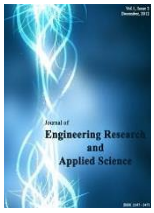
Journal of Engineering Research and Applied Science
Available at www.journaleras.com
Volume 14 (1), June 2025, pp 71-85
ISSN 2147-3471 © 2025



Experimental Investigation of the Effects of Fiber Direction and GNP Reinforcement on the Structural Behavior of CARALL FML Composites

Mustafa Dündar*

Machinery and Metal Technologies, Biga Vocational School, Çanakkale Onsekiz Mart University, Çanakkale, Turkey

Accepted 15 May 2025

Abstract
The design of lighter structures to reduce fuel costs and ensure environmental sustainability has become one of the primary goals for aircraft manufacturers and researchers in the aerospace industry. In this context, fiber metal laminate (FML) structures, which are distinguished by their superior fatigue resistance and mechanical properties, have gained significant attention in aerospace applications. Among the newest and most advanced types of FMLs, carbon fiber reinforced aluminum laminates (CARALL) have emerged as a focal point of research. In this study, CARALL FML composites—representing a novel member of the FML family—were fabricated with a 3/2 stacking sequence and two different fiber directions (0°–0° and 0°–90°), both with and without 0.5 wt.% Graphene Nanoplatelet (GNP) reinforcement using the hot press molding method. The fabricated specimens were subjected to tensile tests according to ASTM D3039 and three-point bending tests according to ASTM D790 standards. The results revealed that fiber direction is the most influential parameter affecting mechanical performance, while the addition of 0.5 wt.% GNP led to a reduction in both tensile and flexural strength.

Keywords: *Fiber Metal Laminate(FML), CARALL, Tensile Test, Three-Point Bending, Graphene Nano Plate(GNP), Mechanical Properties, Hybrid Composites*

1. Introduction

Composite materials are widely used in various industrial sectors such as aerospace, space, transportation, sports, household goods, and electronics due to their advantageous properties, including light weight, enhanced mechanical performance, and cost-effective availability. Numerous mechanical properties of composites are influenced by factors such as manufacturing techniques, fiber volume fraction, type of reinforcement, particle size, and distribution [1]–[3]. Fiber Metal Laminates (FMLs) are hybrid structures composed of alternating thin metal sheets and fiber-reinforced composite layers [4]. Depending on the type of fiber used, FMLs are classified as GLARE (glass fibers), ARALL (aramid fibers), and CARALL (carbon fibers) [5], [6]. These hybrid materials combine the mechanical advantages of both metal and fiber constituents, offering high specific strength, high specific stiffness, and other superior characteristics. For these reasons, FMLs have found extensive use in aerospace applications and are considered promising candidates for the automotive industry as well [7]. As a result, they have attracted growing interest as a subject of academic and industrial research [8]. Since the development of FMLs in 1978, ARALL and subsequently GLARE systems have been widely adopted, especially in the aerospace industry. However, recent advancements in manufacturing technologies and the increasing need to reduce structural weight in aviation have significantly intensified interest in carbon fiber-reinforced systems [9]. Within this context, Carbon Fiber Reinforced Aluminum Laminates (CARALLs) have emerged as one of the more recent and promising members of the FML family. Thanks to their excellent fatigue resistance, low density, high impact strength, and stiffness, CARALLs offer an ideal balance between lightness and strength—making them highly suitable for critical aerospace applications. Accordingly, in-depth investigation of the structural behavior of CARALL materials is not only essential for expanding academic literature, but also for developing practical engineering solutions in high-performance structural design [10].

Numerous researchers in the literature have investigated the tensile and flexural behavior of Fiber Metal Laminates (FMLs). Rahman et al. [11] examined the mechanical properties of laminated

*Corresponding author: m.dundar@comu.edu.tr

polyester composites reinforced with Betel nut (Areca palm) stem fibers at different orientations. Specimens with a 0°/90°/0° fiber configuration exhibited more than 50% higher tensile strength and 16% higher flexural strength compared to those with a −45°/0°/45° configuration. Additionally, due to the direct alignment of the 0° fibers with the loading direction, the impact resistance was also found to be higher in the 0°/90°/0° specimens. These results highlight that fiber orientation is a critical parameter for optimizing the mechanical performance of natural fiber-reinforced composites. Zal et al. [12] investigated the mechanical behavior of FML structures composed of glass fiber reinforcements and 420-grade stainless steel interlayers with fiber orientations of 0°, 15°, 30°, and 45°. Static and dynamic tests revealed that the highest mechanical performance was obtained in specimens with 0° fiber alignment, which was attributed to the alignment of the fibers along the load path. Their study confirmed the critical role of fiber direction in determining the mechanical behavior of FMLs. Kumar et al. [13] produced hybrid FML specimens consisting of 316L stainless steel, E-glass fibers, and carbon/epoxy layers with a 50:50 metal-to-fiber ratio, as part of a study on the design of underwater pressure vessels. The results demonstrated that 0° fiber alignment significantly improved mechanical performance, particularly enhancing flexural and impact strength. Wang et al. [14] focused on GLARE specimens with a ±45° fiber orientation and showed that fiber bridging played a decisive role in tensile strength. Their findings also revealed that fiber orientation directly affects both damage development and strain distribution within the laminate.

The incorporation of various reinforcement phases into the matrix is a widely adopted and effective strategy in the literature to enhance the mechanical performance of polymer-based composites (FRPs) [15], [16]. Studies have shown that the addition of nanoscale reinforcements to the FRP layers in Fiber Metal Laminate (FML) systems is a common approach to improve overall composite behavior. Abd El-Baky et al. [15] investigated the effect of helically structured carbon nanotubes (HCNTs) at various weight ratios (0%, 0.25%, 0.5%, 1%, 2%, and 3%) on GLARE composites. Their results indicated that the optimum mechanical performance was achieved with 1 wt.% HCNT addition. At this concentration, the elastic modulus increased by 8.5%, flexural strength by 28.85%, and tensile strength by 35.67%. Raja and Sreenivasan [17] examined the influence of nanoclay addition in epoxy-based FML structures reinforced with E-glass fibers and AA2022 aluminum. They reported that specimens containing 3 wt.% nanoclay exhibited improvements of 87.5% in tensile strength, 29.7% in flexural strength, and 47.2% in impact resistance. Based on these results, the authors suggested that such FML systems are promising alternatives for aerospace and automotive structural applications. Kim et al. [18] produced various CFRP composite laminates by reinforcing them with 2 wt.% and 3 wt.% carbon nanotubes (CNTs) and 0.5 wt.% and 1 wt.% graphene nanoplatelets (GNPs). It was found that 3 wt.% CNT and 0.5 wt.% GNP contributed to a 30% greater increase in elastic modulus compared to 1 wt.% GNP reinforcement. Azimpour-Shishevan et al. [19] studied the effects of multi-walled carbon nanotube (MCWNT) and GNP nano-reinforcements on the mechanical and thermal properties of CFRP composites. Their results showed that the incorporation of MCWNT and GNP significantly improved elastic modulus, tensile strength, flexural modulus, critical buckling load, and natural frequency, thereby enhancing both mechanical and dynamic performance of the CFRP structures.

This study aims to investigate the effects of fiber directions and graphene nanoplatelet (GNP) reinforcement on the mechanical performance of carbon fiber reinforced aluminum laminates (CARALL). For this purpose, CARALL composites were fabricated with two different fiber orientations (0°/0° and 0°/90°) by incorporating 0.5 wt.% GNP into the epoxy matrix. The produced specimens were subjected to tensile and three-point bending tests in accordance with ASTM standards. By examining the combined effects of fiber alignment and nano-reinforcement on mechanical behavior, this study provides unique and valuable insights for the development of high-performance and lightweight hybrid laminate structures. The findings have the potential to contribute to innovative material solutions for advanced engineering applications, particularly in aerospace and automotive industries where structural integrity and weight reduction are critical.

