This is the accepted manuscript (postprint) of the following article:
Sisan, M. M., & Eslami-Farsani, R. (2019). An experimental study on impact resistance of different layup configuration of fiber metal laminates. Fibers and Polymers, 20(10), 2200-2206.
https://doi.org/10.1007/s12221-019-7108-z

An Experimental Study on Impact Resistance of Different Layup Configuration of Fiber Metal Laminates

Mohsen Mirzaee Sisan, Reza Eslami-Farsani*

Faculty of Materials Science and Engineering, K. N. Toosi University of Technology, Tehran, Iran

* Corresponding author: eslami@kntu.ac.ir

Abstract

Fiber metal laminates (FMLs) are composed of thin metal sheets and fiber-reinforced composite layers. Compared to monolithic aluminum alloys, FMLs combine lower density, higher fatigue resistance, and improved damage tolerance. The present study aimed to investigate the low-velocity impact induced by drop-weight instrument and the tensile strength on various lay-up configurations of FMLs fabricated. FML samples were composed of two layers of aluminum 2024-T3 and two layers of epoxy resin, which were reinforced with carbon fabric, glass fabric, and Kevlar fabric made in pairs. In addition, another type of FMLs was developed with carbon/Kevlar fabric under the same circumstances. Force-time histories of impact forces were recorded, and the damaged specimens were inspected using optical microscopy in terms of the impact side, non-impact side, and cross-sectional side. Experimental results indicated that the maximum impact force corresponded to the FMLs that were composed of Kevlar fabric on the impact side and glass fabric on the non-impact side. In addition, the highest tensile strength and Young's modulus among FMLs belonged to FML with Kevlar fabric and glass fabric.

Keywords: Fiber metal laminate, Carbon fibers, Kevlar fibers, Glass fibers, Drop-weight impact

This is the accepted manuscript (postprint) of the following article:
Sisan, M. M., & Eslami-Farsani, R. (2019). An experimental study on impact resistance of different layup configuration of fiber metal laminates. Fibers and Polymers, 20(10), 2200-2206.
https://doi.org/10.1007/s12221-019-7108-z

1- Introduction

Fiber metal laminates (FMLs) are composed of alternative stacked metal and fiber-reinforced adhesive layers. FMLs combine the high fracture properties and fatigue associated with fiber-reinforced composite materials with the plastic behavior and durability of metals [1, 2].

There are three types of commercial FMLs, including the aramid reinforced aluminum laminates (ARALL), glass laminate aluminum reinforced epoxy (GLARE), and carbon fiber-reinforced aluminum laminates (CARALL). ARALL was introduced in 1978 by the Faculty of Aerospace Engineering at Delft University of Technology in the Netherlands. GLARE was first developed for aeronautical applications as an improvement for ARALL using advanced glass fibers and was introduced in 1990 at Delft University of Technology [3-7].

Borgonje and Ypma [8] investigated the long-term behavior of aluminum-glass fiber epoxy laminates, observing that the performance of hybrid laminates is better than monolithic aluminum in terms of corrosion. Furthermore, they reported that thin aluminum alloy sheets have better corrosion resistance when used in hybrid laminates compared to the sheets of conventional thickness.

Reyes and Kang [9] investigated the mechanical behavior of thermoplastic glass-fiber reinforced polypropylene composite and aluminum alloy hybrid laminates, reporting that these composites have excellent forming properties similar to that of the monolithic aluminum alloy of comparable thickness. On the other hand, Vlot [10] investigated the high- and low-velocity impact on aluminum-glass fiber epoxy laminates, aluminum-Kevlar fiber epoxy laminates, and aluminum-carbon fiber epoxy laminates. According to the findings, the energy required to create the first crack in the outer aluminum layer on the non-impacted side was higher in glass-fiber laminates compared to carbon and Kevlar fibers. Moreover, the dent

This is the accepted manuscript (postprint) of the following article:
Sisan, M. M., & Eslami-Farsani, R. (2019). An experimental study on impact resistance of different layup configuration of fiber metal laminates. Fibers and Polymers, 20(10), 2200-2206.
https://doi.org/10.1007/s12221-019-7108-z

depth of the hybrid laminates was observed to be relatively equal to that of the monolithic aluminum alloy, and the damage area after the impact was considerably lower compared to plain glass-fiber reinforced polymers and carbon fiber-reinforced polymer laminates.

The present study aimed to develop a preliminary understanding of the damages caused by low-velocity drop-weight impact on various fibers-reinforced sequences. Glass, Kevlar and carbon fabrics were used in various sequences with 2024-T3 aluminum sheets. The sequences were investigated to evaluate the effects of the layers on low-velocity impact. In addition, the force-time curve and optical imaging for the non-impact side, impact side, and cross-sections of the specimens were used to assess the impact damages. Furthermore, tensile test was used to measure tensile strength and Young's modulus for the FMLs.

2- Experimental

In the present study, the FML panels were composed of 2024-T3 aluminum with a thickness of 0.2 mm per layer, 5225 epoxy resin hardener, and various reinforcing fabrics, including carbon, glass, Kevlar, and Kevlar-carbon fabrics. Configuration of the FML panels and the typical properties of the fabrics are presented in Tables 1 and 2, respectively. The FMLs were produced using a hand lay-up process. Sheets of Al2024-T3 were surface modified mechanically to allow proper bonding between the sheets and the epoxy resin layer. A 100 mm sandpaper applied at a 45 degree angle was used for the surface modification. For hand lay-up process, a 5 bar pressure was applied during curing.

