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A Review: Fiber Metal Laminates (FML's) - Manufacturing, Test methods and Numerical modeling

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Abstract- Weight reduction of components is the main aim of different industrial sectors. This leads to increasing application areas of fiber composites for primary structural components. Aiming this objective, a new lightweight Fiber/Metal Laminate (FML) has been developed. Fiber metal laminate is one such material which is being widely investigated for its performance compared to existing material.. The most commercially available fiber metal laminates (FML's) are ARALL (Aramid Reinforced Aluminium Laminate), based on aramid fibers, GLARE (Glass Reinforced Aluminium Laminate), based on high strength glass fibers and CARALL (Carbon Reinforced Aluminium Laminate), based on carbon fibers. The mechanical properties of FML show advantages over the properties of both aluminium alloys and composite materials individual. This paper reviews relevant literature which deals with different manufacturing techniques for FML's with excellent properties under tensile, flexure and impact conditions. It also reviewed recent modeling techniques on FML's. Modeling of tensile, flexure and impacts behavior on fiber metal laminates requires understanding the bonding between the metal and composite layer. Further research is necessary in the assessment of mechanical performance of complex structures in real world conditions.

Index Terms- Fiber Metal Laminates (FML), Mechanical properties, Computational models.

I. INTRODUCTION

In most of industrial and structural applications the important parameters in material selection are specific strength, weight and cost. Fiber Metal Laminate (FML) is a family of hybrid composite structure formed from the combination of metal layers sandwiching a fiber-reinforced plastic layer. The metal currently being used is either aluminium, magnesium or titanium, and the fiber-reinforced layer is either glass fiber, carbon fiber and aramid fiber reinforced composite. Fiber-Metal Laminates (FML's) are composed of alternatively stacked metal and fiber reinforced composite layers shown in Fig. 1,with advantages of hybrid nature from two different constituents (Metal and fiber), the FML's gives excellent mechanical properties like high corrosion resistance, outstanding strength to weight ratio compared to conventional composite lamina [1]. The development of first FML's, namely aramid reinforced aluminium laminate called as, ARALL started in the 80's at the Delft University of Technology. Subsequently in order to improve the mechanical properties of FML's, carbon fiber reinforced (CARALL), glass fiber reinforced (GLARE) aluminium laminates are developed [2].These laminates consist of thin high- strength aluminium alloy sheets (typically 0.3-0.5 mm thick) bonded together with alternating unidirectional composite prepregs. The prepregs are aramid, carbon or glass fibers in an epoxy resin [3].

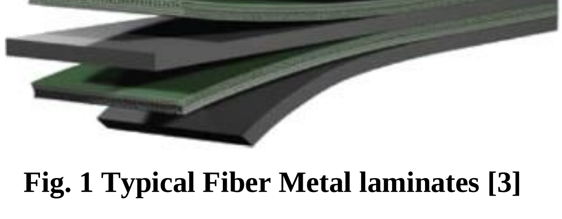

Fig. 1 Typical Fiber Metal laminates [3]

Fig. 2 gives a classification of FML based on metal plies. The most commercially available FML's are ARALL1, based on aramid fibers and GLARE1 based on high strength glass fibers.

