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Constitutive modelling of the strain-rate dependency of fabric reinforced polymers

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ABSTRACT

Among the various mechanisms which occur during impact, the strain rate effect plays a significant role on the mechanical response of layered carbon fibre reinforced polymer structure. In this work, the viscoelastic behaviour of the material is studied to introduce a strain-rate dependency. To preserve numerical efficiency the generalised Maxwell model, formulated in the strain-space, is taken as a basis. The non-linear viscoelastic behaviour is introduced by coupling the generalised Maxwell model with a pre-existing intralaminar matrix continuum damage model. The fact that the Maxwell model preserves the explicit scheme of the damage model leads to an efficient material model for impact simulations. This paper proposes a complete framework to implement the strain-rate sensitive damage model in an explicit finite element code (for low-speed impact simulations). For this purpose, the procedure of parameter identification, based on DynamicMechanical Analysis, is given. Furthermore, a challenging experimental procedure on high-speed jack device with a particular attention paid to the consistency of the results is proposed to validate the developed model.

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1. Introduction

The use of Carbon Fabric Reinforced Polymers (CFRP) in the automotive industry increases significantly because of higher specific stiffness and strength and higher energy absorption compared to common metals. However the behaviour modelling, notably through the finite element method, is essential for their deployment on mass-product vehicles. This work is included in a wide project dedicated to simulate the behaviour of CFRP under low-speed impact, such as pedestrian impact, on non-structural components (engine bonnet, roof, door, etc.). It is focused on the modelling of the strain-rate sensitivity and its coupling to a pre-existing intralaminar damage model. The reinforcement damage, as well as the interlaminar matrix damage (so-called delamination) is not considered in the present study, even though needed for simulation of low-speed impact on the considered layered CFRP.

To introduce a strain-rate sensitivity for dynamic loading, phenomenological models exist and they describe empirically the dependence of the elastic modulus (and possibly also the damage evolution, the failure criterion, etc.) on the strain rate by polynomial or logarithmic functions [1,2]. However, these models may suffer of numerical instabilities during finite element analysis due to the difficulty to obtain a realistic instantaneous strain rate.

In the wide family of the viscoelastic models used to model strain rate sensitivity of the elastic behaviour, the rheological ones are the most simple ones. They are based on the combination of two basic components, a purely elastic spring (Hooke element) and a purely viscous damper (Newton element), connected in parallel and/or in series and lead to a linear viscoelasticity. General forms are given by the two generalised rheological viscoelastic models: the generalised Kelvin model and the generalised Maxwell model.

The generalised Kelvin model is well-adapted to a stress-space formulation of a constitutive model since the stress applied to each sub-element is equal to the total stress applied to the material. Instead, the generalised Maxwell model is preferred for strain-space formulations. These models are widely used in the commercial finite element analysis software but suffer two drawbacks. The first one is the use of a significant number of parameters. Second, as defined, these generalised rheological viscoelastic models are linear and cannot represent the non-linear viscoelastic behaviour of the fibre reinforced polymers.

Another group is the family of the spectral models. Compared to the previously mentioned generalised rheological models, the spectral models provide a continuous spectrum of the relaxation times. The number of parameters to identify is thus reduced without losing

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accuracy for describing the viscous phenomena. By using a Gaussian description of the spectrum, Maire [3] introduces a spectral model for the fibre reinforced polymers. Thereafter, Rémy-Petipas [4], Schieffer et al. [5], Huchette [6], Berthe et al. [7] have gradually improved the model by introducing thermal effects and damage coupling. The spectral models expressed as such, however, are suffering substantial computational times in case of explicit simulation scheme.

Functional formulations are also used to describe time irreversibility problems. These formulations rely on the basis that the instantaneous response of a material depends on the loading history. Thus, the Boltzmann superposition principle can be applied to viscoelastic stress analysis problems. Initially using a linear creep compliance in the formulation, Lou and Schapery [8] introduced a non-linear viscoelastic formulation for the fibre reinforced polymers. This model was successfully used for various unidirectional composites [9–11] but essentially for creep simulations.

Other authors [12–14] use a functional formulation of the generalised Maxwell model introduced by Simo and Hughes [15] to model the behaviour of polymers or composites at high strain-rates. They introduce also a non-linear viscoelastic behaviour by coupling the damage and the viscoelasticity. This formulation is very attractive by its computational efficiency, notably in explicit finite element simulations, and its simple implementation. But by using a generalised Maxwell model as basis it always remains to identify many parameters.