2. Materials and Methods

2.1. Materials

As the metal layer, Al2024-T3 aluminum alloy with a thickness of 0.5 mm—known for its high ductility and excellent strength-to-weight ratio—was selected. This material was supplied by Amag Rolling GmbH. As the reinforcement fiber, carbon fibers manufactured by DowAksa were used, while the matrix material was an epoxy resin provided by Fibermak Kompozit. Additionally, the graphene nanoplatelets used as the nano-reinforcement additive were supplied by Nanografi. The mechanical and physical properties of all materials used in the study are presented in detail in Table 1.

In this study, four different Fiber Metal Laminate (FML) specimens with a 3/2 stacking configuration were designed and coded as C1, C2, C3, and C4 in order to evaluate the effects of fiber direction and graphene nanoplatelet (GNP) reinforcement. Detailed information regarding the stacking sequences and material compositions of the specimens is presented in Table 2, while the schematic representations of the laminate structures are illustrated in Figure 1. During the FML fabrication process, prepregs—both with and without GNP reinforcement—were first prepared to produce the carbon fiber reinforced polymer (CFRP) layers. Additionally, to enhance the mechanical integrity of the FML structure and improve the interfacial adhesion between layers, Phosphoric Sulfuric Acid (PSA) anodizing was applied to the aluminum metal layers prior to fabrication. Further details regarding this surface treatment are provided in the following section.

2.2. Surface Treatment of Metal Sheets

Since the interfacial bonding between the FRP and metal layers is a critical factor affecting the performance of Fiber Metal Laminates (FMLs), the metallic layers must undergo appropriate surface pretreatment to ensure stronger interfacial adhesion. Well-prepared metal surfaces are among the key parameters that influence the impact behavior of FMLs. Although electrochemical treatments are commonly preferred due to their simplicity, Phosphoric Sulfuric Acid (PSA) anodizing has gained prominence for providing superior interfacial bonding characteristics [20]. Accordingly, all aluminum plates subjected to chemical surface preparation were treated using the PSA anodizing process at 21 °C, under a potential of 22 volts, for a duration of 20 minutes.

2.3. Manufacturing of CARALL FMLs with and without GNP Reinforcement

Two different prepreg preparation methods were employed for the fabrication of CFRP laminates with and without GNP reinforcement. Initially, GNP-free prepregs were produced, and these materials were used to fabricate C1 and C2 coded CARALL specimens with dimensions of 500 × 500 mm (Figure 2). For the fabrication of C3 and C4 specimens, GNP-reinforced prepregs were prepared, and CARALL laminates of the same dimensions (500 × 500 mm) were produced accordingly (Figure 3). The production steps followed the procedures illustrated in Figures 1 and 2, respectively. Following the fabrication process, all CARALL materials were cut into test specimens using a waterjet cutting method. The tensile specimens were prepared in accordance with ASTM D3039, and the three-point bending specimens were prepared according to ASTM D790 standards.

Table 1. Types and mechanical properties of the materials used

Material	*Type*	*Material Properties*
Alüminum	2024-T3	E: 72 GPa ρ= 2.7 g/cm³
Carbon fiber	Uni Directional (UD)	ρ_A = 300 g/m², Normal thickness= 0.3 mm
Epoxy system	F-RES 21/ F-HARD 22	ρ = 1.1 g/cm³
Graphene	Graphene Nano Plate	Purity : %99.9, Thickness : 3 nm, SSA: 800 m²/g

Table 2. The types of FMLs.

FML	*Lay-up*	*GNP Content (%wt)*	*Thickness (mm)*
C1	Al/0°-90°/Al/90°-0°/Al	-	2.75
C2	Al/0°-0°/Al/0°-0°/Al	-	2.75
C3	Al/0°-90°/Al/90°-0°/Al	0.5	2.95
C4	Al/0°-0°/Al/0°-0°/Al	0.5	2.95

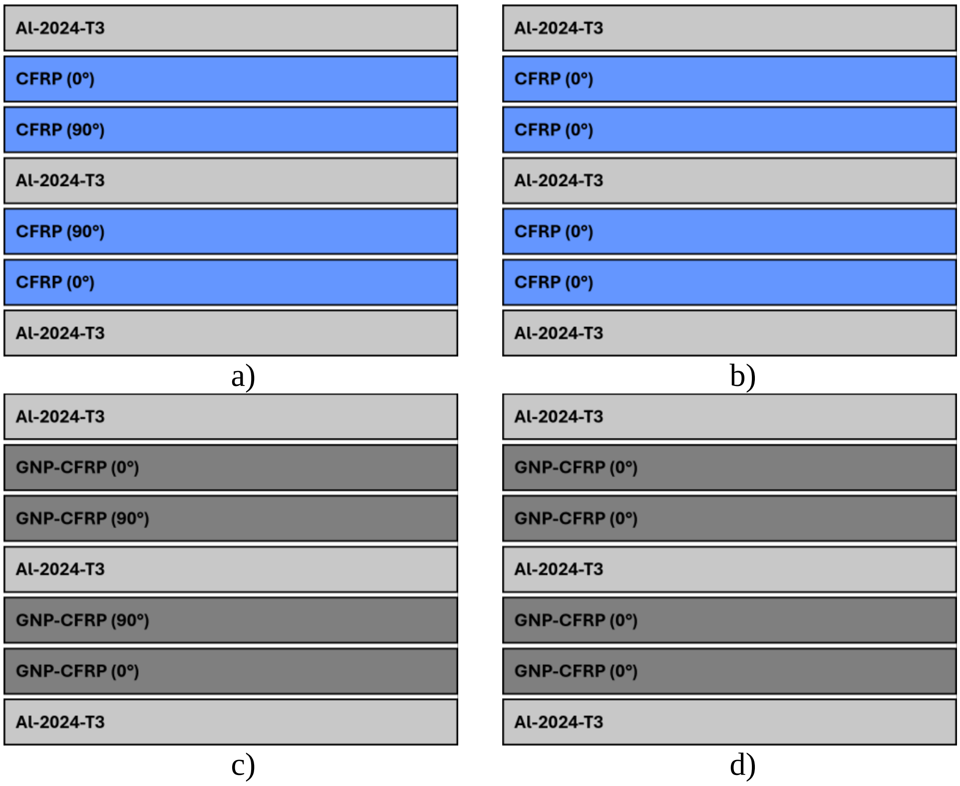


Figure 1. Schematic illustration of the layer configurations for FML specimens C1, C2, C3, and C4 based on fiber orientation and GNP reinforcement.

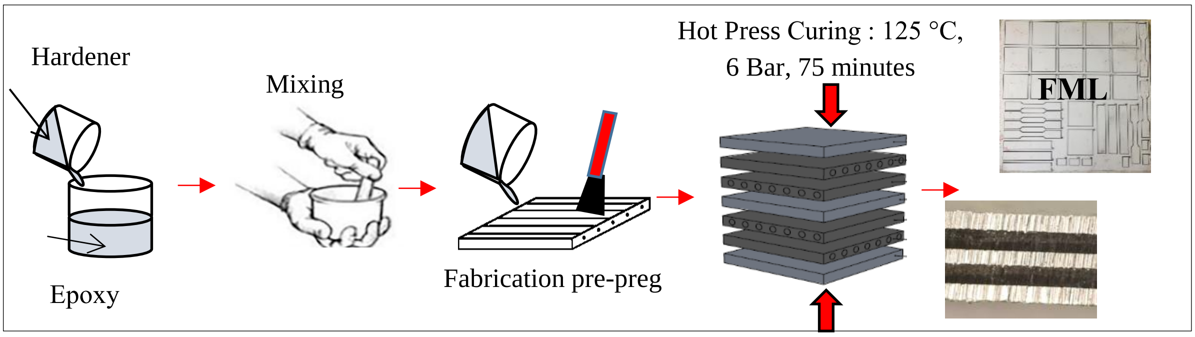


Figure 2. Schematic illustration of the production process for CARALL composite without GNP reinforcement

2.4. Tensile Test

To determine the elastic modulus and tensile strength of the fabricated CARALL composites, specimens were prepared in accordance with the ASTM D3039 standard, and tensile tests were conducted (Figure 4). These tests aimed to evaluate the influence of fiber orientation and GNP reinforcement on the tensile behavior of the materials. Prior to testing, to prevent fiber breakage due to clamping pressure from the grips of the testing machine, four tabs were bonded to each specimen (Figure 5).

