Evaluation of Mechanical Properties of Composite Laminates by Fractal Dimension

Amjed Saleh Mahmood
Electromechanical Engineering Department, College of Engineering, University of Samarra, Samarra, Salah Ad Din, Iraq
dramjed78@gmail.com

Abstract. This study focuses on the evaluation of mechanical properties of composite laminates by fractal dimension (FD). The fibre distribution in a laminate or FD could be changed according to different manufacturing processes, such as hand lay-up, resin infusion and resin transfer moulding. These manufacturing processes are considered in this study. Woven Kevlar / epoxy composite panels were manufactured with a [0/90]_{2S} stacking sequence. The materials were characterised for interlaminar shear strength (ILSS) and flexural strength. The fibre volume fraction (V_f) and FD of the laminates were determined from optical microscopic images of polished cross-sections using ImageJ software (box counting method) with the Fractal and Lacunarity add-in. The results show significant relationships between the mechanical performance of the composite laminates and the FD.

1. Introduction
Fibre reinforced composites are widely used globally in the industry. They are usually used for lightweight structures where they can reduce energy consumption, especially in transport applications, such as space vehicles, aircraft, trains, cars and yachts. The quantification of microstructures of composite laminates requires image analysis and processing. It could be achieved by histograms derived from tessellation (e.g. Voronoi) or as a single number using fractal dimension (FD), which is a non-integer physical dimension. Numerous studies [1–7] have investigated the impact of fibre distribution on the performance of the composite laminates. They found that the reinforcement alignment has a significant impact on the physical properties. These studies also concluded that the waviness or random orientation of fibres can result in a decrease in the mechanical properties due to the low properties of resin. As resin has low elastic modulus, the resin areas show a high strain relative to the fibres. Lomov et al. [8] concluded that the resin areas have minimal strain, especially regarding carbon fibre composites. Sudarisman and Davies [9] studied the influence of several factors, such as holding time, compressive pressure and epoxy concentration, on the performance of laminates. The results of this study confirm weak bonding between individual prepreg layers due to resin areas. A crowded region of the fibres could lead to resin areas and the resulting strain concentration [10]. Despite this, none of the above studies have characterised the microstructure of the composites or studied the fibre distribution effect.

The measurement of the uniformity and characterisation of complex composite microstructures has evolved over the last few decades [11–16]. A study by Picu et al. [17] stated an effective argument between composites and fractal microstructure. FD is a powerful tool for measuring the degree of roughness of highly irregular objects [18,19] and is used to characterise the performance of composite laminates, such as connecting the toughening procedures with rupture surfaces (e.g. [11, 20]) and the
development of voids in composite materials [21] and their impact on different mechanical and physical properties (e.g. [17, 18, 22]). The uniformity of fibre distribution, which is influenced by the manufacturing pressure, weave style and the stacking sequence, is an important parameter that has a large impact on the mechanical properties of composites [23, 24]. The objects that are considered in physics or mathematics are generally continuous, linear and smooth. However, nature has shown us that this is not always the case. Ordinary objects are normally rough and irregular [25]. Using FD to characterise irregular objects began scientifically approximately four decades ago [26] to quantify the fracture surfaces of different levels [27] and characterise the level of roughness of irregular objects [28]. Furthermore, fractal geometry deals with highly disordered morphologies [29]. Therefore, FD, which is measured using the box counting method, is widely used in quantifying the mechanical properties in metals, alloys and composites materials [30–34]. The aim of this study is to find out whether it is possible to use the FD to evaluate the performance parameters of composite material laminates by analysing the microstructure images. Through this, it would be possible to link the mechanical properties with microstructure images, which could avoid repeatedly performing mechanical tests when manufacturing new composites.

2. Experimental Methodology

Woven kevlar / epoxy composite panels were manufactured with a [0/90]2S stacking sequence with six layers using different manufacturing processes. The following three manufacturing processes were chosen: hand lay-up, resin transfer moulding (RTM) and infusion. The reinforcement was woven kevlar (310 g / m2). The resin used in this study was SR8100 and SD8824 as the hardener, and the weight mixing ratio was 100 / 22. The RTM procedure was applied with a fixed two mm cavity, and the mould was closed using a vacuum. The vacuum was maintained while the resin cured. Five plates for each manufacturing process were manufactured. The Image J software was used to calculate the fibre distribution for 60 images. Image J has been widely used by researchers [35–38]. The area of the object under consideration that is represented by one pixel is a function of the magnification used when obtaining the images. This study considers images obtained at a magnification that allows imaging of the complete sample thickness in sensible digital image sizes. The polishing process of the samples is illustrated in Table 1. Before using the image analysis, all images should have the same size and background (e.g. black background with a black resin colour) and should set the Image J options to get the same sized grid calibres. All microscopic images have been changed to binary images, as shown in Figure 1. The most efficient cover FD is generated from box counting data over multiple grid positions, as shown in Figure 2, with different grid positions. In each grid position, the minimum box size was one pixel, and the maximum box size was 45 % of the region of interest. The microstructures were quantified when the background and resin pixels were the same colour (black) and the fibre pixels (white) were characterised as the foreground.

