European Journal of Mechanics A/Solids 50 (2015) 87–99

Contents lists available at ScienceDirect

European Journal of Mechanics A/Solids

journal homepage: www.elsevier.com/locate/ejmsol

Anisotropic large deformation of geometrically architectured unfilled silicone membranes

L. Meunier [a, c, 1], G. Chagnon [b, *], D. Favier [b], L. Orgéas [a, c]

[a] CNRS, 3SR Lab, F-38000 Grenoble, France
[b] Université de Grenoble/CNRS, TIMC-IMAG UMR 5525, Grenoble, France
[c] Univ. Grenoble Alpes, 3SR Lab, F-38000 Grenoble, France

ARTICLE INFO

Article history:
Received 4 October 2013
Accepted 5 November 2014
Available online 13 November 2014

Keywords:
Architectured material
Homogenisation
Anisotropy

ABSTRACT

Many applications, especially in the medical field, need the use of highly deformable membranes with required anisotropic properties. The present work is a contribution towards the processing, characterisation and modelling of anisotropic hyperelastic membranes. An unfilled silicone rubber with perfect hyperelastic behaviour is used. The anisotropy is generated by adding orientated crenels on the upper and lower surfaces of thin membranes during their elaboration. The influence of the relative orientation of the crenels on the mechanical response is characterised by performing tensile tests combined with kinematic field measurements by Digital Image Correlation. Two modellings are proposed. First, a simple analytical equivalent membrane model is proposed aiming to represent the behaviour of the architectured silicone membranes without any more parameter than those used in the hyperelastic constitutive equation of the silicone rubber. Second, the effective properties of the membranes are obtained by an a homogenisation approach with multiple scale asymptotic expansions written in the framework of hyperelasticity and by solving localisation problems on Representative Elementary Volumes with a finite element software. Finally, the experimental results are compared with predictions of two modelling, both approaches are equally efficient to describe them.

1. Introduction

Architectured materials take a place more and more important in many applications (Dunlop and Brechet, 2009) due to their specific properties including mechanical properties (Bouaziz et al., 2008; Bouaziz, 2013; Fleck et al., 2010), especially in medical applications. They can be used at different scales (Bréchet and Embury, 2013), from the molecular scale (Pouget et al., 2010) with biomolecules (Patterson et al., 2010) to materials for tissues (Kidoaki et al., 2008; Ma, 2008; Chen et al., 2008). The ability of materials to exhibit anisotropic behaviour is a key point to mimic living tissues. These materials are inspired from industrial materials, since there exist many different microstructures classically studied as foams or cellular materials (Gibson and Ashby, 1982, 1988; Jacobsen et al., 2008; Melchels et al., 2010) or composite materials (Laszczyk et al., 2008) like manufactured woven or non-woven two dimensional (2D) textiles. The design of such structures permits to obtain very particular and non classical properties (Ashby, 2013).

These materials are often anisotropic due to the orientation of the material microstructure in some privileged directions. The knowledge of these properties is a key point for their use in real structures. Such structures are usually periodic with a Representative Elementary Volume (REV) that is repeated in space. The design of such structures needs the use of finite element (FE) calculations to optimise them. But the creation of the geometry and the mesh of such structures necessitates a large number of elements which leads to non-usable FE models, as the calculation time is not compatible with an optimising process.

Instead of considering the geometrical details of the architectured material, it is preferred to use an equivalent constitutive equation that permits to describe the mechanical behaviour of the REV of the architectured material. The best way is to propose a simple analytical form that can easily be implemented in finite element codes. This allows to optimise a structure and to take into account the microstructures of the architectured material without a

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* Corresponding author. Fax: +33 4 76 76 88 44.
E-mail address: gregory.chagnon@imag.fr (G. Chagnon).

[1] In memory of Luc Meunier.

http://dx.doi.org/10.1016/j.euromechsol.2014.11.002

disproportionate number of elements. In this way, many works were developed to propose an equivalent constitutive equation for architectured materials. The reader can for example refer to Talbi et al. (2009) for cardboard, Hard af Segerstad et al. (2008) for honeycombs, Toll (1998) for entangled fibrous materials or Holzapfel et al. (2000) for living tissues.

The difficulty is often to validate analytical model on experimental results because of non-linear phenomena often present in these materials as for example plasticity, damage or viscoelasticity. In this paper, it is proposed to develop an architectured anisotropic hyperelastic material based on an unfilled silicone rubber and to write an equivalent constitutive equation easily usable in finite element codes. The paper focuses on a methodology which starts from experimental measures to analytical equations. It details all the steps of an equivalent modelling and permits to validate experimentally an analytical constitutive equation for architectured materials.

In Section 2, the process to elaborate architectured periodic silicone structures is detailed and the experimental devices to fabricate the specimens are presented. In Section 3, experimental results on the silicone rubber constituent material and on the architectured material are presented. In Section 4, an equivalent analytical anisotropic hyperelastic constitutive equation is written by the superposition of the contribution of each element of the REV *i.e.* the core membrane and the crenels. In Section 5, the theoretical basis for the homogenisation method with multiple scale asymptotic expansions for periodic structures are detailed and implemented in a finite element code to evaluate the equivalent properties of REV of crenellated silicone membrane. In Section 6, the ability of the two modellings to represent experimental data are discussed. Finally, some concluding remarks close the paper.

