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Research Article

# Investigation of mechanical properties in variable oriented glass fiber reinforced insulators

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ABSTRACT

This study investigates the influence of fiber orientation on the mechanical performance of composite insulators produced by the hand lay-up method. E-glass fiber-reinforced epoxy composites were fabricated using three types of glass fiber fabrics: unidirectional (L300), ±90° biaxial (LT600), and ±45° biaxial (X600). Additionally, silica sand-filled epoxy insulators were also evaluated—both factory-produced and commercially sourced—to benchmark performance differences with glass fiber-reinforced counterparts. The primary objective is to assess how varying fiber alignment and material configurations affect mechanical properties, particularly under tensile loading. Specimens were prepared in four distinct orientation configurations and subjected to tensile testing. The results demonstrated significant variations in tensile strength, highlighting that even minor differences in fiber orientation can substantially alter mechanical behavior. Failure mode analysis further emphasized the critical role of fiber orientation in load distribution and structural integrity. Overall, this study provides insights into enhancing the mechanical reliability of composite insulators by optimizing fiber placement and evaluating alternative filler systems such as silica sand.

## Introduction

Composite materials have emerged as essential engineering materials across various industries due to their ability to provide tailored properties through the combination of different constituents. Among these, fiber-reinforced polymer (FRP) composites stand out for offering an excellent balance between strength, weight, and environmental resistance. Their versatility has led to widespread adoption in sectors such as aerospace, automotive, and energy, including high-voltage electrical systems.

In the maritime industry, glass fiber reinforced polymer (GFRP) composite panels are used on the outer surfaces of sandwich panels that form the hull coverings of vessels. A recent example of this application is the Visby Corvette, which is part of the Swedish Navy's fleet. Polymer laminates composed of hybrid carbon and glass fibers are layered around a core made of polyvinyl chloride (PVC). These sandwich composite panels have been used as exterior cladding in the construction of the corvette's hull [1].

When considering examples from the aerospace industry, rear pressure bulkhead of the Airbus A380, which plays a vital role in maintaining cabin pressure, is manufactured from carbon fiber-reinforced composite material. Given that this component separates the pressurized fuel compartment from the rear of the aircraft, it operates in a highly critical position. Similarly, the cargo door of the Airbus A400M, measuring 7 by 4 meters, is also constructed using carbon fiber-reinforced composite material[2].

GFRP composites have also found increasing applications in the automotive industry due to their favorable strength-to-weight ratio, corrosion resistance, and potential to improve fuel efficiency through weight reduction. These materials are commonly used in structural and semi-structural components, including leaf springs, bumper beams, and body panels. In a recent study on electric vehicles, GFRP was utilized in the design of a transverse composite leaf spring for the rear suspension system. Specifically, E-glass fibers were employed as reinforcement material, highlighting their suitability for load-bearing applications in lightweight vehicle platforms [3], [4].

In recent years, fiber-reinforced polymer (FRP) composites have become increasingly important in electrical insulation applications due to their excellent mechanical strength, lightweight structure, corrosion resistance, and dielectric properties. Particularly in the production of insulators, the combination of glass fibers with thermoset resin matrices such as epoxy has proven to be a cost-effective and highly adaptable solution.

One of the most influential factors affecting the mechanical and dielectric behavior of composite insulators is fiber orientation. Different stacking sequences and fiber alignment patterns can significantly alter the stress distribution, crack propagation, and overall failure behavior under loading. This is especially critical in hand lay-up processes, where manual fiber placement can introduce variability in the final product quality. Although the hand lay-up method is known for its simplicity and low cost, it remains sensitive to inconsistencies in fiber distribution, resin saturation, and void formation.

Glass fiber reinforced polymer (GFRP) composites are widely used in electrical and mechanical applications due to their high strength-to-weight ratio and excellent dielectric properties. However, as reported by Tuncer et al. [5], the dielectric breakdown strength of GFRP significantly varies depending on the material's thickness and field orientation. In their study, FR4 and cryogenic-grade GFRP samples showed up to 14% difference in breakdown strength, and a decrease in dielectric strength with increasing thickness was observed, following a power law. This sensitivity to material structure highlights the importance of laminate quality and consistency, especially for applications involving complex field directions or manual lay-up processes. These findings support the need to further investigate both mechanical and electrical performance in GFRP composites with different fiber orientations.

