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MECHANICAL BEHAVIOR OF ALUMINUM HYBRID LAMINATES

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ABSTRACT

This work has been dedicated to investigating the stiffness and strength of FML components under static axial and bending loads. There are two types of fiber metal laminates (FML) called Al3G4 and Al3G2K2 labeled according to the plate design. Al3G4 is Glare 3/2 -0.4 contains 4 layers of laminated glass/epoxy laminate. Al3G2K2, is a hybrid fiber laminate, has two aramid fiber laminates adjacent to the inner metal layer. Experimental stiffness and strength are discussed and compared with the theoretical data. The relationship between tensile and bending forces is discussed. Referred to the end bending condition, results of free end support have been compared with the corresponding results of fixed end support. The experimental work was carried out on both unnotched and notched samples to study remaining stresses due to circular aperture openings. The outcome of the present study indicates that the mechanical properties of the FML structures which named Al3G2K2 were slightly higher than glare (Al3G4) in both notched and unnotched cases. Failure patterns were also observed and identified.

Keywords: tensile, flexural, woven glass, aramid fabric, epoxy resin, hybrid aluminum composite.

1. INTRODUCTION

Fibre metal laminates (FML) are made of a combination of fibre reinforced laminated composites and thin layers of metals. These hybrid materials provide superior mechanical properties compared to the polymer matrix composites or aluminum alloys. FMLs have better tolerance to fatigue crack growth and impact damage especially for aircraft applications. Different combinations of metal alloys and composite laminates produce different families of FMLs. The most common types of FMLs are Glass Reinforced Aluminum Laminate (GLARE), Aramid Reinforced Aluminium Laminate (ARALL) and Carbon Reinforced Alumnium Laminate (CARALL) [1, 2].

Many researchers have tried to understand FML properties and design parameters. These parameters can be summarized in a few elements such asmetal thickness, metal type, surface treatment of metal layers, geometry and fiber reinforced fabric, joining type, group order type, and manufacturing process [3-9].

The first hybrid metal laminate is known as ARALL (Aramid Reinforced Aluminum Laminate). Combination of sheet metal (aluminum layers) and kevlar fiber /epoxy laminate (aramid layers) generates a new composite material with a new set of properties. ARALL laminates offer many advantages such as strength and fatigue properties. Moreover, they retain the advantages of aluminum alloys, namely lower cost, easy machining, forming, and mechanical fastening abilities, as well as ductility. The fibres are seems to be insensitive to the fatigue loading, which key benefit of this material regarding crack propagation.

GLARE laminates belong to fibre metal laminates family, they consist of alternating layers of glass fibre reinforced pregregs or laminate and monolithic aluminum alloy sheets. At first, they were developed for aeronautical applications as an improvement of ARALL with advanced glass fibre. GLARE (glass reinforced fibre metal laminate), using glass fibres, was then introduced recently, due to the good compressive properties of glass. These compressive properties lead to a better loading flexibility of GLARE compared to ARALL since Aramid fibres show a very poor behavior under compressive loading [2, 10-11].

These compression properties provide better flexibility in loading of GLARE than ARALL because the aramid fibers exhibit very poor behavior under compressive loading. GLARE is now an applicable material in the aircraft industry. One of the advantagesof hybrid composite materials in the designing is that the composite properties can be controlled largely by choosing the fiber matrix and tailoring the required properties. The advantages and disadvantages of the different fibers of metal fiber sheet structures were discussed before [6-7, 11].

The scope of studying the material properties is much greater when different types of fibers are incorporated into the same resin matrix. To study the potential of these materials, in this work the samples were prepared with glass/epoxy laminates and Kevlar fiber/epoxy laminates. Kevlar fibers are characterized by special strength and stiffness rather than glass fiber. It is known that, the main deficiency of Kevlar fiber is that the strength of low pressure and high cost. Therefore, this work is dedicated to owning a large benefit of fiberglass and aramid fibers.

