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Probability-based studies on the tensile strength of GFRP, CFRP and hybrid composites

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Abstract

In the present work, two parameter Weibull distribution is used to measure the variability of the tensile strength of cross ply glass/epoxy, carbon/epoxy and hybrid (glass-carbon/epoxy) composites for different strain rates from 0.0083 to 542 s^{-1}. The Weibull parameters (shape and scale parameters) are obtained using linear curve fit method. The shape and scale parameters will be useful for composite product designers to quantify the component reliability. Using Hitachi SEM instrument, the failure mechanisms observed in the tested samples of GFRP, CFRP and hybrid composites, are discussed.

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1. Introduction

In the recent years, the Weibull statistic analysis **[1]** is used to investigate the accuracy of the mechanical properties of polymeric matrix composites **[2].** The flaws induced for brittle fibers (glass and carbon) due to misalignment and handling of the fibers during fiber cutting and laminate preparation **[3-4].** To measure the

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accuracy of the tensile strength values, two parameter Weibull statistic analysis is used based on the difference between theoretical and experimental cumulative probability density (cumulative failure probability) values. The tensile strength values are accurate when the theoretical and experimental cumulative probability density values are closer to each other**. Ou and Zhu [5]** have used Weibull statistics to find the tensile strength distribution of GFRP composites in the range of strain rates from 0.0016 to 160 s^{-1} and observed that the cumulative failure probability vs. strength curves move towards a higher strength direction with the increase of strain rate. **Alqam et al. [6]** analysed pultruded composite mechanical properties (Tensile, compressive and shear) of fiber reinforced polymer (FRP) composites using two and three parameter Weibull distribution. It is observed that both distributions are useful to characterize the mechanical properties of FRP composites and not much variation between the distributions.

In this study, the Weibull analysis is used to determine the tensile strength distribution of (0°/90°) GFRP, CFRP and hybrid composites at the strain rates of 0.0083 to 542 s^{-1}. The Weibull parameters are determined using linear curve fit method. The theoretical cumulative probability density values are calculated from Weibull parameters. The results indicate that the tensile strength increases for glass/epoxy and hybrid composites whereas the tensile strength is approximately constant for carbon/epoxy composites, as strain rate increases from quasi-static to 542 s^{-1}.

Nomenclature

σ	Tensile strength
$\dot{\varepsilon}$	Strain rate
F	Cumulative probability density (cumulative failure probability)
η	Scale parameter (characteristic strength)
β	Shape parameter

2. Materials selection and specimen fabrication

Materials such as glass fibers woven roving mat of 610 gsm, carbon fibers woven roving mat of 450 gsm and epoxy resin are used for the study. Using the compression molding technique, (0°/90°) GFRP, CFRP and hybrid (glass-carbon/epoxy) laminates are prepared. For each laminate, four layers are used. The thickness of each layer is 0.4 mm.

3. Experimental setup and procedure

Using an Instron universal testing machine, 3 samples are tested at the strain rate of 0.0083 s^{-1} (quasi-static) for each material. The drop mass setup is shown in Fig. 1. Using this test setup, experiments can be carried out in the strain rate ranges from 10 s^{-1} up to 1000 s^{-1} **[7-8]**.

The velocities are measured by falling mass at different heights using the expression: $V = \sqrt{2gh}$ and the nominal strain rates are determined by the expression: $\dot{\varepsilon} = \frac{V}{L_0}$

Where V is the impact velocity; g = 9.81 ms^{-2} = gravitational acceleration; h is the height from which mass is falling down and L_0 represents the gauge length of the specimen which is equal to 10 mm.

4. Results and discussion

In dynamic studies, 5 samples were tested for each material and at each height, in our earlier work **[9].** In this paper, out of 5 samples, best 3 samples are used for the Weibull statistic analysis. The two parameter Weibull distribution is used to measure the variability of the tensile strength for each sample of (0°/90°) glass/epoxy, carbon/epoxy and hybrid composites in the strain rate ranges from 0.0083 to 542 s^{-1}. Cumulative probability density is expressed in terms of Median rank formula **[2, 3]**, which is given by