Therefore, if we keep using a smaller box size, the count will be higher, and the count approaches infinity when the box size approaches zero. The limit was found to be the slope of the regression line; therefore, the FD was computed by Equation 1 [35–38] for each grid position. The FD of the whole image has been computed by Equation 2 [35–38].

\[
\text{FD} = \lim \left[ \frac{\log (F_\varepsilon)}{\log (\varepsilon)} \right]
\]

\[
\text{FD} = \text{slope} \left[ \ln \left( \frac{\text{Boxes with Foreground Pixels}}{\ln(\varepsilon)} \right) \right]
\]

\[
\text{Mean FD} = \frac{\Sigma (FD)}{\text{GRIDS}}
\]

Where \(F_\varepsilon\) = the foreground pixels
\(\varepsilon\) = the box size.
Table 1. The polishing process.

| Grinding (SiC Grade) | Force (Newton) | Time (minute) | Rotation Speed (rev / min) |
|----------------------|----------------|---------------|---------------------------|
| 320                  | 25             | 5             | 300                       |
| 400                  | 25             | 5             | 300                       |
| 600                  | 25             | 5             | 300                       |
| 800                  | 25             | 5             | 300                       |
| 1200                 | 25             | 5             | 300                       |

| Polishing Grade (µm) | Force (Newton) | Time (minute) | Rotation Speed (rev / min) |
|----------------------|----------------|---------------|---------------------------|
| 15                   | Hand force     | 5             | 300                       |
| 6                    | Hand force     | 5             | 300                       |
| 1                    | Hand force     | 5             | 300                       |

Figure 1. Microscopic image with its binary image.
3. Mechanical Tests

The interlaminar shear strength (ILSS) was used to measure the bonding force between the fibre and resin and to confirm that the plates are manufactured at an acceptable level. The ILSS test was conducted according to EN ISO 14130:1998 standards. Three rectangular samples with 10 cm x 20 cm x 2 mm (L x W x T) were cut from five different plates for each type of manufacturing process (45 samples in total). The 4-point bending test was conducted according to EN ISO 14125:1998 standards for polymer composites. The Instron Electropuls E300 (model 5527-103, serial number 107190) with a ± five k Newton dynamic load cell and the test speed was one mm per min. The flexural stress $\sigma$ (Pa) was evaluated using Equation 3.

$$\sigma = \frac{3Fa}{bh^2}$$  

Where $F$ is the force (N), $a$ is the distance between the supports (mm) and applied force, $h$ is the thickness of the samples (mm) and $b$ is the width of the samples (mm).

The flexural modulus of elasticity was calculated using Equation 4.

$$E_f = \frac{0.21 h^3 L^3}{b s b h^3}$$  

Where $E_f$ in (MPa), $L$ is the span (mm) and $s$ is the beam mid-point deflection (mm). The fibre volume fraction ($V_f$) for specimens with a different type of manufacturing process was calculated using Equation 5 [38].

$$V_f = \frac{n AF}{\rho_f t}$$  

Where $n$ is the number of layers, $AF$ is the areal weight of the fabric (kg / m2), $\rho_f$ is the volume weight of fibre (kg/m3) and $t$ is the laminate thickness (m).
4. Results and Discussion
The microstructures were characterised for composite laminates. The FD and the Vf were calculated. ILSS and flexural tests were conducted. The ILSS, flexural elastic modulus and ultimate flexural stress (UFS) were calculated. Figure (3) illustrates that the FD increases when the manufacturing process is changed from hand lay-up or infusion to RTM. This increase depends on the level of consolidation because more pressure leads to an increase in the Vf of the laminate, which leads to a high ILSS, as illustrated in Figure (4). This means that the FD correlates with the ILSS and Vf. Figure 5 shows that the UFS and flexural elastic modulus is proportional to the level of consolidation due to the increase in FD, Vf and ILSS, as shown in Figures 3 and 4. All the results show that the FD correlates with the mechanical properties for the composite laminates. A high FD means a high Vf and high mechanical performance when we analyse the resin as a background. However, if we analyse the fibre as a background, the issue will be reversed.