The mechanical properties of composite insulators, particularly their bending stiffness and equivalent elastic modulus, are significantly influenced by fiber orientation and lay-up angles. Wang et al. [6] emphasized that skew-symmetric laminates with specific winding angles, such as ±30°, affect the mechanical response of post insulators under loading. Their study also demonstrated that theoretical predictions based on laminate theory are in close agreement with experimental results, supporting the idea that fiber alignment is critical in optimizing structural rigidity. These insights highlight the importance of precise fiber arrangement, especially in manually fabricated systems like the hand lay-up method.

Glass-fiber reinforced polymer (GFRP) composites have been widely employed in outdoor electrical insulation due to their excellent dielectric properties, high mechanical strength, and resistance to environmental degradation. As highlighted by Park et al. [7], the combination of glass fibers with epoxy resin offers enhanced durability under ultraviolet exposure, humidity, and pollution, making it a preferred choice for high-voltage insulators. However, the mechanical and insulation performance of such composites is not only dependent on the material constituents but also significantly influenced by the orientation of the fibers. Fiber alignment angles determine the load transfer efficiency, failure modes, and stiffness of the composite. Misalignment or suboptimal lay-up angles (such as deviations from 0°, ±45°, or ±90°) may lead to stress concentrations, delamination, and premature failure, particularly in hand lay-up processes where manual placement introduces variability. Therefore, understanding and optimizing fiber orientation is essential for ensuring consistent performance in both mechanical and dielectric aspects of GFRP-based insulators.

Furthermore, several studies have demonstrated that glass fiber-reinforced polymers exhibit their highest mechanical strength when the applied load is aligned parallel to the fiber direction, and the lowest when the load is applied perpendicularly. This anisotropic behavior represents both strength and a limitation of fiber-reinforced polymer (FRP) composites, depending on the intended application and loading conditions. This phenomenon is also observed in the present study, where significant differences in tensile performance were recorded depending on the fiber orientation [8], [9]. Salgar et al. [10] produced epoxy matrix composites with varying fiber volume fractions (40%, 50%, and 60%) and compared their tensile test results. The best mechanical performance was achieved at a fiber content of 50%.

Sheng et al. [11] proposed a novel mechanical model to simulate the seismic behavior of composite insulators and cylindrical electrical equipment, which was developed based on combined experimental and numerical studies. In their investigation, the failure response of composite insulators under hysteretic bending was examined, and three distinct failure types were identified: (I) cracking of the metal flange, (II) tearing of the fiberglass composite tube, and (III) bond failure between the fiberglass tube and adjoining components.

Park [12] investigated the mechanical and dielectric properties of glass cloth composites. The study revealed that as the angle between the fiber orientation and the tensile loading axis increases, the load-bearing capacity of glass–epoxy composites decrease significantly.

Previous studies [13] have shown that increasing the fiber weight fraction up to 55% enhances tensile strength and stiffness, although flexural strength may decrease due to surface imperfections and porosity.

Different lay-up sequences in GFRP composites have a significant effect on tensile performance, with mechanical properties varying according to fiber orientation and stacking arrangement. The hand lay-up method remains widely used in the fabrication of fiber-reinforced composites, and its effect on tensile performance has been evaluated in various studies [14], supporting its relevance to experimental investigations like the present one.

Recent studies have compared different manufacturing techniques such as hand lay-up and vacuum infusion, highlighting that hand lay-up GFRP laminates typically exhibit lower tensile strength due to increased porosity and lower fiber volume fraction [15]. This reinforces the relevance of hand lay-up composites for performance benchmarking in experimental studies.

Failure mechanisms in fiber-reinforced composites can vary significantly depending on the fiber orientation, with common failure modes including matrix cracking, fiber fracture, and interlaminar delamination. These phenomena have been extensively detailed in recent literature, emphasizing their prevalence in both unidirectional and multidirectional laminates [16].

