Journal of Engineering and Applied Sciences

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Behavior of Hybrid Composite Structure Under Low Impact Velocity

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Key words: Fiber metal laminate, aluminum, woven glass, Kevlar fabric, quasi-static indentation, drop weight test

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Page No.: 2772-2780
Volume: 15, Issue 14, 2020
ISSN: 1816-949x
Journal of Engineering and Applied Sciences

Abstract: FMLs represent a significant evolution in airframe material technology. In the present study, two different types of FMLs (aluminum/reinforced fiberglass and aluminum/reinforced Kevlar) are manufactured and investigated. FMLs specimens were prepared using hand layup process with Vacuum Assisted Process (VAP). Physical properties of the constituents have been determined. The current work is focused on the low velocity impact properties of FMLs material and their fracture mechanics. Quasi-static indentation test for the same impact test condition was carried out to make the preliminary prediction for failure energy levels. The experimental results demonstrate higher impact resistance of FML comprising fiberglass than that including Kevlar fibers. FMLs having Kevlar composite laminate exhibited good impact resistance compared to the their resistance to the quasi-static indentation. Failure modes were analyzed and discussed.

INTRODUCTION

Composites are with complex internal structures combine the best aspects of dissimilar constituents[1, 2]. Polymer-matrix composites are much easier to fabricate than metal-matrix[3]. Fiber Metal Laminates (FMLs) represent a relatively new type of hybrid material, based on arrangements of plies of fiber reinforced composite material and thin aluminum alloy sheets[4, 5]. The superior fatigue and fracture characteristics associated with fiber-reinforced composite materials, combined with the durability offered by many metals[4, 6-10]. A common high-performance FMLs types are ARALL (Aramid fiber Reinforced epoxy/Aluminum) and GLARE (Glass fiber Reinforced Epoxy/Aluminum). These kinds of FMLs are attracting the interest of a number of end-users including the aerospace industry[4]. The first product developed was aramid fiber-reinforced Al laminate (ARALL) and the second was glass fiber-reinforced Al laminate (GLARE)[6]. Some FMLs applications have been fully evaluated and can be accurately judged such as stringers, frames, firewalls, bulkheads, fuselage skin, upper and lower wing skins, floors in passenger and cargo areas, cargo barriers[9]. ARALL has been also developed for the lower wing skin panels of the former Fokker 27 aircraft and the cargo door of the Boeing C-17. ARALL also was selected in production and flight test on the C-17 cargo doors and GLARE is selected for the Boeing 777 impact resistant bulk cargo floor[10]. An aircraft structure should be able to tolerate a certain amount of impact energy and damage, dependent on the probability of impact and location[9]. Fiber reinforced composite structures are restricted in their ability to deform plastically. The kinetic impact energy is dissipated through, interlaminar shear deformations, flexure, fracture and delamination of the laminate results in strength and stiffness reduction[11]. A composite material's response to impact is much different than that of a metal. Low and intermediate impact energies are absorbed by the metallic structures through elastic and plastic deformation results as a small effect on the load carrying capacity. Botelho *et al*.[12, 13] have demonstrated that FMLs possess superior impact resistance compared to the conventional Fiber-Reinforced composite laminates (FRPs). Low velocity impact (<11 $msec^{-1}$) occurs through damage form. Such damage arises from service trucks, cargo containers impact and also from dropped tools during maintenance operations[9]. Impact testing remains important as new FMLs continue to replace monolithic aluminum in impact-sensitive airframe structures[5]. Many investigations have been conducted on the low velocity impact behavior of the FMLs. Laliberte[5] carried out an investigation of the of low-velocity impact damage in FMLs, 67 J was the maximum absorbed energy by the studied certain GLARE type. Cicco *et al*.[7] when they studied the impact damage response of Mg-fiberglass FMLs, 70 J was the maximum energy absorbed by the FMLs at full perforation. Mendibil *et al*.[4] investigated FMLs of (Al-fiberglass) and showed that the fiber brakeage starts at 42 J impact energy and the failure is extended to all the composite layers and the puncture has occurred at 80 J. On the other hand Mendibil *et al*.[4], proved that from the failure mode that the first cracking in the outer aluminum layer appears before the fiber breakage. Also Vlot *et al*.[14-16] carried out low impact test on GLARE and observed from the cross-section of impacted zone that fiber cracking in the composite ply did not start without cracking in the outer aluminum layers. Fan *et al*.[8] studied the impact resistance of FMLs from series of glass fiber reinforced epoxy/aluminum alloy fiber metal laminates. They concluded failure modes include; fracture and plastic deformation of the metal layers, delamination between the composite and metal layers and fiber fracture. Volt[16] when studied the effect of the strain rate on the FML materials, concluded that; 18, 37 and 95 J of energy were the values required to cause the first crack in the GLAAR-3 at different strain rates; quasi-static, 10 and 100 $msec^{-1}$, respectively. In addition, Volt[16] proved that, ALLAR with its Kevlar fiber laminate has less indentation resistance under impact load than GLAAR's with its fiber glass laminate.