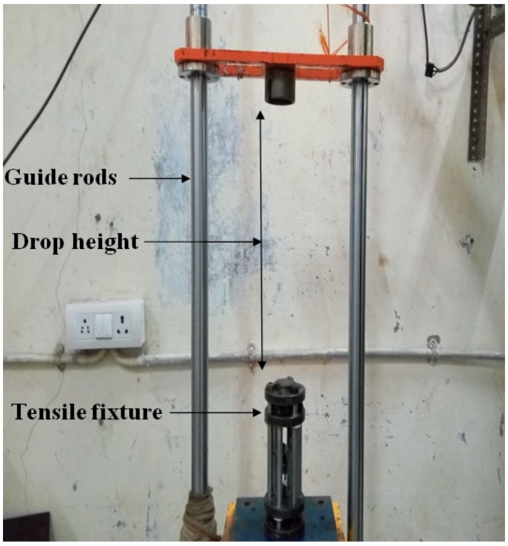

Fig. 1 Drop mass setup

$$F = \frac{i-0.3}{(n+0.4)} \tag{1}$$

Where i and n are the current and total test numbers (number of data points), respectively.

The straight line Equation is written as

$$y = mx + c \tag{2}$$

Where m represents the slope of the line.

For glass/epoxy, carbon/epoxy and hybrid composites, at each strain rate 3 samples were tested. Therefore, at each height and for each material, $i = 1\ to\ 3\ and\ n = 3$.

The two parameter Weibull distribution expression for the cumulative probability density is given as **[2, 10 & 11]**

$$F(\sigma) = 1 - e^{-(\frac{\sigma}{\eta})^{\beta}} \tag{3}$$

Where F is the cumulative probability density (cumulative failure probability). σ denotes the tensile strength. η is the scale parameter (characteristic strength) and β represents the shape parameter.

Eq. (3) can be written as

$$\mathrm{y} = \ln\left(\ln\left(\frac{1}{1-F(\sigma)}\right)\right) = \beta\ ln\,\sigma - \beta\ ln\,\eta \tag{4}$$

Combining Eq. (2) and Eq. (4)

$$\mathrm{y} = \ln\left(\ln\left(\frac{1}{1-F(\sigma)}\right)\right), m = \beta,\ x = \sigma, c = -\beta \ln \eta;$$

Scale and shape parameters are calculated by using Eq. (4) and the known strength values by linear curve fit method, which are seen in Figs. 2-4.

For all curves (Figs. 2-4) of GFRP, CFRP and hybrid composites from quasi-static to 542 s^{-1}, R^2 (coefficient of determination) values obtained are greater than or equal to 0.91, 0.95 and 0.97, respectively. From Figs. 2-4, scale and shape parameters are determined using linear curve fit method from experimental cumulative probability density values and tensile strength values. The experimental and theoretical cumulative probability density values are calculated by using Eq. (1) and Eq. (3), respectively. The Weibull parameters (Table 1) are useful to determine theoretical cumulative probability density values. The Weibull parameters for GFRP, CFRP and hybrid composites are given in Table 1.

