CREEP BEHAVIOUR OF GRAPHITE-EPOXY COMPOSITES: TEMPERATURE AND MOISTURE EFFECTS

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ABSTRACT

Experimental and analytical results are presented for the individual and coupled effects of temperature and absorbed moisture on the creep compliance of unidirectional, cross-plied and angle-plied laminates of carbon/epoxy composites. The mathematical model describes the composite behaviour starting from the matrix one that is supposed to follow a general creep equation of the form $\varepsilon = A\sigma^m t^n$. The value of the coefficients A, m, n have been obtained from tests on an epoxy-resin type "Epikote 828" using dry and moisture-saturated at 100% relative humidity specimens.

KEYWORDS

Composite materials, laminates, epoxy laminates, creep properties, moisture, swelling.

INTRODUCTION

In the field of composite materials creep studies need further investigation: in fact internal stress in Gr/Ep can be observed when creeping, plastic deformation or microcraks in the resin are allowed.
Some mathematical analyses of creep phenomenon for metallic composites were developed by De Silva (1968), Kelly and Street (1972) and by Sorensen, Pederson, Liholt (1975). In this work a computational model, extending the application field of the De Silva's theory to plastic composites, is presented; the model takes into account different conditions of temperature and humidity.
Analytical creep curves have been fitted to the experimental tests obtained on specimens of Gr/Ep with different orientation and on epoxy-resin.

BASIC CONCEPTS

The external stress applied to the composite laminate is σ_c:

$$\sigma_c = E_f V_f \phi \varepsilon_c + E_m V_m \varepsilon_c , \tag{1}$$

where, for a fiber of length l, diameter d, having a uniform shear stress, the factor ϕ is:

$$\phi = 1 - \frac{d}{4\tau l} E_f \varepsilon_c . \tag{2}$$

The initial strain ε_{c0}, taking into account that $\tau = \sigma_m/2$ and $\sigma_m = E_m \varepsilon_{c0}$, is:

$$\varepsilon_{c0} = \frac{\sigma_c}{\left(1 - \frac{E_f d}{2E_m l}\right) E_f V_f + E_m V_m} . \tag{3}$$

It is supposed that the creep behaviour of the matrix follows the Bailey-Norton law:

$$\varepsilon_m = A\sigma^m t^n , \tag{4}$$

where ε_m is the creep strain and A, m, n are coefficients to be found experimentally. Temperature and moisture may change.

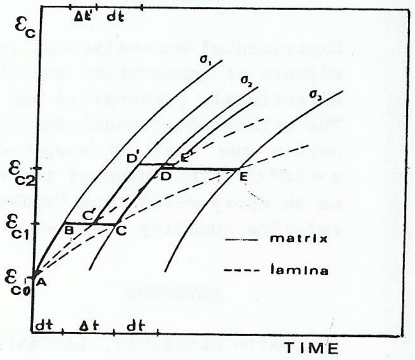

Fig. 1 – Schematic representation of the proposed model.

In Fig. 1 the creep diagram for a single layer is presented, for constant temperature and moisture, by the dashed line ACE. The interval AC can be approximately considered composed by AB and BC. During AB, which corresponds to the stress σ_1, the matrix areas near the fibers end follow the creep curve of the matrix corresponding to the stress σ_1. Then a relaxation interval BC follows, during which the value of the shear stress τ, between the matrix and the fibers, decreases of a quantity $d\tau$ where:

$$d\tau = \frac{d\varepsilon_c}{\dfrac{E_f^2 \varepsilon_c^2 V_f}{E_f V_f + (d\sigma_m/d\varepsilon_c) V_m - 2E_f^2 V_f \varepsilon_c K} \left(- \dfrac{d}{4\tau^2 l}\right)} \tag{5}$$

and

$$K = \frac{d}{4\tau l} .$$

By differentiating eq.(4), we obtain the expression of the interval time Δt of BC:

