



# Creep rupture of a GFRP composite at elevated temperatures

Piyush K. Dutta<sup>a</sup>, David Hui<sup>b,\*</sup>

<sup>a</sup>*US Army Cold Regions Research and Engineering Laboratory, Hanover, NH 03755, USA*

<sup>b</sup>*University of New Orleans, New Orleans, LA 70148, USA*

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## Abstract

A study of the tension and compression behavior of glass-fiber reinforced polyester composite material under sustained loads and elevated temperature is presented. Time-dependent thermal deformation and failure stresses were measured at three different temperatures ( $T = 25, 50, \text{ and } 80^\circ\text{C}$ ). Using curve-fitting equations a simple empirical model was developed to predict the time-to-failure. The model takes into account superposition of time-temperature effects. Creep curves predicted by this model are similar to those reported in literature. © 2000 Published by Elsevier Science Ltd. All rights reserved.

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## 1. Introduction

Over past years, research on creep characteristics of fiber reinforced polymers has resulted in better understanding of their structural behavior at elevated temperatures. Knowledge of the elevated temperature durability of composite material structures such as beams, columns, and decks is essential for assessing conditions for survival time under fire, especially in case of an on-board fire of a ship, or a fire in facilities constructed by using fiber reinforced polymer (FRP). Basically, the heat resistance of an FRP composite is a question of time, stress, and temperature. Short or long-term deformation data, with or without stress, are available in composite literature [1–4]; however, predictions of time-dependent thermal deformations made by some of these studies do not show quite good agreement with the experimental result [5]. Creep in an anisotropic and multi-phase material like FRP composite

is much more complex than the creep in homogeneous metallic materials is, where thermodynamic principles to characterize molecular motions resulting in creep deformation can be deduced with relative ease.

In composite materials, initial attentions were focused on creeps under simple stress conditions, for example tensile creep [6–9]. Others studied creep under long-term interlaminar shear [10,11]. The power law approach to modeling the creep in plastics and FRP is primarily due to Findley [12,13]. Numerous other work have also been reported in literature to develop the fundamental understanding of the creep processes in composites and the final attempts to model them. These include addressing the visco-elastic and visco-plastic behavior of polymer composites. In this regard, Schapery's nonlinear-viscoelastic theory based on the fundamental principles of irreversible thermodynamics has been used extensively by some researchers [14,15].

The present study aims to develop, by simple laboratory tests, just a few engineering constants as material parameters that can allow, through a model, a prior assessment of heat durability of these materials. In in-

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\* Corresponding author.

frastructure, and in many other civil engineering applications of FRP structures, a fire situation may cause a very rapid rise of temperature, and consequently strength degradation and final collapse. Thus, a predictability of life under a rapidly rising temperature is extremely important for the FRP structural designers. In naval applications, in order to address the fire issues, two guiding criteria for application of composites have been established [19]. They are: (1) the composites system will not be a fire source, and (2) the ignition of the composite system will be delayed until the crew can respond to the primary source of fire. The last requirement highlights the critical issue that strength of composites must be maintained at elevated temperature at least for a period of 30–60 min.

In this paper time-dependent mechanical properties of glass-fiber/polyester have been discussed on the basis of the results from time-dependent thermal deformation tests, and the predictions of time-to-failure (TTF) have been developed by the analysis of the curve fitting equations.

## 2. Modeling

### 2.1. Time–temperature superposition model

In general, polymers are subjected to both time, and temperature dependent deformation. Thus, it generally presents a problem to predict their behavior when both time and temperature have changed significantly. An isothermal creep curve can be developed much more easily by performing a simple creep test at constant load and at constant temperature while recording the strain. However, if the temperatures change during the test, we will see two effects: first, the effect of temperature as change in strain, and second, the effect of creep as additional strain. Attempts have been made in the past to express both changes by what is called “Time–temperature superposition model”. We will discuss this model by first taking a general approach to approximate the behavior as its initial elastic modulus  $E(t, T_0)$  at a time  $t$ , and temperature  $T_0$ , to its later modulus  $E(t_1, T_1)$  at a time  $t_1$ , and temperature  $T_1$  by the following equation:

$$E(t, T_0) = \frac{\rho_1 T_1}{\rho_0 T_0} E(t_1, T_1) \quad (1)$$

where  $\rho_1$  and  $\rho_0$  are the densities of the polymer at temperatures  $T_1$  and  $T_0$ , respectively.