This is the accepted manuscript (postprint) of the following article:
Sisan, M. M., & Eslami-Farsani, R. (2019). An experimental study on impact resistance of different layup configuration of fiber metal laminates. Fibers and Polymers, 20(10), 2200-2206.
https://doi.org/10.1007/s12221-019-7108-z

Table 1. Lay-up configurations of fiber metal laminates

FML Type*	Lay-up Configuration
FML-KC	Al 2024-T3/Epoxy Resin-Kevlar Fabric/Epoxy Resin-Carbon Fabric/Al 2024-T3
FML-CK	Al 2024-T3/Epoxy Resin-Carbon Fabric/Epoxy Resin-Kevlar Fabric/Al 2024-T3
FML-CG	Al 2024-T3/Epoxy Resin-Carbon Fabric/Epoxy Resin-Glass Fabric/Al 2024-T3
FML-GC	Al 2024-T3/Epoxy Resin-Glass Fabric/Epoxy Resin-Carbon Fabric/Al 2024-T3
FML-KG	Al 2024-T3/Epoxy Resin-Kevlar Fabric/Epoxy Resin-Glass Fabric/Al 2024-T3
FML-GK	Al 2024-T3/Epoxy Resin-Glass Fabric/Epoxy Resin-Kevlar Fabric/Al 2024-T3
FML-CKH	Al 2024-T3/Epoxy Resin-Carbon-Kevlar Hybrid Fabric/Epoxy Resin-Carbon-Kevlar Hybrid Fabric/Al 2024-T3

*C: carbon fabric; G: glass fabric; K: Kevlar fabric; CKH: carbon/Kevlar hybrid fabric

Table 2. Specifications of fabrics

Specification	Glass Fabric	Kevlar Fabric	Carbon Fabric	Carbon/Kevlar Fabrics
Fiber Type	-	-	3k	3k
Weave Type	Plain	Plain	Plain	Twill 2×2
Surface Density (g/m^2)	588	75	200	220

Low-velocity impact tests were performed in accordance with the ASTM D7136 standards [11, 12] using a four-gripper clamp. The produced FML samples were cut into square panels with dimensions of 80×80 mm^2 for the low-velocity impact tests. The specimens were tested using an impactor with a hemispherical steel head (diameter: 12.7 millimeters) and total weight of 9.5 kilograms dropped from a 470-millimeter height.

After the impact tests, the specimens were carefully removed from the fixture for optical imaging analysis. Measurement process of the post-impact permanent central deflection is illustrated in Figure 1. Delamination was detected using cross-sectional imaging, and the damage area for each specimen was measured by an image processing code in MATLAB software.

This is the accepted manuscript (postprint) of the following article:
Sisan, M. M., & Eslami-Farsani, R. (2019). An experimental study on impact resistance of different layup configuration of fiber metal laminates. Fibers and Polymers, 20(10), 2200-2206.
https://doi.org/10.1007/s12221-019-7108-z

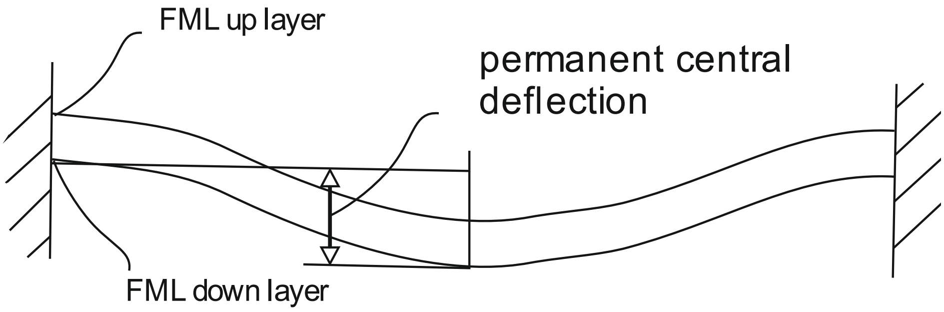

Figure 1. Measurement of permanent central deflection.

In this study, the SANTAM universal testing machine (STM 150) was used at a rate of 2.5 mm/min for tensile test. Samples were cut in the dimensions of 250×25 mm^2 in accordance with ASTMD3039 standard [13, 14].

3- Results and Discussion

Several parameters could affect the impact response and damage patterns of FMLs in low-velocity impact testing, such as the laminate thickness, fiber orientation, temperature, and different indenters [15, 16]. In the current research, the effects of various lay-up configurations on the impact and tensile properties of FMLs were investigated. Materials used for various configurations included Kevlar, carbon, glass, and Kevlar-carbon hybrid fibers.

3-1- Comparison of FML-CK and FML-KC

Figure 2 shows the load versus time responses of the FML-CK and FML-KC specimens with equal fiber volume fraction and impact energy (43 J). The fluctuations observed in the measured force-time curves were not only caused by the amplification system noise, but also by other sources such as the vibrations of the specimen and impactor [1, 17].

The maximum force implies the maximum composite endurance against the drop-weight impact [18]. The mentioned FMLs had identical behavior until reaching the maximum force.

The maximum impact force for the FML-KC was estimated to be higher by 840 N compared to that of the FML-CK. Therefore, it could be inferred that the FML-KC required more energy than FML-CK in order to achieve its maximum impact force during the low-velocity impact.

Post-impact optical images of the resultant damage patterns on the impact and non-impact sides are depicted in Figure 3. The cross-sectional fractographs of the FML-KC and FML-CK are shown in Figure 4. As can be seen in Figures 3 and 4, damage modes such as fiber and matrix breakage and penetration occurred in both FMLs.

According to the findings, the back faces of the FMLs experienced larger plastic deformation compared to their front faces since the layers in the front faces were supported by the back layers and could absorb most of the impact energy. Delamination in the FML-CK occurred between the carbon layers and aluminum sheets. However, no obvious delamination was observed in the FML-KC (Figure 4). Therefore, it could be argued that when carbon fabrics are in the front faces of FMLs, delamination occurs due to the higher modules of carbon fabrics compared to that of Kevlar fabrics.

According to Figure 3, there was a larger damaged zone in the FML-KC specimen compared to the FML-CK. On the other hand, Figure 4 indicates that when an impact event ended, the central deflection in the FML-CK was smaller compared to the FML-KC sample with the same impact energy. This could be due to the fact that the Kevlar fabric absorbed more impact energy than the carbon fabric. Correspondingly, FML-KC provided higher impact tolerance compared to FML-CK in the drop-weight impact test as evidenced by the delamination observed in FML-CK.

