Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN	: 2549-1999	No.	: 4	Month	: August
p-ISSN	: 1693-5462	Volume	: 22	Year	: 2024

Article Processing Dates: Received on 2024-05-28, Reviewed on 2024-07-09, Revised on 2024-08-18, Accepted on 2024-08-22 and Available online on 2024-08-30

Characterization of the Mechanical Properties of Fiberglass/Epoxy Prepreg Composites as Horizontal Axis Wind Turbine Blade Material: Influence of Fiber Orientation on Impact and Bending Strength

Budi Istana[1*], Fitto Alfredo[1], Sunaryo Sunaryo[1]
[1]Department of Mechanical Engineering, Universitas Muhammadiyah Riau, Pekanbaru, 28292, Indonesia
*Corresponding author: budiistana@umri.ac.id

Abstract

This study aims to investigate the effect of fiber orientation on the impact and bending strength of fiberglass/epoxy prepreg composites used in horizontal axis wind turbine applications. The use of fiberglass/epoxy composites in the renewable energy industry, particularly in horizontal axis wind turbines, is increasing due to their superior mechanical properties. One crucial factor influencing the performance of these composites is the fiber orientation within the material structure. Proper fiber orientation can enhance impact and bending strength, which are critical for resisting dynamic and static loads during wind turbine operation. In this study, various fiber orientation angles were tested to determine their impact on composite performance. The analysis provides valuable insights for optimizing the design and improving the performance of wind turbines by maximizing the properties of the composite materials used. The study focused on 45° and 90° fiber orientations with epoxy resin as the matrix. The impact test results indicated that the highest impact strength was achieved with the 45° fiber orientation, showing a value of 0.113 J/mm² and an absorbed impact energy of 11.307 Joules. Similarly, the bending test results demonstrated that the 45° fiber orientation produced the highest bending strength. These findings highlight the significant effect of 45° fiber orientation on the impact strength and bending properties of the composite material. The results are expected to contribute to the development of more optimized composite materials for renewable energy applications, especially in the wind turbine industry.

Keywords:
Prepreg fiberglass, composite, epoxy, fiber orientation, impact and bending strength.

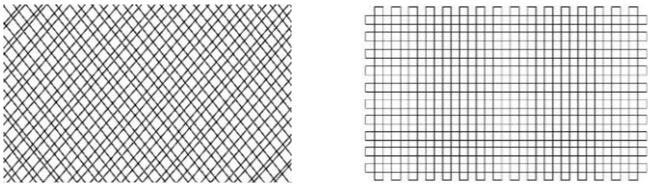
1 Introduction

The increasing demand for renewable energy sources has triggered the development of more efficient and sustainable wind turbine technologies. Horizontal axis wind turbines are among the most used types due to their efficiency in converting wind energy into electrical energy [1]. The main components of wind turbines, such as the blades, are generally made from composite materials known for their high strength-to-weight ratio and resistance to harsh environmental conditions. However, the performance of these composite materials is greatly influenced by the orientation of the fibers used [2]. Proper fiber orientation can improve the impact and bending strength of the material, which is crucial for ensuring the viability of wind turbines under various changing wind load conditions [3], However, information regarding the effect of fiber orientation on the mechanical characteristics of fiberglass/epoxy prepreg composites in wind turbine applications is limited. In response to this, various materials have been developed and researched to create new materials that are efficient, cost-effective, and environmentally friendly [4]. In recent decades, the development of composite materials, particularly fiberglass/epoxy prepregs, has become a major focus in the horizontal axis wind turbine manufacturing industry. These composite materials are selected for their superior mechanical and physical characteristics, such as a high strength-to-weight ratio, corrosion resistance, and adaptability to extreme environmental conditions.