It should be noted that usually at room and lower range of temperatures over a short period of time (say 15 min to 1 h) the time dependent creep strain is extremely small, and the strain effect is primarily due to temperature. The method of drawing the time–tem-

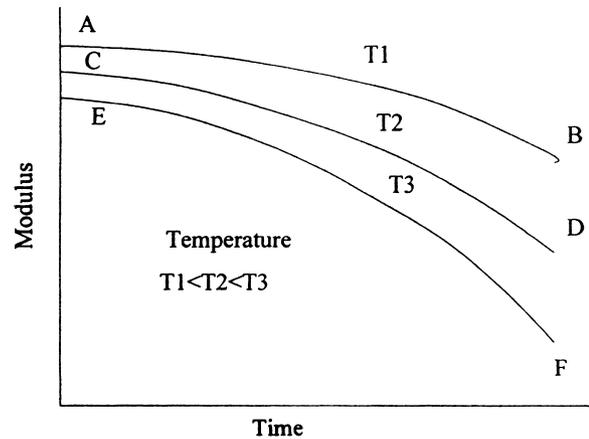


Fig. 1. Short-term creep data as change of modulus at various temperatures.

perature superposition curve involves first, performing a number of short-term (15 min–1 h) tests on creep deformation at various temperatures, Fig. 1. And then plotting these curves along the time scale as modulus versus time, by matching the tail end of each curve to the beginning of the next curve as shown in Fig. 2. When the amounts of time shift needed for each temperature for this plot (e.g.  $\Delta T_1$  and  $\Delta T_2$  in Fig. 2), are plotted against the test temperatures ( $T$ ), one can obtain the shift factor plot. The shift factor plot essentially transforms the effects of temperature on the time scale. Thus, by knowing the shift factor for a given temperature one can predict the creep deformation of a polymer over time for a given temperature. However, although this approach has remained popular in research communities, in practical engineering applications of composites a still simpler method is desired.

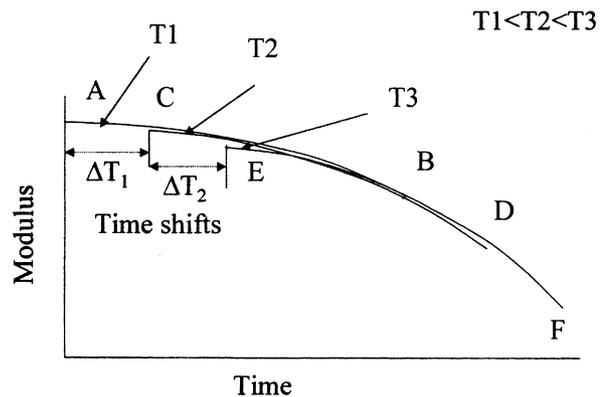


Fig. 2. Time–temperature superposition curve drawn from the data in Fig. 1.

2.2. Constitutive modeling

Predictive equation of creep deformation of a polymer or a polymer matrix composite by considering the nonlinear-viscoelastic constitutive equation parameters was developed by Schapery [14–16] and further reviewed and confirmed by others [17,18]. For an applied stress  $\sigma_0$ , the creep strain for uniaxial loading at a constant temperature is given by

$$\varepsilon(t) = \left[ g_0 D_{(0)} + c \frac{g_1 g_2 t^n}{a_\sigma^n} \right] \sigma_0 \tag{2}$$

where  $D_{(0)}$  is the initial compliance;  $g_0, g_1, g_2, a_\sigma$  are stress-dependent constants; and  $C, n$  are stress-independent constants.

At low stress levels,  $g_0, g_1, g_2,$  and  $a_\sigma$  are equal to unity, so that Eq. (1) change to

$$\varepsilon(t) = [g_0 D_{(0)} + c t^n] \sigma_0 \tag{3}$$

At higher stress levels  $g_0, g_1, g_2,$  and  $a_\sigma$  are not equal to zero, and requires creep and creep recovery tests to determine these constants by some curve fitting techniques using graphical or computational methods [1,17].