$$\Delta t = - \frac{m}{n} \frac{t + dt}{\sigma} 2 \, d\tau . \tag{6}$$

The process continues during the next intervals CD, DE and so on... If we have a temperature and moisture variation the creep diagram of a layer is the dashed line AC'E'. In fact when the temperature and moisture rise, in the interval time where the matrix areas, near the fibers end, lenghten for the creep, all the others matrix areas lenghten by a value corresponding to the thermal and igrometric rising. Obviously the relaxation size is smaller than in the previous case, because it depends on the elongation difference between the matrix areas, near the fibers end, and all the other layer areas.
The average value of the layer elongation rises, and the increment can be expressed as:

$$d\varepsilon_c' = (\alpha_m r_m + \alpha_f r_f) \Delta T_{AB} + (\beta_m r_m + \beta_f r_f) \Delta H_{AB} \tag{7}$$

where α_m is the thermal expansion coefficient (C.T.E.), β_m the swelling of the matrix, $r_m = V_m E_m/(V_f E_f + V_m E_m)$ and ΔT_{AB}, ΔH_{AB} are respectively the temperature and moisture difference between A and B.
Eq.(5) then becomes:

$$d\tau = \frac{d\varepsilon_c - d\varepsilon_c'}{\dfrac{E_f^2 \varepsilon_c^2 V_f}{E_f V_f + (d\sigma_m/d\varepsilon_c) V_m - 2E_f^2 V_f \varepsilon_c K} \left(- \dfrac{d}{4\tau^2 l}\right)} . \tag{8}$$

As the relaxation value $d\tau$ is smaller than in the previous case, also the relaxation interval duration is smaller: the relaxation interval is, in this case, BC' (smaller than BC). The process continues in the next intervals C'D', D'E' and so on...
This theory is applied to the development program for the multicomposed layer laminates with different fibers orientation angle.

NUMERICAL MODEL

Let us consider the case of a laminate composed by two layers with fibers orientation like in Fig. 2; an external stress σ_x is applied to the laminate. For the antisymmetry there is not shear strain between the axes x and y and the external stress causes only an elongation with x and a shrinkage with y.
Two shear stresses equal and opposite, that the two layers exchange with each other, are necessary to set to zero the shear strain γ_{xy} between the axes x and y.
The external stress σ_c can be split up into a stress σ_f, along the fibers direction, into a σ_{fn} along their normal and a shear stress τ_{12} between the two perpendicular directions.

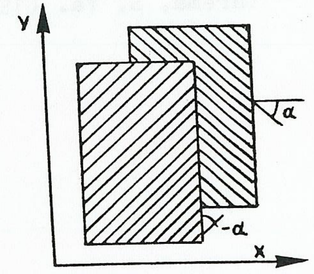

Fig. 2 – Composite laminate.

The elongation along the fibers, ε_f, is:

$$\varepsilon_f = A\sigma_f^m t^n + \varepsilon_{f0} . \tag{9}$$

The elongation ε_{fn} along the perpendicular direction to the fibers is:

$$\varepsilon_{fn} = A\sigma_{fn}^{m}\, t^{n} + \varepsilon_{fn0} \quad . \tag{10}$$

After the relaxation interval the shear strain γ_{12} must be such that the shear strain of the laminate $(+\alpha, -\alpha)$ is zero so that:

$$\gamma_{12} = ((\varepsilon_{fn} - \varepsilon_{f}) \sin\alpha \cos\alpha)/(\cos^2\alpha - \sin^2\alpha) \quad . \tag{11}$$

The shear strain γ_{12} follows the Bailey-Norton law:

$$\gamma_{12} = A_g\, \tau_{12}^{m}\, t^{n} + \frac{\tau_{12}}{G_{12}} \quad . \tag{12}$$

Differentiating the (12) we obtain:

$$d\tau_{12} = \frac{d\gamma_{12} - A_g\, \tau_{12}^{m}\, n t^{n-1}\, dt}{A_g\, t^{n}\, m\tau_{2}^{m-1} + 1/G_{12}} \quad , \tag{13}$$

from which it is possible to know τ_{12} at every step of the program. Subsequently the shear stress can be calculated by:

$$\tau_{xy} = (\sigma_f - \sigma_{fn}) \sin\alpha \cos\alpha + \tau_{12}(\cos^2\alpha - \sin^2\alpha) \quad . \tag{14}$$

The determination of the new values for σ_f and σ_{fn} is allowed by the knowledge of the new value of τ_{xy} and so on.....