This is the accepted manuscript (postprint) of the following article:
Sisan, M. M., & Eslami-Farsani, R. (2019). An experimental study on impact resistance of different layup configuration of fiber metal laminates. Fibers and Polymers, 20(10), 2200-2206.
https://doi.org/10.1007/s12221-019-7108-z

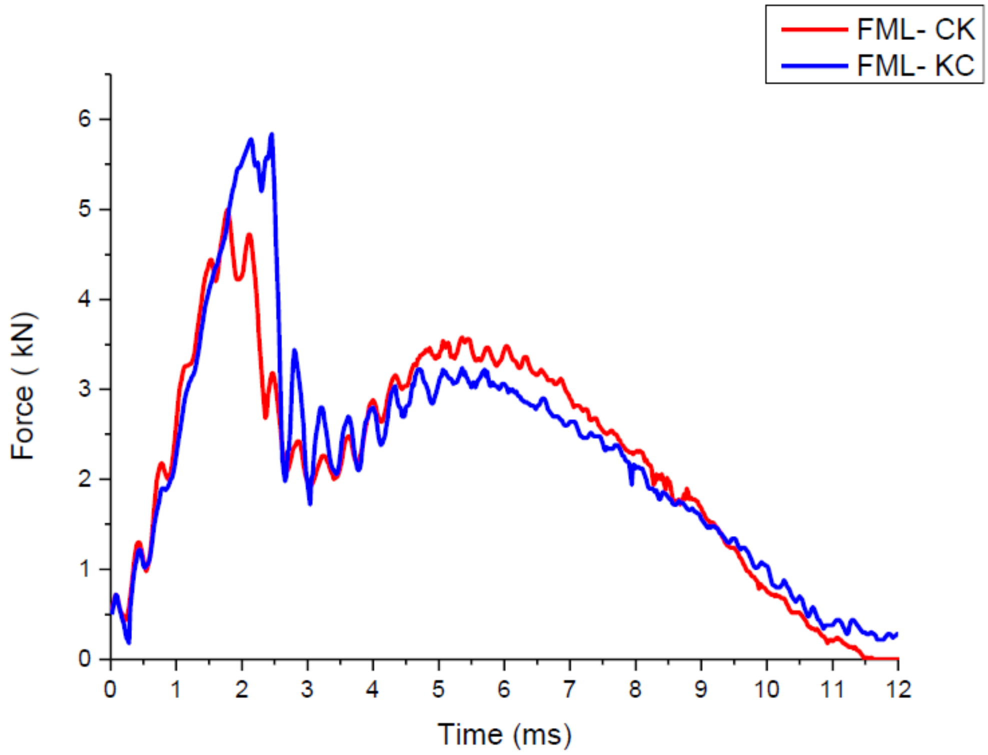

Figure 2. Force-time curves of FML-CK and FML-KC.

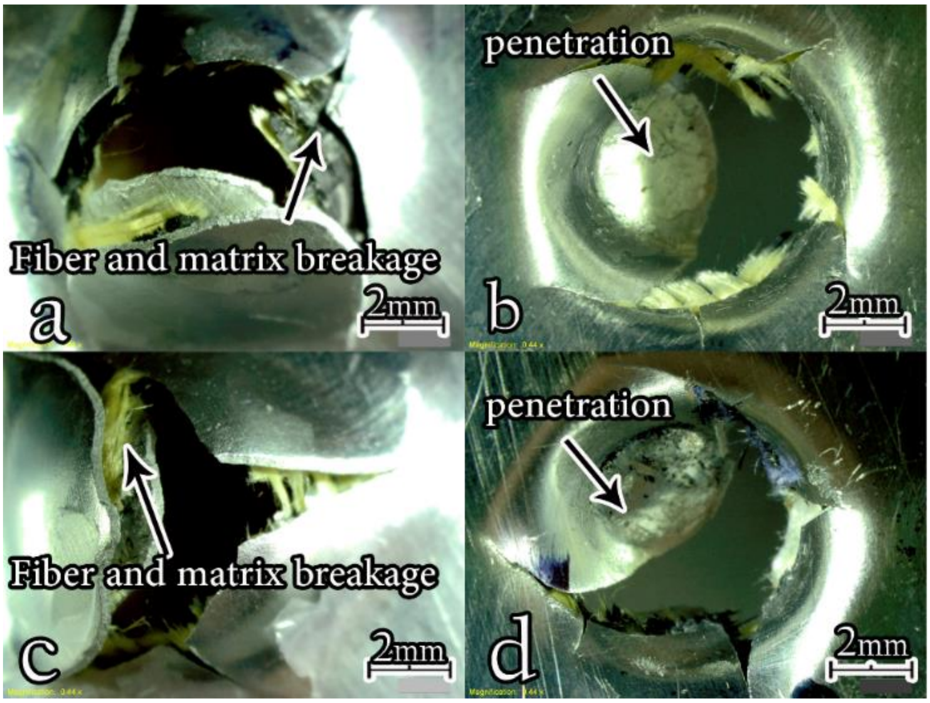

Figure 3. Damage patterns of (a, b) FML-KC and (c, d) FML-CK.

This is the accepted manuscript (postprint) of the following article:
Sisan, M. M., & Eslami-Farsani, R. (2019). An experimental study on impact resistance of different layup configuration of fiber metal laminates. Fibers and Polymers, 20(10), 2200-2206.
https://doi.org/10.1007/s12221-019-7108-z

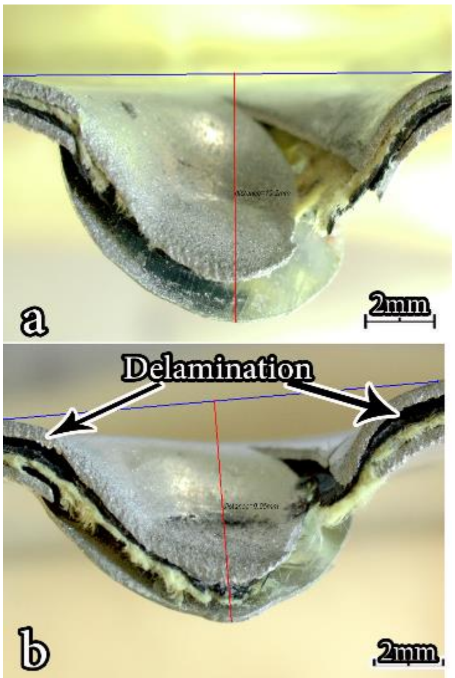

Figure 4. Cross-sectional micrographs of (a) FML-KC and (b) FML-CK.