3. Experimental tests

A series of coupon level tension and compression tests were performed using glass/polyester FRP plates of nominal 0.25 in thick specimens. The test specimens were cut in shapes and sizes following the ASTM standards noted in Table 1, which gives the test matrix.

The specimens were first tested for determining their mechanical properties,  $E$  (Elastic modulus),  $\nu$  (Poisson’s ratio),  $\sigma_u$  (ultimate strength), and  $\varepsilon_f$  (strain at failure) at room temperature (25°C). And then tested under sustained loads in the range of 60–80% of ultimate load for determining TTF ( $t_f$ ) at three different temperatures (25, 50, and 80°C).

The test arrangement included an MTS testing machine with an well-insulated environmental chamber

around the loading fixtures. Applied loads were sustained by adjusting the controller of the MTS testing system, and were monitored by a data logging system. A hot air blowing system with thermostat control maintained the temperature inside the chamber. The temperature of the test specimen was monitored by a thermocouple. The compression tests were performed according to ASTM D-3410 using the Wyoming compression testing apparatus for holding the specimens. Tension test was done according to ASTM D-638 method. Wedge grips were used for the tension tests. Each specimen was strain gauged on both sides to monitor the strain and their average was taken as the specimen strain.

4. Test results

The room temperature (25°C) stress–strain data for compression tests are given in Fig. 3, and for tension tests in Fig. 4. For each test both longitudinal and transverse strains were recorded from which Poisson’s ratios were measured. The stress–strain relations in both compression and tension are only approximately linear with stiffness degrading at higher loads. The failures were semi-brittle. The average failure strength at 25°C in compression was 304.4 MPa (44,131 psi) in compression, and 271.5 MPa (39,374 psi) in tension.

The duration of sustained load applied in the range of 60–80% of room temperature failure load was measured in each test. At 25°C the specimens continued to strain under creep load for longer than 30 min when the tests were usually terminated, but at 50 and 80°C temperature tests were continued until the specimens failed. In some tests the applied load was increased to a new higher level, and then kept constant until the specimen failed. The time dependent increases in strain (creep) values were recorded. Typical result of a compression creep test at 25°C is shown in Fig. 5, where the specimen subjected to a constant compressive stress of 188 MPa (27,233 psi) did not fail over a period of 28 min. However, when the same stress of 188 MPa (27,233 psi) was applied at 50°C, as shown in

Table 1  
Test matrix for the elevated temperature creep tests

Type of test	Test conditions	Parameters measured
Compression ASTM D-3410	25°C	$\sigma_u, \varepsilon_f, \nu, E$
Compression creep	25°C, 50°C, 80°C	$t_f$
Tension ASTM D-638	25°C	$\sigma_u, \varepsilon_f, \nu, E$
Tension creep	25°C, 50°C, 80°C	$t_f$

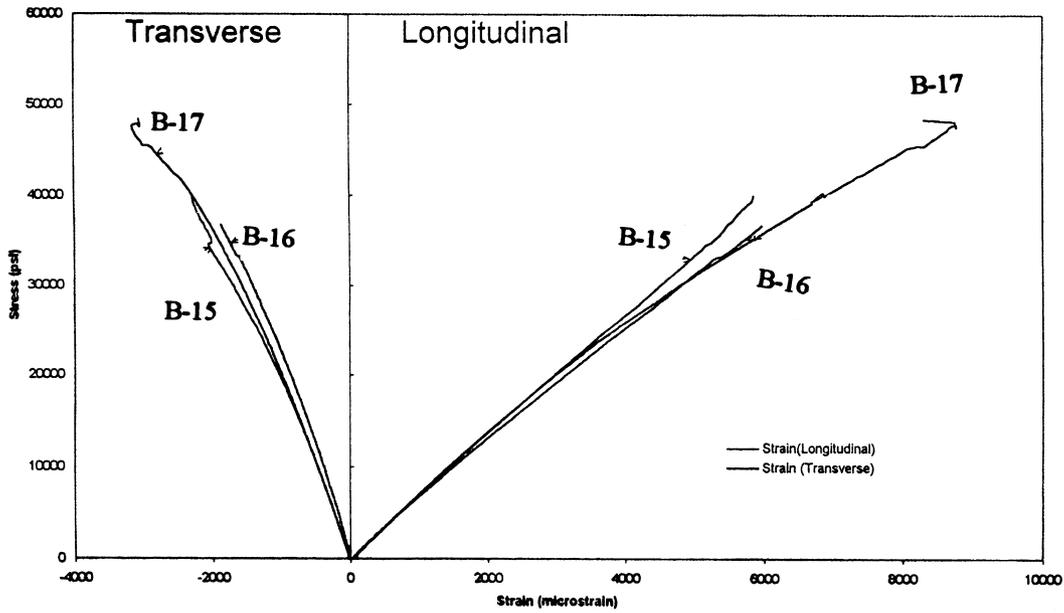


Fig. 3. Room temperature (25°C) data from compression tests to failure.