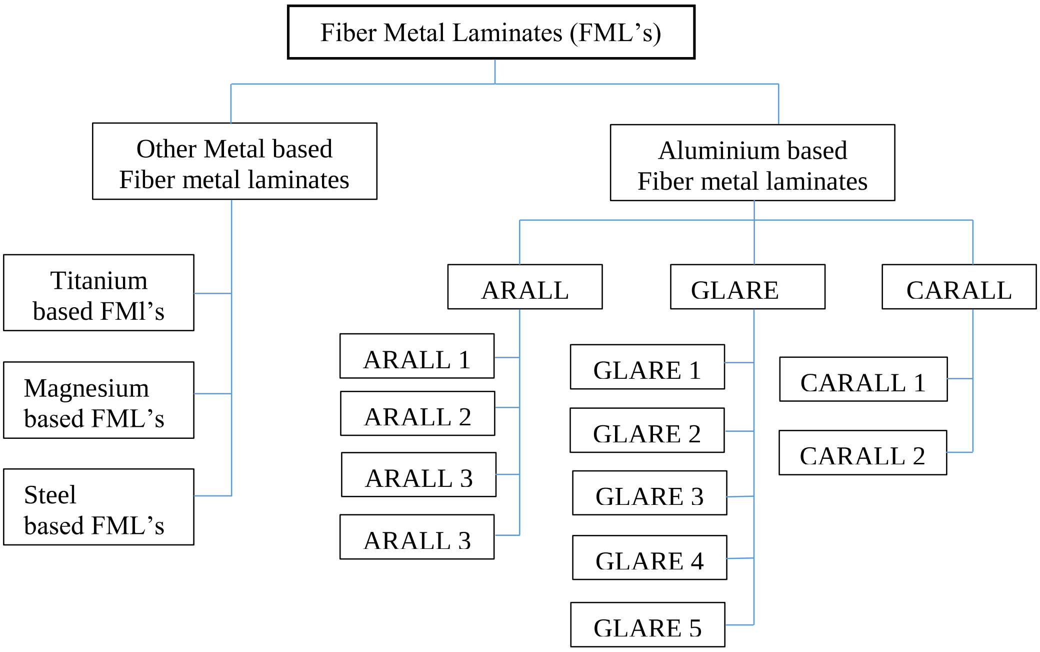

Fig 2: Typical Classes of FML's

1.1 Advantages, Disadvantages and Applications of FML's

Due to the combination of metal and composite material, FML's take advantages of metal and fiber-reinforced composites; it gives superior mechanical properties to the conventional lamina which consisting fiber-reinforced lamina or monolithic aluminium alloys only. Advantages of fiber metal laminates depending on previous investigations are summarized in Table 1. Long processing cycle to cure the matrix in composite plies is the major disadvantage associated with epoxy based fiber metal laminates. This long curing time increases the cycle time of whole production and decreases productivity. Ultimately increases labour costs and overall cost of FMLs [4-6].

Table 1. Advantage of fiber metal laminates

Key Parameters	Ref.	Details
High strength	[4,5]	FML's are hybrid structures based on thin metal alloy sheets and plies of fiber-reinforced polymeric materials. Metal and fiber reinforced composites both which have high strength and stiffness result in high strength and stiffness FML's.
Low density	[7]	Due to the presence of thin layers of metals and composite piles, it has low density. So, FML's are a weight saving structural material compare to others.
Excellent corrosion resistance	[7-10]	FML's gives excellent moisture resistance and high corrosion resistance because of polymer based.
Excellent moisture resistance	[1,10]	Due to the presence of metal layers at outer surface the moisture absorption in FML's composites is slower when compared with polymer composites, even under the relatively harsh conditions. Additionally pregreg layers are able to act as moisture barriers between the various aluminium layers inside of the FML's.
High fatigue resistance	[5,10]	It gives high fatigue resistance because of intact bridging fibers in the wake of the crack, which restrain crack opening. FML's have excellent fatigue characteristics over conventional metal and composite.
High energy absorbing capacity	[6,10]	Based on investigation data, FML's are absorbing significant energy through localized fiber fracture and shear failure in the metal plies.
High impact resistance	[8,11]	Impact deformation is actually a significant advantage of FML's, especially when compared to composites.

Above advantages of FML's finds great use in aerospace and automobile applications. Now a day's most of companies have interest in aluminium components by FML's composites. ARALL and GLARE laminates are now being used as structural materials for manufacturing aircrafts. Fiber Metal Laminates have been effectively used into the Airbus A380 [4, 5].
In spite of mentioned advantages of FML's their properties still need more understanding and attention. Although many articles have been published regarding to mechanical properties of FML's, the research on this part of FML's performance is still in the early stages. There are several issues to be addressed related to the modeling and experimental investigation of FML's. The purpose of this paper is to review relevant literature related to different manufacturing techniques, properties of FML's and numerical modeling. During this review, the key technical issues that need to be solved in future are also addressed.

II. MANUFACTURING OF FML's

2.1 Manufacturing of Fiber Meta laminates (FML):

The most common process used to produce FML's, as for polymeric composite materials, involves the use of autoclave processing. The overall production of FML's composite involves following major steps [7, 11-13].

- During this step, the surface of metal layer is pre-treated by acidic solution e.g. chromic acid or phosphoric acid, in order to improve the bond between the adhesive system and the metal surface.
- Applying resin uniformly over metal plates and reinforced material as glass or carbon fiber by using hand layup.
- Applying uniform pressure by compression moulding machine or vacuum bag techniques.
- After that cure process takes place which, including the flow-consolidation process, the chemical curing reactions, as well as the bond between fiber/metal layers.
- Last step consists of Inspection, which is done usually by ultrasound, X ray, visual techniques and mechanical tests.

The cure preparation step involves primarily the bagging of the part and the placement of many ancillary materials. The common cure preparation arrangements, including the part, the tool, the bagging are shown in Fig 3.