Tensile tests were carried out using a BESMAK BMT-100E universal testing machine with a capacity of 100 kN, equipped with a video extensometer to enable precise measurement of specimen elongation (Figure 6). All experiments were conducted at room temperature, in accordance with the ASTM D3039 standard, using a crosshead speed of 1 mm/min. Each test was repeated three times to ensure experimental reliability. Due to the layered structure of FML materials, the FRP layers typically fail first during tensile loading. However, the aluminum layers continue to deform plastically, allowing further elongation. Therefore, testing was continued until complete failure of all laminate layers occurred.

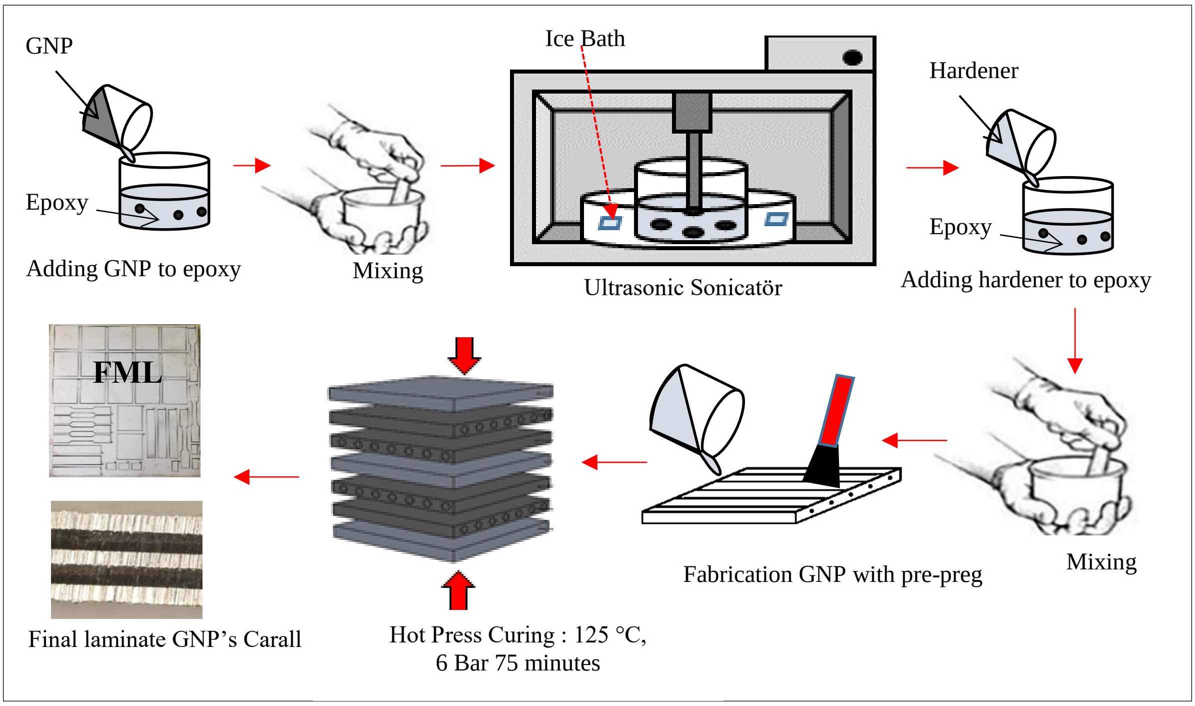


Figure 3. Schematic representation of the production process for GNP-reinforced CARALL composite

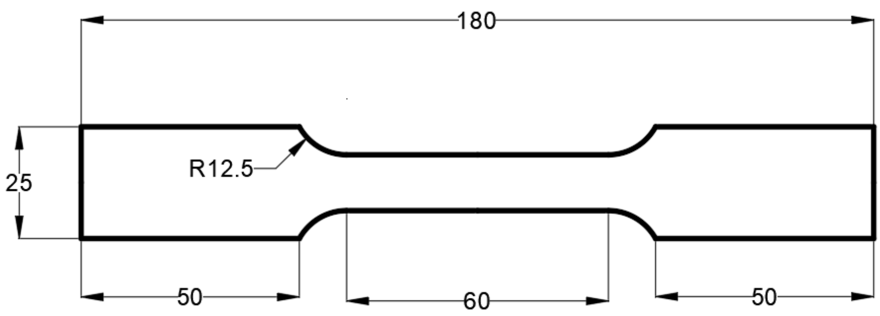


Figure 4. Dimensions of the tensile test specimen (mm)

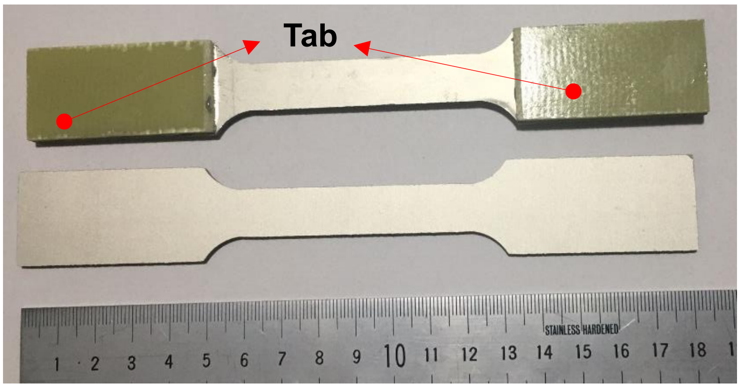


Figure 5. Tensile test specimen cut by waterjet and tab bonding process

2.5. Three-Point Bending Test

Three-point bending tests were conducted to investigate the flexural behavior of the fabricated CARALL FML composites. Test specimens were prepared using a waterjet cutting method with dimensions of 152.4 mm × 25.4 mm, in accordance with ASTM D790 (Figure 7). The flexural tests were performed using a Shimadzu AGS-X electromechanical universal testing machine with a 10 kN load capacity, as shown in Figure 8. The test setup employed the three-point bending fixtures illustrated in Figure 9. In the test configuration, the bending fixture was mounted on the lower table of the device. The support rollers and the loading nose were designed as two separate components of the fixture. The support rollers were fixed in place using a spring-loaded mechanism and allowed for an adjustable span up to 180 mm. In this study, the support span was set at 101.6 mm. The diameter of both the support and loading rollers was 12.7 mm. The loading nose was rigidly attached to the upper crosshead of the testing machine, and the applied load was centered precisely at the midpoint of each specimen. All tests were repeated three times under identical conditions to ensure data reliability, and the force–displacement data were recorded using the machine's integrated data acquisition software. Each test was continued until permanent structural damage occurred in the specimen. The recorded force and displacement values were converted into stress–displacement data using the following equation:

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

Here;
σ = Maximum flexural stress at the mid-span of the beam surface (MPa)
P = Applied load at the midpoint of the beam (N)
L = Span length between the two supports (mm)
b = Width of the specimen (mm)
d = Thickness (depth) of the specimen (mm)