Fig. 6, the specimen failed within 18 min of the applied stress. And within approximately same load range, i.e. at 209 MPa (30,352 psi) at 80°C the specimen failed within 12.5 min, as shown in Fig. 7.

The tension test series also showed the similar results as above. Fig. 8 shows that at 25°C the failure did not occur within 30 min when the load level was 198 MPa (28,733 psi). But at 50°C, failure occurred within 30

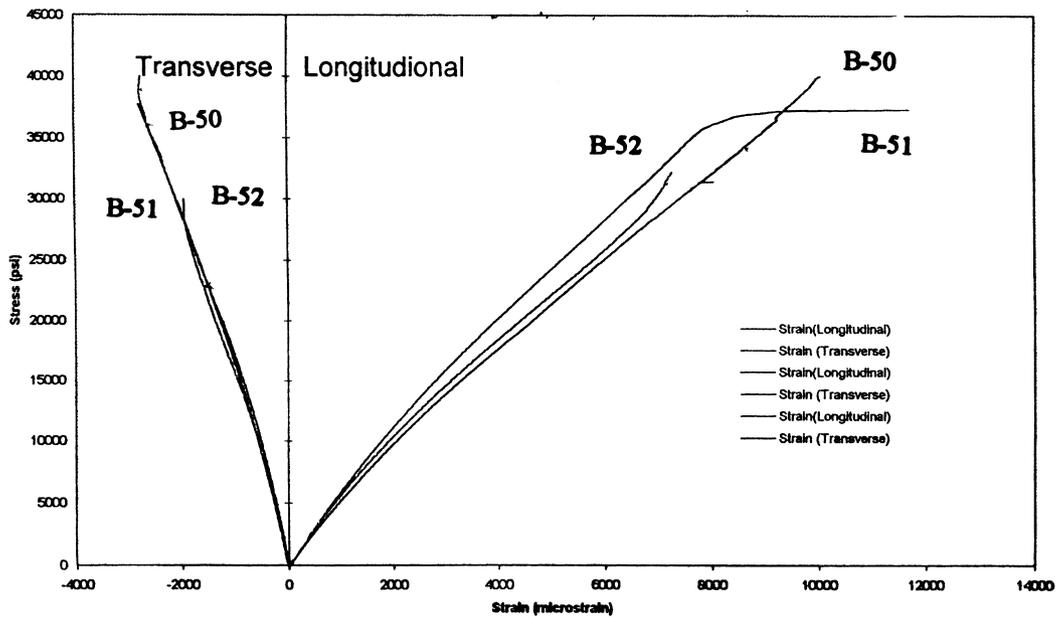


Fig. 4. Room temperature (25°C) data from tension tests to failure.

