The effect of different number of layers and fiber distribution on the performance of composite laminates

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Abstract. Fiber-reinforced composites are widely used in world industries such as transportation vehicles, sports tools, space crafts, and more. This research investigates the influence of the number of layers and fiber distribution on the mechanical properties of woven fiber-reinforced composites by changing the number of layers or the manufacturing process. Hand lay-up and infusion processes are used to manufacture the composite plates. Three mechanical tests are conducted for all composite plates, such as Interlaminar shear stress (ILSS), ultimate tensile strength (UTS), and ultimate flexural strength (UFS). Furthermore, analyzing the microstructure of the laminates is conducted to evaluate fractal dimension (FD). It is observed that the distribution of the fibers measured by FD had an effective role in improving the mechanical properties. Also, the use of vacuum molds had an additional role in improving the mechanical properties. One could conclude that all the mechanical properties have proportional relationships with FD.

Keywords: composites, glass fiber, polymers matrix composite, woven fiberglass.

1. Introduction

The use of fiberglass with resins had good mechanical properties. So it led to its use in making boats, planes. The good quality of the glass fibers led to the widening of their fields of use. Conventional metal alloys can be replaced by other observed composite materials. It has been observed that even if composite materials lead to a cost slightly higher, you can find the difference in low weight. Reducing the weight as one pound helps to save commercial jet fuel every year. Fuel expenditures are a problem of the total operating costs. For a commercial airline, lower costs make it more profitable [1]. The aviation industry's research has focused its efforts on profit, and here is the role of composite materials in limited properties due to their low cost [2]. Adherence to standards is a major reason for eliminating defects, and this falls on the shoulders of production engineers [3]. The glass fibers consist of silica and oxides. Where it is produced by melting the glass and crossing through a small opening, this method is the most diffuse and arranged in the second place with the most glass fiber. Advanced fibers such as compounds made of graphite/epoxy fibers are used continuously in space structures. According to literature, some researchers studied the effects of some processing parameters on the mechanical properties in fatigue and static test [1]. The use of many types of fibers, where these fibers proved to improve the mechanical properties of different types of fiber if the carbon fiber [2] or nylon fiber [4] or natural fibers [5]. One of the composite materials is the woven fabric and has many positive advantages such as high specific strength and good formability. Therefore, there is interest in using it as
in many industrial fields such as the aviation, automotive, and energy industries. They are produced in the form of woven ply tied with more than a layer of woven fabric and imitated with polymeric materials. They are used in directions inside the plane, where pressure is applied during the injection of the polymer with the woven on each other in the direction of accumulation, and complex internal structures can be formed[6]. High mechanical properties and light weight allow wide use of the reinforced fiber compounds. These areas include space structures, the automotive industry, and energy and marine areas. There is an increase in demand for high-performance materials that it contains high ratios of strength to weight and high rigidity in addition to an improvement in fatigue performance. This improvement in performance in mechanical properties led to rapid progress in the field of fiber-reinforced vehicles. This quantity is used in various applications due to the widespread use of the system for composite materials, e.g., the private transportation sector in the airspace. Where the compound is made of two materials matrix resin (epoxy or other polymers), and the second material is fibers such as aramid, glass, and carbon. The manufacturing and method of fiber distribution and engineering guidance in addition to the size of each material according to the criteria on which it depends. The infusion process does not require the autoclave stage. Not passing through the autoclave stage during manufacturing can increase the production rate of composite materials. Likewise, high-performance compounds need to standardize the autoclave to improve mechanical properties in addition to the possibility of reducing energy consumption. The use of autoclaves leads to a decrease in the size of the fiber breakage. It can also lead to an increase fiber volume fraction (Vf) due to the increase in the resulting pressure when using the autoclaves. The use of the traditional autoclave is in addition to the role of improving autoclave treatment to achieve its use in the facility, but it varies in the degree of pressure [7], [8]. The porosity of materials and their new properties such as high compressibility and excessive elasticity have appeared in recent years. Therefore, some modifications have been used on the internal microstructure[9]. Simple fiber models are mostly relied on, where the standard is by taking maximum stresses. Friction cohesive surfaces are investigated, meaning additional analyzes are performed to verify the damage tolerance of the compound [10]. Image microstructure analysis is used by different researchers [11], [12]. To correlate the mechanical properties with microstructure. In this paper to investigate the fiber structure and to know the effect of the fiber distribution on the mechanical properties.