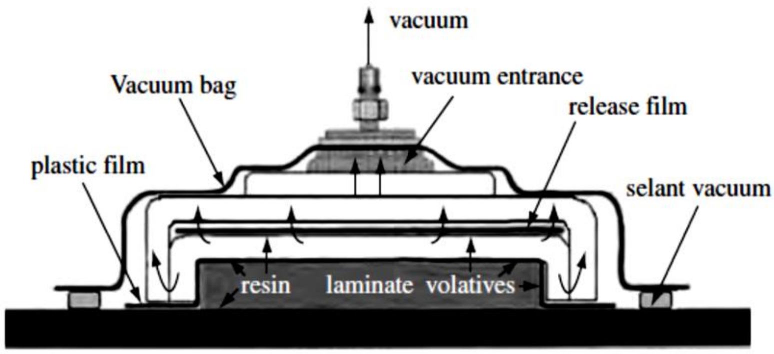

Fig 3. Schematic Representation of Vacuum bag system [14]

Recent investigation has shown that manufacturing of FML's by Resin Transfer Moulding (RTM) could also be a possibility. This manufacturing process is a family of closed-mould low-pressure processes that allow the fabrication of composites ranging in complexity from simple, low performance to complex high performance articles and in size from small to very large. The common feature of all the resin transfer moulding processes is the flow of resin material through the unwetted fibers. During the injection of the resin a pressure difference is applied in the closed mould, which forces the resin to flow through the reinforcement. Therefore the permeability of the reinforcement is an important factor. The process is typically used with low viscosity fast-curing resins, such as polyester, epoxy and chopped or continuous mat reinforcement at low fiber volume content. However, the process has been demonstrated with higher fiber volume contents (50 to 60%) [15].

Table 2. Historical development in manufacturing of fiber metal laminates:

Year	Ref.	Fiber Material and metal	Manufacturing techniques and its key details
2016	[16]	Carbon/Glass fiber with Al 6061	–Carbon/Glass fiber and Aluminium alloy 6061 sheet are fabricated using Compression moulding at room temperature. By considering the density, specific gravity and mass. The weight fraction of the fiber also determined.
2015	[17]	Carbon fiber reinforced polymer (CFRP) with Stainless steel SUS316 plate.	–Woven fabric prepregs were used to fabricate the CFRP sheet by means of the hot process. The fiber prepregs were first paved on surface of stainless steel plates and retained in the molds under a clamping press at a constant temperature 130°C for 2hr; then cured at room temperature for another 2hr. Thus, through the hot process, the CFRP and stainless plate were firmly bonded.
2015	[18]	M21/T700GC carbon fiber UD and FM94/S2 glass fiber UD with AISI 304L stainless steel	–Carbon fiber UD and FM94/S2 glass fiber UD with AISI 304L stainless steel FML prepared by auto clave process.
2014	[19]	Glass/carbon fibers, Al alloy 6061 with epoxy resin (LY 556), Hardener(HY 917)	–FML panel were prepared by hand layup techniques followed by heating to 150 C followed by pressuring them during curing.
2013	[20]	Carbon and jute fibers reinforced with aluminium 2024 T3	–They cured at room temperature and compressed for ten minutes in the compression molding machine at a pressure of 70 kg cm^2 and at temperature of 70^0C and thus the final FML is obtained by applied thermoset.
2009/ 2006	[21,22]	Polypropylene fiber-reinforced polypropylene composite with 2024-0 aluminum alloy	–FML's were manufactured by stacking the composite, the interlayer material and the metal plies in a picture-frame mould. The stack was heated to 165ºC under a pressure of 7 bars in a pneumatic press, before cooling slowly to room temperature at a rate of approximately 5ºC/min.
2000	[12]	Glass fiber reinforced thermoplastic with aluminium alloy 2024-T0	–To achieve adhesion between the composite and the aluminium, a chromate coating was applied to the aluminium alloy and a layer of maleic acid hydride modified polypropylene was incorporated at the composite-metal interface. The laminates were then heated to 185°C in an air circulating oven before stamping in a cold press.

In order to ensure good bounding between metal and fiber reinforcement, it is necessary to develop metal surfaces by using mechanical treatment, chemical treatment, and dry surface treatments. In mechanical treatment, the primary step, mechanical abrasion has been used to produce a macro-level roughened surface, different roughness level of the surface textures and also used to remove an undesirable oxide layer [23]. This method typically involves abrasive scrubbing of the substrate surface with sand paper. This mechanical treatment would introduce physicochemical changes which yield a wet table surface and modify the surface topography, i.e., a macro-roughened surface. Mechanical treatments also include the pretreatment by blasting using different fine material likes alumina or silica grit or glass beads to change the topography by the introduction of a ‘‘peak-and-valley’’ type morphology [13,24]. The chemical process which is also known as acid etching, involve the treatments of acidic solution on the surface of substrate, basically acidic solution based on a chromic–sulphuric acid etch [25, 26]. This treatment consists of immersion of the substrate in a solution of potassium dichromate and sulphuric acid. Typically, chemical treatment, i.e., acid etching, is an intermediate production step between degreasing, alkaline cleaning, and electrochemical treatment [23]. Three main classical acid-etching solutions were used to modify the metallic surfaces: Forest Product Laboratory (FPL) [27], chromic–sulphuric acid (CAE) [28], and sulfuric acid (P2) etches. Mixed chromic and hydrofluoric acids are most effective etches [13]. Several dry treatments for metal alloy surfaces have been developed to replace chemical wet treatment process: As reported in Ref. [23], laser texturing was utilized to modify an aluminium substrate's morphology and micro-structure, resulting in an increased bond strength and durability. Ion beam enhanced deposition (IBED) is a process that cleans and modifies the surface by sputtering with high energy argon ions under vacuum. In ion beam enhanced deposition (IBED) requires a surface activation step, particularly grit-blasting, prior to IBED. Good initial bond strengths were obtained and the improvements in wedge durability compared with peracetic acid (PAA) were found [13].