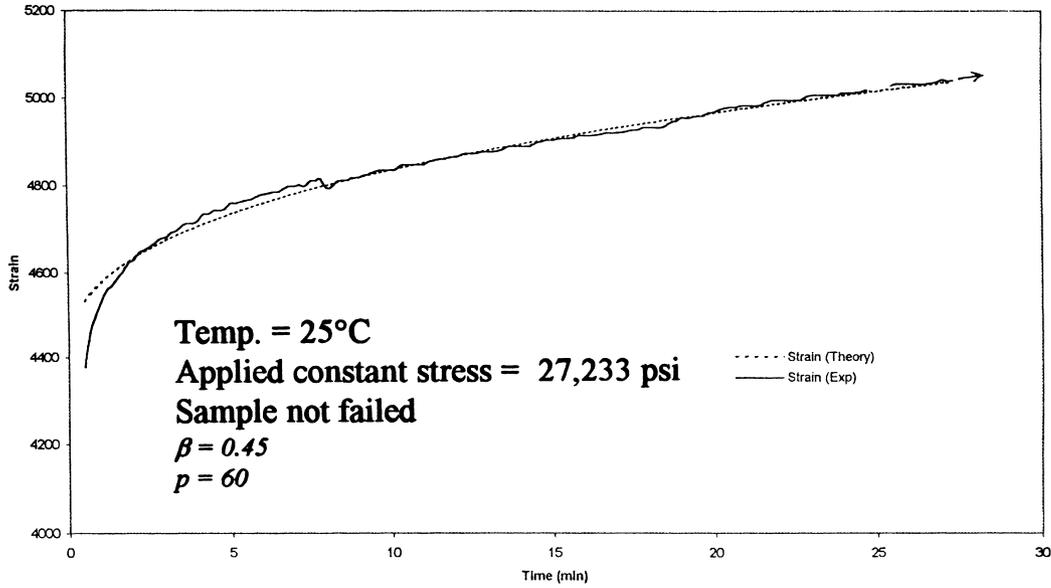


Fig. 5. Data from a typical compression creep test at 25°C.

min at the same range of sustained load. Fig. 9 gives an example of such failure at 180 MPa (26,086 psi) sustained load, and Fig. 10 gives the example for 80°C with a much lower level sustained load of 150 MPa (21,739 psi).

### 5. Discussions

The sustained load duration until failure varied over a wide range. For example, at room tempera-

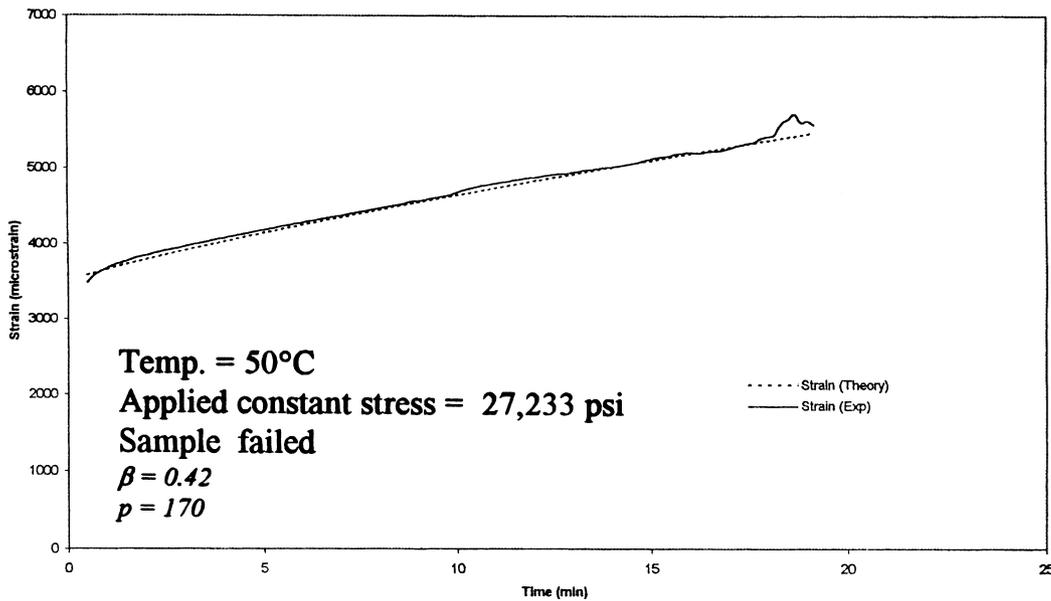


Fig. 6. Data from a typical compression creep test at 50°C.