Recent research has examined the suitability of glass fiber-reinforced polymer (GFRP) composites for use as electrical insulators in power transmission lines. The study compared epoxy and polyester matrix composites by evaluating their mechanical such as tensile strength and dielectric behavior, particularly under environmental stress conditions such as moisture and acid exposure. It was found that moisture absorption negatively impacted breakdown voltage, and acid aging led to minor reductions in tensile strength. Epoxy-based GFRP composites exhibited superior resistance to chemical degradation, indicating their higher reliability for high-voltage insulation applications [17].

The main objective of this study is to investigate how different fiber orientations affect the mechanical performance of glass fiber-reinforced epoxy composite insulators. For this purpose, composite specimens were produced using the hand lay-up method with E-glass fiber fabrics in four orientation configurations: 0°, 90°, ±90°, and ±45°. Additionally, a silica sand-filled epoxy insulator—both factory-fabricated and commercially available—was included for comparison. All specimens were subjected to tensile testing to evaluate the influence of fiber alignment on their structural integrity and load-bearing capacity.

## Material and Method

In this study, epoxy matrix composite insulator specimens were fabricated using different fiber orientations. The reinforcement materials included:

E-glass fiber fabrics produced by Metyx:

- L300 unidirectional (UD) glass fiber fabric (300 g/m²) for specimens with fibers oriented parallel and perpendicular to the tensile direction,

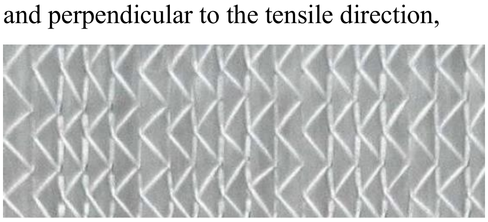

Figure 1. L300 Glass Fiber Unidirectional Fabric

- LT600 biaxial fabric (600 g/m²) for ±90° unidirectional orientation,

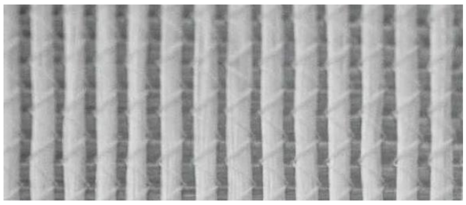

Figure 2. LT600 Glass Fiber Biaxial Fabric

- X600 biaxial fabric (600 g/m²) for ±45° orientation.

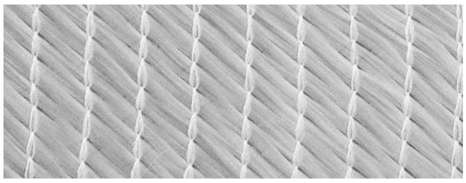

Figure 3. X600 Glass Fiber (Biaxial) Fabric

The resin system consisted of epoxy and hardener mixed at a 55:45 weight ratio, prepared and poured at 70 °C, and cured in a controlled temperature process.

Although both 300 g/m² and 600 g/m² fiber fabrics were used across the specimen types, the fiber volume fraction was kept constant at approximately 40% in all specimens, ensuring consistent material content across different laminates.

## Manufacturing Process

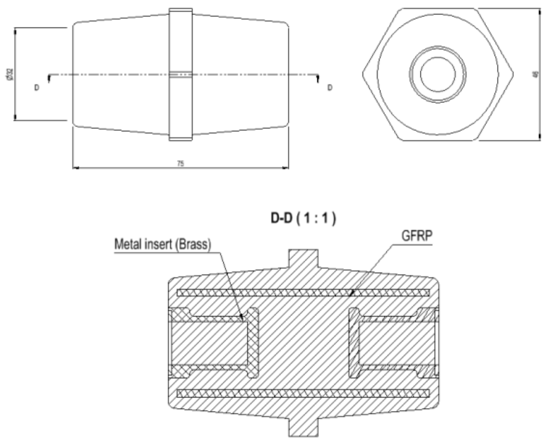


Figure 4. Specimen overview

The specimens were produced via the hand lay-up method. Glass fiber fabrics were cut and laid onto inserts, then rolled into cylindrical shapes and placed into a pre-heated mold.