III. TEST METHODS OF FML's COMPOSITES

Parameters that influence the response characteristics of FML's are a. Type of metal. b. Type of fiber. c. Type of matrix. d. Metal/Composite volume fraction. e. Bonding/Surface treatment etc. Mechanical properties of FML's are being enhanced by the interface bond between composite and metal plies. This enhancement could be controlled by various test methods. This test reports give quality information and are suitable for design specifications. In this review; test methods of bending (flexural), fatigue, tensile, low and high velocity impact tests for determining the mechanical properties of FMLs and research studies utilized from these test methods were explained.

3.1 Flexural Test:

Mechanical properties of FML's composite are derived by the adhesion between fiber and matrix. Beside this, same properties of FML's are also depends on the interface bond between composite ply and metal ply. It is very difficult task to determine this adhesion, therefore various test methods have been proposed for this purpose: inter laminar shear and interfacial fracture tests. These methods give quality control information and not suitable for design specifications.

Flexural properties, such as flexural strength and modulus, are determined by ASTM test method D790. In this test, a composite beam specimen of rectangular cross section is loaded in either a three-point bending mode or a four-point bending mode or five point bending mode shown in fig. 4 [12, 28-30] In either mode, a large span–thickness (L=h) ratio is recommended. Three point flexural tests have received wide acceptance in the composite material industry because the specimen preparation and fixtures are very simple. Beside this few limitations should be recognized. However; Khalili et al. [30] reported that three-point bending tests were carried out on Zwick 1484 by using specifications of ASTM D790 M-93. J.G. Carrillo et al. [21] conducted flexural test on four points bending test and reported that fiber orientation had only a secondary effect on the properties of the FML.

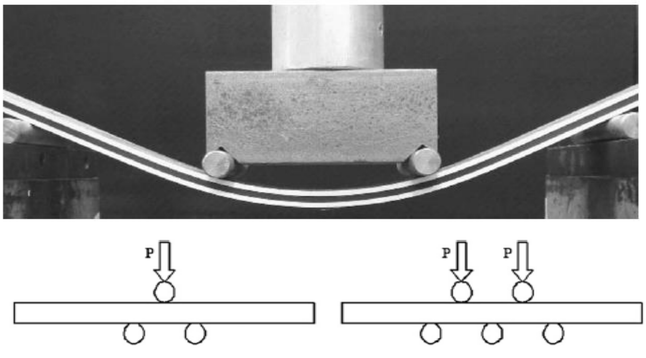

Fig 4. Photograph of a three, four and five point bending test. [13, 21]

3.2 Shear Test:

A variety of test methods [31, 32] have been used for measuring in plane shear properties, such as the shear modulus and the ultimate shear strength of unidirectional fiber reinforced composites. According to the literature survey, there are three kinds of in plane shear for measuring these two properties. 1. ±45 Shear test 2. 10^0Off-axis test 3. Iosipescu shear test [33,34]. Hinz et al. [35] investigated experimentally inter laminar shear properties of FMLs by double-notch shear test (DNS) according to ASTM D3846 at room temperature. Inter laminar shear load between the notches was primarily applied by compression on both ends of the DNS specimen.

Lawcock et al. [29] reported the inter laminar shear test of FMLs by three and five point bending tests with a span of 10 mm at a crosshead speed of 1.3 mm/min. These tests were undertaken at displacement rates between 0.1 and 3 m/s and were stopped once a visible crack had propagated from one of the starter defects.

3.3 Fatigue Test:

Fatigue behavior of a material is usually characterized by an S–N diagram, which shows the relationship between the stress amplitude or maximum stress and number of cycles to failure on a semi logarithmic scale. This diagram is obtained by testing a number of specimens at various stress levels under sinusoidal loading conditions. The majority of fatigue tests on fiber-reinforced composite materials have been performed with uniaxial tension–tension cycling. Tension– compression and compression–compression cycling are not commonly used since failure by compressive buckling may occur in thin laminates. Completely reversed tension–compression cycling is achieved by flexural fatigue tests. The tension–tension fatigue cycling test procedure is described in ASTM D347 [10, 36]. It uses a straight-sided specimen with the same dimensions and end tabs as in static tension tests. Apart from this Kanga et al. [37] performed ASTM E466 test for fatigue behavior of FML. Many research papers reported fatigue test based on the specimens prepared as notched or cracked for initiation of crack. All fatigue tests were conducted with constant amplitude in tension–tension or tension–compression loading at a frequency of 10 Hz at room temperature [10, 38-42]. Beside this in some researchers conducting fatigue test with sinusoidal waves of frequency 5 Hz [43, 44].