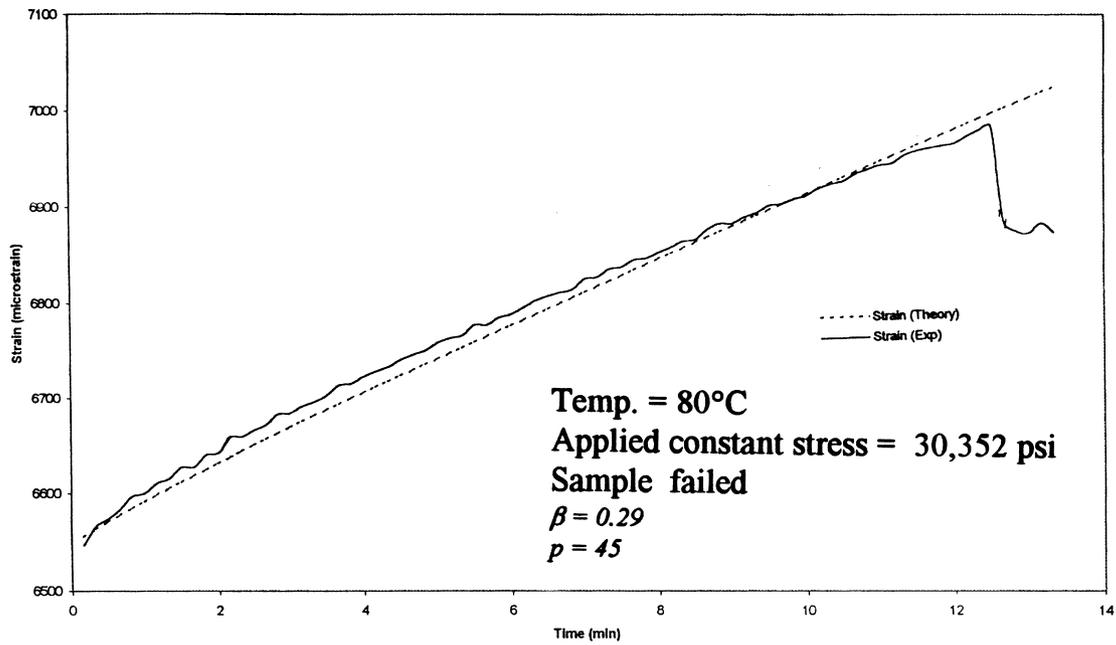


Fig. 7. Data from a typical compression creep test at 80°C.

ture the specimens continued to strain under creep load indefinitely, whereas at 50 and 80°C failure occurred mostly within an hour after the maximum 80% of  $\sigma_u$  was obtained.

FRP creep is influenced by factors like fiber volume and matrix volume fractions, temperature, humidity, age of FRP at loading and stress levels, etc. Many empirical relations based on actual tests

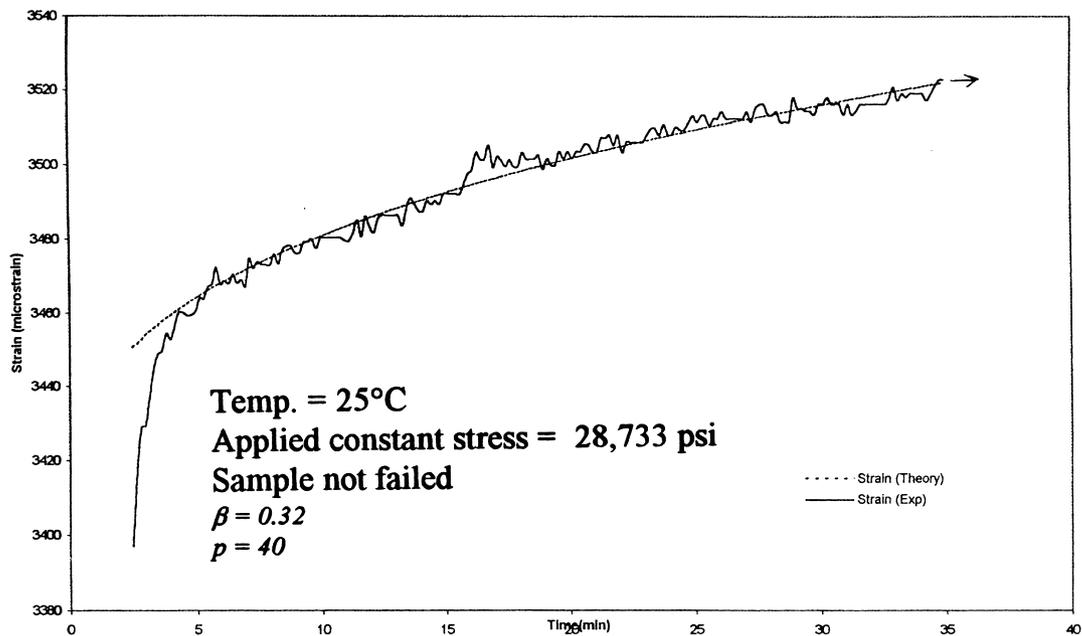


Fig. 8. Data from a typical tension creep test at 25°C.