2. Experimental Work

2.1 Materials

Fiber metal laminates FML used in the present work consist of two composite successive layers and monolithic metal. The metal layers used are thin aluminum sheets of 2024-T3 with a thickness of 0.4 mm. The composite laminate composed of woven E-glass cloth fiber (EBX600) or aramid (Kevlar, Twaron type) fabric fiberslies in epoxy resin EPOLAM2017 with

EPOLAM2018 as a hardener. Mechanical properties of the constituents of the fabricated FML which are used in this work has been used according to the manufacturer datasheet.

2.2 Specimen Fabrication

The goal of the manufacturing process is to obtain two familiar types of FML structures. The first is GLARE, with Aluminum (Al) and glass fiber laminate (G) stacked in the following configuration {Al / G / G / Al / G / G / Al }designated by Al3G4. The second structure is made of glass laminate (G) and Kevlar laminate (K) with stacking sequence {Al / G / K / Al / K / G / Al} and designated by AL3G2K2.

The aluminum sheets are cut to 50 cm square plates and then, subjected to a chemical process to remove any foreign substances that accumulate on their surfaces such as oil, grease or dirt to improve adhesion followed by aluminum anodizing (electrochemical process). The time between anode processing and Aluminum sheets should not be more than 30-40 minutes. The process of manufacturing begins with the drying of the mold and the first aluminum layer, then molding the resin and placing the first fabric layer on the spilled resins.

The previous step is repeated until the FML plate is completed. The FML samples are then put under vacuum pressure 0.1MPa pressure for 240 minutes to remove the excess resin and any air trapped inside samples. FML plates are cured by exposing to 600 ◦C for 240 minutes and then leave to cool gradually in the furnace before placing it under 0.25MPa pressure at 24hr. The hydraulic shearing machine is used to cut the samples with dimensions of 200 mm length and 20 mm width. Some samples were carefully drilled [12-13] with four holes with 4mm diameter in square arranged to discuss the effect of remaining stresses. The fraction of size for each metal, fiber, and matrix is also calculated and included in Table-1.

Table-1. Relative content and density of the fabricated fiber metal laminates.

FML Type (Lay up)	Thickness (mm)	Glass (%)	Kevlar (%)	Epoxy (%)	Al (%)	Laminated density (%)	FML density (%)
Al_3G_4 Al/G/G/Al/G/G/Al)	3.42	10.2	----	56.5	33.3	1.38	1.817
$Al_3G_2K_2$ (Al/G/K/Al/K/G/Al)	3	11.12	6.78	42.1	40	1.372	1.899

2.3 Testing Procedure

In order to obtain the characteristics of FML specimens, tensile and bending tests (3-point bend) are performed for both notched (four holes) and unnotched samples. Tensile and bending tests are carried out on a universal test apparatus, Amsler, with a maximum capacity of 100 kN, at the Materials and Testing Laboratory, Faculty of Engineering, Cairo University. Tests conducted with crosshead stroke rateof 2.5 mm / min and at room temperature. A digital camera was used to record the corresponding force (measured by the machine) and the corresponding deformation of each test. Specimen deformation is determined by fixing a dial indicator on the movable side of the srosshead machine, as shown in Figure-1. The surface of the failure instantaneously is observed visually.

According to ASTM D3039-14 standard regulation, the data obtained from the tensile test for the notched and un-notched samples are then used to determine the strength, elasticity and failure pattern.

The bending test is used to determine bending stiffness and strength. All bending samples are tested according to ASTM D790-15. The bending test is done in two ways: free support ends, and the other way is fixed - fixed end conditions.

Figure-1. Optical micrographic of the experimental setup.

3. RESULTS AND DISCUSSIONS

3.1 Analytical Results

The micromechanical formulas which are used to determination the elastic moduli of composite lamina, can be applied directly to the whole multilayered FML structure. The metal volume fraction (MVF) and composite volume fraction (CVF) can be calculated with relation to the thickness of both constituents (metalic sheet and composite laminate) within the entire specimen. The properties of FMLs are dependent on the static mechanical properties of their constituents. The metal volume fraction (MVF) is defined as the sum of all aluminum layers

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thicknesses over the total thickness of the laminate [14-16].