3.4 Tensile Test:

Tensile properties, such as tensile strength, tensile modulus, and Poisson's ratio of flat composite laminates, are determined by static tension tests in accordance with ASTM D3039 shown in Fig 5.

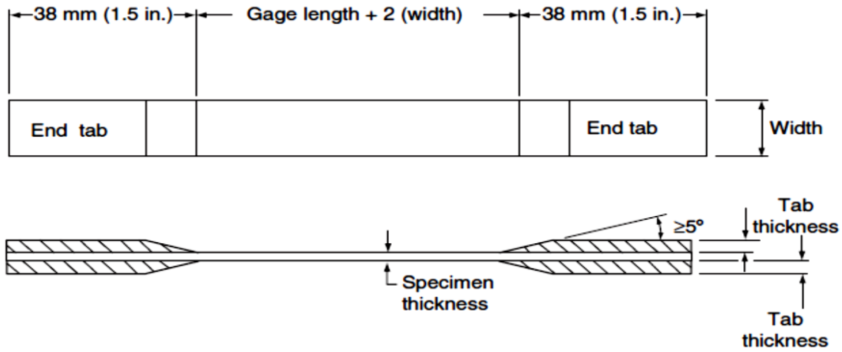

Fig 5.Tensile test specimen configuration

The tensile specimen is held in a testing machine by wedge action grips and pulled at a recommended cross-head speed of 2 mm/min (0.08 in/min). Longitudinal and transverse strains are measured employing electrical resistance strain gages that are bonded in the gage section of the specimen. Tensile tests performed on universal and servo hydraulic testing machines were used [21,30,40,45-49], MTS tensile testing machines (810, RT/50) [29, 41, 48, 50,51] and Shimadzu tensile testing machine [48]. Tensile tests were performed at room temperature at various speeds of 0,1 mm/min [41], 0,5 mm/min [46], 1 mm/min [12,45, 47-50,52], 1,27 mm/min [51], 2 mm/min [6,19,38,42], 5 mm/min [30]. However; in Carrillo et al. [21,40]. studies tensile behavior of FMLs were reported at a constant strain rate of 0.04 min-1 on an Instron 4204 universal test machine according to the ASTM D3039 test standard. In all papers highlighted with tensile properties of FML's, but shape and dimensions are different for the test specimen. Some of them used rectangular tensile specimens [6,38,46] and some of them used dog bone shape tensile specimens [39,41,45,53]. Beside this; few papers that tensile test specimen dimensions were prepared according to the standards.

3.5 Impact Test:

The impact properties of a material represent its capacity to absorb and dissipate energies under impact or shock loading. A variety of standard impact test methods are available for metals (ASTM

E23) and unreinforced polymers (ASTM D256). Basically low and high velocity test should be performed to understand the dynamic loading effect on the FML's. Low velocity impact testing was carried out using a drop weight impact tower with free fall known weight and diameter hemispherical nose, as shown schematically in Fig 6. The purpose of these tests was to characterize the impact response of the FML's, highlight the failure modes as well as to determine the threshold energies for first damage and target perforation [21]. According to present literature, there are many studies reported these test methods applied to the FML's. All from these papers some papers explain about low velocity impact properties of FML's [10,12, 38, 54,55], and some papers deal with high velocity impact properties of FML's [10,22,54-56].

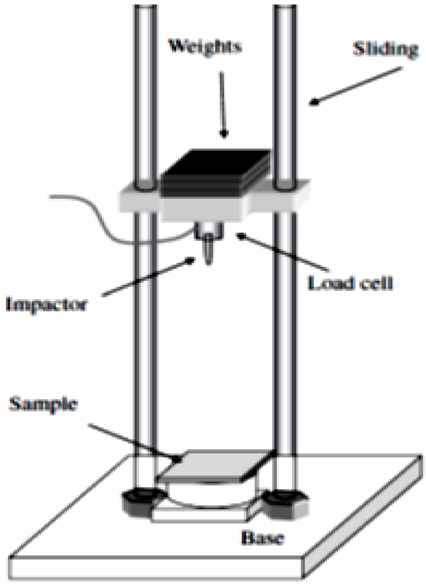

Fig 6. Drop weight impact tower [21].

According to literature survey, high velocity impact test conducted with the help of gas gun consisted of pressure vessel. [10,22,54-56,22]. Fig 7. shows that, square plates were clamped in a steel support square aperture so that the impactor can hit the center of the test specimen. In this test method: a projectile travelling with the velocities ranging between 25 and 100 m/s. The velocity of impactor before to impact can be measured by using light emitting diode photovoltaic cell pairs. Impact testing conducted over a range of impact energies until complete perforation of the FML target was achieved. The resulting perforation energy was then could be used to calculate the specific perforation energy of the target by normalizing the measured perforation energy by the areal density of the target [22]. After testing, the specimens could be sectioned, polished and then viewed under an optical microscope in order to study the failure mechanisms during impact.