3-2- Comparison of FML-CG and FML-GC

Figure 5 shows the load versus time responses in the FML-CG and FML-GC specimens. Obviously, both graphs had the same ascending trend up to the maximum point. The maximum force for the composites was estimated at 5720 and 4560 N, respectively, which implied the relative superiority of the FML-CG composite. Figure 6 depicts a schematic view of the impact-induced damage to the front faces and back faces of the two composites. Accordingly, the damaged area of the FML-CG composite was less than the FML-GC composite.

Fracture cross-sections of the FML-CG and FML-GC composites are illustrated in Figure 7. The penetration depth (i.e., permanent central deflection) of the FML-CG composite was less than the FML-GC. Matrix failure, fiber failure, and penetration were observed in both the FMLs, while delamination also occurred in FML-CG. These findings may explain the relatively good correlation between the young module and stiffness of the glass and carbon fabrics. Therefore, it could be concluded that the FML-CG composite, which experienced delamination, had higher resistance in the drop-weight test compared to FML-GC.

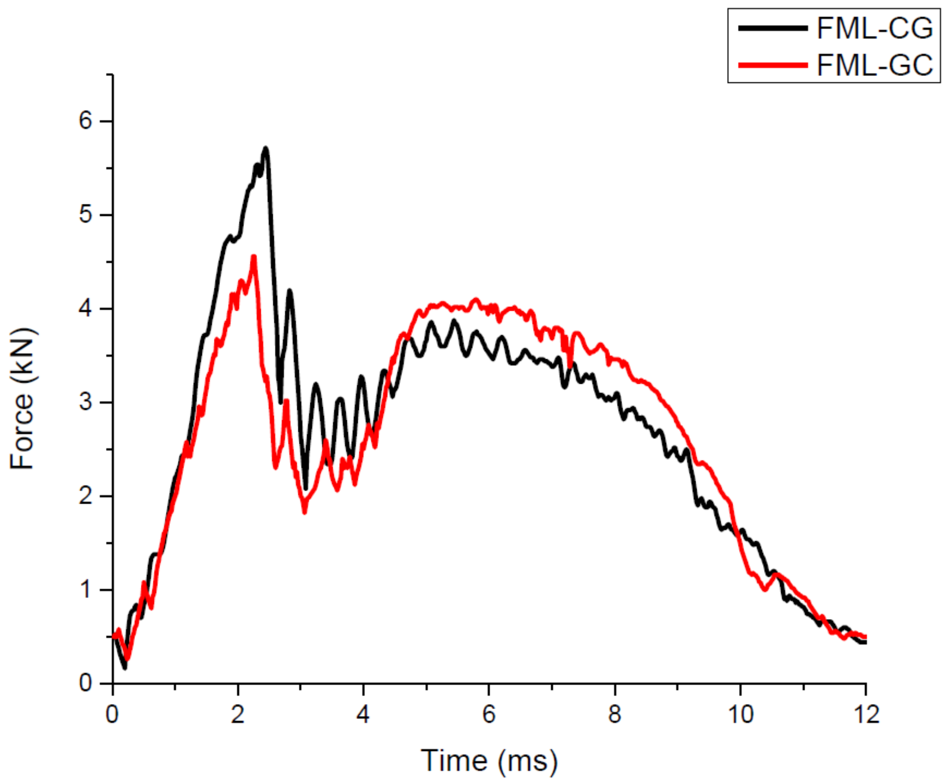

Figure 5. Force-time curves of FML-GC and FML-CG.

This is the accepted manuscript (postprint) of the following article:
Sisan, M. M., & Eslami-Farsani, R. (2019). An experimental study on impact resistance of different layup configuration of fiber metal laminates. Fibers and Polymers, 20(10), 2200-2206.
https://doi.org/10.1007/s12221-019-7108-z

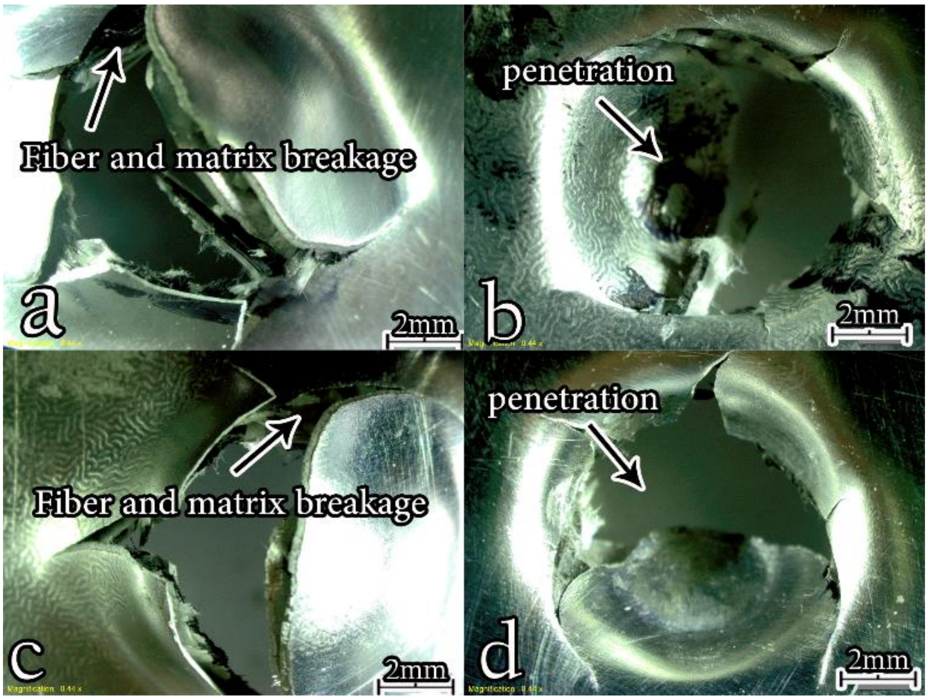

Figure 6. Damage patterns of (a, b) FML-GC and (c, d) FML-CG.

