. 7 Comparison of increment of ultimate load of specimens with different crack length, repaired by F-A-F patch

4. The Effect of FML Patch Lay-up

The tertiary factor is patch lay-up. By looking at the obtained results and Regarding to Fig 4.10, it is found approximately, that the patch type of F-F-AL has better function from the patches type of F-AL-F and AL-F-F. And also, the patch type of Al-F-F is more profitable from the patch type of F-ALF. Therefore we conclude that the location of the metal layer in the patch configuration has a significant contribution upon the efficiency of the repair. Whenever the AL layer is located in the farthest point from the surface of repair, the ultimate load in comparison to other aforementioned state will be more. Also in second step the amount of ultimate load belong to the patch with AL layer being adhered to the repair surface. And finally when the AL layer is in the middle the ultimate load has the lowest amount.

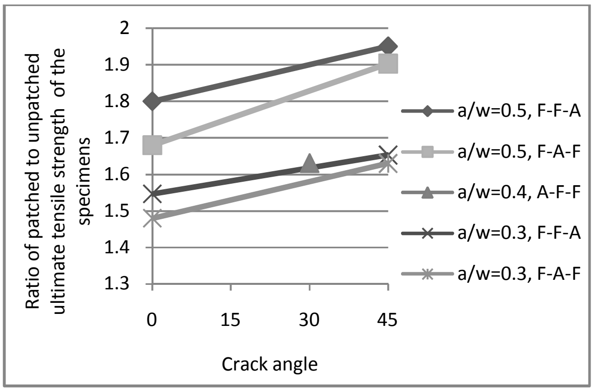

Fig. 8 Comparison of increment of ultimate load of specimens with different crack length and crack angle

Before justifying mentioned phenomenon, we should mention some points as follows:

1. Because the repair is asymmetrical, in the process of tension a moment of bending is made which makes the structure bent toward the patch. This bending results in the opening of the crack front towards the opposite side of the repaired surface, and consequently; the growth of crack will happen very quickly. As a result, if the patches act in a way that prevent the bending of the structure, the specimens will take much more time to fail.

2. Three factors can affect the behavior of the patches simultaneously. a) High stiffness of aluminum. b) High ductility of aluminum. c) High ultimate tensile strength of glass-epoxy composite.

With regard to mentioned points, the FML patch has proper performance in two states as follow:

a) According to point 2, whenever AL layer is bonded the repair surface, ductility is more possible, then the patch able to absorb more energy by plasticity of metal layer. But when it's in the middle of patch lay-up or even more far from repair surface the brittle fracture will occur, because GFRP layer has less ductility and by breaking this layer, AL layer break suddenly too.

b) With respect to point 1, when AL layer is far from the repair surface, due to high stiffness of aluminum, the stiffness of the patch against the bending will increase, so in this situation the structure will bend less and the ultimate load will increase.

Now, considering the result of the tests, it can be understood that the second performance has more effects on the augmentation of the ultimate load. Therefore, when the AL layer is farther, the ultimate load has the highest amount and when the aluminum is in the middle the ultimate load has the lowest amount.

Fig. 9 shows the crack trajectory in different patches. It indicates that all of parts in the specimens, is split together and there is no separation between plates and patches.

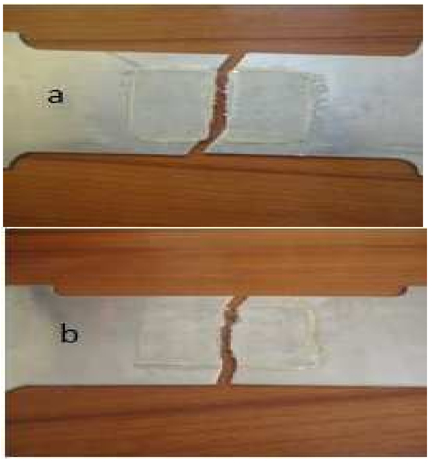

Fig. 9 Crack trajectory in specimens with different patches a)F-AL-F, b)F-F-AL

IV. Conclusion

In order to survey the effect of FML patches on strengthening of cracked Aluminum plates, repairing of the centeral cracked Aluminum plates were done and the specimens were subjected to tensile test.

The following conclusions can be drawn by comparing the obtained results.

1. Decrement of crack length in more crack angle, show less effect on the increment of ultimate load of repaired specimens.
2. Strength of repaired and un-repaired specimens will be decreased by increase in crack length, but there is an important point that is the more effect of using the patches, in more crack length.
3. Unless the crack characteristics, repaired structure strength, depends on type of patch lay-up and when the Al layer of the patch structure is located far from the repair surface of AL plate, amount of ultimate load will be more and when the AL layer is in the middle of other layers the ultimate load has the lowest amount.
4. In this paper, the proportion of the ultimate load of specimen with a/w=0.3 and $\theta = 0°$ and repaired by F-F-AL patch to the ultimate load of same specimen but without repair, is 1.55. while this proportion in the paper "Design, analysis and performance of adhesively bonded composite patch repair of cracked aluminum aircraft panels" presented by A. Chukwujekwu Okafor et al. is 1.42. It is important that the used patch in above-mention paper is 5-ply composite.
5. In all of tests, In adhesive place, there is no separation between plate and patch and also between FML composite layers, while in the test of above-mention paper there is separation. it shows the efficiency of used adhesive and so surface preparation procedure and the patch make up in the present condition.

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