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Characterization of mechanical properties of fiberglass/epoxy prepreg composites as horizontal axis wind turbine blade material influence of fiber orientation direction on impact and bending strengths

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Abstract

This study aims to examine 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, especially in horizontal axis wind turbines, is growing due to their superior mechanical properties. One factor that affects the performance of these composites is the fiber orientation in the material structure. Proper fiber orientation can improve impact and bending strength, which are important characteristics in resisting dynamic and static loads during wind turbine operation. In this test, several fiber orientation variations were applied to determine their effect on composite performance. This analysis provides important insights for more efficient design and improved performance of wind turbines by maximizing the characteristics of the composite materials used. This study used 45º and 90º variations of fiber cut direction orientation with epoxy resin as the matrix. The impact test results showed the highest value was obtained at 45º fiber direction with an impact strength of 0.113 J/mm^2 and absorbed impact energy of 11.307 Joules. For the bending test results, the 45º fiber direction orientation produced the best bending strength. The results show that 45º fiber orientation has a significant impact on the impact strength and bending properties of the material. These findings are expected to contribute to the development of more optimized composite materials for renewable energy applications, particularly in the wind turbine industry.

Keywords:
Prepreg fiberglass, composite, epoxy, fiber orientation, mechanical properties.

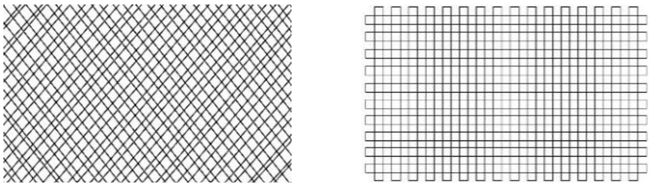
1 Introduction

The increasing demand for renewable energy sources has triggered the development of more efficient and sustainable wind turbine technologies. Horizontal axis wind turbines are one of the most commonly 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 that are known for their high strength-to-weight ratio and resistance to harsh environmental conditions. However, the performance of 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 [3], which is a crucial factor in ensuring the viability of wind turbines under various changing wind load conditions. However, information regarding the effect of fiber orientation on the mechanical characteristics of fiberglass/epoxy prepreg composites in wind turbine applications is limited. As a response to this, various materials have been developed and also researched to obtain new materials that are efficient, cheap, 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 chosen for their superior mechanical and physical characteristics, such as high strength-to-weight ratio, corrosion resistance, and adaptability to extreme environmental conditions.

Previous studies have shown that fiber orientation in composite materials plays an important 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 in various fiber orientation configurations. Rajesh et al's research [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 having 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 increase 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 of Sarifah et al. [8], in his research revealed that the manufacture of composites where the layout, and direction of the fibers in the matrix will determine the mechanical strength of the composite thus affecting the performance of the composite. Widodo et al [9] states that the closer the fiber weave distance makes the composite stronger. Composites that have unidirectional or one direction fibers tend to have higher strength and stiffness than other fiber orientations. On the other hand, composites with multiple fiber orientations (multi direction) 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 becoming increasingly modern, one of which is the application of knowledge in composite technology which is accelerating and is applied to various tools, especially those that require strong and lightweight materials [11][12]. As a response to this, various materials have been developed and also researched to obtain new materials that are efficient, cheap and environmentally friendly [4]. In the manufacturing industry, the use and utilization of composites are also continuously developed [13][14].

Previous research has been done by Sriyono [15] development of jute natural fiber composites with volume fractions of 30%, 40%, 50% with fiber directions of 0º, 45º, and 90º for wind turbine blade applications. The results obtained from the research of the highest tensile strength is in the 45º fiber direction, 40% volume fraction with a value of 27.13 Mpa. The lowest tensile strength is at 90º fiber direction, 50% volume fraction with a value of 16.87 Mpa. However, although the use of hemp 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 attack, which can affect the lifespan and performance of the composite [16]. In addition, resistance to weathering and extreme weather conditions pose 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 the use of 200 gr/m^2 fiberglass prepreg fibers with epoxy matrix with variations in fiber direction orientation of 45º and 90º as illustrated in Fig. 1 for horizontal wind turbine blade applications. The results of this study are expected to provide guidance for the industry in choosing the optimal fiber orientation to improve the performance and durability of horizontal axis wind turbines.