Figure 5. Specimen preparation

The mold was initially heated at 70 °C for 30 minutes, followed by a staged temperature increase of 10 °C every 4 hours up to 120 °C, where it was held for a final curing period before cooling to room temperature. All specimens had a fiber volume fraction of approximately 40%, and the laminated wall thickness was ~7 mm.

Four types of fiber orientations were produced:

- Fibers perpendicular to the tensile direction,
- Fibers parallel to the tensile direction,
- ±90° unidirectional orientation,
- ±45° orientation.

Each specimen type was prepared in triplicate for mechanical testing. In addition to the four fiber-reinforced composite types, resin–silica filled insulator specimens were also fabricated. Furthermore, a commercially available insulator, commonly used in daily applications, was included in the study as a benchmark reference for performance comparison.

## Tensile Testing

Tensile tests were conducted using a Zwick-Roell universal testing machine at Balıkesir University's Center for Science and Technology. Three specimens were tested for each fiber orientation; one representative force–elongation graph is presented, and mean force and strain values from all three specimens are reported in the related tables. Each specimen was mounted using M12 threaded rods and tested under a constant displacement rate of 2 mm/min, following the general principles of ISO 527-4[18] and ISO 527-5[19] , which define test conditions for fiber-reinforced plastics. Both standards refer to ISO 527-1[20] for the general principles regarding the determination of tensile properties. Although the sample geometry did not conform exactly to the ISO standard dumbbell shapes, test parameters such as speed and boundary conditions adhered to the relevant guidelines. Maximum force, strain, and failure modes were recorded for each test.

**±90° fiber-reinforced specimen**

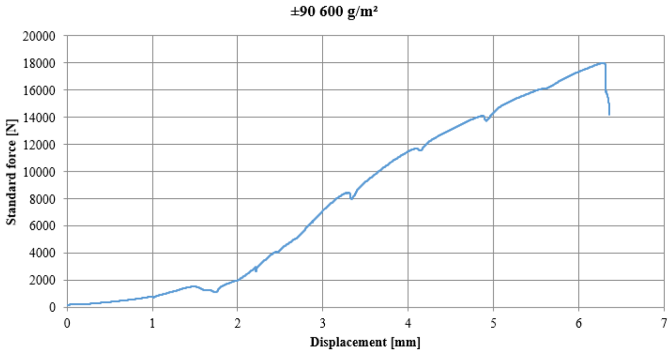


Figure 6 Test result ±90° fiber-reinforced specimen

Table 1 Summary of tensile performance of ±90° lay up

| ±90° specimen | Displacement (mm) | Force (N) |
|---|---|---|
| Mean | 6,63 | 18333 |

A force–elongation diagram of a composite insulator reinforced with 600 g/m² glass fiber is presented here. While three specimens were initially tested, only one has been retained as a representative example in the figure. The table summarizes the average tensile performance across all three samples. Initially, the force increases linearly, reaching a maximum value. Following this peak, a sudden drop in the force is observed as the specimens reach their strength limits and subsequently fail. Minor drops and jumps can be seen throughout the graphs. The small force drops and recoveries, particularly noticeable in specimens 1 and 3, are likely attributed to the microstructural characteristics of the material and instantaneous effects during the testing process. These phenomena can be explained by the following reasons:

- Fiber Fracture in Glass Fibers: In glass fiber-reinforced materials, some fibers may fracture under loading. These fractures cause sudden small drops in force. However, as the remaining structure continues to carry the load, the force rises again.
- Weak Bonding at the Fiber-Matrix Interface: In composite materials, the bond between the polymer matrix and the glass fibers may not be completely uniform. Microcracks may form in regions of weak bonding, temporarily reducing the load-carrying capacity and causing small force drops.
- Load Redistribution: When some fibers break or the matrix cracks, the load is redistributed to the remaining intact regions, resulting in small recoveries observed in the graph.

Figure 7 ±90° fiber-reinforced specimen after test

When it comes to explaining the differences among specimens the second specimen shows the highest maximum force. This suggests that the second specimen is structurally more robust, has fewer discontinuities, or that the resin more uniformly infiltrated the fiber structure. The third specimen reaches a lower maximum force compared to the others and exhibits greater fluctuation. This indicates a higher number of fiber fractures or bonding issues, meaning it has more internal discontinuities. The first specimen demonstrates a moderate level of performance.