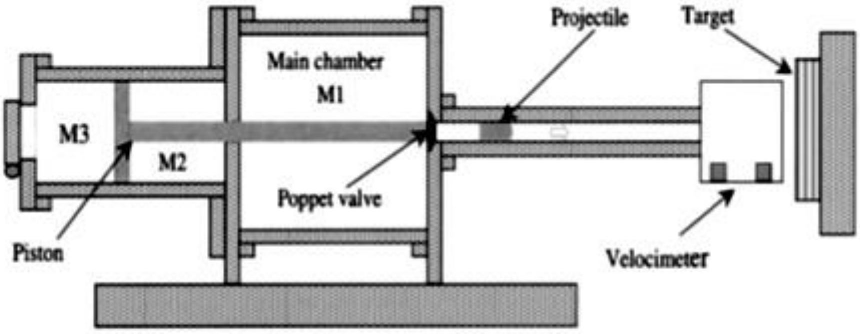

Fig 7. Test arrangement for high Velocity Impact testing [21]

Table 3. The articles that report the experimental studies on FMLs are summarized

Year	Key Feature
2016	–Conducted tensile, flexural and compression experiment on fiber metal laminate based on aluminium alloy 6061 and carbon/Glass fiber to obtain empirical estimates of Load capacity under various loads on universal testing machine (UTM) [16].
2015	–Investigate the fatigue characteristics of (CFRP) sheets and a thin stainless steel plate under the tension–tension loading. Different loading conditions (e.g. same stress and same force), layers of CFRP sheets, and lay-ups of laminates (single and double sides) were considered during experimentation [17].
2015	–An experimental drop-weight impact investigation was performed for stainless steel fiber metal laminates (FMLs) containing carbon-fiber and glass-fiber-reinforced epoxy layers [18].
2014	– Effect of strain rate and lay up configuration on tensile and flexural behavior of four combinations of fiber metal laminates [19].
2014	–Investigated the tensile and flexural properties for three type of fiber orientation were taken such as 4/3 layer of Chopped Strand Mat (CSM), 4/3 layer of woven roving, and 4/3 layer of 450 stitched mat [57].
2013	–Conducted Axial, Flexure and Impact tests on CAJRALL and the CAJRMAL specimens. The effect of the fiber orientations, fiber sequences in stack, metal combinations and the use of alternating metals on the mechanical performance, are experimentally investigated. The experimental data and Finite Element Analysis data were found to be in close agreement [20].
2013	–Address the influence of impactor mass, ply orientation, metal thickness, and plate dimension to low-velocity impact response [58].
2012	–Impact response of magnesium based FML was determined through experiments. From the visual inspection, having a larger shear crack on metal layer with smaller limit to first failure energy level, it was conclude that magnesium based FML offer less impact resistance than aluminum based FML [59].
2012	–Low velocity impact behavior in a lightweight fiber metal laminate (FML) system is studied. FML contain aluminum 2024 T3 and a self-reinforced polypropylene composite (SRPP) [60].
2012	–A progressive quasi-static test and low-velocity impact test were carried out to investigate the impact response of glare specimens. Two glare specimens were experimented: Unidirectional and woven GFRP. Effects of different layups, impact velocity were analyzed and results are validated with numerical simulation [61].
2011/ 2012	–Multiple impacts test on glass based FML was studied experimentally. Ultimate tensile strength, failure strain and ductility percentage are the parameters taken for investigation [62,63].
2011	–Influence of different metal constituents and its thickness on impact response were studied experimentally and validated the obtained data with numerical modeling [64].
2011	–Effect of specimen size, impactor diameter, number of composite layers, metal layers to low velocity impact on glare specimens was investigated [65-67].
2011/ 2006	–Low velocity impact test were performed on titanium and GFRP based FML. Due to plastic deformation and crack initiation on metal layers, damage intensity of internal GFRP layers was reported [68,69].
2011	–Effects of different specimen geometry and lay-up sequence on glare 5-3/2 specimens were investigated, towards the low velocity impact response [70].
2011	–Low velocity impact response of glare FML was investigated at different impact velocity and the nature, shape of the damage were studied through microphotography and non-destructive ultrasonic techniques [71].
2010	–To increase the safety level of mechanical components, the researcher interested to investigate aluminium and carbon based FML. Both experimental and numerical impact study was performed with data analysis [72].
2009	–Effect of material constituents, ply orientation of FML on low velocity impact was investigated in detail. Result were compared with unidirectional glare specimens, cross-ply and found that cross-ply constituents had better impact resistance [25].
2009	–Both low velocity and fatigue test were performed on Glare specimens placed over Al alloy which act as fatigue crack retarder. The fatigue result shows the crack growth is retarded up to a factor of 1.5 to 2 [73].
2009	–FML's offer a higher strength than that of the plain thermoplastic composite. Similarly, the strain to failure of the [Al, ±45]s FML's was much greater than that measured on the plain aluminum alloy. Flexural tests on [Al, 0/90]s and [Al, ±45]s with fiber orientation had a secondary effect on the properties of the FML, with the maximum stress and the strain at failure being similar in both