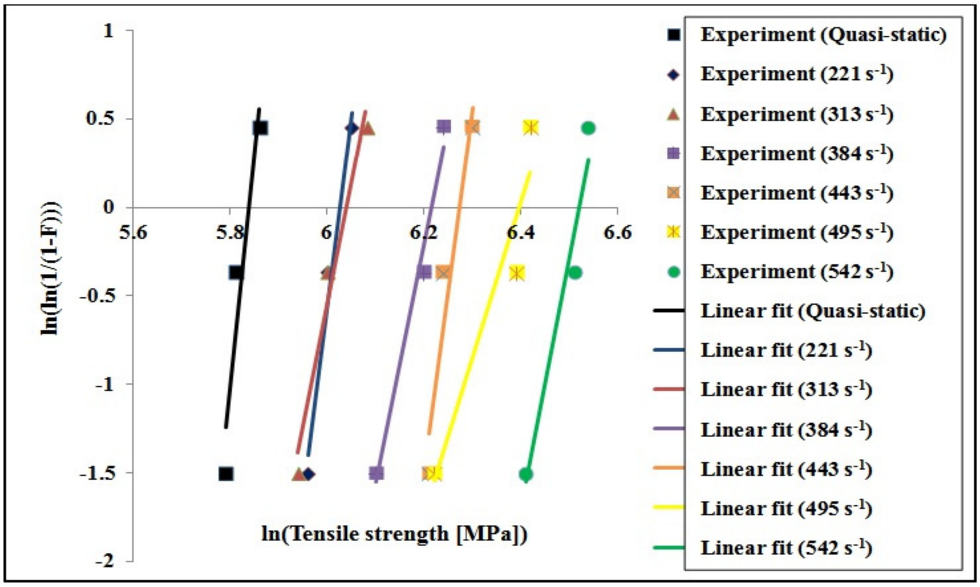

Fig. 2 Weibull plot for different strain rates of the (0°/90°) GFRP composites

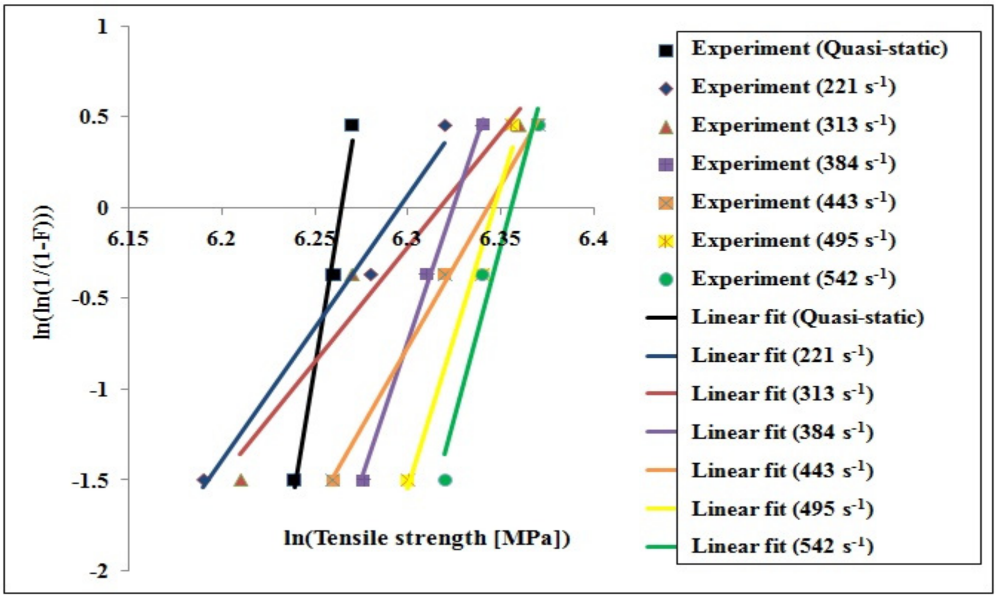

Fig. 3 Weibull plot for different strain rates of the (0°/90°) CFRP composites

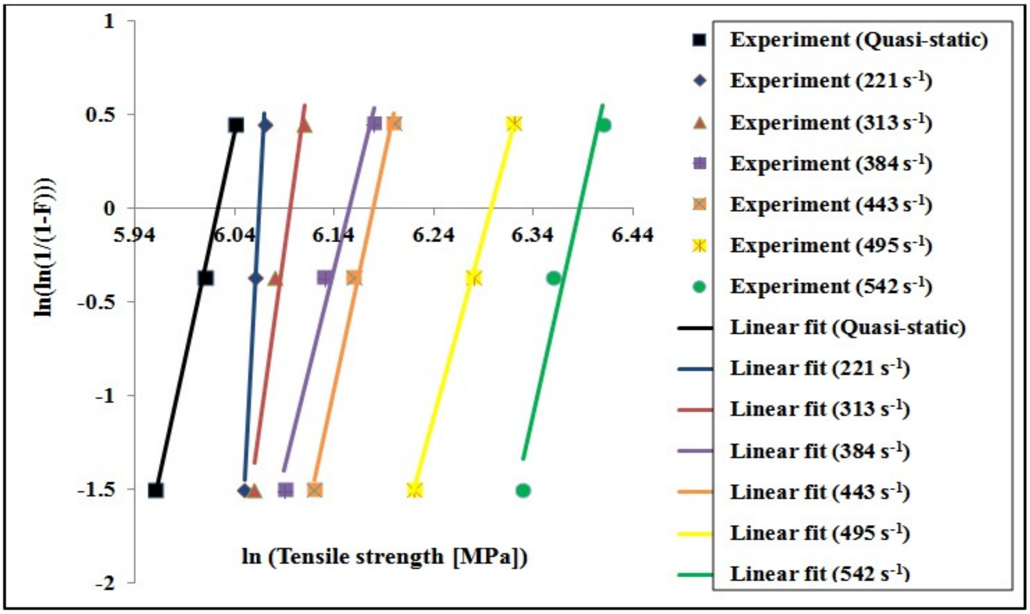

Fig. 4 Weibull plot for different strain rates of the hybrid (glass-carbon/epoxy) composites