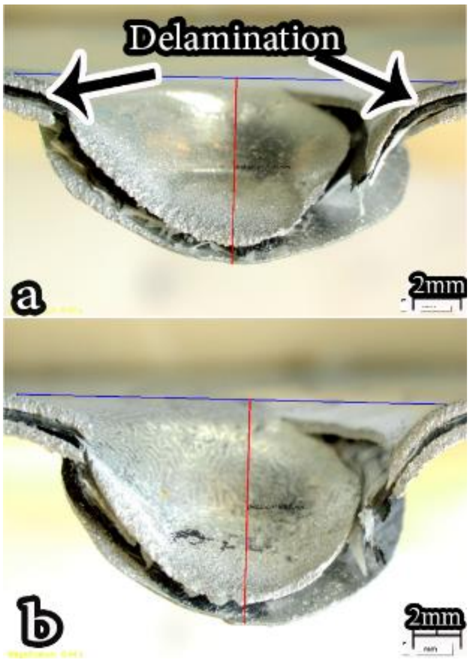

Figure 7. Cross-sectional micrographs of (a) FML-CG and (b) FML-GC.

3-3- Comparison of FML-GK and FML-KG

The load versus time responses for the FML-GK and FML-KG composites are depicted in Figure 8. Similar to the previous cases, the behavior of both these composites was almost identical before reaching the maximum force. However, a difference of 200 N was observed at the maximum force. Figure 9 shows the damaged area of the FML-GK and FML-KG composites. Matrix failure, fiber failure, and penetration were observed in both composites, while no delamination was detected in either composite. This finding implied the better impact and energy absorption properties of Kevlar and glass fibers, as well as the more effective distribution of the impact energy to the surface of their composites, compared to the carbon fiber.

Figure 10 demonstrated the fracture cross-sections of the FML-GK and FML-KG composites. The permanent central deflection of the FML-GK composite was slightly higher than the FML-KG composite. Therefore, the drop-weight impact test indicated a better performance in FML-KG (smaller damaged area) compared to the FML-GK composite.

This is the accepted manuscript (postprint) of the following article:
Sisan, M. M., & Eslami-Farsani, R. (2019). An experimental study on impact resistance of different layup configuration of fiber metal laminates. Fibers and Polymers, 20(10), 2200-2206.
https://doi.org/10.1007/s12221-019-7108-z

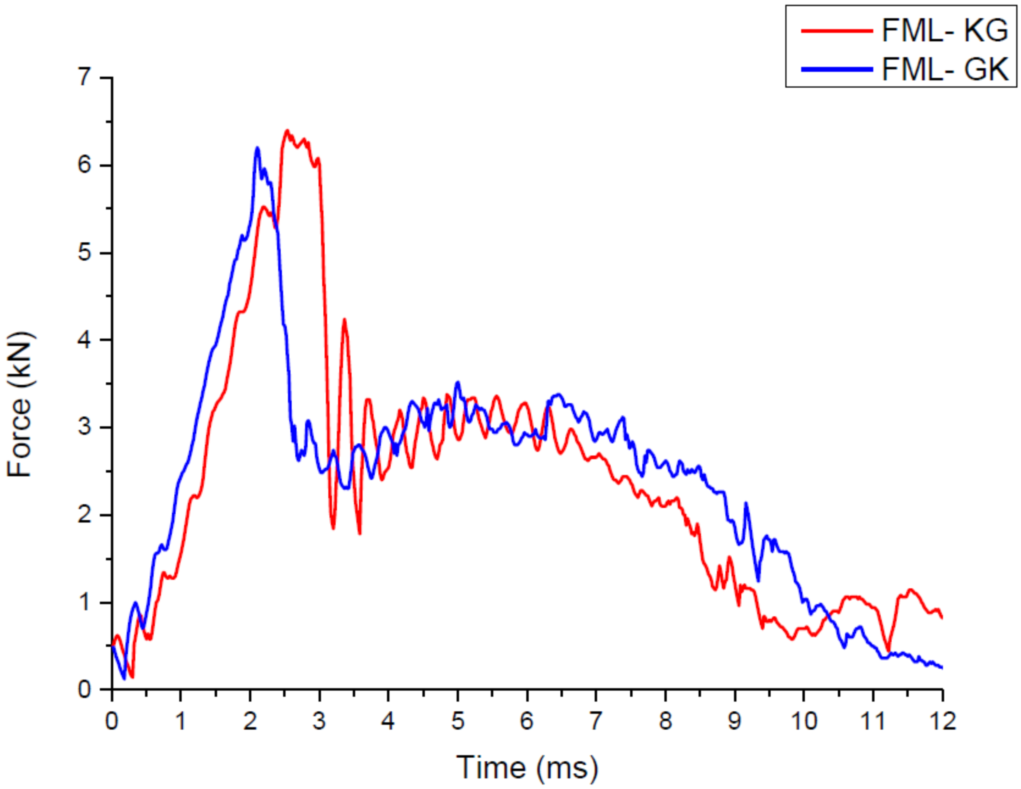

Figure 8. Force-time curves of FML-KG and FML-GK.