In the case where there are more than a couple of layers, the shear strain γ_{xy} is always zero; it is necessary to determine the percentage of the total external stress that catches each couple.

At the beginning of the process we know σ_x and it is possible to determine σ_{fn}, σ_f and γ_{xy} ; if we have a temperature and moisture variation, we take into account the variation of the coefficients A, m, n of the Bailey-Norton law, of the thermal expansion coefficient α_m and of the swelling stress induced by sorbed moisture.

EXPERIMENTAL AND NUMERICAL RESULTS

The value of the coefficients A, m, n of Bailey-Norton law and the thermal expansion coefficient α_m of the matrix have been obtained from tests made in specimens of epoxy resins type "Epikote 828". In Fig. 3 the creep diagrams of the matrix at 25°C, are reported for dry and wet (immersed in distilled water for 2 days) conditions; in Fig. 4 the diagrams, at 70°C and 100°C, in dry conditions are presented.

The thermal expansion coefficients (C.T.E.) have been measured by electronic dilatometer (type push-rod) in the range of temperature −120°C ÷ +150°C on dry and wet specimens: the values of C.T.E. are reported in Fig. 5.

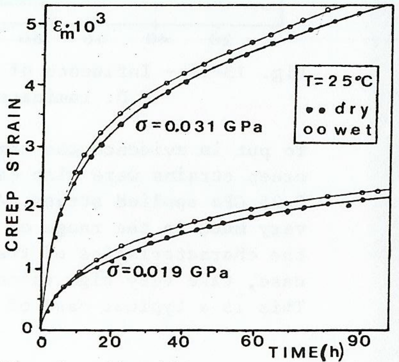

Fig. 3 – Tensile creep curve for epoxy resin in dry-wet conditions.

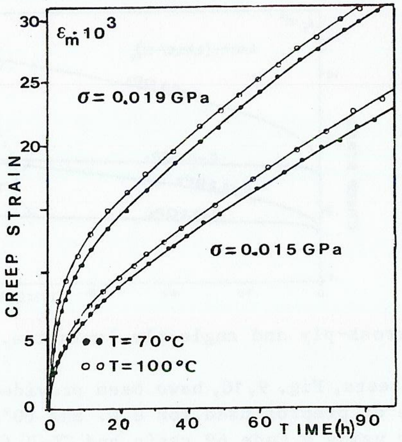

Fig. 4 – Tensile creep curve for epoxy resin at 70°C and 100°C.

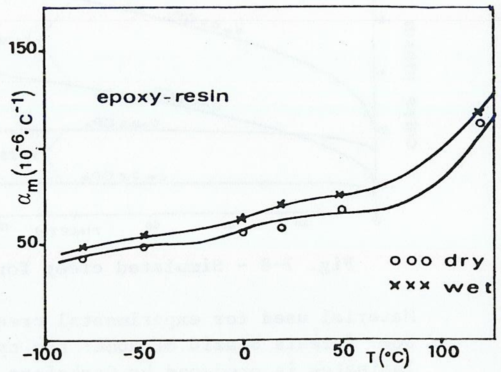

Fig. 5 – Experimental results of C.T.E. for the epoxy resin in dry and wet conditions.

From the experimental tests we have obtained the values, reported in Tab. I, used in the numerical simulation:

TABLE I – Material constants in general creep equation for "Epikote 828" epoxy-resin.

T	A		m		n	
(°C)	dry	wet	dry	wet	dry	wet
25	$1.58 \cdot 10^{-22}$	$1.89 \cdot 10^{-22}$	2.3	2.28	0.46	0.485
70	$5.8 \cdot 10^{-15}$	$5.8 \cdot 10^{-15}$	1.35	1.34	0.53	0.529
100	$2.41 \cdot 10^{-13}$	$2.41 \cdot 10^{-13}$	1.2	1.2	0.42	0.42

The numerical simulation has been done on Gr/Ep laminates with the stacking sequence: unidirectional (U.D.), $(0°/90°)_S$, $(0°/45°/0°/-45°)_S$ the same of the specimens used in experimental tests.