Previous studies have shown that fiber orientation in composite materials plays a crucial role in determining the impact and bending strength of the material [2], [5], [6]. These studies have utilized various experimental and simulation techniques to evaluate the effect of fiber orientation on the mechanical performance of composites. Several analytical methods, such as tensile tests, bending tests, and impact tests, have been conducted to measure the mechanical properties of materials with various fiber orientation configurations. Rajesh et al [7] on the comparison of dynamic behavior between woven and randomly oriented fiber-reinforced composites showed that the use of woven sisal fibers improved the properties of composite materials, such as stiffness and strength, compared to composites with the same fiber weight percentage but random fiber orientation. In other cases, reinforcement in the form of webbing fundamentally increases strength, while randomly oriented short fibers enhance the damping factor of the composite. The effect of the weave pattern on the mechanical properties of composites has also been discussed in the research by Sarifah et al. [8], which revealed that the layout and direction of the fibers in the matrix determine the mechanical strength of the composite, thus affecting its overall performance. Widodo et al [9] state that a closer fiber weave distance makes the composite stronger. Composites with unidirectional fibers tend to have higher strength and stiffness compared to other fiber orientations. On the other hand, composites with multiple fiber orientations generally have lower maximum stiffness values. However, they are able to withstand loads in more directions with the same strength. [10]. The development of technology is advancing rapidly, particularly in the field of composite technology, which is being increasingly applied to various tools, especially those requiring strong and lightweight materials [11][12]. In response, various materials have been developed and researched to create new options that are efficient, cost-effective, and environmentally friendly [4]. In the manufacturing industry, the use and application of composites continue to evolve [13][14].

Previous research by Sriyono et al [15] focused on the development of jute natural fiber composites with volume fractions of 30%, 40%, and 50%, and fiber orientations of 0°, 45°, and 90° for wind turbine blade applications. The results showed that the highest tensile strength was achieved with a 45° fiber orientation and 40% volume fraction, with a value of 27.13 MPa. The lowest tensile strength was observed with a 90° fiber orientation and 50% volume fraction, with a value of 16.87 MPa. However, while the use of jute natural fibers shows promising results in certain applications, there are some limitations that need to be considered. Natural fibers tend to have variable mechanical properties and are susceptible to environmental conditions, such as moisture and biological attacks, which can affect the lifespan and performance of the composite [16]. Additionally, resistance to weathering and extreme conditions poses challenges for natural fiber-based materials when used in intensive outdoor applications, such as wind turbine blades.

To overcome this limitation, the research focused on using 200 g/m² fiberglass prepreg fibers with an epoxy matrix, with variations in fiber orientation at 45° and 90°, as illustrated in Fig 1, for horizontal wind turbine blade applications. The results of this study are expected to provide guidance to the industry in choosing the optimal fiber orientation to improve the performance and durability of horizontal axis wind turbines.



(a) (b)

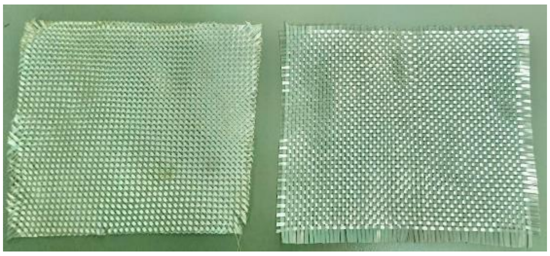
Fig. 1. Illustration of fiber cut direction orientation (a) 45° orientation (b) 90° orientation.

2 Research Methods

This research was conducted using experimental/testing methods. The fabrication of test samples was carried out at the Materials & Metallurgy Laboratory of Mechanical Engineering Department, Universitas Muhammadiyah Riau. Mechanical testing was performed at the Material Test Laboratory, Department of Mechanical Engineering, Politeknik Negeri Bengkalis.

2.1 Materials

The materials used in this research include Epoxy Resin 504 as the matrix and Hardener 504 as the catalyst, with a resin-to-hardener ratio of 5:1, and 200 g/m² fiberglass prepreg as the reinforcement. Fig 2 shows the fiberglass prepreg material used in this study.



(a) (b)

Fig. 2. Fiberglass prepreg 200 gr/cm^2 (a) 45° fiber cut orientation (b) 90° fiber cut orientation.

2.2 Composite Fabrication

The composites were fabricated using the hand lay-up method with a volume fraction of 40% fiberglass prepreg and 60% epoxy. The fiber orientation varied between 45° and 90°, as shown in Fig 2. The matrix and fiber were adjusted to match the specified volume fraction. Table 1 shows the variations in volume fractions used.