In the current study, two different types of FMLs will be manufactured and investigated. The study is focused on the low velocity impact properties of FMLs material and the relevant fracture mechanics. FMLs specimens are planned to be manufactured using hand layup process with (Vacuum Assisted Process) VAP. The metallic surface layers will be pre-treated using special chemical processes in order to improve the bond between the adhesive system and the metal surface. This manufacturing method could lead FMLs to represent a strong competitor in automotive industry as an efficient and low cost process. In order to qualify the manufacturing method, characterization of these two types of FMLs will be carried out. The characterization includes determination of material physical constituents properties. The low velocity impact test will be conducted to evaluate the FMLs impact resistance. The quasi-static indentation test for the same impact test condition will be carried out to make the preliminary prediction for failure energy levels. Fracture mechanics of the tested samples will be discussed. In order to make impact test, a drop weight test rig will be designed and manufactured to meet the standards.

MATERIALS AND METHODS

Experimental work

Material and specimens preparation: The parent materials used in samples manufacturing are aluminum metal sheet, woven fiberglass and woven Kevlar fibers. The manufacturing method includes three stages; sheets cutting and surface treatment, lamination and curing and specimens cutting and preparation. In the first stage, each type of fibers and aluminum sheets were cutting to be 500×500 mm for each layer. The surface treatment of aluminum process is one of the main processes and key factors for manufacturing FMLs. This process is followed first stage, it has done in order to prepare the grains of metal surface for bonding process and to enhance the quality of adhesion between FML's layers. Electrochemical anodizing process with sulfuric acid H_2SO_4 as DC anodizing method is selected in the current research for preparing the experimental specimens. This operation is followed by sealing operation in potassium bichromate bath to increase the corrosion resistance of final parts. The technical requirements are followed according to Cotell *et al*.[17-19]. The material data and lamination process of the FML samples according to the designation and the stacking sequence which shown in Table 1 has been stated before by Elhabak *et al*.[20]. Five specimens from each of FMLs type with 100×100 mm were cut and prepared for each test. Specimens specifications has been determined and tabulated as shown in Table 2.

Testing procedures: Two tests have been carried out for studying the FML indentation resistance using the quasi-static indentation test and drop weight impact test.

Quasi-static indentation test: Quasi-static indentation test was carried out on the Amsler universal testing machine. The sample was clamped on a special fixture as the same as designed one in drop weight test rig. The fixture is as shown in Fig. 1a. The typical preparations for testing fixture and testing machine is shown in Fig. 1b.

Dynamic test (drop weight impact test): Drop weight (low velocity) impact test is carried out on a special manufactured test rig. Typical experimental setup is

Table 1: Experimental specimen's types, symbols, matrix types and stacking sequences

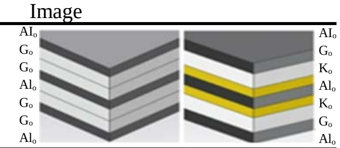
Composite type	Symbol	Matrixx type	Stacking sequence	Image
FML	FML-1	Epoxy	$[Al_0/G_0/G_0/Al_0/G_0/G_0/Al_0]$	
	FML-2		$[Al_0/G_0/K_0/Al_0/K_0/G_0/Al_0]$	

Table 2: Specification of manufactured specimens

				Fibers volume fraction V_f (%)		
Type	Total thickness (mm)	V_{Al}(%)	V_m(%)	V_G (%)	V_K (%)	ρ_{total} (gcm^{-3})
FML-1	3.58	33.5	48.0	18.5	-	1.972
FML-2	3.06	39.2	41.2	10.6	9	1.976

