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# A dissipative constitutive model for woven composite fabric under large strain

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ABSTRACT

Draping composite reinforcement on non-developable shapes necessarily leads to deformations in the plane generating large shears between warp and weft. Sliding between fibers and between yarns creates friction that dissipates energy. This paper presents a constitutive model describing the dissipative behaviour of 2D composite textile reinforcements under large strain. The model is based on two innovative points. First, the additive decomposition of Green-Naghdi is considered, which leads to write the yield function and the plastic law in a conventional manner, which is very uncommon for anisotropic fields. Secondly, nested surfaces according with Mroz Theory define the strong non-linearity of the problem. The use of these two points allows to define a flexible dissipative model for numerical simulations. The dissipation process driven by fibers friction is exclusively associated with the in-plane shear deformation mode. As a result, the material parameters are calibrated using standard methods, like the Picture Frame.



## 1. Introduction

The field of woven fabric offers a wide range of research applications. Depending on the application, these composite materials may be made from different elements and have their own geometrical and mechanical characteristics. Depending on the type of composite, forming processes may range from simple and controlled methods to much more delicate processes that are still subjects to many researches and discussions. In many cases, the composite is made of a reinforcement (often a dry fabric composed by carbon or glass fibers) which gives the major strength of the mechanical characteristics and a matrix, which ensures cohesion between the fibers. One of the forming processes currently used is the RTM manufacturing (Resin Transfer Molding) [1,2]. This process is divided into three steps: (1) Shape the dry fabric, (2) Inject the matrix (often under liquid resin form), (3) Unmold the final part. The aim of this article is to study the dissipative behaviour of the dry woven fabric during the preforming/shaping step. In this step, the matrix is not present and the material undergoes very large deformations in order to fit the desired shape. Macroscopic models based on continuum mechanics are used in finite element simulations to simulate the preforming. Specific shell elements have been developed in this context and are based on the hypothesis of decoupling the deformation modes. Specific shell elements have been developed in this context and are based on the hypothesis of decoupling the deformation modes in the frame of conventional theory of finite deformations of fiber-reinforced solids [3]. Within this framework, the main in-plane deformation modes in the case of dry woven fabrics that are considered in this work are the traction-compression (in warp and weft directions) and the in-plane shear. The influence of in-plane bending deformations is not taken into account since a second order elastic theory is required [4–9]. Moreover, two out of plane bending modes exist [10–12] but will not be used here because of the in-plane consideration (see assumption ii). Secondly, some works attest that a coupling between traction and shear deformation modes [13–16], and between shear and bending [17,18] is relevent. Assumption is made that dissipation is mainly due to shear, since deformation mechanism of woven fabrics is mainly guided by fiber inextensibility. In finite element methods, we rather use quasi-inextensivity by using high rigidity parameters for the fibers. The same approach will be used here, and small strain will occur along fibers.

Most of the mechanical models used in forming simulation are based on non-linear elasticity approaches [9,19–27] but do not propose a plasticity criterion or any dissipative evolution. Previous experimental works have shown that fabrics material under cyclic load exhibit dissipative behaviour [28–31]. It is known that during forming process, large movements occur between warp and weft directions: friction between fibers is most likely responsible for

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energy dissipation [28,32]. For these reasons it is assumed in this article, that only shear mode is responsible for dissipation in the material, and that fibers are stretched elastically. Elastic models can be found in many works [9,19–27,33], visco-hyperelastic models were proposed to investigate the thermal impact of the matrix [34,35]. But none of them describes residual strains. The objective of this paper is to propose an in-plane elasto-plastic model in finite strain, which account for dissipation in shear mode. This works proposes an alternative to the work made by Spencer [36] using a specific yield function and hardening laws with a total lagrangian formulation. One of the novel ideas present in the proposed model is the application of the additive decomposition of Green-Naghdi to woven fabrics. This allows to describe, quite easily, the plastic flow law in a standard way. Under this decomposition, a new yield function exclusively associated with the in-plane shear mode is proposed which was never been enunciated before. Consequently, this method gives the possibility to suggest radial returns under large strains depending on a unique variable (the shear angle), and thereby, basic Newton-Raphson algorithms can be implemented for the numerical resolution.