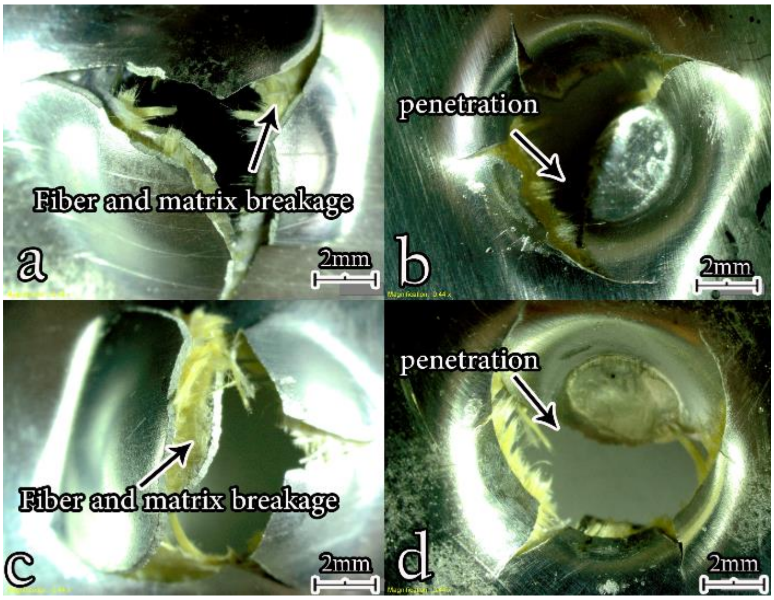

Figure 9. Damage patterns of (a, b) FML-KG and (c, d) FML-GK.

This is the accepted manuscript (postprint) of the following article:
Sisan, M. M., & Eslami-Farsani, R. (2019). An experimental study on impact resistance of different layup configuration of fiber metal laminates. Fibers and Polymers, 20(10), 2200-2206.
https://doi.org/10.1007/s12221-019-7108-z

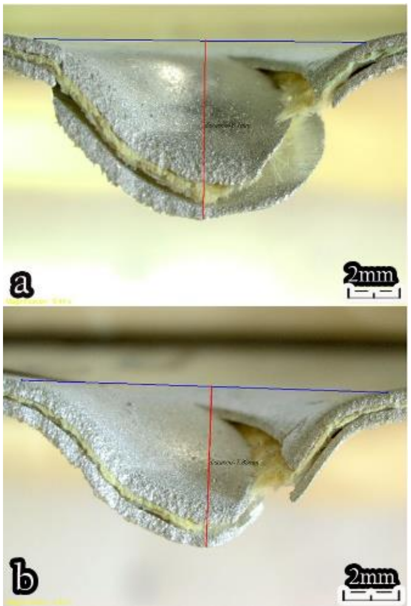

Figure 10. Cross-sectional micrographs of (a) FML-GK and (b) FML-KG.

3-4- Comparison of the FML-CKH, FML-CK, and FML-KC Composites

Figure 11 shows the force-time curves of the FML-KC, FML-CKH, and FML-CK composites. In the present study, the FML-CKH composite was produced for the first time. The main difference between this type of FML and the other two composites (FML-KC and FML-CK) was the lay-up configuration. In the FML-CKH composite, a mixed texture of Kevlar and carbon was used, while the Kevlar and carbon textures were used separately in the FML-KC and FML-CK composites. The maximum force of FML-CKH was 5180 N, while it was 5000 and 5840 N in FML-CK and FML-KC, respectively.

Figure 12 demonstrates the fracture surfaces on the impact and non-impact sides of the specimens in the three FML composites, and Figure 13 depicts the cross-sectional images of the three composites. As can be seen in these figures, the damaged area in the FML-CKH composite was more than the other composites, while the depth of penetration was comparatively lower in FML-CKH. With regard to permanent central deflection, our findings

This is the accepted manuscript (postprint) of the following article:
Sisan, M. M., & Eslami-Farsani, R. (2019). An experimental study on impact resistance of different layup configuration of fiber metal laminates. Fibers and Polymers, 20(10), 2200-2206.
https://doi.org/10.1007/s12221-019-7108-z

indicated that the depth of penetration was higher in FML-KC and FML-CK compared to FML-CKH.

Surprisingly, no delamination was observed in FML-CKH, while the phenomenon was clearly visible in the other composites, particularly in FML-CK (Figure 13). This could be due to the hybridizing of the carbon and Kevlar fibers and development of a hybrid texture of carbon and Kevlar, resulting in the excellent impact absorption properties of the Kevlar fibers and high resistance of the carbon fibers. Therefore, it could be concluded that the properties of FML-CKH are in-between those of FML-KC and FML-CK.

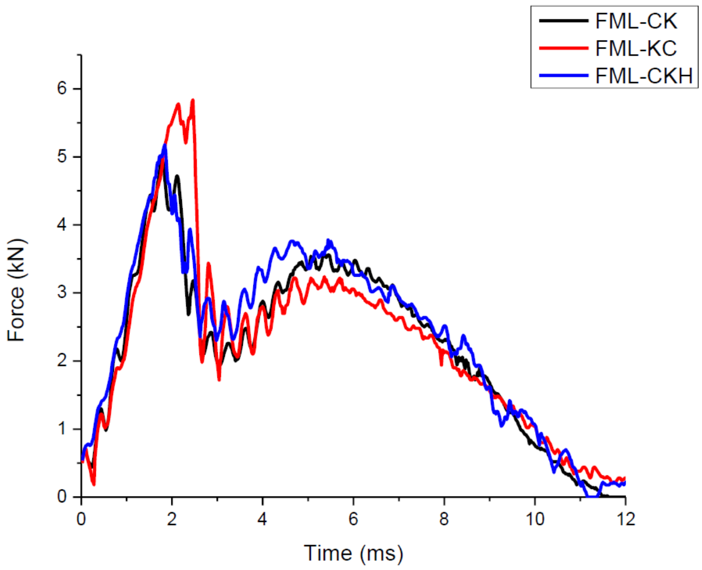

Figure 11. Force-time curves of FML-KC, FML-CK, and FML-CKH.