The strain value observed around 6–7 mm appears relatively high for a brittle structure. As the load is applied, the insert inside the insulator gradually detaches from the matrix at the interface. Although this internal separation is not visibly detectable from the outside, it contributes to the observed strain values of 6–7 mm.

**±45° fiber-reinforced specimen**

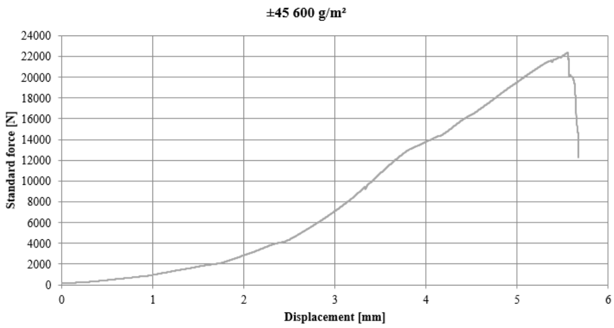


Figure 8 Test Results ±45° fiber-reinforced specimen

Table 2 Summary of tensile performance of ±45° layup

| ±45° specimen | Displacement (mm) | Force (N) |
|---|---|---|
| Mean | 5,56 | 22604 |

The force–elongation diagram and test result images of a composite insulator reinforced with ±45° 600 g/m² glass fiber are presented. Although three specimens were tested, one representative curve is retained in the figure, and the table shows the average tensile results. Although the specimens exhibited similar fracture behaviors, they showed differences at certain points. Among the six types of fiber orientations tested, this insulator type demonstrated the highest fracture loads, reaching approximately 25,000 N. Examination of the fracture structure revealed the effects of the ±45° lamination, where capillary-like crack propagation was observed.

Figure 9 ±45° fiber-reinforced specimen after test

**Specimen with fibers oriented parallel to the tensile direction**

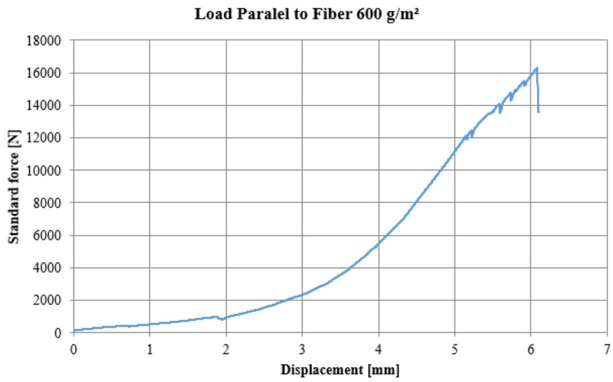


Figure 10 Load Parallel to Fiber Direction

Table 3 Summary of tensile performance of fiber parallel to load direction

| Load paralel to fiber specimen | Displacement (mm) | Force (N) |
|---|---|---|
| Mean | 5,95 | 15297 |

In this specimen type, the fibers were laminated with an orientation parallel to the tensile direction. As expected, based on the stacking structure, this group of specimens exhibited the lowest strength among all types [8]. Since the fibers were not loaded along their working direction, the matrix primarily carried the applied load, resulting in deformation at lower force levels. The fracture mode observed is like that of silica-filled insulators, which will be discussed later.

As in the first tests, minor drops and recoveries were observed in the graphs of Specimen 1 and Specimen 2. This behavior suggests that partial deformations occurred within the matrix at the microstructural level. After the failure of some bonds, the remaining structure continued to carry the load, leading to recovery in the force-displacement curve after each drop.

The strain values, again around 6–7 mm, appear relatively high for a brittle specimen structure. As the load increases, the insert inside the insulator gradually detaches from the matrix interface. Although this internal separation is not visible externally, it results in the recorded strain values around 6–7 mm.