	cases which is end result [21].
2008	–Scaling effects in the low-velocity impact response of FML was studied, with aiming to minimizing the manufacturing cost for experimenting the full scale model [74,75].
2008	–Comparative study for evaluation of mechanical properties between long fiber thermoplastic composite (LFT)/ metal laminate (LML) was carried out. At low velocity, LML gives better result than LFT [59].
2007/ 2008	–Study the damage stages of Glare specimens ranges from plastic dent, Residual strength of these different characteristic candidates was investigated through post impact fatigue test [77-79].
2007	–Perforation energy of Glare fiber/aluminum based FML was calculated at different impact energies [80].
2005	–Conducting low-velocity impact test on aluminum and magnesium based GFPP and CFRP specimens and compared the experimental data. It was conclude that Magnesium based GFPP outperforms than its counterparts [27].
2005	–Impact test were performed on different 2/1 standard glare specimens. Studied the magnitude of impact damage. From the analysis, Glare 5 was concluded as a superior impact resistance material than other glare specimens [81].
2004	–Evaluated fatigue and the tensile properties of a novel fiber–metal laminate based on a titanium alloy and carbon fiber-reinforced poly-ether-ether-ketone (PEEK) [82].
2004	–Effect of impact velocity, impactor mass and impact energy was studied. Based on the experimental result, appropriate semi–empirical relations are formulated for different characteristic parameters [83].
2002	–Evaluated post impact fatigue performance of GLARE laminates and found that FML behave superior than isotropic aluminum laminates [84].
2000	–Investigates the impact and quasi-static properties of a novel fiber/metal laminate based on a tough glass-fiber reinforced polypropylene (GFPP) [12].
2000	–For GLARE, ARALL and plain aluminium alloy samples conducted tension-tension fatigue tests and evaluate the crack growth rates pattern [8].
2000	–Strength due to low-velocity impact of different stacking sequence ARALL specimens were investigated through compression after Impact (CAI) test. It found small fiber and micro matric cracks, with delamination of impacted specimen [85].
2000	–The residual strength of FML was reported through Impact test and subsequent tensile test [86].

IV. COMPUTATIONAL MODEL/NUMERICAL MODEL:

Numerical analysis has become crucial to study the properties of FMLs which consist of several material constituents. Numerical models using Finite-Element (FE) analysis are relatively quick and inexpensive to develop. In addition to specific material properties, only a reasonable number of structural tests are required for validation purposes. There are a few articles in the literature [16,17,24,25] that report numerical modeling of FML’s. Modeling of FML’s is a challenging work due to the difficulties associated with the plastic behavior, delamination, crack growth and perforation caused by impact loading, and loading rate [59,87]. Reasonable FE-analysis of FML’s should appropriately involve the behavior of different constituents with suitable element type selection, failure criteria and strain effects.

There are two general articles [59, 87] that describe general modeling and simulation of FMLs. Laliberte et al. [88] developed a user defined material subroutine in LS-Dyna for FMLs to study damage mechanisms in Glare. They used three types of interface models: tied interface (with elastic–plastic aluminum, elastic prepregs), simple-tie break (with the same mentioned behavior as previous) and tiebreak (with elastic–plastic aluminum and damageable prepregs). It was shown that the last one provides better predictions of impact performance. Guan et al. [67] used ABAQUS/ Explicit to perform a FE simulation of the thermoplastic based FML’s subjected to impact velocities up to 150 m/s. The composite layers were modeled as an isotropic material with a tensile failure criterion and the aluminum layers were modeled as an elasto-plastic material with rate dependent behavior. They reported good agreement between resulting failure modes, maximum permanent displacement and decay of the kinetic energy of the projectile with experimental results.

There are 3 approaches in the literature to model FML’s under different loading using ABAQUS /Explicit commercial FEM software. They are separated according to the type of chosen elements, mechanical behavior description and failure criteria selection for the constituents of FMLs. In the first approach [67], solid elements were used for both metal (most of the time aluminum) and composite layers. The aluminum alloy was modeled as an elasto-plastic material with rate-dependent behavior, whereas the composite was modeled as an isotropic material. Both shear and tensile failure criteria were used to simulate the failure processes in the aluminum layers and a similar tensile failure criterion used for the composite layers. The second approach [24] used 8-node solid element (C3D8R) and 8-node shell element (SC8R) for the aluminum alloy and composite layers, respectively. In the implemented model, the Hashin damage initiation criteria were used for the composite layers and no damage criterion was applied to the aluminum sheets. However, due to the fact that realistic modeling of layers and interface between the metal and fiber-reinforced polymer layers requires through-thickness stresses, shell elements with plane-stress assumption are not suitable for composite layers [27]. On the other hand, the failure criteria included in ABAQUS for composite layers are only applicable to continuum shell elements with plane stress conditions. Therefore, in the last approach, Seo et al. [27] developed a user material subroutine VUMAT to simulate progressive damage and failure of composite layers with three-dimensional solid-elements [64].