This is the accepted manuscript (postprint) of the following article:
Sisan, M. M., & Eslami-Farsani, R. (2019). An experimental study on impact resistance of different layup configuration of fiber metal laminates. Fibers and Polymers, 20(10), 2200-2206.
https://doi.org/10.1007/s12221-019-7108-z

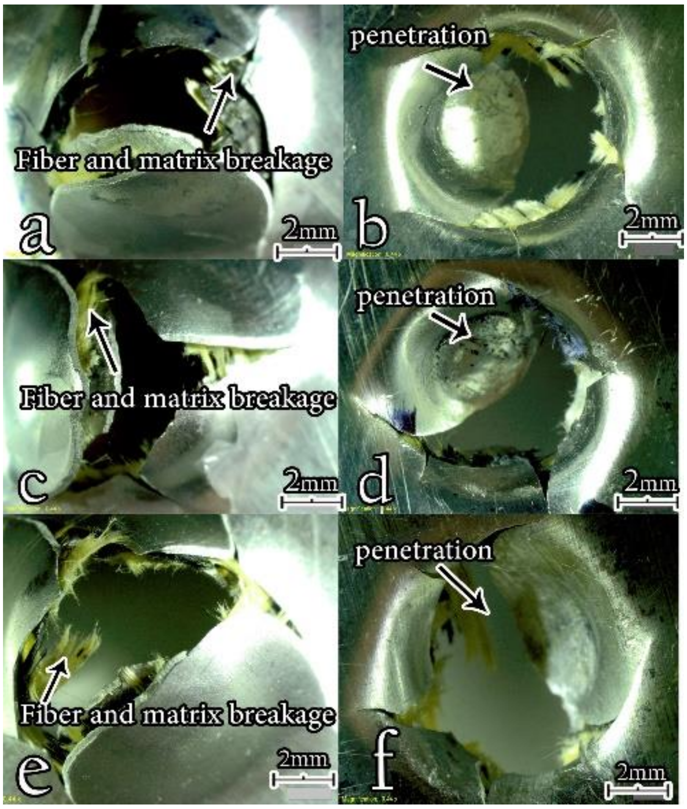

Figure 12. Damage patterns of (a, b) FML-KC, (c, d) FML-CK, and (e, f) FML-CKH.

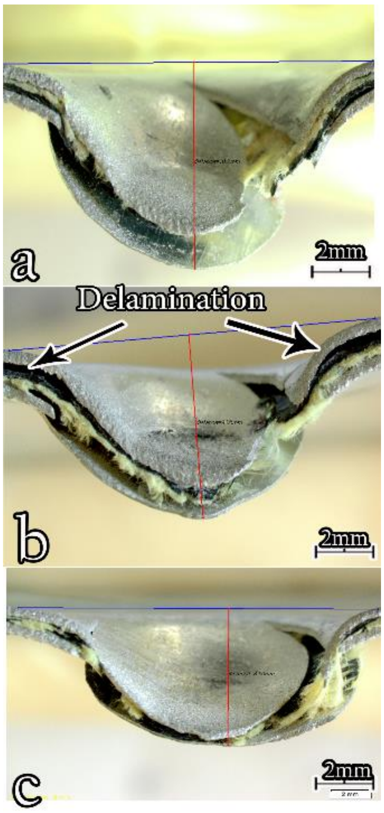

Figure 13. Cross-sectional micrographs of (a) FML-KC, (b) FML-CK, and (c) FML-CKH.

This is the accepted manuscript (postprint) of the following article:
Sisan, M. M., & Eslami-Farsani, R. (2019). An experimental study on impact resistance of different layup configuration of fiber metal laminates. Fibers and Polymers, 20(10), 2200-2206.
https://doi.org/10.1007/s12221-019-7108-z

3-5- Comparison of tensile properties of FMLs

Stress-strain curves for the FMLs (FML-CK, FML-CG, FML-KG and FML-CKH) are shown in Figure 14. Table 3 shows the results of the comparison between the tensile properties of all FMLs. Both the highest tensile strength (262 MPa) and Young's modulus (38 GPa) belonged to FML-KG sample.

The lowest tensile strength (231 MPa) belonged to the FML-CKH. The difference between FML-CKH and FML-CK was in the type of fabric texture. The Tensile strength of the composite FML-CKH was less than the FML-CK. In other words, using carbon-Kevlar hybrid fibers decreased the tensile strength, compared to when they were used separately, and, as a result, fracture occurred in lower tension.

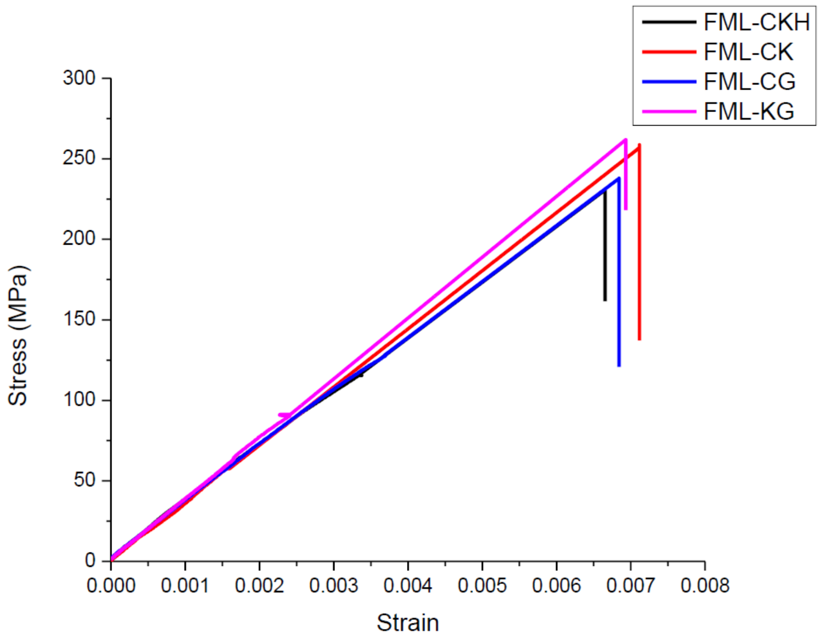

Figure 14. Stress-Strain curves of FML-CKH, FML-CK, FML-CG, and FML-KG.