Table 1. Volume fraction variations

Type:	Code of test sample (impak)	Code of test sample (bending)	Fiber glass (%)	Matrix (%)
Fiber orientation 45°	1 A-45°	2 A-45°	40%	60%
	1 B-45°	2 B-45°	40%	60%
	1 C-45°	2 C-45°	40%	60%
	1 D-45°	2 D-45°	40%	60%
	1 E-45°	2 E-45°	40%	60%
Fiber orientation 90°	1 A-90°	2 A-90°	40%	60%
	1 B-90°	2 B-90°	40%	60%
	1 C-90°	2 C-90°	40%	60%
	1 D-90°	2 D-90°	40%	60%
	1 E-90°	2 E-90°	40%	60%

Experimental testing of fiberglass/epoxy prepreg composites was conducted according to the ASTM D790-02 standard for bending tests and the ASTM D6110 standard for impact tests. Additionally, fracture observations were made on the test samples using macro photography. In this study, descriptive data analysis was employed to present the results in graphical form.

2.3 Composite Manufacturing Process

The composite test samples were fabricated using the Contact Molding Hand Lay-Up method, as shown in Fig 3. Prepare the tools and materials, apply wax evenly to the mold, and wait approximately 15 minutes until it dries. Next, mix epoxy resin 504 and hardener in a 5:1 ratio. Apply the gel coat mixture evenly to the surface of the mold using a sponge, then place it in an oven for about 15 minutes at 45°C. Cut three sheets of 200g/m² fiberglass prepreg with fiber orientations of 45° and 90°. Cut them to match the size of the mold, then attach them to the mold.

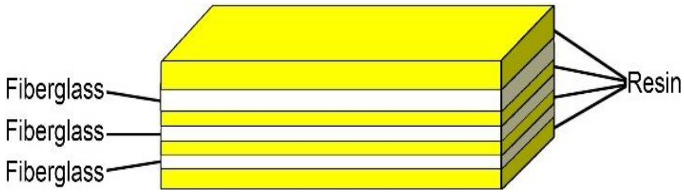


Fig. 3. Illustration of fiber arrangement.

Mix the resin and hardener until the mixture is homogeneous. Then, apply it to the surface of the fiberglass using a brush or roller until the fiberglass is thoroughly wet. Apply three layers of fiberglass in the same manner to form a sandwich structure. Place the mold under sunlight for 90 minutes, then remove the composite from the mold.

2.4 Preparation of Test Samples

2.4.1 Impact Testing

The Charpy impact test is conducted to determine the energy absorbed by the composite specimen until the material breaks.

Tests were conducted according to ASTM Standard D-6110 [17] as shown in Fig 4. The test specimens were 55 × 10 × 10 mm in size with a V-type notch. The test specimen was prepared and a pendulum was dropped to impact the notched area. The maximum energy absorbed by the specimen was recorded.

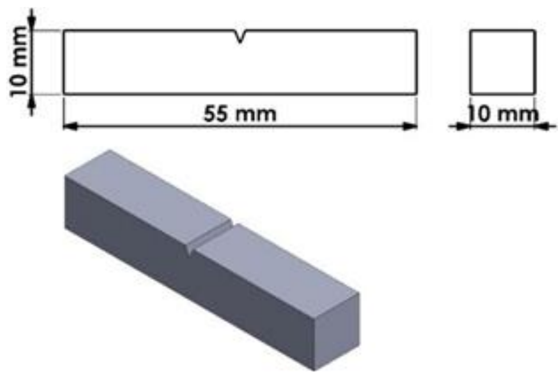


Fig. 4. Dimensions ASTM D-6110.

2.4.2 Bending Testing

The bending test is used to determine the stress on a material just before it yields during bending. The specimen testing scheme is shown in Fig. 5. This technique involves bending the specimen to the point of fracture or yield using the three-point bending test method. The load is applied at the center point of the specimen. In this study, the bending test followed the ASTM D790-02 standard, with test sample dimensions of 130 × 10 × 5 mm [18].

