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CRITICAL REVIEW

A state-of-the-art review on mechanical characteristics of different fiber metal laminates for aerospace and structural applications

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Abstract

The reduction of weight elements is considered as a major objective of several manufacturing companies. This objective will help in growing application sections of the used fiber composites for important structural elements. Modern fiber metal laminate (FML) having lightweight properties is established to be used instead of other substances in different applications including those related to the aerospace industrial sector. Fiber metal laminate is being deemed as an alternative significant substance that is being extensively explored due to its operation, unlike other current materials. There are different profitable FML such as GLARE (glass-reinforced aluminum laminate), established on elevated intensity ARALL glass fibers (aramid-reinforced aluminum laminate), built on fibers of aramid, in addition to CARALL (carbon-reinforced aluminum laminate), centered on fibers of carbon. This paper analyzes important information that contributes to the mechanical characteristics of FMLs under tensile, flexure, impact, etc. conditions.

Keywords Fiber metal laminates · Mechanical characteristics · Tensile · Flexural · Impact · GLARE · ARALL · CARALL

1 Introduction

Fiber metal laminates (FMLs) are mainly hybrid substances that include alternative/reciprocate sheets of composite sheets and delicate metal layers [1]. The layers are considered to be associated together via the composite layer matrix material. FML takes possession of both composite materials and metal's superior characteristics. Fiber metal laminates are designated by superb damage tolerance such as low density, impact and fatigue properties, fire resistance, and corrosion. Moreover, other particular FMLs are specified through the kind of used composite and metal components, layers number, fiber orientation, and thickness of the layer [2]. Commonly, the manufacturing operation of these FML composites consists of the subsequent steps: initially preparing materials and tools which include metal layers pretreatment, adhesive system anodizing and application, and corrosion primer-preventing properties. The second step is element formation which involves cutting, preparing vacuum bags, and lay-up. On the other hand, step 3 is the autoclave cure which includes the consolidation operation. The final step is an inspection by conducting mechanical and nondestructive experiments [3].

During the last decades, the importance of composite substances has increased, particularly in the aerospace sector,

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but due to the weak impact performance of composite substances, industries' major interest was in the establishment of FMLs due to their better impact performance [4]. Likewise, the military applications related to the aircraft sector started commercial use of these composite materials. Composite materials provide several features when assessed to other metallic components, where elevated stiffness along with the strength to the weight proportion is considered. Concerning all these efficient characteristics, composite materials obtained widespread use during the prior decades, especially in the aerospace industry [5]. The past of such FMLs refers back to the 1945s when Rob Schliekelmann at Fokker firm combined aluminum layers and treated them within an autoclave. The slow spread of fatigue cracks within these sheets was remarked by Jaap Schijve; he added that even if the crack reaches a certain layer, the other sheet blocks it [6]. At the dawn of the 1980s, FML combinations were advanced by the Delft University of Technology [7]. Foremost with the name ARALL (aramid-reinforced aluminum laminates) followed by the name GLARE (glass-reinforced aluminum). The major prevalent technique applied to output FML laminates involving GLARE is autoclave processing which is done under specific parameters (elevated temperature, high pressure, vacuum) [8, 9]. In the latest years, new resources were utilized in aerospace production, these materials are known as composite materials which are today mainly called fiber metal laminates. Material and structure quality control in the aircraft industry is an efficient manner, this is also applied for FMLs. Concerning FML sections, the inspection of a 100% non-devasting is required internal quality upon the manufacturing for the procedure [10].

Delamination and porosity are the most important defects that must be inspected using the non-destructive experimenting method in the case of FMLs. Generally, ultrasonic inspection is considered the common suitable test. Whereby, NDT (nondestructive testing) techniques remain relevant and designed for the examination of FML components during in-service and during-production assignments. In the situation when cracks appear but without delamination, the fiber composites extend greatly and then ultimately break. Therefore, an equilibrium state was needed among these characteristics. In this manner, an analytical procedure was done by Marissen to compute the spread of fatigue crack concerning hybrid substances achieved through fiber/aluminum aramid sheets. The examinations conducted by Delft University pushed the university to cooperate with various firms such as 3 M develops adhesives, ALOCA manufactures thin metal sheets, as well as AZKO which is responsible for producing aramid fibers [11]. While Eddy's current examination in addition to thermography has been likewise utilized in the assessment of FMLs under circumstances. A great challenge appears when undergoing nondestructive inspection mechanisms and during in-service maintenance work upon manufacturing operations of these complex laminates. Since these laminates consist of an inhomogeneous structure of both alternating fiber composite layers and metal layers [10]. In the fifties, the enhancement of crack growth characteristics of the structural materials was a major goal when developing aircraft materials [12]. In the seventies, the concept of utilizing two materials to compose a hybrid structural composite material to cope with nearly all the drawbacks of materials started to appear [13]. The reduction of fatigue crack expansion averages in bonded sheet adhesive materials is possible according to Delft University of Technology, in case the materials are constructed via laminating as well as adhesive bond thin sheets of these materials, as a replacement of using one monolithic thick sheet [12]. Throughout the previous three decades, a search for lightweight materials was conducted concerning the replacement of conventional aluminum alloys in the aerospace industry [14]. For a preferable structural design, an unprecedented material is required which merges high elasticity modulus, low density, elevated strength, fatigue properties, improved toughness, and corrosion resistance. Fiber metal laminates nearly overlay all these requests, excluding fracture toughness [13].

1.1 Applications of fiber metal laminates

Disparate firms have shown attention to replacing aluminum conventional elements with FML combinations [15]. Together GLARE along with ARALL materials nowadays are employed as structural substances concerning aircraft structures. FMLs were essentially established within the Airbus aircraft A380 [16]. Figure 1 shows the used FML applications in the plane.

ARALL was advanced for lower skin wing panels regarding previous Fokker 27 aircraft as well as the Boeing C-17 cargo door. GLARE material is used for the cargo floor impact resistance bulk of Boeing 777 [5]. Concerning aircraft industries, they spend around 20% of their costs on repairing and maintaining structures. This made such industries search for new lasting components in the manner

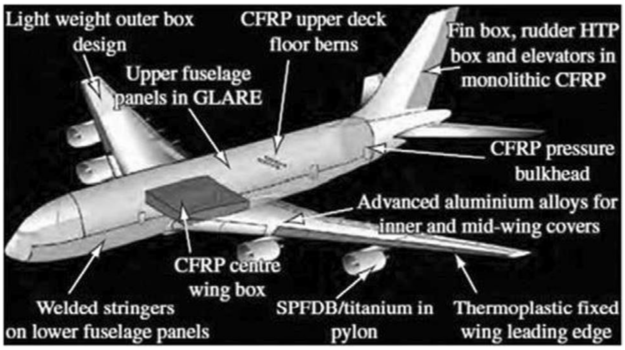


Fig. 1 The functionality of composite assemblies on A380 [5]

of reducing such extra costs, in addition, to utilizing lightweight elements so the total weight of the aircraft will be lessened [14]. Several kinds of research have been carried out to decrease the aircraft's structural weight by applying new various materials such as titanium and aluminum. Concerning this objective, fiber metal laminates are being used in aerospace structures in order to rise the aircraft operation behavior, since these laminates combine metal materials and fiber composites [17]. According to the compensations of FMLs, several aerospace industries apply distinct sorts of FMLs within various components concerning aerospace structural parts throughout the implementation stage [18]. The usage of FMLs via various companies is shown in Table 1 [18], whereas Fig. 2 shows the different applications of FMLs in aircraft structures.

To conclude, FMLs are being used widely in aircraft components due to their interesting characteristics and low cost compared to other metal alloys. The usage of such materials in the automotive and marine sectors is being grown lately, in addition, other industrial sectors are investigating the ability to apply FML structure in different applications other than aerospace, marine, and automotive ones.

2 Review methodology adopted

The review approach observes numerous recommendations of the selected research entries for systematic studies. The papers chosen were in English, others were indifferent languages however the abstracts were in English. Figure 3 illustrates the key stages of our review process. The literature data incorporated in the current study has been achieved from available online records. To begin, the Elsevier, ResearchGate, Springer, MDPI, Taylor and Francis, Wiley as well as SAGE records have been referred, by diverse groupings of the subsequent keywords applied concerning the examinations: FML, MECHANICAL BEHAVIOR, GLARE, ARALL, M5 FIBER, POLYMER FMLS, CARALL, TENSILE IMPACT, RESIDUAL STRESS, CORROSION RESISTANCE, MOISTURE PERFORMANCE, CRACK BEHAVIOR, VELOCITY IMPACT, SURFACE TREATMENTS, FMLS ENHANCEMENT, ETC. In a request to prevent the preference influence, similar standards of value, inclusion, along exclusion were utilized. The quest procedure reports explorations of research articles, records of renowned seminars, as well as book sections. Subsequently, papers were chosen depending on the topic keywords which are mentioned above and related to the mechanical characteristics of fiber metal laminates. A comprehensive understanding of the abstract, the assumptions, along the resources and process segments supplied the best profound knowledge. Soon after, the outcomes portion was investigated in request to verify mathematical values of related mechanical characteristics. A forthright exploration of the App Dimensions exposes the total of occupations regarding FML mechanical performance as shown in Fig. 4.

3 Classifications of fiber metal laminates

FMLs are classified based on the used metal alloy as well as the synthetic fiber orientation in the structure; the categorization of such composite materials is shown in Fig. 5 [15].

The mechanical characteristics of different FMLs like compressive, impact, tensile, flexural, and fatigue properties were examined by several aircraft industries, universities, and research institutes worldwide [22]. The reaction of FML against force loads was considered a major topic of concern to several academics. The circumferential and longitudinal joints concerning the fuselage of aircraft are subjected to fatigue destruction [13]. Therefore, examining the comportment of FML against fatigue loadings is important, and this performance is analyzed through the connection between fatigue strain or stress in addition to several cycles to failure [23]. Numerous factors are impacting the mechanical characteristics of FML as mentioned: strain rate effect of temperature, the impact of polymer and metal matrices, the influence of various surface treatments, thermal cycle, natural fibers, scaling effects, stacking sequence, laminate thickness, etc. [23].

Table 1 The usage of FMLs in various firms (Modified from Reference [17])

Aircraft firm	Elements	Phase	FML sort
Bombardier Inc	Flap shell DHC 8 (base)	Progress/development	ARALL FMLs
Bombardier Inc	Lear 45 face wall	Application stage	GLARE FMLs
Bombardier Inc	Experiment body	Progress/development	Both FMLS
Lockheed Martin	Bottom flap shell of C130	Progress/development	ARALL FMLs
Deutsche Aerospace Firm	Airbus check body	Progress/development	GLARE FMLs
Deutsche Aerospace Firm	Airbus pressure back wall	Progress/development	GLARE FMLs
Boeing Firm	Boeing 777 cargo floor	Application stage	GLARE FMLs
Boeing Firm	Boeing 737 bottom side flap shells	Progress/development	GLARE FMLs

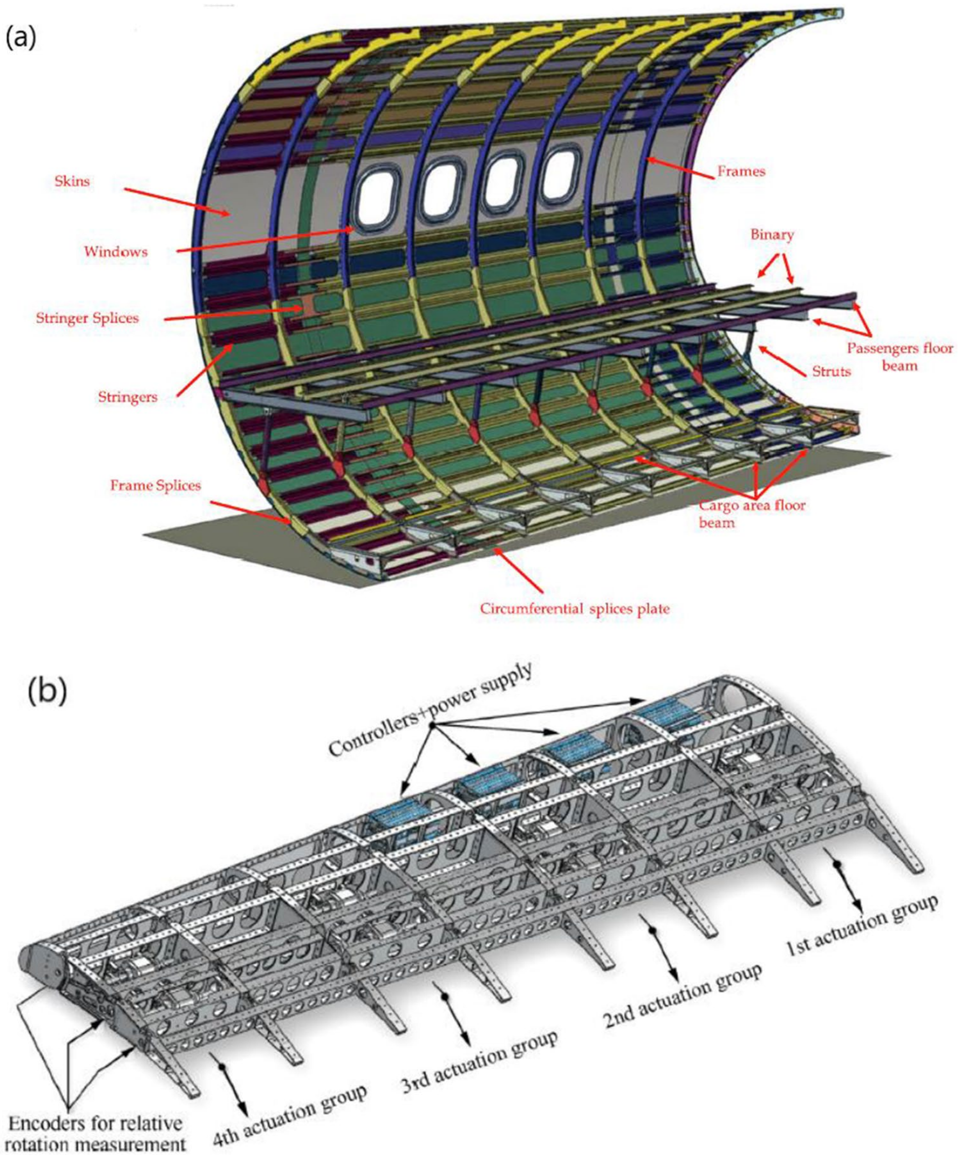


Fig. 2 Air structure applications. **a** Fuselage barrel [19]. **b** Aircraft flap skins [20]

3.1 Aramid fibers (ARALL)

Being built for the initial time for specific applications such as Boring C17 cargo cover as well as the Fokker F27 subshell wings. These FMLs sort utilizes aluminum sheets plus aramid fibers, these FMLs have elevated fatigue resistance, well young modulus in addition to the fact they are considered lightweight materials. However, ARALL FMLs have weak properties in case of torsion, and compression along bending. They are also able to engross moisture [24]. A modern superior-strength fatigue-resistant substance used for aircraft production is illustrated which is known as ARALL and involves light sheets of an elevated-strength aluminum alloy that are attached all together. Into the bondline, thin sheets of aramid fibers are inserted [25]. ARALL was employed within aircrafts such as F27, which led to a weight improvement of 30% besides a durable life [26]. ARALL unidirectional fiber arrangement inhibits the usage of such FML in certain parts like aircraft fuselage since they are imperiled to 2-D loads [12].

