On the importance of anisotropy in biological materials: application to aortic tissues

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***Abstract*— Modelling of biological tissues in numerical simulations requires an accurate choice of the constitutive laws, whose influence could be determinant to obtain reliable results. Although some default materials are already available in commercial software, they might be inappropriate to describe the complex and anisotropic behaviour of soft tissues. The aim of this work is the implementation of a user-defined material, which allows to model in ANSYS LS-DYNA a hyperplastic matrix with two different families of embedded fibres, whose directions can be locally imposed. Finite element simulations on a biological heart valve and a reconstructed aortic root with physiological load were carried out. Stresses comparison in the valve and in the aortic root between the user-defined anisotropic material and an isotropic one show that anisotropy generates more realistic stress fields .**

***Keywords*—Anisotropic, constitutive law, user-defined material, finite element.**

I. INTRODUCTION

THE capability of capturing the complex behaviour of biological tissue is one of the main issues for a correct biomechanical modelling. In the literature, many authors highlighted the importance of material anisotropy of soft tissues [1-3]. In this light, in order to carry out reliable numerical analyses on heart valves and vessels, the presence of different families of oriented fibers has to be taken into account.

Although some material models have already been implemented in most commonly used commercial software, sometimes the nature of the material or the peculiarity of the investigation require more accurate constitutive equations. Nevertheless, constitutive models are a simplified representation of a complex reality and need a thorough validation. Experimental data are needed to extract the parameters that give relevance to the material model.

In this work we present a versatile anisotropic constitutive model implemented in ANSYS LS-DYNA, which allows to describe a hyperplastic matrix with two different families of embedded fibres, whose directions can be locally imposed. The relevance of this model is exploited in finite element simulations on a biological aortic valve and on a reconstructed aortic root.

II. MATERIAL AND METHODS

A. Material Description

The subroutine implemented for ANSYS LS-DYNA solver worked as a user-defined material accounting for the presence of two families of embedded fibres that run in preferred directions. The following form of the strain energy function was used:

$$\mathrm{W} = \overline{\mathrm{W}}_{\mathrm{iso}} + \mathrm{W}_{\mathrm{aniso}} + \mathrm{W}_{\mathrm{vol}} \tag{1}$$

$$\overline{W}_{\mathrm{iso}}(\bar{\mathbf{C}}) = C_{10}(\bar{I}_1 - 3) + D_1\left[e^{D_2(\bar{I}_1 - 3)} - 1\right]$$

$$W_{\mathrm{aniso}}(\boldsymbol{C}, \boldsymbol{a}_{04}, \boldsymbol{a}_{06}) = \frac{k_1}{2k_2}\left[e^{k_2(I_4-3)^2} - 1\right] + \frac{k_3}{2k_4}\left[e^{k_4(I_6-3)^2} - 1\right]$$

$$W_{\mathrm{vol}}(J) = \frac{k}{2}(J-1)^2$$

where $\overline{W}_{\mathrm{iso}}(\bar{\mathbf{C}})$ describes the isotropic behaviour of the collagenous matrix in which the fibres are embedded and W_{aniso} conveys the anisotropic behaviour typical of the soft tissues. I_4, I_6 are the pseudo-invariants of $\mathbf{C}$ and are defined from the unit vectors $\boldsymbol{a}_{04}, \boldsymbol{a}_{06}$ describing the directions of the fibres in the reference configuration. This term has been recently revised by Nolan et al. [1] with respect to the one described in the model of Holzapfel and Odgen [2].

B. Fibres Orientation

In order to give consistence to the anisotropic term W_{aniso}, the definition of a local coordinate system for each element, centered in its centroid, is mandatory. Based on the works of Driessen et al. [4,5] for the valves and Alastrue et al. [6] for the vascular vessels, a local coordinate system at each element was defined according to the principal stress directions, obtained with *ad hoc* pre-analyses (right panels in Fig. 1). The local coordinate system for the leaflet elements was spanned by eigenvectors referring to the circumferential and radial directions, while for the aortic root axial and circumferential directions were found. The LS-DYNA input files of the simulations were modified with MATLAB and a specific coordinate system for the elements was set locally.