The families of creep curves are given in Figs. 6,7,8.

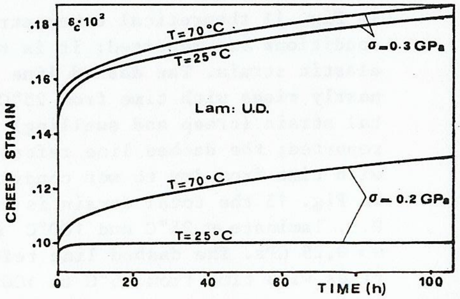

Fig. 6 – Simulated creep for U.D. laminate.

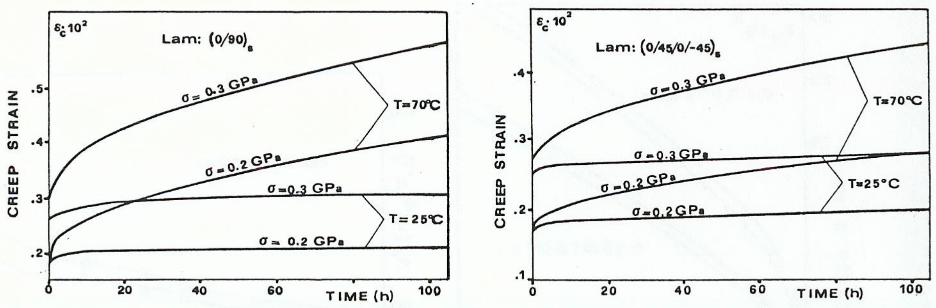

Fig. 7-8 - Simulated creep for cross-ply and angle-ply laminates.

Material used for experimental creep tests, Fig. 9, 10, have been provided by Soc. Selenia Spazio of Rome: the type of prepreg used for U.D. and $(0°/90°)_S$ laminates is produced by Carboform by using a Code 69 resin and GY-70 fibers; for $(0/45/0/-45)_S$ laminate the prepreg used is produced by Fiberite. The specimens have been cut with the 0° fibers direction parallel to the applied stress.

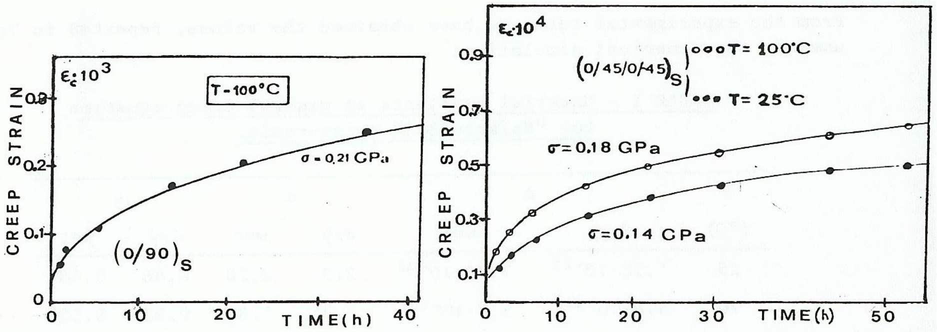

Fig. 9-10 - Experimental results for creep of $(0/90)_S$ and $(0/45/0/-45)_S$ laminates.

In order to analyze the temperature and moisture influence on the creep behaviour, some numerical simulations, on the matrix and unidirectional laminate, have been made.

In Fig. 11 theoretical creep strains for 0.015 GPa applied stress and in dry conditions are reported: it is token into account the thermal expansion and elastic strain. The dashed line refers to the case where the temperature linearly rises with time from 25°C to 100°C. In Fig. 12 the diagrams of the total strain (creep and swelling) respectively in dry and wet conditions are reported; the dashed line refers to the case where the moisture linearly rises with time from dry to wet conditions.

In Fig. 13 the total strain (creep and thermal expansion) for a U.D. laminate at 25°C and 100°C in dry conditions with an external stress σ = 0,25 GPa. The dashed line refers to the case where the temperature linearly rises with time from 25°C to 100°C.

Fig. 14 shows the total strain (creep and swelling) for a U.D. laminate at 25°C, with an external stress σ = 0.25 GPa, respectively in dry and wet conditions. The dashed line refers to the case when the moisture linearly rises versus the time from dry to wet conditions.