Figure 11 Fiber direction parallel to tensile load specimens after test

In conclusion, although all specimens in this group exhibited similar structural behavior, Specimen 2 demonstrated the highest load-carrying capacity among them. For this generally weaker group, it can be stated that they were able to carry an average load of approximately 15,000 N.

**Specimen with fiber-oriented perpendicular to the tensile direction**

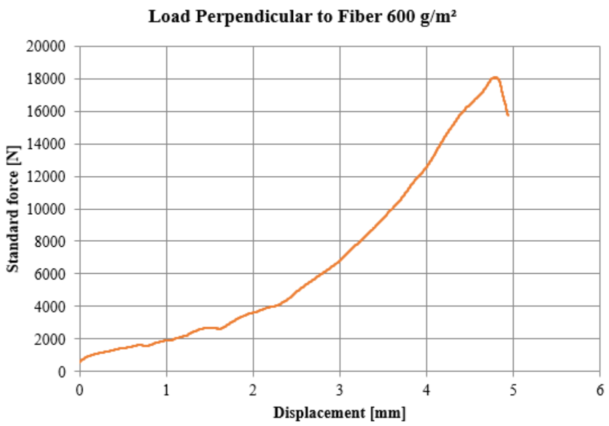


Figure 12 Load Perpendicular to Fiber Direction

Table 4 Summary of tensile performance of fiber perpendicular to load direction

| Load perpendicular to fiber specimen | Displacement (mm) | Force (N) |
|---|---|---|
| Mean | 4,4 | 18958 |

This specimen group exhibited the highest strength following the ±45° lamination configuration. As expected, since the fibers were oriented perpendicular to the loading axis, the specimens were able to withstand higher forces. Minimal surface deformation was observed; however, certain regions showed crack propagation along the matrix.

Figure 13 Fiber direction perpendicular to tensile load specimens after test

**Purchased (outsourced) sand-filled specimen**


Figure 14 Silica Filled Outsourced Test Result

Table 5 Summary of tensile performance of silica filled outsourced specimens

| Purchased specimen | Displacement (mm) | Force (N) |
|---|---|---|
| Mean | 3,3 | 16212 |

The product evaluated in this study is a commercially available insulator manufactured from a sand-filled resin mixture. Similar products are produced by various domestic and international companies. Although it exhibited lower strength than the glass fiber-reinforced specimens with laminations perpendicular to the loading direction, it still demonstrated a moderate level of mechanical performance.

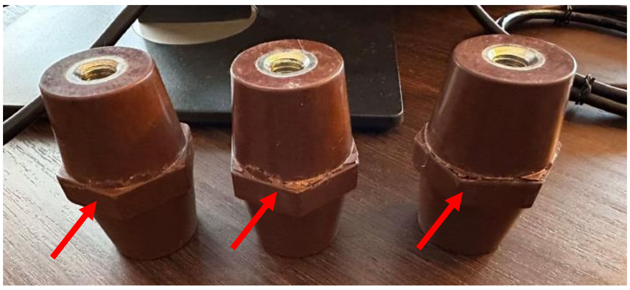

Figure 15 Silica filled purchased specimens after tensile test

While the product's datasheet claims that it can withstand a tensile load of 20,000 N, experimental tests revealed a maximum load-bearing capacity of only 18,000 N, raising concerns about the product's reliability. As expected, the specimen exhibited brittle behavior and failed at the point where the metal insert ended, due to a notch effect.

### In house produced sand-filled specimen

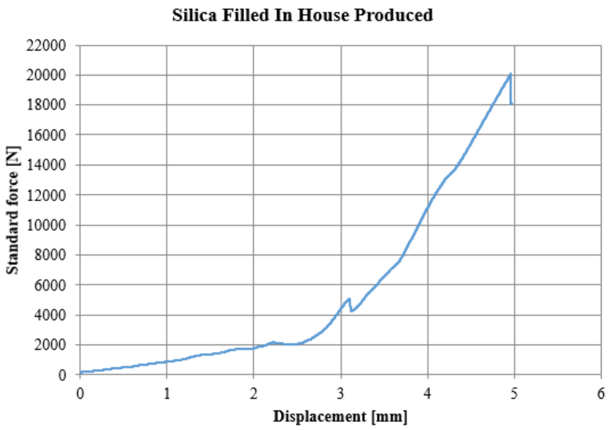


Figure 16 Silica Filled In House Produced Test Result

Table 6 Summary of tensile performance of silica filled in house produced specimens

| In house produced specimen | Displacement (mm) | Force (N) |
|---|---|---|
| Mean | 4,7 | 18496 |