Vlot also studied the impact characteristics of FML. Impact investigations were directed to analyze the impact properties of FML (ARALL and GLARE). Comparative high- and low-speed impact experiments were implemented on FML, carbon thermoplastic composites, and monolithic aluminum. Further impact experiments have proceeded on ARALL and monolithic aluminum specimens under specific tensile loading. The author compared the impact behavior of FMLs with high-behavior structural aerospace materials. He concluded that the outcomes of the test showed the superior performance of GLARE 3 compared with other materials. Moreover, the impact of first tensile loading on the residual

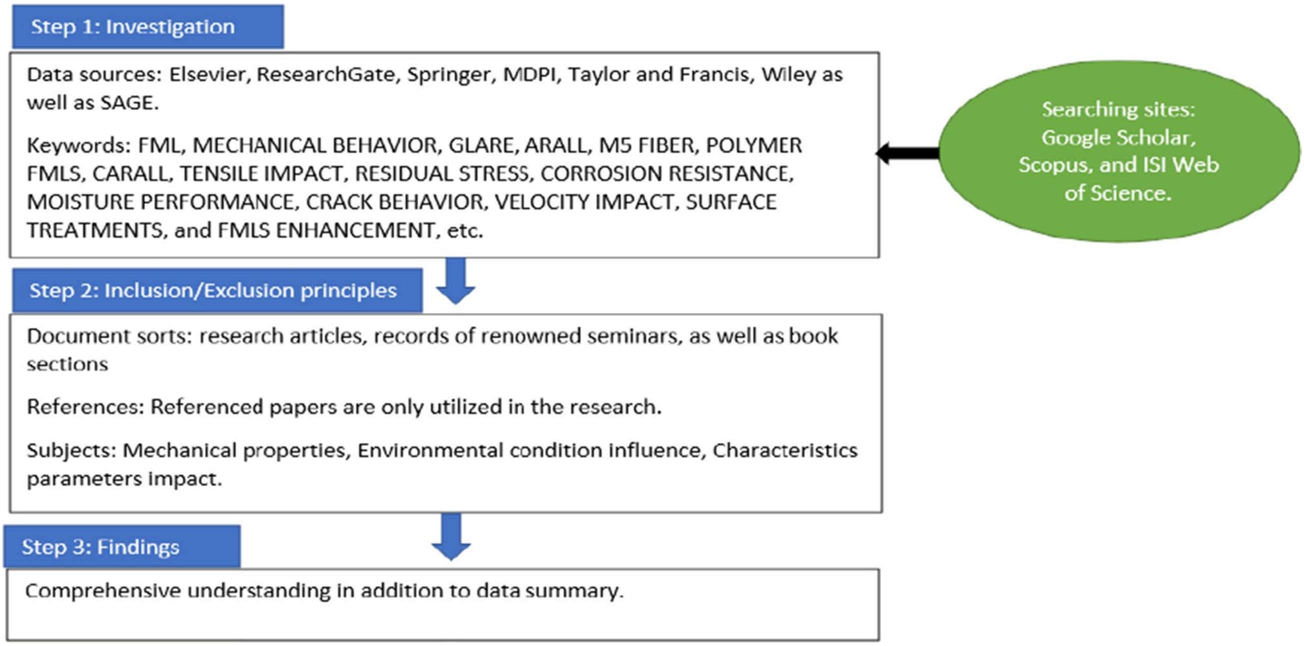


Fig. 3 Major stages concerning the planned review approach

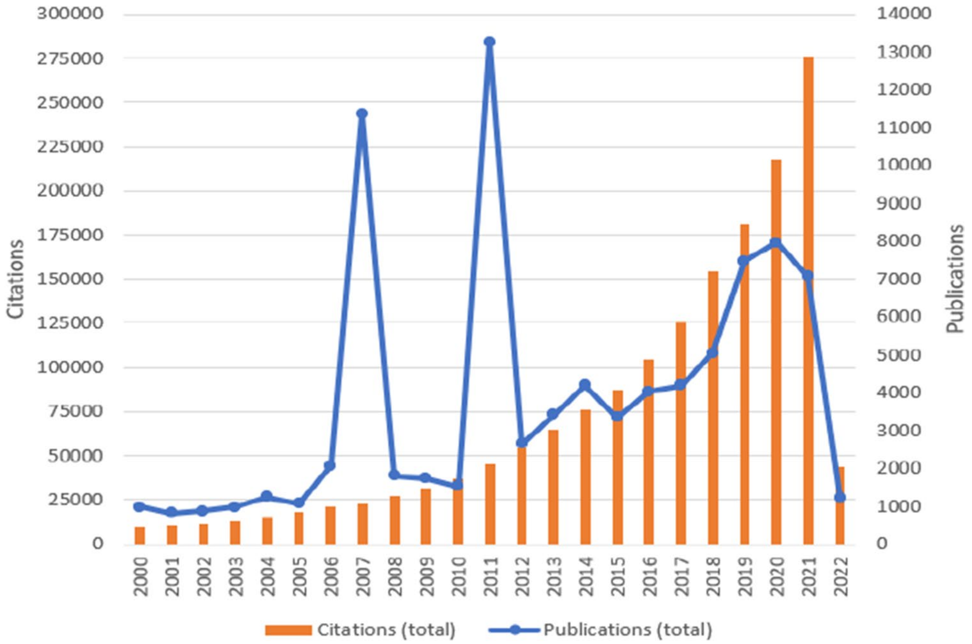
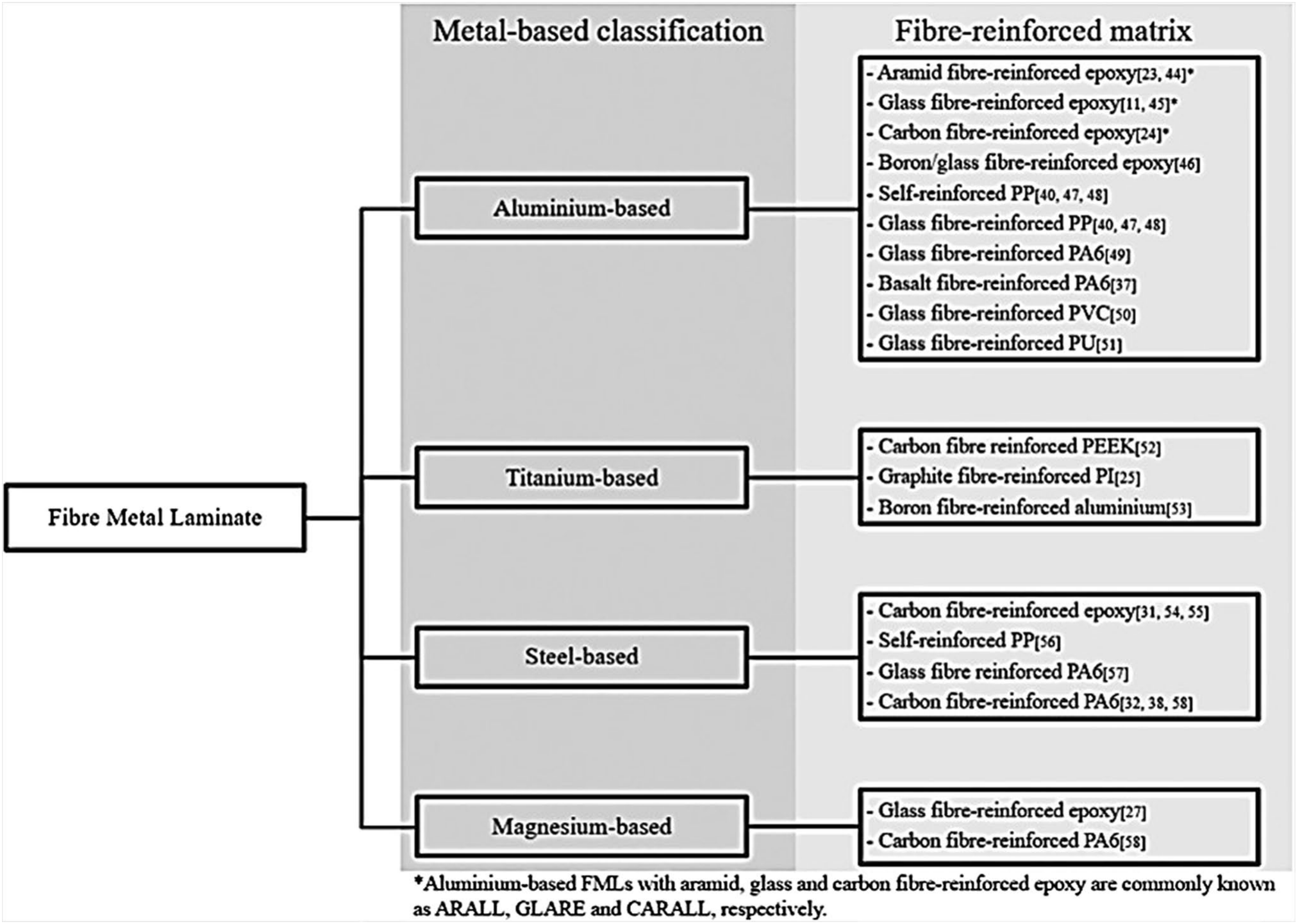


Fig. 4 The number of publications regarding FML mechanical performance along with the yearly citations, from 2000 to 2022. Information supplier: App Dimension, Search title: ("FML" or "FMLs mechanical behavior" and topic: ("Fiber metal laminates")

strength and size of damage of ARALL is considered small concerning sensible operating stresses [27]. Feng et al. [28] researched the fatigue characteristics of ARALL FMLs. The writers added that the responses of fatigue behavior have a high influence on the mechanical performance of these samples. In addition, the fiber alignment, sort, and metallic layer sort are also considerations that alter these mechanical characteristics [28]. Canche et al. [29] analyzed the tensile performance of ARALL-established FMLs. The results showed a rise in the strain/failure, also characteristics such as toughness could be customized to grasp energy at distinct rates [29]. Carrillo et al. [30] investigated the small-speed effect on the mechanical comportment of aramid FMLs. The outcomes have demonstrated that samples with a 3/4 sheet sequence had the ultimate rate of energy immersion. The optical assessment revealed that the splitting of aluminum sheets along with plastic distortion were the major energy-concentration impact processes [30]. Qi et al. [31] studied



*Aluminium-based FMLs with aramid, glass and carbon fibre-reinforced epoxy are commonly known as ARALL, GLARE and CARALL, respectively.

Fig. 5 Categorization of FML [21]

the mechanical performance of aramid FMLs. The toughening influence was examined, and the results have shown that the fracture toughness of used samples could be enhanced [31]. In closing, ARALL-based FMLs or also known as aramid laminates are being used in several aircraft components including various types of airplanes from different firms due to their excellent young modulus and low weight compared to metal alloys. Several authors were interested in investigating the mechanical behavior of these FMLs; some studied their fatigue performance, velocity impact, tensile behavior, etc. Table 2 shows the advantages and disadvantages of aramid fiber laminates.