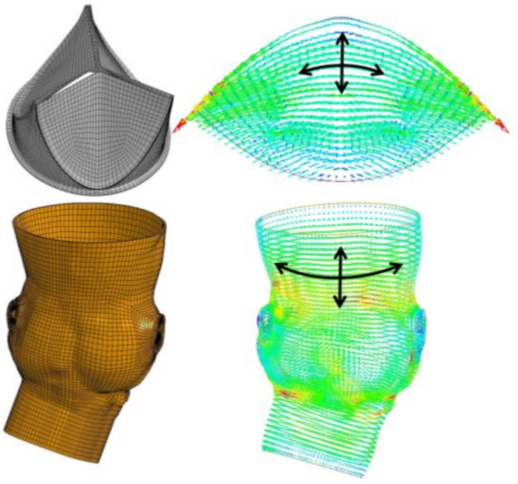

Fig. 1 Models used in the simulations and principal stress directions used to define the local coordinate systems for each elements.

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C. Aortic Valve FE Simulations

A generic tri-leaflets aortic valve (Fig.1, top) with a diameter of 25 mm, discretized with 10,812 hexahedral reduced integrated solid elements was considered. Two cycles, representing a physiological load, were carried out imposing the pressure drop directly to the leaflets. The orientations for the two families of fibres were set to coincide with the axes of the local coordinate systems. Material parameters for the constitutive model in (1) were obtained by means of nonlinear regression analysis of biaxial data from Sacks et al. [7].

D. Aortic Root FE Simulations

An aortic root (Fig.1, bottom), reconstructed from CT images and discretized with 21,824 hexahedral fully integrated solid elements, was used. Two cardiac cycles were carried out imposing the pressure drop to the internal wall. In this case, the orientations of the two families of fibres were imposed considering an angle ±50° [8] with respect to the local axial direction, representing an average of the three layers composing the aorta. Experimental data from Holzapfel et al. [9] were considered.

Simulations considering the material as isotropic were also performed. The isotropic part of model (1) was fitted to average experimental data from Sacks et al. and Holzapfel et al. for the valve and the aorta respectively.

All meshes were created with ALTAIR Hypermesh and the simulations were carried out with ANSYS LS-DYNA 971 release 9.0.

III. RESULTS

The analyses showed how the anisotropy influences the stress field in the models (Fig.2). In particular, the presence of the fibres allowed us to observe different areas of stress concentration during the opening of the valve and the pressurization of the aorta. It is also possible to notice the influences in the structural kinematics; the opening area in the anisotropic valve was a 5% bigger than for the isotropic case.

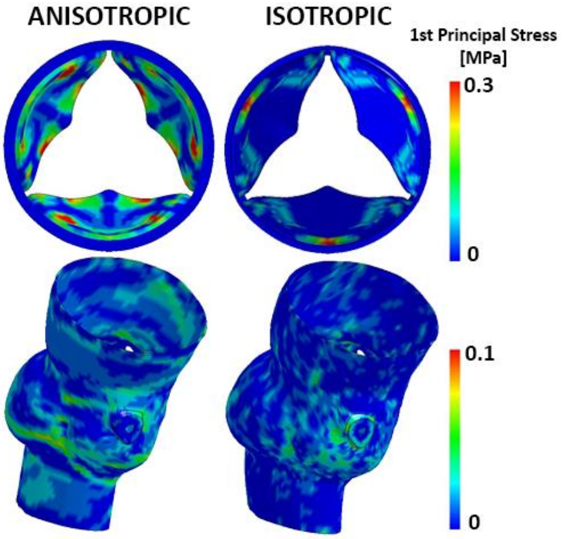

Fig. 2: Comparison of 1st principal stresses obtained from the simulations of the valve and the aortic root with both anisotropic and isotropic material laws.

IV. CONCLUSION

The main relevance of this work is the implementation of a user-defined material, which allows to model in ANSYS LS-DYNA a hyperplastic matrix with two different families of embedded fibres, whose directions can be locally imposed. This user-defined material could be used in structural simulations as well as in Fluid-Structure Interaction simulations, which involve the coupling between valves and vessels with blood. This material description is intended to be a more elegant alternative to the so called multilayer composite approach [10], commonly used in LS-DYNA to model two families of fibres but introducing a discontinuity of the strain and stress fields.

More investigations are required to analyse the influence of the anisotropy with FSI simulations and how the orientation of the fibres influences the material behaviour.

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