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Compared prediction of the experimental failure of a thin fibrous tissue by two macroscopic damage models

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ABSTRACT

Several models for fibrous biological tissues have been proposed in the past, taking into account the fibrous microstructure through different homogenization methods. The aim of this paper is to compare theoretically and experimentally two existing homogenization methods – the Angular Integration method and the Generalized Structure Tensor method – by adapting them to a damage model for a planar fibrous tissue made of linear elastic and brittle fibers. The theoretical implementation of the homogenization methods reveals some differences once damage starts in the fibrous tissue; in particular, the anisotropy of the tissue evolves differently. The experimental aspect of this work consists in identifying the parameters of the damage model, with both homogenization methods, using inflation tests until rupture on a biological membrane. The numerical identification method is based on the simulation of the tests with the real geometry of the samples and the real boundary conditions computed by Stereo Digital Image Correlation. The identification method is applied to human liver capsule. The collagen fibers Young's modulus (19 ± 6 MPa) as well as their ultimate longitudinal strain ($33 \pm 4\%$) are determined; no significant difference was observed between the two methods. However, by using the experimental boundary conditions, we could observe that the damage progression is faster for the Angular Integration version of the model.

1. Introduction

In the field of biomechanics of soft tissues, a lot of studies have been focused on the characterization of the behavior of biological tissues and organs. This is due to the numerous medical applications of a human body model, which usually remain in the physiological range of loadings. However, the potentialities of a virtual human body including information about failure of the tissues are important in several fields, including road safety and surgery. Many fatal cases caused by car crashes and reported in the literature are due to abdominal organ injuries, especially the spleen, the liver and the kidney (Tinkoff et al., 2008). Predicting the occurrence of abdominal injuries by car crash simulation would improve user safety by suggesting technical changes in the passive and active safety systems. Besides, a difficulty in abdominal surgery is to handle the organs without damaging them. Using surgical simulation to predict the overloads responsible

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for injuries could be useful to prevent them. For these applications, a constitutive law representing the elastic or viscoelastic behavior of a soft tissue, associated with geometrical data – *e.g.* external shape – and interaction data – *e.g.* contact behavior with neighboring organs – is not sufficient to predict injuries; a human body model also requires failure properties for these biological tissues.

Two main issues are associated with the study of soft biological tissues failure properties: advanced experimental methods are needed to guarantee the good quality of the measurements despite the softness and the living aspect of the tissues; sophisticated models are required to represent the failure mechanisms occurring in these complex and structured materials. These two features also need to be coupled so that the model complexity (number of parameters) and the experimental possibilities (imaging, identification) are consistent.

Investigating failure properties of soft tissues is experimentally challenging as failure is a local and unstable phenomenon that can be highly influenced by the experimental conditions. The use of full-field measurements for studying failure has been shown (Brunon et al., 2010) and is particularly adapted to soft tissues, as the boundary conditions of the experimental tests are more difficult to control and thus to repeat from one sample to the other. This is due for instance to the existence of multiple stress-free states for a soft tissue, the compression of the tissue in the clamps, the difficulty to cut samples of the same shape, etc. Also, using inflation tests to characterize biological membranes can help making the tests more repeatable as the failure does not occur at the sample edges, where some failure initiations can be created during the cutting phase. However, this loading mode is not common although it usually corresponds to more realistic loadings than uniaxial tension and guarantees a better understanding of non-linearity and possible anisotropy of the tissue (Johannknecht and Jerrams, 1999). Boyce et al. (2008) and Bischoff et al. (2009) among others have used this type of loading to characterize the cornea and artery behavior. A few papers describe inflation tests on biological tissues until rupture. Mohan and Melvin (1983) determined the ultimate stress and strain of human aortic tissue using an analytic model of inflated membrane. Marra et al. (2006) calculated the failure strength of porcine aorta from the measurements of the global deformation and applied pressure. Kim et al. (2011) determined a non-linear constitutive law and rupture criterion for the artery. In a previous paper (Brunon et al., 2011), we determined the hyperelastic constitutive law and ultimate strain of the liver capsule. However none of these studies consisted in the identification of a damage model.

In terms of modeling, several models for fibrous tissues are available in the literature. They consider the fibrous microstructure to drive the macroscopic behavior of the tissue. Either the distribution of the fibers and their reference state are described statistically and further identified (Lanir, 1983; Decraemer et al., 1980), or some histological evidences lead to the construction of specific representations for the microstructure, such as the structure tensor proposed in Gasser et al. (2006). These two types of models correspond to two main homogenization methods, respectively, an Angular Integration (AI) method and a Generalized Structure Tensor (GST) method. Several physical phenomena such as viscoelasticity, plasticity, growth and remodeling are also considered (Gasser and Holzapfel, 2002; Gleason and Humphrey, 2005). But only a few papers address the damage of fibrous biological tissues. Some consider the damage to be solely due to fiber or fibril fracture at the microscale (Hurschler et al., 1997). Balzani et al., Calvo et al. and Rodriguez et al. all use the continuum theory to describe damage in a tissue made of a groundmatrix and bundles of fibers; they use internal macroscopic damage variables associated to either the fiber bundles solely (Balzani et al., 2006), or the fiber bundles and the groundmatrix (Calvo et al., 2006; Rodríguez et al., 2006). The evolution of the damage variables is discontinuous, *i.e.* it is based on the maximum value of an equivalent strain over the past history. In Rodríguez et al. (2006), however, the damage in the fiber bundles is controlled by a probability density function that reflects the stochastic waviness of the fibers in their reference state; it is therefore better suited for biological soft tissues as collagen fibers are usually wavy in an unloaded biological tissue (see *e.g.* Viidik, 1972; Orberg et al., 1982; Hill et al., 2012).

In this study, we focus on two homogenization methods proposed in the literature and investigate their differences in the range of damaging loads. The AI method proposed by Lanir (1983) and the GST method proposed by Gasser et al. (2006) have been theoretically compared in Cortes et al. (2010) for physiological ranges of loading, *i.e.* without any damage. Limits of the GST have been emphasized for fibrous distributions close to isotropy, but the differences between AI and GST methods vanish in the case of quasi-equibiaxial loading. In the present work, the experimental test case combines isotropic tissue and quasi-equibiaxial loading. The experiments are mainly devoted to provide data for the failure mechanism of this kind of tissue. But a by-product of these tests is also to produce some experimental data which allow comparing the non-linear response of the two models in such a configuration.

Although several sophisticated models are available in the literature to account for various physical features – viscoelasticity (*e.g.* Limbert and Middleton, 2004), anisotropy (*e.g.* Ateshian, 2007), fiber crimp *e.g.* (Cacho et al., 2007), etc. – we chose to compare the homogenization methods using a simple model describing an isotropic fibrous membrane, made of linear elastic brittle fibers and loaded with biaxial tension. The tissue macroscopic damage is due to fiber rupture at the microscale. This is the focus of the second part of the paper. A method to identify the two versions of the obtained damage model using inflation tests and full-field measurements is then presented in the third part. The fourth part is an application of this method on human liver capsule; results are discussed in the fifth part.

2. Construction of the damage model and theoretical comparison of the homogenization methods

The proposed model consists of a damage model for the tissue that is homogenized with two homogenization