Table 2 Advantages and disadvantages of aramid laminates (Modified from Reference [24])

Advantages	Disadvantages
Resistance to impact	Difficult treatment
Resistance to abrasion	Torsion
Resistance to cutting	Compression along bending
Well young modulus	Moisture absorption

3.2 Glass fibers (GLARE, central)

Used in developing aircraft operational appliances. they contain delicate aluminum sheets attached with biaxially reinforced epoxy resin prepreg of superior-intensity glass structures. GLARE gives an exceptional sequence of characteristics for example excellent fatigue resistance, elevated precise static characteristics, superb impact endurance, excellent residual, and fire endurance, in addition to corrosion characteristics, besides easiness of manufacture plus refurbishing [25]. GLARE is considered one of the most important types of FMLs since they are used in several aerospace structures. This FML shapes some components of the fuselage and tail surfaces of the Airbus A380 plane [32]. Federal Aviation Administration in 1995 developed the first GLARE freight container for aircraft which is considered to be resistant to blast since it is capable of absorbing fire and explosion from bombs [33]. This sort of FMLs is also applied in the forward bulkhead Radome concerning the Learjet 45 business Bombardier jet [34], which was presented in 1998. This material was also used in regional jets to solve the cargo liner situation; furthermore, GLARE was utilized on military planes such as the C130J Lockheed Martine transportation plane [35]. Likewise, this FML was added to straps in Airbus A400M frames [36]. Vlot and Krull [37] studied the impact damage resistance of different FML GLARE structures. The lay-up regulates the laminate thickness and is specified with the amount of prepreg and aluminum layers, a 4/3 lay-up containing three prepreg intermediate layers bonded simultaneously with four aluminum sheets. The outer sheets are regularly aluminum, and they protect the inner prepreg sheets from moisture breakthrough. Materials used were aluminum AL 2024-T3 and carbon/PEI composites. Every static and impact indentation experiment was implemented using a tipped hemispherical impactor (a diameter of 15 mm). ten specimens were used for each material concerning each speed regime with impact forces near to the impact lowest energy that generated the initial material break. A 40 Nm constant torque was utilized on 8 bolts which were used to hold the experiment area under clamped conditions. The authors used this method since it will be capable of determining the lowest cracking energy with the correctness of convergently ± 5%. The velocity impact experiments were applied by a limit speed of 10 m/s along with a top speed of 10 m/s mass impactor equal to 20,280 g. whereby, high-speed impact tests were done with speeds up to 100 m/s by applying an air gun. The authors compared the behavior of various glass fiber FML alternatives with carbon/PEI composites and aluminum alloy. The impact of the relative glass/epoxy FML content was determined. The authors carried out that FML gave a 15% finer least cracking momentum at the small-speed impact when associated with aluminum alloy, but it acts well at high speeds. In addition, the FML impact damage resistance increased when increasing the glass/epoxy content [37]. In addition, Vlot also conducted further research to consider the impact of loading on FMLs. High, low-speed impact, and static indentation experiments were carried out on samples having a clamped circular experiment area. Monolithic AL 7075-T6 and 2024-T3 aluminum alloys, different grades of FMLs, as well as composites, were checked. The energy used to generate the initial crack-up concerning the FML including carbon fibers combined with aramid was compared to reinforced fiber composite materials and was relatively small when compared to FML and AL 2024-T3 with R-glass fiber (GLARE). The test results showed that FML dent depth was nearly equal to that of aluminum monolithic alloy [38]. Ahmadi et al. [39] conducted a study to examine the high-speed impact characteristics of reinforced glass FMLs. The materials used were GLARE specimens made of unidirectional E-glass fibers, aluminum Al 2024-T3 layers, and epoxy resin. The aluminum layers were of thickness equal to 0.5 mm whereas the glass/epoxy layers had a median thickness of 0.35 mm. Mechanical characteristics of the substances were collected on the report of ASTM D3039 and ASTM E8M for composite plies and aluminum respectively as shown in Table 3. These characteristics were gained using the quasi-static test. Also, the properties of the glass/epoxy plies were gained using the same test. The reinforced glass laminates with various thickness ratios displayed to relatively high-speed impact were examined in both analytical and experimental methods. The tests were conducted via a high gas gun as well as a 14 g cylindrical blunt projective. while the specific perforation energy and the limit ballistic speed were used to compare the results of the experiments. The authors concluded that the examining supported them to attain an analytical term to foretell the perforation energy and the ballistic limit. They added that the results of the experiments signalized that the aluminum sheet's global deformation gave the most influence concerning absorbing energy. Furthermore, the authors stated that increasing the composite plies number might reinforce the absorbed energy of FML; however, it also raises weight and origins in the repel from the optimum situation [39].

Hassan et al. [41] performed research to investigate the mechanical performance of novel FMLs. The utilized materials during the research of GLARE FML were epoxy resin, aluminum alloys, as well as glass fiber sheets of thickness equal to 0.5 mm. The hand lay-up technique was applied to fabricate the GLARE composite with the assistance of new advanced technology concerning the achievement of useful adhesion with each sandwich component. The lay-up consists of specimens with distinct layers (numbered 8, 6, 4, 2, and 1) of the woven structure inserted among two light

Table 3 Mechanical characteristics of the aluminum alloys (Modified from Reference [40])

Substantial property	Unit	Estimate
Density	kg/m^3	2700
Young modulus	GPa	73
Poisson's ratio		0.33
Flow stress	MPa	352
Melting point	°C	520

Table 4 Mechanical characteristics of the GLARE laminates of different layers (Modified from Reference [41])

Specimen layup	Tensile intensity (MPa)	Flexural intensity (MPa)	Flexural young modulus (MPa)
1 sheet	70.8	99	244.6
2 sheets	92.5	99	293.5
4 sheets	146	148	438.9
6 sheets	170	197	531
8 sheets	136	322	682

aluminum sheets. Bending and tension experiments have been implemented for examining flexural along with tensile intensity concerning various lay-up samples. Furthermore, the influence of composite laminate in addition to the linear performance on the aluminum plasticity was examined authors derived that the consequences clarify that as the woven layer number rises both examined strengths increase too. Moreover, the tension sample failure modes were noticed and presented a performance of net mode of tension in the absence of any delamination between glass FMLs and aluminum sheets. Whereas the delamination occurred in the instance of bending failure modes. In addition, the authors indicated that the region of plasticity drops in case the linear total of elastic performance composite laminate inserted among the two sheets of aluminum increases [41]. Table 4 shows the mechanical performance of different GLARE specimens employed in the experiments.

Silva et al. [42] investigated the hygrothermal maturing influence on the fatigue performance of GLARE FMLs. GF/E (glass/epoxy) was employed for the formulation of the composite as well as Al 2024-T3 aluminum alloy sheets. Tensile experiments were carried out on ten specimens for each sort of laminate via a mechanical Instron assessment apparatus during a velocity of 1.27 mm/min. whereby the fatigue experiments were applied also using an Instron fatigue apparatus at various stress ratios. The optical microstructure characteristics of FML using the examples of the GLARE and CARALL laminate types. is shown in Fig. 6. The authors concluded that hygrothermal conditioning could simulate efficient changes in the material characteristics. Furthermore, the fatigue and tensile values were reduced due to hygrothermal aging [42].

Plokker et al. [44] probed the effect of fatigue fracture growth on FMLs upon various amplitude loadings. Experimental research was conducted to investigate the influence of several underloads, overloads, and different loading series on the growth of the crack in FML GLARE. Retardation impacts of the crack growth were examined during the experiments. The authors derived that the retardation of crack growth was lower than those shown in metals due to the impact of fiber bridging GLARE which decreases the crack tip stress intensities. Moreover, the drop in the overload ratio decreases the plastic zone and growth retardation [44]. Mahesh and Kumar conducted a comparison concerning the mechanical characteristics of GLARE laminates of 3 various orientations like woven roving, 45° stitched Mat, and CSM (chopped strand Mat) each of a 4/3 layer. Flexural and tensile experiments were performed, and the samples were cut as per ASTM standards from cutting wire. The tests were done on a controlled computer UTM like AUTOGRAPH-50KN capacity concerning the tensile test along with an Instron-100 KN capacity concerning the flexural test. The authors concluded that the flexural and tensile performance of GLARE laminates were commonly related to the percentage volume of orientation and fiber. Furthermore, the 45° orientation had excellent tensile characteristics when compared to the other sorts; this means it is suitable for withstanding the tensile loading. On the other hand, the woven roving during the flexural strength test had bigger flexural characteristics when compared to other types [45]. Mania et al. [46] carried out comparative research concerning FML plies post-buckling in addition to buckling performance in axial loading. Specimens of dimension 3/2 FML with open cross-portion shapes were exposed to axial loadings under bulging assessments and were utilized to analyze their bulging and post-bulging behavior. The writers derived that the local sort of buckling mode had no influence on the prepreg layers as well as on aluminum profiles [46]. Mendibil et al.

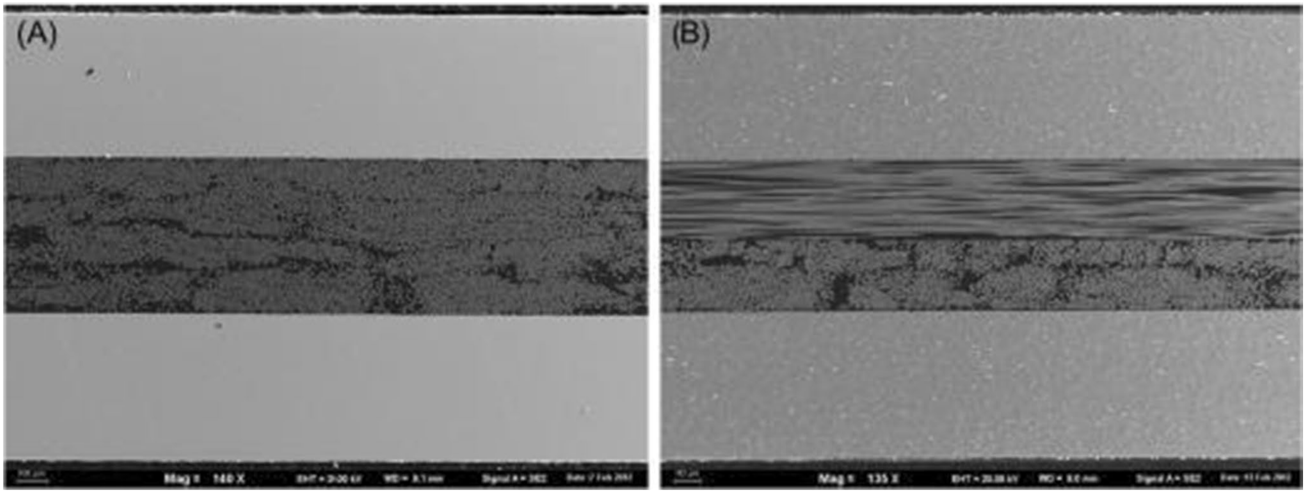


Fig. 6 Typical microstructure characteristics of FML using the examples of the GLARE and CARALL laminate types**. a** Ti/GFRP 2/1 (0/0)2, **b** Al/GFRP 2/1 (90/0)2, SEM images [43]

[47] analyzed the impact performing of GLARE FML manufactured via vacuum-assisted resin molding transfer. FML sheets were structured with a 3/2 arrangement of thickness 2.99 ± 0.08 mm. Both impact performance and low velocity of the GLARE FML were examined; in addition, the effect of flow paths on the mechanism damage, impact peak force, and dissipated energy were investigated through comparing drilled specimens as well as reference samples that have no drilled holes. The authors indicated that reference specimens without drilled holes showed that the FML failure mode was mainly due to metal sheets because the initial cracking sequence appeared in the aluminum sheets before they reached the fiber section. Moreover, the initial delamination between composite layers and distal aluminum appears at approximately 20 J. Thereafter, the preliminary break in the distal aluminum sheets appeared at 40 J, whereas, at 42 J, it started to appear in fiber sheets. The crack initiation, as well as propagation paths concerning the three various hole positions, is shown in Fig. 7 [47].

Park et al. [48] studied the influence of empty substances on the hygrothermal long-period performance of GLARE and glass/epoxy structures. Samples with distinct void substances of ranges of 0.5 to 2% and by adopting various autoclave pressures were acquired for both materials. Two sorts of thermal aging and hydrothermal experiments were conducted. The authors concluded that sterilizer pressure improves a specific limit of GLARE FMLs interfacial attaching [48]. Remmers et al. [14] investigated the delamination buckling performance of GLARE FMLs. The authors focused on this performance under compression. SEM images were captured to show the failure mechanisms and a numerical strategy was derived from the buckling delamination crack after the specimen was subjected to 3-point bending is given in Fig. 8 [14].

Abouhamzeh et al. [49] studied the influence of both overlaps plus gaps on the mechanical characteristics of FMLs. The used laminate is GLARE containing aluminum 2024-T3 layers in addition to prepreg sheets in between them using an adhesive epoxy. The author's main goal was to examine the impact of defects of various severities on the mechanical behavior of these GLARE samples. The authors conducted different mechanical tests to study their impact on the overlaps and gaps of the samples; they added that the gaps led to a drop in the mechanical behavior which in turn altered the properties of the material in distinct manners. Furthermore, the shear strength and tensile behavior were affected by the existence of such gaps. On the other hand, the specimens that had overlaps showed a rise in compression strength [49]. The compression failure occurring in the samples that had gaps is shown in Fig. 9 [49].