![Figure 3](image1.png)

**Figure 3.** The FD against the type of manufacturing process.

![Figure 4](image2.png)

**Figure 4.** The ILSS and the Vf against the type of manufacturing process.
5. Conclusion
The study focuses on the evaluation of mechanical properties of composite laminates by FD to replace the mechanical tests that are expensive and time consuming by analysing the microstructure images. The results illustrate that the FD differs according to the method of manufacturing process. The highest value of FD was in the RTM process due to the increase in $V_f$, FD, $V_f$, ILSS, UFS and the elastic flexural modulus changed according to the type of the manufacturing process. The results show a significant relationship between the mechanical performance of the composite laminates and the FD. The results concluded that FD could be utilised as a factor to characterise the performance of composite laminates.

References
[1] Basford, D. M., P. R. Griffin, S.M. Grove & J. Summerscales. (1995). "Relationship between mechanical performance and microstructure in composites fabricated with flow-enhancing fabrics." Composites 26(9): 675-679.
[2] Aziz, S. H. and M. P. Ansell (2004). “The effect of alkalization and fibre alignment on the mechanical and thermal properties of kenaf and hemp bast fibre composites: Part 1 – polyester resin matrix.” Composites Science and Technology 64(9): 1219-1230.
[3] Gojny, F. H., M. H. G. Wichmann, et al. (2005). "Influence of nano-modification on the mechanical and electrical properties of conventional fibre-reinforced composites.” Composites Part A: Applied Science and Manufacturing 36(11): 1525-1535.
[4] Tzetzis, D. and Hogg, P. J. (2006) 'Bondline toughening of vacuum infused composite repairs', Composites Part A: Applied Science and Manufacturing, 37 (9), pp. 1239-1251.
[5] Dhakal, H. N., Z. Y. Zhang & M.O.W. Richardson (2007). "Effect of water absorption on the mechanical properties of hemp fibre reinforced unsaturated polyester composites." Composites Science and Technology 67(7–8): 1674-1683.
[6] Liu, R. M and Liang, D. K. (2010) 'Experimental study of carbon fiber reinforced plastic with embedded optical fibers', Materials and Design, 31 (2), pp. 994-998.
[7] Amjed Saleh Mahmood, M Neil James, John Summerscales. "Process-property-performance relationships in CFRP composites using fractal dimension", IOP Conference Series: Materials Science and Engineering, 2018
[8] Lomov, S. V., Ivanov, D. S., Verpoest, I., Zako, M., Kurashiki, T., Nakai, H., Molimard, J. & Vautrin, A. (2008) 'Full-field strain measurements for validation of meso-FE analysis of textile composites', Composites Part A: Applied Science and Manufacturing, 39 (8), pp. 1218-1231.

[9] Sudarisman & Davies, I. J. (2008) 'The effect of processing parameters on the flexural properties of unidirectional carbon fibre-reinforced polymer (CFRP) composites', Materials Science and Engineering: A, 498 (1-2), pp. 65-68.

[10] Campos, K. A. de, Augusto, J., Pereira, T. A. & Hein, L. R. d. O., '3-D reconstruction by extended depth-of-field in failure analysis – Case study II: Fractal analysis of interlaminar fracture in carbon/epoxy composites'. Engineering Failure Analysis, 2012, 25 pp 271-279.

[11] Worrall, C.M. and Wells, G.M., Fibre distribution in discontinuous fibre reinforced plastics: characterisation and effect on material performance'. Proc. 7th European Conference on Composite Materials, London, 1996, pp. 247-252.

[12] Gao, S.-L., Mäder, E. & Zhandarov, S. F., 'Carbon fibers and composites with epoxy resins: Topography, fractography and interphases'. Carbon, 2004, 42 (3). pp 515-529.

[13] Pearce, N. R. L., Guild, F. J. & Summerscales, J., 'An investigation into the effects of fabric architecture on the processing and properties of fibre reinforced composites produced by resin transfer moulding'. Composites Part A: Applied Science and Manufacturing, 1998, 29 (1-2). pp 19-27.

[14] Pearce, N.R.L., Summerscales, J. and Guild, F.J., Improving the resin transfer moulding process for fabric-reinforced composites by modification of the fabric architecture, Composites Part A: Applied Science and Manufacturing, 2000, 31(12), pp 1433-1441.

[15] Summerscales, J., Guild, F.J., Pearce, N.R.L. and Russell, P.M., Voronoi cells, fractal dimensions and fibre composites, Journal of Microscopy-Oxford, 2001, 201(2), pp 153-162.

[16] Summerscales, J., Russell, P.M., Lomov, S., Verpoest, I. and Parnas R.S., The fractal dimension of X-ray tomographic sections of a woven composite, Advanced Composites Letters, 2004, 13(2), pp 113-121.