Table 4. Historical development in numerical studies on FML's:

Year	Software/ Code	Type of metal and Fiber	Key aspects/features
2014	ANSYS	ARALL and GLARE	–Studied tensile and flexural strength for ARALL and GLARE [89].
2013	ANSYS/ ABAQUS	Al and Mg/ Carbon and natural jute fiber	–Carbon Reinforced Aluminium Laminate (CARALL), a portion of carbon fiber is replaced by natural fiber jute (CAJRALL). Also, attempt is made in CAJRALL, by replacing aluminium with magnesium metal [20].
2012	ABAQUS	Al/GFRP	–A detailed 3D stress based Hashin failure criteria was implemented through subroutine VUMAT to capture the damage phenomenon of composites and Johnson cook damage model for metal layers [61].
2011	ABAQUS	Titanium/GFRP hybrid	–Study the adhesive layer in between the metal and composite layer, through explicit numerical model. Also evaluated the external and internal damage effects on each metal face [68].
2011	ABAQUS	Al 2024-T3/Glass and Mg AZ31B-H24 /Glass	–Discusses the impact resistance of FML's. Two parameters have been studied relevant to the impact behavior of these materials, i.e. type of metal and its thickness within a laminate [64].
2011	ABAQUS	2024-O Al alloy /woven glass fiber prepreg	–Effect of impactor size, target size and impact location were studied numerically. Contact between the stacking layers, surface-to-surface contact between impactor and target, tensile failure and shear failure criteria for metal layers, 2D Hashin failure criteria for composite layers are some of the important parameters in this simulation [67].
2011	LS-DYNA	Al/GFRP	–Glass based multilayered FML was modeled using shell elements and both intra and inter laminar failure was specified using proper damage criteria. Study extended to quantify the magnitude of damage and its severity [71].
2010	ABAQUS	Al/ Carbon fiber	–Numerical study was carried out to demonstrate the effect of different impact energies on carbon based FML using 2-D stress based Hashin damage model for composite layer [72].
2010	ABAQUS	Al/GFRP	–Highlight the importance of solid elements over continuum shell elements, also shows importance of 3D Hashin failure criteria over its 2D form on low velocity impact were demonstrated extensively through numerical simulation [52].
2009	ABAQUS	Al alloy/(PP)fiber	–Thermoplastic based FML with elastic-plastic metal layers and an isotropic composite layer was simulated [90].
2008	LS-DYNA	CARALL	–Developed model for low velocity impact on FML based on continuum damage mechanics (CDM) for composite layers. The post-processing results shows delamination is not a significant damage in low-velocity impact [88].

V. CONCLUSION

A vast number of available literatures showed that FML's have great potential in aerospace as well as automobile applications. It is found in many cases that FML's are superior mechanical properties compared to conventional aluminum alloy or fiber reinforced polymer composites. Excellent fatigue characteristics, high modulus of elasticity with improved toughness, high strength to weight ratio are major advantages of FML's. In this review paper different manufacturing techniques and test methods with numerical modeling for FML's are reviewed. An adequate manufacturing process and good surface treatment of FML's is required to get a good mechanical and adhesive bond between the composite laminates and adjacent metal layer. Surface treatment methods are discussed and showed comparable performance to improve the FML's. In this review; test methods such as tensile, flexural, shear, fatigue and low and high velocity impact for determining the mechanical properties of FML's. The performance of the FML's depends on type of metal, types of fiber, matrix materials, metal/composite volume fraction and bonding/surface treatment etc. Experimental work on FML's is expensive and time consuming. So, numerical analyses become very effective and crucial to study the mechanical behavior of FML's. ABAQUS and LS-DYNA are the two most explicit codes used by many researchers for numerical modeling and validation purposes. Most of researchers study the modeling of impact behavior which required knowledge of plasticity, fracture mechanics and damage mechanics. Currently a lot of research is needed to improve the methodology used to study the material and further expand the possibilities of applications. There are many study required regarding the structural and material mechanics within the FML's.

VI. FUTURE DEVELOPMENT

1. Comparative study is essential on the mechanical behavior of FML's based on thermoset and thermoplastics matrices.
2. Comparative study required in arrangement and configuration of constituents within FML's and their influences on the mechanical properties.
3. Study required under thermal circumstances.
4. Specimen with different geometries and boundary condition which matches with the real world conditions required to study the mechanical performance.

VII. REFERENCES

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