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Hyperelastic modelling for mesoscopic analyses of composite reinforcements

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ABSTRACT

A hyperelastic constitutive law is proposed to describe the mechanical behaviour of fibre bundles of woven composite reinforcements. The objective of this model is to compute the 3D geometry of the deformed woven unit cell. This geometry is important for permeability calculations and for the mechanical behaviour of the composite into service. The finite element models of a woven unit cell can also be used as virtual mechanical tests. The highlight of four deformation modes of the fibre bundle leads to definition of a strain energy potential from four specific invariants. The parameters of the hyperelastic constitutive law are identified in the case of a glass plain weave reinforcement thanks to uniaxial and equibiaxial tensile tests on the fibre bundle and on the whole reinforcement. This constitutive law is then validated in comparison to biaxial tension and in-plane shear tests.

1. Introduction

Their good mass-mechanical properties ratio and their good corrosion and fatigue properties make textile composites essential materials when saving mass is a main issue. These materials can be manufactured by Liquid Composite Molding (LCM) processes [1–3]: the textile reinforcement is preformed in a first stage, then the resin is injected in the preform.

The reinforcement is made of continuous fibres grouped into yarns (3000–48,000 fibres in a carbon yarn, 1000–12,000 fibres in a glass yarn). These yarns are combined following textile architectures: woven, knitted braided or non-crimped fabrics. These assemblies give the textile reinforcements a multi-scale nature (Fig. 1). This paper focuses on woven fabrics, but the model which will be proposed for the yarn would be similar for other architectures.

The macroscopic scale refers to the whole component level, with dimensions ranging from ten centimetres to several metres. At this level, a woven fabric can be seen as a continuous material whose behaviour is very specific and includes high anisotropy. At the mesoscopic scale, the woven reinforcement is seen as interlaced tows, respectively the warp and the weft (or fill) yarns. Consequently, the working scale corresponds to the yarn dimension, typically one to several millimetres. For periodic materials, mesoscopic models consider the smallest elementary pattern, which can represent the whole fabric by translations. That domain is called the representative unit cell (RUC) [4–6]. Finally, the reinforcement can be analysed at the microscopic scale. In this case each fibre is considered as a 3D beam interacting with its numerous neighbours [7,8]. At the microscopic level, the characteristic dimension is about one to several micrometres. This is the only scale at which the material is actually continuous.

During the forming process, the woven unit cell reaches its position and geometry in the final composite. This geometry is important regarding the resin flow [9,10] and the final mechanical properties of the composite part. The changes of geometry of the fibre bundles are analysed using mesoscopic scale modelling. The studied domain is then the representative unit cell, which gives the solid skeleton for permeability evaluation.

In addition to permeability calculation, mesoscopic analyses can be used as virtual mechanical tests: they allow the mechanical properties of a woven reinforcement to be obtained without performing the experiments and hence without necessarily manufacturing the reinforcement under consideration [4]. In mesoscopic computations the yarn is considered as a continuum but with a very specific behaviour which accounts for his fibrous and discontinuous composition. Some mesoscopic analyses of the woven unit cell submitted to tension, in-plane shear and compression have been set up based on a hypoelastic behaviour of the yarn [4,5,11,12]. These hypoelastic models require the use of an objective derivative, i.e. of a derivative in a frame as close as possible of the fibre orientation. Despite being fairly frequently employed, these models have drawbacks, especially they do not allow a complete recovering after a closed loop loading path. The objective of the development of a hyperelastic constitutive model is to avoid these drawbacks. In addition, a hyperelastic model has been developed recently to analyse the mechanical behaviour of macroscopic textile composite reinforcements modelled as membranes with

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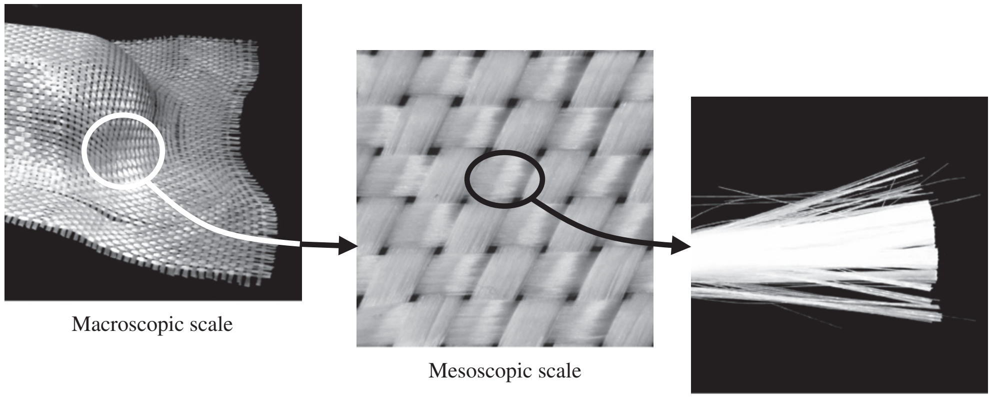