(a) (b)

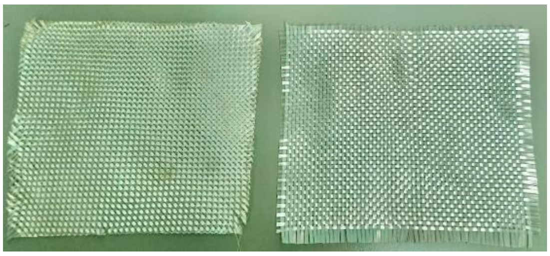
Fig. 1. Illustration of fiber cut direction orientation (a) 45º orientation (b) 90º orientation.

2 Research Methods

This research was conducted using the experimental/testing method. Fabrication of test samples was carried out at the Materials & Metallurgy Laboratory of Mechanical Engineering, Muhammadiyah Riau University. Mechanical testing was carried out in the Material Test Laboratory, Mechanical Engineering Department, Bengkalis State Polytechnic.

2.1 Materials

Materials used in this research: epoxy resin 504 as the matrix and hardener 504 as the catalyst with the ratio of resin and hardener 5:1, fiberglass prepreg 200 gr/m^2 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) 45º fiber cut direction orientation (b) 90º fiber cut direction 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 orientation variation of the fiber cut direction was determined to be 45º and 90º as seen in Fig. 2. The matrix and fiber were varied in such a way as to match the volume fraction. Table 1 shows the variations of the 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-45º	2 A-45º	40%	60%
	1 B-45º	2 B-45º	40%	60%
	1 C-45º	2 C-45º	40%	60%
	1 D-45º	2 D-45º	40%	60%
	1 E-45º	2 E-45º	40%	60%
Fiber orientation 90º	1 A-90º	2 A-90º	40%	60%
	1 B-90º	2 B-90º	40%	60%
	1 C-90º	2 C-90º	40%	60%
	1 D-90º	2 D-90º	40%	60%
	1 E-90º	2 E-90º	40%	60%

Testing of fiberglass/epoxy prepreg composites was carried out using ASTM D790-02 standard for bending testing and ASTMD 6110 for impact testing. Furthermore, fracture observations were made on the test samples through macro photos. In this study, descriptive data analysis was used to describe the results of the study in graphical form.

2.3 Composite Manufacturing Process

Print the composite test sample using the contact molding hand lay up method as shown in Fig. 3. Prepare the tools and materials used, apply wax to the mold until evenly distributed, then wait about 15 minutes to dry, then the process of mixing epoxy 504 resin and hardener in a ratio of 5: 1, apply the gel coat mixture on the surface of the mold using a sponge (foam) until evenly distributed then put into the oven for about 15 minutes at (temperature 45°C), cut 200 gr/m² fiberglass prepreg as many as 3 sheets with variations in fiber cut orientation 45º and 90º cut according to the size of the mold then stick to the mold.

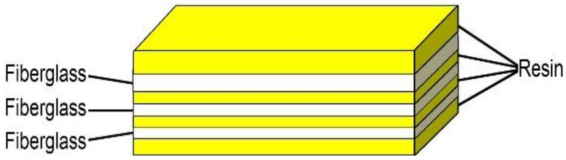


Fig. 3. Illustration of fiber arrangement.

Stir the mixture of resin and hardener until homogeneous. Then apply it on the surface of the fiberglass using a brush/roll until the fiberglass is wet, then paste the fiberglass 3 times in the same way to form a sandwich layer. Dry the mold in the sun for 90 minutes and 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 that can be absorbed by the composite specimen until the material is broken.

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 and the notch was V-type. The test specimen was prepared and a pendulum was dropped to impact the notched specimen. The maximum energy absorbed by the specimen was recorded.

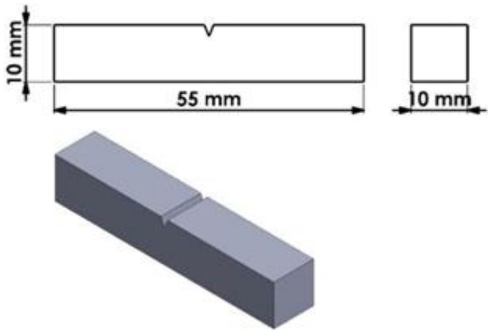


Fig. 4. Dimensions ASTM D-6110.

2.4.2 Bending Testing

The bending test is a test to determine the stress on the material just before the material yields in the bending test. 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 center point of the specimen is focused on as the load point to be applied to the specimen. In this study, the bending test standard used is ASTM D790-02 standard with a test sample size of 130 × 10 × 5 mm. [18].

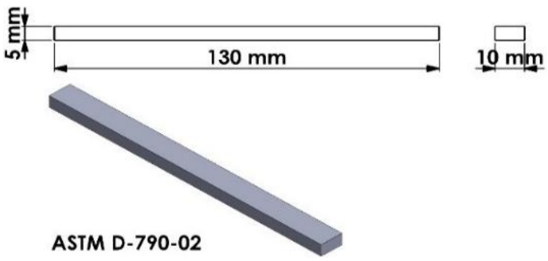


Fig. 5. Dimensions ASTM D790-02.