This is the accepted manuscript (postprint) of the following article:
Sisan, M. M., & Eslami-Farsani, R. (2019). An experimental study on impact resistance of different layup configuration of fiber metal laminates. Fibers and Polymers, 20(10), 2200-2206.
https://doi.org/10.1007/s12221-019-7108-z

Table 3. Tensile properties of FML-CK, FML-CG, FML-KG and FML-CKH

Composite	Tensile strength (MPa)	Young's modulus (GPa)
FML-CK	**259**	**36**
FML-CG	**238**	**35**
FML-KG	**262**	**38**
FML-CKH	**231**	**35**

4- Conclusion

According to the findings regarding the low-velocity impact and tensile test responses of the FMLs in the present study, the following conclusions could be drawn:

1. FML-CK composed of carbon and Kevlar fabrics had the lowest impact resistance, followed by the FML-CKH, FML-CG, FML-KC, and FML-GK composites, and the FML-KG composed of Kevlar fabric on the impact side and glass fabric on the non-impact side showed the highest impact resistance and lowest damage area among the FMLs. In general, higher impact resistance was observed in the fiber metal laminates with the Kevlar fabrics on the impact side of the composite.
2. Delamination occurred in FML-CK and FML-CG between the carbon layers and aluminum sheets, while no obvious delamination was observed in the other FMLs. Therefore, it could be inferred that the placement of carbon fabrics in the front faces of FMLs leads to delamination due to the higher young modulus compared to Kevlar and glass fabrics.
3. For the first time, a new combination of metal and fabric composites has been reported for FML composites, namely, the Al 2024-T3/epoxy resin-carbon-Kevlar hybrid fabric/epoxy resin-carbon-Kevlar hybrid fabric/Al 2024-T3 laminates (FML-CKH). The impact properties of FML-CKH are in-between those of FML-KC and FML-CK with no delamination. This could be due to the hybridizing of the carbon and Kevlar fibers and developing a hybrid texture of carbon and Kevlar, resulting in the excellent impact

absorption properties of the Kevlar fibers and high resistance of the carbon fibers. In other words, FML-CKH is a cost-efficient composite with acceptable impact properties. Therefore, further investigation is required in order to assess the effects of other pertinent parameters on the impact resistance of FML-CKH.

4. Both the tensile strength and Young's modulus of the FML which contained Kevlar and carbon fabrics separately was higher than the hybrid of carbon and Kevlar fabric. This was due to the presence of carbon- Kevlar hybrid fibers in this composite; and because of the strength of the carbon fibers was greater than that of Kevlar fibers, the fracture in this FML occurred in lower tension. The highest tensile strength, and Young's modulus belonged to the FML having Al 2024-T3/epoxy-Kevlar fabric/epoxy-glass fabric/Al 2024-T3 layers. The lowest tensile strength belonged to the FML that include carbon-Kevlar hybrid layers; this was due to the low efficiency of carbon- Kevlar hybrid fibers in the tensile test compared to carbon and Kevlar fibers separately.

References

1. A. Vlot, Report LR-718, Delft University of Technology, Delft, 1993.
2. R. Eslami-Farsani, S. M. R. Khalili, and V. Daghigh, *Int. J. Damage Mech.*, **23(6)**, 729 (2014).
3. S. Zhu, and GB. Chai, *J. Mater. Des. Appl.,* **228(4)**, 301 (2014).
4. M. Sadighi, RC. Alderliesten, and R. Benedictus, *Int. J. Impact Eng.*, **49**, 77 (2012).
5. Y. Liu, and B. Liaw, *Appl. Compos. Mater.*, **17(1)**, 43 (2010).
6. GR. Villanueva, and WJ. Cantwell, *Compos. Sci. Technol.*, **64**, 35 (2004).
7. SH. Song, YS. Byun, TW. Ku, WJ. Song, J. Kim, and BS. Kang, *J. Mater. Sci. Technol.*, **26**, 327 (2010).
8. B. Borgonge, and MS. Ypma, *Appl. Compos. Mater.*, **10**, 243 (2003).

This is the accepted manuscript (postprint) of the following article:
Sisan, M. M., & Eslami-Farsani, R. (2019). An experimental study on impact resistance of different layup configuration of fiber metal laminates. Fibers and Polymers, 20(10), 2200-2206.
https://doi.org/10.1007/s12221-019-7108-z

9. G. Reyes, and H. Kang, *J. Mater. Process. Technol.*, **16**, 284 (2007).

10. A. Vlot, *Int. J. Impact Eng.*, **1(3)**, 291 (1996).

11. ASTM D7136/D7136M-07, Standard test method for measuring the damage resistance of a fiber-reinforced polymer matrix composite to a drop-weight impact event. *ASTM Book of Standards*, **15(3)**, (2005).

12. GR. Rajkumar, M. Krishna, HN. Narasimha Murthy, SC. Sharma, and KR. Vishnu Mahesh, *Int. J. Soft Comput. Eng.*, **1(6)**, 50 (2012).

13. ASTM D 3039–00 Standard test methods for tensile properties of polymer matrix composite materials, *ASTM Book of Standards*, **15(3)**, (2000).

14. MM. Shokrieh, A. Saeedi and M. Chitsazzadeh, *J. Nanostruct. Chem.*, 3(20), 1 (2013).

15. BM. Liaw, YX. Liu, and EA. Villars, Proc. of the SEM Annual Conference on Experimental and Applied Mechanics, U.S.A. (2001).

16. BM. Liaw, G. Zeichner, and XY. Liu, Proc. of the SEM International Congress on Experimental Mechanics, U.S.A. (2000).

17. A. Vlot, E. Kroon, and GL. Rocca, *Key. Eng. Mater.*, **141-143**, 235 (1998).

18. E. Sevkat, B. Liaw, and F. Delale, Mater. Des., **52**, 67 (2013).