Esfandiar et al. [50] studied the tensile nonlinear performance of FMLs GLARE sort upon loading in-plane situations. The authors added that it is important to contemplate and examine the actions of inelastic deformation since the elastic and plastic performance of aluminum sheets is not sufficient to foresee the tensile reaction. Conclusions were carried out; the GLARE performance was nearly bilinear against the tensile load circumstances. Moreover, the tensile intensity of the GLARE laminates was tougher than those of aluminum sheets [50]. Hagenbeek et al. [51] studied the yield strength behavior of GLARE FMLs. The authors

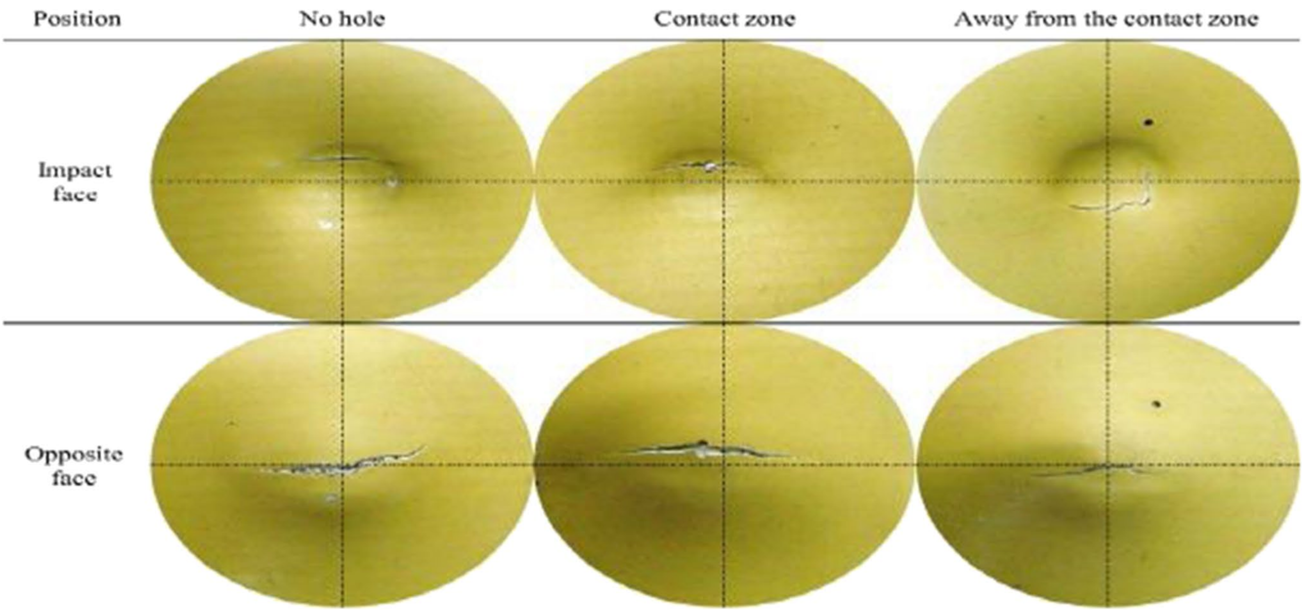


Fig. 7 Typical crack beginning and spread paths for the three distinct hole positions [47]

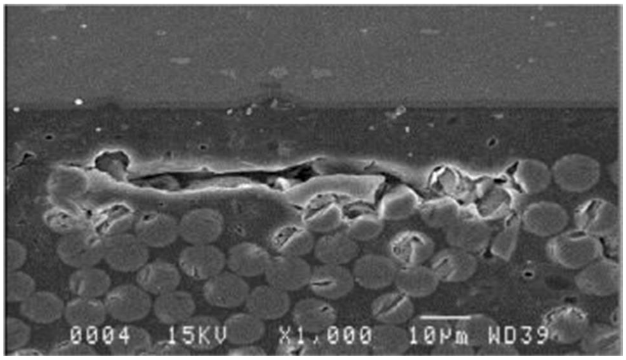


Fig. 8 Crack tip of Glare 2–3/2–0.3 of delamination buckling following being exposed to a three-point bending examination [14]

deduced that this strength was under the average for 90° and 0° orientations, while the yield strength was enhanced effectively at 45° orientations [51]. Baumert et al. [52] studied the fatigue and tensile characteristics of FMLs which contained aluminum 2024-T3 sheets and reinforced glass fiber epoxy. The authors concluded that initial fatigue cracks have been detected to exist within the outer sheets [52]. Kawai and Kato [53] investigated the impact of stress ratio on fatigue performance of FML GLARE type. The authors concluded that when rising the stress ratio, the fatigue threshold stress concentration leans to become above-average [53]. Kashani et al. [54] studied the influence of splitting a particular energy quantity into different levels as well as its structure on the FML samples undergoing low-speed impact. They concluded that the energy separation had a significant effect on the impact parameters plus failure modes [54]. Sharma et al. [55] explored the influence of aluminum sheets allocation throughout the FML thickness on the speed impact reaction. They indicated that this mechanism decreased the maximum force [55]. Pärnänen et al. [56] conducted impact drop weight experiments on fiber metal AZ31B-H24 magnesium-based laminates in addition to GLARE FMLs. The outcomes showed that the magnesium metal sheets have undergone cracks but with smaller impact energy while damage was further extensive compared to the other GLARE samples [56]. GLARE FMLs are one of the most important composites due to their good properties such as superb resistance to fatigue cracks, high static behavior, well impact endurance, and lightweight. Such composites are utilized in aircraft-effective applications; they include fine aluminum layers in addition to glass composites. Investigations on the mechanical performance of GLARE fiber composites were developed by researchers concerning the fracture, tensile, impact, velocity impact, corrosion, and moisture behavior of these composites. Table 5 represents the advantages and disadvantages of GLARE fiber laminates.

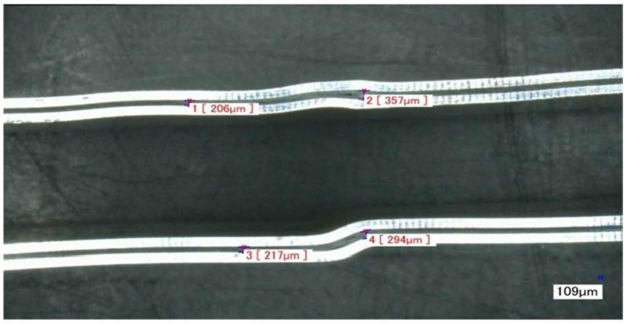


Fig. 9 Compression failure occurred in the samples that had gaps [49]

Table 5 Advantages and disadvantages of GLARE fiber laminates (Modified from Reference [25])

Advantages	Disadvantages
Excellent fatigue resistance	Low stiffness
Elevated precise static characteristics	Lower effective yield stress
Superb impact endurance	Delamination
Excellent residual	High cost
Fire endurance	

3.3 Carbon Fibers (CARE/CARALL)

CARALL is created of carbon/epoxy prepreg adhesively attached to the varying sheets of Al metal. It has outstanding pressure intensity than aramid-based FMLs; this material is useful in permitting break associating, thus an exceptionally small fracture development ratio. Applications of this laminate involve helicopter struts to absorb shocks as well as plane chairs. The arrangement of aluminum besides carbon fibers remains sensitive to deterioration generated through the variation in capability among the two substances [57]. Leonard et al. [58] researched the impact damage assets of FML by using X-ray computed technology (CT). The utilized materials were carbon-reinforced aluminum laminates (CARALL) FMLs in addition to two various structures, and the materials were subjected to impacting energies ranging from 10 to 30 J. initially, employed CT was found efficient to estimate the FML impact damage. The authors concluded that the results have shown that impact damage in composite and metal structures could be estimated and connected to the laminate structures. Moreover, concerning the identical impact energy, the framework having the lowest number of plies was subjected to more plastic deformation developed in the metal layers, whereas the structure having the highest number of plies showed further delamination sort damage. The authors also derived that the consequences supplied by CT analysis could be utilized to support numerical and analytical models that effort to simulate evolution damage in complex anisotropic hybrid laminates [59]. The use of FML composites in aircraft structures is efficient since they help in reducing just about 25% of the total aircraft load, enhancing fly effectiveness. This is also a purpose that might authorize these materials to be applied as ship's structure types, leading to a safe fuel condition as well as rising the ship's effectiveness at the sea. Damato et al. [60] studied the outcome of the environmental conditions on the fatigue performance of carbon fiber-epoxy with aluminum laminates. The authors used CARALL laminates containing delicate sheets of carbon fiber/epoxy prepreg inserted among the layers of aluminum Al 2024-T3 alloys sheets, which in turn results in a hybrid composite. Environmental conditions like moisture are taken into consideration in the project materials since they could lead to changes in mechanical characteristics. The authors reported the impact of the seawater environment on the fatigue performance of CARALL laminates. Samples were immersed in an artificial sweater for 20 days; they were also subjected to fatigue experiments and the consequences were compared with specimens subjected to hygrothermal conditions (water immersed on 70°C) as well as dry samples. The authors concluded that the seawater condition method was less effective than hygrothermal conditioning [60]. Botelho et al. [8] analyzed the hygrothermal effect on the shear characteristics of CARALL combinations. The composites utilized contain layers of aluminum 2024-T3 alloy along with prepreg composite layers. CARALL hybrid structure was developed by assembling the varying laminates regarding the carbon fiber/epoxy as well as the aluminum piece posterior to the lay-up operation; the samples were placed within a void bag and then set in the sterilizer mechanism. The healing phase took place at a level of heating ranging equal to 2.5°C/min and reaching 120°C for 1 h. The vacuum and pressure applied were 0.083 and 0.69 MPa, respectively. To find the impact of the environmental conditions on the strength of shear, both the CARALL samples and carbon/epoxy specimens were subjected to a sequence of humidity along with temperature by a conditioning ecological cavity. The rate of moisture was monitored periodically concerning the period by calculating the mass of models till the equilibrium humidity situation was attained. The interlaminar brief beam shear examination was brought out concerning ASTM D2344. The failure modes in both samples are shown in Fig. 10. The authors indicated that the CF/epoxy composite was able to absorb 1.4% humidity during the saturation spot (6 weeks). Whereas, the absorption of moisture concerning the aluminum sample was considered to be negligible in identical hygrothermal conditioning [8].

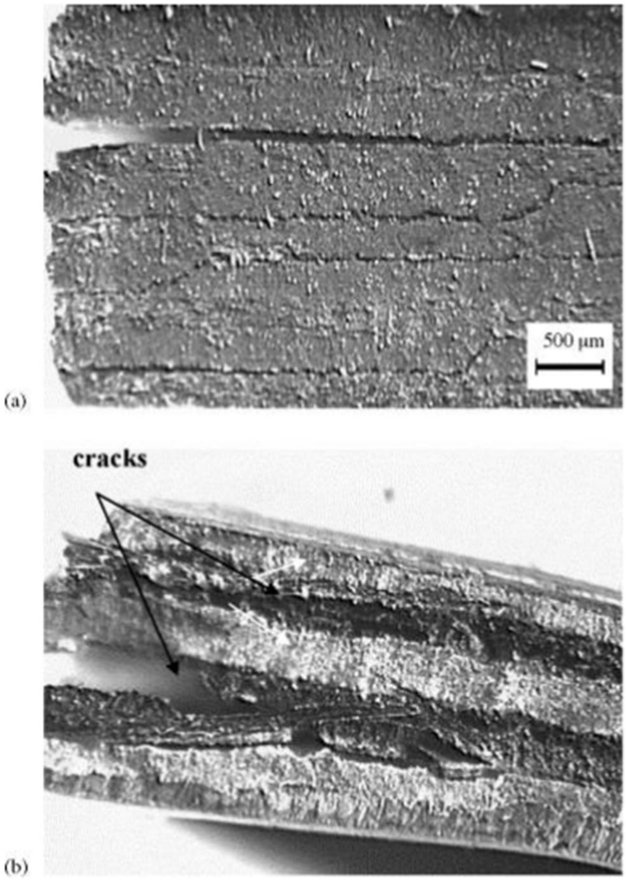


Fig. 10 Failure approach in **a** CF/E composite as well as **b** CARALL [8]

Lin et al. [61] considered the failure performance of carbon fiber-reinforced aluminum laminates. The materials utilized were aluminum 2024-T3 pieces having 1 mm depth, T-300 Torayca unidirectional prepregs P3E01-12 containing 37% resin as well as GFE # 213 (epoxy resin glass-cloth prepreg) with a resin content equal to 34%. To enhance the adhesion between the epoxy resin and aluminum sheets, different aluminum surface pretreatments were predestinated. Tensile experiments were conducted as well as fatigue tests the authors indicated that both modulus and tensile strength in longitudinal direction rise as the thickness of CARALL laminates increases. Whereas CARALL laminate's thermal residual stress increases also with the carbon/epoxy sheet thickness. In addition, CARALL structures show extreme fatigue fracture development resistance under the fatigue test in the 0-degree orientation [61]. Lin et al. [62] also studied the influence of thermal residual strains on carbon fiber-reinforced aluminum structures. The evaluation of their mechanical properties was done by both theoretical analysis and experimental methods. The experimental mechanisms applied consisted of the yield point shift concerning the aluminum sheets in the CARALL structure as well as the asymmetric laminate deflection. The theoretical computation carried out was based on lamination classical theory. The authors derived out that residual strains obtained by both theoretical and experimental methods presented well agreement. Moreover, the aluminum sheet's thermal residual stress was realized to remain severely relational to the fraction amount concerning the carbon/epoxy sheet [62]. Gilat et al. [63] researched the strain rate performance of carbon/epoxy IM7/977–2 composite matrix. Tensile experiments were carried out utilizing a hydraulic apparatus at static-quasi strain rates approximately equal to 10^{-5} 1/s as well as at intermediate strain values equal to 1 1/s, moreover, elevated strain rates tensile experiments were done too at values between 400 and 600 1/s. The authors derived that bigger stiffness is obtained as the strain ratio is boosted [63]. Mohammed et al. [64] studied the compression, tensile, along with flexural strengths concerning the sequence FMLs made of natural/synthetic fiber composites. The substances contained carbon fibers, flax fibers, aluminum alloy 2024, kenaf fibers, in addition to epoxy. Hybrid FML structures were prepared as distinct sheets of natural/synthetic fibers besides the aluminum alloy having a similar thickness. Established on the conclusions attained from the mechanical experiments, the CAFRALL specimens generated clearer mechanical characteristics, where they gave the greatest modulus of elasticity equal to 4.4 GPa. Additionally, the CAFRALL sample was 14.8% plus 20.4% bigger than the CAKRALL specimen in conditions of tensile along with compressive concentrations, correspondingly, also it gave a 33.7% smaller flexural strength. The conclusions achieved during the research show that mutually composites encountered the lowest characteristics necessary for usage within the fire-assigned region of an airplane engine because of their appropriate mechanical performance [64]. CARALL is developed from carbon/epoxy prepregs adhesively connected to variable layers of Al metal. This FML has better pressure strength than ARALL structures. The most important property of them is their ability to withstand cracks. The usage of such material could be seen in helicopters and other aerospace components. However, they suffer from some weaknesses concerning mechanical characteristics. Therefore, investigations have been carried out to study their mechanical behavior under different circumstances. Table 6 shows the advantages and disadvantages of carbon fibers (CARALL).

