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Tensile mechanical behavior of T300 and M40J fiber bundles at different strain rate

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Tensile mechanical behavior of T300 fiber bundles and M40J fiber bundles have been studied in the strain rate range from 0.001 1/s to 1300 1/s and complete stress strain curves were obtained. Results show that both ultimate strength and failure strain of two materials are strain rate insensitive, and T300 fiber and M40J fiber can be regarded as strain rate insensitive materials. On basis of the fiber bundles model and the statistic theory of fiber strength, single Weibull distribution model and bimodal Weibull distribution model have been developed to describe mechanical behavior of fiber bundles. And a method for determine the statistic parameters of fibers by tensile tests of fiber bundles is established, too. The simulated stress strain curves from the model are in good agreement with the test data. Simulated results show that the strength of T300 fiber can be described by single Weibull distribution function, and the strength of M40J fiber should be described by bimodal Weibull distribution function.

1. Introduction

An understanding of the behavior of fiber-reinforced composites at high strain rate is important because such materials cater for the bulk of advanced applications. The fibers are the main load-bearing elements and it is therefore important to have a means gaining reliable information about the properties of fiber strength at high strain rates. However, owning to technical difficulties in tests, it is impossible to obtain the dynamic properties of a single fiber directly at present. Chi *et al.* [1] proposed a procedure for determining the static properties of single fiber by measuring those of fiber bundles. Xia *et al.* [2] extended the method to the dynamic state and first successfully performed tensile impact tensile impact tests on fiber bundles. Their testing strain rate was up to 1100 1/s. Wang *et al* established a single Weibull distribution and a bimodal Weibull distribution model for strain-rate and temperature-dependent fiber strength. The method for determining mechanical parameters of fibers by tensile impact tests of fiber bundles is established. On basis of these model, the strain-rate and temperature-dependence of E-glass fiber and Kevlar fiber have been studied systematically [3, 4].

Carbon fibers have been widely utilized as a reinforcing component in composite structures. In the present paper, static and dynamic tensile mechanical behavior of T300 fiber and M40J fiber will be studied.

2. Statistical damage constitutive model of fiber bundles

The fiber bundles model is shown in Fig. 1. In this model, the N parallel fibers of the same length, L, cross-sectional area, A, are rigidly fixed between the two ends. The following three terms are assumed:

- Each fiber remains completely elastic until it ruptures when the tensile force in the fiber reaches its rupture strength.
- The interaction between fibers is neglected. As n single fiber break, the residual load is equally allotted to the N-n surviving unbroken fibers. The load and stress of fiber bundles can be described as:

$$P = E\varepsilon A(N - n) \tag{2.1}$$

$$\sigma = E\varepsilon\left(1 - \frac{n}{N}\right) \tag{2.2}$$

- The strength of the single fiber is satisfactorily given by a particular probabilistic distribution. For failure analysis of brittle material the "weakest link" approach is usually adopted as a criterion of failure; that is, a brittle material fails when the stress at any one flaw becomes larger than the ability of surrounding material to resist local stresses. The cumulative distribution function can be given by:

$$G(\varepsilon) = \frac{n}{N} = 1 - \exp\left[-\left(\frac{E\varepsilon}{\sigma_0}\right)^{\beta}\right] \tag{2.3}$$

where β is the shape parameter and σ_0 is the scale parameter. In recent years, however, it was proposed that the distribution should be given by the modified modal Weibull distribution based on the

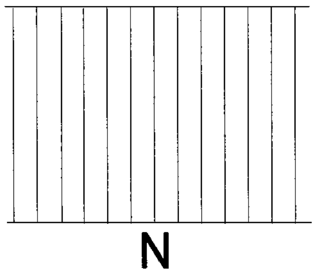

Figure 1 Model of fiber bundles.

multi-risk model, if two or more kinds of strength-limiting defect population exist together in brittle material. For two concurrent flaw population, a bimodal Weibull distribution function is described as following:

$$G(\varepsilon) = \frac{n}{N} = 1 - \exp\left[-\left(\frac{E\varepsilon}{\sigma_{01}}\right)^{\beta_1} - \left(\frac{E\varepsilon}{\sigma_{02}}\right)^{\beta_2}\right] \tag{2.4}$$

Then the stress strain curve of fiber bundles can be rewritten as:

$$\sigma = E\varepsilon\left[-\left(\frac{E\varepsilon}{\sigma_0}\right)^{\beta}\right] \quad \text{(Single Weibull distribution)} \tag{2.5}$$

$$\sigma = E\varepsilon\left[-\left(\frac{E\varepsilon}{\sigma_{01}}\right)^{\beta_1} - \left(\frac{E\varepsilon}{\sigma_{02}}\right)^{\beta_2}\right] \quad \text{(bimodal Weibull distribution)} \tag{2.6}$$

Equation 2.5 and 2.6 are statistic constitutive equation for single Weibull distribution and bimodal Weibull distribution.

