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A novel approach for the strain rate dependent modelling of woven composites

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ABSTRACT

This study proposes a new computational model for polyamid-matrix woven composites that takes into account rate effects for high speed impact applications. The rate effects are captured solely through the use of a spectral viscoelastic model, used in parallel with a conventional damage elastic-plastic model. It appears that, for very different load rates, neither plasticity nor damage kinetics need any first order rate dependency to capture the nonlinear envelope response until failure. To verify this hypothesis, a dedicated experimental setup is proposed that allows strain-controlled interruption of high speed tension loadings. Cycled loading sequences may therefore be applied to a sample even in the dynamic regime, and loss of stiffness and irreversible strains may be measured until total failure. A specific and rigorous identification procedure is proposed to that effect. Our experimental findings confirm the ability of the model to predict both the envelope response curve and the evolution of the internal mechanisms at very different strain rates.

1. Introduction

Car manufacturers are looking for solutions to reduce the mass of their vehicles in order to meet pollutant emission requirements – for thermal engines – or to extend their range – for electric vehicles. Composite materials, among other solutions, offer excellent strength and durability. However increased unit cost and manufacturing time are among the main issues material producers have to overcome in order to make composite solutions viable for mass-market production. With that in mind, woven glass fibers and thermoplastic matrices respectively are more serious contenders than aeronautic-grade composites, at least on paper. However their adaptability to various automotive applications remains to be proved. In this paper we study the behavior of a glass fiber woven composite using a 2×2 twill weaving pattern and a polyamid 6,6 matrix, manufactured by thermostamping and produced by Du Pont de Nemours. The intended application is a door reinforcement module, whose main function is to act as a safety net by adding its own stiffness and strength to that of the steel door and preventing any foreign object from entering the passenger compartment. Thus a major concern is the constitutive behaviour of that material under strain rates varying from $10^{-3}\,s^{-1}$ to approximately $10\,s^{-1}$.

Early experimental investigations reveal a very strong strain-rate sensitivity, even at low strain rates, of the material in all directions[1] (see Fig. 1). Stiffness is noticeably affected, mostly in the bias direction, while the effect on strength is even more obvious, even in the fibers' directions. Higher strain rates exacerbate these trends. There is also a strong anisotropy: Stiffness and strength vary by a ratio of 10 and 3 respectively with load direction, much less than carbon fiber reinforced plastics. But the most visible aspect of anisotropy rather concerns ultimate strains, which vary from $\simeq 1.75\%$ in the fibers' direction to $\simeq 30\%$ and more in the bias direction. However these large strains are never observed in practical applications, since stress redistributions and multiaxiality always cause fiber failure before shear strains exceed 8–10%. Therefore finite strains will not be investigated in the following.

Few composite damage models take into account the rate dependency of the response up to the onset of failure in intermediate dynamics. Traditionally this has been for good reasons, since epoxy, PEEK, and other aeronautic-grade matrices display little rate dependency in this dynamic regime, unlike the materials considered here. Some authors have considered strictly elasto-visco-plastic models [1,2], but given the critical role of damage mechanisms in these materials, they have not been investigated further. Let us briefly examine the properties of a few recent rate-dependent damage models suited for impact modelling.

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[1] Thereafter relative orientations with respect to the warp direction may be used instead of material directions to describe prescribed loadings. The 0° orientation refers to the warp direction, 90° to the weft direction, and 45° to the bias direction. Warp and weft are indistinctively referred to as the fibers' directions, and since the weave is balanced, the behaviour is assumed and verified to be similar in both directions.

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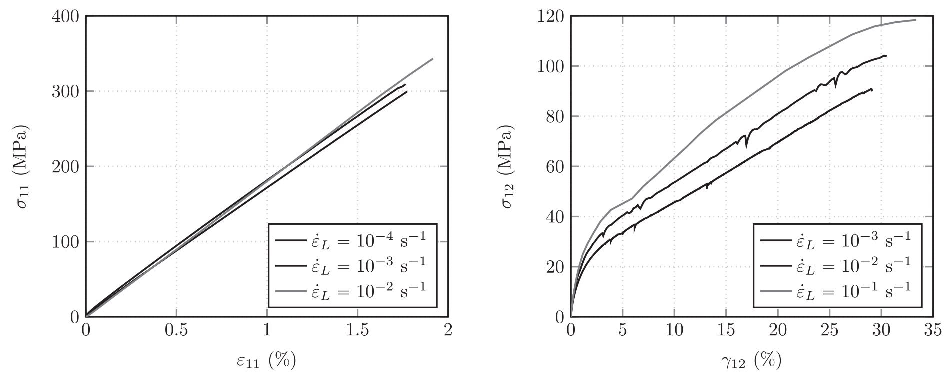

(a) 0° (b) 45°

Fig. 1. Monotonous response in their material frame of 0°- and 45°-oriented samples submitted to low strain rates.