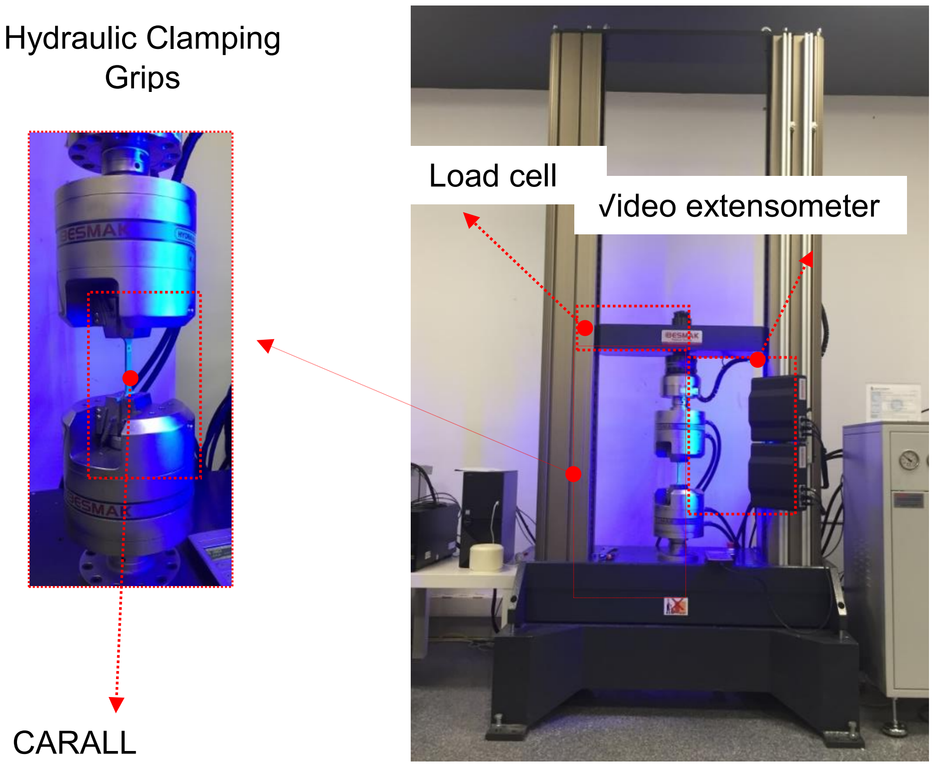


Figure 6. BESMAK BMT-100E tensile testing machine

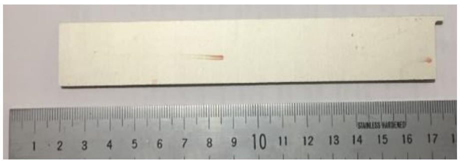


Figure 7. CARALL FML specimen used for three-point bending test

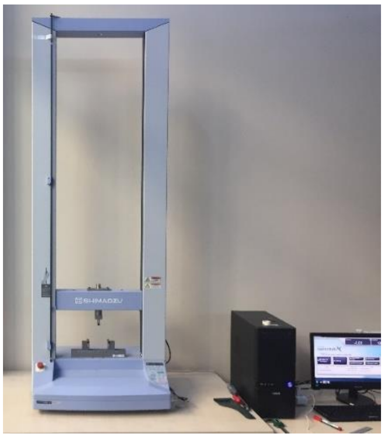


Figure 8. Shimadzu AGS-X 10 kN electromechanical universal testing machine

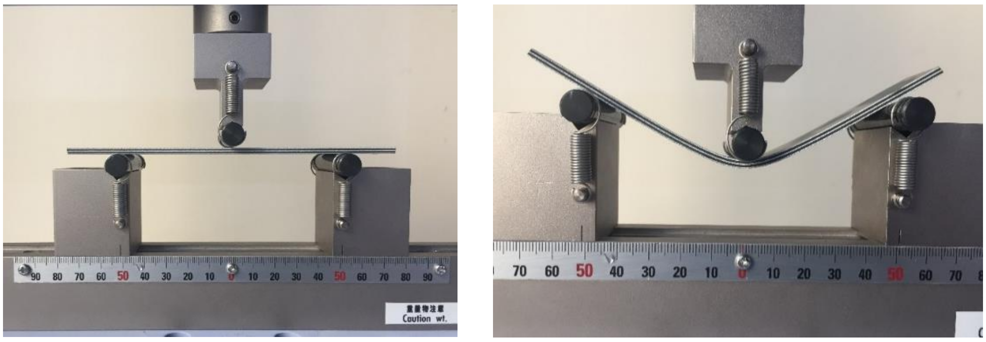


Figure 9. Experimental setup and fixture used for the three-point bending test

3. Result and Discussion

3.1. Tensile Behavior of CARALL FML Composites

The tensile behavior of FML composites can be evaluated in two distinct stages, depending on the mechanical properties of the metallic and FRP constituents. While the aluminum layers exhibit elastic–plastic behavior, the FRP layers are assumed to retain their elastic properties until failure [21]. The tensile test results of CARALL specimens manufactured with different fiber orientations and graphene nanoplatelet (GNP) reinforcement are presented in Figure 10. All specimen groups exhibited similar trends, and a noticeable change in the stress–strain curves was observed particularly at the region marked by line A–A, which corresponds to the yielding of the aluminum layer. This change indicates that the aluminum reaches its yield point, after which the load is predominantly carried by the fiber layers. In specimens with 0°–0° fiber orientation (C2–C4), the drop observed before fracture can be attributed to fiber breakage. A high concentration of fiber rupture was observed in this region [22]. A photograph of a damaged specimen after tensile testing is provided in Figure 11. According to Figure 10, specimens with a unidirectional (UD) fiber architecture (C2–C4) demonstrated higher tensile strength. In contrast, the specimens with a 0°–90° fiber configuration (C1 and C3) exhibited lower tensile strength due to their off-axis fiber orientation. In CARALL-type FML composites, the load-bearing capacity during tensile loading is largely governed by the mechanical performance of the FRP layers. Specimens with 0°–0° fiber alignment achieved the highest tensile strength, as the fibers are aligned with the loading direction and can carry the load directly (see Figure 10, line

A–A). On the other hand, in specimens with fibers oriented at 90°, the fibers are placed perpendicular to the loading axis, resulting in a significant reduction in tensile strength. The elastic modulus and tensile strength values obtained from the tests are presented in detail in Table 3.

Table 3. Comparison of Elastic Modulus and Tensile Strength of CARALL Laminates with Different Fiber Directions and GNP Additions After Tensile Testing

	Modulus of Elastic (GPa)	*Tensile Strength (MPa)*
C1	59,95	720
C2	83,05	1238
C3	56,42	705
C4	78,72	1141

