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Experimental and statistical investigation of fracture strength of pan/phenolic-based carbon/carbon composite materials

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ABSTRACT

PAN/phenolic-based carbon/carbon composites are finding more and more use, and becoming more and more important for space/aviation industries, and general structural applications. The primary constituents of these materials are fragile, and cracking occurs through random failures caused by imperfections-induced random failures. The strength of a fragile material follows Weibull distribution. The variation of the flexural strengths has been modeled using Weibull distribution. In order to compute m and σu, first, the values of σi were ordered from the smallest to the largest, and then applying linear regression to these values. From the linear regression, the Weibull modulus and the characteristic strength were estimated. The CFRP composites show maximum flexural strength which decreases during the pyrolysis at the temperature of 1000 0C. The reduced flexural strength can be related to void defects. These defects probably act as a source of fractures during loading. The failure probabilities for CFRP and C/C composites are 0.55 and 0.78, respectively, and these values 334 and 92 MPa, and 29 and 10.2 GPa for mean flexural strength and flexural modulus, respectively, would be quite useful for understanding the fiber-matrix interfacial bonding properties, which have a strong influence on the mechanical properties of these composites.

1. Introduction

Flexural tests have gained extensive usage in assessing the mechanical characteristics of resin and laminated composites due to relative simplicity of the test method and minimal instrumentation and equipment requirements [1-5]. Flexure tests can be used to explore the interlaminar shear strength (short beam) and interlaminar fracture toughness (mode II) of the laminates [6-8]. The main elements of these materials are brittle, and cracking occurs due to random failures caused by defects. The strength of these types of materials follows the Weibull distribution [7, 9].

After measuring the density and porosity, 8 flexural specimens from each CFRP and C/C composites [9-13] were assessed using the three-point bending tests specified in ASTM D2344. A 5kN Instron Universal Testing Machine (Model: 2519-107) was used at the conditions thickness to length ratio 1:16, width to length ratio 2:7, and a crosshead speed 0.5mm/min as shown in Fig. 1. Flexural Strength, and flexural modulus of the specimens can be approximated [6-9] with the following Eqs. (1), (2) and (3).

$$\sigma_f = \left(\frac{3PL}{2bd^2}\right)\left[1+6\left(\frac{D}{L}\right)^2 - 4\left(\frac{d}{L}\right)\left(\frac{D}{L}\right)\right] \quad (1)$$

$$D = \frac{\varepsilon_f L^2}{6d} \quad (2)$$

$$E_B = \frac{mL^3}{4bd^3} \quad (3)$$

where σ_f is the maximum bending stress, ε_f the strain rate, P the load at the moment of break, L the support span, E_B the modulus of elasticity, b the width of the specimen, d the thickness of the specimen, D the deflection of the centerline of the specimen at the middle of the support span and m is the slope of the tangent to the initial straight-line portion of the load-deflection curve.

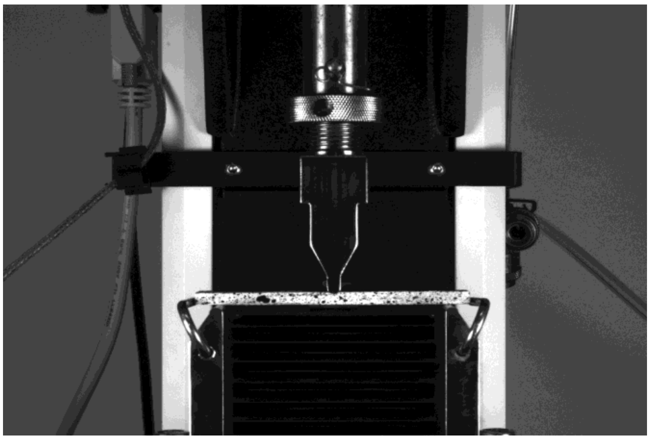

Fig. 1. Setup of flexural test

While some research has been conducted on simple materials under basic loading scenarios, the understanding of flexural behavior in more realistic and intricate situations remains limited [8-11]. Furthermore, the incorporation of advanced numerical methods and computational techniques into flexural modeling has not been extensively explored. Addressing these research gaps is essential to enhance our comprehension of the mechanical response of materials under bending loads. The variation of the flexural strengths has been modeled using Weibull distribution [10].

