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Effect of strain rate and temperature on the dynamic tensile properties of GFRP

ZONG HUANG, XU NIE, YUANMING XIA*
Department of Mechanical Engineering, University of Sci. & Tech. of China, Key Laboratory of Mechanical Behavior and Design of Materials, Hefei, Anhui 230027, People's Republic of China
E-mail: ymxia@ustc.edu.cn

Unidirectional fiber reinforced polymer composites are widely used in many fields. The fundamental understanding of the strain-rate effect on the mechanical properties of unidirectional fiber reinforced epoxy matrix composite laminate is particularly important to the engineering applications of composite materials resisting impact loading. Xia *et al.* [1] have investigated the dynamic tensile properties of unidirectional glass fiber reinforced polyester (GFRP) at room temperature systematically, but they did not report the temperature effect on GFRP under dynamic loading. Reference [2] indicates that the glass fiber bundles are strain rate and temperature dependent. So it is important to further investigate the dynamic response of GFRP at different temperatures. In the present paper, tensile tests on unidirectional GFRP are performed at different strain rates (300, 600 and 1100 s^{-1}) and temperatures (−20, 20, 60, and 100 °C). A bi-modal Weibull statistical constitutive equation is established to describe the temperature and strain rate dependence of this material.

The GFRP specimens used in the present work are made by glass fiber/epoxy prepreg, which is produced by ShangHai YaoHua Glass Works. Dynamic tensile experiments were performed on a self-designed Bar–Bar Tensile Impact apparatus with a high speed rotating disk [3]. Different temperatures in the experiment are acquired with an environmental chamber [4, 5]. The experimental method and the specimen are the same with reference [1]. The experimental results are shown in Fig. 1 and Table I. It shows that (1) under the same strain rate, with increasing temperature, the initial modulus of GFRP decreases linearly (Fig. 2a), and the strength also decreases. These exhibit a temperature softening characteristic. (2) At the same temperature, with increasing strain rate, the initial modulus of GFRP increases linearly (Fig. 2b), and the strength also increases. These exhibit a strain-rate strengthening characteristic. (3) The unstable strain increases with both increasing strain rate and temperature, which shows that GFRP is high-temperature and high-velocity ductile [6] under tensile impact loading. (4) Due to the time–temperature superposition of GFRP, the changing tendency of its modulus and strength with increasing strain rate is equivalent to that of its modulus and strength with decreasing temperature.

A modified strain-rate-dependent coated-fiber-bundle model was proposed in [7]. In this paper, based on the experimental results, we extend it to the case of both rate and temperature dependence. The one-dimensional bi-modal Weibull statistical constitutive equation is used in the present work:

$$\sigma = E\varepsilon \exp\lfloor -(E\varepsilon/\sigma_{01})^{\beta_1} - (E\varepsilon/\sigma_{02})^{\beta_2} \rfloor. \quad (1)$$

Here $\sigma_{01,}\sigma_{02}$, β_1, β_2, and E are functions of temperature and strain rate. Using $\ln(E\varepsilon)$ as abscissa, $\ln(-\ln\frac{\sigma}{E\varepsilon})$ as ordinate, the Weibull plot can be obtained based on the experimental results. The Weibull distribution plots of GFRP are shown in Fig. 3a–d. The four parameters $\sigma_{01,}\sigma_{02}$, β_1, and β_2 of the constitutive equation can be determined by the regression analysis method [2] with the Weibull plot. Their values are listed in Table II. From this table, we can see that (1) the shape parameters β_1 and β_2 change little under different strain rates and temperatures. Considering β_1 and β_2 stand for the strength dispersion of GFRP, the average values of β_1 and β_2 ($\bar{\beta}_1 = 1.31$, $\bar{\beta}_2 = 19.98$) are used in different strain rate and temperature states. (2) The scale parameters σ_{01} and σ_{02} are rate and temperature dependent. At the same temperature, these two parameters increase with increasing strain rate, while in the same strain rate, they decrease with increasing temperature. From Fig. 2 and Table II, the parameters σ_{01}, σ_{02}, and E in Equation 1 can be written as follows:

$$\begin{cases} \sigma = E\varepsilon \exp[-(E\varepsilon/\sigma_{01})^{\beta_1} - (E\varepsilon/\sigma_{02})^{\beta_2}] & (1) \\ E = E_0 + \lambda_1 \lg \dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_0} + \alpha_1(T - T_0) & (2) \\ \sigma_{01} = \left(\sigma_{01}^0 + k_1 \lg \dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)[1 + \theta_1(T - T_0)] & (3) \\ \sigma_{02} = \left(\sigma_{02}^0 + k_2 \lg \dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)[1 + \theta_2(T - T_0)]. & (4) \end{cases}$$

Equations 2, 3, 4 and 1 form the one-dimensional strain-rate- and temperature-dependent constitutive equation of GFRP. Take 300^{-1} and 20 °C as the reference state, $\bar{\beta}_1 = 1.31$, $\bar{\beta}_2 = 19.98$ as the average values of β_1, β_2. λ_1, α_1 can be obtained by the least-squares method while k_1, k_2, θ_1, and θ_2 can be obtained by the nonlinear regression analysis. The values of these parameters are

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*Author to whom all correspondence should be addressed.