Despite this, this last model is chosen as viscoelastic model in the present work by its attractiveness for impact simulations thanks to its explicit scheme. An explicit suitable damage model for the intralaminar damage of fabric reinforced polymers [16] is coupled with the viscoelastic model. The coupling, by its original formulation, preserves the explicit schemes of both viscoelastic and matrix damage model, while introducing non-linear viscoelasticity. Hence, the numerical efficiency of the complete model is preserved. In addition, the present paper suggests a complete framework dedicated to the implementation of the strain rate sensitivity to a given intralaminar damage model in an explicit finite element code. The identification procedure of the viscoelastic parameters is explained, the formulation in a discrete strain space for the finite element method is provided and finally, the challenging validation procedure is detailed.

In Section 2, the linear generalised Maxwell model is described, with the application of the Boltzmann superposition principle to obtain the constitutive equation. Then, a coupling with a matrix damage model [16] is proposed in the second section. Moreover, in a third section, the formulation of this model in the finite strain framework is discussed. The implementation of this newly formulated model into an explicit finite element code is given afterwards. The next section presents the parameter identification through straightforward Dynamical Mechanical Analysis. Finally, the model is validated by an experimental test campaign carried out on a high-speed hydraulic jack facility. The details of these tests are provided in a last section, with a particular attention to the scale effect, critical in the damage analysis of the fabric reinforced polymers due to substantial side effects.

2. Formulation of the constitutive model

2.1. Functional formulation of the generalised maxwell model

The generalised Maxwell model relies on the combination of only two basic elements: a spring called a Hooke element, and a dumper called a Newton element. By arranging these elements in series and in parallel according to a scheme given by the generalised Maxwell model, the model is able to describe the increase of the stiffness of polymers at increasing strain rates.

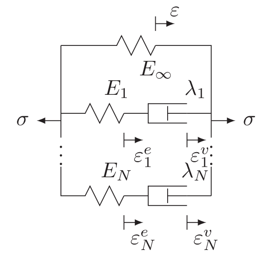

Fig. 1. Generalised Maxwell model.

To approach the real dynamic mechanical spectrum of the fibre reinforced polymers, the various relaxation times are introduced by using N Maxwell elements, made up a Hooke element and a Newton element in series, in parallel of the Hooke element (Fig. 1).

The strain ε applied to the generalised Maxwell model is equal to the strain applied to each branch (ε_j being the strain of the jth branch):

$$\varepsilon = \varepsilon_j = \varepsilon_j^e + \varepsilon_j^v \qquad \forall j \in [\![1, N]\!], \tag{1}$$

where the subscripts e and v are respectively relative to pure elastic and viscoelastic parts. The total stress is the sum of the stress applied to each branch:

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}_\infty + \sum_{j=1}^{N} \boldsymbol{\sigma}_j, \tag{2}$$

where the subscript j indicates the properties of the jth Maxwell element. The stress at time t is then determined through the superposition theorem and is given by:

$$\boldsymbol{\sigma}(t) = \boldsymbol{\sigma}_\infty + \sum_{j=1}^{N} \boldsymbol{\sigma}_0 \cdot \exp\left(-\frac{t}{\tau_j}\right), \tag{3}$$

with $\tau_j = \frac{\lambda_j}{E_j}$ the relaxation time of the jth Maxwell element and leads to the relaxation modulus which is defined by: (Fig. 2)

$$E(t) = E_\infty + \sum_{j=1}^{N} E_j \cdot \exp\left(-\frac{t}{\tau_j}\right), \tag{4}$$

with E_j the elastic modulus of the jth Maxwell element. This expression of the relaxation modulus follows the form of Prony series.

To simplify the resolution of the differential equations, a single strain increment was considered as loading of the viscoelastic model and the relaxation stress response was described by introducing a relaxation modulus (Eq. (4)). But the response of the viscoelastic model has to be determined for random loading cases. The Boltzmann superposition principle suggests that the response of a material to a strain increment is independent of responses due to strain increments which have been previously initiated. Thus, let $\sigma_k(t)$ the stress at time t due to a strain increment $\Delta\varepsilon_k$ applied at a time ξ_k previous to t. By considering for example two strain increments, the total stress at time t can be obtained by superposition as follows:

$$\begin{aligned} \boldsymbol{\sigma}(t) &= \boldsymbol{\sigma}_1(t) + \boldsymbol{\sigma}_2(t) \\ &= E(t-\xi_1) \cdot \Delta\varepsilon_1 + E(t-\xi_2) \cdot \Delta\varepsilon_2. \end{aligned} \tag{5}$$

In a more general case, the total stress at time t is obtained by summing the effects of an infinite number of perturbations and is given by:

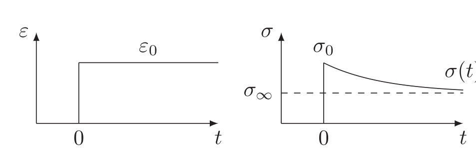

Fig. 2. Strain and stress histories of the Maxwell model in a relaxation test.

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