For single Weibull distribution, we take double logarithms on both sides of Equation 2.5. i.e.

$$\ln\left[-\ln\left(\frac{\sigma}{E\varepsilon}\right)\right] = \beta\ln(E\varepsilon) - \beta\ln(\sigma_0) \tag{2.7}$$

From Equation 2.7, a test stress strain curve of fiber bundles can be rewritten to a straight line in Weibull coordinate system. And β and σ_0 can be determined according to the slop and intercept of the straight line. By taken double logarithms on both sides of Equation 2.6, one can obtain:

$$\ln\left[-\ln\left(\frac{\sigma}{E\varepsilon}\right)\right] = \ln\left[\left(\frac{E\varepsilon}{\sigma_{01}}\right)^{\beta_1} + \left(\frac{E\varepsilon}{\sigma_{02}}\right)^{\beta_2}\right] \tag{2.8}$$

The non-linear parameters σ_{01}, σ_{02}, β_1 and β_2 can be determined by the regression analysis method [7]. Let

$$y = \ln\left[-\ln\left(\frac{\sigma}{E\varepsilon}\right)\right] \tag{2.9}$$

$$x = \sigma \tag{2.10}$$

$$b_1 = \sigma_{01}, \quad b_2 = \sigma_{02}, \quad b_3 = \beta_1, \quad b_4 = \beta_2 \tag{2.11}$$

Substitute Equation 2.9, 2.10 and 2.11 into Equation 2.8

$$y = \ln\left[\left(\frac{x}{b_1}\right)^{b_3} + \left(\frac{x}{b_2}\right)^{b_4}\right] \tag{2.12}$$

and

$$\mathrm{d}y = -\frac{b_3/b_1}{1+u_2/u_1}\mathrm{d}b_1 - \frac{b_4/b_2}{1+u_1/u_2}\mathrm{d}b_2 + \frac{\ln(x/b_1)}{1+u_2/u_1}\mathrm{d}b_3 + \frac{\ln(x/b_2)}{1+u_1/u_2}\mathrm{d}b_4 \tag{2.13}$$

where

$$u_1 = \left(\frac{x}{b_1}\right)^{b_3}, \quad u_2 = \left(\frac{x}{b_2}\right)^{b_4} \tag{2.14}$$

From experimental data, the value of module E can be estimated. Every bimodal Weibull plot curve can be regarded as combination of two straight lines, each of which provides initial values of b_1, b_2, b_3 and b_4. In Equation 2.13

$$\mathrm{d}y = y_\mathrm{a} - y_\mathrm{b} \tag{2.15}$$

where y_a is the result of Equation 2.9 while y_b is the result of Equation 2.12. Each curve contains hundreds of points, so the values of $\mathrm{d}b_i$ $(i = 1, 2, 3, 4)$ can be obtained from Equation 2.13 by using the least-squares method. The values of $b_i + \mathrm{d}b_i$ $(i = 1, 2, 3, 4)$ can be seen as initial values and the steps above mentioned can be iterated until $|\mathrm{d}b_i|$ $(i = 1, 2, 3, 4)$ are less than certain given small values.

3. Data analysis and discuss

The specimen are T300 fiber bundles and M40J fiber bundles. The specimen and its connection with bars is shown in Fig. 2. First the lining blocks (1) were glued on the supplement plate (2) perpendicularly, ten fiber bundles (3) were winded onto the lining blocks parallelly, and then glued to slots in the ends of input bar (4) and output bar (5) using high shear strength adhesive. The supplement plate was taken off before testing.