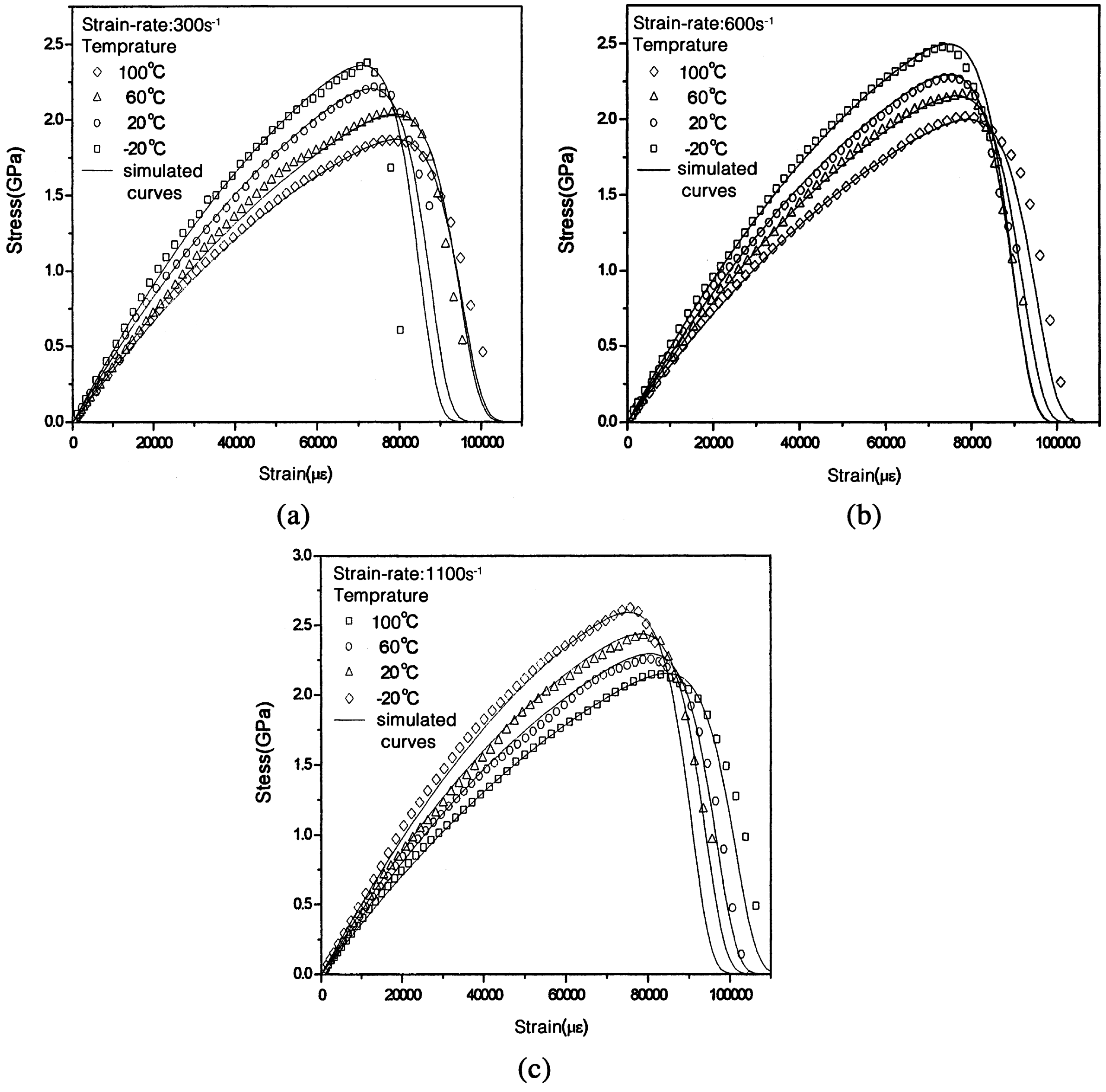
0022–2461

TABLE I The mechanical properties of GFRP at different strain rates and temperatures