3 Results and Discussion

3.1 Impact Test Result

From the impact test results, it shown that the largest impact test value was achieved by the 45° fiber cut orientation with an average value of 11.307 Joules. Meanwhile, the 90° fiber cut orientation test sample was only able to absorb potential energy with an average value of 7.034 Joules. The test data can be seen in Tables 2 and 3. The placement and orientation of fibers in the matrix will determine the mechanical strength of the composite, fibers can withstand loads from various directions more effectively, so they can absorb 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 Impact Test Fracture Shape Analysis

In test specimens with a 45° fiber orientation, the fractures that occur are generally fibrous fractures, where the failure is caused by the large impact force received by the specimen. Another form of fracture is fiber pull out as shown in in Fig. 6. The fibers come out quite long, this happens when the distribution of fiber and resin is not evenly distributed during the process of making the test sample, so that there are air voids that cause weak bonds between the matrix and the fiber, and there are gaps (voids) between the two surfaces of the fiber and resin due to the failure of the matrix to bind, due to the shock load given so that the fiber cannot bear the load and the process of fracture takes place simultaneously.

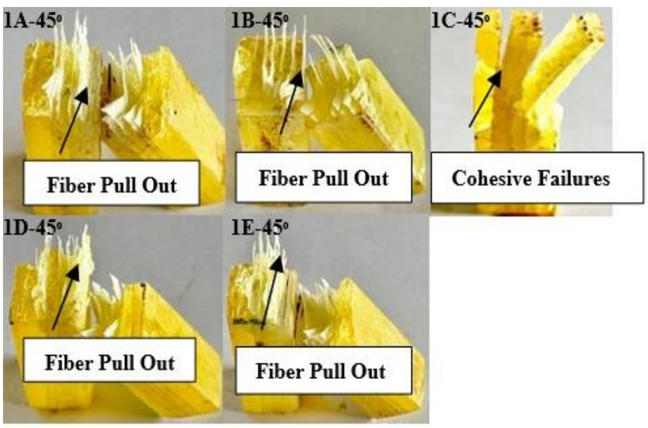


Fig. 6. Impact fracture shape of 45° fiber direction.

The relationship between the test values obtained and the phenomena of fibrous fracture and fiber pull-out reflects the effects of uneven fiber and resin distribution and the quality of the composite manufacturing process. Fibrous fracture and fiber pull-out indicate that although fiber orientation can provide strength, unevenness in the manufacturing process and the quality of the bond between fiber and matrix affect the overall test results. We can see that the 1C-45° test specimen which experienced cohesive failure has a small impact energy of 6.71 Joules in contrast to the 1E-45° specimen which has the largest impact energy of 19.65 Joules. These different test results emphasize the importance of quality control in the manufacturing process as well as the reliability of the test equipment used.

From Fig. 7, test specimens 1A-90°, 1B-90°, and 1C-90° show a cohesive failure which is a failure to break the filler/fiber component. This occurs when the matrix interaction is not strong enough to withstand the load received, resulting in separation between the fiber layer and the matrix, while in the 1D-90° and 1E-90° test specimens it can be seen that the shape of the fracture shows that many fractures occur when several fibers in the composite are broken together or almost simultaneously along the trajectory under load. This occurs because the fiber and matrix distribution is perfect, resulting in a strong cohesive bond.

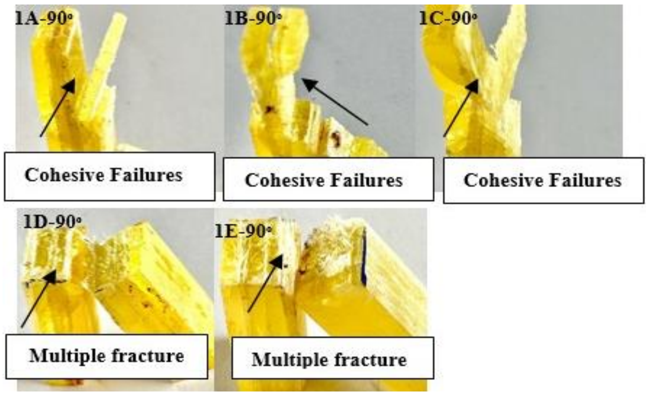


Fig. 7. Impact fracture shape of 90° fiber direction.