The strength and stiffness of the unidirectional fiber are first documented, and then the corresponding values of woven fibrous fibers (bi-directional fibers) can be calculated.

The mechanical properties of the composite layer have been explained in terms of constituents with simple formulas on the assumption that the layer is transversely isotropic with a balanced reinforcement of woven fabrics [15]. A simple approach analysis of micro mechanics based on property predictions is easy to use, such as the classical equations of the unidirectional layers to determine the characteristics of the woven tissue in terms of the two components. FML properties depend primarily on the configured properties as well as on the relative size segment. Therefore, the rule of mixture, in this work, is the basic method used to determine the rigidity and strength of the FML structure. The strength and stiffness of polymer composite laminate have been discussed, and then the hybrid rule of the mixture can be applied to determine the properties of FML [2, 15]. The rule of mixture (ROM) approach can only be applied to the individual constituent of the FML and laminate properties can be specified in the following model:

$$P_{FML} = MVF * P_m + (1 - MVF) * P_c$$

The subscripts FML, m, and crepresent the fiber metal laminate property, monolithic sheet metal property, and composite lamina property respectively.

Using ROM and the fractional data in Table-1, both tested types of FML strength and modulus of elasticity are calculated. The theoretical tensile strength is 326.87 MPa and 334.5 MPa for samples of Al3G4 and Al3G2K2, respectively. The elastic moduli for the same samples, respectively, are 20.61 GPa and 29.2 GPa. One can observe that the irrespective change of the composite laminate type (glass or/and Kevlar) with the change of ultimate strength seems to be insignificant. However, a great influence is cleared strongly on the modulus of elasticity for the two samples.

3.2 Tensile Results

The purpose of tensile testing is to determine the basic mechanical properties under axial load such as strength and stiffness as well as damage failure. Figure-2 shows the average tensile load- deformationi results of the unnotched and notched samples. The experimental tensile strength of the unnotched samples is found to be 318.2 mpa with total failure strain of 1.82%. The linear relationship between load and deformation reveals the experimental tensile elastic modulus of 20.02GPa. Similarly, the corresponding strength of the notched samples is 285.7 MPa. The tensile data show that the average tensile stiffness (K=F/Δ) is 13.21 kN / mm and 12.62 kN / mm for the unnotched and notched samples, respectively.

The average tensile load - deformation of the Al3G2K2 samples is shown in Figure-3. The tensile strength and the corresponding failure strain of the unnotched samples are 335.8 MPa, 2.08%, respectively, and the modulus of elasticity is 22.4GPa. The corresponding strength of notched samples is 297.6 MPa. The average tensile stiffness (K=F/Δ) of Al3G2K2 is 11.4 KN / mm for the unnotched samples and 9.46 KN / mm for the notched samples. Theexperimental results show that the introduction of the Kevlar layer instead of the glass layer, around the interior aluminum layer, positively affects the material strength and negatively affects the stiffness of the samples.

Figure-4 shows a comarison between the experimental and theoretical values of the tested materials. One can observe that the theoretical tensile strength values are close to the corresponding experimental results. However, the theoretical moduli of elasticity are higher than the experimental values with a difference of about 2.86 %, and 23.29 % for Al3G4 and Al3G2K2, respectively. Experimental data as well as the theoretical values show that the elastic modulus of Al3G2K2 samples is higher than the equivalent values of Al3G4. This is due to the difference in stiffness between glass fibers, E = 72 GPa, and Kevlar fibers, E = 124 GPa.

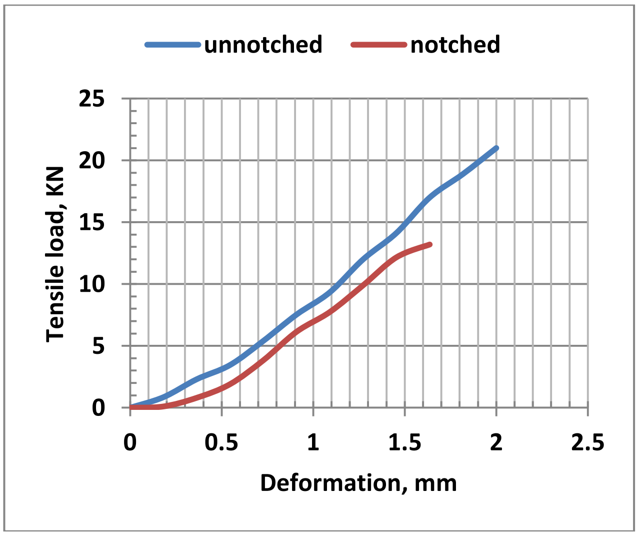

Figure-2. Tensile Load-Deformation curve for notched and un-notched specimens of Al3G4.

