Analysis of Fiber Orientation on the Bending Strength of Aluminium-Carbon Fiber FML Composites

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Abstract

One such innovation is the application of composite materials as subtitutes for conventional metals. However, pure composites exhibit poor resistance to shock loads, leading to the development of Fiber Metal Laminates (FMLs), which combine carbon fber and aluminium sheets. This research investigates the flexural behavior of carbon fiber-reinforced FMLs with varying fiber orientations (0°, 45°, dan 90°). The study employed a quantitative approach using an experimental method to evaluate the mechanical response under bending conditions. The laminates were manufactured using the vacuum infusion process, with epoxy resin as the matrix and aluminium as laminates and core. Bending tests were conducted in accordance with ASTM D790, using a Tarno Grocki universal testing machine. The results were evaluated based on maximum flexural strenght. The results showed significant differences in bending strenght based on fiber orientation. The highest bending strenght was recorded at 0° (111.43 MPa), followed by 45° (90.92 MPa), and 90° (69.87 MPa). This research may serve as a reference for futher development of FML composites for automotive body aplications.

Keyword: *Bending, Carbon Fiber, Composite, Fiber Metal Laminate, Vacuum Infusion*

I. INTRODUCTION

The increasing demand for high-performance and lightweight materials in the automotive industries has accelerated the development of advanced composite structures. These materials offer superior mechanical properties, such as high strength-to-weight ratio (Utomo, 2020), stiffness, and durability, making them suitable candidates for structural applications. Among various composite systems, those combining sheetmetal and fiber-reinforced polymers have gained particular attention due to their potential to overcome the limitations of conventional monolithic materials.

Recent research has shown that fiber metal laminates (FMLs) exhibit improved flexural behavior and energy absorption capacity compared to traditional materials when subjected to mechanical loading conditions (Gao et al., 2023). Furthermore, the effectiveness of FMLs is influenced by various factors such as fiber orientation, stacking sequence, and matrix bonding quality, which significantly affect their bending resistance and interfacial strength (Costa et al., 2023).

FML is a hybrid material composed of bonded layers of metal sheet and fiber-reinforced composites (Eslami-Farsani et al., 2022). The manufacturing of FML aims to generate superior mechanical properties from each of its constituent materials, resulting in a material with lighter mass compared to conventional metals (Chen et al., 2020).

FML can also be classified as a sandwich-structured composite due to its symmetrical composition structure (Patel et al., 2023). In automotive applications, FML has the potential to replace pure metals for better vehicle weight efficiency without reducing its mechanical strength. In its early development, GLARE and ARALL were types of FML that offered good fatigue and corrosion resistance (Abd El-Baky et al., 2020); however, these materials were found to experience several interlaminar failures due to weak mechanical bonding (Chen et al., 2020). Typically, metals applied as the outer skin layers in FML include titanium, magnesium, and various aluminum sheets such as Al 6061, Al 2024, and Al T3 (Utomo, 2020).

The choice of fiber type significantly influences the mechanical strength of FML. GLARE, which uses glass fiber, has a low elastic modulus and flexural strength, and the material is prone to delamination when subjected to pressure (Kakati et al., 2023). Meanwhile, ARALL, reinforced with aramid fiber, tends to absorb moisture and experiences thermal degradation, making it less suitable for the dynamic and high-temperature demands of the automotive industry (Pulikkalparambil et al., 2021). FML with glass fiber also has lower fatigue resistance compared to carbon fiber (Bieniaś et al., 2020). Based on these shortcomings, an alternative fiber is needed to improve interlaminar strength and stiffness in FML.

The selection of carbon fiber as a reinforcing fiber/filler in composites has been widely developed in recent years. Carbon fiber is chosen because it has a high strength-to-weight ratio, making it ideal as a reinforcing fiber in FML. In this study, carbon fiber is used because it can provide the necessary mechanical properties such as stiffness and resistance to high temperatures. FML with a combination of carbon fiber has superior fatigue resistance compared to glass and aramid fibers (Naito et al., 2020). Therefore, the use of carbon fiber as reinforcement results in a significant improvement in interlaminar strength and impact resistance (Naito et al., 2020).

