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Modelling of the intralaminar matrix damage with friction effects of fabric reinforced polymers

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ABSTRACT

Needed to simulate the behaviour of industrial components through finite element analysis, a continuum damage model formulation for fabric reinforced polymers is provided. Based on the Onera Damage Microstructure Model, it considers the influence of privileged direction of intralaminar matrix damage on the stiffness. In this work, the stored strains are considered as representative of the position of the crack lips. Thus, after calculation of the stresses applied to the crack lips, a friction law has been newly implemented in order to represent the hysteresis loops during cyclic loading. Moreover, the possibility of a shear locking, very common among the textile simulations for large shearing, is introduced with its effect on the matrix damage. The present model is applied to simulate various fabric preforms (woven or non-crimp) under cyclic in-plane shear. Because of similarities of the physical phenomena which occur in each investigated materials, the present model is able to represent a realistic behaviour for every preforms investigated.

1. Introduction

In these last decades, the use of carbon fabric reinforced thermoplastics (CFRP) in the automotive industry increased very significantly. The high specific stiffness and strength, the great energy absorption as well as the reduced manufacturing cost of these materials widely encourage their diffusion.

Previously limited to small runs (premium vehicles, racing), last advances in highly productive manufacturing process lead to the use of CFRP for high volume automotive production. Therefore, the behaviour understanding and modelling of these materials become essential for their implementation into the design loop, needed for the deployment on mass-produced vehicles. This article is focused on the non-linear behaviour introduced by the intralaminar matrix damage. As a consequence, the reinforcement damage, the strain-rate dependency as well as the interlaminar matrix damage (so-called delamination) are not considered in the present study.

Although not considered in this paper, the modelling of these last phenomena are on-going research topics. The strain-rate sensitivity can be introduced through phenomenological models [25,62], spectral models [13,66] or functional formulations [29,49,68,72,75]. Energetic fibre failure criteria have been proposed by Hill [30] and Tsai and Wu [71], but by coupling the different failure mechanisms the prediction is highly enhanced [2,25,37,51,57,60,74]. The propagation of the reinforcement damage can be regulated through non-local models [7,33,56,69], limitation of the damage rate [3,42,43] or by means of a smeared crack formulation [16,17,24,59] Regarding the delamination, the cohesive laws for fibre reinforced polymers have been, and still are, widely studied [4,15,27,34,48,53,58]. Another solution is the formulation of layered theories and specific finite elements dedicated to the simulation of laminated materials [6,8–11,23,38,39,47,63,64,67].

However, even if they contribute to the global behaviour of a CFRP structure, they are limited in case of in-plane quasi-static loading. The material model in its complete form is made up modules dedicated for each physical phenomenon. In this paper, the focus is only given on the modelling of the intralaminar matrix damage.

The present model is established within the framework of the Continuum Damage Mechanics (CDM). It was first introduced by Kachanov [35] and Rabotnov [61] by considering the damage as a distributed defects through defining thermodynamic state variables. These variables are categorised as observable (or measurable) state variables – such as strains, stresses or temperature – or

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internal state variables (not directly measurable) – such as damage.

Thereafter, Lemaitre [46] introduced the concept of *equivalence principle* which gave a physical interpretation of damage variables. This idea is based on the definition of an *effective stress tensor*. It may be interpreted as the stress leading to the same amount of deformation by replacing the damaged material by a hypothetical virgin one.

Originally set for isotropic materials, such as metals, the use of CDM for anisotropic and composite materials was introduced by Chaboche [18] and Ladeveze and LeDantec [43]. The damage variables are given in null-, second- or fourth-order tensor forms. In case of privileged damage directions, scalar variables are sufficient to well-described the crack influences on the material behaviour. On the other hand, when the damage direction depends on the loading direction second- or fourth-order tensor forms are used.

Besides, it is important to take into account the unilateral character of damage. The closure of the crack, given by the stress state applied to it, leads to the recovery (partial or total) of the initial stiffness of the material. This unilateral character may be easily introduced thanks to the use of the Macaulay brackets for the stress normal to the crack orientation [1,43]. However, it leads to an incorrect behaviour in case of multi-axial loading [19]. Two approaches were then proposed by Chaboche:

- The first one consists of closing the diagonal terms of the stiffness tensor [20]. As a result, the initial shear stiffness is not recovered. Physically this may be seen as crack closure with a perfect slippage of the lips.
- The second approaches [21] leads to the complete recovery of the initial stiffness. By comparison to the previous one, it may be seen as an infinite friction between crack lips. In order to do so, an additional internal variable, the stored strain, is added to the model. It may be seen as representative of the position of the lips at closure. By definition it ensures the continuity at closure, but leads to discontinuities at re-opening when closure and opening do not occur at same loading configuration.