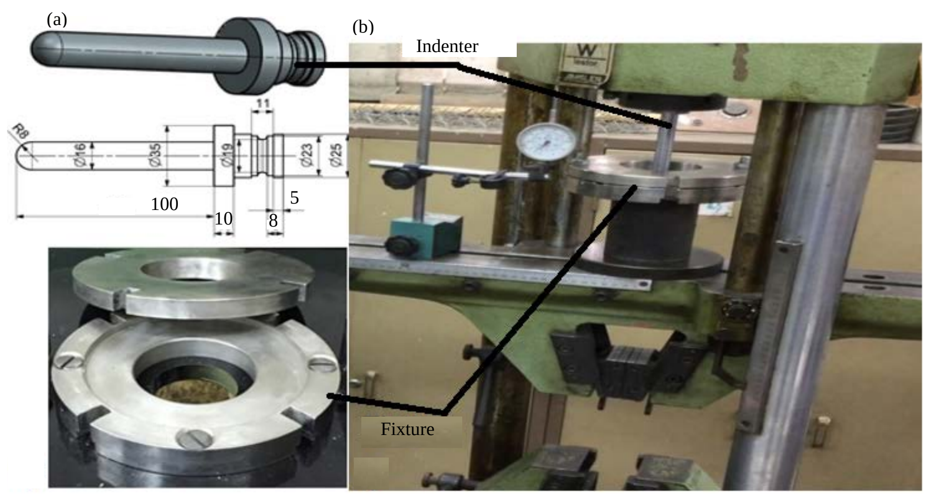


Fig. 1(a, b): Fixture and indenter (a) and Fixture positioning in the quasi-static test (b)

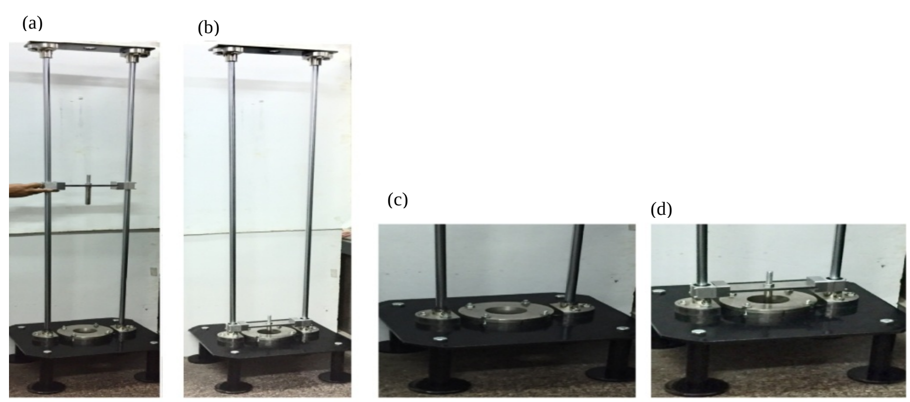


Fig. 2(a-d): Typical experimental setup, (a) and (c) show adaptation of desired energy by adjusting the load with defined height, (b) and (d) after releasing load on specimen (the depth of indentation)

shown in Fig. 2 showing adaptation of desired energy by adjusting the load with defined height and releasing load on specimen. A test rig was designed and fabricated for this purpose. The low velocity impact test is carried out according to ASTM D5628-10 and ASTM D 5420-16. Fixation also is as the same in the (QSI). For each specimen, the input start load was the equivalent first failure energy from quasi-static test results with +10% for strain rate effect. The specimen after test was measured for plastic deformation if it is exist. Then the second specimen was tested with another +10% or till the plastic deformation appeared. Then the third specimen was tested with another +10% or till the complete puncture appeared. The indentation depth of the examined samples by quasi-static indentation test were recorded against the applied force during the test. While the samples of drop weight impact test were cut into two similar halves at the center of the impacted zone to measure the depth of indentation.

RESULTS AND DISCUSSION

Generally, the variation of properties between FML-1 and FML-2 is governed by many factors; volume fraction of; fibers, epoxy resin and aluminum metal and either the fiber's characteristics. The results of quasi-static and impact tests will be discussed in the following sections.

Quasi-static indentation test results: The quasi-static indentation test was carried out to predict the impact energy required to cause perforation at the FMLs materials. The results of quasi-static indentation test are graphed in Fig. 3 for the force-indentation depth relationship. Comparison between FML-1 and FML-2 in quasi-static indentation test shows the first failure force and the maximum failure force of FML1 is equal 3 times and 4.73 times of those of FML-2, respectively. Since, the stiffness equal 1240.5 and 263.8 N mm^{-1} for FML-1 and FML-2, respectively, the stiffness of FML-1 is equal 4.7 times of FML-2. The first failure deformation and the total failure deformation of FML-1 equals 0.58 times and 0.93 times of FML-2 type's, respectively. The maximum force is 8340 N for FML-1 and is 1765 N for FML-2 while they have the maximum indentation depth values 7.9 and 7.5 mm, respectively (close values). In addition, the total failure test energy of FML-1(68.5 J) is equal 5 times of FML-2 value's (13.5 J). The finding in this concern is the FML-1 quasi-static indentation properties with its G/G insert laminates are better than FML-2 properties with its G/K insert laminates. This maybe attributes to occurring, so much delamination between Kevlar fibers and epoxy resin when there is enough span of time. Which it is associated with the quasi-static indentation with its low strain rate.

Fracture modes of quasi-static indentation test: The observation during testing shows the first failure in quasi-static indentation test for FML-1 (Fig. 4a) began as a failure in aluminum outer layer. The first failure for FML-2 started as a delamination failure around Kevlar laminates followed by failure in aluminum layers, glass fibers and Kevlar fibers (Fig. 4b).