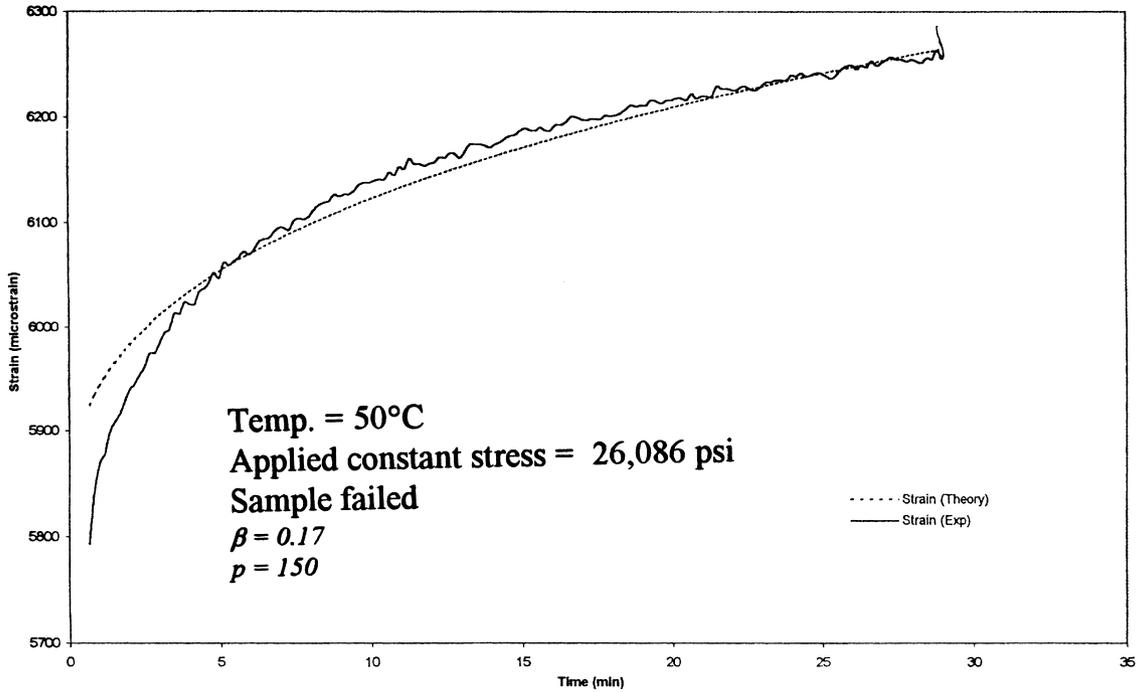


Fig. 9. Data from a typical tension creep test at 50°C.