The manufacturing method used in this study is Vacuum Assisted Resin Infusion (VARI). This method has advantages such as smooth resin flow, minimal voids, and uniform resin distribution within the mold. Additionally, it is considered more economical compared to Resin Transfer Molding (RTM), which involves high pressure (Huberty et al., 2024). In the manufacturing process of FML composites, one of the key parameters affecting their mechanical strength is fiber orientation. The tensile strength of carbon fiber material with fiber orientation angles of 0°, 45°, and 90° results in better tensile strength compared to orientations of 30° and 60° (Fajarudin, 2021).

II. THEORY

A. Configuration of Carbon Fiber Orientation

To achieve optimal performance in the use FML sandwich composite, the placement of lamina orientation is one key factors influensing the mechanical strenght of the composite material. In this study, carbon fiber was used as the reinforcement material, as ilustrated in the Figure 1 (0°), Figure 2 (45°) and Figure 3 (90°).

- 0° fiber orientation

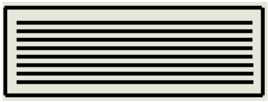

Figure 1. *Illustration of 0° Carbon Fiber Orientation*
(Source: Author's own documentation)

- 45° fiber orientation

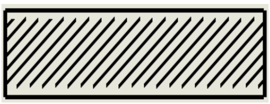

Figure 2. *Illustration of 45° Carbon Fiber Orientation*
(Source: Author's own documentation)

- 90° fiber orientation

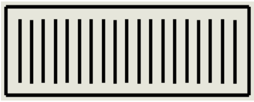

Figure 3. *Illustration of 90° Carbon Fiber Orientation*
(Source: Author's own documentation)

In this research, the FML composite specimens consist of two filler layers, positioned on the top and bottom sections, which are laminated and combined with an sheet metal alumnium core, as ilustrated in Figure 4

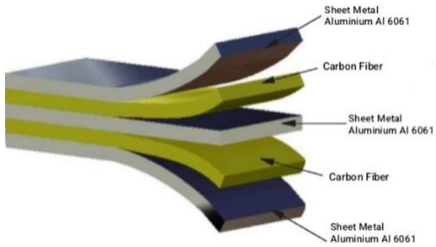

Figure 4. *Illustration of Fiber Metal Laminate (FML)*
(Source: Author's own documentation)

B. Bending Test

The bending test in this study was carried out in accordance with ASTM D790: "Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials. The specimens were tested using dimensions specified by ASTM D790, with a length of 200 mm, width of 50 mm, and thickness of 4 mm, each with a tolerance of ±2 mm. The test employed a Tarno Grocki Universal Testing Machine (Figure 5 and Figure 6) . The flexural strength (σ) can be calculated using the following equation:

$$\sigma = \frac{3PL}{2bd^2} \quad (1)$$

Where:
σ = flexural stress (MPa)
P = maximum load (N)
L = span length (mm)
b = width of the specimen (mm)
d = thickness of the specimen (mm)

Figure 5. *Tarno Grocki Universal Testing Machine*
(Source: Author's own documentation)

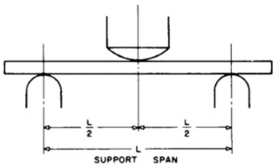

Figure 6. *Schematic of Three-oint Bending Test, Based on ASTM D790*
(Source: Author's own documentation)

C. Carbon Fiber

Carbon fiber is a high-performance reinforcement material commonly used in composite structures due to its exceptional mechanical strength, low density, and high stiffness. The material is composed of thin filaments of carbon atoms aligned in a crystalline structure, which provides superior tensile strength, dimensional stability, and fatigue resistance, even under extreme environmental conditions. Its high strength-to-weight ratio makes it ideal for aerospace, automotive, and advanced structural applications where weight reduction without compromising performance is critical. In composite, carbon fiber is typically embedded within a polymer matrix, forming a fiber-reinforced composite with enhanced mechanical integrity. The choice of carbon fiber as reinforcement, with its physical properties summarized in Table I, significantly influences the laminate's bending strength, stiffness, and resistance to delamination.