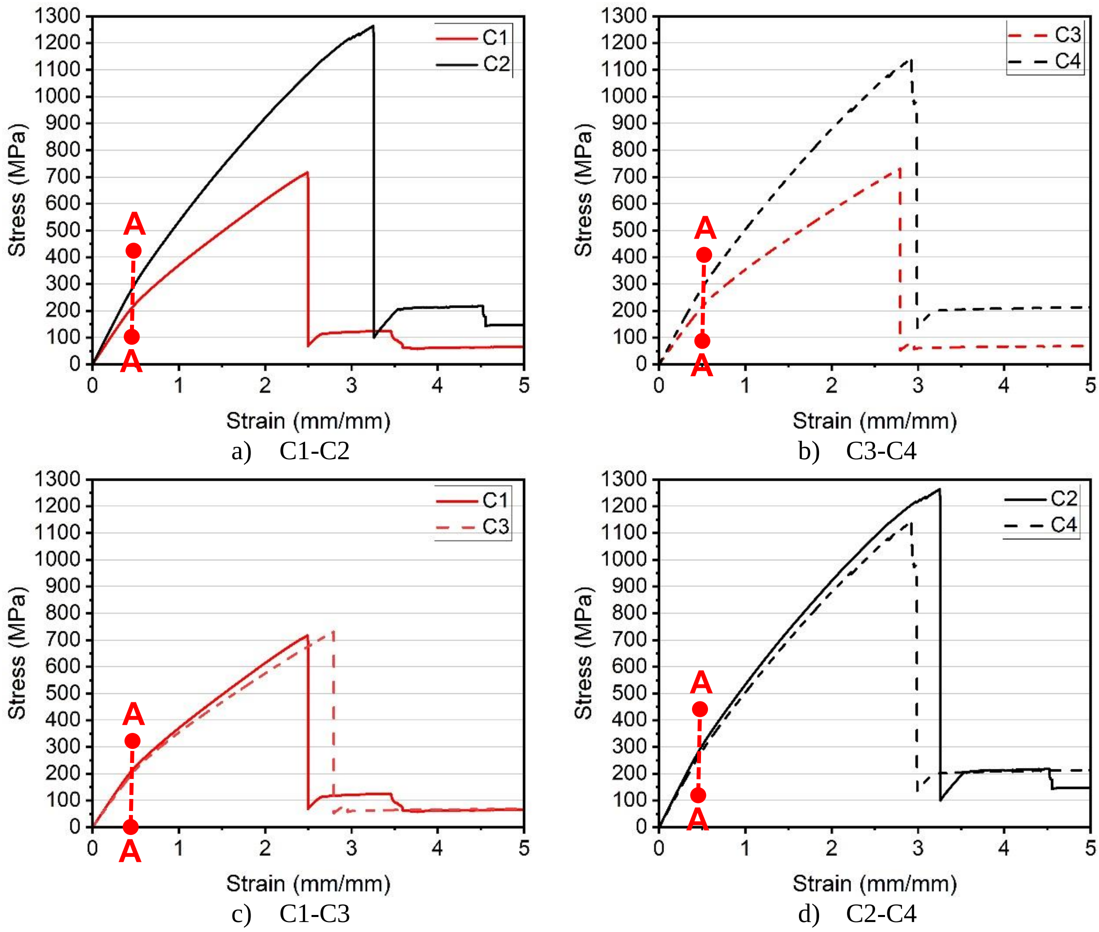


Figure 10. Tensile test results of carall laminates with different fiber directions and gnp additions (C1: 0°–90°, C2: 0°–0°, C3: 0°–90° with GNP, C4: 0°–0° with GNP)

According to the data presented in Table 3, the specimens with unidirectional (UD) fiber alignment (C2–C4) exhibited significantly higher tensile strength compared to the others. In contrast, the specimens with 0°–90° fiber orientation (C1 and C3) demonstrated lower tensile performance due to their off-axis fiber configuration. The 0°–0° fiber architecture provided both higher elastic modulus and higher tensile strength. This configuration enables CARALL composites to achieve their maximum tensile performance.

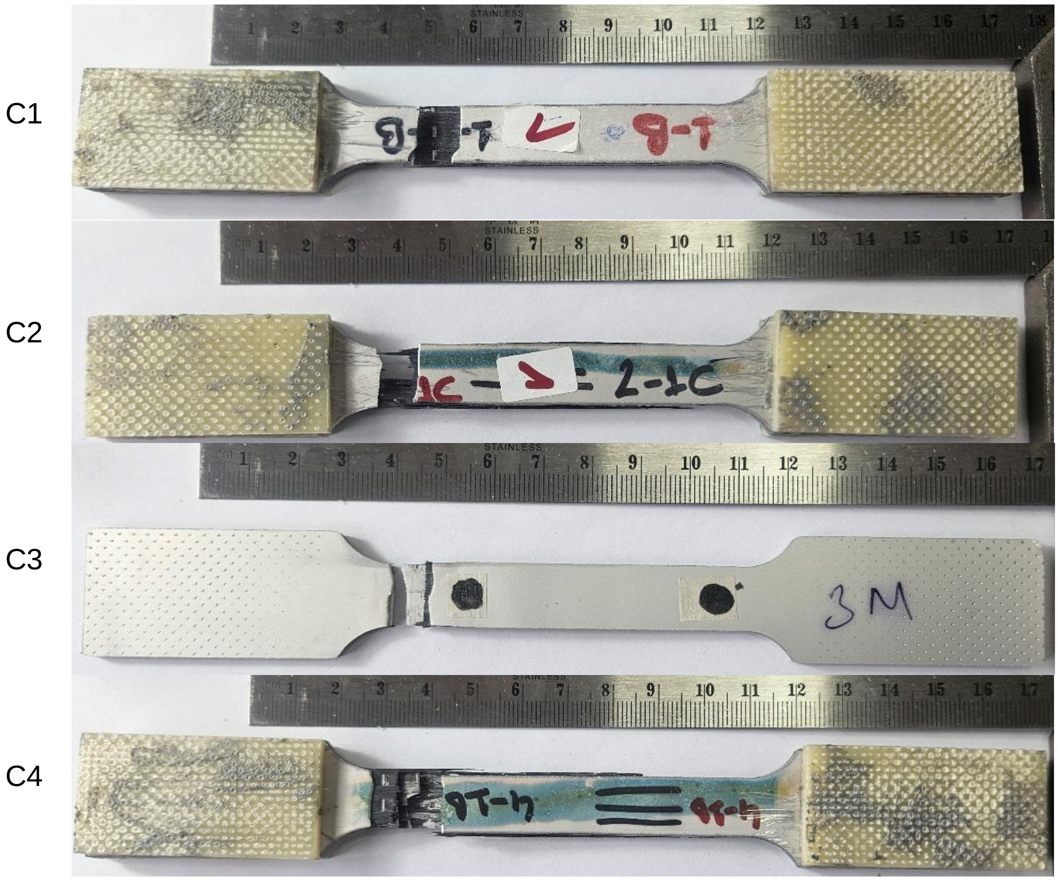


Figure 11. Macroscopic damage observed on carall specimens after tensile testing

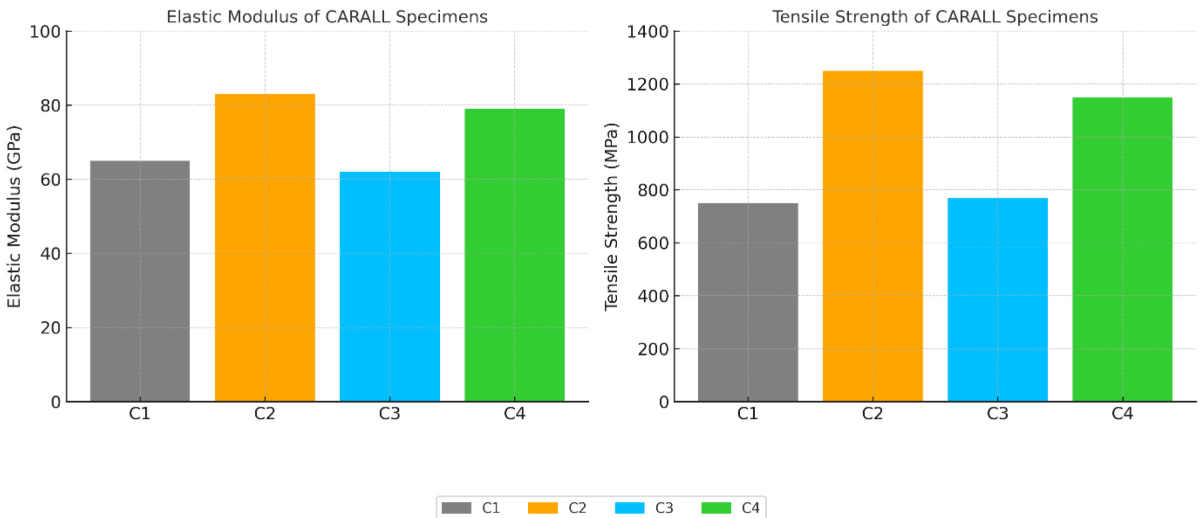


Figure 12. Elastic modulus and tensile strength of carall specimens with different fiber directions and gnp additions

A higher elastic modulus increases the stiffness of the CARALL structure, yet it also limits the material’s elastic deformation capacity. Despite this limitation, a high elastic modulus has a positive influence on tensile strength. On the other hand, fibers with a 0°–90° orientation exhibit lower elastic modulus values, and structures with this configuration show reduced resistance to tensile forces. As a result, more matrix cracking occurs within the laminate, and while the material becomes generally more flexible, both its tensile strength and stiffness decrease [23], [24]. The influence of GNP reinforcement on tensile properties is illustrated in Figure 12. Based on the results, the best mechanical performance was achieved in the C2 specimen, which had no GNP reinforcement and a 0°–0° fiber orientation. The C2 specimen exhibited an elastic modulus that was 5%, 38.53%, and 47.2% higher than those of the C4, C1, and C3 specimens, respectively. Similarly, in terms of tensile strength, the C2 specimen outperformed the C4, C1, and C3 specimens by 8.5%, 71.95%, and 75.6%, respectively. These findings clearly demonstrate that fiber orientation is the dominant factor affecting mechanical performance. Conversely, the presence of GNP reinforcement was observed to have an adverse effect on the mechanical behavior of CARALL FML composites.