Table 1 Weibull parameters for GFRP, CFRP and hybrid composites

Material	Weibull parameters	0.0083 s^{-1}	221 s^{-1}	313 s^{-1}	384 s^{-1}	443 s^{-1}	495 s^{-1}	542 s^{-1}
GFRP	η (MPa)	343.08	413.64	420.26	505.06	528.95	600.12	678.92
	β	25.73	21.51	13.77	12.39	19.12	8.71	13.81
CFRP	η (MPa)	525	542	554.1	557	569.5	571.2	575.4
	β	61.69	14.63	12.73	30.62	17.81	33.65	38.19
Hybrid	η (MPa)	412.64	430.44	444.47	471.12	482.57	544.29	593.65
	β	24.26	97.8	38.19	21.51	24.45	19.50	23.63

From Table 1, it is observed that the scale parameter increases with the strain rate. Higher values of the β indicate a uniform strength distribution. Similar observations are seen in the literatures **[12, 13]**. For GFRP, CFRP and hybrid composites, the scale parameter increases by 98%, 9.5% and 44%, respectively, as strain rate increases from 0.0083 to 542 s^{-1}. It leads to the conclusion that the strain rate sensitivity is more for (0°/90°) glass/epoxy and hybrid composites than CFRP composites. The experimental and theoretical cumulative probability density function vs. tensile strength of GFRP, CFRP and hybrid composites are seen in Figs. 5, 6 and 7, respectively.

From Figs. 5 and 7, it is observed that for GFRP and hybrid composites, the cumulative probability density curve moves towards right (higher strength direction) as strain rate increases from 0.0083 s^{-1} (quasi-static) to 542 s^{-1} whereas for CFRP composites (Fig. 6), the cumulative probability density curves are closer to each other for the same strain rates. This clearly indicates that there is a significant strain rate effect on the tensile strength of the (0°/90°) GFRP and hybrid composites whereas the strain rate effect on the tensile strength of the (0°/90°) CFRP composites is less. The theoretical and experimental cumulative probability density values match well, which leads to the conclusion that the tensile strength values are accurate.