2. Fabrication Of Composite Plates

In the infusion process, A 400 x 400 mm glass mold is used in the manufacture of composite plates. Initially, the mold is cleaned with a special cleaning liquid. The mold was coated with a special wax. The matrix is a mixture of both polyester and hardener, and the ratio used is 100:1. The layers of glass fibers are placed inside the glass mold. A special type (peel ply) cloth was used as a cover in direct contact over the glass layers fibers. The peel ply is removed after the sample has hardened. Polyester was mixed with hardened for two minutes with continuous stirring. The resin is pumped into the mold by the action of vacuum pressure, and the plates are left for 24 hours until it is completely solidified. Then, the plates are cut into samples in a rectangular shape to be ready for testing according to the standards. On the other hand, for the hand lay-up process, A 400x400 mm glass mold is used in the manufacture of composite sheets. Initially, the mold was cleaned with a special liquid for cleaning. The mold was coated with a special wax. The matrix is a mix of both polyester and hardener using a ratio of 100:1. The layers of fiberglass were placed according to the number required in each plate. The thickness of the sample varies according to the number of layers of glass fiber required in each plate. The matrix is moved in all directions to obtain a uniform thickness of the plate. Each sample takes 24 hours to completely solidify. The resulting plate is cut according to the standards to be ready for testing.
3. Mechanical Tests And Microstructure Image Analysis software

Glass composite panels are manufactured, and eight panels are arranged in three layers, four layers, five layers, and six layers for each manufacturing process, Infusion, and hand lay-up. Five test samples for each test type were cut from each of the four panels for both the manufacturing process to determine Ultimate tensile strength (UTS), Ultimate flexural strength (UFS), Interlaminar shear strength (ILSS). The device used for the three tests is Magnus INTERNATIONAL Model No SSR-2514 TONNES AT WP. 23.4 STROKE. MM. 362 and fractal dimension. Image analysis software is used to analyze more than 100 images, as shown in Figure 2. At the beginning of the polishing process shown in Figure 3, the work showed pictures of low quality that were not sufficient, as illustrated in Figure 4. After modifying the polishing method, it became possible to obtain the final images, as illustrated in Figure 5. Through these images, the fiber dimension distribution measured by FD is determined.

Figure 1: infusion processes

Figure 2. Fractal dimension FD calculated by Image J software

Figure 3. Grinding and Polishing Processes
The test samples are cut from the composite plates according to British standards. The tensile samples are cut from the composite plates according to the British standard BS EN ISO 527-5. The test is conducted with a constant velocity at (1 mm/min). At least five samples were tested for each type of plate that was established to measure mechanical properties. When fixing the sample on the device, the vertical scale is used to ensure that the sample is fixed vertically. The flexural strength of the composite plates is performed according to the British standard BS EN ISO 14125:1998. Samples are cut from composite materials with dimensions (15 × 60) mm. Five samples were cut from each type of plate. The interlaminar shear stress ILSS test is performed according to the British standard BS EN ISO 14130:1998. Samples are cut from composite plates according to the equation. Length=10 x thickness; width=5 x thickness.

The microstructure analysis aims to search for correlations between the measured properties (static) and the microstructure measured as a fractal dimension (FD) since this fractal dimension measures the distribution of the fibers within the dimensions in each microstructure image. More than five pictures are prepared for each type of plate that was produced. The fractal dimension is obtained from these images after being analyzed by the image analysis software. The correlation between the uniformity of the distribution of the fibers and the mechanical properties of the composite films leads to improved performance. Where the scale using the fractal dimension (R2) can reach one real number and thus helps in describing the microstructure. If the mechanical properties of woven fabrics are predicted from a specific microscopic form, they can be able in a shorter time and less costly for the mechanical (static) tests necessary to characterize a composite material.