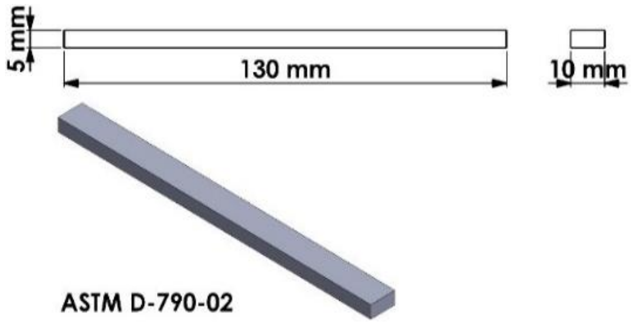


Fig. 5. Dimensions ASTM D790-02.

3 Results and Discussion

3.1 Impact Test Result

The impact test results show that the highest impact value was achieved by the 45° fiber orientation, with an average of 11.307 Joules. In contrast, the 90° fiber orientation test sample absorbed potential energy with an average value of 7.034 Joules. The test result data can be found in Tables 2 and 3. The placement and orientation of the fibers within the matrix determine the composites mechanical strength, as fibers can more effectively bear loads from various directions, thereby absorbing more energy during impact [15].

Table 2. Impact test result data of 45° fiber cut direction orientation

Sample code	Angle before the pendulum swings/α	Angle after pendulum swung/β	Impact energy (J)	Impact strength (J/mm^2)
1 A-45°	130°	110.5	13.76	0.138
1 B-45°	130°	116	9.61	0.096
1 C-45°	130°	120	6.71	0.067
1 D-45°	130°	119.9	6.80	0.068
1 E-45°	130°	103	19.65	0.197
Average			11.307	0.113

Table 3. Impact test result data of 90° fiber cut direction orientation

Sample code	Angle before the pendulum swings/α	Angle after pendulum swung/β	Impact energy (J)	Impact strength (J/mm^2)
1 A-90°	130°	110.5	6.71	0.067
1 B-90°	130°	116	7.43	0.074
1 C-90°	130°	120	6.90	0.068
1 D-90°	130°	119.9	8.15	0.082
1 E-90°	130°	103	7.43	0.074
Average			7.034	0.073

3.2 Analysis of Impact Test Fracture Patterns

In the test specimen with 45° fiber orientation, the fractures were generally fibrous, with failure caused by the significant impact force received by the specimen. Another type of fracture observed was Fiber Pull-Out, as shown in Fig. 6. The fibers protruded quite long, which occurred due to the uneven distribution of fibers and resin during the sample preparation process. This led to air gaps that weakened the bond between the matrix and fibers, as well as voids between the fiber and resin surfaces caused by the matrix's failure to bond. Consequently, the fibers could not bear the load, and the fracture process occurred simultaneously due to the applied shock load.

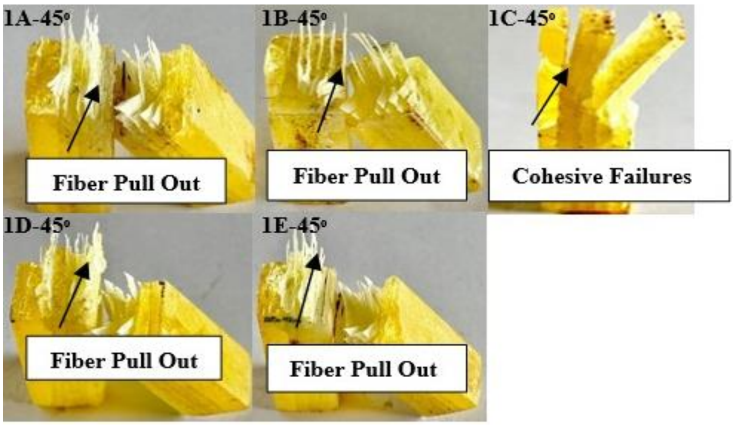


Fig. 6. Impact fracture shape of 45° fiber direction.