3.4 Polymer fibers (HP-PE, Zylon) and M5 fibers

Instead of exploring the use of aramid, glass, or carbon fibers, various investigations concentrated on the operation of polymer fibers in FMLs. Such as, during the ARALL initial period progress, Alderliesten [65] examined usage of superior-functioning polyethylene (HP-PE) fibers within FMLs. The author concluded that the rigidity of the nonimpregnated along with impregnated fibers direct the functioning of the fibers within FML including aluminum sheets. A further polymer fiber that was analyzed for FML purposes further lately was Zylon fiber [66]. Zylon, an artificial polybenzoxazole (PBO) fiber of modulus in addition to strength nearly twice that of Kevlar fibers(p-aramid) accompanied by a density comparable to fibers of aramid [25].

Table 6 Advantages and disadvantages of carbon fibers (Modified from Reference [5])

Advantages	Disadvantages
Outstanding pressure intensity	Harder production procedure
Excellent impact resistance	Low specific strength
Energy absorption	Failure strain

With the quality of small pressure strength as well as small structure elasticity modulus associated with polymers, AKZO established a strict rod fiber polymer known as M5 [64]. The fiber holds an outstanding sequence of strength coupled with stiffness, delivering adequate strain to fail to gain from this fiber variety in FMLs. The linked experiments presented by Delft Technology University, nevertheless, demonstrated that M5-FML tensile intensity is around 34% smaller than assessed to average GLARE; this later is mainly connected to the strain collapse. Mechanical characteristics of composite substances are regulated through the bond between fiber combined with the matrix [25]. Several studies were conducted concerning polymer-related FML's mechanical performance. The advantages and disadvantages of these fibers are shown in Table 7.

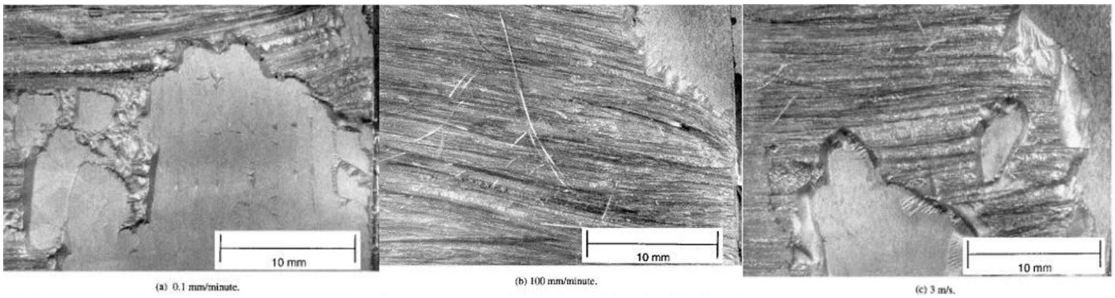
Vo et al. [67] studied the low-impulse performance of FMLs. The authors presented 3-D finite element models concerning small-impulse localized loading blast restraint of FMLs established on an aluminum 2024-T0 alloy as well as glass fiber/polypropylene woven composite (GFPP). The authors developed a VUMAT (vectorized user material subroutine) to explain constitutive mechanical performance as well as 3-D Hashin's collapse conditions including strain-ratio influences in the GFPP. Setting the blast localized load needs a subroutine operator VDLOAD to demonstrate the allocation of pressure among the plate unprotected area. The authors concluded that a decent connection was acquired among the examined investigational and mathematical displacements, failure modes, and panel deformations. Moreover, they indicated that by applying validated models, good parametric surveys could be conducted to enhance FML blast resistance established on a stacking sequence range as well as layer thickness [67]. Reyes and Cantwell researched

Table 7 Advantages and disadvantages of polymer fibers (HP-PE, Zylon) and M5 fibers (Modified from Reference [67])

Advantages	Disadvantages
High compressive strength	Shear weakness
High tensile modulus	Damage and eventual failure as a result of repeating cycling
Good adhesion	Low modulus of elasticity

to explore the mechanical characteristics of FMLs which are built on reinforced glass fiber polypropylene. The FMLs investigated in the research were established on an Al 2024-T0 aluminum alloy as well as a reinforced glass fiber thermoplastic. The authors focused on finding the impact and quasi-static properties; initial experiments have shown that well adhesion could be attained by surface treatments concerning the aluminum along with incorporating an interlayer established on a modified maleic-anhydride copolymer polypropylene by the interface level amid the aluminum plus composite layers. Cantilever individual experiments have shown that rupture energy is considerably high along with a wide domain of loading rates. Posterior experiments concerning several laminates indicated that the tensile characteristics of the layered systems are highly attached to the composite volume fraction. Relatively low-speed impact experiments on 3 various stacking series have shown that the materials utilized offer great resistance against dynamic loading. The surface fracture concerning the samples is shown in Fig. 11 [68].

Bienias et al. [69] studied the damage characterization and impact performance of reinforced carbon fiber polymer as well as hybrid aluminum laminates with low-energy impact and low speed. Internal failure modes, impact damage properties, damage initiation as well as progression, and understanding the part of the metallic layers concerning the impact performance upon low energy were investigated and debated. The authors concluded that the damage system of the examined laminates is so complex. An internal degradation appeared in the material, in addition to plastic deformation concerning FMLs. Matrix cracks characteristics such as shearing and bending cracks were obvious as initial damage mode at the interface of the fiber-matrix in the composite layers. The delamination (which appeared as critical damage mode) was perceived between the composite layers with various orientations also delamination appeared at the interface of metal composite concerning the FMLs. The authors added that in the instance of FMLs, the absorbed energy was related to the laminate's plastic deformation taking place essentially in metal layers. Whereby, during the situation of reinforced carbon fiber compounds, the absorbed energy concerning the impact is commonly linked with the elastic response along with the laminate damage. The damaged



(a) 0.1 mm/minute.
(b) 100 mm/minute.
(c) 3 m/s.

Fig. 11 Micrographs displaying the fracture overlay of conventional SCB specimens after experimenting at crosshead dislocation velocities of **a** 0.1 mm/min, **b** 100 mm/min in addition to **c** 3 m/s. Crack spread is as of right towards left [68]

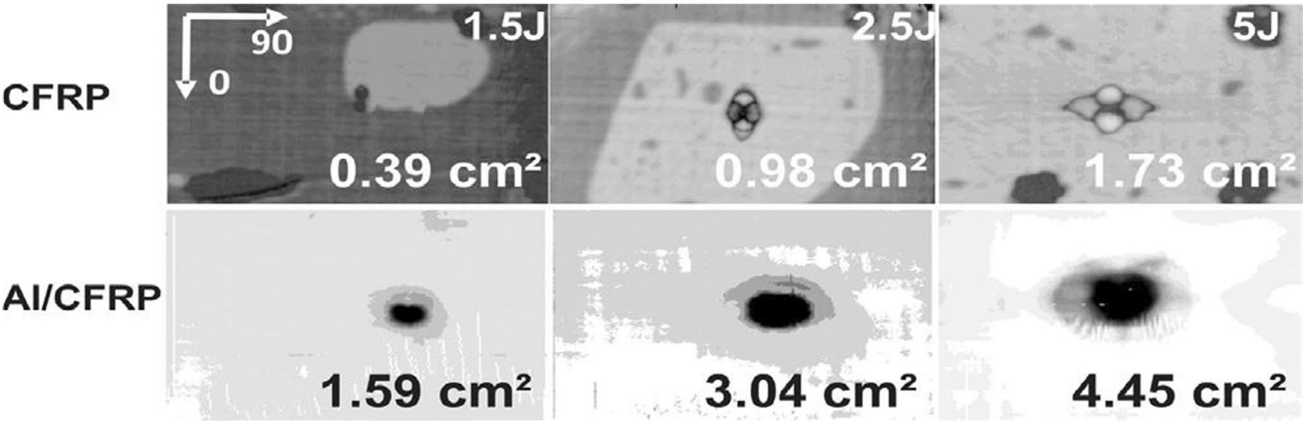


Fig. 12 Destruction section of CFRP as well as Al/CFRP following small-energy shock–ultrasonic view [69]

zone of both CFRP and AlCFRP posterior to the low-energy impact is displayed in Fig. 12 [69].

Cortes and Cantwell researched the fracture characteristics of magnesium alloy-established FML. Two types of reinforced composites have been examined, which were unidirectional glass fiber braced propylene and woven carbon fiber reinforced epoxy during the research. Premier experiments utilizing the SCB geometry (single cantilever beam) have indicated that small or even no cure of the surface is needed to accomplish a significantly tough bond between the magnesium alloy and the composite plies. Experiments on both sorts of laminates showed that boosting the composite volume fraction in the FML generated a considerable rise in the FML tensile strength. Similar experiments indicated that the increment of plies concerning the woven carbon fiber/epoxy led to a persistent drop in the modulus of plastic-matrix mechanisms. Additional fatigue experiments were carried out by the authors concerning two sorts of laminates that highlighted the practical support of the FML composite plies. The authors added that the presence of crack growth rates in the tension center-notched samples was relatively smaller in the case of FMLs compared to those of the magnesium alloy plain system. The fatigue failure is shown in Fig. 13 [70].

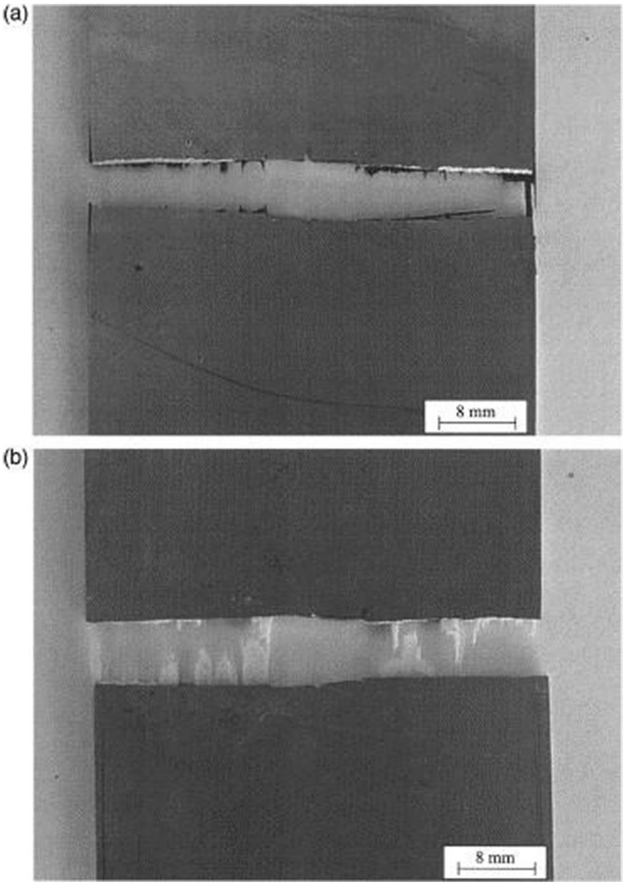


Fig. 13 The central area of the low power of failed sample is **a** Mg/CFRP and **b** Mg/GFPP [70]

Hu et al. [71] examined the change of temperature divergence on the mechanical performance of polyether ketone/base FMLs. Both interlaminar shear strength and tensile strength were examined at different temperatures containing room temperature, 120 °C, 170 °C as well as 220 °C, respectively. The consequences specified that the interlaminar shear strength and tensile strength dropped by 60% and 52% when examined at 220. Furthermore, thermal fatigue was applied at a temperature range from − 65 to 135 °C for 250, 500, 750, as well as 1000 cycles. After thermal fatigue, ILSS and tensile characteristics were investigated at room temperature. The authors derived that results were not efficient since thermal fatigue did not influence the mechanical characteristics of the FMLs [71]. Liu et al. [72] conducted experimental research to explore the fatigue properties of CFRP-steel hybrid structures. The materials used were CFRP (carbon fiber reinforced polymer) layers along with stainless steel thin plates. Tension-tension loadings were utilized through various loading options (same force, same stress, etc.), laminate lay-ups (double and single slides), and CFRP sheets layers were taken into consideration. Some investigational analyses were applied to find the influence of CFRP, adhering to the prolongation of fatigue fracture life, fatigue crack reproduction presentation, and fatigue life-extending concerning the hybrid laminates. Three various collapse approaches, delamination bending, delamination, as well as fiber were examined during the experiments. The authors indicated that both CFRP depth along loading restrictions are the crucial factors manipulating the mentioned failure modes as well as fatigue resistance. In addition, the initiation crack life along with fatigue life expectancy of the FMLs raised by circumstances that ranged from 1.06 to 1.96 plus 1.17 to 2.07, respectively, concerning the steel plates under identical force situations. On the other hand, these properties dropped under factors ranging from 0.63 to 0.89 and 0.28 to 0.61 respectively below identical stress situations. Furthermore, FMLs with double side bonding gave better fatigue characteristics and additional stable propagation of crack when compared to single side specimens [72]. The failure modes regarding the samples are shown in Fig. 14.