Fathi et al. [7] investigated the effect of graphene nanoparticle (GNP) reinforcement at weight fractions of 0%, 0.1%, 0.2%, and 0.4% in glass fiber-reinforced epoxy matrix composites. Their tensile test results indicated that the optimal mechanical performance was achieved at 0.2% GNP content. However, it was also observed that increasing the GNP concentration led to a decline in both tensile strength and elastic modulus. Esfandiar et al. [25] examined the in-plane tensile behavior of six different commercial GLARE laminates with varying fiber orientations. Their findings indicated that unidirectional GLARE configurations demonstrated higher tensile strength than monolithic aluminum sheets. Additionally, the study highlighted the structural advantages of using FML composites in engineering applications. Jin et al. [26] investigated the effect of fiber orientation on the mechanical behavior of FML structures under tensile and flexural loading conditions, using three-dimensional damage criteria and experimental validation. According to their results, fiber orientation plays a key role in determining the load-bearing capacity of FMLs. Fibers aligned with the loading direction were shown to significantly enhance both strength and stiffness, thereby delaying damage initiation at higher load levels. In contrast, fibers oriented perpendicular to the loading direction made only limited contributions to load transfer, ultimately resulting in decreased mechanical performance.

3.2. Flexural Behavior of CARALL FML Composites under Three-Point Bending

The three-point bending test is a widely used experimental method for evaluating the stiffness and flexural strength of CARALL composite materials. In this section, the effects of fiber orientation and GNP reinforcement on the three-point bending behavior of CARALL structures are analyzed. Figure 13 presents the stress–deflection curves obtained from the bending tests. The stress values were calculated using Equation (1). These curves clearly demonstrate the influence of structural variables on the flexural performance of the composites. Additionally, post-test images of damaged specimens are shown in Figure 14. The obtained stress–deflection curves generally exhibit two characteristic regions. The first region is the lower linear portion of the curve, starting from 0 mm of displacement and extending up to the line denoted as A–A. This point is commonly referred to in the literature as the “knee point”, which represents the end of the elastic region and the onset of plastic deformation. Beyond this point, the specimen can no longer return to its original shape, and permanent deformation occurs. This lower region primarily reflects the elastic behavior and yield point of the aluminum layers. The second region, located beyond the knee point, is referred to as the “upper region”, which characterizes the flexural behavior of the carbon fiber composite layers [27]. All tested specimens exhibited similar behavioral trends in this context.

The maximum flexural stresses of the CARALL specimens coded C4, C2, C3, and C1 were measured as 1030.37 MPa, 949.020 MPa, 811.430 MPa, and 759.710 MPa, respectively. The C4 specimen exhibited approximately 8%, 22%, and 28% higher flexural stress compared to the C2, C3, and C1 specimens, respectively. These results indicate that specimens with 0°–0° fiber orientation demonstrate superior mechanical performance in terms of flexural strength. In this configuration, the fibers are aligned parallel to the loading direction, allowing for more efficient load transfer and resulting in higher strength.

Conversely, in specimens with a 0°–90° fiber orientation, greater displacements were observed under loading. Since a portion of the fibers in these specimens are oriented perpendicular to the loading direction, their load-bearing contribution is limited, and a significant portion of the applied load is transferred to the matrix. This leads to matrix crushing and the formation of microcracks, which in turn allow for greater deformation. On the other hand, the 0°–0° oriented specimens exhibit a more rigid structure and tend to fail abruptly after reaching a certain deformation level. This results in a lower deformation capacity and is typically associated with sudden fracture caused by the rapid release of stored elastic energy. In summary, fiber orientation significantly influences not only flexural strength but also the deformation characteristics of CARALL composites. Parallel fiber alignment (0°–0°) ensures high strength but limited ductility, while cross-ply alignment (0°–90°) results in lower strength but greater deformation tolerance. Furthermore, the force fluctuations observed in the peak regions of the stress–displacement curves for all specimens suggest the occurrence of multiple simultaneous damage mechanisms [28]. The maximum force and corresponding flexural stress values obtained from the three-point bending tests are presented in Figure 15 and Table 4. The findings clearly demonstrate that fiber orientation is a key parameter governing the flexural performance of CARALL composites.

Wu et al. [29] investigated the effect of different fiber orientations on the mechanical behavior of six commercial GLARE laminates. Their study concluded that fiber orientation directly influences the interlaminar damage mechanisms.

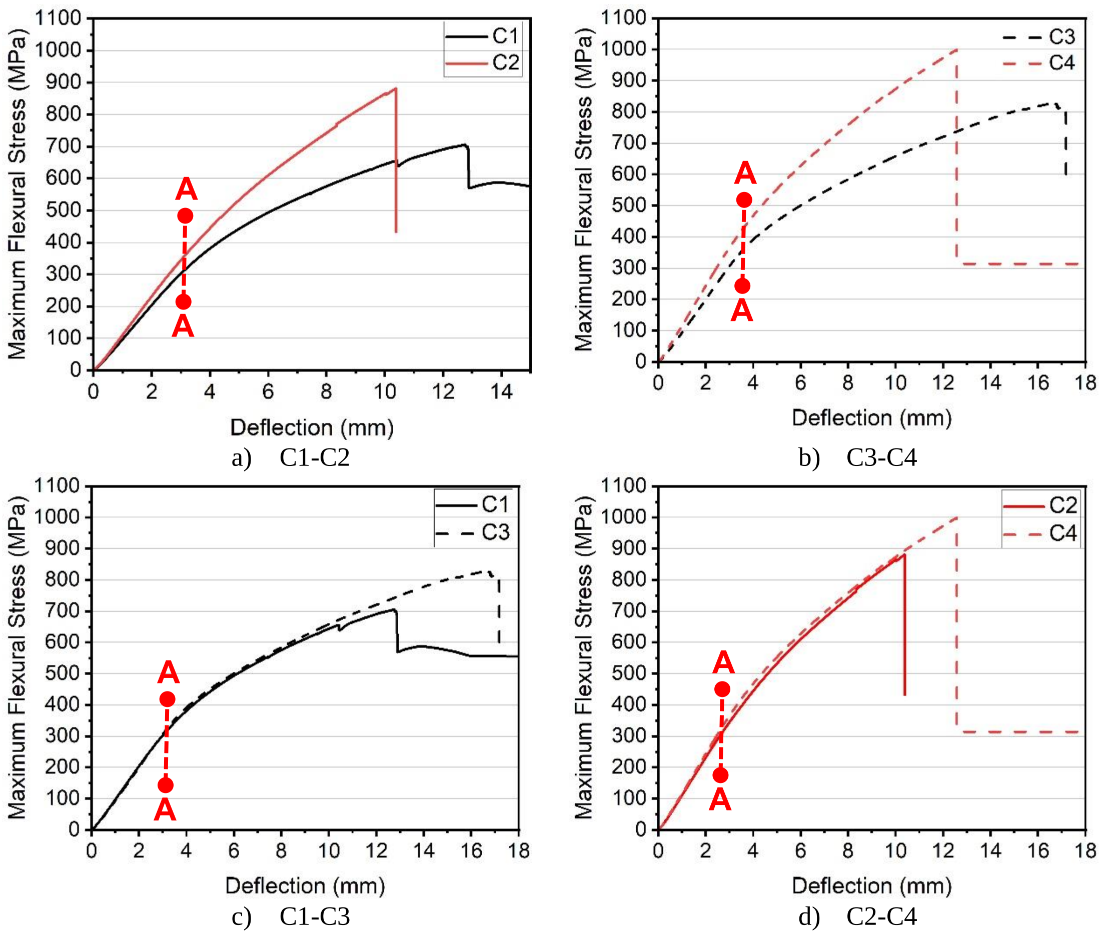


Figure 13 Three-point bending test results of carall specimens with different fiber directions and gnp additions (C1: 0°–90°, C2: 0°–0°, C3: 0°–90° with GNP, C4: 0°–0° with GNP)