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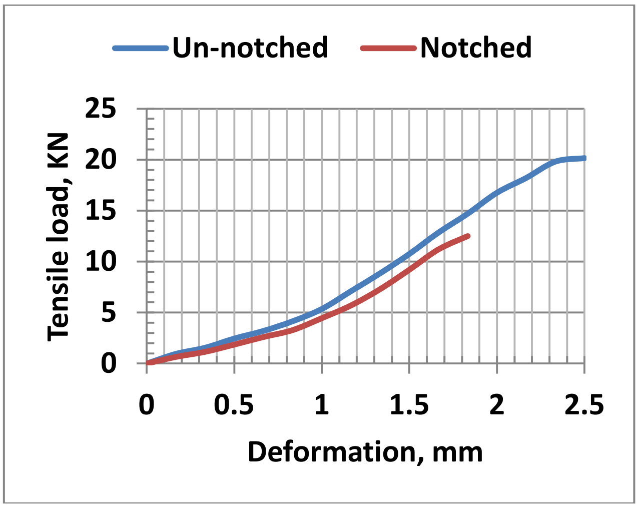
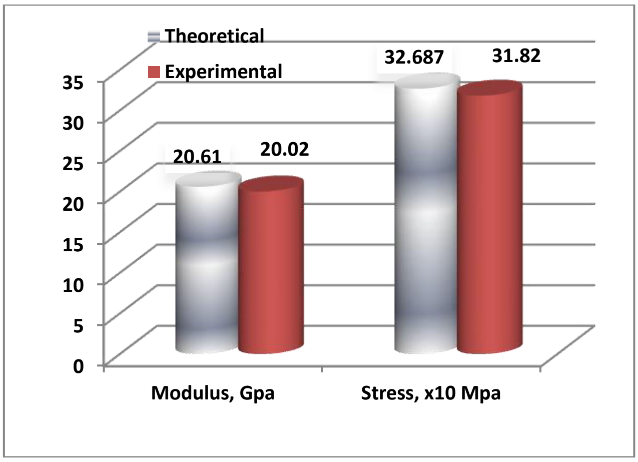
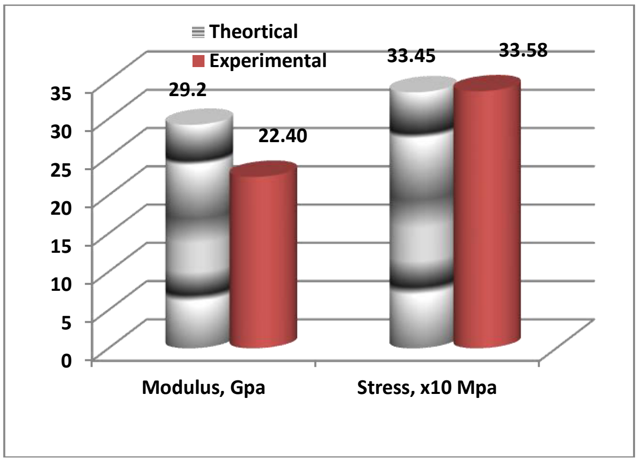


Figure-3. Tensile Load-Deformation curve for notched and un-notched specimens of Al3G2K2.



(a)



(b)

Figure-4. Theoretical and experimental strength and moduli values for a) AL3G4 and b) AL3G2K2.