TABLE I
Physical Properties of 3000-filament Carbon Fiber

No	Physical Properties	Metric	Comments
1	Density	1.79gr/cc	
2	Mechanical Properties	Metric	
3	Tensile Strenght Ultimate	4070MPa	
4	Elongation at Break	1.8%	
5	Modulus of Elasticity	228GPa	Tensile modulus calculated at second 6000-1000

(Source: ASM (Aerospace Specification Metal, inc.)

D. Fiber Metal Laminate

Fiber Metal Laminates (FMLs) are advanced hybrid composite materials that consist of alternating layers of metal sheets and fiber-reinforced polymer composites. FMLs combine the beneficial properties of both constituents, offering high specific strength, improved fatigue resistance, and better damage tolerance compared to conventional monolithic metals. In this study, aluminum alloy is used as the metal layer due to its lightweight nature, corrosion resistance, and good structural performance, while carbon fiber is selected as the reinforcement because of its high stiffness, excellent tensile strength, and low density, as ilustrated in Figure 7 and Figure 8. The synergy between aluminum and carbon fiber within the laminate structure results in enhanced mechanical behavior, particularly in bending resistance. FMLs have found increasing applications in aerospace, automotive, and structural engineering fields where weight reduction and high performance are critical.

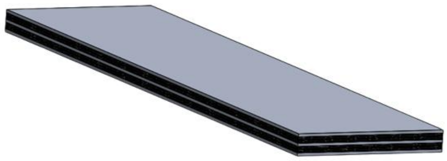
Figure 7. *Illustration of The FML Composite Bending Test Specimen*
(Source: Author's own documentation)

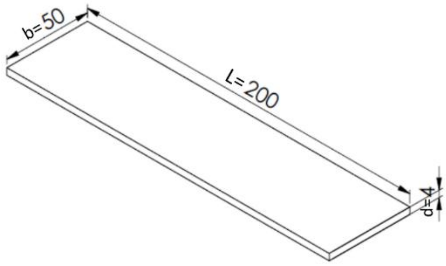

Figure 8. Illustration of Specimen Dimensions
(Source: Manual Book of ASTM D790 Standart Test)

E. Vacuum Infusion

Vacuum infusion is a composite manufacture method where fiber reinforcements are placed inside a sealed mold, and liquid resin is drawn into the laminate through vacuum pressure. The process begins with laying up the fiber and core materials, followed by covering them with peel ply, infusion mesh, and a vacuum bag film. A vacuum pump is connected to the system to evacuate air, creating negative pressure that pulls the resin from a resin reservoir through an infusion tube into the mold. As the resin flows through the laminate, it saturates the fibers uniformly. A catchpot is installed between the mold and the vacuum pump to prevent excess resin from being sucked into the pump, acting as a resin trap, as shown in Figure 9. Once the resin has fully impregnated the laminate, the inlet and outlet lines are clamped to maintain vacuum until the resin cures.

Figure 9. Vacuum Infusion Process of FML Specimen
(Source: Author's own documentation)

III. METHOD

This research employs a quantitative approach. According to (Sugiyono, 2016), quantitative research is a method based on positivist philosophy, used to examine a particular population or sample using random sampling techniques. Data collection is carried out using research instruments, and the analysis involves statistical and quantitative methods testing predefined hypotheses. Quantitative research classified into three types: experimental research, descriptive-correlational research, and evaluation research. This study adopts an experimental research approach, which study to determine the effect of a specific treatment on another variable under controlled conditions.

IV. RESULT AND DISCUSSION

A. Bending Test Result

TABLE II
Table of Bending Test Result (MPa)

Carbon Fiber Orientations	Specimens	Bending Strenght Value (MPa)
0°	1	117.60
	2	119.23
	3	97.45
	Average	**111.43**
45°	1	98.54
	2	86.02
	3	88.20
	Average	**90.92**
90°	1	80.57
	2	67.51
	3	61.52
	Average	**69.87**

(Source: Author's own documentation)