	Temp (°C)											
	−20			20			60			100		
Rate (s^{-1})	300	600	1100	300	600	1100	300	600	1100	300	600	1100
$\bar{E}$ (Gpa)	48.7	50.3	51.9	44.3	45.5	47.4	37.9	39.4	41.5	34.9	36.9	38.1
$\Delta E\sqrt{E}$ (±%)	1.6	1.8	1.5	1.7	1.9	1.8	1.9	2.0	1.7	1.5	1.5	1.7
$\bar{\sigma}_b$ (GPa)	2.38	2.49	2.63	2.21	2.31	2.43	2.05	2.17	2.29	1.88	2.01	2.12
$\Delta\sigma_b\sqrt{\sigma_b}$ (±%)	3.8	4.1	3.6	2.9	3.1	2.4	3.3	4.0	3.7	2.9	3.4	3.2
ε_b (%)	7.27	7.41	7.63	7.44	7.56	7.85	7.64	7.82	8.13	7.83	7.92	8.33
$\Delta\varepsilon_b\sqrt{\varepsilon_b}$ (±%)	3.2	2.5	2.9	2.6	2.3	3.0	3.4	3.8	3.1	2.7	2.9	2.4

TABLE II Bi-modal Weibull parameter for GFRP

	Temp (°C)											
	−20			20			60			100		
Rate (s^{-1})	300	600	1100	300	600	1100	300	600	1100	300	600	1100
β_1	1.31	1.31	1.29	1.33	1.29	1.30	1.32	1.31	1.32	1.30	1.31	1.31
β_2	19.95	20.09	20.14	20.00	19.88	19.94	20.05	20.07	19.90	19.83	19.92	19.95
σ_{01} (GPa)	7.60	7.85	8.00	7.07	7.30	7.55	6.58	6.80	7.00	6.10	6.28	6.50
σ_{02} (GPa)	4.15	4.49	4.75	3.89	4.16	4.45	3.62	3.87	4.14	3.38	3.60	3.79



(a)

(b)

(c)

Figure 1 Stress–strain curves of GFRP at indicated strain rates and initial temperatures: (a) at strain rate 300 s^{-1}, (b) at strain rate 600 s^{-1}, and (c) at strain rate 1100 s^{-1}.

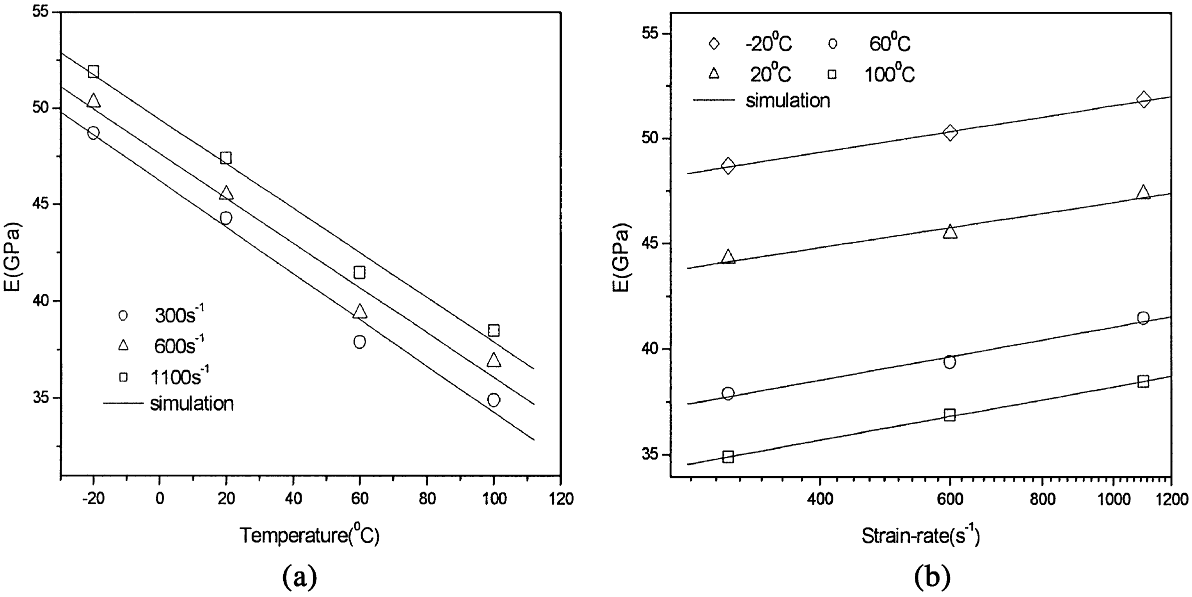


Figure 2 (a) The relations between initial modulus and temperature. (b) The relations between initial modulus and strain rate.