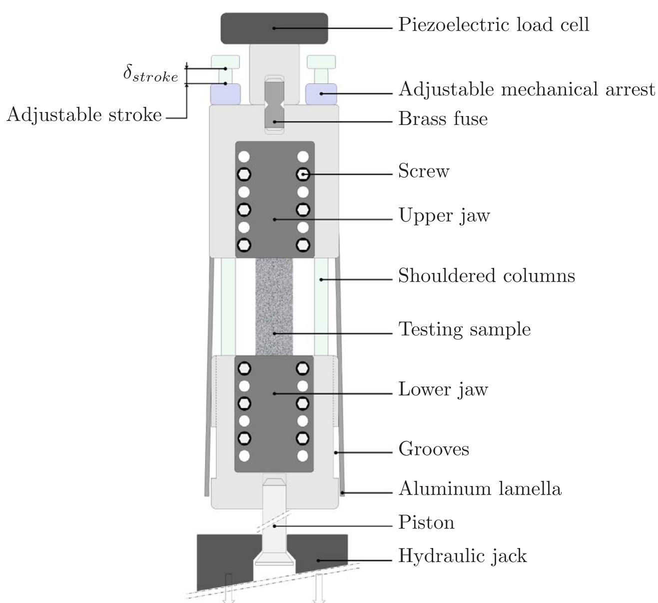

Fig. 2. Schematics of the strain interruption testing device.

In [3], strain rate is introduced in three ways. The elastic moduli are strain rate dependent, but in a parametric manner – i.e. no visco-elastic model is considered; plastic flow obeys a Norton-Hoff isotropic law; and the damage rate is bounded by a decreasing exponential [4]. The latter dependency has for its sole objective the regularization of the softening model by preventing damage from increasing at a quasi-infinite rate once localization initiates. This aspect is retained in our study; apart from regularization, damage is therefore considered rate-independent, while plasticity is, conversely, strongly affected. This hypothesis, similar to metal models, is however difficult to justify *a priori*; and we will see that it does not apply to the material we considered. Finally elasticity is introduced as log-dependent with strain rate. Although this is a fair approximation at first order, such a formulation causes all nonlinear mechanisms to be strongly coupled with strain rate. In order to keep the identification procedure simple and robust, a different approach will be favoured.

In [5], the authors consider that the strain rate only affects the nonlinear behaviour beyond a certain elastic limit. They introduce a rather quirky rate dependent plastic law:

$$\boldsymbol{\varepsilon}_p = \chi(\dot{\boldsymbol{\varepsilon}}_p)^m(\boldsymbol{\sigma})^n \tag{1}$$

where $\boldsymbol{\varepsilon}_p$ and $\boldsymbol{\sigma}$ are plastic strains and stresses respectively, and χ, m, and n are material parameters. Although no damage model is considered in this study, a strain rate dependent failure criterion is also introduced. For that purpose, the authors use the Monkman-Grant equation, in analogy with metals, and extend it to the anisotropic case. This approach departs strongly from a phenomenological modelling philosophy, yet the attempt to keep the number of parameters to a minimum is a preoccupation we share.

In [6], only the reversible behaviour of ± 45° laminates is studied. The authors rely on a so called spectral viscoelastic model, usually applied to quasi-static loadings [7,8]. In their work, it is extended to dynamic ranges thanks to a second spectrum, covering high strain rates. The spectral viscoelastic model has the benefit of accurately covering a wide range of characteristic times – even more when two spectra are used – yielding excellent viscoelastic predictions. It further requires relatively little parameter identification. It is however computationally expensive: To integrate the influence of so many characteristic times, the integral is discretized in a sum of several linear viscoelastic Kelvin-Voigt mechanisms (up to 200 in this study). With the addition of a nonlinear stress dependent function, it becomes necessary to solve a cumbersome Jacobian and to store of as many rank 2 tensors as elementary mechanisms. The principle of using a spectrum of characteristic times will be retained in our study and extended to the nonlinear regime, yet with a very different implementation.

In [9], the authors propose a damage viscoelastic model for unidirectional and discontinuous fiber composites. Rate effects are introduced as part of the viscoelastic response of the matrix, which is then homogenized through an Eshelby inclusion method [10]. The viscoelastic model is a modified single Maxwell model. The modification lies in a rate-dependent viscosity parameter, that takes into account the influence of increasing strain rates. In Fig. 2 of [9] (where Viscosity units should probably be in GPa/s), it is shown how an inverse calibration method based on a gradient minimization allows proper identification of the 2 parameters describing this viscosity-strain rate relation. The model offers interesting predictions, but with significant discrepancy with experimental results in small strains (Fig. 3b). This might be explained by the absence of a progressive nonlinear damage or plastic model in this strain range. The use of homogenization principles also eases the identification of multiaxial coupling parameters without multiplying the number of characterization tests.

In [11], the authors also rely on homogenization principles – this time numerical periodic asymptotic homogenization [12] – to extract the overall behavior of a plain weave composite from that of its elementary constituents. Rate effects are again concentrated in a single viscoelastic phase corresponding to the polymer matrix. In this work, the authors use a generalized Maxwell model, i.e. with multiple parallel mechanisms. The strain rate dependence is captured using a Prony series representation of the relaxation modulus, truncated at order 10. This has the benefit of limiting the number of linear viscoelastic mechanisms, compared to [6], but requires the identification of 20 material parameters, which in the present case were obtained from