2. Experimental procedure

2.1. Architectured membranes: design and processing

To avoid interface problems such as those often encountered in usual fibre reinforced composite materials, an approach based on a unique material and geometrical reinforcement was here preferred.

An unfilled silicone rubber formulation (RTV141, Bluestar Silicones, France) was chosen. The mechanical behaviour of the material was studied by Meunier et al. (2008) and Rey et al. (2013). It was chosen due to its very interesting properties: it allowed the design and the processing of nearly hyperelastic architectured membranes, with reduced hysteresis and Mullins effect on the contrary of filled silicone rubber (Machado et al., 2010, 2012a, b). Compared with the silicone studied in Meunier et al. (2008), the curing time was here increased from 150 to 360 min in order to strengthen the membranes and to saturate the reticulation (Rey et al., 2013). After processing, a very weak Mullins effect was observed but it could be considered as negligible.

The upper and the lower external surfaces of the flat silicone membranes were ascribed geometrical motifs, *i.e.* two lattices of parallel crenels (see Fig. 1 for the dimensions of the crenels) with a relative orientation 2α between the upper and lower crenels (see Fig. 2). This type of architecture was chosen because it ensures an anisotropic response of the membranes and no out of plane bending modes while in-plane stretching can be observed.

Such architectured membranes were processed by injection moulding. For that purpose, a specific mould was designed, as shown in Fig. 3. It is composed of two 16 cm diameter circular crenellated metallic plates which are locked on each side of a holed plate. The holed plate is equipped with injection gates in order to inject the uncured silicone into the mould before its curing. The two crenellated plates can be fixed separately in any wished angular position. Thus, a single apparatus permits to elaborate many architectured mesostructures, by adjusting the angle 2α between the upper and lower crenels directions. Finally, the mould was used to process circular crenellated plates, with six angles 2α: 25°, 45°, 65°, 115°, 135° and 155°. An example is shown in Fig. 3.

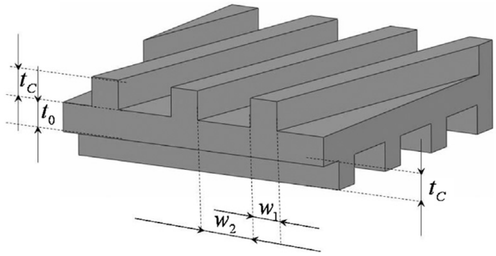

Fig. 1. Sketch and dimensions of the studied architectured membranes: $t_0 = t_c = 1$ mm, $w_2 = 2w_1 = 2$ mm.

2.2. Mechanical characterisation

Tensile, pure shear and bulge tests were performed on the bulk silicone rubber to analyse and model its behaviour, as in Meunier et al. (2008). The architectured membranes were also subjected to tensile loadings. For that purpose, rectangular specimens were cut from the processed crenellated plates. The specimen cutting was such that their initial length L_0 was parallel to the bisection of the crenels, as shown in Fig. 2. Likewise, by taking into account the constraints imposed by the processing route and by the testing conditions, the maximum number of crenels along the width of the specimen was used. For angles of 25°, 45°, 65°, 115°, seven crenels were used, but larger values of the angles lead to very large sample which were not compatible with tensile test hypothesis, thus only five crenels were used for 135° and three for 155°.

Whatever the tested sample, the tensile and pure shear tests were realised on a universal mechanical testing machine (MTS 4M). This machine was equipped with a 250 N load cell used to measure the tensile force F. Together with the initial sample width h_0, F was used to estimate the nominal tension $T = F/h_0$ required to deform the membranes.

Furthermore, prior all tests, the external surfaces of each specimen were coated with a random pattern made of small speckles (it can be seen on the surface of the specimen in Fig. 2) in order to allow the measurement of local strain fields on the samples surface with digital image correlation (DIC). For that purpose, the 7D DIC software was also used for the tensile and pure shear tests (Vacher et al., 1999). For the bulge tests (Machado et al., 2012a, b), stereo digital image correlation (SDIC, Orteu (2009)) was used, only the top of the bulge test was treated, as it represents an equibiaxial loading.

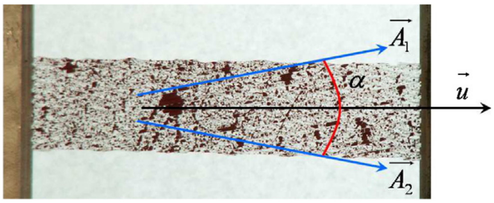

Fig. 2. Tensile rectangular specimen cut from the processed circular plate shown in Fig. 3. Definition of the relative orientation 2α between the upper and lower crenels. The specimen is mounted in the gripping system of the tensile testing machine. It is also coated with a random pattern of small speckles to allow DIC measurements (Meunier et al., 2008).