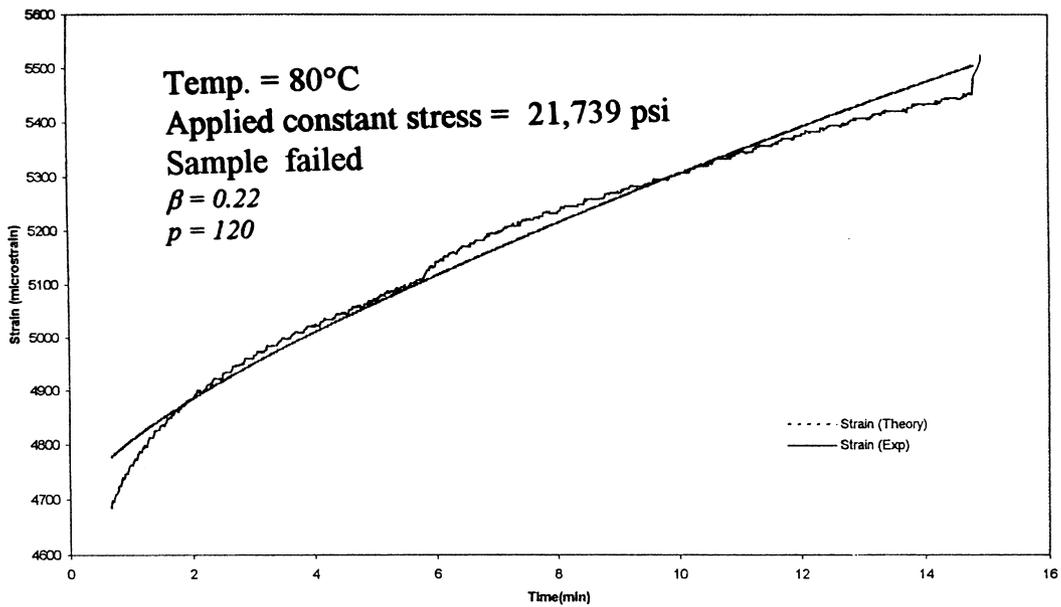


Fig. 10. Data from a typical tension creep test at 80°C.

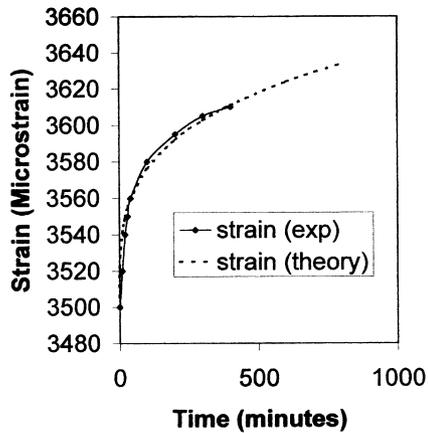


Fig. 11. Data from Ref. [20] superimposed on the predictable curve.

are available for the prediction of creep coefficients for a given duration of loading.

A curve fitting equation was developed to characterize the creep curves obtained from the test data. This equation follows the well-known Findley's equation except that the two creep constants of Findley's equation are now replaced with functions of time ratios and temperature ratios. The semi-empirical equation is given below.

$$\varepsilon(t) = \left[ \varepsilon_0 + p \left( \frac{t}{t_0} \right)^{\beta(T/T_0)} \right] \quad (4)$$

As opposed to four constants of Eq. (2), there are now only two constants,  $p$  and  $\beta$ , in Eq. (4). The linear coefficient  $p$  for time ratio ( $t/t_0$ ) directly relates to the strain with time, whereas coefficient  $\beta$  modifies the slope of the creep curve by relating the slope to the temperature ratio ( $T/T_0$ ). This relationship matches very well to many published creep curves. As an example, in Fig. 11, one of the experimental curves obtained by Pasricha (a coworker of Tuttle) for [90]<sub>16</sub> IM7/5260 composite is shown by solid line and the predicted curve from Eq. (4) by the dotted line.

## 6. Comparison with experimental data

To use the above equation, the initial parameters, for example the initial strain,  $\varepsilon_0$  at time  $t_0$ , need to be arbitrarily fixed. In analyzing our creep data, we have considered the initial strain  $\varepsilon_0$  after 1 min of the start of the tests and determined the creep constant parameters,  $p$  and  $\beta$ . Using these parameters, the theoretical curves were drawn as dotted lines on each experimental curves from Fig. 5–10 showing that the

creep curves can be represented well using the Eq. (4). The values of  $p$  and  $\beta$  will vary with the initial stress level, temperature, and of course the material constituents. By running systematic tests for each material, values of time constant  $p$ , and temperature constant  $\beta$ , can be generated, and thus, the strain–time–temperature curve predicted. Also, using the maximum strain criteria, the TTF ( $t_f$ ) too under different temperatures can be predicted by this model.

## 7. Conclusions

An attempt has been made to generate a procedure for accelerated characterization of composite material at higher temperatures. A simple engineering approach to model this behavior using only two material constants has been proposed. The essence of classical visco-elastic and visco-plastic behavior that dominates the composite behavior at higher temperatures has been kept intact. The proposed equation is similar in nature to Findley's power law equation for creep; only the coefficients of his equations have now been replaced with expressions involving time and temperature ratios. The new equation seems to satisfy the results obtained by other researchers as well. The cumbersome time–temperature superposition method, or more rigorous visco-elastic/visco-plastic Schapery–Tuttle Eq. (2) provides more accurate characterization, but for engineering characterization of the composites at higher temperature the proposed method is simpler.

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