Poodts et al. [73] studied the experimental properties of FML concerning underwater applications. The laminate was comprised of a GFRP solid core and protected by thin layers of stainless steel to counter the absorption of moisture. The suggested lay-up was chosen to reduce the hygrothermal degradation concerning underwater applications. Both unprotected and protected structures were examined during both dehydrated and saturated wet environments. Critical attention was offered to the shear intensity of the laminates since it is related to low-speed impact resistance. The

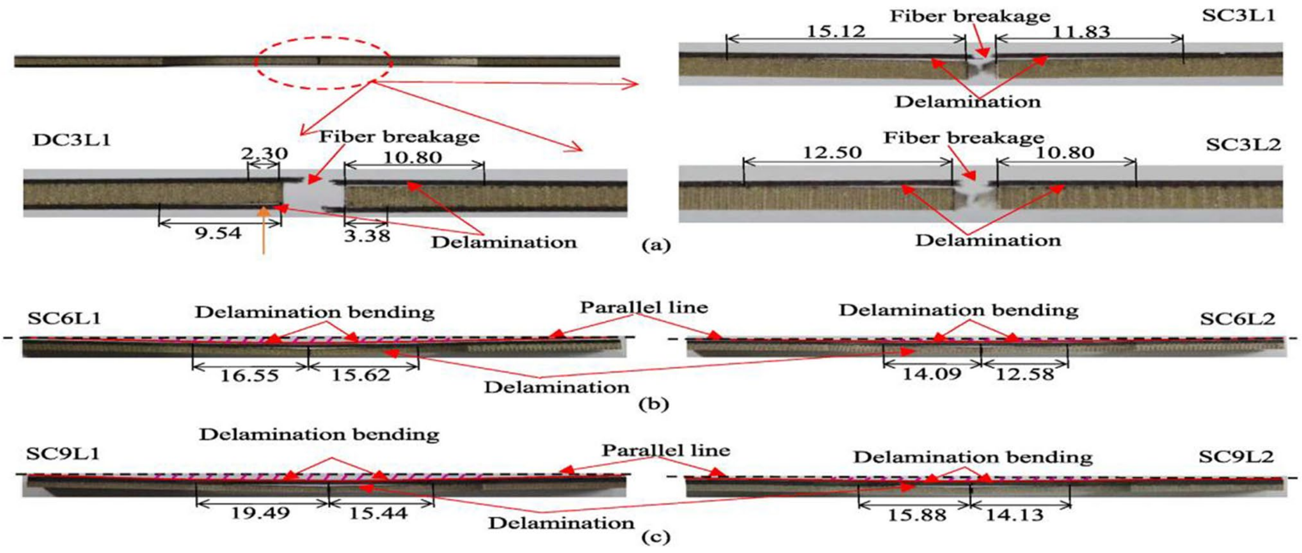


Fig. 14 Failure forms of analyzed samples: **a** 3-ply, **b** 6-ply, and **c** 9-ply [72]

authors focused on the impact of the caring steel sheets on the coefficient of diffusion out-of-plane shear strength and the impact of in-plane liquid absorption, on the low-speed impact performance, and finally on the dynamic characteristics. They derived that the steel layers offered excellent protection counter liquid absorption, therefore inhibiting the failure of mechanical characteristics linked to it, whereas the saturated samples showed a flexural modulus along with shear intensity loss of 20% approximately [73]. Prussak et al. [74] researched to examine the impact of thermal residual process-related stress on the mechanical characteristics of FMLs and how to reduce these impacts. Various modifications of co-cure steel/carbon epoxy-bonded sheets were examined. Particular tests were carried out on UP-CFRP-steel samples, adjusting the heat, and pressure, or utilizing a thermal extension clamp upon production. Different tests and methods were done and compared in the manner of reducing the residual stress and improving the mechanical characteristics. The authors indicated that the temperature modification or pressure process was found efficient in reducing the residual stresses up to approximately 33% when compared with the standard manufacturing operation. Furthermore, the utilizing of thermal expansion clamps produces the best consequences as well it decreases the residual stresses by approximately 65%, whereas it can be only applied for specific parts. Moreover, the residual stresses have shown an important impact on the tensile intensity of the laminates. The models with an MVF of 65% were subjected to an increase of tensile strength ahead to 3.3%, while models with smaller volume fractions and a considerably larger influence were expected [74]. Zhang et al. [75] explored the impact of elevated temperature and strain rate on the mechanical behavior of carbon fiber reinforced polyamide-6 structures. The laminates were assembled via a hot molding press. The impact of strain rate elevated temperature, and lay-up were examined by the authors via dynamic and quasi-static tests. Four various sorts of laminates with distinct stacking series were utilized during the experiments. The input parameters of strain rate ranged from 2.2×10^{-4} 1/s to 2200/s whereas the temperature variables were 293 k, 333 k as well as 373 k. The subsequent derivations were reported from the tests, the CGFRTs specimen's elastic modulus and strength of failure increased as the strain rate rises. Likewise, the intensity of failure along with modulus of elasticity concerning the used materials dropped when the temperature increased from 293 k to its maximum of 373 k. Furthermore, the 4 sorts of laminates gave distinct failure modes regarding tensile behavior because of the variation in malfunction processes of 0, 45/ − 45, and 90-degree layers [75]. Schossig et al. [76] analyzed the mechanical behavior of thermoplastic glass fiber reinforced materials under elevated -velocity tensile test. The substance of the glass fiber varied from 0 to 40 wt. % concentration, whereby the strain rate shifted from 0.007 to 174 1/s. The main goal of the research was to find how the carbon-fiber concentration and strain rate affects the performance of the material. When the strain rate was above 20 1/s, the tensile strength strictly increased unlike when the strain rate values were lower. Furthermore, the change of the fracture performance appeared as the glass-fiber concentration increased [76]. Reyes et al. [77] studied the mechanical performance of lightweight FML thermoplastics. The used materials were 2024-T3 aluminum and thermoplastic polypropylene prepreg; Curv 2 composites were used, one containing reinforced polypropylene matrix with fibers of the same thermoplastic material, whereby the second composite consisted of polypropylene prepreg glass fibers. A chromate

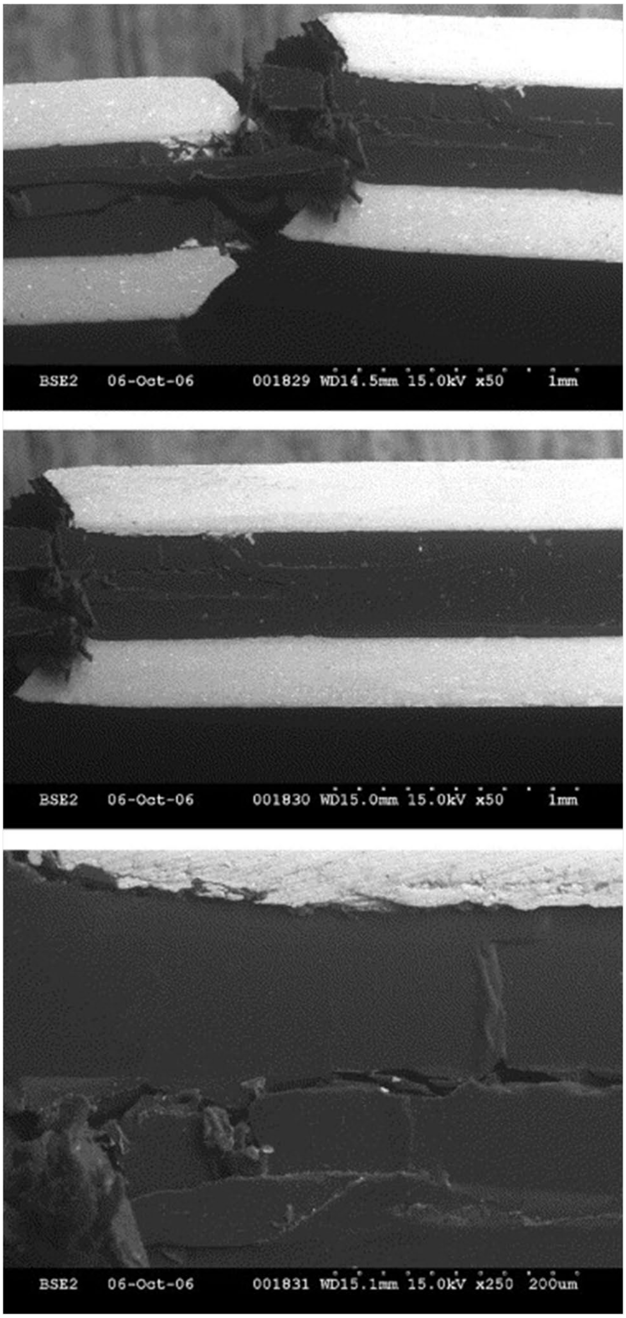


Fig. 15 Fracture procedures appear in a Curv-founded TFML through the formability experiment [77]

amorphous surface coating treatment was done concerning the aluminum alloy before the lamination method took place. Both fatigue and tensile strength experiments were developed to find the TFML characteristics under both fatigue and quasi-static loading situations. Curv TFML is shown in Fig. 15 under the formability experiment. The authors concluded that the primary tensile experiment showed that the curve hybrid substances exhibited a ductile behavior, and the superior strain and tensile strength were mainly dominated by the aluminum alloy. The investigation of the broken samples failed to show a clue of an interfacial division of layers among the divergent substances [77].

Rajkumar et al. [78] explored the impact of strain rate along with laying structure on flexural and tensile performance of 4 groupings of FMLs. Tensile as well as flexural experiments were performed upon a universal assessment device under standards. The consequence indicates that the tensile concentration grew with rising the strain rate. Nevertheless, the flexural intensity lessened with rising the strain rate. Both the flexural plus tensile concentration is highest for carbon-built FML forms, least concerning glass-established FML plus hybrid FML formation rests amid them. Carrillo and Cantwell studied the scaling impacts in a recent lightweight FML. The FMLs were established on a self-reinforced composite of polypropylene, an aluminum alloy, along with a polypropylene film interlayer epoxy resin. The research concentrates on the possibility of utilizing scale types to foresee the complete-scale performance of the laminates. Tensile experiments were conducted on laminates which were arranged utilizing three distinct scaling methods, 1D (scaling the dimension of thickness), 2D (in-plane dimension scaling), in addition to 3D scaling. All the mentioned dimensions were scaled properly. Geometric impacts were examined by observing the strength, stiffness, strain to failure as well as the stress/strain reaction concerning the FMLs. During the 1D as well as 3D-scaled models, a slight drop in tensile intensity was noted with boosting scale range, an influence that was linked with a shift in the collapsed form from tensile crack to the delamination. In disparity, the 2D-scaled model's intensity grew with expanding scale size, an influence that was credited to the reducing effect of edge delamination during the bigger experiment models. FML elastic modulus did not show any scale impact, staying nearly steady across the four sizes of the considered samples [79]. Elanchezhian et al. [80] investigated the mechanical performance of carbon and glass fiber reinforced composites at distinct temperatures as well as stress rates. The mechanical properties were examined by testing the laminates for flexural (at various strain rates), tensile (at distinct temperature and strain rates) as well as impact behavior. The authors concluded that carbon FRPs had better characteristics when compared to glass FRPs under flexural and tensile tests [80]. Lastly, polymer-related FMLs are widely used in different industrial sectors since they combine the properties of different sorts of composites such as Zylon, M5 fibers, FRPS, etc., along with different polymer materials including thermoplastics, GFRP, and CFRP types of polymers. Such kinds of FMLs have exceptional progression of intensity combined with stiffness, providing a sufficient strain-to-fail ratio. Examinations were done concerning the plastic deformation, elasticity, damage behavior, fracture performance, scaling impacts, etc. Other studies were carried out concerning different types and laying sequences of FMLs. Jones [81] studied the impact performance of FMLs. Theoretical investigations were carried out for the denting and deformation of FMLs while subjected to uniform blast loadings or low-speed impact loads, as well as these investigations, were compared with accessible experimental results. The author also clarified how theoretical plastic rigid solutions, several of that are obtainable in published literature, might be utilized to foresee the dynamic performance of FML. An unpretentious adjustment to reflect the FML actual cross section exposes that the theoretical investigations for denting (ductile damage) due to low-speed impact loading supply logical concurrence with the consequences of diverse experimental programs. The author concluded that the obtained theoretical analysis equations could be used for planning experimental efficient test programs. Moreover, the used modification investigation method is suitable to predict the blast impact performance of FML [81]. Silva et al. [82] also analyzed the cause of environmental conditioning on titanium FML mechanical characteristics. The samples of FMLs were developed with carbon/epoxy resin prepreg and titanium plates. The author's goal was to investigate the influence of two various environmental conditions (thermal shock and hygrothermal) on the elastic and mechanical behavior of the titanium FML because the mentioned environmental impacts should be reserved for consideration always while discussing the structural elements. The authors derived that during hygrothermal, there was a lower moisture absorption because of the presence of Ti sheets, whereas in the case of thermal shock, the viscoelastic and mechanical characteristics dropped [82]. Moussavi et al. [22] researched to investigate the tensile characteristic of novel fiber/metal laminates. Kevlar along with glass fibers were applied simultaneously and the influence of fibers placement on the tensile performance of the used novel structure was examined. To predict the strain and stress responses of the FMLs, a classical laminate modified theory (CLT), which takes into consideration the plastic-elastic performance of aluminum sheets, in addition, a numerical simulation technique was applied. Samples were manufactured and mechanical experiments were implemented to regulate plane-tensile characteristics concerning this sort of FMLs. The authors assumed that the fiber sheets having zero orientation within the material enhanced the elastic modulus, ultimate tensile stress, along yield stress noticeably. Furthermore, the independent interactions and variables' influence concerning their virtual importance on tensile performance was given. The samples following the tensile analysis are indicated in Fig. 16 [22].