2. Materials And Method

2.1 Determination Of Density And Porosity

30 specimens of size 10mm × 5mm and thicknesses between 4 and 4.5mm were cut, for the measurement of density and porosity. The weight of the specimens was assessed by the analytical balance with an accuracy of 0.1mg. The determination of density and (ρ_s) porosity (V_v) of the specimens using Archimedes principle were conducted and following with ASTM D792. The density and the porosity are given by Eqs (4) and (5), respectively.

$$\rho_s = \frac{m\rho_0}{m_1 - m_2} \tag{4}$$

$$V_\upsilon = 100 - \rho_s \left(\frac{\%m_{matrix}}{\rho_{matrix}} + \frac{\%m_{fibre}}{\rho_{fibre}} \right) \tag{5}$$

where ρ_s is the density of specimen, V_v the porosity of specimen, $\%m_{matrix}$ the mass fraction of matrix, $\%m_{fiber}$ the mass fraction of fiber, ρ_{matrix} the density of matrix, ρ_{fiber} the density of fiber, ρ_0 the density of water, m the specimen weight in the air, m_1 the specimen weight measured after being immersed in the water for 24 hours and then wiped, and m_2 is the specimen weight in distilled water.

Table 1 presents the calculated values for density and porosity. It provides information about the composition of porous specimens, including solid, open and closed pores. In addition, the table shows the measurement of water absorbed into the open porosity when weighed under suspended or soaked conditions.

Table 1

The void volume fraction, and the actual density values of composites.

Specimen	m (g)	m_1 (g)	m_2 (g)	ρ_s (g/cm^3)	V_v (%)
CFRP	166.8	208.6	95	1.47	3.95
C/C	162.8	210.6	85	1.29	17.7

2.2 Statistical Analysis of Fracture Strength

Fracture toughness of the specimens from CFRP and C/C plates were analyzed using the 3-point bending method [5]. The mode II fracture toughness [9, 17] was determined. The following Weibull equation describes the data for flexural strength [21, 22]:

$$\ln\left[\ln\left(\frac{1}{1-F(\sigma_i)}\right)\right] = m\ln(\sigma_i) - m\ln(\sigma_u) \tag{6}$$

where m is the Weibull modulus, σ_u the characteristic strength of the material and $F(\sigma_i)$ is the probability of failure at the applied stress (σ_i). The failure probability is calculated with:

$$F(\sigma_i) = \frac{n}{1+N} \quad (7)$$

where n is the strength order number, and N is the total number of observations.

3. Results And Discussion

In the graph, the load vs. displacement for specimens is presented as shown in Fig 2. The CFRP composites show maximum flexural strength which decreases during the pyrolysis at the temperature of 1000 ^{0}C. These defects probably act as a source of fractures during loading. At the preliminary stages of loading curves, non-linearity is observed. The non-linear behavior arises from the interaction between the elastic deformation of the fiber and matrix. At a certain value in loading curves, the shear stays at constant as the displacement increases. The flexural strength and modulus of elasticity were successfully determined as shown in Fig 3.

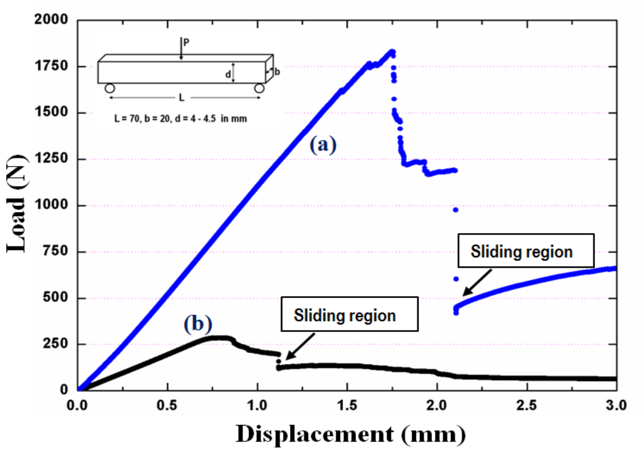

Fig. 2. The load-displacement curves for (a) CFRP and (b) C/C composites materials