The reduction of experimental fracture strength (FSR) was calculated. FSR values represented by the relationship between the notched and unnotched strength [2, 17]. In the same way, the stress concentration coefficient (K_t) was calculated for the specified width of the tested specimens as follows:

$$K_t = 2 + (1 - d / w)^3$$

where d represent the hole diameter and w is the plate width.

The fracture factor (K_f) which represents the final tensile stress ratio of the unnotched sample to the stress of the notched sample is obtained through the total area. The FSR, K_t, and K_f [18-21] factors are listed in Table-6. There appears to be no difference in FSR from the two tested samples.

This may be attributed to the position of the stacking sequence of the kevlar laminates. FSR values reveal that the remaining stress in the materials tested is tensile stress are almost the same. The current experimental results confirm that the high quality of the manufacturing process and the precise drilling of holes. It is known that the notch sensitivity (q) [2] is a key parameter in the design against the failure of the material with any type of loading. Notch sensitivity factor, calculated and listed also in Table-2 in which has a value of 0.486 for the Al3G4 samples and 0.503 for the Al3G2K2 samples. Tino [18] showed that the residual strength represented by FSR for composite fiber-glass sheets in the fill direction is 82% and 89% at angle ± 45. In general, the openings area had a negative impact on the mechanical properties of materials.

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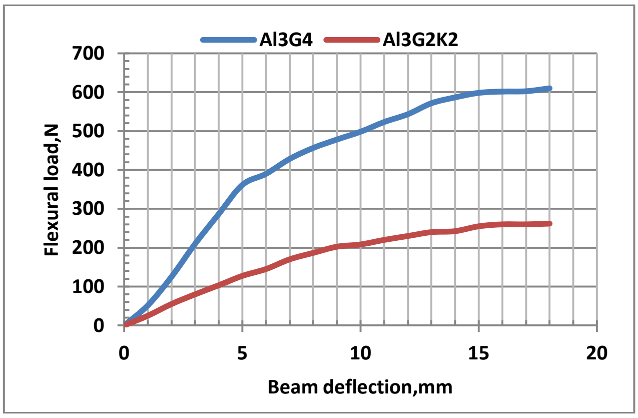
Table-2. Notched specimen factors.

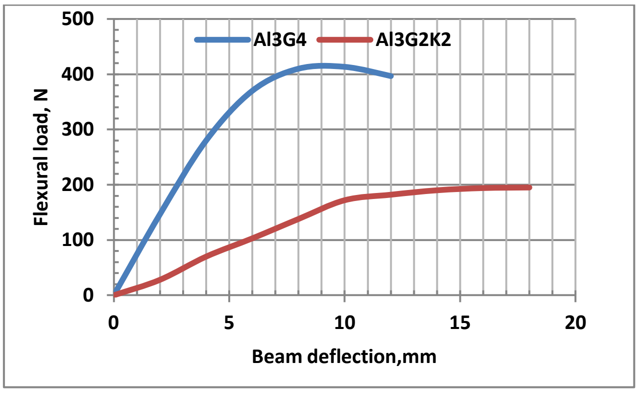
FML Type	Static stress concentration (Kt)	Notch Factor (Kf)	Notch sensitivity (q)	Fracture Stress Reduction (FSR)
Al3G4	2.216	1.591	0.486	0.898
Al3G2K2	2.216	1.612	0.503	0.886

3.3 Flexural Results

Figure-5(a) shows the flexural load versus - beam deflection for un-notched specimens of materials Al3G4 and Al3G2K2 with free end supports. The bending modulus of elasticity can be determined from experimental data in addition to bending stiffness (K=F/Δ). The bending tensile strength is 597.5 MPa for samples of Al3G4 and 349.3 MPa for Al3G2K2. The modulus in bending is 36.87 GPa for Al3G4 and 28.67 GPa for Al3G2K2. Also, the sample bending stiffness (K) is 72.2 N / mm for Al3G4 and 25.5 N / mm for Al3G2K2. Current results show that Al3G4 (Glare) samples are more stiff than the Al3G2K2 samples.