Fig. 8 shows the impact strength comparison data. It can be seen that the test specimen with 45° fiber cut direction has the highest impact strength with an average of 0.113 J/mm^2 while the test specimen with 90° fiber cut direction has an impact strength with an average of 0.073 J/mm^2. From the results of impact testing, it can also be seen that when the angle after impacting the test sample is small, the impact strength is greater and vice versa. Based on the analysis of the shape of the fracture, it can be concluded that the test specimens with a fiber orientation direction of 45° have a strong cohesive bond between the fibers and the matrix resulting in better impact strength.

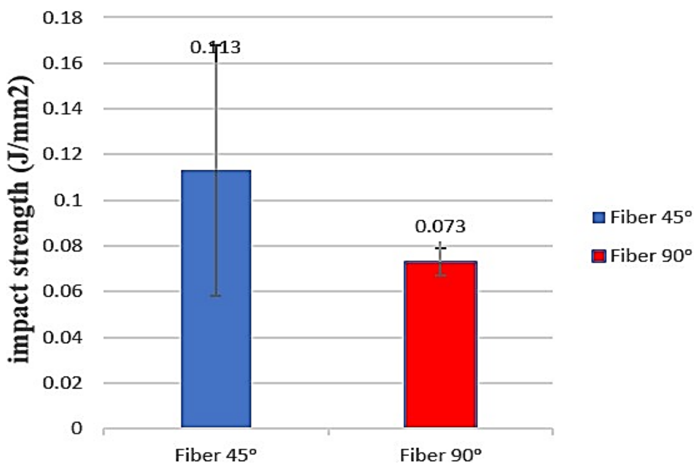
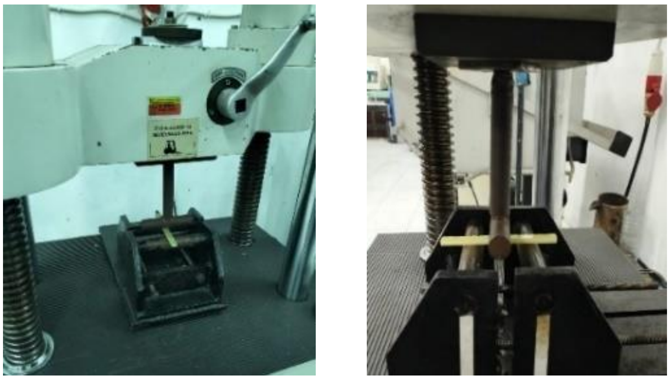


Fig. 8. Comparison chart of impact strength.

3.3 Bending Test Result

This bending test uses the three point bending method to determine the bending stress value produced. This test uses Gotech Testing Machine GT-7001-LC 30. The test instrument can be seen in Fig. 9.



(a) (b)

Fig. 9. Composite bending testing.

From the bending test results, it can be seen that the largest bending test value was achieved by the 45° fiber cut direction orientation with an average value of 379.59 MPa. Meanwhile, the 90° fiber cut orientation test sample has a bending stress with an average value of 217.26 MPa. The test data can be seen 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 Bending Test Fracture Shape Analysis

Test specimens 2A-45°, 2C-45°, and 2E-45° experienced fiber pull out failure. This indicates insufficient adhesion interaction so that the connection or bond between the fibers and the matrix is not strong enough to withstand the load applied during the bending test. When the composite is subjected to a bending load, fiber and matrix must work well together in order to be able to withstand the load until it breaks or detaches from the matrix. The 2B-45° test specimen showed a cohesive failure, the specimen was only able to withstand the bending stress with a value of 245.37 MPa while the 2E-45° test specimen became the test specimen that had the maximum bending stress value with a value of 536.25 MPa as can be seen in Fig. 10.

In Fig. 11, specimen 2A-90° experienced fiber pull out failure which was thought to be due to poor adhesion between the fiber and matrix so that the test specimen was unable to withstand the applied load. In the 2B-90° test sample a single fracture occurred, this failure occurred because the test sample was unable to withstand the load due to the influence of the fiber orientation direction so that a single fracture occurred in one plane. The 2C-90° test specimen experienced a form of multiple fractures when the number of fibers that broke due to the load was still small and the matrix was still able to support the load received (good surface strength) by distributing the load to the surroundings so that the fracture occurred in more than one plane. Test samples 2D-90° and 2E-90° showed a cohesive failure which is a breakage failure in the filler/fiber component. This failure occurs when the matrix interaction is not strong enough to withstand the applied load, resulting in separation between the fiber and matrix layers. It is suspected that the influence of fiber orientation that is not in accordance with the load direction can cause the fiber to be ineffective in withstanding the load, resulting in failure of the composite.