After a given loading/unloading then followed by a relaxation, permanent strains are observed and are imputed to the presence of damage. It can be explained by a release of residual stresses inherent to the manufacturing process and because of different thermal dilatations between the constituents [65,66], but also by friction effects and microscopic plasticity of the matrix in the vicinity of the cracks [1,43,50]. Schieffer et al. [66] models these permanent strains by means of residual strains evolving linearly with damage, whereas Ladeveze and LeDantec [43], Abisset et al. [1], Maim et al. [50] use a plastic formulation.

Regarding the modelling of the frictional microcracks, various micromechanical studies have been proposed in last decades. Based on Kachanov [36], these models proposed by Gambarotta and Lagomarsino [26], Basista and Gross [12], Krajcinovic and Fanella [41], Sumarac and Krajcinovic [70] are stress-based formulated and most of them do not follow a thermodynamic approach which allow an easy connection with macroscopic models. An interesting approach is proposed by Andrieux et al. [5] to model two-dimensional frictional sliding micro-cracks in a strain-space which follows the thermodynamic approach. Various authors have extended this framework such as Halm and Dragon [28], Wrzesniak et al. [73], Zhu et al. [76], Pense et al. [55] through different homogenisation techniques. However these methods are extremely complex to be implemented and coupled with pre-existing material models.

Further works took interest in micromechanical considerations such as the diffuse matrix damage or the fibre/matrix decohesion. A crack density, based on the stress and an energy balance, is introduced to take into account the ply thickness on the kinetics of damage [44,45]. Huchette et al. [32] integrated this microscopic crack density in a viscoelastic formulation to provide the latter additional non-linearity.

Marcin [52] adapted and extended the micromechanics based CDM model proposed by Chaboche and Maire [21] to the fabric reinforced materials. While remaining within the mesoscopic scale, he introduced a coupling between in-plane loading and damage normal to the thickness direction.

For the present work, the constitutive relation derived from Marcin's formulation is recalled Section 2. An adaptation of the stored strains to take into account the friction mechanisms inside the composite materials is formulated. This formulation allows a simple and efficient coupling with the Onera Damage Model. Hence, these friction mechanisms are strongly linked to the damage evolution and the model is able to represent the hysteresis loop during cyclic loading. The possibility of a shear locking for textile preforms is then added to the model. This shear locking leads to a damage mechanism which is added to the previous formulation. Section 4 concerns the identification of the model parameters. Finally the model, and particularly the friction mechanisms, is validated through simulations of quasi-static cyclic in-plane shear tests.

2. Continuum matrix damage model

This work relies on a closed version of the *Onera Damage Model MicroStructure* (ODM_MS) proposed by Marcin [52]. Although the model has to describe the physical mechanisms, it is intended to be used in an industrial environment. Hence, the ODM_MS being based at the mesoscopic scale and formulated in the strain-space (ideal for an implementation for finite element analysis), it was well suited for basis of the complete material model.

The matrix damage modelling is based on the assumption that the preferred damage directions at the mesoscopic scale correspond to the directions of reinforcement. This assumption is confirmed by basic experimental observations on two different fabric preforms after an in-plane shear test (Fig. 1).

Moreover, this model is able to depict the effects of the crack closure on the recovery of the initial stiffness. For this purpose the internal variable so-called stored strain, representative of the position of crack lips at closing, is used. However, as depicted by Chaboche and Maire [21], the re-opening may lead to stress discontinuities that may be critical for the stability of finite element analysis. A further development was to introduce friction effects but was never followed up.

Yet, these friction mechanisms are fundamental for structural simulations with complex loading, notably in case of positive/negative shear switchover. Consequently, an efficient and Coulomb-based friction formulation is introduced in the present model and is described in Section 2.8 relative to the stored strains.

Another important improvement is the consideration of the shear locking which is specific to textile preforms. The effect of the shear locking on the damage kinetics are also considered and is given Section 2.9.

2.1. Finite strain framework

Given the strong anisotropic behaviour induced by the reinforcement of the fabric composite plies, it is essential that the formulation may be able to follow the directions of anisotropy for large displacements and moderate strains. As a result, the base (or undeformed) and the current (deformed) configurations of the material cannot be assumed identical. This hypothesis is the basis of the small displacement and small deformation theory, making it