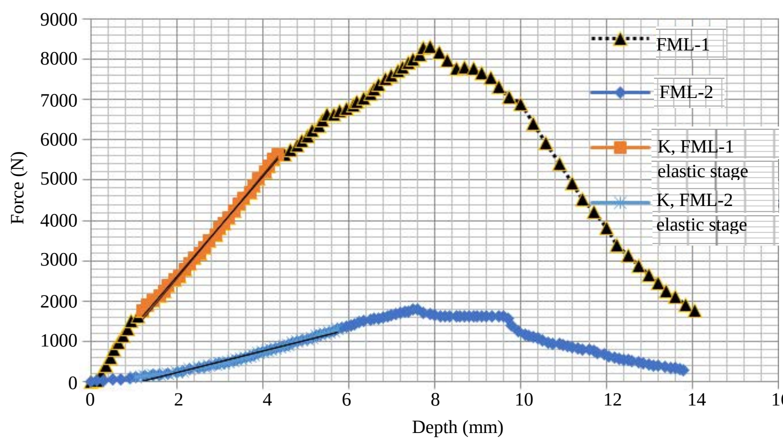


Fig. 3: Comparison results of force-deflection curves of FMLs specimens

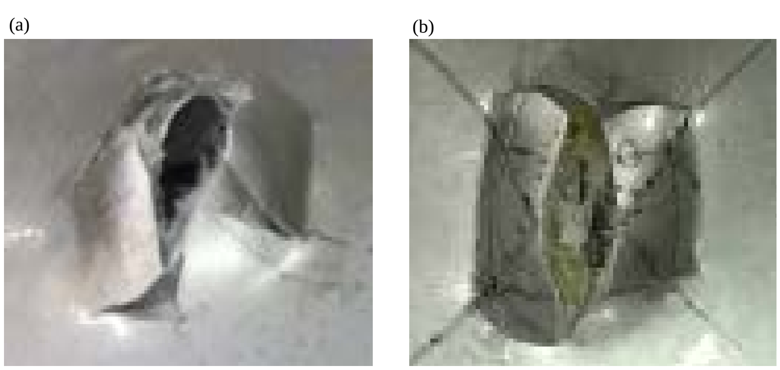


Fig. 4(a, b): FMLs, specimen after quasi-static test, (a) FML-1 and (b) FML-2

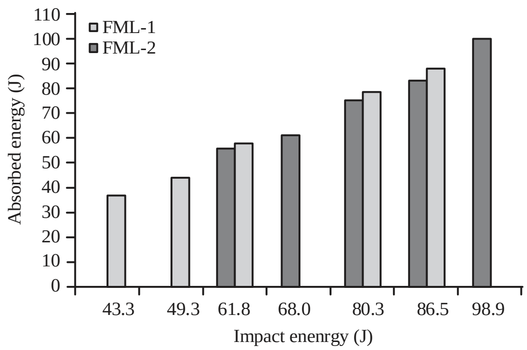


Fig. 5: FMLs, absorbed energy against the impact energy

Low velocity drop weight impact results: With the aid of the quasi-static indentation test, the energy values were predicted in drop impact test. A mass of 6.3 kg is selected to drop both FML types from different height levels. Five specimens of both of FML-1 and FML-2 were required for this test. The last specimen (fifth) of both of FML-1 and FML-2 reached its maximum absorbed energy which is almost equal to the associated impact energy. Figure 5 includes the chart of the impact energy values and associated absorbed values. The FML-1 samples were dropped from levels; 100, 110, 130, 140 and 160 cm height. FML-1, sample 1 was dropped with starting energy of 60.3 J and the last sample (fifth sample) was dropped with 98.9 J in which the absorbed energy was the whole impact energy (98.9 J). Figure 5 implies the absorbed energy percentage out of the impact energy increases as the impact energy increases. Whereas 90% (55.3 J) was the absorbed energy by the first sample, out of 61.8 J impact energy. Similarly, the absorbed energy percentage increases at the other levels till reaching 100% of impact energy at 98.9 J. The same behavior is achieved for FML-2 samples. In this case the drop weight levels are different; 70, 80, 100, 130 and 140 cm height. Also, it is clear that at the same impact energy, the FML-1 type absorbs less amount of energy than that absorbed by FML-2.

Discussing the indentation depth arises from the drop weight impact is essential in this study, Fig. 6 displays the indentation depth versus the impact energy. Normally, the indentation depth increases with increasing in the impact energy values for both FML-1 and FML-2. Obviously, the less indentation is caused in the FML-1 than in the FML-2 at the same impact energy.