By controlling the height and the range of input pulse, three groups (corresponding to strain-rate of 100 s^{-1}, 500 s^{-1} and 1300 s^{-1}) of tensile impact test for T300 fiber bundles and M40J fiber bundles have been performed. In addition, the quasi-static tensile experiment have been performed on the Shimadzu-5000 testing apparatus for comparing with the above tensile impact

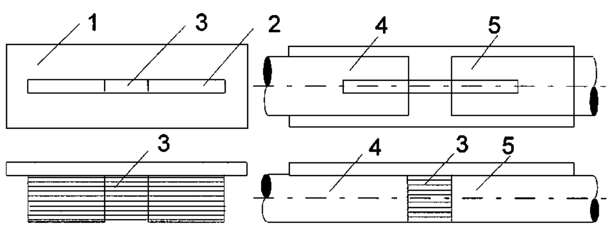

Figure 2 Specimen and its connecting.

results. The strain rate is 0.001 1/s. Figs 3 and 4 show the complete stress strain curves of M40J fiber bundles and T300 fiber bundles at different strain rate. The average experimental values and their maximum deviation at different strain rates are listed in Table I.

TABLE I Mechanical parameters of M40J and T300 at different strain rate

	$\dot{\varepsilon}(\mathrm{S}^{-1})$	E(GPa)	$\lvert\Delta E/E\rvert$	ε_b(%)	$\lvert\Delta\varepsilon_b/\varepsilon_b\rvert$	σ_b (GPa)	$\lvert\Delta\sigma_b/\sigma_b\rvert$
M40J	0.001	357.9	2.3%	1.26	4.1%	3.339	3.2%
	100	359.6	2.5%	1.28	2.2%	3.336	2.6%
	500	360.1	2.0%	1.29	2.3%	3.354	1.2%
	1300	359.1	2.1%	1.29	3.4%	3.347	2.6%
	average value	359.2	—	1.28	—	3.344	—
T300	0.001	223.2	4.5%	1.35	4.1%	2.387	3.6%
	100	227.4	3.7%	1.32	4.0%	2.415	3.2%
	500	223.5	3.4%	1.34	3.6%	2.404	2.8%
	1300	225.6	4.1%	1.34	3.7%	2.418	3.4%
	average value	224.9	—	1.34	—	2.406	—

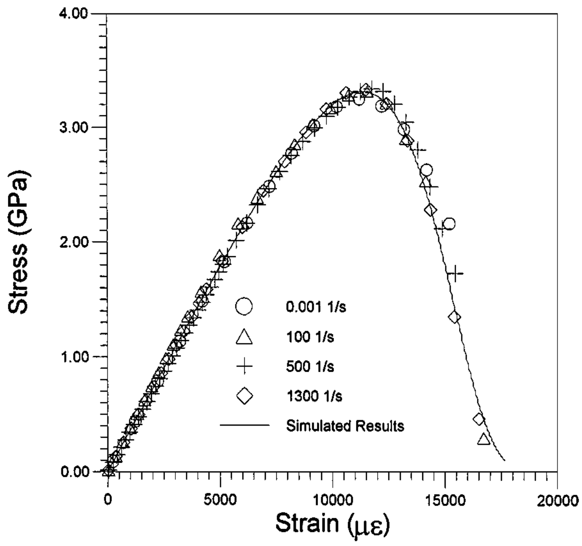

Figure 3 Stress strain curves of M40J fiber bundles at different strain rate.

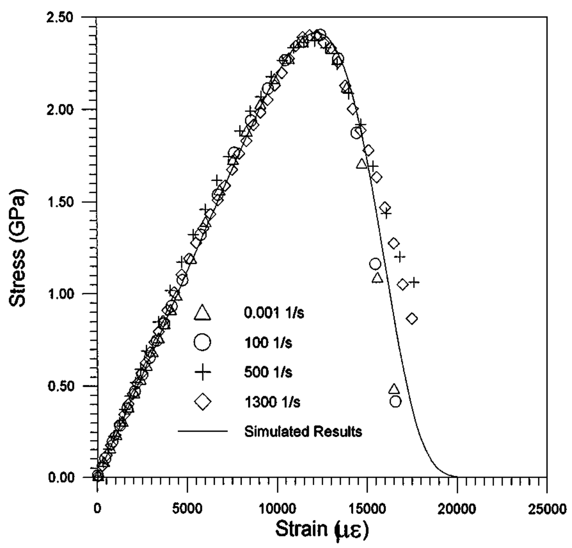

Figure 4 Stress strain curves of T300 fiber bundles at different strain rate.