Correlation between the test values and the phenomena of fibrous fractures and fiber pull-out reflects the effects of uneven fiber and resin distribution and the quality of the composite manufacturing process. Fibrous fractures and fiber pull-out indicate that while fiber orientation can enhance strength, inconsistencies in the manufacturing process and the quality of the bond between the fibers and matrix significantly affect the overall test results. For instance, test specimen 1C-45°, which experienced cohesive failure, had a low impact energy of 6.71 Joules, whereas specimen 1E-45° achieved the highest impact energy of 19.65 Joules. This discrepancy underscores the importance of quality control in the manufacturing process and the reliability of the testing equipment used.

From Fig 7, test specimens 1A-90°, 1B-90°, and 1C-90° show cohesive failure, which indicates breakage within the filler/fiber components. This occurs when the matrix is not strong enough to support the applied load, leading to separation between the fiber layers and the matrix. In contrast, test specimens 1D-90° and 1E-90° exhibit fracture patterns where multiple fibers in the composite break simultaneously or nearly simultaneously along the loaded path. This is due to the perfect distribution of fibers and matrix, resulting in a strong cohesive bond.

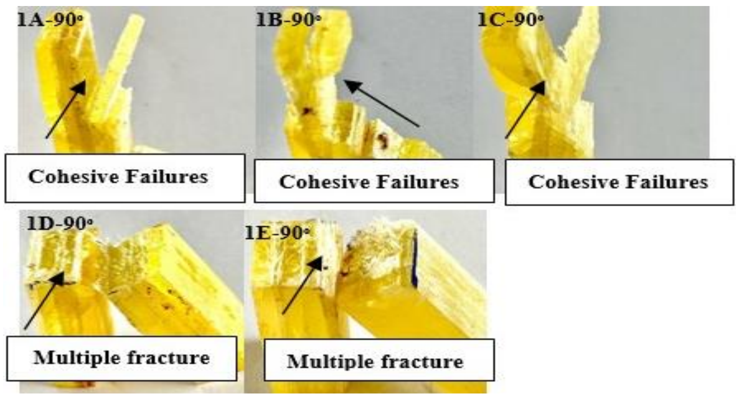


Fig. 7. Impact fracture shape of 90° fiber direction.

Fig. 8 shows a comparison of impact strength data. It is evident that test specimens with a 45° fiber orientation have the highest impact strength, with an average of 0.113 J/mm², while specimens with a 90° fiber orientation have an average impact strength of 0.073 J/mm². The impact test results also reveal that as the angle of impact decreases, the impact strength increases, and vice versa. Based on the fracture pattern analysis, it can be concluded that specimens with a 45° fiber orientation have a stronger cohesive bond between the fibers and the matrix, resulting in better impact strength.

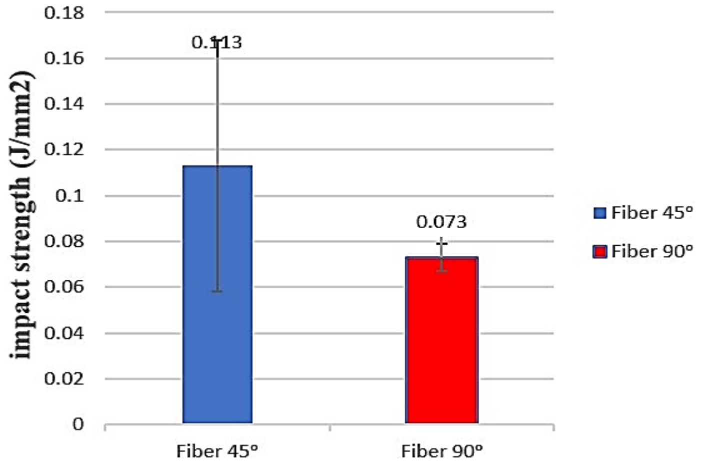


Fig. 8. Comparison chart of impact strength.

3.3 Bending Test Result

This bending test employs the three-point bending method to determine the bending stress values. The test was conducted using a Gotech Testing Machine GT-7001-LC 30. The testing instrument is shown in Fig. 9.