Concerning the velocity of weight dropping, the velocity increase as the height level of dropping increase (constant weight = 6.3 kg). The results of velocity-indentation are graphed in Fig. 7, an increase in indentation occurred in both FML types with an increase in the impact velocity. An important result could be revealed, it is to cause the same indentation depth, a higher velocity and concequantley more impact energy is required in the case of FML-1 type. For example, to cause

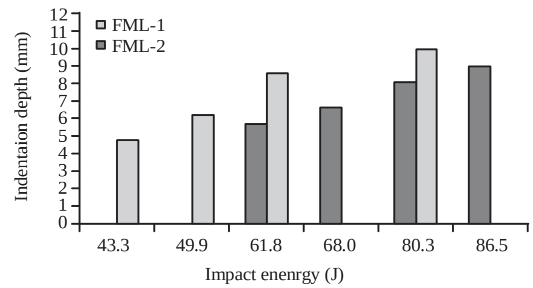


Fig. 6: FMLs, relationship between indentation depth and impact energy

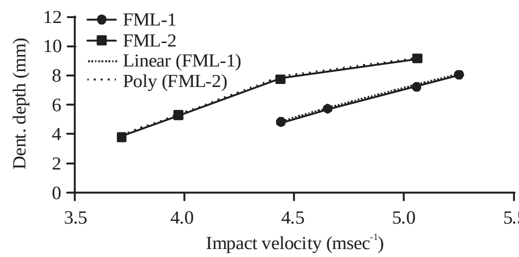


Fig. 7: FMLs, indentation depth versus the impact velocity

9 mm indentation distance, it needs striking velocity of 5.25 m sec^{-1} in FML-1 case while it needs 4.5 m sec^{-1} in case of FML-2, this with constant mass (6.3 kg). Thus, the resistance to impact of FML-1 is more than the FML-2 impact resistance, this confirms the results in Fig. 5. On the other hand, the velocity-indentation relation is almost linear in FML-1 with positive slop (+0.2508) while it is a curve profile with a polynomial equation of negative slop (-0.2.139 in FML-2). This implies, to cause more indentation depth in FML-2, the velocity should increases but with decreasing rate. Also, the results of FML-2 prove its good impact resistance at higher strain rate.

Comparing the impact results of the current study to the relevant investigations in this concern, the literature results above of reference Mendibil *et al*.[4, 5, 7] could be by recalled.

Fracture analysis of low impact velocity test for FMLs types: The images of the magnified fracture zones are displayed in Fig. 8 individually. From Fig. 8, the sample dropped with 61.3 J impact energy underwent longitudinal cut in the aluminum sheet and at the fiberglass in the back surface (tension side). While smaller damage in the front side as it in the crack form in the aluminum sheet. The same fracture modes are induced in the back surface (back aluminum sheet) of samples; 68 and 80.3 J but with more crack opening in its original direction (longitudinal). Also, a transverse crack initiation branched from the back longitudinal crack, in addition, longitudinal cut in front the aluminum sheet. On the other hand, the side view of cut samples proves that the internal fiberglass laminate

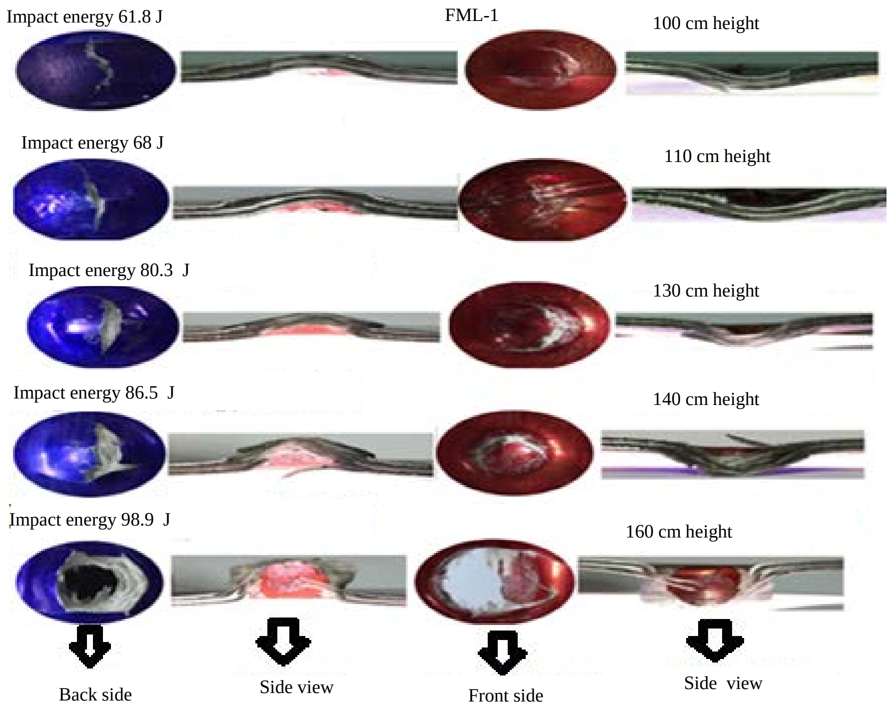


Fig. 8: FML-1, magnified scale of fracture surface due to drop weight impact test