Figure 14. Macroscopic damage in carall specimens following three-point bending test

Table 4. Comparison of elastic modulus and tensile strength of carall laminates with different fiber directions and gnp additions after tensile testing

	Maximum Force (N)	*Flexural Stress (MPa)*
C1	1050	759,71
C2	1221,75	949,020
C3	1141,74	819,43
C4	1557,8	1030,37

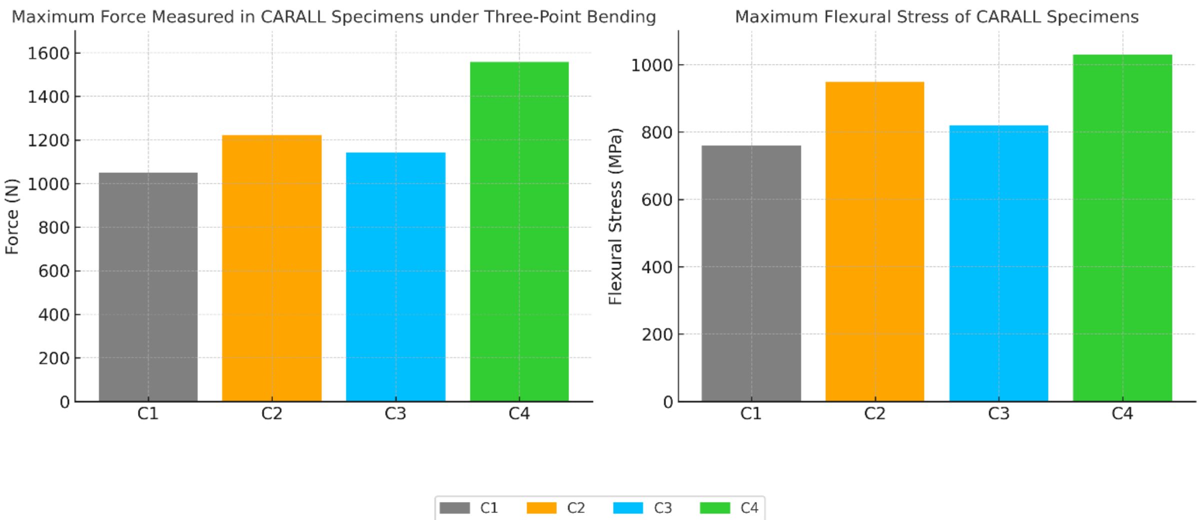


Figure 15. Comparison of maximum force and flexural stress of carall specimens under three-point bending test

In particular, fibers aligned along the specimen's longitudinal axis were found to play a critical role in load-bearing capacity and significantly affect the flexural modulus. Cepeda-Jimenaz [30] emphasized that the ultimate tensile strength of fibers in GLARE laminates is a key factor influencing their flexural stress. Ostapiuk et al. [27] studied the cracking and fracture behavior of FML composites under three-point bending. In their work, GLARE and CARALL specimens with 0°–0°, 0°–90°, and 45°–45° fiber orientations were tested, and their flexural performances were compared. The findings revealed that fiber orientation has a dominant influence on flexural strength, with 0°–0° oriented specimens reaching the highest flexural stress. In this context, the C3 and C4 specimens, which contained GNP reinforcement, demonstrated higher flexural stress due to the presence of nano-reinforcement. This improvement is attributed to the enhanced compressive strength of the GNP-modified epoxy matrix. Furthermore, it was determined that GNP addition reduced the displacement capacity of the material, resulting in a more rigid structure. The improved flexural performance of the GNP-reinforced specimens can be explained by two opposing mechanisms: (1) mechanical strengthening of the matrix and fiber–matrix interface, and (2) localized deterioration caused by particle agglomeration and poor wetting behavior due to the high viscosity of the epoxy matrix [31]. Similarly, Prashantha et al. [32] reported that the addition of HCNT to polypropylene matrix composites led to a modest increase in flexural strength at low reinforcement levels, while a decline in strength was observed at 8% HCNT due to agglomeration effects.

4. Conclusion

In this study, the mechanical behavior of Fiber Metal Laminate (FML) composites known as Carbon Fiber Reinforced Aluminum Laminates (CARALL) was experimentally investigated under the influence of fiber orientation and graphene nanoparticle (GNP) reinforcement. Four different CARALL specimens were fabricated with 0°–0° and 0°–90° fiber orientations, both with and without GNP reinforcement. Tensile tests in accordance with ASTM D3039 and three-point bending tests in accordance with ASTM D790 were conducted on the specimens.

The experimental results revealed that fiber orientation is a key parameter governing both the tensile and flexural performance of CARALL composites. Specifically, specimens with a 0°–0° fiber orientation exhibited superior tensile and flexural strength due to the alignment of fibers parallel to the loading direction. Conversely, specimens with a 0°–90° configuration showed lower strength due to transverse fiber alignment but demonstrated greater deformation tolerance.

The effect of GNP reinforcement on mechanical performance presented a complex trend. GNP-reinforced specimens exhibited increased stiffness and reduced displacement capacity compared to unreinforced ones. However, partial improvements in flexural strength were observed, attributed to the reinforcing effect of GNPs in the matrix. These findings suggest that while GNP addition can enhance interfacial bonding between fiber and matrix, adverse effects such as increased viscosity and nanoparticle agglomeration may compromise the overall performance.

Therefore, it is recommended that further systematic investigations be conducted using various GNP concentrations to better understand their influence on mechanical behavior. Such studies would help determine the optimal reinforcement level and mitigate potential drawbacks.

In conclusion, this study demonstrated that the mechanical performance of CARALL FML composites can be finely optimized through precise control of fiber orientation and nano-reinforcement content. The findings provide valuable and applicable engineering insights for the advanced structural design of composite materials, particularly in high-performance sectors such as aerospace, automotive, and defense industries.

Acknowledgment

This study is supported by Düzce University Research Fund Project Number: 2020.06.05.1123

References

[1] Abd El-baky, M. A., & Attia, M. A. (2020). Experimental study on the improvement of mechanical properties of GLARE using nanofillers. Polymer Composites, 41(10), 4130–4143. https://doi.org/10.1002/pc.25699

[2] Azimpour-shishevan, F., Akbulut, H., & Mohtadi-bonab, M. A. (2020). Synergetic effects of carbon nanotube and graphene addition on thermo-mechanical properties and vibrational behavior of twill carbon fiber reinforced polymer composites. Polymer Testing, 90(April), 106745. https://doi.org/10.1016/j.polymertesting.2020.106745

[3] Cepeda-Jiménez, C. M., Pozuelo, M., García-Infanta, J. M., Ruano, O. A., & Carreño, F. (2008). Influence of the alumina thickness at the interfaces on the fracture mechanisms of aluminium multilayer composites. Materials Science and Engineering: A, 496(1), 133–142. https://doi.org/https://doi.org/10.1016/j.msea.2008.05.015

[4] Dündar, Mustafa, Uygur, İlyas, & Ekici, Ergün. (2024). Optimization of low-velocity impact behavior of FML structures at different environmental temperatures using taguchi method and grey relational analysis. Journal of Composite Materials, 59(7), 885–906. https://doi.org/10.1177/00219983241301751

[5] Esfandiar, H., Daneshmand, S., & Mondali, M. (2011). Analysis of Elastic-Plastic Behavior of Fiber Metal Laminates Subjected to In-Plane Tensile Loading. Int J Advanced Design and Manufacturing Technology, 5(1), 61–69.