Khalili et al. [83] researched the mechanical characteristics of steel and aluminum/GRR structures. Three mechanical experiments (tensile, 3-point bend, Charpy impact assessments) were carried out upon the samplings. Specimen number 1 (epoxy resin), specimen no. 2 (GRP layers), specimen no. 3 (aluminum AA. 1050), and specimen no. 4 (stainless steel 316 L), four sorts of FML layers, were developed by hand laying technique, and the specimens were coded with different sequences. The bending deformation of FML specimens is shown in Fig. 17. The authors concluded that the existence of steel sheets in FML specimens helped in raising the absorption of energy, displacement, and stiffness concerning remaining FML specimens [83].

Naik et al. [84] investigated the tensile performance of specific composites (woven fiber E-glass/epoxy) under elevated strain. The experiments were applied via SHPB (split strain pressure bar) device at strain rates varying from 140 to 400/s; furthermore, the quasi-static characteristics were even developed and a raise of 75–93% was shown throughout the elevated strain rate thickness of tensile strength when compared to this strength at the quasi-static condition. The authors derived that when the strain rate raised, an increase of up to 11% concerning the tensile strength was observed ahead of the thickness path. Whereas, this strength increased by 16% ahead of the fill direction [84]. Okoli studied the effect of failure modes and strain rate on the energy failure of fiber-reinforced composites. Tensile experiments were conducted concerning the ASTM D3039 method. In addition, 3-point bond tests, and impact instrumentation tests were done too, and the planes of the specimens have been investigated by utilizing SEM micrographs while the shear tests were carried out upon the ASTM D5379-93 method. The results derived concerning the woven glass laminate showed a raise in shear tensile as well as flexural energy of 5.9%, 17%, and 8.55%, respectively; after that, the strain rate increased. The failure modes concerning the examined laminates showed several changes as fiber brittle failure and fracture [85]. He et al. [86] investigated the impacts of the layer direction along with hole quantity on the tensile performance along with malfunction processes of multi-hole FMLs by investigational procedures. In addition, tensile experiments are applied to acquire mechanical reactions of various multi-hole FMLs. Afterward, a mathematical simulation regarding thermal residual stress was carried out to clarify the failure approaches concerning the multi-hole FMLs. Definitively, numerical expectations were observed in a decent deal with investigational measurements, in conditions of mechanical reactions as well as fracture morphologies. Findings prove that the amount of gaps has an insignificant effect on the essential tensile intensity; however, it alters the multi-hole FMLs final failure strain [86]. An example of multi-hole FMLs is shown in Fig. 18.

Yamada et al. [88] carried out flexural experiments to examine the influence of the metal sheet number on the breakdown mode as well as the mechanical characteristics throughout plane loading. The utilized FMLs entailed prepregs of thin plies plus stainless-steel sheets with a thickness of ply equal to 0.04 mm. The authors concluded that the

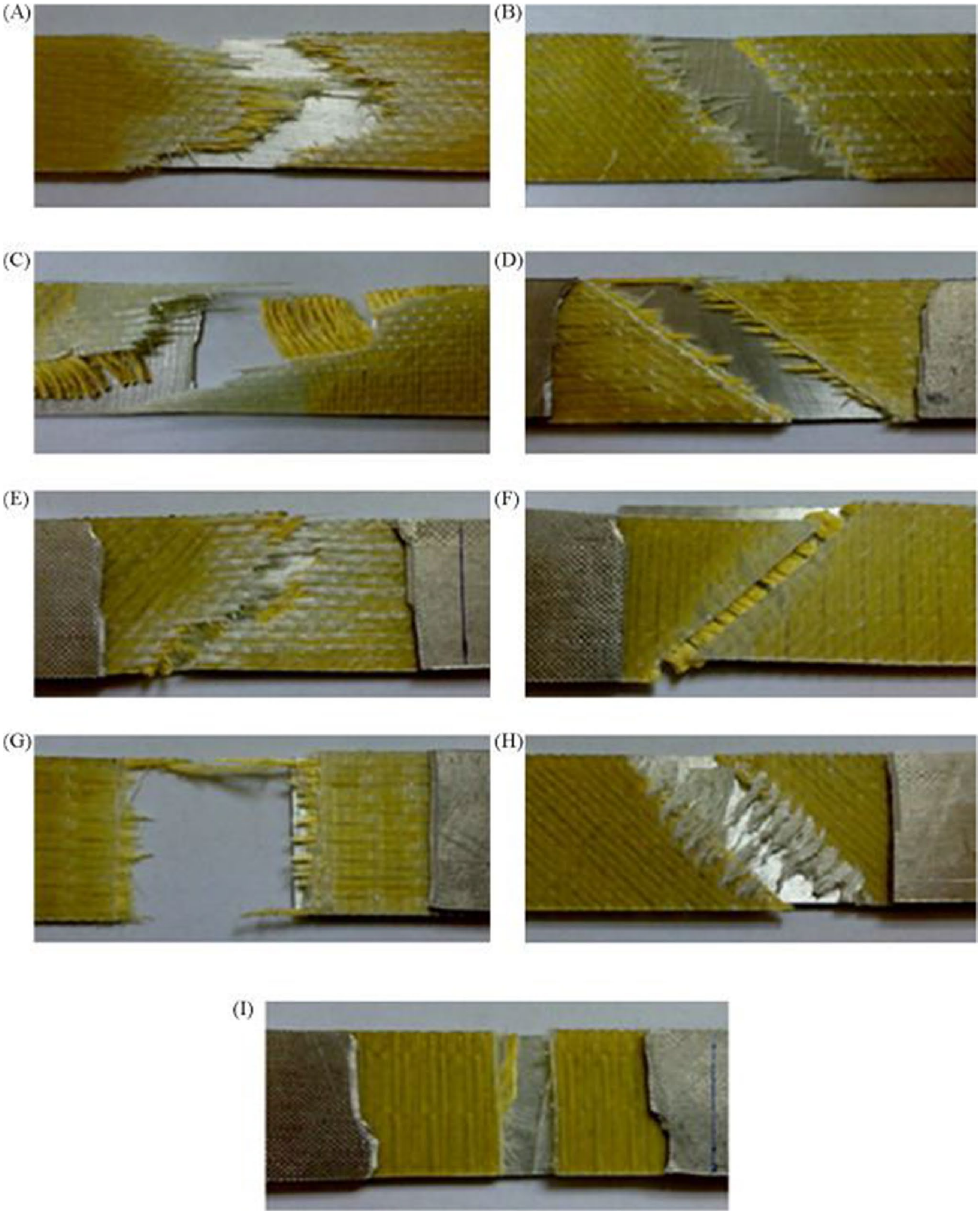


Fig. 16 Samples after tensile examination [22]

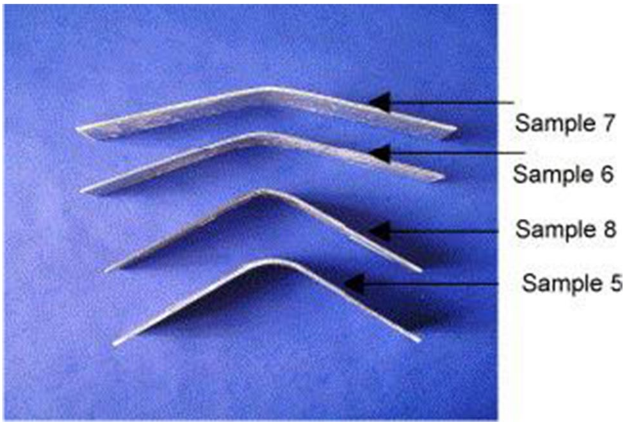


Fig. 17 Bending distortion of FML specimens [83]

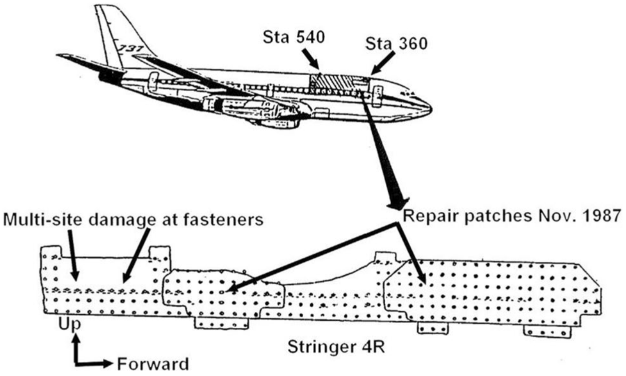


Fig. 18 FML multi-hole of the fuselage skin [87]

metal layers' plastic deformation played a role in enhancing the energy dissipation; therefore, the breakdown happened within a partial selection of positions. They added that the flexural modulus in addition to strength were both enhanced when implanting metal foils [88]. Hu et al. [89] investigated the mechanical characteristics of polyimide FMLs consisting of different layup structures as well as different fiber sheet orientations. The samples were exposed to tensile and compressive stresses on both the lower and upper surfaces respectively via the flexural strength function. Whereby the buckling local failure and delamination dominated the primary position. The authors derived that the interlaminar strength of the shear characteristic was higher in the case of FMLs that were subjected to pretreatment coatings unlike those that were kept untreated. In addition, the utilized load was significantly relocated through the polyimide resins to the carbon fibers. Moreover, the interlaminar shear was higher in the unoriented FML sheets unlike those that were applied to orientation which had low values [89]. The failure samples are demonstrated in Fig. 19.

Li et al. [90] examined the mechanical characteristics of FMLs by considering the influence of graphene oxide taking into account the performance of tensile, interface shear, and flexural characteristics. The authors added that the specimens with graphene oxide showed a well tensile behavior when compared to the FML samples without the oxidation; also, the tensile strength plus young modulus of the oxidized specimens were raised by 11.7% and 13.5% correspondingly [90]. Li et al. [91] studied the mechanical performance of FMLs by examining the influence of shot peen, and the authors focused on studying the static intensity, interlaminar, and fatigue characteristics concerning the FML's shot peened samples. The authors concluded that the tensile intensity of the laminate samples was boosted due to the work hardening within the metal sheets which was caused by the shot peening. On the contrary, the hardening had no impact on the case of weakening the FML elongations. In addition, during the tensile experiments, 2 yield phases were noted due to the variation in the conditions of stress among the inner and outer sheets of metal [91]. Hao et al. [92] studied the mechanical characteristics of FMLs that contained sheets of magnesium alloy plus permanent Zn-Al reinforced carbon fiber composite sheet. Tensile tests were carried out and the consequences revealed an enhancement in the tensile intensity as well as the modulus of elasticity by 103% besides 41% correspondingly; this improvement took place in the case of the Zn-Al alloys unlike the magnesium sheets [92]. Kali et al. [93] investigated the mechanical characteristics of FMLs containing AL 7075-T6 aluminum alloy by conducting experiments concerning the strength of tensile behavior; the tests were done on 2 samples of the laminates under both damaged and undamaged situations. The main purpose of the test was to recognize the influence of damages on the performance of tensile strength. The authors illustrated that the strain and stress relation played a role in reducing the tensile static strength because of the lack of relaxation in stress within the circular hole, which in turn advances to an elevated stress intensity among the brittle breakdown and damage [93]. Kuan et al. [94] investigated the impact and tensile characteristics of FMLs. Four specimens were examined, and the authors added that the model they conducted was efficient in finding these properties [94]. Baumert et al. [52] studied the fatigue and tensile characteristics of FMLs which contained aluminum 2024-T3 sheets and reinforced glass fiber epoxy. The authors concluded that initial fatigue cracks have been detected to exist within the outer sheets [52]. Gupta et al. [95] studied the mechanical behavior of FMLs under fatigue experiments. The authors deduced that the cracks did not spread vertically to the loading in the case of the metal sheets [95]. Chang et al. [96] investigated the fatigue crack performance of FML. They added that the hybrid composite sheet decreases the stress level of the aluminum layers leading to an extreme