may underwent delamination from the epoxy while did not undergo a cut till 80.3 J impact energy. The 86 J sample began suffering internal fiberglass cutting at 86 J and more cut in these fibers happened at 98.9 J sample. The whole layers failed at last sample (98.9 J) and the fracture mode obviously is localized in a circular region.

Concerning the FML-2 type, Fig. 9 displays the fracture images. Sample one (43.3 J) reveals a longitudinal crack in the aluminum sheet in the back surface (tension side) while no cut in the fibers in both front and back surfaces but a little damaged points at the aluminum front sheet. In the 49.4 J-sample, fractures show spread cracks in radial directions around the specimen center (indenter contact area). This in the back aluminum surface and in the central aluminum sheets while no cut in the fibers. The 61.8 J sample underwent enlarged fracture in the back and front aluminum sheets and in the internal aluminum sheet as well. In addition, fiberglass has been cut which is clear at from side view of the sample. The last two samples (80.3 and 86 J) have severe fractures in the their layers while a rest of Kevlar fibers retain some of their continuity till 80.3 J but they are cut entirely at 86 J.

Generally, the inspection of cross-sections of the perforated FMLs demonstrated failure modes including fracture and plastic deformation of the metal layers, delamination between the composite and metal layers and fiber fracture, the same modes was evidenced by Fan *et al*.[8]. Also in the current investigation. It was observed from the cross-section of impacted zone that fiber cracking in the composite ply did not start without cracking in the outer aluminum layers, this was confirmed by the observation of Vlot *et al*.[14-16]. In the current work, both FMLs types always underwent more damage int tension sides (back surface) than in the compression side (front surface). Obviously, the same value of energy induced less damage in FML-1 than that in FML-2 type which it confirms and enhances the experimental results collected from the impact test. Two example for this finding could be understanding by comparing images of Fig. 8 and 9 for the same energy values. The first example, is comparing the 80.3 J sample fracture surface of FML-1 in Figure 8 to that of FML-2 in Fig. 9. As well, comparing the 86.5 J samples of both FML-1 and FML-2 is the second example. The comparison reveals the FML-1 fracture mode is another prove for its high impact resistance. Another finding from the fracture mechanism of FML samples is that, no delamination away from the indentation area in the whole material layers of aluminum and fibers after subjected to the drop weight impact test. Whereas only localized damaged region were fractured even after undergoing the puncture. This evidenced a strong bonding between layers and good manufacturing of FML materials with their different types. Comparing the current results to the references is useful. In the current study it is proved that the fracture mode of FMLs is metal dominated as the first cracking in the outer aluminum layer which agrees with Mendibil *et al*.[4] investigation.

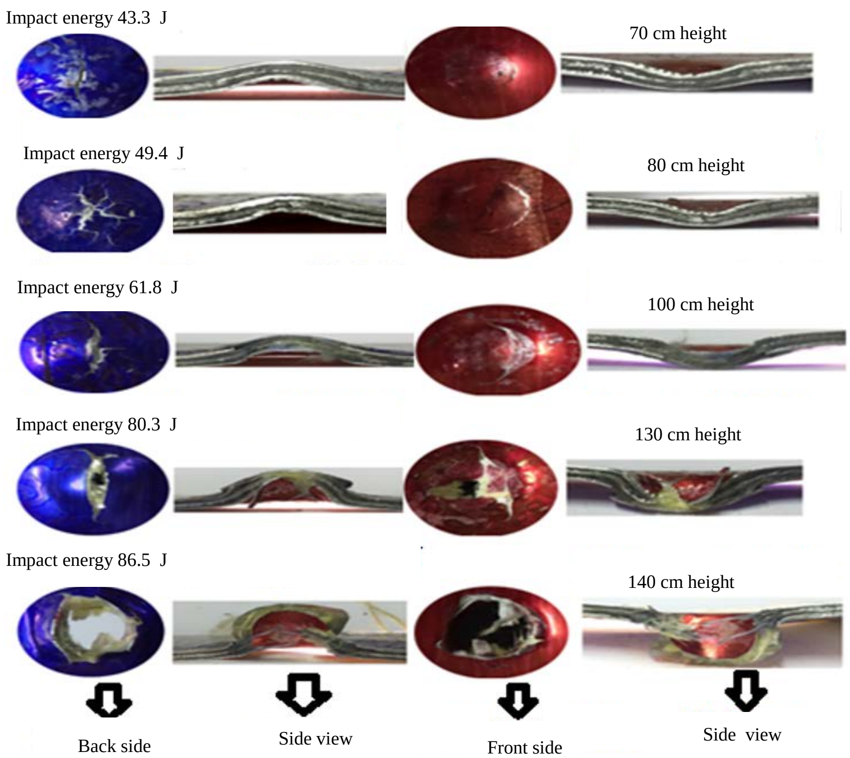


Fig. 9: FML-2, magnified scale of fracture surface due to drop weight impact test