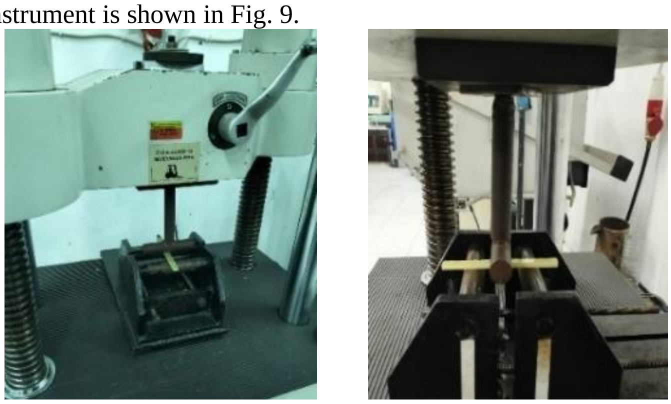

(a) (b)

Fig. 9. Composite bending testing.

The bending test results show that the highest bending stress value was achieved by the 45° fiber orientation, with an average of 379.59 MPa. In contrast, the samples with a 90° fiber orientation had an average bending stress of 217.26 MPa. The test result data can be found in Tables 4 and 5.

Table 4. bending test result data of 45° fiber cut direction orientation

Sample code	Distance between supports (mm)	Pmax (N)	Bending stress (Mpa)
2 A-45°	96	653	376.70
2 B-45°	96	426	245.37
2 C-45°	96	452	260.35
2 D-45°	96	780	449.28
2 E-45°	96	931	536.25
Average		648	379.59

Table 5. bending test result data of 90° fiber cut direction orientation

Sample code	Distance between supports (mm)	Pmax (N)	Bending stress (Mpa)
2 A-90°	96	405	233.28
2 B-90°	96	272	156.67
2 C-90°	96	390	224.64
2 D-90°	96	220	126.72
2 E-90°	96	599	345.02
Average		377	217.26

3.4 Analysis of Bending Test Fracture Patterns

Test specimens 2A-45°, 2C-45°, and 2E-45° experienced fiber pull-out failure. This indicates inadequate bonding, resulting in a weak connection between the fibers and the matrix, which was not strong enough to withstand the applied load during the bending test. When a composite undergoes bending stress, the fibers and matrix must work effectively together to support the load until failure or detachment from the matrix occurs. Test specimen 2B-45° showed cohesive failure, being able to withstand a bending stress of 245.37 MPa. In contrast, specimen 2E-45° achieved the highest bending stress value of 536.25 MPa, as shown in Fig. 10.

In Fig. 11, specimen 2A-90° experienced fiber pull-out failure, likely due to poor adhesion between the fibers and the matrix, which prevented the specimen from withstanding the applied load. Test sample 2B-90° exhibited a single-plane fracture, occurring because the sample could not support the load due to the fiber orientation, resulting in a fracture in just one plane. Specimen 2C-90° displayed a fracture pattern where multiple fibers broke under the load, but the matrix still supported the load effectively (good surface strength), distributing the load to surrounding areas and causing fractures in more than one plane. Test samples 2D-90° and 2E-90° showed cohesive failure, characterized by breakage of the filler/fiber components. This failure happens when the matrix's interaction is insufficient to withstand the applied load, leading to separation between the fiber layers and the matrix. It is suspected that improper fiber orientation relative to the load direction may cause ineffective load bearing by the fibers, leading to composite failure.

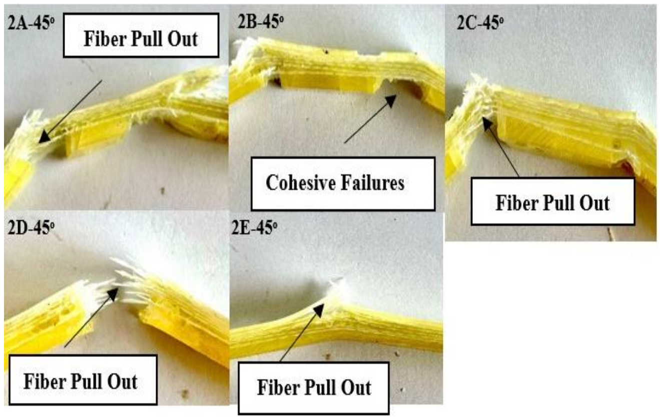


Fig. 10. Bending fracture shape of 45° fiber direction.