4. Experimental Results

Figure 6 illustrated the ultimate tensile strength versus the number of layers for hand lay-up. It shows that the four layers plates provided the highest tensile strength. The four layers plates have high UTS due to the best fiber distribution of it. Microstructure Image Analysis software which is measured by FD as shown in figure 7. Figure 7 illustrated that the UTS is proportional with fractal dimension, and the relationship between them is presented by equation 1.
Similarly, figure 8 illustrated the ultimate flexural strength versus the number of layers for hand lay-up. It shows that the four layers plates provided the highest flexural strength. The four layers plates have high UTS due to the best fiber distribution of it, Microstructure Image Analysis software which is measured by FD as shown in figure 9. Figure 9 illustrated as well that the UFS is proportional with fractal dimension, and the relationship between them is presented by equation 2.

$$UTS (MPa) = 1574.6FD^2 - 5512.7FD + 5010.3$$  \hspace{2cm} (1)

$$y = 3945.1x^2 - 13872x + 12432$$ \hspace{2cm} \hspace{2cm} R^2 = 0.8898 \hspace{2cm}$$

The results of the Interlaminar shear strength (ILSS) are confirmed the results of UTS and UFS, which are discussed above. Similarly, figure 10 illustrated the ILSS versus the number of layers for hand lay-up. It shows that the four layers plates provided a high value of ILSS due to the best fiber distribution of it, Microstructure Image Analysis software which is measured by FD as shown in figure 11. Figure 11 illustrated as well that the ILSS is proportional with fractal dimension, and the relationship between them is presented by equation 3.
ILSS (MPa) = 35.051 \( FD^2 \) - 113.84FD + 105.63 \hspace{1cm} (3) 

For the infusion process, the results show that the mechanical properties are proportional to the fiber distribution measured by fractal dimension. Figure 12 illustrated the ultimate tensile strength versus the number of layers. It shows that the five layers plates provided the highest tensile strength. The five layers plates have high UTS due to the best fiber distribution of it, Microstructure Image Analysis software which is measured by FD as shown in figure 13. Figure 13 illustrated that the UTS is proportional with fractal dimension, and the relationship between them is presented by equation 4.

UTS (MPa) = -19982 \( FD^2 \) + 79162FD - 78122 \hspace{1cm} (4) 

Similarly, figure 14 illustrated the ultimate flexural strength versus the number of layers for Infusion, and it shows that the four layers plates provided the highest flexural strength. The four layers plates have high UTS due to the best fiber distribution of it, Microstructure Image Analysis software which is measured by FD as shown in figure 15. Figure 15 illustrated as well that the UFS is proportional with fractal dimension, and the relationship between them is presented by equation 5.
Similarly, to hand lay-up, the results in the infusion process show the same trends. Interlaminar shear strength (ILSS) is confirmed the results of UTS and UFS, which are discussed above. Figure 16 illustrated the ILSS versus the number of layers for Infusion; it shows that the five layers plates provided a high value of ILSS due to the best fiber distribution of it, Microstructure Image Analysis software which is measured by FD as shown in figure 17. Figure 17 illustrated as well that the ILSS is proportional with fractal dimension, and the relationship between them is presented by equation 6.

\[ \text{ILSS} = 3007.5 \times (\text{FD})^2 - 11491 \times \text{FD} + 10993 \quad (6) \]