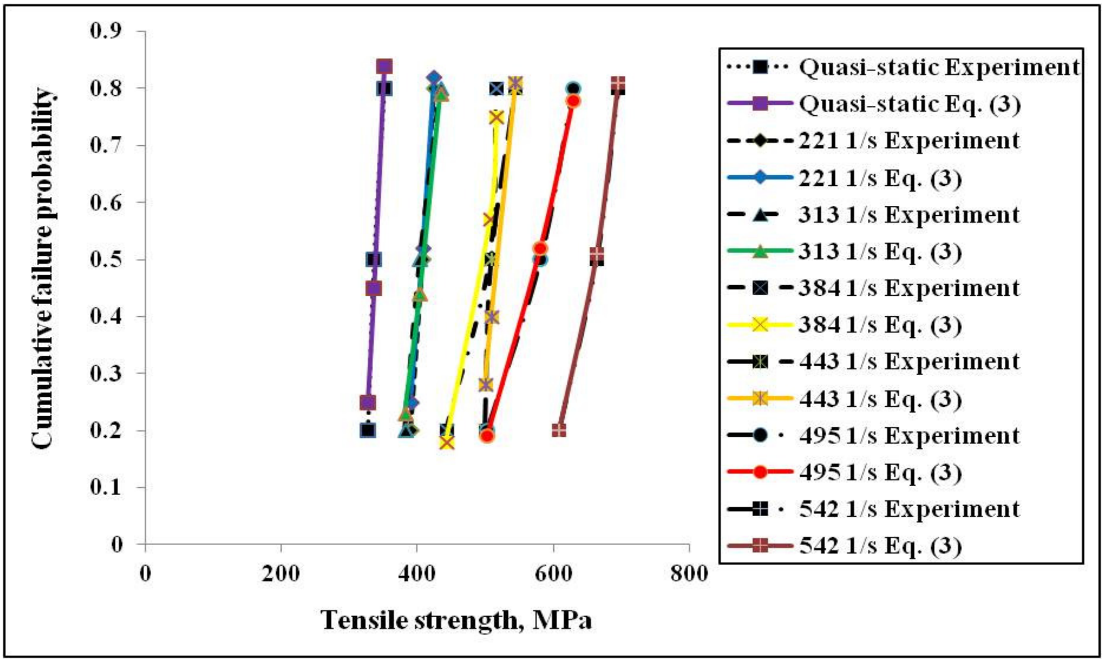

Fig. 5 Experimental and theoretical cumulative probability density vs. tensile strength for GFRP composites

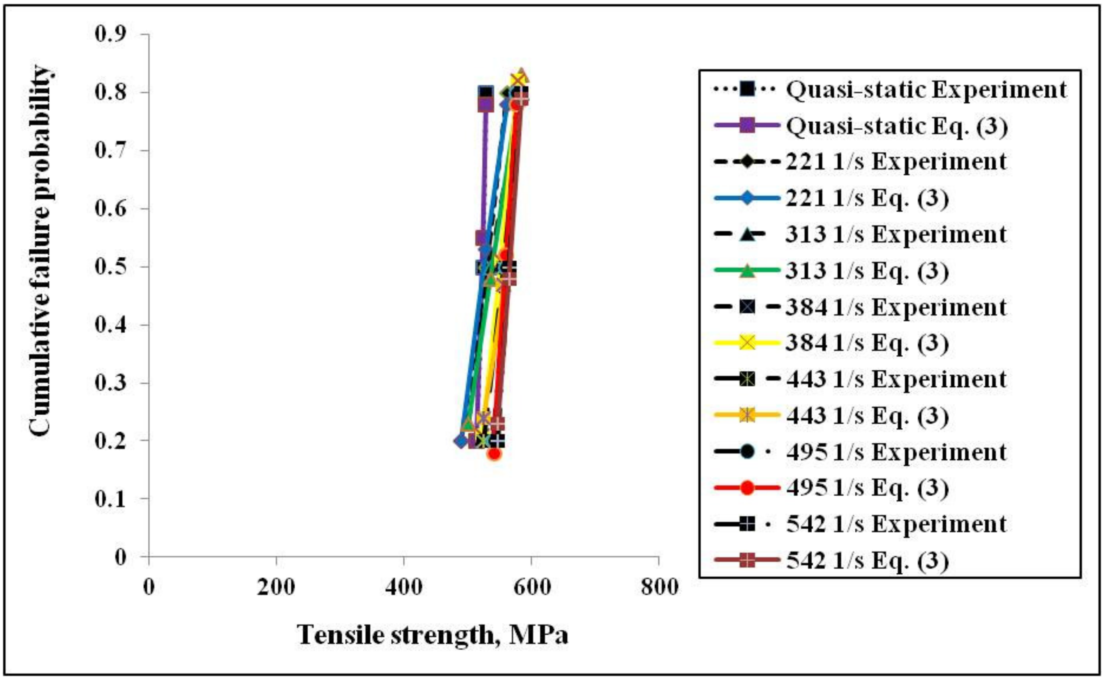

Fig. 6 Experimental and theoretical cumulative probability density vs. tensile strength for CFRP composites

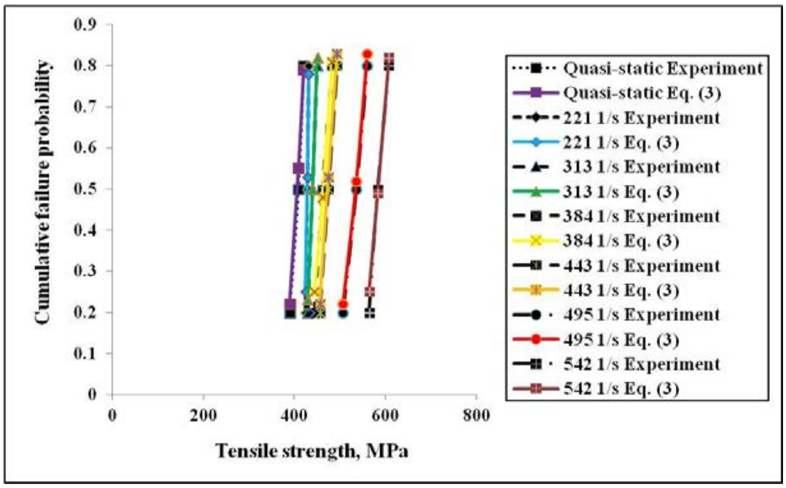

Fig. 7 Experimental and theoretical cumulative probability density vs. tensile strength for hybrid (glass-carbon/epoxy) composites