[17] Mikhaluk, D. S., Truong, T. C., Borovkov, A. I., Lomov, S. V. & Verpoest, I., 'Experimental observations and finite element modelling of damage initiation and evolution in carbon/epoxy non-crimp fabric composites'. Engineering Fracture Mechanics, 2008, 75 (9). pp 2751-2766.

[18] Picu, R.C., Li, Z., Soare, M.A., Sorohan, S., Constantinescu, D.M. and Nutu, E., ‘Composites with fractal microstructure: The effect of long range correlations on elastic–plastic and damping behaviour’, Mechanics of Materials, 2014, 69 pp 251-261.

[19] Allen, M., Brown, G. J. & Miles, N. J., ‘Measurement of boundary fractal dimensions: review of current techniques’. Powder Technology, 1995, 84 (1). pp 1-14.

[20] Pimenta, S. and Pinho, S.T., An analytical model for the translaminar fracture toughness of fibre composites with stochastic quasi-fractal fracture surfaces, Journal of the Mechanics and Physics of Solids, 2014, 66 pp 78-102.

[21] Aniszewska, D. and Rybaczuk, M., ‘Fractal characteristics of defects evolution in parallel fibre reinforced composite in quasi-static process of fracture’. Theoretical and Applied Fracture Mechanics, 2009, 52 pp 91-95.

[22] Mishnaevsky, L., ‘Hierarchical composites: Analysis of damage evolution based on fiber bundle model’. Composites Science and Technology 2011, 71 pp 450-460.

[23] Hale, R. D., 'An experimental investigation into strain distribution in 2D and 3D textile composites'. Composites Science and Technology, 2003, 63 (15). pp 2171-2185.
[24] Mahadik, Y., Brown, K. A. R. & Hallett, S. R., ‘Characterisation of 3D woven composite internal architecture and effect of compaction’. Composites Part A: Applied Science and Manufacturing, 2010, 41 (7). pp 872-880.

[25] Pitchumani, R. and B. Ramakrishnan, A fractal geometry model for evaluating permeabilities of porous preforms used in liquid composite molding. International journal of heat and mass transfer, 42(12): p. 2219-2232, 1999.

[26] Campos, K.A.d., et al., 3-D reconstruction by extended depth-of-field in failure analysis – Case study II: Fractal analysis of interlaminar fracture in carbon/epoxy composites. Engineering Failure Analysis, 25(0): p. 271-279, 2012.

[27] Gao, S.-L., E. Mäder, and S.F. Zhandarov, Carbon fibers and composites with epoxy resins: Topography, fractography and interphases. Carbon, 42(3): p. 515-529, 2004.

[28] Allen, M., G.J. Brown, and N.J. Miles, Measurement of boundary fractal dimensions: review of current techniques. Powder Technology, 84(1): p. 1-14, 1995.

[29] Carpinteri, A. and B. Chiaia, Power scaling laws and dimensional transitions in solid mechanics. Chaos, Solitons & Fractals, 7(9): p. 1343-1364, 1996.

[30] Celli, A., et al., Fractal analysis of cracks in alumina–zirconia composites. Journal of the European Ceramic Society, 23(3): p. 469-479, 2003.

[31] Biancolini, M.E., et al., Fatigue cracks nucleation on steel, acoustic emission and fractal analysis. International Journal of Fatigue, 28(12): p. 1820-1825, 2006.

[32] Kuznetsov, P.V., V.E. Panin, and J. Schreiber, Fractal dimension as a characteristic of deformation stages of austenite stainless steel under tensile load. Theoretical and Applied Fracture Mechanics, 35(2): p. 171-177, 2001.

[33] Venkatesh, B., D.L. Chen, and S.D. Bhole, Three-dimensional fractal analysis of fracture surfaces in a titanium alloy for biomedical applications. Scripta materialia, 59(4): p. 391-394, 2008.

[34] Yuan, C.Q., et al., The use of the fractal description to characterize engineering surfaces and wear particles. Wear, 255(1–6): p. 315-326, 2003.

[35] Foroutan-Pour, K., Dutilleul, P. & Smith, D., ‘Advances in the implementation of the box-counting method of fractal dimension estimation’. Applied Mathematics and Computation, 1999, 105 (2). pp 195-210.

[36] Pitchumani, R. & Ramakrishnan, B., ‘A fractal geometry model for evaluating permeabilities of porous preforms used in liquid composite molding’. International journal of heat and mass transfer, 1999, 42 (12). pp 2219-2232.

[37] Li, J., Du, Q. & Sun, C., ‘An improved box-counting method for image fractal dimension estimation'. Pattern Recognition, 2009, 42 (11). pp 2460-2469.

[38] Amjed Saleh Mahmood, Processing-performance relationships for fibre-reinforced composites'. PhD thesis 2016, University of Plymouth.