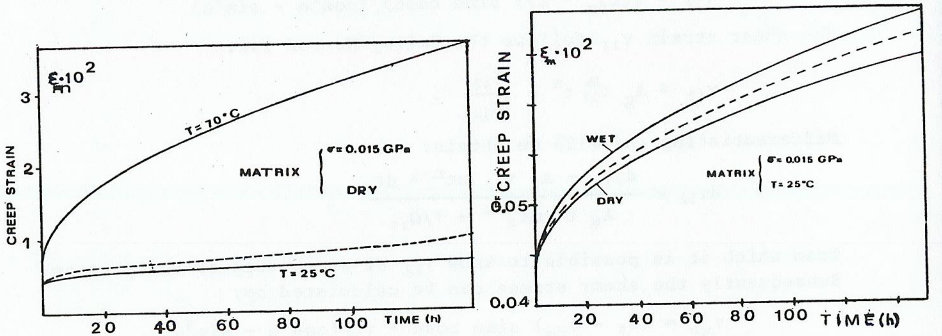

Fig. 11-12 - Influence of temperature and moisture on the creep behaviour of the matrix.

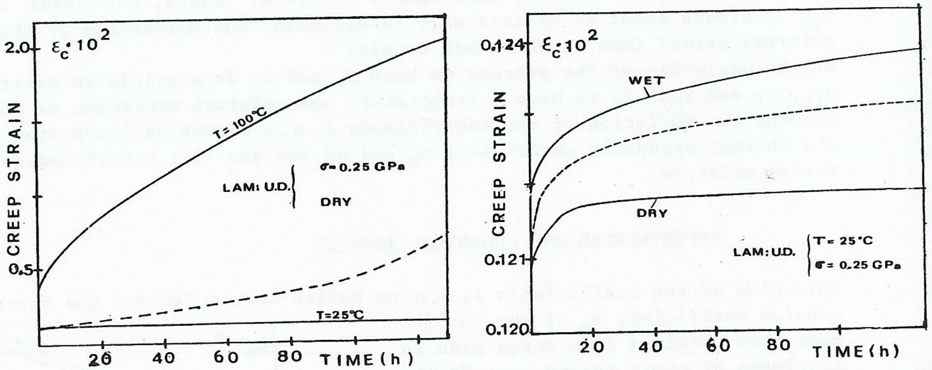

Fig. 13-14 - Influence of temperature and moisture on the creep behaviour of U.D. laminates.

To put in evidence the temperature influence on the creep fracture, theoretical creep strains were also calculated for 0-deg unidirectional laminates for 0.25 GPa applied stress. As we can see in Fig. 15 the fracture time decreases very much in the range of temperature 90-100°C: that is due essentially to the characteristics of the resin and particularly to the C.T.E. that, in our case, take very high values in the range of the over mentioned temperature. This is a typical case of debonding of the matrix from the fiber (Fig. 16).

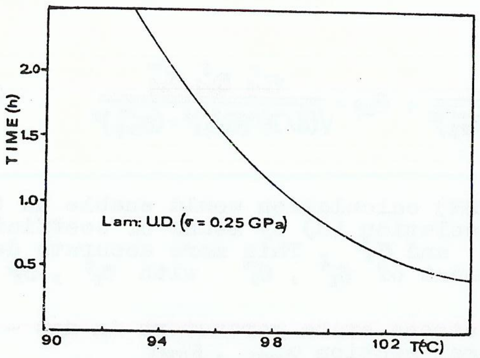

Fig. 15 - Influence of temperature on the fracture time of U.D. laminate.

Fig. 16 - SEM photograph of the fracture surface of U.D. laminate.

CONCLUSIONS

As we can see from the obtained results there is a certain influence of the thermal rising (about nearly 100°C) on the creep behaviour.
The creep strenght or the fracture time decreases (practically the laminate can't bear an external stress 2.5 GPa for more than an hour at 100°C). On the contrary the influence of the moisture is very poor, because the strain (due both to the creep phenomenon and to swelling) is not far from the corresponding value at equal temperature and dry conditions.

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