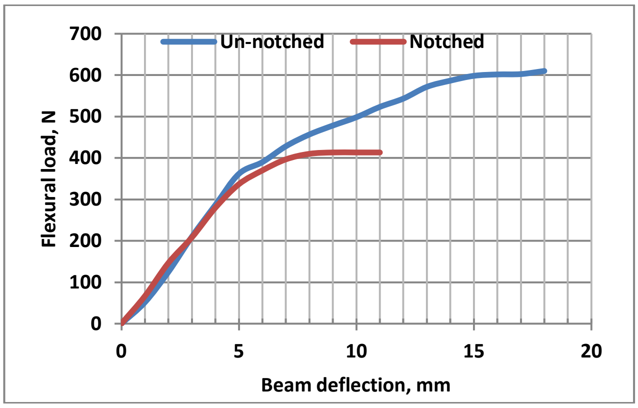
(a)



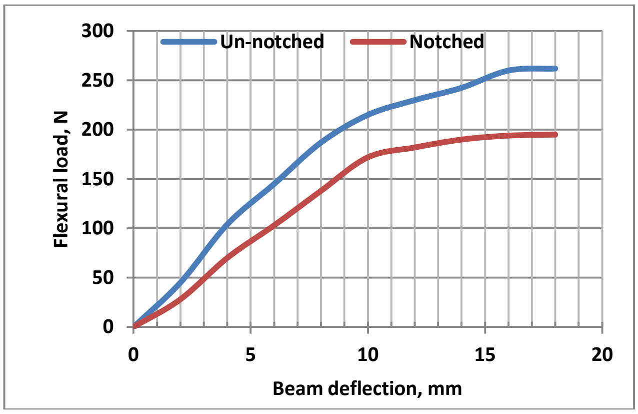
(b)

Figure-5. Flexural trend of Al3G4 and Al3G2K2 for a) un-notched specimens and b) notched specimens.

Figure-5 (b) shows the bending results of free end condition for notched specimens. Results indicate that the bending stiffness is 67.34 N/mm and 17.2 N/mm for specimens of Al3G4 and Al3G2K2,respectivelly. In order to clarify the notch effect on the bending results , the previous experimental data are replotted to compare the bending behavior for notche and un notched samples in Figure-6. The current results show that the elastic limit of bending loads are 336.5 N and 361.7 N for the notched and un notched samples of Al3G4 at an approximate beam deflection of 5 mm.While the corresponding values for Al3G2K2 for notched and un notched samples are 172 N and 215 N, respectivelly, at beam deflection about 5 mm.



(a)



(b)

Figure-6. Flexural load versus beam deflection for notched and un notched specimens fora) Al3G4 and b) AlG2K2.

To understand the flexural response of the FML under combined tensile load and bending loads, the previous bend tests, free end condition, are conducted with fixed - ends conditions. Figure-7 presents the flexural load versus beam deflection for un-notched specimens with both end conditions. The initial bending stiffness (K) are found to be 93 N / mm for samples of Al3G4 and 26 N / mm for samples of Al3G2K2 for fixed end conditions. The bending results of the free or fixed endings show that the initial bending stiffness of Al3G4 and Al3G2K2 has

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almost the same as shown in Figure-7. Flexural results reveal the initial bending trend, generally, independent of the end condition, especially in the elastic range. Influence of the tensile load due to the fixed end condition of the bending test appears clearly at beam deflection of 5 mm and 10 mm for Al3G4 and Al3G2K2 samples, respectively. The bending strength to the tensile strength ratios is found to be 1.878 and 1.041 for Al3G4 and Al3G2K2 samples. Similarly, the corresponding stiffness ratios are approximately 1.932 and 1.195. This means that the Glare samples, Al3G4, have more rigidity than the corresponding samples of the modified one, Al3G2K2.