Flexural testing was performed using ASTM D790 standards. Three specimens were tested for each fiber orientation (0°, 45°, 90°), and the average values were calculated, as summarized in Table II. The results revealed significant variations in flexural strength based on fiber orientation. The 0° specimens showed the highest strength with an average of 111.43 MPa, followed by 45° with 90.92 MPa, and 90° with the lowest at 69.87 Mpa, as illustrated in Figures 10–12

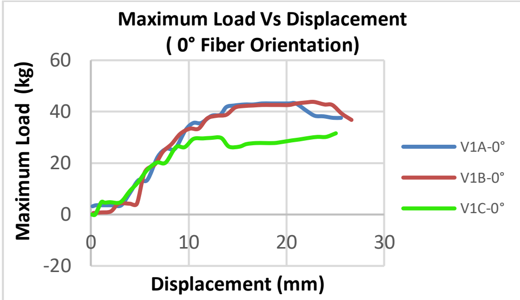

Figure 10. Maximum Load vs Displacement Graph for FML Specimens with 0° fiber orientation
(Source: Author's own documentation)

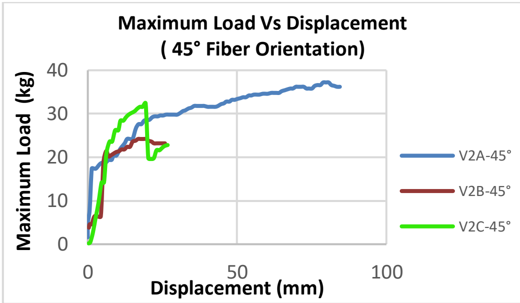

Figure 11. Maximum Load vs Displacement Graph for FML Specimens with 45° fiber orientation
(Source: Author's own documentation)

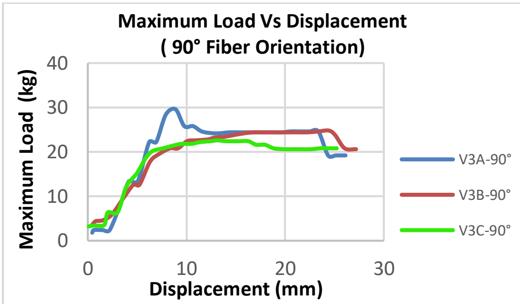

Figure 12. Maximum Load vs Displacement Graph for FML Specimens with 90° fiber orientation
(Source: Author's own documentation)

The data obtained from the bending test consisted of load and displacement values. These data were then plotted as load vs. displacement. Prior to plotting, the load values were converted from kilograms (kg) to Newtons (N), which can be calculated as follows using the 0° fiber orientation as an example:

$$P = \text{Maximum Load (kg) X Gravity} \left(\frac{m}{s^2}\right) \quad (2)$$

$$P = 43.2 \text{ kg X } 9{,}8 \left(\frac{m}{s^2}\right)$$

P = 423.792 kg$\left(\frac{m}{s^2}\right)$

P = 423.792 N

Based on the result of the load coversion, the maximum bending load for each variable was obtained in units of Newton (N). To calculate the bending strenght of the FML composite, using the equation 1:

$$\sigma = \frac{3PL}{2bd^2} \quad (1)$$

$$\sigma = \frac{3\ X\ 423.792\ N\ X\ 148mm}{2\ X\ 50mm\ X\ 4^2mm}$$

$$\sigma = \frac{188.163\ Nmm}{1600\ m^3}$$

$$\sigma = 117.60N/mm^2$$

$$\boldsymbol{\sigma = 117.60MPa}$$

Where:
σ = bending stress (MPa)
P = maximum load (N)
L = span length (mm)
b = width of the specimen (mm)
d = thickness of the specimen (mm) (3)

The calculation to obtain the average value of the bending strenght can be determined using the following equation:

$$\sigma_{average} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$$

$$\sigma_{average} = \frac{117.60 + 119.23 + 97.45}{3}$$

$$\sigma_{average} = \frac{334.28}{3}$$

$$\boldsymbol{\sigma_{average} = 111.43MPa}$$

Based on the bending test results of the specimens, it was shown that the fiber orientation of the carbon fiber significantly affects the flexural strength of the FML. The bending test data for fiber orientations of 0°, 45°, and 90° will be interpreted in a graph to illustrate the mechanical performance of each specimen, highlighting the differences in bending strength according to fiber direction variation, as presented in Figure 13.