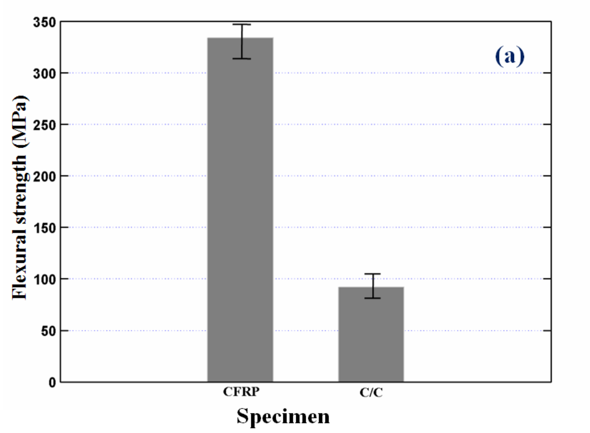

Fig. 3. (a) Flexural strength

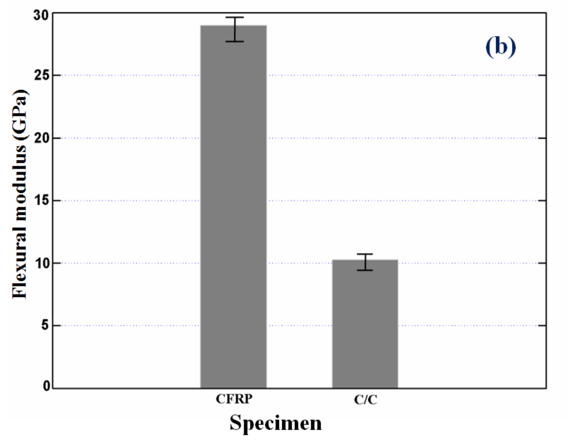

Fig. 3. (b) flexural modulus for composites

The mean flexural strength values of 334 MPa and 29 GPa, and the mean flexural modulus values of 92 MPa and 10.2 GPa for CFRP and C/C composites, respectively, provide valuable insights into the interfacial bonding properties. These properties significantly impact the mechanical characteristics of these composites.

The Weibull modulus plot for these materials is shown in Figs 4. When the applied stress is σ_u, the probabilities of failure for CFRP and C/C composites are 0.55 and 0.78, respectively. In order to compute m and σ_u, first, the values of σ_i were ordered from the smallest to the largest, and then applying linear regression to these values [22]. The Weibull modulus and the characteristic strength were estimated. Values of the Weibull modulus and its characteristic strength are shown in Table 2.

Table 2

Weibull modulus and characteristic strength for CFRP and C/C composite materials.

Specimen	Straight line eqn.		σ_u (MPa)	R^2
	m	Intercept		
CFRP	6.72	-38.81	321.87	0.92984
C/C	12	-54.27	92.02	0.98817

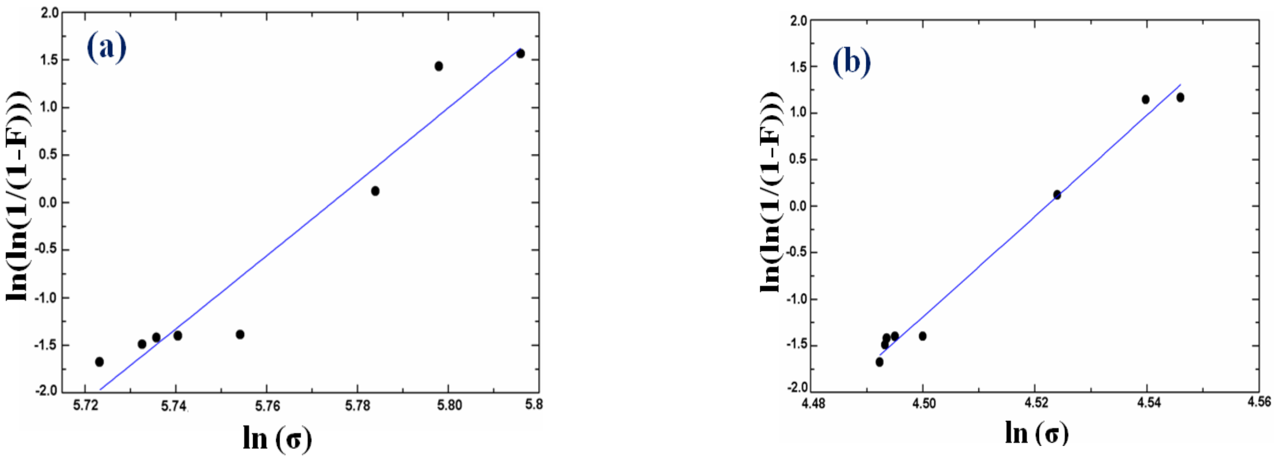

Fig. 4. Weibull probability plots for (a) CFRP and (b) C/C composite materials

4. Conclusion

This study presents the outcomes of a modeling endeavor conducted on PAN/phenolic-based carbon/carbon composite materials. Experimental characterization of the material was carried out using 3-point bending tests, and the resulting data was modeled using the Weibull distribution. The mean flexural strength and flexural modulus were 334 and 92 MPa, and 29 and 10.2 GPa, respectively. The calculated failure probabilities for CFRP and C/C composites are 0.55 and 0.78, respectively. Advancements in flexural modeling could significantly benefit industries such as civil engineering, aerospace, and material sciences, leading to safer and more cost-effective designs of structures and components. Further research and investigation are thus warranted to bridge the current gap in flexural modeling knowledge and pave the way for innovative solutions and improved designs in the engineering field.

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