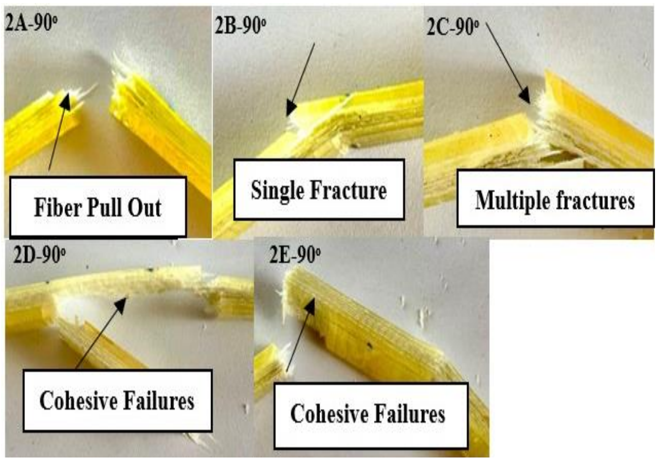


Fig. 11. Bending fracture shape of 90° fiber direction.

Based on the calculation data shown in Fig. 12, it can be seen that the test specimen with 45° fiber cut direction became the highest bending stress test specimen with an average of 379.59 Mpa, the fibers managed to bind the matrix well because they are intertwined and crossed, resulting in higher stability and allowing even load distribution on each fiber. Meanwhile, the test sample with 90° fiber cut direction has a bending stress with an average of 217.26 Mpa this is because 90° fibers only work in one direction and are less effective at resisting stress from other directions.

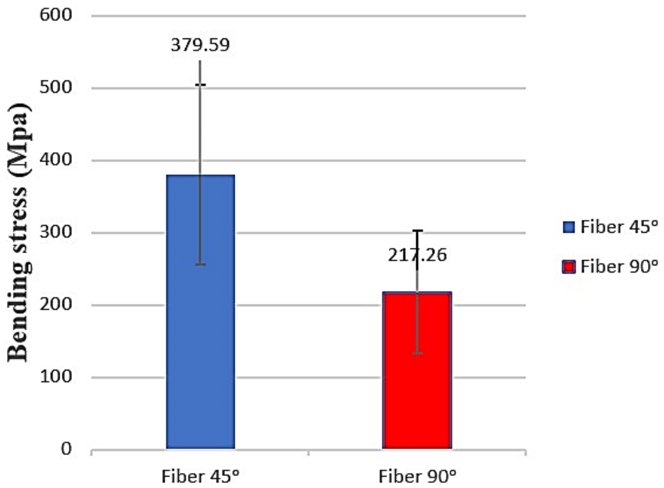


Fig. 12. Bending stress comparison chart.

4 Conclusion

The interaction between the matrix and fibers can create high-performance materials suitable for specialized applications, such as wind turbine blade manufacturing. A 45° fiber orientation is optimal for composites reinforced with fiberglass and an epoxy resin matrix. The fibers provide strength and stiffness to the composite, while the matrix distributes the applied stress evenly across the fibers, helping to prevent stress concentrations that could lead to local failure. This makes it suitable for horizontal wind turbine blades.

Mechanical tests revealed that some samples experienced failures, including fiber pull-out, single-plane fractures, and cohesive failures. These failures are suspected to be due to inadequate interaction and distribution of fibers and matrix, leading to air gaps (voids) that weaken the bond between the matrix and fibers. Improper fiber orientation relative to the load direction can also result in ineffective load-bearing by the fibers, causing composite failure.

Impact test results showed that the 45° fiber orientation produced better impact strength, with a value of 0.113 J/mm² and energy absorption of 11.307 Joules. In contrast, the 90° fiber orientation had lower impact strength, with a value of 0.073 J/mm² and energy absorption of 7.034 Joules. For bending tests, the 45° fiber orientation achieved a bending stress of 379.59 MPa, while the 90° fiber orientation achieved a bending stress of 217.26 MPa.

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