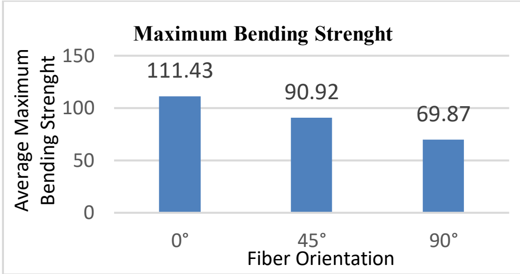

Figure 13. Maximum Bending Strenght of FML
(Source: Author's own documentation)

B. Bending Test Failure

In addition to the flexural strength data obtained from the bending test, the failure behavior of the specimens was also analyzed to further evaluate the test results. The failure characteristics observed from the fractured specimens provided additional insight into the mechanical response of the FML composites under bending load. The following figure presents the visual analysis of failure behavior observed in the specimens after the bending test

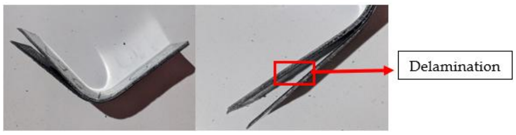

Figure 14. Delamination Failure in FML Specimen
(Source: Author's own documentation)

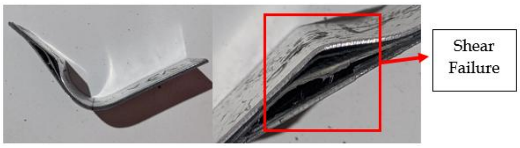

Figure 15. Shear Failure in FML Specimen
(Source: Author's own documentation)

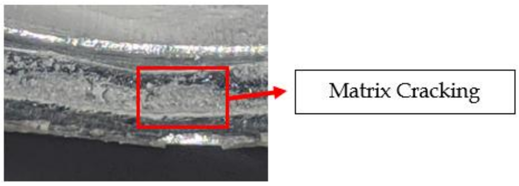

Figure 16. Matrix Cracking in FML Specimen
(Source: Author's own documentation)

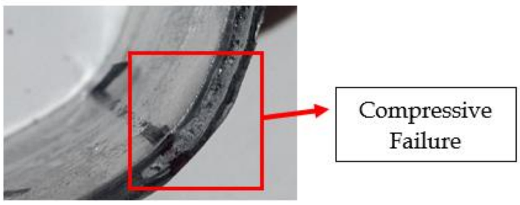

Figure 17. Compressive Failure in FML Specimen
(Source: Author's own documentation)

In Figure 14, the FML composite specimen with 0° fiber orientation exhibits delamination failure. This delamination occurred due to excessive **bending loads on the FML, which caused** interlayer separation resulting from the mismatch of mechanical properties between the layers, including the carbon fiber–matrix and matrix–sheet metal interfaces (Utomo, 2020). The failure modes observed in the 45° fiber orientation specimen, as shown in Figure 15, include delamination, shear failure, and matrix cracking. Shear failure in FML is triggered by bending-induced shear deformation that exceeds the bonding strength between the matrix and fiber (Firmansyah, 2018). Additionally, matrix cracking occurs when the matrix is unable to withstand excessive bending stress (Zhu, 2020). The failure modes shown in Figures 16 and 17, for specimens with 90° orientation, are identified as compressive failure and matrix cracking. Compressive failure in the FML structure is caused when the upper skin exceeds its elastic limit during deformation. The skin layer subjected to the bending load fails as the deformation of the filler and core progresses under the applied bending stress (Faiz, 2021).

V. CONCLUSION

This study concluded that fiber orientation plays a crucial role in the flexural strength of carbon fiber-reinforced aluminum-based FMLs. The 0° orientation achieved the highest flexural strength (111.43 MPa), followed by 45° (90.92 MPa), and 90° (69.87 MPa). The observed failure modes include delamination, matrix cracking, shear failure, and compression failure, all of which were influenced by fiber direction and load distribution.

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