Fig. 1. Different scales for a woven composite reinforcement.

satisfactory results [13]. Nevertheless the model necessary to analyse the deformation of the fibre bundle is quite different since it must be 3D with a single fibre direction while the previous macroscopic model is 2D with two fibre directions. Furthermore the transverse deformation of the yarn (i.e. its compression and shape change), which is essential to the yarn behaviour, cannot be described by a macroscopic membrane approach.

An important research effort has been devoted to the development of hyperelastic models through the last decades. Isotropic models have been developed first, to model the behaviour of materials which can be subjected to very large elastic deformation, such as rubber–like materials. These models are usually sorted into two classes, depending on whether the strain energy depends on invariants of the strain tensor in use (e.g. Mooney–Rivlin models [14]), or on principal elongations (e.g. Ogden models [15]). The development of hyperelastic constitutive models for anisotropic materials appeared more recently. They are used to model the mechanical behaviour of strongly anisotropic materials which can undergo large elastic deformations, e.g. reinforced elastomers [16–18] and some biomaterials (biological tissues [19], tendons and ligaments [20]). The formulation of anisotropic hyperelastic models is usually based on structural tensors [21–23] which describe the local orientation (i.e. the preferred directions) of the material.

In this paper an anisotropic hyperelastic model is proposed and validated for the mechanical behaviour of textile composite reinforcements. It is based on specific physically motivated invariants. First the specificities of the yarn behaviour are analysed in order to formulate the different assumptions of this work. The mechanical behaviour model of the yarn is then presented, and the identification of its parameters is performed in the case of a glass plain weave, by use of uniaxial and biaxial tensile tests. Finally the model is used to simulate the in-plane shear behaviour of the woven unit cell, and the obtained results are compared to experimental data.

2. Mechanical behaviour of the fibre bundle and assumptions

2.1. Transverse isotropy

The yarn is an assembly of fibres oriented approximately in the same direction (Fig. 2). The fibres are assumed to be numerous and compact enough in order to avoid independent movements. In this case, it is possible to consider the yarn as a continuum, and consequently to define a continuous material equivalent to the fibre bundle. In a recent study [24], an X-ray tomography technique was combined to a mechanical test on a fibre bundle. This approach allowed an accurate observation of the motion of fibres inside the yarn, and showed that such a continuous approach is well-founded. The homogenized material has a preferred direction which is the fibre one. The spatial distribution of fibres inside the yarn has been analysed on deformed cross sections and, even if this observation may differ for other types of fabrics [25], it has been concluded that this distribution is isotropic [5] for the considered fabric. The "yarn" material will then be assumed to be transversely isotropic.

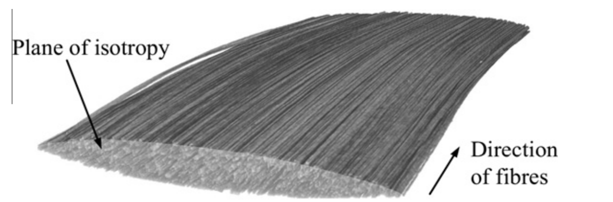

Fig. 2. Transverse isotropy of the yarn in a textile reinforcement. X-ray tomography imaging.

2.2. Deformation modes

A phenomenological approach based on experimental observations is used to define the constitutive law. It is consequently necessary to describe the specific deformation modes of the yarn, which are related to the behaviour of the fibres and to their interactions at the microscopic scale. Four deformation modes are considered: the elongation in the fibre direction, the compaction in the transverse section of the yarn, the distortion (shear) in the transverse section and the shear along the fibre direction (Fig. 3). The last one (longitudinal shear) is a measure of the angle between the covariant cross section and the initial cross section. It is then compound of both longitudinal shear deformations. This deformation mode mainly controls the bending rigidity of the yarn.

The experimental analysis of the tensile behaviour of the yarn is quite easy, so its identification can be performed directly from a tensile test on the yarn. This is not the case for the three other deformation modes. The weaving gives cohesion to the fibre bundle in the yarn and it is not easy to define elementary tests for the compaction and shear on a single yarn because of the lack of this cohesion if the yarn is extracted from the fabric. An inverse approach is used in the present work for the determination of the material parameters in transverse compression and shear (modes