It was manufactured from a mixture of sand and resin. It exhibited approximately 10% higher strength compared to the commercially available counterpart. The specimen fractured at an average load of 18,500 N. As expected, it displayed a brittle fracture behavior and failed at the point where the metal insert ended due to a notch effect.

Figure 17 Silica filled inhouse specimens after tensile test

### Results and Discussion

Overall, the six types of tested specimens exhibited relatively consistent mechanical behavior without significant deviations. However, specific specimen types demonstrated clear superiority in terms of load-bearing capacity. The specimens with ±45° 600 g/m² glass fiber laminations showed the highest tensile strength among all tested groups. Following them, the specimens with fibers oriented perpendicular to the tensile direction and the unidirectional ±90° 600 g/m² fiber specimens exhibited relatively high performances, respectively. Although the literature generally suggests that specimens with fibers oriented perpendicular to the loading direction tend to exhibit the highest strength [9], [12], the present study revealed that the ±45° configuration outperformed all other types in terms of maximum tensile load. Among the sand-filled specimens, the manufactured specimen distinguished itself by achieving approximately 10% higher tensile strength compared to the commercially purchased one. This finding indicates that controlled fabrication processes can significantly enhance the mechanical performance of resin-sand composite insulators.

Overall, the results emphasize that fiber orientation has a decisive impact on the tensile behavior of composite insulators. Laminations that enable effective load transfer through fiber alignment, particularly ±45° orientations, provide superior mechanical properties. In contrast, configurations where fibers do not efficiently contribute to load bearing results in lower performance, requiring greater reliance on the matrix material.

Table 7. General Evaluation of the Results

| Type | Mean Displacement (mm) | Standard Deviation (mm) | Mean Force (N) | Standard Deviation (N) | % Difference Force vs Min | % Difference Displacement vs Min |
|---|---|---|---|---|---|---|
| ±90° | 6,63 | 0,36 | 18333,33 | 1505,55 | 19,80 | 100,90 |
| ±45° | 5,56 | 0,08 | 22603,67 | 2351,15 | 47,80 | 68,50 |
| Load Paralel to Fiber 600 g/m² | 5,95 | 0,63 | 15297,33 | 1790,80 | Reference (min) | 80,30 |
| Load Perpendicular to Fiber 600 g/m² | 4,40 | 0,74 | 18958,33 | 2787,00 | 23,90 | 33,30 |
| Silica Filled Outsourced | 3,30 | 0,31 | 16212 | 1495,00 | 6,00 | Reference (min) |
| Silica Filled Inhouse Produced | 4,70 | 0,82 | 18496,33 | 1331,90 | 20,90 | 42,40 |

**Conclusion**

This study demonstrated that fiber orientation plays a critical role in determining the tensile performance of epoxy matrix composite insulators manufactured using the hand lay-up method. The key findings of the study are summarized below:

- ±45° fiber-oriented specimens exhibited the highest tensile strength among all configurations tested.
- Specimens with fibers perpendicular to the tensile direction and ±90° unidirectional layups followed in performance.
- Manufactured sand-filled specimens performed approximately 10% better in tensile strength than their commercially available counterparts.
- The results emphasize the significance of precise fiber alignment and controlled manufacturing processes in improving the mechanical reliability of composite insulators.

These findings provide a foundation for further research into optimizing fiber orientation strategies in composite insulator design and improving the performance of manually fabricated polymer-based components.

## Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared.

There is no conflict of interest with any person / institution in the article prepared.

## Authors' Contributions

-Study conception and design: Bilgin, Çetinel, Yalçın

-Acquisition of data: Bilgin

-Analysis and interpretation of data: Bilgin, Çetinel, Yalçın

-Drafting of manuscript: Bilgin

-Critical revision: Çetinel, Yalçın

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