Furthermore, during the experimental campaigns, it appears that the behaviour of the material during unloading is strongly nonlinear and follow an asymptotic path. Different models have been proposed in order to describe the dissipation process associated with fiber friction. These models can be based on the definition of internal variables, representing the frictional forces, and governed by evolution equations according to differential equations [37] or fractional derivatives [38]. However, these approaches has only been applied in the case of small deformations [22,37,39–41]. Instead, a theory based on nested surfaces is adopted in this work. Thus a theory based on nested surfaces is chosen in order to approach this behaviour. The work presented in this article is inspired by the Mroz theory [42] as well as other Mroz application as the work of Ziegler, Prager or other [42–46] which cannot be used here because of their specificities or because of the strong non linearity of the dissipative behaviour in shear. In fact, to manage this behaviour, nested surfaces have to inflate and deflate proportionally to the plastic deformation which is not described in the models already written.

The second objective of this article is to calibrate the model through experiment and inverse methods. Many parameters have to be identified since the use of nested surfaces imposes different evolution laws for each surfaces. A Picture Frame experiment was conducted in order to identify each parameters and then perform some numerical simulations.

Specific attention will be put on the additive decomposition of Green-Naghdi [47]. Indeed, this decomposition has been used and adapted for large deformations while being thermodynamically admissible [48–51]. Coupled with the multiplicative decomposition of Kröner-Lee [52], it provides a total lagrangian model. [50,53].

## 2. Model assumptions and conditions of use

This model can be used under certain conditions. If necessary, other less critical assumptions are also made at the beginning of each section.

(i) Traction-compression deformation modes (elastic) and in-plane shear (dissipative) are decoupled. This is a common assumption adopted in the large majority of experimental and simulation analyses. As mentioned before, it must be pointed that recent studies report a direct influence of the yarn tension [14,16,54] and the out plane and in-plane bending behaviour with the in-plane shear deformation [5–7,9]. However, modelling the coupling between the different deformation modes in an elastic frame is already quite complicated. In the case of an elastoplastic frame is even more challenging regarding the definition of the yield function, the plastic flow law and the implementation of corresponding resolution algorithms. As a first approach, this assumption is adopted.

(ii) Stress and strain tensors are assumed to be written with generalised quantities that have already been integrated into the thickness of the fabric. For simplicity reasons, the tensors of generalised stress and generalised strain are simply called stress and strain tensors. Given this hypothesis, the potential of free energy is therefore per unit surface instead of volume. This hypothesis can be justified by the fact that in many cases, the thickness of a composite reinforcement is relatively small compared to the other dimensions. In this case, only the projection of the transformation gradient in the plane formed by the material involved. This leads to write the transformation gradient tensor with only four components.

(iii) As the carbon or glass fibers are very rigid, they cannot be too much deformed, thus, it does not lengthen [29–31]. Yarns are considered to be quasi-inextensible given the high rigidity of the carbon/glass fibers. The constitutive behaviour of the elongation/compression modes is purely elastic and does not dissipate energy. Therefore, after assumption (i) the dissipation process follows a kinematics of pure shear [55–57].

(iv) At the macroscopic scale, the fabric is considered as an homogenous material. The model presented here can be seen as a macroscopic model.

**Remark 0.** In this article, the tensor are writing with bold letters ($\mathbf{S}, \mathbf{E}, \mathbf{F}\ldots$), the vectors with an over bar ($\overline{u}, \overline{v}\ldots$,) and the scalar quantities by normal font.

## 3. Kinematics of the deformations

The aim of this chapter is to define the set of fundamental tensors necessary to write the model. For this purpose, a discussion of the additive decomposition of Green-Naghdi is made and coupled with the multiplicative decomposition of Kröner-Lee. This type of decomposition allows the decoupling of the total transformation and deformation tensors into an elastic part and a plastic part. Moreover, given the assumptions about the characteristics of the material, it is possible to define the plastic transformation kinematics and then the associated plastic transformation tensor. Finally, since the total transformation tensor is known (during the characterisation test for example) then it becomes possible to define every elastic quantities.

### *3.1. Discussion about these decompositions under large strain*

The decomposition of Green-Naghdi is a relatively common formalism in the hypothesis of small perturbations and in the framework of crystalline materials [58]. The best of our knowledge, there is no application in finite strain for anisotropic material. After a thermodynamical analysis inspired by works already done [48,53,59], the compatibility of this decomposition with the field of finite strain and anisotropic structures allows to write the formulation defined by Eq. (1). Coupled with the multiplicative decomposition of Kröner-Lee formulated by Eq. (2), this couple permits to define tensors in the initial configuration (Lagrangian).

$$\mathbf{E} = \mathbf{E}_e + \mathbf{E}_p \qquad (1)$$