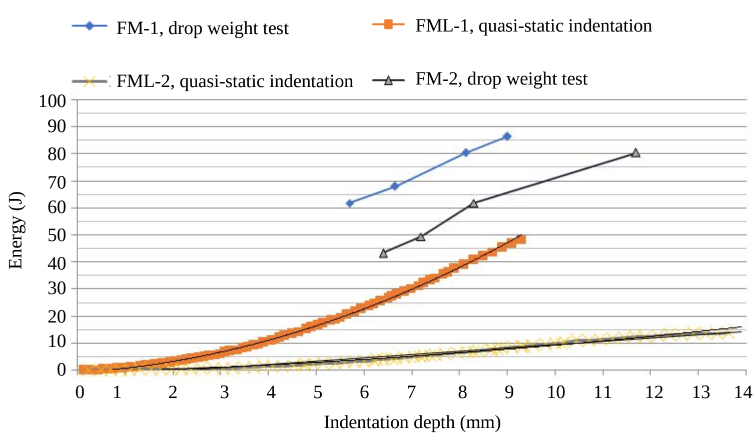


Fig. 10: FMLs, comparison between the quasi-static indentation test and drop weight impact test

Low impact velocity versus quasi-static indentation test: Studying the strain rate effect on the FML types could be with the aid of chart in Fig. 10. The relationship is proportional between the indentation depth and the energy at all conditions (impact and quasi-static) for both FMLs types but the increasing rate is so, far different. The slops of all relationships in Fig. 10 reveal higher increasing rates of energy in dynamic than in quasi-static. Generally, FMLs demonstrated more levels of energy are required to cause sample crack in the high strain rate condition (dynamic impact load) than those energies in low strain rate (quasi-static load) condition. Apart from the impact behavior of the FML types, the values of the impact energy compared to the quasi-static indentation should be highlighted. Figure 10 implies the impact energy values are about the double values of the quasi-static indentation at the same indentation distance for FML-1 type. For the other type (FML-2), the energy level of the impact is extremely higher than that in quasi-static at a similar indentation distance. For example, at 9 indentation distance, the energy of impact is 65 J while in the quasi-static is 10 J only. As 10 times or more of static energy are required to cause the same indentation in case of dynamic in such FML with its glass/Kevlar laminates. Thus, the strain rate has significant effect on the FML-1 type while it has a very strong effect on the FML-2 material. Therefore, FML-2 impact properties proves high resistance to indentation at higher strain rate. Seemingly, the not enough time in the impact test to cause, so, much delamination between Kevlar and epoxy resin leads to the good resistance of FML-2 at high strain rate. On the other hand, FML-1 with its glass fiber laminates demonstrates greater resistance to both of quasi-static indentation and drop weight impact than the FML-2 resistance. The experimental results agree with Volt[16] conclusions (above in introduction section).

CONCLUSION

Comparison between FML-1 and FML-2 in quasi-static indentation test shows that the first failure force and the maximum failure force of FML1 is equal 3 times and 4.73 times of those of FML-2, respectively. Also, the stiffness of FML-1 is equal 4.42 times of FML-2. In addition to, the first failure energy of FML-1 equals 1.87 times of FML2 and its failure energy at maximum force is 4 times of FML-2 types. Moreover, the total failure test energy of FML-1 is equal 5 times of FML-2.

Good prediction between the energy values in the quasit-static indentation and the equivalent values in thedrop weight impact test has been verified only in the case of FML-1 while it was a large deviation in the case of FML-2.

FML-1 proves greater resistance to both of quasi-static indentation and drop weight impact than the FML-2 resistance, perhaps it refers to the stronger bonding between G/G laminates in FML-1 than that in the G/K laminates in FML-2. On the other hand, the FML-2 has a very high resistance to the drop weight impact compared with the quasi-static indentation. Therefore, better FML-2 properties in drop impact proves high resistance to indentation at higher strain rate. Thus, the not enough time in imact test to cause, so, much delamination between Kevlar and epoxy resin leads to a good resistance of FML-2 at high strain rate.