It is found that the mechanical properties in the infusion plates such as UTS, ILSS, and UFS are greater than the mechanical properties of hand lay-up plates. One of the main reasons is the distribution of the fiber, which is evaluated by FD in infusion plates, is higher than FD of hand lay-up plates. Also, the Infusion process could help to reduce voids. These voids could reduce mechanical properties.
5. Conclusion
In this work, the effect of the fiber distribution and the number of different layers of fiberglass on the mechanical properties is studied. Three layers, four layers, five layers, and six layers are used in hand lay-up. A similar number of layers are used in the infusion process. Three mechanical tests are conducted for all composite plates, such as Interlaminar shear stress, ILSS, ultimate tensile strength, UTS, and ultimate flexural strength, UFS. Furthermore, analyzing the microstructure of the laminates is conducted to evaluate fractal dimension FD. It is observed that the distribution of the fibers measured by FD had an effective role in improving the mechanical properties. Also, the use of vacuum molds had an additional role in improving the mechanical properties. All the mechanical properties have proportional relationships with FD.
6. Reference

[1] A. K. Kaw and F. Group, Composite. 2006.

[2] A. D. Pertuz, S. Díaz-cardona, and O. A. González-estra, “Static and fatigue behaviour of continuous fibre reinforced thermoplastic composites manufactured by fused deposition modelling technique,” Int. J. Fatigue, vol. 130, no. September 2019, p. 105275, 2020.

[3] E. Sarikaya, H. Çallio, and H. Demirel, “Production of epoxy composites reinforced by different natural fibres and their mechanical properties,” vol. 167, no. 15, pp. 461–466, 2019.

[4] D. K. K. Cavalcanti, M. D. Banea, J. S. S. Neto, R. A. A. Lima, L. F. M. Silva, and R. J. C. Carbas, “Mechanical characterization of intralaminar natural fibre-reinforced hybrid composites,” Compos. Part B, vol. 175, no. June, p. 107149, 2019.

[5] P. V. Reddy, P. R. Prasad, D. M. Krishnudu, and P. Hussain, “Materials Today : Proceedings Influence of fillers on mechanical properties of prosopis juliflora fiber reinforced hybrid composites,” Mater. Today Proc., no. xxxx, pp. 1–4, 2019.

[6] J. Tang, G. Zhou, X. Wang, C. Li, and V. V Silberschmidt, “Failure analysis of plain woven glass / epoxy laminates : Comparison of off-axis and biaxial tension loadings,” Polym. Test., vol. 60, pp. 307–320, 2017.

[7] T. Wu, Z. Huang, D. Wang, and J. Qu, “Advanced Industrial and Engineering Polymer Research Effect of continuous elongational flow on structure and properties of short glass fiber reinforced polyamide 6 composites,” Adv. Ind. Eng. Polym. Res., vol. 2, no. 3, pp. 93–101, 2019.

[8] A. M. Rique, A. C. Machado, D. F. Oliveira, R. T. Lopes, and I. Lima, “Nuclear Instruments and Methods in Physics Research B X-ray imaging inspection of fiberglass reinforced by epoxy composite,” Nucl. Inst. Methods Phys. Res. B, vol. 349, pp. 184–191, 2015.

[9] F. Bazzocchi, S. Bertagni, C. Ciacci, E. Colonna, and V. Di, “Mechanical characterisation of a low-thickness ceramic tile cladding subject to ageing phenomena,” J. Build. Eng., vol. 29, no. December 2019, p. 101105, 2020.

[10] I. O. P. C. Series and M. Science, “Evaluation of Mechanical Properties of Composite Laminates by Fractal Dimension Evaluation of Mechanical Properties of Composite Laminates by Fractal Dimension,” 2020.

[11] G. Kubo, T. Matsuda, and Y. Sato, “International Journal of Mechanical Sciences A novel basic cell modeling method for elastic-viscoplastic homogenization analysis of plain-woven laminates with nesting,” Int. J. Mech. Sci., vol. 146–147, no. January, pp. 497–506, 2018.

[12] M. Tatarians, S. Yousef, G. Denafas, and M. Tichonovas, “Recovery of gold , other metallic and non-metallic components of full-size waste random access memory,” J. Clean. Prod., vol. 172, pp. 2811–2823, 2018.