[6] Etri, H. El, Korkmaz, M. E., Gupta, M. K., Gunay, M., & Xu, J. (2022). A state-of-the-art review on mechanical characteristics of different fiber metal laminates for aerospace and structural applications. International Journal of Advanced Manufacturing Technology, 123(9–10), 2965–2991. https://doi.org/10.1007/s00170-022-10277-1

[7] Fang, Y., Sheng, D., Lin, Z., & Fei, P. (2024). Study of Low-Velocity Impact Behavior of Hybrid Fiber-Reinforced Metal Laminates. Polymers, 16(2). https://doi.org/10.3390/polym16020173

[8] Fathi, A., Liaghat, G., Sabouri, H., Chizari, M., Hadavinia, H., & Chitsaz Charandabi, S. (2021). Experimental investigation of quasi-static behavior of composite and fiber metal laminate panels modified by graphene nanoplatelets. Journal of Reinforced Plastics and Composites, 40(13–14), 518–532. https://doi.org/10.1177/0731684420985275

[9] Heydari-Meybodi, M., Mohammadkhani, H., & Bagheri, M. R. (2017). Oblique Low-Velocity Impact on Fiber-Metal Laminates. Applied Composite Materials, 24(3), 611–623. https://doi.org/10.1007/s10443-016-9530-3

[10] Jin, K., Wang, H., Tao, J., & Du, D. (2019). Mechanical analysis and progressive failure prediction for fibre metal laminates using a 3D constitutive model. Composites Part A: Applied Science and Manufacturing, 124, 105490. https://doi.org/https://doi.org/10.1016/j.compositesa.2019.105490

[11] Jin, K., Wang, H., Tao, J., & Zhang, X. (2019). Interface strengthening mechanisms of Ti/CFRP fiber metal laminate after adding MWCNTs to resin matrix. Composites Part B: Engineering, 171(May), 254–263. https://doi.org/10.1016/j.compositesb.2019.05.005

[12] Kazemi, M. E., Shanmugam, L., Yang, L., & Yang, J. (2020). A review on the hybrid titanium composite laminates (HTCLs) with focuses on surface treatments, fabrications, and mechanical properties. Composites Part A: Applied Science and Manufacturing, 128, 105679. https://doi.org/https://doi.org/10.1016/j.compositesa.2019.105679

[13] Khalili, S. M. R., Mittal, R. K., & Kalibar, S. G. (2005). A study of the mechanical properties of steel/aluminium/GRP laminates. Materials Science and Engineering A, 412(1–2), 137–140. https://doi.org/10.1016/j.msea.2005.08.016

[14] Kim, C., Kim, S., Park, J., & Song, J. (2015). Fabrication and Evaluation of Mechanical Properties of CF / GNP Composites. Procedia Manufacturing, 2 (February), 368–373. https://doi.org/10.1016/j.promfg.2015.07.065

[15] Liu, C., Du, D., Li, H., Hu, Y., Xu, Y., Tian, J., Tao, G., & Tao, J. (2016). Interlaminar failure behavior of GLARE laminates under short-beam three-point-bending load. Composites Part B: Engineering, 97, 361–367. https://doi.org/https://doi.org/10.1016/j.compositesb.2016.05.003

[16] Lu, B., Zhang, J., Zheng, D., Xie, J., & Zhang, L. (2023). Theoretical analysis on carbon fiber reinforced aluminum laminate under off-center impact. International Journal of Mechanical Sciences, 248, 108247. https://doi.org/https://doi.org/10.1016/j.ijmecsci.2023.108247

[17] Moussavi-Torshizi, S. E., Dariushi, S., Sadighi, M., & Safarpour, P. (2010). A study on tensile properties of a novel fiber/metal laminates. Materials Science and Engineering A, 527(18–19), 4920–4925. https://doi.org/10.1016/j.msea.2010.04.028

[18] Mukesh, A. M., & Hynes, N. R. J. (2019). Mechanical properties and applications of fibre metal laminates. AIP Conference Proceedings, 2142(1), 100002. https://doi.org/10.1063/1.5122456

[19] Ostapiuk, M., Bieniaś, J., & Surowska, B. (2018). Analysis of the bending and failure of fiber metal laminates based on glass and carbon fibers. 25(6), 1095–1106. https://doi.org/doi:10.1515/secm-2017-0180
[20] Park, S. Y., Choi, W. J., Choi, H. S., Kwon, H., & Kim, S. H. (2010). Recent trends in surface treatment technologies for airframe adhesive bonding processing: A review (1995-2008). Journal of Adhesion, 86(2), 192–221. https://doi.org/10.1080/00218460903418345
[21] Prashantha, K., Schmitt, H., Lacrampe, M. F., & Krawczak, P. (2011). Mechanical behaviour and essential work of fracture of halloysite nanotubes filled polyamide 6 nanocomposites. Composites Science and Technology, 71(16), 1859–1866. https://doi.org/https://doi.org/10.1016/j.compscitech.2011.08.019
[22] Rahman, F., Rafi, I. H., Chowdhury, S., Rohan, S. I., Wahid-Saruar, M., Haque, M. R., Gafur, M. A., & Hassan, M. (2024). Effect of fiber orientation on mechanical properties of betel nut (areca palm) stem fiber reinforced laminated polyester composites. Advances in Materials and Processing Technologies, 00(00), 1–18. https://doi.org/10.1080/2374068X.2024.2341520
[23] Raja, S. P., & Sreenivasan, V. S. (2024). Effect of Nanoclay Addition on Mechanical and Microstructure Properties of E-Glass Fiber and AA2022 Metal Skin Reinforced Epoxy Laminates. Jom. https://doi.org/10.1007/s11837-024-06962-z
[24] Sharma, A. P., Khan, S. H., & Parameswaran, V. (2017). Experimental and numerical investigation on the uni-axial tensile response and failure of fiber metal laminates. Composites Part B: Engineering, 125, 259–274. https://doi.org/10.1016/j.compositesb.2017.05.072
[25] Thirunavukkarasu, A., Shanmugasundaram, K., & Latha, G. (2024). Hybrid Composites for the Design and Development of Pressure Vessel for Underwater Applications. Defence Science Journal, 74(1), 108–118. https://doi.org/10.14429/dsj.74.19184
[26] Tong, A., Zhang, J., Wang, D., Chen, Y., & Xie, L. (2024). Research on static tensile properties and damage mechanism of GLARE laminates. Latin American Journal of Solids and Structures, 21(11), 1–15. https://doi.org/10.1590/1679-78258122
[27] Uygur, I. (1999). Environmentally assisted fatigue response of Al-Cu-Mg-Mn with SiC particulate metal matrix composites. Phd. Thesis, University of Wales Swansea, UK.
[28] Uygur, I. (2004). Tensile Behavior Of Powder Metallurgy Processed (Al-Cu-Mg-Mn) /SiCp Composites. Iranian Journal of Science & Technology, 28(B2), 239–248.
[29] Uygur, I., Evans, W., Bache, M., & Gülenç, B. (2004). The fatigue behaviour of aluminium alloy 2124 reinforced with SiC particulates. Metallofızıka I Noveıshıe Tekhnologıı, 26(7), 927–939. https://doi.org/10.1016/j.matdes.2004.09.024
[30] Wu, G., & Yang, J.-M. (2005). The mechanical behavior of GLARE laminates for aircraft structures. JOM, 57(1), 72–79. https://doi.org/10.1007/s11837-005-0067-4
[31] Zal, V., Sadooghi, A., Hashemi, S. J., Rahmani, K., Roohi, A. H., Khodayari, H., & Babazadeh, J. (2024). Experimental Study of Polyester/Fiberglass/Stainless Steel Fiber Metal Laminates Mechanical Properties. Arabian Journal for Science and Engineering, 49(8), 11167–11179. https://doi.org/10.1007/s13369-023-08610-1
[32] Zhai, L. L., Ling, G. P., & Wang, Y. W. (2008). Effect of nano-Al2O3 on adhesion strength of epoxy adhesive and steel. International Journal of Adhesion and Adhesives, 28(1), 23–28. https://doi.org/https://doi.org/10.1016/j.ijadhadh.2007.03.005