Both FML types always underwent more damage int tension sides (back surface) than in the compression side (front surface) when subjected to the impact stress. On the other hand, the fracture mechanism obviously demonstrated less damage induced by the same value of energy in FML-1 than that in FML-2 type. This confirms and enhances the experimental results collected from the impact test.

The fracture mechanism of FML samples proves no delamination a way from the indentation area in the whole material layers of aluminum and fibers after subjected to the drop weight impact test. Whereas only localized damaged region are fractured even after the puncture. This evidenced a strong bonding between layers and good manufacturing of FML materials with their different types

REFERENCES

01. Chawla, K.K., 2012. Composite Materials: Science and Engineering. 3rd Edn., Springer, New York, USA., ISBN: 978-0-387-74365-3, Pages: 542.
02. Chung, D.D.L., 2010. Composite Materials: Science and Applications. 2nd Edn., Springer, London, ISBN: 978-1-84882-831-5, Pages: 371.
03. Kar, K.K., 2017. Composite Materials: Processing, Applications, Characterizations. Springer, Berlin, Germany, ISBN: 978-3-662-49512-4, Pages: 686.
04. Mendibil, I.O.D., L. Aretxabaleta, M. Sarrionandia, M. Mateos and J. Aurrekoetxea, 2016. Impact behaviour of glass fibre-reinforced epoxy/Aluminium fibre metal laminate manufactured by vacuum assisted resin transfer moulding. Compos. Struct., 140: 118-124.
05. Laliberte, J.F., 2002. Investigation of low-velocity impact damage in fibre-metal-laminates. Ph.D. Thesis, Carleton University, Ottawa, Ontario.
06. Yi, X.S., S. Du and L. Zhang, 2018. Composite Materials Engineering. Vol. 1, Springer, Singapore, ISBN: 978-981-10-5696-3, Pages: 765.
07. Cicco, D.D., Z. Asaee and F. Taheri, 2017. Low-velocity impact damage response of fiberglass/magnesium fiber-metal laminates under different size and shape impactors. Mech. Adv. Mater. Struct., 24: 545-555.
08. Fan, J., W.J. Cantwell and Z.W. Guan, 2011. The low-velocity impact response of fiber-metal laminates. J. Reinf. Plast. Compo., 30: 26-35.
09. Vlot, A. and J.W. Gunnink, 2001. Fibre Metal Laminates: An Introduction. Springer, Dordrecht, Netherlands, ISBN: 9781402000386, Pages: 527.
10. Sinmazcelik, T., E. Avcu, M.O. Bora and O. Coban, 2011. A review: Fibre metal laminates, background, bonding types and applied test methods. Mater. Des., 32: 3671-3685.
11. Snoo, R.H.D., 2015. Assessing composite and fibre metal laminate materials for automotive applications through impact and quasi-static indentation testing. M.Sc. Thesis, Carleton University, Ottawa, Ontario.
12. Botelho, E.C., R.S. Almeida, L.C. Pardini and M.C. Rezende, 2007. Elastic properties of hygrothermally conditioned glare laminate. Int. J. Eng. Sci., 45: 163-172.

13. Vlot, A. and M. Krull, 1997. Impact damage resistance of various fibre metal laminates. J. Phys., 7: C3-1045-C3-1050.
14. Vlot, A., E. Kroon and G. LaRocca, 1998. Impact response & dynamic failure of composites & laminate materials. Key Eng. Mater., 141: 235-276.
15. Vlot, A., 1991. Low velocity impact loading on fiber reinforced aluminum laminates (ARALL and GLARE) and other aircraft sheet materials. Ph.D. Thesis, Delft University of Technology (TU Delft), Delft, Netherlands.
16. Vlot, A., 1993. Impact properties of fibre metal laminates. Compos. Eng., 3: 911-927.
17. Cotell, C.M., J.A. Sprague and F.A. Smidt Jr, 1994. ASM Handbook, Surface Engineering. Vol. 5, ASM International, Ohio, USA., ISBN: 9780871703842, Pages: 1039.
18. ASTM., 2010. STM D3933-98(2010): Standard guide for preparation of aluminum surfaces for structural adhesives bonding (Phosphoric acid anodizing). ASTM International West Conshohocken, Pennsylvania, USA. https://www.astm.org/DATABASE.CART/HISTORICAL/D3933-98R10.htm
19. ASTM., 2016. ASTM D2651-01(2016): Standard guide for preparation of metal surfaces for adhesive bonding. ASTM International West Conshohocken, Pennsylvania, USA. https://www.techstreet.com/standards/astm-d2651-01-2016?product_id=1916303
20. Elhabak, A.A., M. Shazly, T.A. Osman and A.A. Khattab, 2019. Experimental and numerical behavior of plain hybrid fiber metal laminate composites. J. Eng. Applied Sci., 14: 8874-8882.