5. Scanning electron microscopy studies

The fracture surface of tensile specimens is examined using Scanning electron microscope (SEM). The failure mechanisms such as fiber-matrix debonding, fiber pull-out and fiber breakage are observed during high strain rate testing for glass/epoxy, carbon/epoxy and hybrid composites, respectively using SEM analysis, which are seen in Figs. 8 (a-c).

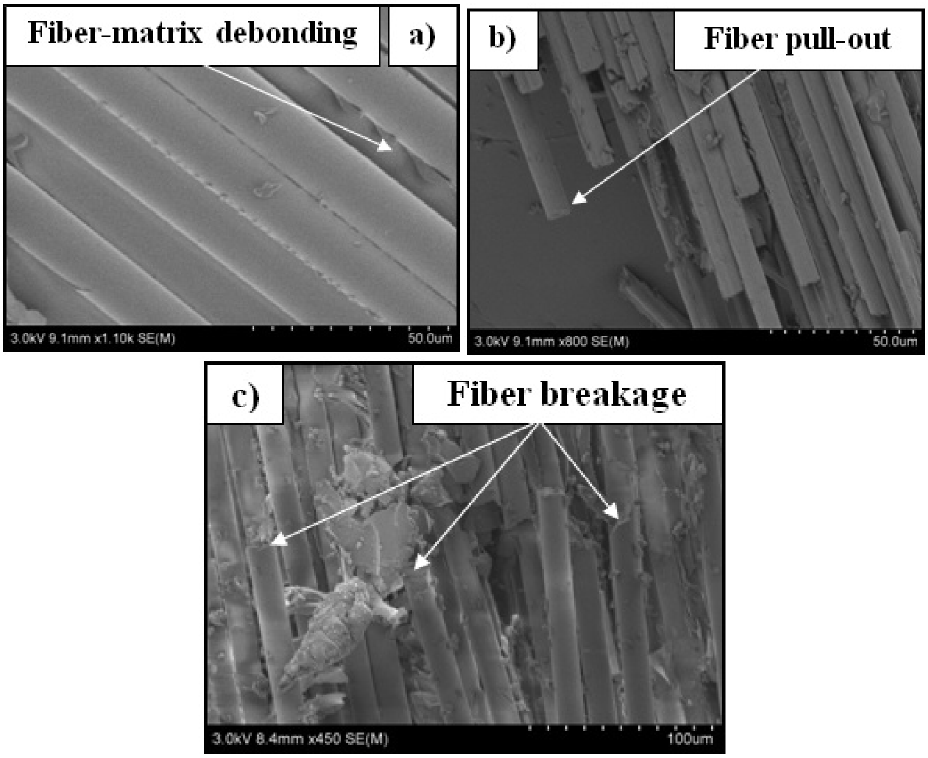

Fig. 8 SEM Images at dynamic loading rates a) fiber-matrix debonding (GFRP composites) b) fiber pull-out (CFRP composites) c) fiber breakage (hybrid composites)

6. Conclusions

The tensile strength distribution of glass/epoxy, carbon/epoxy and hybrid (glass-carbon/epoxy) composites are studied from quasi-static (0.0083 s^{-1}) to high strain rate (542 s^{-1}) using two parameter Weibull statistic analysis. The Weibull parameters are obtained using linear curve fit method. The obtained scale and shape parameters are useful for engineering applications. Using Weibull parameters, the theoretical cumulative probability density values were determined. The theoretical and experimental cumulative probability density values match well. The results obtained from this study indicate that there is a significant strain rate effect on the tensile strength of (0°/90°) GFRP and hybrid composites but the tensile strength of cross ply carbon/epoxy composites is approximately constant, as strain rate changes from 0.0083 to 542 s^{-1}. Using SEM analysis, the fiber-matrix debonding, fiber pull-out and fiber breakage are seen during high strain rate tensile testing in GFRP, CFRP and hybrid composites, respectively.

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