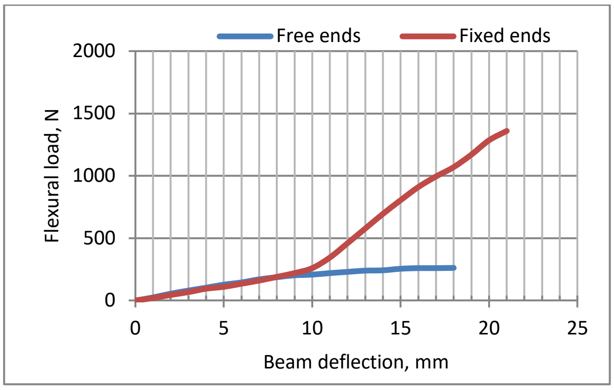
3.4 Fracture Analysis

Figure-9 shows the fracture surface of the tensile test for un-notched and notched Al3G4 specimens. The net tensile fracture observed clearly on the aluminum layers attendant in the fiber breaking of the laminates. The fracture surface trend has not influenced by the circular open hole. Visual observation shows that there are no any delaminations or matrix cracks on the tensile test specimens of Al_3G_4 materials. Figure-9 shows the fracture surface of the tensile test for un-notched and notched Al3G2K2 specimens. The net tensile fracture occurs in the aluminum layers for all tested specimens. The fracture surface of Al3G2K2 specimens due to the presence of holes seems to be the same failure of unnotched and notched specimens of Al3G4.Fracture of unnotched specimens of Al3G2K2 occurs as a net tensile failure accompanied with the separation of the Kevlar fabric layers from the interior aluminum layer and the glass laminate which still in contact with the outer aluminum layers.

Bending tests show that the tensile fracture occurs in the outer aluminum layer at the tensile side of the unnotched and notched specimens of Al3G4 irrespective the end condition of the bending test, as shown in Figure-10. In contrast, the tested specimens of Al3G2K2 were flexible and the failure surface disappeared.

Present observation of the fracture surface of the notched specimens under the bending test has confirmed with earlier investigators as Tino [18].

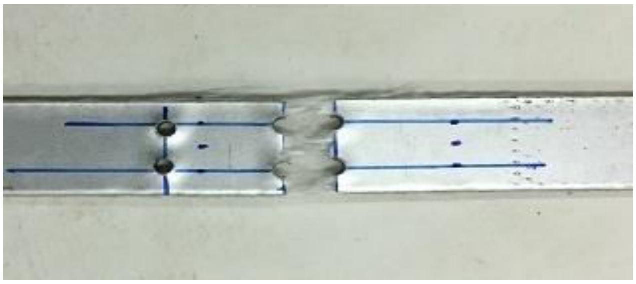
(a)



(b)

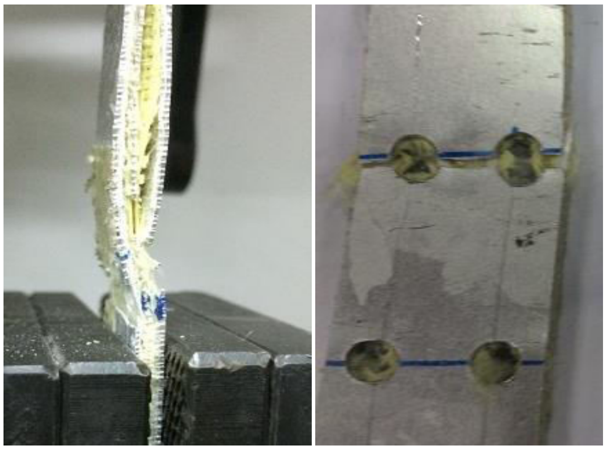
Figure-7. Flexural load with different end condition for un notched specimens of a) Al3G4 and b) Al3G2K2.

(a)