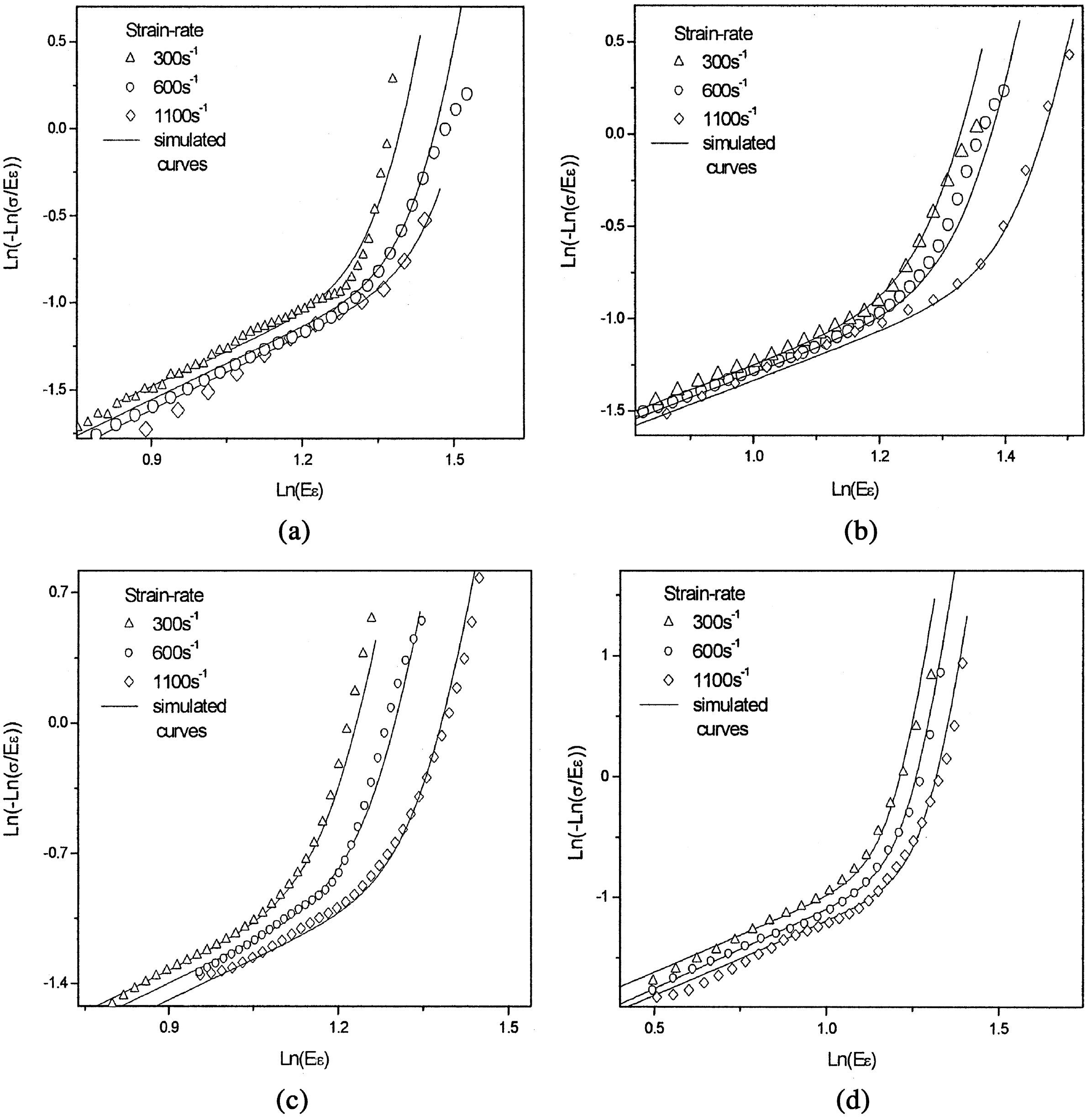


Figure 3 Weibull plots of GFRP at different temperatures: (a) at −20 °C, (b) at 20 °C, (c) at 60 °C, and (d) at 100 °C.

$\lambda_1 = 5.79$ GPa, $\alpha_1 = -1.18 \times 10^{-1}$ (Gpa/°C), $k_1 = 0.3293$ GPa, $k_2 = 0.4020$ GPa, $\theta_1 = -1.729 \times 10^{-3}$ (1/°C), $\theta_2 = -1.749 \times 10^{-3}$ (1/°C).

The simulated curves by Equation 1 are also plotted in Fig. 1, and it can be seen that the theoretical curves coincide with the experimental results well. This indicates that the modified coated-fiber-bundle model can be extended to the rate- and temperature-dependent case, and the bi-modal Weibull statistical constitutive equation is effective in describing the stress–strain relations of GFRP under different strain rates and temperatures.

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