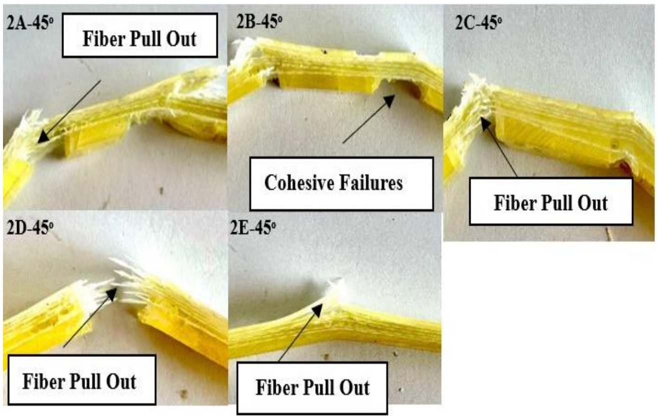


Fig. 10. Bending fracture shape of 45° fiber direction.

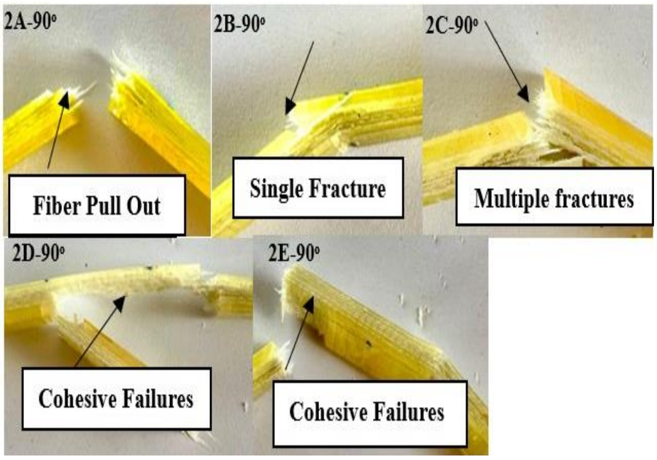


Fig. 11. Bending fracture shape of 90° fiber direction.

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.

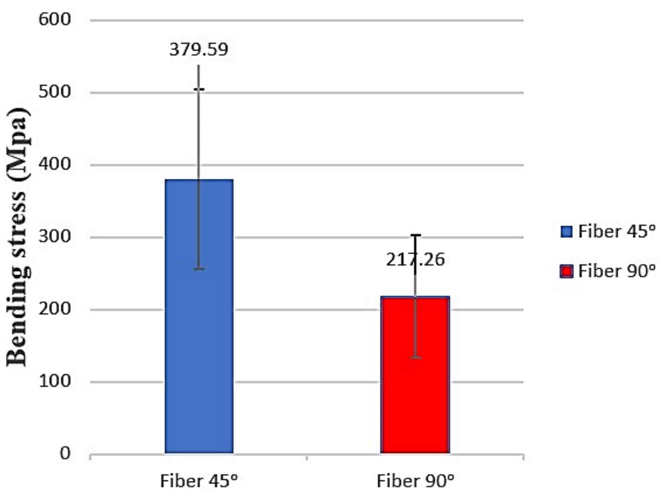


Fig. 12. Bending stress comparison chart.

4 Conclusion

The interaction between matrix and fibers can produce high performance materials suitable for special applications such as wind turbine blade manufacturing. The result of 45^o fiber orientation is optimal in fiberglass fiber reinforced composite with epoxy resin matrix. The fibers provide strength and stiffness to the composite while the matrix distributes the stresses received by the material evenly across the fibers, helping to prevent stress concentrations that could cause localized failures, making it good enough for horizontal wind turbine blade manufacturing applications. After mechanical testing, several test samples failed, namely fiber pull out, single fracture, and cohesive failure. This is thought to occur due to poor interaction and distribution of fibers and matrix resulting in the formation of air voids (voids) which cause the bond between matrix and fiber to be weak. Fiber orientation that is not in accordance with the load direction can also cause the fiber to be ineffective in withstanding the load, resulting in failure of the composite.

The results of the 45^o fiber orientation impact test produced a better impact strength of 0.113 J/mm^2 and absorbed impact energy of 11.307 Joules while the 90^o fiber cut direction orientation produced a lower impact strength of 0.073 J/mm^2 and absorbed impact energy of 7.034 Joules. For the bending test results, the 45^o fiber cut orientation obtained a bending stress of 379.59 Mpa while the 90^o fiber cut orientation obtained a bending stress of 217.26 Mpa.

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