From Figs 3 and 4, it can be observed that the stress strain curves of carbon fiber bundles at different strain rate are overlap. Fig. 5 shows the relationship between the strain rate and the ultimate strength of M40J, T300, E-glass and Kevlar49 fiber bundles. The data of E-glass and Kevlar49 fiber bundles are obtain from reference [4, 5]. It can be concluded that M40J and T300 are strain rate insensitive material.

On the basis of Equation 2.7, typical Weibull plots are drawn in Fig. 6. For the T300 fiber, the Weibull plots are linear. The fiber strength therefore obey the single Weibull distribution over the strain rate range of tests. The average value for single Weibull parameters are $\beta = 8.26$ and $\sigma_0 = 3.58$ GPa. For M40J fiber, the Weibull plots are nonlinear. The fiber strength therefore obey the bimodal Weibull distribution over the strain rate range of tests. The average value for bimodal Weibull parameters are $\beta_1 = 3.74$, $\sigma_1 = 6.45$ GPa, $\beta_2 = 10.4$ and $\sigma_2 = 5.62$ GPa. Solids in Figs 3, 4 and 6 are simulated results, which fit experimental points well.

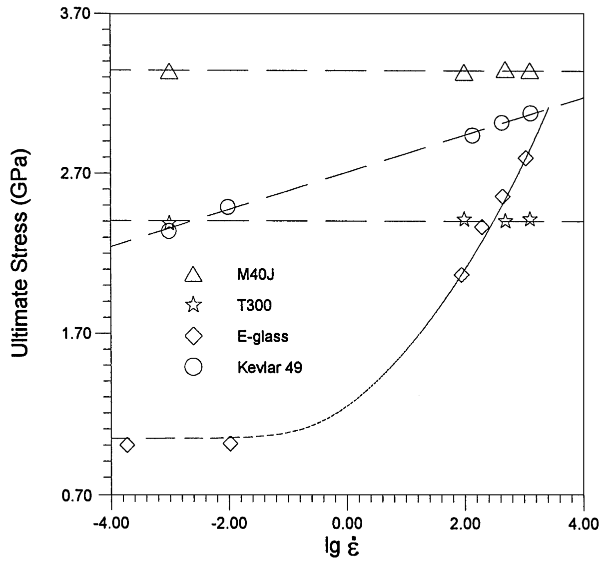

Figure 5 Effect of strain rate on ultimate strength of fiber bundles.

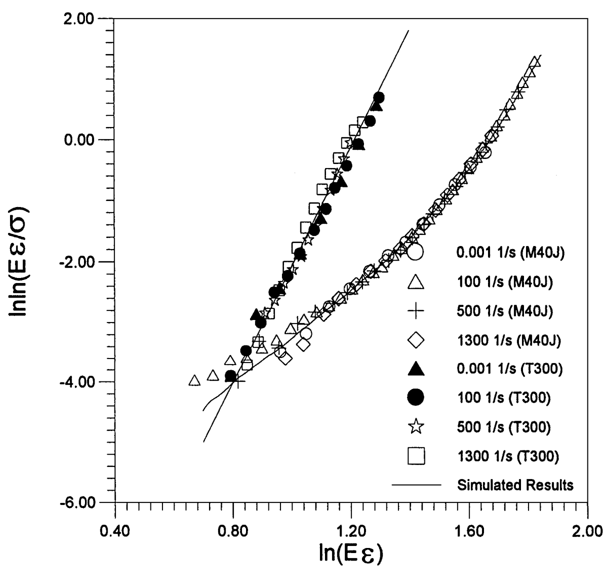

Figure 6 Weibull plots of carbon fiber bundles at different strain rate.

4. Conclusion

1. The single and bimodal Weibull distribution modal of fiber and fiber bundles are established in this paper. The simulated stress strain curves from modals are in good agreement with the test data. This shows that the testing method of determining the mechanical parameters relationship between fibers and fiber bundles are valid and feasible.

2. The tensile tests of T300 and M40J fiber bundles have performed in the strain rate range from 0.001 1/s to 1300 1/s. The experimental results exhibit that the strain rate have no effect on the initial elastic modulus, the ultimate strength and the failure strain of two materials. Both T300 fiber and M40J fiber can be regarded as strain rate insensitive material.

3. The Weibull plots of T300 fiber are linear, the strength of T300 fiber obey the single Weibull distribution. The Weibull plots of M40J fiber are nonlinear, the strength of M40J fiber obey the bimodal Weibull distribution.

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