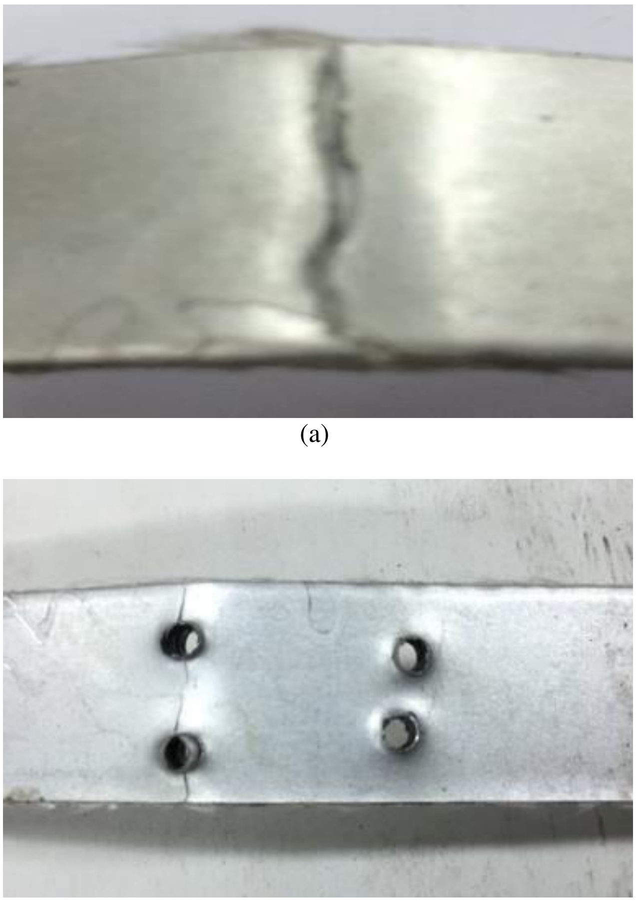
(b)

Figure-8. Tensile fracture of Al_3G_4 specimens, a) un-notched, b) notched.



(a) (b)

Figure-9. Tensile fracture of $Al_3G_2K_2$, (a) un-notched and (b) notched.



(a)

(b)

Figure-10. Fracture surface under bending for (a) un-notched and (b) notched specimens of Al_3G_4.

CONCLUSIONS

In many cases, FML is superior in mechanical properties compared to ordinary aluminum alloys or compound of fiber-reinforced polymer. This leads to its use in aerospace applications. To use the FML compound in these applications the assembled parts will be used as riveted joints. These joints are exposed to mixed loads of tension, bending and fatigue. Then studying the properties of FML material and determining the change in the characteristics of the notched samples is necessary.

This paper presents data of the tensile and bending characteristics of two FML composites (Al3G4 and Al3K2G2) and how these properties are affected by changing in fiber type and presence of holes. The experimental results reveal that the introducing of Kevlar laminates instead of the glass laminates around the interior aluminum layer positively affects the elastic material property but negatively affects the stiffness of the samples. Each of Al3G4and Al3K2G2specimens'strength slightly decreases when notched; proving that the hybrid FML composites have a lower strength reduction resulting from the holes less than the metals.

Fracture modes area nettensile fracture. Typicallya fiber breaking and pull out failure occurs for each of the FML materials at the loading area for unnotched specimens and at the center of two of the four holes for the notched ones.

Separation occurred between the kevlar layers and the internal aluminum layer, while no separation observed between the glass layer and the outer aluminum layers.

Future work can be done by studying the riveted joint as a whole and defining its properties to find FML composite materials that have better joint stiffness and strength. Also, fatigue tests are very vital in this work since these subjects are common to load fatigue in real applications. Crack initiation and spreading can be investigated and discussed.

The observed fracture surface confirmsthe experimental results obtained. The data obtained for FML samples can be summarized in order to illustrate the effect of Kevlarlaminates added to glass laminates on FML strength and stiffness, as shown in Table-3.

Table-3. Summary of the material property as obtained experimentally.

Property	Units	AL3G4	AL3G2K2
Density , ρ	gm/cm^3	1.817	1.899
Bending to tensile stress, σ_t / σ_b	--------------	1.878	1.041
Bending to tensile stiffness, E_t /E_b	--------------	1.932	1.195
Specific tensile stress, σ_t / ρ	MPa .cm^3 /gm	175.12	176.83
Specific tensile stiffness, E_t / ρ	MPa .cm^3 /gm	10.51	12.628
Specific Bending stress, σ_b / ρ	MPa .cm^3 /gm	328.84	184.04
Specific bending stiffness, E_b / ρ	MPa .cm^3 /gm	20.29	15.097
Bending Stiffness, K_b	N/mm	72.2	25.5
Tensile Stiffness,K_t	N/ mm	13.8	11.55

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