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On the influence of preloading in the nonlinear viscoelastic–viscoplastic response of carbon–epoxy composites

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ABSTRACT

On an ongoing research for the nonlinear viscoelastic response of composites and polymers, a study of the influence of preloading applied to composite laminates subjected to creep–recovery loading is performed. In cases where high stress levels are applied, this response becomes highly nonlinear and has to be taken into account when designing composite parts. A major problem encountered in the experimental investigation of the nonlinear viscoelastic behaviour is the mode of the initial applied loading and its effect in the overall viscoelastic response of the test sample. The damage that occurs due to the instantaneous application of the load leads to an additional viscoelastic/viscoplastic strain component. In order to investigate this effect as well as to compare different preloading modes, as far as viscoelastic/viscoplastic response is concerned, a test program was initiated and the experimental data were investigated in the current study. A preloading mode is applied in each specimen prior to the creep–recovery testing at different applied stress levels. Useful results concerning the effect of preloading in the time dependent response of the material are concluded. Variation of the values of viscoplastic strain in respect to the preloading mode is also of great concern.

1. Introduction

The long-term mechanical characterisation of fibre reinforced plastics has recently received much attention, as the use of these materials for manufacturing structural parts rapidly increases in a wide spectrum of engineering applications.

Early attempts for the description of the nonlinear viscoelastic response, led to the *Modified Superposition Principle* (MSP) which has been proposed by Leaderman [1] and has also been used by Findley and Kholsla [2]. A most common formulation quite applicable and simple in use was introduced by Schapery [3,4]. According to this model the nonlinearity is controlled by four parameters, g_0, g_1, g_2 and α_σ, which are stress and temperature dependent, reflecting the deviation from the linear viscoelastic response.

Lou and Schapery [5], proposed a mixed graphical and numerical technique for the estimation of these parameters using one step creep–recovery experiments. Schapery's formulation has been used from various researchers [6–9] for the description of the viscoelastic response of many polymeric systems. It has also been proved adequate for describing complex loading histories [10,11]. Moreover Schapery's constitutive equation is convenient for use in 3D numerical analysis with implementation of recursive algorithms [12,13].

In a previous work [14] the authors developed a new methodology where Schapery's nonlinear parameters were separately determined from simple step creep–recovery curves.

In the present work an investigation of the influence of the initial applied loading i.e. preloading, in the overall viscoelastic response of the test samples is attempted. The impact of the mode of the applied loading as well as of the loading rate on the nonlinear viscoelastic parameters and the viscoplastic strain are further studied. Similar observations are denoted by Tuttle and Brinson [10], Dillard et al. [15] and Govaert et al. [16] as well as Giles et al. [17] and Pradas and Calleja [18] in biomechanical applications.

2. Theoretical background

At low stress levels, the creep strain is related to the applied stress by the so called *creep compliance* which is defined as:

$$D(t) = \frac{\varepsilon(t)}{\sigma_0} \tag{1}$$

Then in the linear region, the Boltzmann's superposition principle can be formulated as:

$$\varepsilon(t) = D_0\sigma_0 + \int_0^t \Delta D(t-\tau)\frac{d\sigma_0}{d\tau}d\tau \tag{2}$$

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However, in most cases polymeric composites may exhibit nonlinear viscoelastic response. Schapery's nonlinear constitutive equation can describe this behaviour and for the case of uniaxial isothermal loading can be given as:

$$\varepsilon(t) = g_0 D_0 \sigma_0 + g_1 \int_0^t \Delta D(\psi - \psi') \frac{d(g_2 \sigma_0)}{d\tau} d\tau \tag{3}$$

where D_0 and $\Delta D(\psi)$ are the initial and transient compliance components respectively, while ψ and ψ' are the so-called reduced times defined by :

$$\psi = \int_{0^-}^{t} \frac{dt'}{a_\sigma} \quad \text{and} \quad \psi' = \psi(\tau) = \int_{0^-}^{\tau} \frac{dt'}{a_\sigma}$$

and g_0, g_1, g_2 and a_σ are stress and temperature dependent nonlinear factors each expressing different contributions of nonlinearity in the strain response.

Assuming that a loading σ_0 is applied at the moment $t = 0^+$, then the response of the material can be given as:

$$\varepsilon(t) = g_0 D_0 \sigma_0 + g_1 \int_0^t \Delta D(\psi - \psi') \frac{d(g_2 \sigma_0)}{d\tau} d\tau + \varepsilon_{vp}(t)$$
$$\text{for } 0 < t < t_a \tag{4}$$

where $\varepsilon_{vp}(t)$ is the viscoplastic strain that is developed in the material during loading.

Considering now that the load is removed at time t_a^+, then the recovery response according to Eq. (3) can be given as:

$$\varepsilon_r(t) = \left[\Delta D\left(\frac{t_a}{a_\sigma} + t - t_\alpha\right) - \Delta D(t - t_\alpha)\right] g_2 \sigma_0 + \varepsilon_{vp}(t_a^+) \quad \text{for } t > t_a \tag{5}$$

It is important to note that useful supplementary information concerning the nonlinear viscoelastic behaviour of the material can be obtained from its recovery response, the nature of which strongly depends on the time dependent nature of its respective creep response.