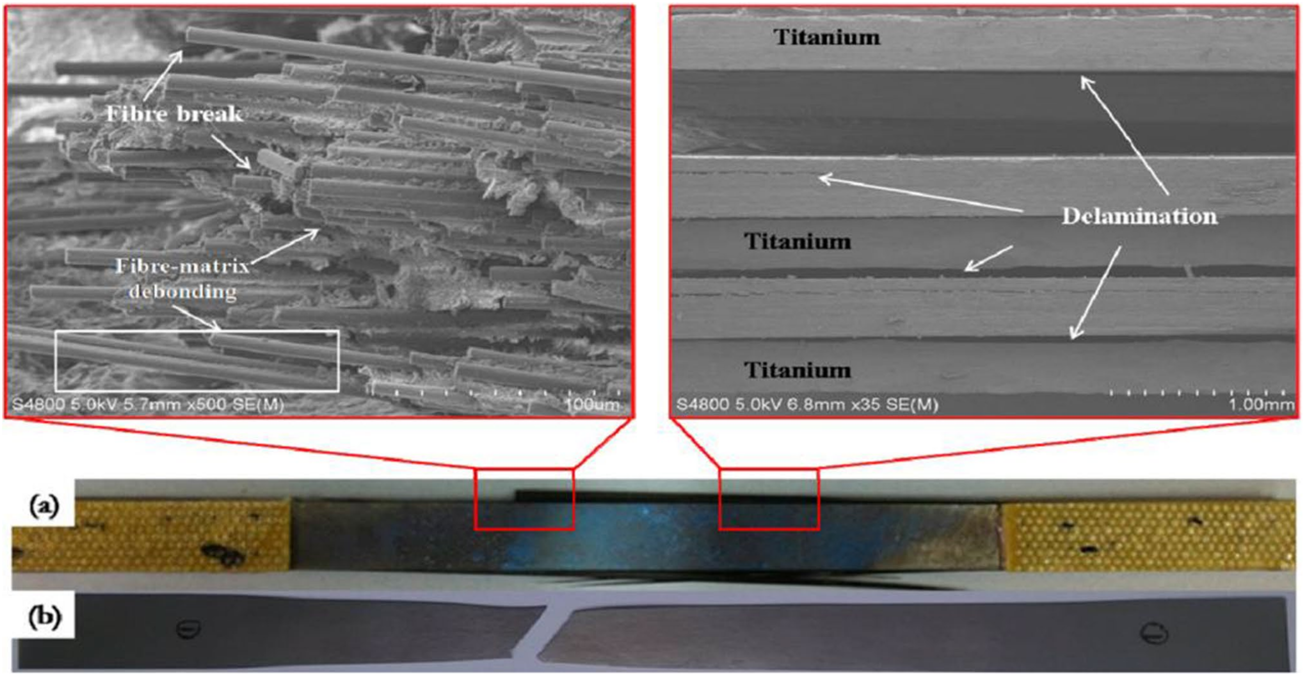


Fig. 19 The breakdown of the tensile samples **a** FMLs in addition to **b** TA2 [89]

barrier against fatigue cracks [96]. Singh and Angra [97] studied the impact and flexural characteristics of glass fiber-stainless steel-epoxy fiber laminates and glass/epoxy fiber. The authors concluded that the mechanical characteristics of reduced in the case of stainless-steel samples [97]. De Cicco et al. [98] studied the influence of impact features on different FML structures. Conclusions showed obvious discrepancies in the case of 3 and 2 sheets of magnesium, particularly taking into consideration the capacity of energy absorption [98]. Pärnänen et al. [56] conducted impact drop weight experiments on fiber metal AZ31B-H24 magnesium-based laminates in addition to GLARE FMLs. The outcomes showed that the magnesium metal sheets have undergone cracks but with smaller impact energy while damage was further extensive compared to the other GLARE samples [56]. Finally, the previous studies took into consideration the mechanical behavior of other sorts of FMLs in addition to these composites when linked to other metal alloys. Flexural, impact, fracture, tensile, and compression behaviors have been studied. The recent approaches to study the mechanical characteristics of FMLs are summarized in Table 8.

4 Methods to improve the FML mechanical performance

Lately, FMLs have been used by several industries due to their attractive properties including mechanical ones. These structures are hybrid substances developed by the adhesion of fiber sheet composites with other narrow sheets of metals. Unfortunately, these structures suffer some weaknesses and disadvantages when it comes to specific mechanical characteristics. Therefore, the improvement of such characteristics is efficient. Farsani et al. [131] mentioned that the use of nanofillers consisting of graphene nanoplates, carbon nanotubes, or clay/oxide nanoparticles are various methods applied in the matter of enhancing such mechanical behavior. The writers also stated that these nanoparticles enrich these properties; they, in turn, depend on numerous aspects like metal layers surface treatment, the kind of nanoparticle used, the dimensions of specimens, fabrication constraints, in addition of the nanoparticle's morphology, etc. [131]. Owing to their outstanding mechanical and thermal characteristics, CNTs known as carbon nanotubes were the highly prevalent strengthening of polymeric structures. The improving systems of CNTs on the mechanical performance of FMLs rely on specific factors [132]. Surface management of metal layers is considered the most substantial impacting constraint on FML's performance. To improve the adhesion between the composites and metals, several surface improvement techniques could be used such methods are classified into chemical, electrochemical as well as mechanical [133]. The application of such treatments before the lamination process can considerably impact the surface morphology and mechanical properties of FMLs [134–136]. Konstantakopoulou and Kotsikos [137] examined the behavior of GFRP under the influence of multi-walled carbon. The writers implied that

Table 8 Recent approaches to study the mechanical characteristics of FMLs

Year	Authors/ref	Test	Remarks
2021	Yao et al. [99]	Tensile mechanical behavior	The layer direction has a quiet impact on the tensile force as well as failure processes of FMLs
2009	Baumert et al. [52]	Tensile and fatigue properties	The fatigue cracks recruit at holes in an extremely straight approach vertical to the load axis
2017	Hamill et al. [100]	Mechanical performance and galvanic corrosion of FML	Tensile intensity plus modulus of BMG-established FMLs are larger than Al-founded FMLs
2015	Kumar et al. [101]	Compressive strength GlARE	The physical intensity of the FML did not increase as the metal thickness increased
2020	Azghan et al. [102]	Flexural performance of FMLs	Flexural strength, modulus, and fracture energy rates correspondingly expanded to 10, 14, and 9% when utilizing 40 thermal cycles, evaluated to experiment in absence of thermal cycles, the flexural characteristics were lessened during 60 cycles
2017	Kashfi et al. [103]	FML mechanical properties	Tests showed a nonlinear elastic performance concerning the GFRE sheet
2019	Tobalina-Baldeon et al. [104]	Dynamic tensile-compressive stress performance of CFRTP FMLs	The material used is resistant to deformation, superior to steel in sound, and dynamic along damping characteristics
2016	Dhaliwal et al. [105]	Dynamic and static behavior of CARALL	The veil cloth layer does not reduce thermal residual stress, also it rises the flexural strength of both specimens
2019	Sun et al. [106]	Tensile failure behavior of FMLs	Metal sheet near to the 0^0 fiber sheet fails concurrently, the metal layer bonded with the 90^0 fiber sheet fails independently posterior to delamination
2006	Woo [107]	Tensile performance plus fracture toughness of GFAL	The tensile concentration of GFAL essentially depended on fiber orientations
1970	Lifshitz aand Rotem [108]	Tensile experiments on unidirectional composites	The tensile intensity of the samples under impact was found three times larger than those of the static situations
1976	Daniel and Liber [109]	Strain rate test	Specimens revealed a 20% growth for both the tensile modulus and the failure strength within the longitudinal path
1983	Harding and Welsh [110]	Dynamic tensile experiments concerning UD graphite/epoxy	The dynamic modulus plus strength of specimens were 2–3 times bigger than the static values
2004	Ochola et al. [111]	Examined material strength	Dynamic substance intensity of GFRP boosted with rising strain ratios, however, the strain to malfunction of both CFRP plus GFRP lessened while rising strain values
2009	Shokrieh and Omidi [112]	Compressive assessments	Compressive strength combined with modulus increased while expanding strain rates
2001	Hosur et al. [113]	The reaction of both cross-ply and unidirectional carbon/epoxy combination	The strength PLUS stiffness of the laminates during elevated strain rate boosted noticeably compared with static values
2019	Massaq et al. [114]	Compressive mechanical reaction ofPA6/glass structure	Encouraging rate sensitivity concerning the failure stress and elastic modulus were noted
1987	Smiley and Pipes [115]	Double cantilever beam (DCB) examinations	The rates of fracture toughness of the composites were observed to be diminishing
1998	Kusaka et al. [116]	Fracture performance within unidirectional carbon/epoxy laminates	Fracture toughness estimates were reduced with rising loading rates
1996	Camacho and Ortiz [117]	Impact damage	The computed data were found to be in fair settlement with the experiment
2006	Corigliano et al. [118]	Dynamic delamination of composite by a numerical model	The global crack energy and the crack spread speed participating in the procedure could be extremely affected via rate sensitivity constraints

Table 8 (continued)

Year	Authors/ref	Test	Remarks
1998	Hauch and Marder [119]	Dynamic fracture	The presence of traverse cracks as well as a subsurface damage area results in velocity dependence concerning fracture energy
2005	Zhou et al. [120]	Crack propagation test	The growth in fracture energy has a greater crack speed was generated by little branching cracks
2009	Guimard et al. [121]	Rate causes in the mode-II delamination	The rate impacts of the composites were not similar for crack speeds under the Rayleigh wave velocity
2006	Mulliken and Boyce [122]	Rate-related plastic-elastic deformation	A significant transition occurred in the disposition of the material yield performance rate dependency
2002	Yu et al. [123]	Influence of a unidirectional graphite/epoxy laminates	Regional hot marks were developed alongside the fracture surfaces of a dominated intersonic shear crack
2015	Asaee et al. [124]	Low-speed impact reaction	The bending solidity of 3DFG-FML was noted to be bigger than FML properties
2003	Borgonje et al. [125]	Moisture performance of GLARE	The thinner layers utilized in Glare have improved corrosion characteristics
2013	Sadeghpour et al. [126]	Influence of blunt notch intensity	Improving aluminum thickness marginally improves the exact yield strength
2018	Lee et al. [127]	Impact performance	Fiber alignment primarily impacted the path of crack transmission in the FMLs
2012	Da Costa et al. [128]	Impact of thermal phases	Thermal-shock phases had no important influence on the FML microstructure
1999	Hashagen et al. [129]	Delamination performance	The effect on the stress/strain link was slight
2015	Lan et al. [130]	Microstructure in addition to tensile characteristics	Regional microstructure, as well as geometry, have a slight impact on tensile characteristics

the accumulation of MWCNTs with two intensities of 0.1 along with 0.3 wt.% managed to the increase joint intensity rate [137]. Khurram et al. [138] conducted similar research but with MWCNTs concentrations (1, 1.5, 2, 2.5 then, 3 wt.%) on the mechanical performance of FMLs comprising Al2024 sheets combined with GFRE composites. They dedicated the various substances of these MWCNTs did not raise the strength bond of the used specimens [138]. Fereidoon et al. [139] researched the impact of the accumulation of mutually MWCNTs as well as functionalized-MWCNTs on the bond amid the Al2024 in addition to glass fibers/epoxy composite. They assumed that the shear intensity rate of trials was advanced upon the supplement of all intensities of nonfunctionalized MWCNTs. Nevertheless, the accumulation of functionalized/MWCNTs triggered a significant decline in the shear strength rate concerning the models [139]. Zhang et al. [140] considered the impact of MWCNTs with different concentrations equal to 0.5, 1 along with 2 wt.% on low speed besides flexural influence on the mechanical performance of FMLs. They indicated that 0.5 wt.% concentration enhanced the flexural intensity along with the modulus of the used FML specimens [140]. Mactabi et al. [141] indicated that fatigue resistance of FML specimens was enhanced under MWCNTs with an intensity equal to 1 wt.%. Wolf et al. [142] expanded the bond behavior of FMLs via combining CNT-specific peptides with protein compounds. The calculations demonstrated that the shear intensity with 0.7 wt.% concentration was around 18.8 MPa; however, pristine epoxy shear intensity was 15.4 MPa [142]. Zhu et al. [143] examined the effect of different surface pretreatment methods such as anodizing, surface modification, as well as the sand mechanism on the mechanical behavior of FMLs. The writers concluded that such treatments had a good influence on the bonding behavior of these FMLs [143]. Last of all, the importance of FML structures for different industrial sectors has made them an important field of investigation for various researchers, which in turn examined the mechanical behavior of such materials. Results have shown a few weak behaviors concerning distinct properties. In that manner, studies have been done to improve the mechanical performance of different types of FMLs using several methods as surface treatments.

5 Conclusions and future scope

FMLs known as fiber metal laminates, a new lightweight material combining the properties of both the fiber composites addition to the metal or material used are considered a very important substance in nowadays industrial sectors, with several attractive characteristics from lightweight, great strength, superior corrosion resistance, and exceptional strength-to-weight ratio matched to the standard composite lamina. Furthermore, they offer superb fatigue properties. Combining all these benefits, FML structures have achieved extensive usage in the aerospace manufacturing sector throughout the past decades. This material is separated into several forms of various compositions such as GLARE, CARALL, ARALL, etc., which have different mechanical properties. The broad usage of fiber metal laminates in automotive, aerospace, etc., makes this material an essential composite structure due to its critical qualities, particularly for lightweight applications. Corresponding to the significance of FMLs, it is desirable to be informed of the mechanical performance awareness concerning this composite structure. The recent literature review is an attempt to aggregate numerous research papers performed on the mechanical properties of FMLs as well as diverse types of such composite structures under various experimental tests and conditions. The review concentrates on the different test methods used, their input qualities, their impact, the environmental situations, and other prominent closures that may affect the mechanical performance of these laminates. Other studies were conducted in the manner of enhancing the mechanical performance of FMLs using different methods including treatments of the surface.

The increased requirement for FML materials in marine, automobile, as well as aerospace sectors has made such materials an efficient replacement for standard metal alloys. However, the usage of FMLs in other fields continues to be an accessible investigation subject for several purposes such as railway vehicle-associated applications, protection tools along with marine high-speed vehicles, etc. In spite of extensive advancement done over time, analytical models for FMLs remain in their early stages and several research questions could be addressed for future studies. In addition, the improvement of FMLs is also not sufficient to date and important future studies could be developed to enhance those materials using advanced new technologies and novel substances.

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Declarations

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