2.1. Applied technique for the estimation of the nonlinear parameters

A technique for the estimation of the nonlinear parameters has been described by Zaoutsos et al. [19] and Papanicolaou et al. [20] elsewhere. According to this technique, the nonlinear parameter g_0, accounting for the nonlinear instantaneous response, can be estimated from the ratio of the instantaneous compliance at the considered stress level and the instantaneous compliance at a stress level in the linear region.

Then, the g_1 values can be estimated using the following relationship:

$$g_1 = \frac{\Delta\varepsilon_c - \varepsilon_{vp}}{\Delta\varepsilon_c - \Delta\varepsilon_0 - \varepsilon_{vp}} \tag{6}$$

where all parameters are shown in Fig. 1.

The stress shift factor is estimated numerically by curve fitting the experimental data of the recovery response to the nondimensional time formulation proposed by Schapery [21] and thoroughly investigated by Hiel et al. [22,23]. This expression is derived from Eq. (3), assuming that the creep compliance of the material follows Findley's power law.

$$\varepsilon_r(t) = \frac{\Delta\varepsilon_c}{g_1}\left[(1 + a_\sigma\lambda)^n - (a_\sigma\lambda)^n\right] + \varepsilon_{vp}(t_a^+) \quad \text{for } t > t_a \tag{7}$$

where $\lambda = \frac{t - t_a}{t_a}$, is the nondimensional time and $\Delta\varepsilon_c$ is the amount of transient strain accumulated during creep, given by:

$$\Delta\varepsilon_c = g_1 g_2 C \left(\frac{t_a}{a_\sigma}\right)^n \sigma_0 \tag{8}$$

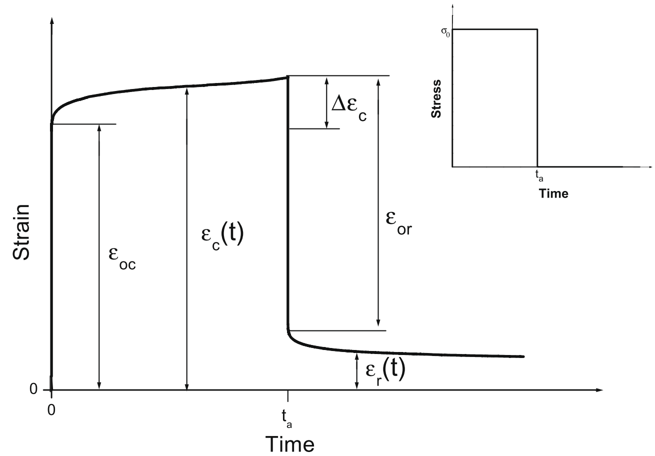

Fig. 1. A typical strain–time $\varepsilon(t)$ curve, for a creep/recovery test under a constant stress σ_0.

For $g_1 = a_\sigma = 1$, i.e. for linear viscoelastic behaviour, Eq. (7) becomes:

$$\varepsilon_r(t) = \Delta\varepsilon_c\left[(1 + \lambda)^n - (\lambda)^n\right] \quad \text{for} \quad t > t_a \tag{9}$$

The evaluation of the stress shift factor, a_σ, is now possible using Eq. (7), since, on one hand, the parameter g_2 is not included in it, while, on the other hand, the determination of the time dependence of the viscoplastic term is not needed to be known anymore. In addition, as it follows from Eq. (9), a time independent value of the exponent n can be found if one applies a curve fitting technique at any time interval of the recovery curve, under the condition that the material exhibits a linear viscoelastic response in the time interval considered.

Also, according to previous works [19,20] the author has shown that the analytical expression for the nonlinear parameter g_2 is given by:

$$g_2 = \frac{\Delta\varepsilon_{0(nl)}}{\Delta\varepsilon_{c(l)}} \frac{a_\sigma^n}{(g_1 - 1)} \frac{\sigma_{0(l)}}{\sigma_{0(nl)}} \tag{10}$$

where $\sigma_{0(l)}$ and $\sigma_{0(nl)}$ refer to two different applied stress levels leading to linear and nonlinear response of the material respectively. $\Delta\varepsilon_{0(nl)}$ represents the difference between the instantaneous strain responses at the time of unloading ($t = t_a^+$) and at the time of loading ($t = 0^+$) observed when the applied stress level is $\sigma = \sigma_{0(nl)}$. Finally, $\Delta\varepsilon_{c(l)}$ represents the linear creep response of the material observed in the time interval 0–t_a when the applied stress level is $\sigma = \sigma_{0(l)}$ (Fig. 1).

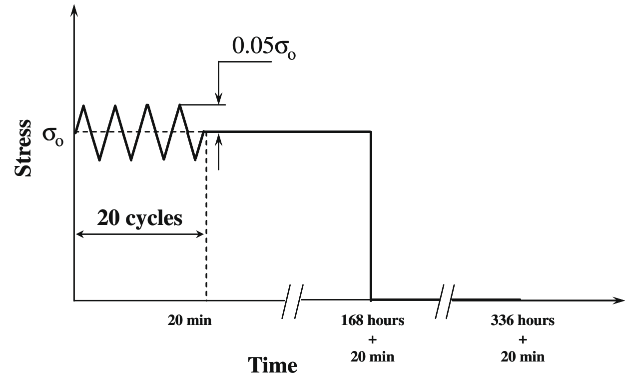

Fig. 2. Schematic view of the combined loading mode (preloading + static) applied at the 90° carbon/epoxy composite specimens for the study of the influence of preloading.